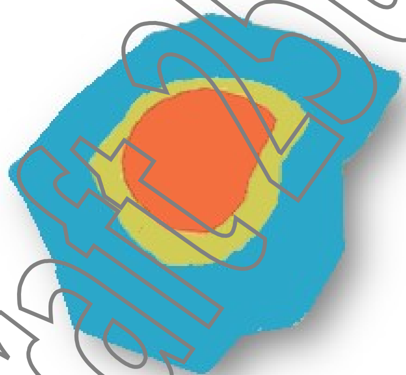
# International Handbook on the Assessment of Odour Exposure using Dispersion Modelling



**Handbook Odour Exposure Modelling**



Olores.org

AMIGO

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# Contents

## International Handbook on the Assessment of Odour Exposure using Dispersion Modelling

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In addition, seven *Task Groups* (TG) were created. Each was assigned a leader/leaders:

- TG1: Definitions (Imelda Shanahan)
- TG2: Meteorology (Christelle Escoffier / Jennifer Barclay/ Loren Trick)
- TG3: Emissions and source characterisation (Andrew Balch / Roberto Bellasio)
- TG4: Dispersion algorithm (Giuseppe Brusasca / Gianni Tinarelli)
- TG5: Output dose-response (Rodrigo Rosales)
- TG6: Reporting (initially Tiziano Zarra / Giusy Oliva, later replaced by Silvia Trini Castelli/ Geordie Galvin)
- TG7: Other approaches (Carlos Nietzsche Diaz)

Monthly meetings were held online on the last Thursday of each month at alternative times separated by 12 hours to have a more equitable distribution of time slots for volunteers from different time zones. The first meeting took place on the 27th of August, 2020. The first draft was ready for comments on the 30th of June, 2022. The second draft was prepared for comments on the 25th of May, 2023 The final version was released on XX/XX/XXXX.

This handbook is here thanks to the active contributions of these volunteers (in alphabetic order):

| **Name** | **Company \ Research Institute** | **Country** |
|---|---|---|
| Andrew Balch | Air Environment | Australia |
| Carlos Nietzsche Diaz | Ambiente et Odora | Spain |
| Christelle Escoffier | Wood Environment & Infrastructure Solutions the United Kingdom, | UK |
| Dietmar Öttl | Dept Housing, Energy, Tech.of the Gov. Styria | Austria |
| Emmanuelle Duthier | Numtech France, | France |
| Eva Berbekar | Uppenkamp + Partner, Germany | Germany |
| Geordie Galvin | Astute Environmental Consulting Pty Ltd | Australia |
| Gianni Tinarelli | Arianet | Italy |

| | | |
|---|---|---|
| Giuseppe Brusasca | Arianet | Italy |
| Giusy Oliva | University of Salerno | Italy |
| Günther Schauberger | University of Veterinary Medicine | Austria |
| Heike Hauschildt | Olfasense GmbH | Germany |
| Helga Lauerbach | Lohmeyer | Germany |
| Hellen Arichábala | IKANI S.A. | Ecuador |
| Imelda Shanahan | TMS Environment Ltd | Ireland |
| Jean-Michel Guillot | IMT Mines Ales France | France |
| Jennifer Barclay | Atmospheric Science Global Ltd | New Zealand |
| Laura Hinderink | Uppenkamp + Partner, Germany | Germany |
| Loren Trick | LT Environmental LLC | USA |
| Osnat Yosef | Ministry of Environment of Israel | Israel |
| Phyllis Diosey | Hazen and Sawyer United States of America, | USA |
| Roberto Bellasio | Enviroware srl | Italy |
| Rodrigo Rosales | Environmental Assessment Service of Chile, | Chile |
| Rossella Prandi | Simularia | Italy |
| Silvia Trini Castelli | CNR-ISAC (National Council for Research) | Italy |
| Tiziano Zarra | Università degli Studi di Salerno | Italy |

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| | | |
|---|---|---|
| Andrea Peña | Environmental Assessment Service of Chile | Chile |
| Andrea Rossi | Progress SRL. | Italy |
| Angie Wanger | Trinity Consultants | USA |

| | | |
|---|---|---|
| Catalina Pérez | Environmental Assessment Service of Chile, | Chile |
| Claudio Dipietro | Progress SRL | Italy |
| Constanza Fariña | Variable Ambiental | Chile |
| Débora Lia Perazzoli | Envex | Brazil |
| Dov Skibin | Ministry of Environment | Israel |
| Eric Concepción | Ceimic | Peru |
| Hélène Piet Sarnet | Egis Group France, | France |
| Hugo van Belois | NEN Commission on odour | Netherlands |
| Jerome Godart | Atmo Normandie France, | France |
| Kenny K M Lok | EnviPro Technology Company Limited, China, | China |
| Laura Capelli | University Politecnico di Milano, Italy, | Italy |
| Luis Diaz | Particulas Chile, | Chile |
| Manuel Santiago | Advisian Spain, | Spain |
| Martí de Riquer | Meteosim | Spain |
| Nick Jones | Olfasense | UK |
| Oliver Olang | Element Qatar, | Qatar |
| Rafael Geha | Ambiental RB, | Brazil |
| Rebecca Kavanagh | Ambiente et Odora | Spain |
| Roberto Sozzi | Independent Scientific Consultant | Italy |
| Sarveshkumar Sharma | Indian Institute of Technology Bombay, | India |
| Valérie Nastasi | Suez | France |

# Foreword

This document has been prepared by a group of experts under the umbrella of the website olores.org and the *International Environmental Society of Odour Managers* (AMIGO, for its acronym in Spanish).

This handbook shall be given the status of an international document. That means that the authors have tried to include as many international references as possible while striving to create a valuable worldwide handbook.

# Introduction

Odour issues are currently one of the major causes of environmental grievances worldwide and, in some countries, are routinely the cause of most environmental complaints to regulatory authorities (Schusterman, 1992; Kaye & Jiang, 2000). There continue to be multiple reasons for the prominence of odour complaints, including an unrelenting urban expansion of residential areas into land-use areas once predominantly agricultural with few largely isolated facilities; increases in facility operations and their size; increasingly higher aesthetic, and environmental expectations of citizens, who are less familiar and tolerant of odours than in the past, and concerns over potential health risks from airborne odorous substances.

In most countries, environmental regulations cover the most common air pollutants, including $NO_2$ or $SO_2$. The criterion is based on the occurrence of health effects following short- and/or long-term exposure to the contaminants. There is slight health risk variation between jurisdictions, states, and countries. However, odour regulation tends to be much more varied across a broad spectrum: from having little to no specific mention in environmental legislation to extensive and rigid requirements that include a combination of odour source testing, odour dispersion modelling, ambient odour monitoring, setback distances, process operations, and odour control procedures. Odour legislation can be highly variable from one country to the next, and it can also be highly variable from one jurisdiction to the next within the same country (Bokowa et al., 2021).

For regulatory purposes, much of the focus of attention in the last couple of decades has been on establishing odour guidelines in the hope of bringing consistency to the control and regulation of odours. With the focus on setting rules, less effort has been spent in a variety of jurisdictions on assessing the best tools suited for the computation of odour impacts concerning accurate emission rates, source characterisation, and the critical role of local meteorology, interpretation of modelled results, or the suitability and applicability of one dispersion model over another. The handbook addresses several key issues central to the theme of effective management and odour regulation.

This handbook is a collaborative work by more than 50 international odour experts from seventeen countries, including; Australia, Austria, Belgium, Brazil, Chile, China, Ecuador, France, Germany, Ireland, Italy, New Zealand, Peru, Qatar, Spain, United Kingdom and the United States of America.

Experts within this group met monthly in 2020, 2021, 2022 and 2023 via teleconference to discuss different aspects of this work. Six special Task Groups (TGs) were initially created. Later a further TG was also created to deal with all aspects not included in previous chapters. Each task group had between 5 and 10 members responsible for writing and reviewing individual sections within each task group. The task groups were the following:

- TG1 - Definitions;
- TG2 - Meteorology;
- TG3 - Emissions and Source characterisation;
- TG4 - Dispersion Algorithms;

- TG5 - Output dose-response;
- TG6 - Reporting;
- TG7 - Other approaches.

The structure of this handbook follows more or less the division of TGs. The exception is TG7, which has been located after TG5, leaving TG6 reporting as the last.

This handbook on odour dispersion modelling aims to guide the use of dispersion modelling of odours.

# 1. Scope

This handbook presents different aspects needed for evaluating odour exposure by using dispersion modelling to help the final user. This handbook applies to

- calculating the odour/odorant level in ambient air from odour emission sources;
- choosing appropriate odour models depending on a project's specific conditions, in particular, dealing with complex situations;
- selecting appropriate meteorology.
- understanding the dose-response criteria and how the Frequency-Intensity-Duration-Offensiveness-Sensitivity scheme fits in a result; and
- the preparation of an odour report based on the results of a model.

# 2. Terms, Definitions, Abbreviations and Symbols

## 2.1 Terms and Definitions

**ADMS**
Atmospheric Dispersion Modelling System developed by Cambridge Environmental Research Consultants (CERC) in the United Kingdom and approved as the regulatory model in some countries.

**AERMAP**
AERMOD program geophysical processor.

**AERMET**
AERMOD program meteorological processor.

**AERMIC**
American Meteorological Society Environmental Protection Agency Regulatory Model Improvement Committee.

**AERMINUTE**
Meteorological processor to re-process the ASOS 1 and 5-minute data.

**AERMOD**
A steady state Gaussian US EPA regulatory plume dispersion model.

**AERSCREEN**
US EPA guideline model for screening applications. Includes many of the AERMOD algorithms.

**Albedo**
is the amount of solar radiation reflected by some surface and is often expressed as a percentage or a decimal value. Overall, albedo is a measure of the reflectivity of the surface of the Earth.

**AMS**
Measuring system permanently installed on-site for continuous monitoring of emissions or measurement of peripheral parameters.

**Annoyance**
The complex human reactions that occur as a result of immediate exposure to an ambient stressor (odour) that, once perceived, causes negative cognitive appraisal that requires a degree of coping.
NOTE: Annoyance may or may not lead to ‘nuisance’ and a complaint action.

**AODM**
Gaussian plume model. Austrian regulatory odour model.

**AQMG**
US Air Quality Management Group.

**ARIA Impact**
Gaussian plume model developed by ARIA Technologies, France and also used in other countries.

**ARW**
Advanced Research Weather and Forecast Model.

**Atmospheric Stability**
Atmospheric stability is a measure of the tendency for air to move vertically. The dominant influences on this vertical movement are atmospheric temperature and pressure.

**AUSPLUME**
Gaussian plume model developed by EPA of the Australian State of Victoria. AERMOD replaced AUSPLUME in January 2014.

**AUSTAL**
The official German Federal Environmental Agency regulatory model. AUSTAL (formerly AUSTAL2000 or AUSTAL2000g) is a Lagrangian particle model. Based on the LASAT model.

**Back-trajectory**
Back-in-time trajectory of an airborne parcel.

**Bowen Ratio**
The ratio of sensible heat flux to latent heat flux densities.

**BPIPPRM**
BPIPPRM is a standalone program that should be used to prepare Building Downwash data for dispersion models.

**CALMET**
Diagnostic Meteorological Model.

**CALPUFF**
Lagrangian Puff Dispersion Model.

**CALPOST**
Post processing program of CALPUFF.

**CFD**
Computational Fluid Dynamic Models (example models are WRF-CFD, OpenFOAM, Code_Saturne, FLOW-3D, FLUENT).

**Copernicus**
The European Union's Earth Observation Programme implemented by ECMWF

**COSMO**
A group of meteorological and military services within Europe and Russia who have developed and maintain the NWP model COSMO

**CTDMPLUS**
A US EPA Complex Terrain steady-state Gaussian plume model. Developed for convective conditions. It is a refined Gaussian plume model.

**CTSCREEN**

Screening version model of CTDMPLUS.

**Duration**

The duration of the odour occurrence is how long an individual is exposed to odour in the ambient environment.

**ECMWF**

ECMWF is the European Centre for Medium-Range Weather Forecasts, producing global numerical weather predictions and other data for their Member and Co-operating States and the broader community. ECMWF is an independent intergovernmental organisation supported by 35 states.

**EQs**

Empirical Equations. Screening methods with regulatory status used in Europe to determine separation distances.

**EPA**

Environmental Protection Authority. Used in the general term to apply to more than one country.

**ETA levels**

ETA (greek letter $\eta$) is a vertical coordinate for atmospheric models, defined with a steplike representation of topography, with mountains formed of the model's grid boxes. The vertical coordinate surfaces are quasi-horizontal, intersecting model mountains or forming their nearly horizontal upper sides.

**Eulerian Models**

Eulerian models are based on the observation of the atmospheric motion at a specific location in space while time passes. “Location” must not be intended as a point but as a volume of the atmosphere. Eulerian models discretise the simulation domain with volume grids and solve the conservation equations within each volume.

**European odour unit**

The amount of odorant(s) that, when evaporated into one cubic metre of neutral gas at standard conditions, elicits a physiological response from a panel (detection threshold) equivalent to that elicited by one European Reference Odour Mass (EROM), evaporated in 1 $m^{Acce}$ of neutral gas at standard conditions.

**FLEXPART**

Lagrangian particle model used in Austria / Germany / Norway. Developed at BOKU Vienna, the Technical University of Munich and NILU.

**Frequency**

The frequency of the odour occurrence is how often an individual is exposed to odour in the ambient environment.

**Gas Detector Tube**

Gas detector tubes are sealed glass tubes containing reactive chemicals coated onto solid materials. The chemicals change colour when the target substances are present in the test gases and the extent of the colour change is proportional to the concentration of the target analyte.

**Gaussian Models**

Under certain idealised conditions (homogeneous turbulence, constant wind direction and speed), the mean concentration of a pollutant emitted by a point source has a Gaussian distribution. The atmospheric dispersion models based on this approach are called Gaussian models.

**GFS**
GFS (Global Forecasting System) is a global numerical weather prediction system containing a global computer model and variational analysis run by the United States National Weather Service (NWS).

**GRAL**
The GRAZ Lagrangian particle model. Developed at GRAZ University of Technology and the Regional Governments of Styria and Tyrol, Austria.

**GRAMM**
Prognostic mesoscale model used as a wind field model in GRAL.

**Harmonie**
A NWP forecast system operated at 2.5km horizontal resolution over a domain that covers Iceland and the surrounding seas. HARMONIE is the abbreviation from HIRLAM-ALADIN Research on Mesoscale Operational NWP In Europmed (in this case Euromed is itself an abbreviation of European-Mediterranean, and ALADIN is A Limited Area Dynamic International model)

**Hedonic (odour) tone**
Hedonic tone is a property of an odour related to its pleasantness. It is assessed in a classificatory testing process and usually varies between “extremely pleasant” and “extremely unpleasant”.

**HIRLAM**
A NWP forecast system developed by the international HIRLAM programme, a cooperation of European meteorological services.

**HRRR**
A NWP model operated by NCEP over North America with a 3km resolution, radar data assimilation every 15 minutes and a complete data refresh every hour.

**Humidity**
General term related to the amount of water vapour in the air.

**IFS**
A global numerical weather prediction system developed and maintained by ECMWF

**Intensity**
How strong an odour is perceived to be. Odour intensity describes the relative magnitude of an odour sensation as experienced by a person.

**Intermittent sources**
Sources that produce short-term peaks in odorant emissions at a particular time of the day (for example, because of loading/unloading or cleaning operations).

**Instrumental Odour Monitoring Systems (IOMS)**
Instrumental Odour Monitoring Systems (also known as e-noses) are electronic devices with different types of sensors that can carry out either of the three necessary functions to identify odour in ambient air: presence-absence, classification and measurement.

**ISCST3**
Industrial Source Complex Short-Term Model. Steady State Gaussian plume model that was the US EPA near field regulatory model until it was superseded by AERMOD and phased out in 2006.

**Klug-Manier**
A German stability classification system based on wind speed and cloud cover.

**LAPMOD**
Lagrangian Particle Model developed by Enviroware. The model is part of ARIES, the official Italian modelling system for nuclear emergencies operated by ISPRA and the EPA of Emilia-Romagna, Italy.

**LASAT**
Lagrangian particle model, developed by Ingenieurburo Janicke Gesellschaft fur Umweltphysik.

**Lagrangian Model**
Lagrangian models are based on tracking each small portion (e.g., particles) of the atmospheric flow as it moves while time passes. Atmospheric Lagrangian models determine the position of each particle and its properties (e.g., associated mass) as a function of time.

**Leak Detection and Repair (LDAR)**
Leak detection and repair is the process of identifying leaking equipment and repairing it to minimise emissions.

**LOWWIND**
AERMOD low wind options.

**MAKEMET**
A program that interfaces with AERSCREEN to generate a site-specific matrix of screening meteorological conditions for input into AERMOD.

**MMIF**
Mesoscale Model Interface Program developed by US EPA that converts prognostic meteorological model output fields to the parameters and formats required for direct input into dispersion models.

**MM5**
Penn State University (PSU) / National Centre for Atmospheric Research (NCAR) Mesoscale Model, now superseded by Weather Research and Forecasting (WRF) Model.

**Mixing height**
Height of the layer adjacent to the ground over which an emitted or entrained inert non-buoyant tracer will be mixed (by turbulence) within a time scale of about one hour or less.

**NAM**
A NWP model operated by NCEP that generates multiple grids over North America.

**Non-static receptors**

Receptors that are not continuously at a certain point. For example, people returning from work at a particular hour or tourist locations that get occupied during a certain period of the year.

**Nuisance**

Nuisance is the cumulative effect on a person or group of people caused by repeated events of annoyance over an extended period, leading to modified or altered behaviour.

Definition adapted from *Van Harreveld, A.P.: From odorant formation to nuisance: new definitions for discussing a complex process, Water Science & Technology 44:9-15 (2001)*

**Odour Concentration**

The concentration of an odorant mixture is defined as the dilution factor to be applied to an effluent to be no longer perceived as odorant by 50% of people in a population sample. By definition, the odour concentration at the detection limit is 1 $ou_E/m^3$.

**Odour Impact Assessment (OIA)**

Odour impact assessment is the process of qualitatively and / or quantitatively assessing the impact of odour emissions on a neighbourhood or receptor.

**Odour unit**

Odour concentration of an odorous sample at the odour threshold. Any odour unit measured outside of the scope of EN 13725.

Note: Any measurement carried out in Europe before 2002 (date of first EN 13725) measured “odour units” instead of “European odour units”. p.e with a different flow and velocity of odorous air emanating from the ports, with a number lower than four assessors, or with no methodology to evaluate the performance of assessors before a measurement.

**Odour emission rate (OER) / Odour flow rate**

Quantity of odour units which cross a given surface per unit of time.

**ÖNORM**

A standard published by Austrian Standards International, the Austrian member of the European Committee for Standardisation (CEN) and the International Organisation for Standardisation (ISO).

**Offensiveness**

The character relates to the ‘hedonic tone’ of the odour, which may be pleasant, neutral or unpleasant.

**PMSS**

PMSS (Parallel Micro Swift and Spray) is the parallel version of the SPRAY Lagrangian Particle Dispersion Model, able to run also at the microscale at the level of street canyons, explicitly considering the presence of buildings and their effects on the mean flow, turbulence and dispersion”

**Particle-puff Approach**

A simplification of a three dimensional Lagrangian Particle method mixing a Puff approach (typically in the horizontal) and the solution of a Langevin equation (typically in the vertical) to describe the dispersion of a plume

**Pasquill-Gifford**

A stability classification system based on wind speed, cloud cover, and ceiling height.

**Peak-to-Mean**
Is the ratio between the short-term and long-term odour concentration. Short-term usually refers to a few seconds up to a few minutes, while long-term refers mostly to one hour.

**PRIME**
Building downwash algorithm whose development was funded by EPRI, the US Electric Power Research Institute.

**Receptor**
Location where odour concentration is measured or computed.

**QUIC**
The QUIC (Quick Urban & Industrial Complex) dispersion modelling system is a fast response urban dispersion model including a 3D wind field model called QUIC-URB, a transport and dispersion Lagrangian particle model called QUIC-PLUME, a pressure solver, QUIC-PRESSURE, and a graphical user interface called QUIC-GUI. QUIC is developed by the Lawrence Livermore National Laboratory, USA.

**RASS**
A radio acoustic sounding system which remotely measures temperature profiles in the atmosphere up to an average altitude of 1,000 metres.

**Sensitive receptor**
Sensitive receptors are receptor locations in the odour study area where routine or normal activities could experience adverse effect(s) from odour discharges from a facility. They include private residences, apartment houses, and other distinct residential areas, hospitals, nursing homes, rehabilitation facilities, schools and daycare facilities; public gathering centres, including public plazas and shopping centres; outdoor recreational public places, such as parks, playgrounds, campgrounds, and trailer parks. Office spaces and other external workspaces may also be considered sensitive receptors. Professional judgement should be applied to assess which receptors are the most sensitive for a specific study.

**Sensitivity**
Sensation and emotional responses by individuals to an odorous atmosphere at one time of their daylife/life and the location where the odour is perceived.

**SODAR**
A sonic distance and ranging system which remotely measures a vertical profile of wind speed, direction, thermal stratification and turbulence parameters up to an average altitude of 3,000 metres.

**Sonic anemometer**
Instrument that measures components of the wind vector by determining the effect of the wind on transit times of acoustic pulses transmitted in opposite directions across known paths. Wind speed will increase or decrease the speed of sound depending on whether it is a tailwind or a headwind. Measuring the speed of sound in both directions along that one axis allows the wind speed to be calculated. A two-axis or three-axis sensor can then be used to calculate horizontal or horizontal plus vertical wind speed and wind direction.

**SCICHEM**
The SCIPUFF model expanded to include the treatment of gas- and aqueous-phase chemical reactions and aerosol thermodynamics.

**SCIPUFF**
SCIPUFF (Second-order Closure Integrated PUFF model) is a time-dependent Gaussian

puff dispersion model that employs second-order closure turbulence modelling techniques to relate the dispersion rate to velocity fluctuation statistics.

**SPRAY**

Lagrangian Particle Dispersion Model distributed by ARIANET and ARIA Technologies and developed by an Italian / French research group involving the CNR (Italian National Research Council) and other Universities.

**Source Term Estimation**

Source Term Estimation (STE) algorithms are methods used to reconstruct the source of an atmospheric release, namely its location, time of emission and strength, starting from concentrations observed by sensors. STE methods include using a dispersion model, often in its backward or time-reversed configuration starting from measuring points, coupled to optimisation or probabilistic methods to infer the source parameters.

**Stack Tip Downwash**

Stack tip downwash is the capture of the plume in the downwind side of a stack close to it. It happens when the ratio between exit speed and wind speed at the height of the stack is smaller than 1.5. STD is more pronounced for large-diameter stacks.

**TA Luft**

German Air Quality control regulation, titled: "Technical Instructions on Air Quality Control" (*Technische Anleitung zur Reinhaltung der Luft*) and commonly referred to as TA Luft.

**TAPM**

TAPM (The Air Pollution Model) PC-based, nestable, prognostic meteorological and air pollution model driven by a Graphical User Interface, developed and maintained by The Commonwealth Science and Industrial Research Organisation (CSIRO), Australia.

**STAGMAP**

Stagnation Model Analysis, Medford, Oregon, SF6 tracer release under calm conditions.

**Topography**

Representation of surface features such as mountains, hills, rivers, and valleys.

**Unified Model (UM)**

A NWP and climate modelling software suite developed by the United Kingdom Met Office.

**Wind direction**

Orientation of the wind vector in the horizontal direction. Wind direction for meteorological purposes is defined as the direction from which the wind is blowing and is measured in degrees clockwise from true north. Wind direction determines the transport direction of a plume or puff in air quality modelling applications.

**WRF**

A public domain mesoscale NWP system designed for both atmospheric research and operational forecasting applications,

## 2.2. Abbreviations and Acronyms

| | |
|---|---|
| ADMS | Atmospheric Dispersion Modelling System |
| AFWA | Air Force Weather Agency (US) |
| ARW | Advanced Research Weather and Forecast Model |
| AQ | Air Quality |
| AQMG | Air Quality Management Group (US) |
| ASOS | Automated Surface Observing Systems |
| BT | Back-Trajectory |
| CCCS | Copernicus Climate Change Service |
| CERC | Cambridge Environmental Research Consultants |
| CFD | Computational Fluid Dynamics |
| COSMO | Consortium for Small-Scale Modelling |
| DWM | Diagnostic Wind Models |
| ECMWF | European Centre for Medium-Range Weather Forecasts |
| EPA | Environmental Protection Authority |
| EPRI | Electric Power Research Institute (US) |
| FAA | Federal Aviation Authority |
| FSL | Forecast Systems Laboratory |
| FDDA | Four-dimensional Data Assimilation |
| GDT | Gas Detector Tube |
| GFS | Global Forecast System |
| GUI | Graphical User Interface |
| HARMONIE | HIRLAM-ALADIN Research on Mesoscale Operational NWP In Europmed. ALADIN is A Limited Area Dynamic International model). |
| HIRLAM | High-Resolution Limited Area Model |
| HRRR | High-Resolution Rapid Refresh model |
| HYSPLIT | Hybrid Single-Particle Lagrangian Integrated Trajectory model |
| ISCST3 | Industrial Source Complex Short Term Model |

| | |
|---|---|
| IFS | Integrated Forecasting System |
| IOMS | Instrumental Odour Monitoring Systems |
| LCP | Lambert Conformal Projection |
| LDAR | Leak Detection and Repair |
| LPDM | Lagrangian Particle Dispersion Models |
| MM5 | Penn State University (PSU) / National Centre for Atmospheric Research (NCAR) Mesoscale Model, now superseded by WRF |
| MMIF | Mesoscale Model Interface Programme |
| NAAQS | National Ambient Air Quality Standards |
| NAM | North American Mesoscale Forecast System |
| NCAR | National Centre for Atmospheric Research |
| NCEP | National Centre for Environmental Prediction |
| NES | National Environmental Standards |
| NILU | Norsk Institut for Luftforskning (Norwegian Institute for Air Research) |
| NOAA | National Oceanic and Atmospheric Administration |
| NWP | Numerical Weather Prediction |
| NWS | National Weather Service |
| OAQPS | Office Of Air Quality Planning and Standards |
| OCD | Offshore and Coastal Dispersion Model |
| OIA | Odour Impact Assessment |
| OIC | Odour Impact Criteria |
| OER | Odour Emission Rate |
| PtMR | Peak-to-Mean Ratio |
| PBL | Planetary Boundary Layer |
| PDF | Probability Density Function |
| P&ID | Piping and Instrumentation Diagram |
| RAP | Rapid refresh numerical weather model |
| RASS | Radio Acoustic Sounding System |
| RDM | Reverse Dispersion Modelling |

| | |
|---|---|
| SMOD | Screening Model for Odour Dispersion |
| SODAR | Sonic Detection And Ranging |
| SOER | Specific Odour Emission Rate |
| STD | Stack Tip Downwash |
| STE | Source Term Estimation |
| TAPM | The Air Pollution Model |
| TIBL | Thermal Internal Boundary Layer |
| UM | Unified Model |
| US EPA | United States Environmental Protection Agency |
| VOC | Volatile Organic Compound |
| WWTP | Waste Water Treatment Plant |
| WRF | Weather Research and Forecast Model |

## 2.3. Symbols and Units

| **Symbol** | **Description** | **Unit** |
|---|---|---|
| $A$ | Area | $m^2$ |
| $c_{od}$ | Odour concentration | $ou_E/m^3$ |
| *EROM* | European Reference Odour Mass | µg n-butanol |
| *ou* | Odour unit | |
| $ou_E$ | European odour unit | |
| $p_s$ | Absolute pressure in stack | kPa |
| $q_{od}$ | Odour flow rate | $ou_E/s$ |
| V | Volume | $m^3$ |
| $\dot{V}$ | Volume Flow Rate | $m^3/s$ |
| Z | Dilution factor | |
| $\eta_{od}$ | Odour abatement efficiency | % |

# 3. Meteorology

## 3.1 Introduction

In science, engineering, and even social science disciplines, a model consists of equations defining individual processes. A model must be constructed or written and then calibrated by observation and sampling to have a predictive value.

A traditional mathematical model contains the following elements:

- assumptions and constraints;
- governing equations; and
- initial and boundary conditions.

Within the context of odour modelling, a model must describe how the vertical wind profile will develop as an air mass moves across the surface of the earth based on friction forces caused by land use. In addition, a model should deal with how the temperature profile of a column of air will develop throughout the day based on parameters like latitude, surface characteristics, cloud cover, and moisture. Last but not least, a model should address the variation in odour concentration downwind from a source based on the chaotic motions of odorants.

There are a number of different approaches to solving these questions. These separate approaches involve different equations, which are called algorithms. One approach is neither "correct" nor "incorrect" but may be described as yielding a better prediction of reality under certain conditions. Numerous varieties of models have evolved for specific uses, and today there are perhaps 100 atmospheric dispersion models mentioned in the literature.

In all cases, accurate inputs to the model are required to achieve reliable results. Meteorological parameters constitute an essential set of inputs to an odour model, along with information about the source(s) and the land surface above which the interactions between these inputs play out. This chapter discusses these meteorological parameters and their use within the various models.

## 3.2 Meteorological conditions

### 3.2.1 Introduction

A basic understanding of the motions and characteristics of the atmosphere is a prerequisite to assessing odour impacts using dispersion modelling. Therefore it is necessary to review some pertinent details about the layer of air within which we live and work (Stull, 2017). The atmosphere of Earth extends hundreds of kilometres from the surface before vanishing into space. However, most of the atmosphere's mass is located within the troposphere. The term troposphere derives from the Greek words *tropos* (rotating) and *sphaira* (sphere), indicating that rotational turbulence mixes the layers of air and so determines the structure and the phenomena of the troposphere. The troposphere extends from the ground surface up to an average altitude of about 11 kilometres (see Figure 3-1).

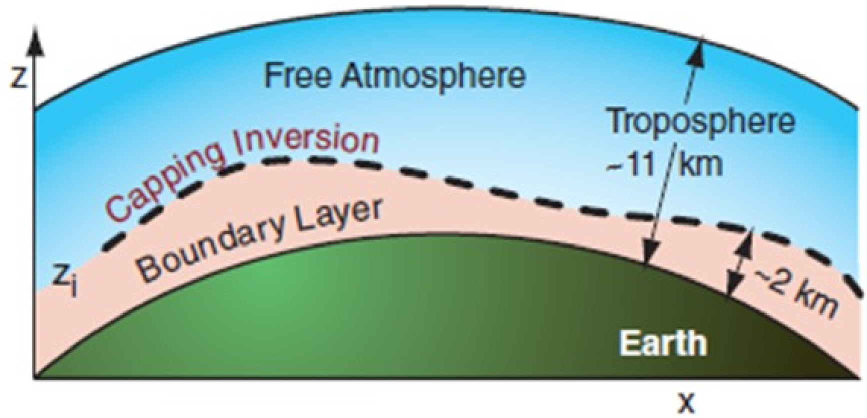



**Figure 3-1** Layers within the troposphere (Stull, 2017)

Within the troposphere, the layer closest to the Earth's surface is the Planetary Boundary Layer (PBL) or Atmospheric Boundary Layer (ABL). The PBL varies from a few hundred to perhaps a few thousand metres thick. The remainder of the air in the troposphere above the PBL is called the free atmosphere. All conditions within the PBL derive from solar radiation that reaches the ground surface and is absorbed. As the ground warms and cools in response to this incoming solar energy (insolation), the meteorological conditions of wind direction and speed, air temperature and humidity, air pressure, and atmospheric stability (the vertical temperature gradient) constantly change.

These meteorological conditions within the PBL create the weather people experience daily as hot/cold, wet/dry, windy/calm, and sunny/cloudy. The same meteorological conditions that create the weather are essential within the context of odour transport and modelling. However, the conditions are interrelated, and it is impossible to completely separate their meaning and impact into individual discussions. The following sections, therefore, provide a general discussion with brief details of each condition to help understand the challenges associated with dispersion modelling. This chapter is not meant to be a complete treatise on meteorology; the interested reader is encouraged to seek additional details in the reference material.

### 3.2.2 Insolation, Surface Heating, and the Energy Budget

The Sun drives all energy processes within the atmosphere. At the Earth's surface, a balance exists between insolation, sensible heating (during which a temperature change occurs between the surface and atmosphere), latent heating (during which a phase change occurs between the surface and atmosphere), and heat transport from the surface to the sub-surface. However, not all the solar radiation that reaches the Earth’s surface is absorbed by it, since a part of the radiation is reflected back to space by what is known as the Earth’s surface albedo. The albedo is defined as the fraction of the incident radiation that is reflected by the surface. Since the Earth’s surface is not uniform everywhere, the albedo varies widely from place to place depending upon the nature and composition of the underlying surface. For example, the albedo of a dense forest is very different from that of a freshly covered snow surface.

Sensible heat flux is related to atmospheric heating from below. The atmosphere is nearly transparent to incoming shortwave radiation from the sun. Daytime heating of the PBL is then accomplished by sensible heating from the underlying surface, which has absorbed a fraction of the incoming shortwave radiation. At night, the flux reverses direction as the surface loses sensible heat to the air above as illustrated in Figure 3-2.

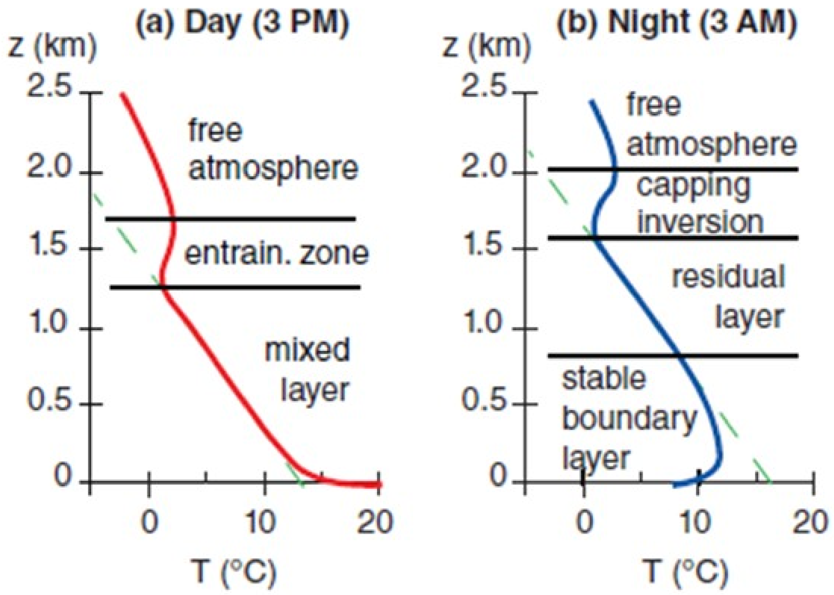



**Figure 3-2** Examples of boundary-layer temperature profiles during the day (left) and night (right) during fair weather over land. The adiabatic lapse rate is dashed. The heights shown here are illustrative only. (Stull, 2017)

This diurnal cycle varies by latitude and season. Cloud cover affects the daily energy budget at the surface, so cloud cover is an essential meteorological condition. Latent heat flux is related to phase changes of water: evaporation of soil moisture or surface water; transpiration by vegetation; or melting and sublimation of frozen surfaces. Where there is little surface water, the latent heat flux is near-zero (or even negative), and it has large positive values over warm bodies of water or hot, wet soils. It is generally negative over land during the local night time hours.

The Bowen ratio is the ratio between the sensible and latent heat fluxes. The Bowen ratio is smallest over oceans and wet land surfaces such as marshes and jungles. It is largest in deserts and drought-ridden locations. The Bowen ratio is related to the strength of vertical mixing within the PBL: larger Bowen ratios are associated with stronger, deeper vertical mixing.

### 3.2.3 Wind, Turbulence, and Buoyancy

When the air in direct contact with a warmed surface undergoes sensible heating, the air becomes less dense and begins to rise, and that vertical motion is called convection. Cooler and dense surrounding air moves to replace the warmer, less dense air. That lateral air motion is called advection, or wind. As the air mass moves along the ground surface, it interacts with surface features through friction, imparting a turbulent motion to the air by a process called mechanical mixing. The friction is quantified in terms of a roughness length that depends on the nature of the surface. This roughness length varies by nearly four orders of magnitude depending on whether the surface is open water, grass prairie, cultivated farm fields, mature forests, or dense urban areas. The result of this friction and mechanical mixing is to slow the horizontal movement of the air mass. The rising air mass also experiences turbulence, but it is associated with vertical motion due to the temperature gradient, and that turbulence is called convective mixing.

These mixing phenomena are important to our understanding of dispersion modelling since entrainment of the surrounding air during that mixing will cause dilution of any contaminants, including odour. The depth of air within the PBL in which mixing occurs is called the mixing height. Moving air masses at distances above the surface experience less interaction with surface features but are still subject to frictional forces, which cause turbulence and mixing.

Consider a mass of air moving horizontally and smoothly (laminar flow) over a stationary mass of air. Even though the molecules in the stationary air are not moving horizontally, they move about and collide. At the boundary separating the air layers, there is a constant exchange of molecules between the stationary air and the flowing air. The overall effect of this molecular exchange is to slow down the moving air (Ahrens, 2018). If molecular viscosity were the only type of friction acting on moving air, the effect of friction would disappear in a thin layer just above the surface. There is, however, another frictional effect that is far more important in reducing wind speeds.

When laminar flow gives way to irregular turbulent motion, there is an effect similar to molecular viscosity, which occurs throughout a much larger portion of the moving air. Near the Earth's surface, it is related to the roughness of the ground. As the wind blows over a landscape dotted with trees and buildings, it breaks into a series of irregular, twisting eddies that can influence the airflow for hundreds of metres above the surface. The wind speed and direction fluctuate rapidly within each eddy, producing the irregular air motion we know as wind gusts. These eddy motions create a drag on the flow of air far greater than that caused by molecular viscosity.

Besides the mean horizontal wind speed and eddies, there is one more motion within the atmosphere, called wave motion. Unlike the turbulent ones, these oscillations move in a pseudo-harmonic way and have a substantially deterministic character. The presence in the atmosphere of these non-turbulent movements, with a characteristic time between an hour and a minute, are collectively referred to as “submeso motions”. Waves (vertical oscillations propagating horizontally on a density interface) can exist in the air and behave similarly to water waves. These waves are frequently observed in the night-time boundary layer where stable air is overridden by a warmer residual layer, transporting little heat, humidity, and other scalars such as pollutants. They are, however, effective at transporting momentum and energy. Waves can be generated locally by mean-wind shears and by wind flow over obstacles. Waves can also propagate from distant sources, such as thunderstorms or explosions. One classic waveform is a mountain wave where stable air flows over a ridge or mountain setting up a downwind oscillation.

The total airflow, or wind, is the sum of these three motions, as depicted in Figure 3-3. Figure 3-3 (a) displays mean wind, which is relatively constant, but varying slowly over the course of hours. Figure 3-3 (b) displays waves in the air flow which represent regular (linear) oscillations of the wind, often with periods of ten minutes or longer. Figure 3-3 (c) displays the turbulence, irregular, quasi-random, non-linear variations with durations of seconds to minutes.

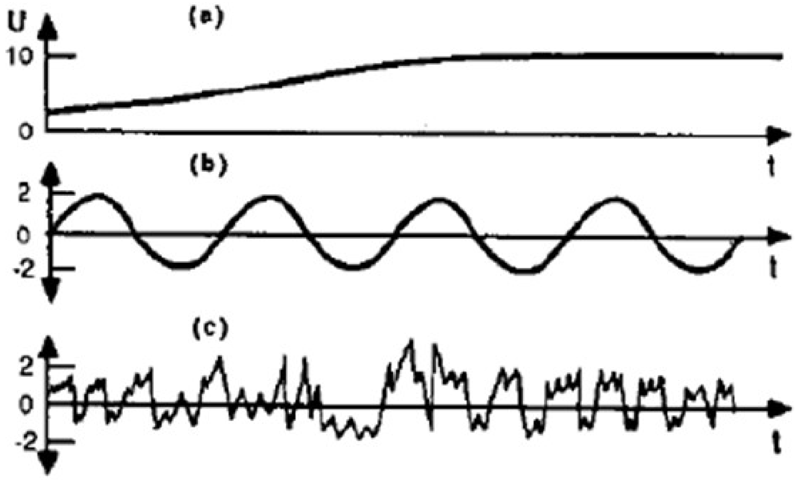



**Figure 3-3** Diagram showing the three motions of airflow (Stull, 2017)

### 3.2.4 Development of the Planetary Boundary Layer (PBL)

The usual classification of the PBL is based on buoyancy effects. Consider a package (parcel, particle) of air, like the air within a balloon but without the membrane. If a parcel of air is displaced upward adiabatically (no heat enters or leaves the parcel), it will expand because of the reduced pressure aloft; hence, its temperature will decrease. The resulting temperature profile for dry air is called the adiabatic temperature profile. Under this ideal condition, displaced parcels have precisely the density of their surroundings and thus experience no net buoyant force or tendency to return to their original position. We call this neutral stratification. Should the mean temperature decrease with height more slowly than the adiabatic profile, a vertically displaced parcel will experience a force tending to restore it to its original position. This situation is called stable stratification. The final case where the decrease of temperature with height exceeds the adiabatic lapse rate is called unstable stratification; here, displaced parcels tend to be vertically accelerated away from their original positions. These tendencies define what is called atmospheric stability.

The PBL has pronounced structural differences between day and night. The surface energy budget drives this diurnal cycle. After sunrise, the depth of the PBL increases with time as surface heating drives buoyant convection. The depth typically reaches a maximum in mid to late afternoon (Figure 3-4). On a clear night, a much shallower, stably-stratified boundary layer develops at the surface in response to the surface cooling through emitted radiation. In clear weather over land, the mean wind speed in the surface layer can have a diurnal cycle of substantial amplitude, with higher speeds in unstable daytime conditions and lower speeds in stable conditions at night.

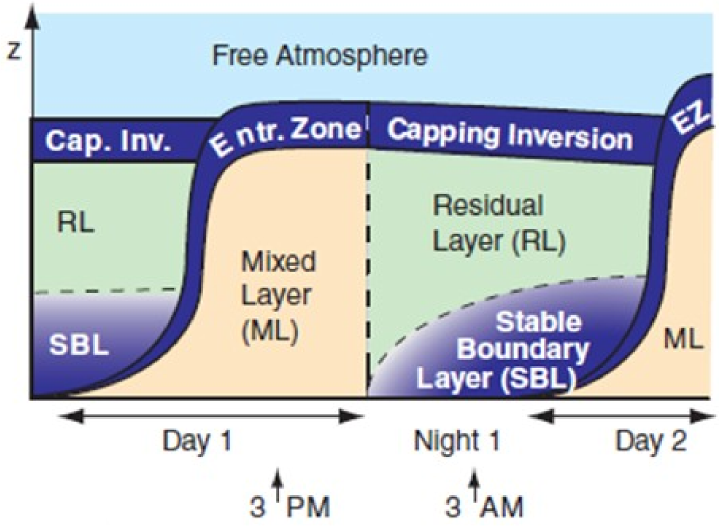



**Figure 3-4** Components of the boundary layer during fair weather in summer over land (Stull, 2017)

Note: Pink indicates non-locally statically unstable air, light blue (as in the RL) is neutral stability, and darker blues indicate stronger static stability.

The PBL is constantly evolving in response to both the diurnal heating cycle and changing synoptic (large-scale) weather conditions. As a result, its structure and depth can vary considerably over space and time. However, it typically has distinct states that we can idealise somewhat and discuss in fairly simple terms (Stull, 2017).

#### 3.2.4.1 Mixed (Convective) Layer

During clear days, a land surface is normally warmer than the air aloft because of heating by incoming solar radiation. This warmer, near-surface air is buoyant and establishes convective, turbulent motions. In some situations, over water, for instance, near-surface air becomes buoyant because it contains more water vapour (less dense than air) than the air at upper levels. Density changes at constant pressure can thus be caused either by actual temperature changes or changes in the specific humidity; in other words, buoyant air is either warmer or more humid, or both, than its surroundings. At the top of the convective boundary layer there may be an overlying layer of stably stratified air which typically ranges from a few hundred metres to a few kilometres thick, as schematically shown by the capping inversion in Figure 3-4.

This "inversion" layer acts as a lid for the convection by damping vertical motions and establishes the depth of the convective PBL.

This inversion lid can be eroded from below by turbulence and displaced vertically by a motion such as that induced by convergence or divergence in the horizontal wind field. Therefore, the convective PBL normally becomes deeper as the day progresses because of turbulent entrainment of air down into the PBL; however, in some instances, its depth can be held stationary or even lowered by subsidence. The latter situation can cause air pollution episodes by trapping pollutants in an abnormally thin PBL.

#### 3.2.4.2 The Neutral PBL

If the PBL has an adiabatic lapse rate throughout, which can happen if the surface moisture and heat fluxes are negligible and there is no inversion aloft, we have the neutral case. Here turbulence is due entirely to the wind shear (the change in wind velocity with height), and there are no buoyancy effects. Although it is possible that a truly neutral PBL can occur if only briefly before some change in heat flux occurs, there is no persistent neutral PBL in the real world. It has been widely studied theoretically, and we mention it here to be complete but will not discuss it further.

#### 3.2.4.3 Residual Layer

About a half hour before sunset, the thermals cease to form (in the absence of cold air advection), allowing turbulence to decay in the formerly well-mixed layer. The resulting layer of air is sometimes called the Residual Layer because its initial mean state variables and concentration variables are the same as those of the recently-decayed mixed layer. The Residual Layer contains the pollutants and moisture from the previous mixed layer but is not very turbulent. The Residual Layer is considered to be neutrally stratified, resulting in turbulence that is nearly of equal intensity in all directions.

#### 3.2.4.4 Stable Boundary Layer

At night, a land surface typically cools because of radiative heat loss to space. The near-surface air cools and creates a positive (stable) temperature gradient in the PBL. This has strong dynamic effects on turbulence and hence on the structure of the layer. Energy must be expended to maintain vertical velocity fluctuations in the presence of the stable lapse rate; since turbulence is inherently three-dimensional, with energy exchanges taking place among all three velocity components, the effect of extraction of energy from the vertical motions is transmitted to the horizontal components as well.

### 3.2.5 The Concept of Stability Classes

Frank Pasquill (Pasquill, 1961) defined a method for describing atmospheric stability based on his observations of the surface parameters like wind speed, cloudiness, and solar irradiance. Pasquill defined six categories of stability ranging from very unstable to stable, as follows:

A. Very Unstable
B. Unstable
C. Slightly Unstable
D. Neutral
E. Slightly Stable
F. Stable

The dispersion parameters (the standard deviation of plume concentration in the lateral ($\sigma_y$) and vertical ($\sigma_z$) associated with this method) are used by default in most of the EPA recommended Gaussian dispersion models. These parameters are often referred to as the Pasquill-Gifford (P-G) sigma curves. For routine applications using the P-G sigma curves, the Pasquill stability category (hereafter referred to as the P-G stability category) is calculated using the method developed by Turner (1964) which uses actual data provided by the National Weather Service (NWS). The Turner method expands the wind speed scale slightly, uses numerical categories 1 through 7, and in essence includes an additional P-G stability category 'G', Extremely Stable. For US EPA regulatory modelling applications, stability categories 6 and 7 (F and G) are combined and considered category 6. Table 3-1 provides a key to the Pasquill stability categories as originally defined.

**Table 3-1** Meteorological conditions that define the Pasquill Stability Classes

| Surface wind speed | Daytime incoming solar radiation | Night-time cloud cover |
|---|---|---|

| m/s | miles/hr | Strong | Moderate | Slight | ≥ 4/8 | ≤ 3/8 |
|---|---|---|---|---|---|---|
| < 2 | < 5 | A | A – B | B | E | F |
| 2 – 3 | 5 – 7 | A – B | B | C | E | F |
| 3 – 5 | 7 – 11 | B | B – C | C | D | E |
| 5 – 6 | 11 – 13 | C | C – D | D | D | D |
| > 6 | > 13 | C | D | D | D | D |

**Class D applies to heavily overcast skies, at any windspeed day or night**

Incoming solar radiation is based on the following: strong (> 700 $Wm^{-2}$), moderate (350 – 700 $W\ m^{-2}$), slight (< 350 $W\ m^{-2}$)

In terms of odour dispersion, the more unstable the atmospheric conditions are, the greater the dilution effect. Under atmospheric instability (Class A and B) conditions, odours are transported over shorter distances before being diluted below the odour threshold, while under stable conditions (Class E and F), odours travel undiluted for longer distances.

### 3.2.6 Time Scale / Meteorological Data Resolution

Frequent and accurate updates to meteorological data are necessary and demanded by many technical fields, including odour modelling. In recent years, numerous key developments in data forecasting and recording methods have led to long-term and more reliable data availability. This has also allowed for more frequent data updates. For example, the atmosphere satellite remote sensing refreshes and provides crucial data multiple times per day (Emery, 2017).

The major importance of meteorological data calls not only for more frequent updates but also for high-resolution data. Resolution is a significant factor for advancing the data forecasting capability as more information and details are available in high-resolution data. Increased computer capacity and speed have led to smaller grid cell sizes which means higher data resolution. This provides more accurate forecasts and reliable data to study atmospheric dynamics. High-resolution data helps predict large-scale changes in the data patterns, such as topographic effects and small disturbances.

Even more so than in the study of atmospheric pollution, where the hourly average is the reference parameter for air quality control, the dispersion of odorous substances requires greater detail since the perception of annoyance occurs over a time order of seconds. This is the time scale in which the human olfactory system detects the odorants in the inhaled air during a single breath. Consequently, the modelling process must determine the peak values generated around the odorous sources. For this, it is necessary to know the meteorological variables of the site with the best possible temporal detail, compatible with the parameters that the dispersion models will be able to use.

In any case, the experimental observations must provide the meteorological input to the models and indicate the degree of uncertainty with which the real situation is described. It is thus possible to highlight meteorological situations that well represent the dynamics of the atmosphere from more uncertain situations in which the approximation of the meteorological description can generate only a limited adherence to the real expected concentrations.

## 3.3 Types of Meteorological Data Sets

Meteorological data are one of the most important inputs into any air dispersion model. Two meteorological elements primarily control ground-level concentrations of contaminants: wind direction and speed (for transport); and turbulence, buoyancy, and mixing height of the boundary layer (for dispersion). There is a choice between meteorological data sets derived from internationally accepted observation techniques (WMO, 2021), (US EPA, 2000), (US EPA, 2017) measured at specific sites, or from prognostic models or forecast data run in hindcast mode.

The meteorological data requirements for steady-state Gaussian plume models and advanced dispersion models vary considerably. Empirical equations, screening models, and simple Gaussian plume models typically require 1-dimensional meteorological data (wind speed, wind direction and temperature) from a single surface station. These models assume the single surface station data apply to the whole modelling domain, both spatially and vertically. From the surface to the top of the boundary layer, meteorological conditions are assumed to not vary with height.

More advanced Gaussian plume models require 2-dimensional meteorological data from a single surface and upper air station. These models also assume the meteorological data applies to the whole modelling domain; however, conditions can vary with height according to the upper air profile. There are several international repositories of surface and upper air raw data; Appendix A contains links to these data, and more information about the data variables and formats can be obtained from these data sources. The hourly raw surface data typically consists of a record for each date/time of observation. Each record is of variable length and consists of a control and mandatory data section and may also contain additional, remarks, and element quality data sections. This data is usually compressed to minimise file size. Upper air data which consists of fewer variables is organised such that it can be viewed in fixed-width columns. Figure 3-5 shows a portion of a surface data file, and Figure 3-6 shows upper air data.

```
0127082210999992022010100004+40500-003583FM-12+063399999V0
9+00301+00201999999ADDMA1103001999999REMMET051METAR LEMD 0
A103000091GA1001+999999999GE19AGL   +99999+99999GF19999900
0494-003567FM-15+061099999V0203201N001012200019N009999199+
A1240N+00001MA1999999096101MD1710041+9999REMSYN09408221 02
203501N001519999999Y009900599+00001+00001999999ADDMA110300
1 20011 39621 40335 52011 80000 333 60007=0078082210999992
LEMD 011030Z VRB02KT CAVOK 07/03 Q1030 NOSIG=0178082210999
0005199999999Y009900599+01201+00601999999ADDMA1103001999999
19999999N030000199+01501+00551102771ADDGA1999+999999021GE1
R LEMD 011500Z 00000KT CAVOK 17/03 Q1028 NOSIG=00780822109
+99999GF102991001999999999999999MA1999999095971MD1610021+9
Q1028 NOSIG=0078082210999992022010118304+40494-003567FM-15
```

**FIgure 3-5** Example surface data from Madrid-Barajas (USAF 082210) for January 2022 (ISD Format)

```
 254      0       1       JAN    2022
   1  99999    8221  40.47N  3.58W    638    2315
   2    100     116      99     61  32767       0
   3           LEMD                  32767      kt
   9    956     638      76     45    325       4
   4   1000     266   32767  32767  32767   32767
   5    950     690      84     46  32767   32767
   5    947     716     110     50  32767   32767
   4    925     904     134     44     15       4
   5    896    1172     156   -174  32767   32767
   6    878    1343   32767  32767    210      10
   5    870    1420     138    -42  32767   32767
   4    850    1617     130    -70    215      13
   5    798    2141      94   -106  32767   32767
```

**Figure 3-6** Example upper air data from Madrid-Barajas (USAF 082210) for January 2022 (FSL Format)

Advanced Lagrangian puff and particle dispersion models require 3-dimensional data for analysis. Because there will not be meteorological sites at every point on the ground in the modelling domain, and monitoring in the upper air (anything above the height of a tower) is normally very sparse, meteorological models must be used to provide this 'missing data'. These models use data from all relevant surface networks (land and sea) and upper air stations in conjunction with atmospheric physics to interpolate and develop a matrix of meteorological variables across the modelling domain. The advanced dispersion models then use this spatially and vertically varying pre-processed meteorological data.

Two types of meteorological models can be used to provide a 3-dimensional grid of meteorological data:

- Diagnostic Wind Models (DWM), which interpolate and/or extrapolate meteorological observations; and
- Numerical prognostic models, also known as mesoscale models or Numerical Weather Prediction (NWP) models.

The unaltered meteorological model outputs of these two types of models are typically used to drive advanced dispersion models. Prognostic and diagnostic meteorological models can either form part of an air dispersion modelling system, such as CALMET which is part of the CALPUFF modelling system, or they can stand alone entirely like the Weather and Research Forecast system, commonly known as WRF.

The biggest concern with using prognostic data directly is related to the horizontal grid resolution of the modelling domain. Typically, prognostic models are run on multiple nested domains where the innermost nest has a grid of 1 km to 4 km. If the resolution is fine enough to resolve important meteorological features such as the sea and land breezes, developing cyclones and fronts, terrain, and non-homogeneous land uses, then it is appropriate to use prognostic gridded data directly in a dispersion model. However, sometimes these features cannot be resolved, and it is not computationally practical to run the prognostic model at much finer grid resolutions. Combining gridded coarse prognostic model data into a fine-scale diagnostic model is far less computationally demanding than running a prognostic meteorological model at less than 1 km resolution. In addition, the diagnostic model can also incorporate observational data.

In that case, the diagnostic meteorological model can be used at a much higher spatial resolution of, for example, 150 m, with no computational inefficiencies. The prognostic model provides a 'first-guess field', which the diagnostic model then modifies to take into account terrain and land-use features at a finer spatial scale than the prognostic model. The output of the diagnostic model is then passed to the dispersion model, which will assess the odour dispersion at the same fine-scale as the diagnostic model. The sampling grid used in the CALPUFF model may be set even finer. For example, considering 150 m for the CALMET grid, CALPUFF may be used with the nesting factor MESHDN=3, which means dividing the CALMET grid by 3. Therefore the CALPUFF sampling grid would be 50 m, a grid size that is not uncommon in odour applications.

Combining prognostic model output data as input to a diagnostic meteorological model is being used in many odour assessments worldwide today and has become the preferred approach for obtaining representative on-site data if no measurements are available. The US EPA (2017) has stated that "For a near-field dispersion modelling application where there is no representative NWS station, and it is prohibitive or not feasible to collect adequately representative site-specific data, it may be necessary to use prognostic meteorological data for the application" (p. 5200).

Some well-known prognostic meteorological models produce output data in a format that can be used by plume models. Prognostic model results may be extracted at a single location (the site of pollution emissions) in a format compatible with the plume model, and it is then considered a pseudo-observation for input to the dispersion model. The practical advantage of extracting single-point meteorological data for a plume model is that there is no missing data. In addition to providing surface data, the prognostic model will also provide a vertical profile of temperature, wind direction, and wind speed. This is a significant advantage to those plume models which can use 2-dimensional meteorology.

### 3.3.1. Screening meteorological data

Screening meteorological data sets have been developed using idealised hourly standard combinations of wind speed, stability class and mixing heights, aiming to mimic the range of atmospheric conditions that are likely to occur in any given location. A sample of a screening meteorological data file is displayed in Table 3-2. The screening data sets provide a simple option to run air dispersion models and can be applied in most locations. The maximum ground level concentration predicted using a screening data set is considered conservative. This means that the model likely over-predicts concentrations expected to occur in reality, assuming that other input data are of good quality.

Idealised meteorological data sets of a few hundred hours can only model one-hour averages, and they cannot provide an indication of how frequently an event might occur. These data sets should only be used to gain a 'first cut' estimate of the magnitude of the maximum ground-level odour concentration for a particular source.

**Table 3-2** METSAMP.MET – An example of a screening meteorological data file

| Date | Temp. | W. Speed | W. Dir. | Stability | Mix. Ht. |
|---|---|---|---|---|---|
| 00010101 | 25 | 0.5 | 270 | A | 100 |
| 00010102 | 25 | 1.0 | 270 | A | 100 |
| 00010103 | 25 | 1.5 | 270 | A | 100 |
| 00010104 | 25 | 2.0 | 270 | A | 100 |
| 00010105 | 25 | 2.5 | 270 | A | 100 |
| 00010106 | 25 | 3.0 | 270 | A | 100 |
| 00010107 | 25 | 0.5 | 270 | B | 100 |

| | | | | | |
|---|---|---|---|---|---|
| 00010108 | 25 | 1.0 | 270 | B | 100 |
| 00010109 | 25 | 1.5 | 270 | B | 100 |
| 00010110 | 25 | 2.0 | 270 | B | 100 |
| 00010111 | 25 | 3.0 | 270 | B | 100 |
| 00010112 | 25 | 4.0 | 270 | B | 100 |

### 3.3.2. Observations data sets - ready-made data

Urban and regional ready-made meteorological data sets derived from measurements are sometimes available from local and regional regulatory authorities worldwide. The benefit of ‘ready’ prepared single station data sets is;

- they are sequential hourly datasets;
- they are often representative of at least one or more years;
- they meet the criteria of the ambient air quality requirements of the local regulatory authority in that they have been properly evaluated;
- they are sufficiently accurate;
- they can be used directly into screening models and empirical equations; and
- they resolve the need for a complex, expensive and timely component of meteorological data sets processing.

These data sets, if available, are usually stored by the local authority and can be easily obtained. Normally, they would be in a spreadsheet format or simple ASCII format. Ordering the data into the format required for the model is normally straightforward. Normally, these data are simple one-dimensional data with an emphasis on wind speed, wind direction, atmospheric stability and temperature. Appendix A includes a table with links to US State and Canadian Provincial authorities that maintain AERMOD-ready data sets, plus links to authorities in other countries that maintain similar data.

### 3.3.3. Observations data sets - developing site-specific data sets

Provided it is of good quality, on-site measured data are always the preferred source of meteorological input data. A distinct advantage of having on-site data is that they can also be used for dispersion model evaluation studies, and it greatly improves the accuracy of the dispersion model results, especially when making decisions about separation distances.

However, developing a meteorological data set can be expensive and time-consuming. Depending on the complexity of the site, a degree of meteorological expertise may be required to ensure the data accurately represent the conditions experienced at the site. Further, for any odour assessment, the data needs to be assessed for quality assurance.

The collection of site-specific meteorological data is fully covered in documents such as the ‘Guide to Instruments and Methods of Observation: Volume I - Measurement of Meteorological Variables, WMO-No. 8 (WMO, 2021) and ‘Meteorological Monitoring Guidance for Regulatory Modelling Applications’ (US EPA, 2000). These documents provide details on site location, recording mechanisms, data communication, sampling rates, system accuracies, data handling, quality control and treatment of missing data. It is recommended that this guidance be adopted as best practice for the collection and processing of meteorological data for use in dispersion modelling applications.

In general, a meteorological station should be located away from the influences of obstructions such as buildings and trees to ensure that the general state of the environment (wind direction and temperature) is best represented. A 10 m high mast for measuring wind direction and speed and temperature differentials is recommended. However, where the mast is located in good free-flow conditions, and there are height restrictions from local council bylaws, a 6m high mast can be used instead.

For major industrial sources with tall stacks, or a site within a complex terrain environment, higher monitoring masts (30 m and higher) are recommended to monitor lower boundary-layer wind and temperature profiles adequately. It may be necessary for these situations to supplement such data with monitoring via remote sensing instruments such as SODAR / RASS or tethered-sonde systems.

The following parameters need to be monitored at the site: surface temperature; temperature profile (between 1.5 m and 10 m or higher); relative humidity (%); wind speed (m/s); wind direction (degrees); solar radiation or cloud cover; and cloud ceiling height.

While all the above variables provide valuable information for modelling, the most important variables are wind speed and direction, and temperature. Cloud cover information, pressure and relative humidity can usually be obtained from a nearby airport or automatic weather station. The costs for setting up a 10 m meteorological station to record and log these three parameters are modest and within reasonable budgets for most projects, with small additional costs associated with site maintenance and data management.

When developing a meteorological data set, the representativeness of the data set must be assessed and demonstrated in terms of climatic means and extremes. This can essentially be established in two ways: by undertaking long-term (three to five years) monitoring of on-site data collection or by establishing correlations between on-site data, climatic averages and regional extremes.

#### 3.3.3.1. Selecting a representative weather station

As a rule, site-specific data are always preferred when developing a meteorological data set for a specific source. However, sometimes this is not possible. Under situations like this, when there is no on-site data, usually the nearest suitable station to the source is allowed to be used, as long as it is in a similar meteorological regime as the source or within 5 km of the source, a recommendation from Victoria EPA in Australia.

For simple single-station plume modelling, off-site data should only be used if the weather station site has similar topographic characteristics, likely to result in similar meteorological conditions for the site concerned. For example, when the source and weather station are located in the same valley or are located at a similar distance to a coastline. The representativeness of off-site data must be established before being used in any dispersion modelling study. Appendix A includes links to repositories of global surface hourly data.

#### 3.3.3.2. Selecting a representative vertical profile

More advanced Gaussian dispersion models require a single vertical profile of upper air data. This data can be obtained from airports that routinely measure the upper air temperature, pressure, geopotential height, wind speed and wind direction at a minimum once or twice daily. For example, vertical distributions of temperature, humidity and winds also called upper-air datasets were developed originally for North America (Schwartz and Goyett, 2005) but have been extended worldwide and are usually measured at airport locations. Radiosonde are instruments which are sent airborne on weather balloons to sample data as they move upwards. Appendix A includes links to this type of data.

Other instruments can be used to measure vertical profiles of temperature, humidity and winds.Remote sensing instruments like SODAR/ RASS or tethered-sonde systems can provide this information.

### 3.3.4. Diagnostic models meteorological data

Diagnostic meteorological models use data from all available locations and assign values to the meteorological variables throughout a three-dimensional grid by interpolation, extrapolation and objective analyses. The conservation of mass principle is applied throughout the process. The term 'diagnostic' is used because the input data and model results are for the same time period. Diagnostic models are not predictive, and their calculated fields for each time interval do not depend on fields at previous times. The model's output is a data file in a format required by a particular air dispersion model.

Diagnostic models need meteorological data to run, they can incorporate available measurements, and some can directly incorporate the data output of prognostic models. They can provide meteorology through interpolation and objective analysis in regions with little data. Diagnostic models are usually run at a horizontal grid resolution varying from 250 m to 4 km.

The outputs of these models typically provide three-dimensional data sets as required by more complex dispersion models. The output of these models can also provide datasets for gaussian plume models, the data sets are extracted as a single surface station and vertical profile at a given location.

### 3.3.5. Prognostic models meteorological data

Prognostic models are driven by large-scale synoptic analyses and numerically solve the equations of atmospheric dynamics to determine local meteorological conditions. They do not require local meteorological data to run. However, if data are available in hindcast model runs (as opposed to forecasting), prognostic models use this historical data to assist in nudging the numerical solution toward the observation.  Prognostic models run in hindcast mode can assimilate local meteorological data through a process known as 'nudging'. Essentially, the prognostic model solution is forced towards the observations during the model run. At best, the model solution is already close, so the forcing is small - hence the term 'nudging'. Nudging can benefit the model solution but must be used carefully. For example, nudging will not help with a poor prognostic model set-up, and can produce numerical instabilities when the model dynamics oppose the observation.

Prognostic models can represent all scales, from global down to features on scales in the range 1-10 km. Most are run in a nested format with the outer domain covering distances in the order of 500-1000 km - the regional scale, and at least three inner nests.

Figure 3-7 shows a numerical model setup over New Zealand, consisting of three nests of increasing spatial resolution.

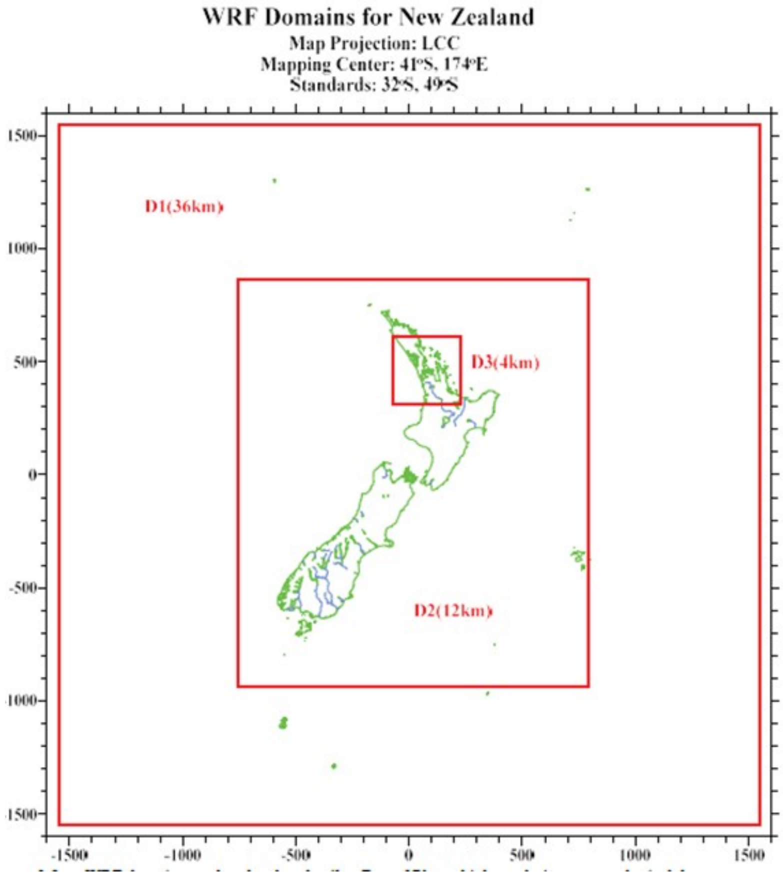



**Figure 3-7** Three nested model domains (36 km, 12 km and 4 km) for a numerical prognostic model (courtesy of Atmospheric Science Global)

All model domains are initialised using coarse analyses from global or limited-area models, usually run by national weather services. These are provided by many forecasting agencies or similar institutions, such as the US National Meteorological Center for Atmospheric Research, the European Centre for Medium-Range Weather Forecasts, the UK Meteorological Office, or the Australian Bureau of Meteorology. The outer domain is also driven at its boundaries by the global or limited-area models as the run progresses - this feeds into weather systems' effects on the domain of interest. The prognostic models describe the three-dimensional fields of temperature, wind speed and direction, and moisture through the region at a much higher spatial resolution than the initial analysis provided to the model.

Prognostic models contain realistic dynamical and physical formulations and potentially produce the most realistic meteorological simulations for regions where data are sparse or non-existent. The extracted output of prognostic meteorological models can be used in dispersion models:

- as a surface and upper air station at a single location;
- as 3-dimensional gridded data; and
- as 3-dimensional gridded data into a diagnostic meteorological model at a much finer resolution.

Prognostic model data are now routinely used in odour assessments, usually as the provider of meteorological weather data in regions with sparse meteorological data. The data are usually of high quality, with little or no missing values.

Prognostic models do not need local meteorological observations to run, so they can simulate the meteorology through physics and 'observational nudging' in regions where little data are available. The innermost horizontal grid spacing for a prognostic model varies widely from a resolution of 1000 m to 12 km.

The output of prognostic models can be extracted at a single location to provide surface data and vertical profile data sets at that location for gaussian plume models but also provides three-dimensional data sets for more complex dispersion models as required. Appendix A includes links to data generated by the global prognostic model WRF.

## 3.4 Meteorological data requirements for key dispersion models used in odour assessments

This section focuses on key meteorological models routinely used in odour assessments worldwide and their meteorological data requirements. Some models, such as WRF, stand alone and are not attached to any dispersion model; this means that the meteorological output data from WRF can be transformed into any format for input to dispersion models. Other models, such as AERMET, the meteorological processor for the dispersion model AERMOD, only prepare meteorological data for AERMOD. This section is broken up into five different types of models; meteorological models, screening models, advanced Gaussian Plume models, and Lagrangian models. They are briefly discussed below.

- **Meteorological models** – particularly WRF, the Weather and Research Forecast model. WRF is a primary mesoscale numerical prognostic model whose data are used to routinely drive air pollution dispersion models. In addition to WRF, the *Mesoscale Model Interface Program* (MMIF), which converts prognostic meteorological model output fields to the parameters and formats required for direct input into dispersion models, is also discussed.
- **Screening models** - in particular AERSCREEN and ADMS-SCREEN, which are the screening models of two of the most well-used Gaussian plume models today, AERMOD and ADMS, which are used in odour assessments all over the world.
- **Advanced Gaussian plume models** – particularly, AERMOD, ADMS, AODM and ARIA Impact. AERMOD and ADMS are widely known, advanced models. AERMOD and AODM enjoy regulatory status in the US and the UK, and AERMOD is also widely regulated worldwide. AODM is the Austrian Odour Dispersion Model developed specifically for odour assessments. ARIA Impact is a Gaussian model that enjoys widespread use throughout Europe and South America.
- **Lagrangian Puff Models** – in particular CALPUFF and SCIPUFF. CALPUFF is a widely known favourite for odour applications due to its ability to handle complex atmospheric environments and calm conditions and its long history as a US regulatory model. SCIPUFF is a new generational second-order closure model. The sophisticated approach of the new turbulence model is exciting for odour applications.
- **Lagrangian Particle-Puff models** – in particular, CSIRO's TAPM. TAPM is widely used throughout Australia and New Zealand and overseas. The model enjoys a Particle-puff approach whereby it uses a Gaussian puff model in the horizontal and regular particle model to describe the vertical dispersion. TAPM is primarily used in Australia and New Zealand to develop upper air meteorological data in data-sparse regions.
- **Lagrangian Particle models** - specifically, SPRAY, AUSTAL (LASAT), LAPMOD

and GRAL. This suite of dispersion models is developed in Europe. It is connected to different meteorological data processors, including both prognostic and diagnostic models able to reconstruct flow over complex terrain. These models are routinely used in odour applications and assessments.

Figure 3-8 shows a flow chart showing how meteorological data are developed from global weather models such as ECMWF and GFS, which are run at a coarse resolution of approximately 0.25 to 0.50 degrees over the entire world. These models provide the initial data necessary to drive a mesoscale model such as WRF, which is typically run for multiple nests of increasing grid resolution. The US EPAs MMIF interface model can translate the WRF data directly into the correct format for CALPUFF, AERMOD and SCIFPUFF, essentially by-passing those models' meteorological processors. In addition, the WRF model output data can also be passed directly to a diagnostic meteorological model (such as CALMET), which then uses the data to determine the initial guess wind field, and applies fine-scale terrain adjustments as well as user-determined distance weightings to observations at a much finer resolution than that from WRF. The output of the diagnostic meteorological model is 3D gridded data at a fine resolution, which can then be used to drive advanced Lagrangian dispersion models such as CALPUFF and LAPMOD.

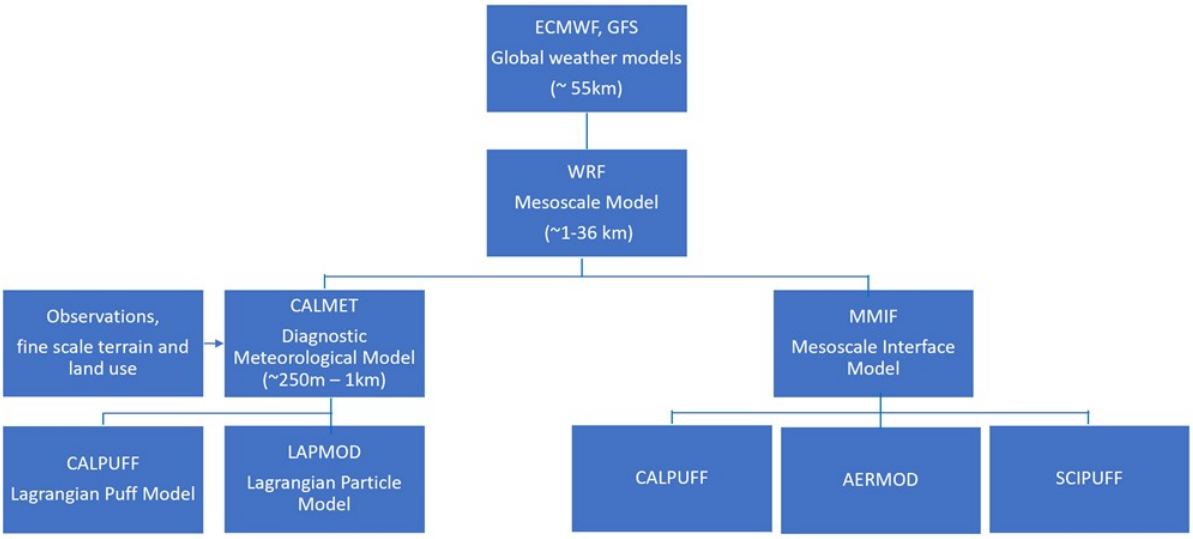



**Figure 3-8** Development of meteorological data from global forecast models (courtesy of Atmospheric Science Global)

Note: ECMWF and GFS data can be processed through the mesoscale model WRF, and transformed via the MMIF interface into dispersion model-ready data, or be passed to a diagnostic meteorological model like CALMET which is executed on a much finer resolution than the prognostic data to provide a 3D gridded data set for dispersion modelling purposes

### 3.4.1. Prognostic Meteorological Models – WRF

There are multiple mesoscale meteorological models whose data are used in air quality applications worldwide today. Some of these in the USA include: North American Mesoscale Forecast System (NAM); High Resolution Rapid Refresh (HRRR); and the Rapid Update Cycle (RUC) weather forecast model developed by National Centers for Environmental Prediction (NCEP). Similar models in Europe include the ECMWF IFS model, developed by the European Centre for Medium-Range Weather Forecasts, the Consortium for Small-Scale Modelling (COSMO) led by the Deutscher Wetterdienst, the HIRLAM and HARMONIE developed by a consortium of meteorological institutes from Sweden, Norway, Denmark, Iceland, the Netherlands, Ireland, Spain, Estonia and Lithuania, and the Unified Model (UM), developed by Met Office UK. For information about these models, see Appendix A which contains links to each modelling system home page.

Of these models, one of the most popular is the Weather Research and Forecast Model (WRF). WRF is a next-generation mesoscale numerical weather prediction model designed to serve operational forecasting and atmospheric research needs. The development of WRF has been a collaborative partnership, principally among the National Centre for Atmospheric Research (NCAR), the National Oceanic and Atmospheric Administration (NCEP), the Forecast Systems Laboratory (FSL), the Air Force Weather Agency (AFWA), the Naval Research laboratory, University of Oklahoma, and the Federal Aviation Administration (FAA). WRF is a state-of-science three-dimensional numerical weather prediction model maintained at the National Centre for Atmospheric Research (NCAR) in collaboration with several governmental agencies (Skamarock et al. 2008, NCAR 2011). In 2004, WRF officially replaced MM5 (which is short for the Fifth Generation Penn State / NCAR Mesoscale Model) as the forecast engine. WRF includes much more recent technology and techniques in its system than MM5. MM5 was a regional mesoscale model used for creating weather forecasts and climate projections. It was a community model maintained by Penn State University and the National Centre for Atmospheric Research and was widely used in air quality applications. Over the last decade, there has been a switch from using MM5 to the more sophisticated WRF model, especially as the development of MM5 has ceased and the model is no longer being maintained as a workhorse model.

WRF is a three-dimensional weather prediction model with non-hydrostatic dynamics, a variety of physics options and the capability to perform Four-Dimensional Data Assimilation (FDDA). The model can simulate meteorological phenomena such as tropical cyclones, severe convective storms, sea-land breezes and terrain-forced flows such as mountain valley wind systems. The Advanced Research WRF (ARW) can be used in applications ranging from horizontal scales of metres to thousands of kilometres. The model can be run over multiple nested grids. WRF is well suited for performing retrospective FDDA simulations to develop a three-dimensional high-resolution meteorological data set to support air quality modelling.

WRF is routinely used to generate meteorological data either as a single surface station and\ or a single vertical profile of data or as gridded 3D data in data-sparse regions. The model is typically initialised with a global forecast model such as ECMWF (European Centre for Medium-Range Forecasts), or the Global Forecast System (GFS) at a resolution of approximately 0.5°. The first coarse domain is typically at a grid size of 36 km, followed by two or three nested domains within grid resolutions close to the ratio of 3:1. WRF is routinely run with 30 – 40 vertical layers from the surface to 100 hPa. Figure 3-9 shows the vertical distribution of layers. The layer thickness increases from the surface to the upper atmosphere.

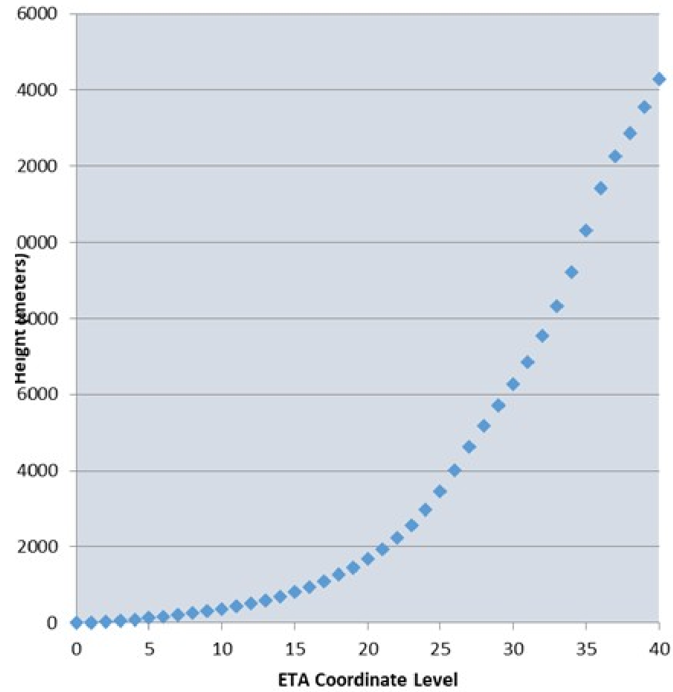



**Figure 3-9** Typical vertical layer structure and levels of WRF (courtesy of Atmospheric Science Global)

Figure 3-10 shows crosshair cursors, each representing a vertical profile of 40 levels of meteorological data (wind speed, wind direction, temperature and moisture parameters) which combined represent a gridded hourly 3D WRF data set. This gridded data can then be used to represent the 'Initial Guess wind field' of a diagnostic meteorological model, which is run at a much finer spatial resolution than the WRF model.

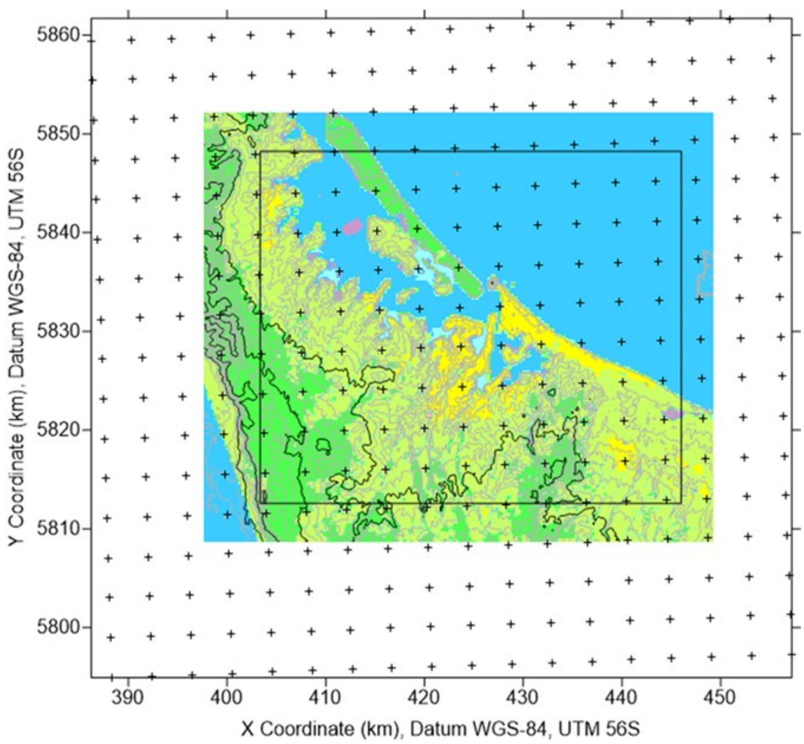


**Figure 3-10** WRF grid points used as gridded data encompass the meteorological model domain of a diagnostic meteorological model (courtesy of Atmospheric Science Global)

Some models contain software that will allow the transformation of the numerical model data into a format that either the dispersion model or the meteorological processor of the dispersion model can read directly. Usually, this software is independent, short and straightforward and must be executed on the same computer that created the meteorological data. The extracted output of such software is usually a large ASCII-format data set of a specific period in time, which may be a few months or a year-long data set, and may be a subset of the original model domain at either the innermost nest or outer nests. The output data can be a single point or multiple points. Multiple gridded data points can generate huge files, so they must be split up by month. It should be noted that WRF is typically run under Linux servers and is highly computational demanding. Other tools which run easily on a PC, such as the MMIF, convert prognostic meteorological model output files to the parameters and formats required for direct input into dispersion models, including AERMOD, SCHICHEM and CALPUFF. MMIF is briefly discussed below.

### 3.4.2. Prognostic Meteorological Model Data – Mesoscale Model Interface Program (MMIF)

The Mesoscale Model Interface Program (User Manual, 2021) was developed by Ramboll US Consulting, Inc. (formerly ENVIRON) on behalf of the US EPA, Office of Air Quality Planning and Standards (OAQPS).

MMIF is an interface program developed to convert prognostic meteorological output fields to the parameters and formats required for direct input into dispersion models. MMIF specifically processes geophysical and meteorological output fields from the Fifth Generation Mesoscale Model (MM5, Version 3) and the Weather Research and Forecasting (WRF) model.

Many models now support output data from prognostic meteorological models, particularly MM5 and WRF; this capability has proven very useful in data-sparse areas. With the advancement of prognostic meteorological output quality, prognostic data are increasingly used in air quality modelling. Key features of the MMIF program include:

- applicability on either Linux or Windows platforms;
- a simple text-based user interface control file;
- options to re-diagnose or pass through Planetary Boundary Layer depth;
- an option to generate output on a subset of the meteorological modelling grid;
- an optional mass-weighted vertical aggregation of multiple MM5/WRF layers; and
- an optional mass-weighted vertical interpolation from MM5/WRF layers to a fixed height above ground layer structure.

The MMIF program supports AERMOD, CALPUFF and SCIPUFF.

In summary, there are advantages of running MMIF to transform prognostic data directly to a form that dispersion models can use; these typically include:

- removing the need for significant decisions by the modeller concerning meteorological data switches and choices;
- providing uniformity of meteorological data for review;
- no missing data; and
- providing data over data-sparse regions.

However, there are also significant disadvantages, the most prominent being that the prognostic model output is often too coarse (12 - 36 km) and will not represent the fine-scale topography and inhomogeneous land use types surrounding the location of odour emissions. In addition, numerical model data are known to be primarily responsible for the positive wind speed biases seen at the surface (Jimenez & Dudhia, 2013).

## 3.4.3. Screening Meteorological Models – MAKEMET (for AERSCREEN) and ADMS-SCREEN

### 3.4.3.1. MAKEMET

The AERSCREEN model employs MAKEMET, a program that generates a matrix of meteorological conditions in the form of AERMOD-ready surface and profile files based on user-specified surface characteristics, ambient temperatures, minimum wind speed and anemometer height (Figure 3-11). Recommended default values for routine MAKEMET are 0.5 m/s for the minimum wind speed and 10 m for the anemometer height. MAKEMET allows the user to specify more than one set of surface characteristics and ambient temperature, such as for seasonal or monthly variations in surface characteristics and will concatenate the resulting meteorological matrices into single surface and profile files. MAKEMET will also allow the user to specify a single or range of wind directions – useful for assessing building downwash. However, AERSCREEN will set the wind direction to a single direction of 270 degrees.

*ENTER SFC MET FILE NAME*

*ENTER PFL MET FILE NAME*

*ENTER MIN. WS (M/S)*

*ENTER ANEM HT (M)*

*ENTER OPTION TO ADJUST U* (Y=adjust,N=no adjustment)*

*ENTER NUMBER OF WIND DIRECTIONS*

If the user enters one for the number of wind directions
*ENTER WIND DIRECTION*

Otherwise
*ENTER STARTING WIND DIRECTION*

*ENTER CLOCKWISE WIND DIRECTION INCREMENT*

*ENTER MIN AND MAX AMBIENT TEMPS IN KELVIN*

*ENTER ALBEDO*

*ENTER BOWEN RATIO*

*ENTER SURFACE ROUGHNESS LENGTH IN METERS*

*DO YOU WANT TO GENERATE ANOTHER MET SET THAT WILL BE APPENDED TO CURRENT FILE?*
*[TYPE EITHER "Y" OR "y" FOR YES; OR HIT "ENTER" TO EXIT*

If ("Y" or "y") then the program loops through prompts 7 through 10 for each additional data set (e.g. seasonal).

**Figure 3-11** User Prompts for MAKEMET

MAKEMET calculates friction velocity (m/s), Monin-Obukhov length (m), and mechanical mixing height (m). MAKEMET also calculates the convective mixing height (m) for convective cases and computes the matrix's boundary layer parameters for each combination. MAKEMET typically generates around 300-400 hours of meteorological data.

#### 3.4.3.2. ADMS-SCREEN

The ADMS-SCREEN model uses either standard ADMS format meteorological files or on-screen meteorological input. Figure 3-12 shows the ADMS-SCREEN Graphical User Interface Page for user-defined meteorological input data. The user is required to enter a value for the surface roughness both at the site of emission release and at the site of the meteorological station. Meteorological data can either be entered from an external file or directly into the screen. Unlike MAKEMET, the model does not create a range of combinations of meteorological data. The model will require essential input such as wind speed, wind direction, temperature and cloud cover or solar radiation and will then compute the boundary parameters for each given meteorological hour. However, ADMS-SCREEN can utilise statistical meteorological data from the UK Cambridge Environmental Research Centre (CERC), which is free for ADMS-Screen users. This data would be input into ADMS-SCREEN as an external file.

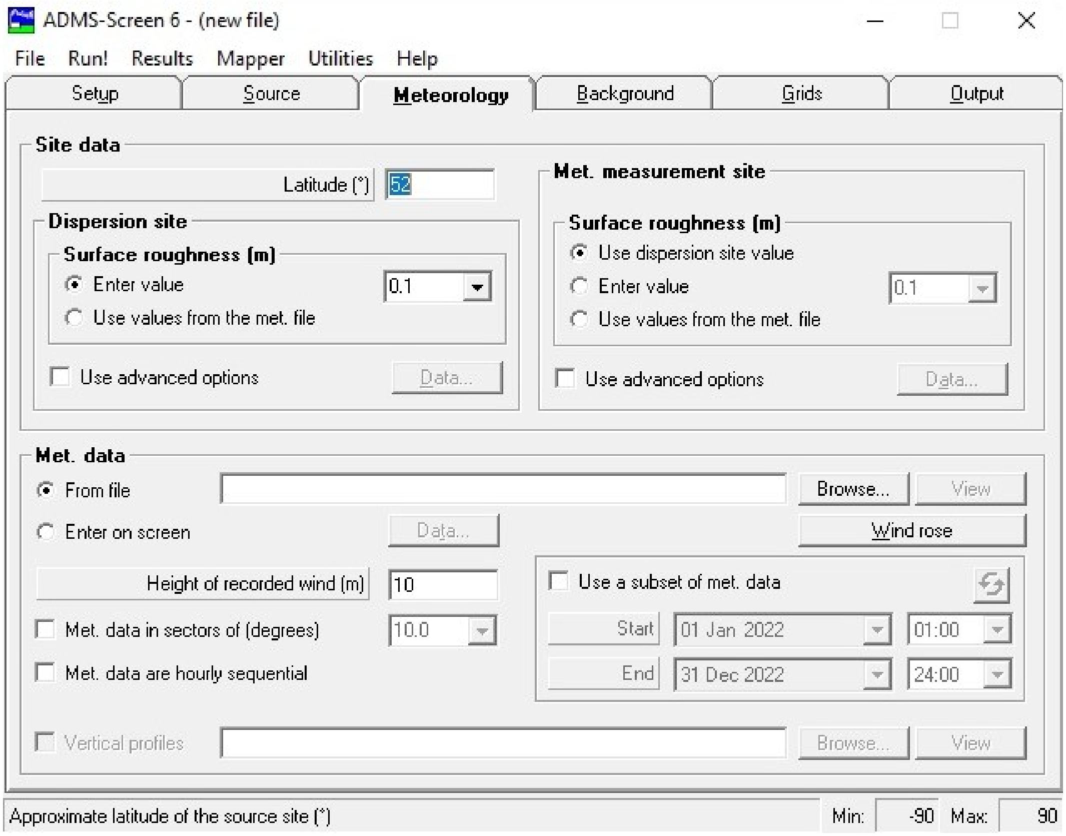



**Figure 3-12** Graphical User Interface for entering meteorological data into ADMS-SCREEN

### 3.4.4. Gaussian Plume Models – AERMOD, ADMS, AODM, ARIA Impact

### 3.4.4.1. AERMET for AERMOD

AERMOD[1] is supported by a meteorological preprocessor, AERMET, which organises the available meteorological data into a format suitable for use by the dispersion model. AERMET is programmed to read US National Weather Service hourly surface observations and US National Weather Service twice-daily upper air soundings. In addition, the program can read on-site specific meteorological data, and, beginning with AERMET Version 22112 (April 2022) can read prognostic meteorological data processed through MMIF.

There are two stages of data processing with AERMET. The first stage extracts meteorological data from archive data files and processes the data through various quality assessment checks. The second stage estimates the necessary boundary layer parameters for use by AERMOD. The processor writes two files for AERMOD. The first is the hourly boundary layer parameter estimates, and the second is a file of multi-level observations of wind speed and direction, temperature and standard deviation of the fluctuating wind components.

There is no standard format for site-specific meteorological data, allowing multiple levels of data from a tower or remote sensing instrumentation to be easily included in the model. In addition, the model allows near-surface measurements such as insolation, net radiation and temperature difference to be included in the database.

The output data from AERMET for AERMOD consists of two files, one a surface file that includes all the surface parameters listed in Figure 3-13 and a vertical profile file of meteorological data, Figure 3-14, which is usually from the nearest relevant airport where twice daily radiosonde soundings are normal.

```
   27.330S  152.975E          UA_ID:          SF_ID:          OS_ID: 00011111     VERSION: 19191  ADJ_U*
18  7  1 182  1   -6.6  0.060 -9.000 -9.000 -999.   50.     4.0 1.0000   1.62  1.00   1.45 232.8  10.0 288.5  10.0 9999 -9.00   94. 1025.    2 NAD-OS
18  7  1 182  2   -5.6  0.050 -9.000 -9.000 -999.   50.     2.8 1.0000   1.62  1.00   0.93 229.6  10.0 288.6  10.0 9999 -9.00   94. 1025.    0 NAD-OS
18  7  1 182  3   -5.6  0.050 -9.000 -9.000 -999.   50.     2.8 1.0000   1.62  1.00   1.00 230.6  10.0 288.1  10.0 9999 -9.00   95. 1025.    0 NAD-OS
18  7  1 182  4   -6.7  0.060 -9.000 -9.000 -999.   51.     4.0 1.0000   1.62  1.00   1.62 230.4  10.0 288.4  10.0 9999 -9.00   95. 1025.    0 NAD-OS
18  7  1 182  5   -8.8  0.080 -9.000 -9.000 -999.   57.     7.0 1.0000   1.62  1.00   2.00 232.3  10.0 288.8  10.0 9999 -9.00   94. 1024.    2 NAD-OS
18  7  1 182  6   -8.8  0.080 -9.000 -9.000 -999.   65.     7.0 1.0000   1.62  1.00   2.11 231.8  10.0 288.9  10.0 9999 -9.00   94. 1024.    2 NAD-OS
18  7  1 182  7   -7.8  0.080 -9.000 -9.000 -999.   65.     7.0 1.0000   1.62  1.00   2.09 229.7  10.0 289.2  10.0 9999 -9.00   93. 1025.    5 NAD-OS
18  7  1 182  8    4.4  0.200  0.308  0.005  242.  215.  -165.8 1.0000   1.62  0.44   2.41 222.9  10.0 289.9  10.0 9999 -9.00   92. 1025.    8 NAD-OS
18  7  1 182  9   70.1  0.210  0.827  0.005  295.  231.   -12.1 1.0000   1.62  0.29   2.34 223.0  10.0 290.9  10.0 9999 -9.00   88. 1026.    6 NAD-OS
18  7  1 182 10  132.6  0.200  1.360  0.005  695.  215.    -5.5 1.0000   1.62  0.24   1.97 206.8  10.0 292.1  10.0 9999 -9.00   83. 1026.    2 NAD-OS
18  7  1 182 11  120.8  0.180  1.403  0.005  838.  183.    -4.4 1.0000   1.62  0.22   1.71 203.9  10.0 293.4  10.0 9999 -9.00   77. 1026.    8 NAD-OS
18  7  1 182 12  160.6  0.170  1.617  0.005  965.  168.    -2.8 1.0000   1.62  0.22   1.49 187.9  10.0 294.1  10.0 9999 -9.00   76. 1026.    7 NAD-OS
```

**Figure 3-13** Format of hourly surface data developed by AERMET for AERMOD

The header record for a surface parameter file contains: the longitude and latitude of the surface station; the IDs of the upper air (UA), surface (SF) and on site (OS) stations; the AERMET version used for preparing the file; a flag indicating if the surface friction velocity has been adjusted for low wind speed stable conditions; the threshold applied for 1-minute winds; and flags for substitution of missing cloud cover or temperature.

The data records in columns from left to right stand for;

*year, month, day, j_day, hour, H, u*, w*, VPTG,* $Zi_c$, $Zi_m$, *L,* $Z_o$, $B_o$, *r,* $W_s$, $W_d$, $Z_{ref}$, *temp, ztemp, ipcode, pamt, rh, pres, ccvr, WSADJ*

*and where*

| | | | |
|---|---|---|---|
| *j_day* | *= Julian day* | $W_s$ | *= reference wind speed (m/s)* |

1The US EPA in conjunction with the American Meteorological Society are the main developers of the AERMOD modelling system.

*H* = *sensible heat flux (W/m2)*

*u** = *surface friction velocity (m/s)*

*w** = *convective velocity scale (m/s)*

*VPTG* = *vertical potential temperature gradient above Zic (K/m)*

*$Zi_c$* = *convective boundary layer height (m)*

*$Zi_m$* = *mechanical boundary layer height (m)*

*L* = *Monin-Obukhov length (m)*

*$Z_o$* = *surface roughness length (m)*

*$B_o$* = *Bowen ratio*

*r* = *albedo*

*$W_d$* = *reference wind direction (degrees)*

*$Z_{ref}$* = *reference height for temperature (m)*

*Ipcode* = *precipitation code (0=none, 11=liquid, 22=frozen, 99=missing)*

*Pamt* = *precipitation amount (mm/hr)*

*Rh* = *relative humidity (percent)*

*Pres* = *station pressure (mb)*

*Ccvr* = *cloud cover (tenths)*

*WSADJ* = *wind speed adjustment and data source flag.*

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 18 | 7 | 1 | 1 | 10.0 | 0 | 244.97 | 1.37 | 15.37 | 99.00 | 99.00 |
| 18 | 7 | 1 | 1 | 30.0 | 0 | 203.25 | 2.35 | 19.08 | 99.00 | 99.00 |
| 18 | 7 | 1 | 1 | 60.0 | 0 | 209.38 | 2.57 | 19.16 | 99.00 | 99.00 |
| 18 | 7 | 1 | 1 | 100.0 | 0 | 204.91 | 3.19 | 19.21 | 99.00 | 99.00 |
| 18 | 7 | 1 | 1 | 140.0 | 0 | 199.19 | 3.68 | 19.09 | 99.00 | 99.00 |
| 18 | 7 | 1 | 1 | 240.0 | 0 | 84.61 | 2.94 | 18.52 | 99.00 | 99.00 |
| 18 | 7 | 1 | 1 | 480.0 | 0 | 75.35 | 2.61 | 17.22 | 99.00 | 99.00 |
| 18 | 7 | 1 | 1 | 820.0 | 0 | 74.82 | 2.13 | 15.25 | 99.00 | 99.00 |
| 18 | 7 | 1 | 1 | 1250.0 | 1 | 35.09 | 6.01 | 9.54 | 99.00 | 99.00 |
| 18 | 7 | 1 | 2 | 10.0 | 0 | 232.43 | 0.78 | 15.47 | 99.00 | 99.00 |
| 18 | 7 | 1 | 2 | 30.0 | 0 | 178.96 | 1.47 | 18.84 | 99.00 | 99.00 |
| 18 | 7 | 1 | 2 | 60.0 | 0 | 131.74 | 1.82 | 18.90 | 99.00 | 99.00 |
| 18 | 7 | 1 | 2 | 100.0 | 0 | 115.58 | 2.24 | 18.93 | 99.00 | 99.00 |
| 18 | 7 | 1 | 2 | 140.0 | 0 | 103.25 | 2.75 | 18.82 | 99.00 | 99.00 |
| 18 | 7 | 1 | 2 | 240.0 | 0 | 86.04 | 2.97 | 18.27 | 99.00 | 99.00 |
| 18 | 7 | 1 | 2 | 480.0 | 0 | 70.79 | 3.07 | 17.07 | 99.00 | 99.00 |
| 18 | 7 | 1 | 2 | 820.0 | 0 | 68.37 | 2.65 | 15.21 | 99.00 | 99.00 |

**Figure 3-14** Format of an hourly vertical upper profile developed by AERMET from twice daily radiosonde soundings for AERMOD

There is no header row in a profile data file. The data records in columns from left to right stand for;

*year, month, day, hour, height, top, WDnn, WSnn, TTnn, Sann, SWnn*

*where*

*height* = *measurement height (m)*

*top* = *1, if highest level, else 0*

*WDnn* = *wind direction at current level (deg)*

*WSnn* = *wind speed at current level (m/s)*

*TTnn* = *temperature at the current level (ºC)*

*SAnn* = *sigma theta (degrees)*

*SWnn* = *sigma w (m/s)*

Where turbulence values of sigma theta and sigma w are not measured these values are represented in the file as missing value indicator '99.00'. The model then computes the turbulence using similarity theory.

In addition to AERMET, which outputs hourly data from NWS data (where the hourly averaged wind speed and wind direction are represented by the average of the last two minutes before each hour), there is another US EPA-developed meteorological preprocessor called AERMINUTE which reads 1-minute and optionally 5-minute ASOS data to calculate hourly average winds for input into AERMET.

AERMINUTE was developed as there were several concerns related to the use of NWS meteorological data especially if there was a high incidence of calms and variable winds reported from the automatic stations (ASOS). AERMINUTE was developed to reduce the number of calms and missing winds in the surface data file as AERMOD cannot simulate dispersion under either calm or missing wind conditions. The effect of using AERMINUTE can be significant. Figure 3-15 shows (as grey arrows) the 1-minute wind direction as recorded. The blue arrow represents the hourly average wind represented by the final 2 minutes before the hour as done by AERMET. In contrast, the orange wind arrow represents the mean hourly AERMINUTE wind direction. In addition to computing a new, more accurate and representative one-hour average wind speed and wind direction, AERMINUTE also decreases the number of calms by increasing the number of very light winds in the range 0.1 – 0.5 m/s. Figure 3-16 provides a wind rose with and without the use of AERMINUTE. For this example, the number of calms was reduced from 27% to 2%.

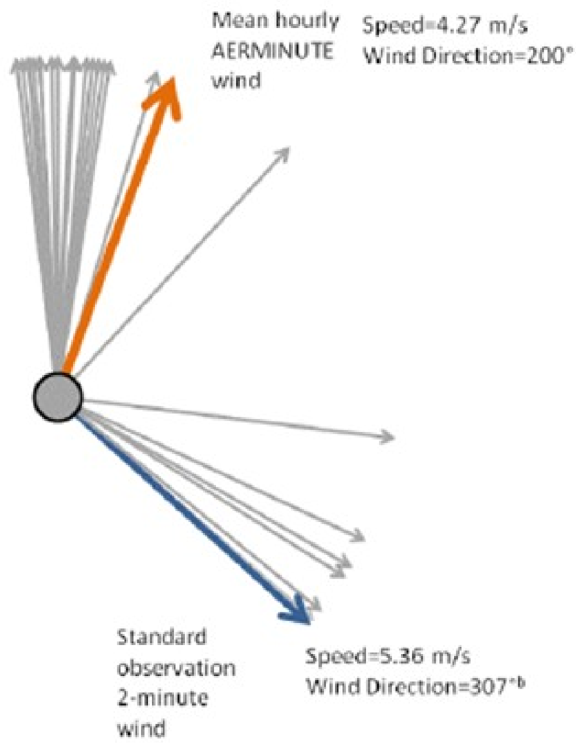



**Figure 3-15** AERMINUTE recomputes the hourly average wind speed and wind direction from 1 and 5-minute ASOS data (courtesy of Atmospheric Science Global)

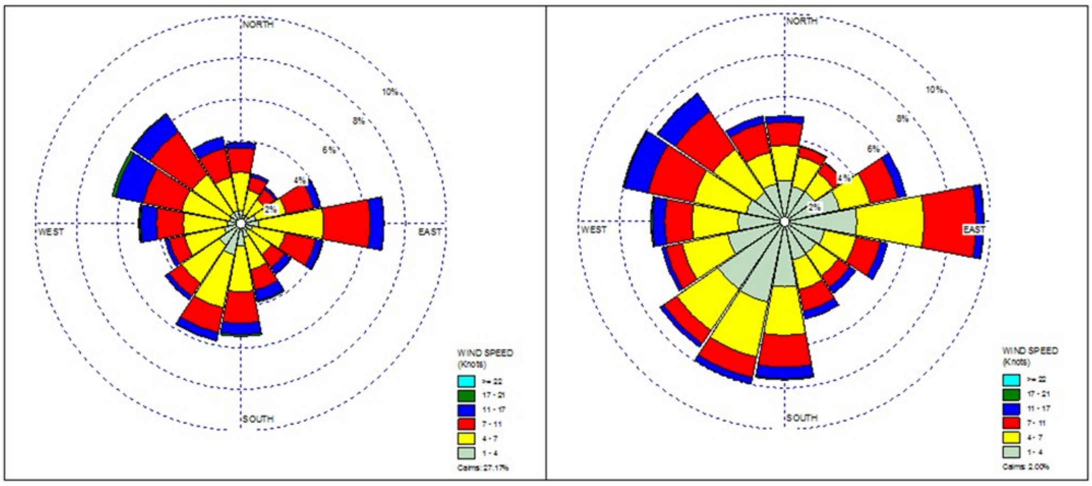



**Figure 3-16** Annual wind rose with (right) and without AERMINUTE (left) (courtesy of J. Barclay)

### 3.4.4.2. ADMS

ADMS 5 has a built-in meteorological preprocessor that allows both standard and more specialist input of flexible input meteorological data. Hourly sequential and statistical data can be processed, and all input and output meteorological variables are written to a file after processing. The ADMS meteorological processor is similar to AERMET in that the user must provide basic surface input data such as wind speed, wind direction, temperature, pressure, cloud cover, and cloud ceiling height. In addition, twice daily upper air data must also be provided as well as surface characteristics such as surface roughness length, albedo and Bowen ratio. The meteorological processor then computes the boundary layer parameters similarly to AERMET.

The WRF-to-Met utility (Cambridge Environmental Research Consultants, 2016) is a command line application which extracts meteorological data from WRF netCDF files and creates ADMS format *.met files. For the purposes of using WRF data in ADMS, it is assumed to represent the overall meteorological conditions for the previous hour, thus matching the hour-ending ADMS convention. The WRF-to-Met utility always extracts data from the lowest grid layer, except if the U10, V10 option for wind speed is selected, in which case the wind speed and direction will be extracted from the values at 10 metres. The utility does not create a profile file containing meteorological data at multiple heights. The utility extracts most WRF variables with the assumption that their units in WRF are the same as those required in ADMS, so it does not perform any unit conversions except for temperature, where a conversion from Kelvin to Celsius is required.

An example output file created by the WRF-to-Met utility is shown below as Figure 3-17, viewed in Notepad.

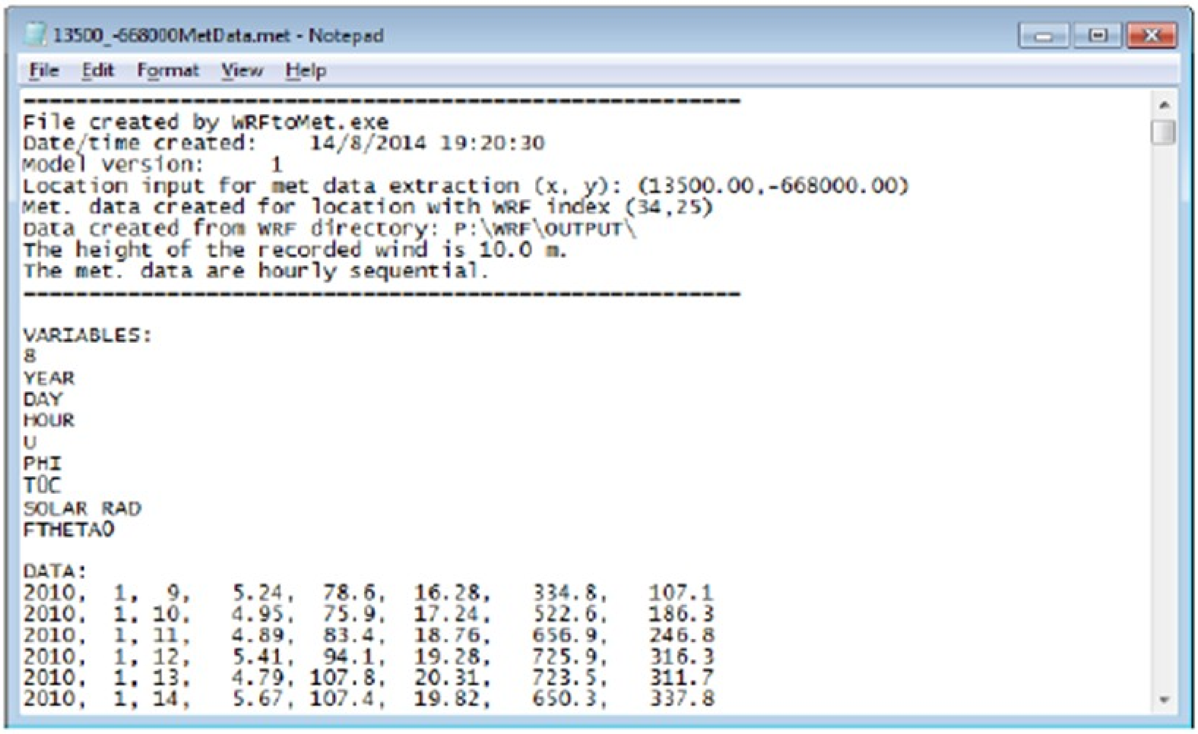



**Figure 3-17** Example WRF-to-Met Utility output file

#### 3.4.4.3. AODM

The Austrian Odour Dispersion Model, AODM (Shauberger, 2000), is a Gaussian model adapted to predict odour sensation. It estimates the daily and seasonal variation of the odour emission, the average ambient odour concentration and the momentary (peak) concentration for the time interval of a single human breath (approximately 5 seconds). Peak concentrations further downwind are modified by an exponential attenuation function for which the ratios of the standard deviations of the wind components to the average wind speed (σ/u) must either be taken from the literature or calculated from ultrasonic anemometer data.

AODM estimates mean ambient concentrations by the Austrian regulatory dispersion model (ÖNorm M 9440, 1992/96; Kolb, 1981) and transforms these to instantaneous values depending on the atmosphere's stability. ÖNorm M 9440 is a Gaussian dispersion model for continuous, buoyant plumes from stationary sources for use in flat terrain areas. The odour concentration of the plume's centre line is calculated using statistics of stability classes representative of the Austrian flatlands north of the Alps. The model is applied for single-stack emissions and distances from 100 metres to 15 kilometres. Plume rise formulae used in the model are a combination of formulas suggested by Carson & Moses (1969) and Briggs (1975). The model uses a traditional discrete stability classification scheme with dispersion parameters developed by Reuter (1970). AODM was developed in cooperation with the University of Veterinary Medicine Vienna and has been used mainly to determine adequate separation distances to populated areas from livestock buildings.

#### 3.4.4.4. ARIA Impact

ARIA Impact has a built-in meteorological preprocessor that allows the user to define or import a time series of real meteorological data conforming to one of the available formats and to create an internal meteorological database. The user must provide basic input data by choosing from a list of available meteorological parameters (such as wind speed, pressure or cloud cover), defining a sensor type and then associating one or more stations. At least wind speed, direction and temperature parameters are necessary to import in order to be able to carry out dispersion simulations later on. The position (x, y, height) and sensor type are required for each station. It is possible to choose different time resolutions of the meteorological data in relation to the statistical calculation time step. The user interface has a wizard for importing data and parameters, with buttons and tables of all available options and variables, as in the following example (Figure 3-18).

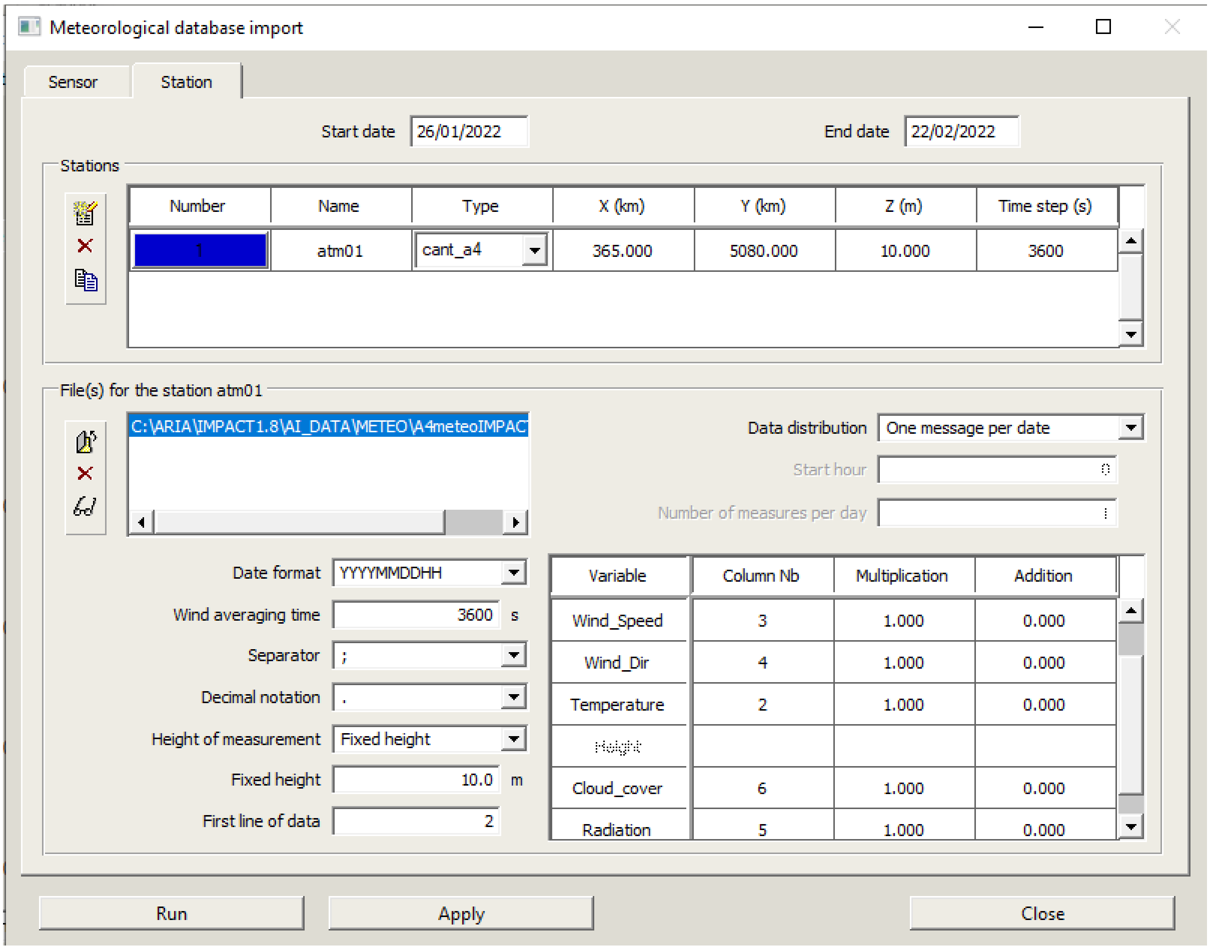



**Figure 3-18** Example of the ARIA Impact Graphical User Interface to import / generate meteorological data (courtesy of ARIANET)

All meteorological parameters are categorised into different classes, which allow the calculation of frequency distributions and serve as a basis for the statistical analysis and calculation of wind roses based on the meteorological data available. The user can select the formula for stability class computation from the option list according to the parameters found in the meteorological database.

In order to consider the vertical variation of meteorological variables, ARIA Impact can compute vertical profiles of both wind speed and temperature based on measurements made at ground level as well as on atmospheric turbulence, in order to calculate their values at the stack height and to use them in the dispersion calculation.

## 3.4.5. Lagrangian Puff Models – CALPUFF, SCIPUFF

### 3.4.5.1. CALMET for CALPUFF

In its simplest terms, CALMET (Scire et al., 2000) is a meteorological model that develops hourly wind and temperature fields on a three-dimensional gridded modelling domain. CALMET can read both numerical weather data output from the WRF model and surface observation data to assist in the development of three-dimensional wind fields. Associated two-dimensional fields such as mixing height, surface characteristics, and dispersion properties are also included in the file produced by CALMET. CALPUFF, CALMET's dispersion model, is a transport model that reads the output of the CALMET model to advect 'puffs' of material emitted from modelled sources, simulating dispersion and transformation processes along the way.

The CALMET meteorological model consists of a diagnostic wind field module and micrometeorological modules for over-water and over-land boundary layers. The diagnostic wind field module uses a two-step approach to the computation of the wind fields (Douglas & Kessler, 1988). In the first step, an initial-guess wind field is adjusted for kinematic effects of terrain, slope flows, and terrain blocking effects to produce a Step 1 wind field. The second step consists of an objective analysis procedure to introduce observational data into the Step 1 wind field to produce a final wind field.

The CALMET model contains two boundary layer models for application to over-land and over-water grid cells. Over land surfaces, the energy balance method of Holtslag and van Ulden (1983) is used to compute hourly gridded fields of the sensible heat flux, surface friction velocity, Monin-Obukhov length, and convective velocity scale. Mixing heights are determined from the computed hourly surface heat fluxes and observed temperature soundings using a modified Carson (1973) method based on Maul (1980). The model also determines the gridded fields of Pasquill-Gifford-Turner (PGT) stability class and optional hourly precipitation rates. Over water, the model uses a profiling technique, using the air-sea temperature difference to determine the micrometeorological parameters in the marine boundary layer.

The CALPUFF model can be run in several modes, where each mode requires a different type of meteorological data. The following lists three modes to run CALMET and a fourth mode using other meteorological processors.

- **CALMET No-Observations (NOOBS) Mode.** CALMET using gridded numerical model output (e.g., from the MM5, WRF, RAMS, RUC, Eta or TAPM models). No surface, upper air or buoy observations are used in No-Obs mode.
- **CALMET Hybrid Mode (HYBRID).** CALMET using a combination of gridded numerical meteorological data supplemented by surface and optional over-water buoy data.
- **CALMET Observations-Only (OBS) Mode.** – CALMET using observed surface and upper air data, plus optional buoy data.
- **Single meteorological station dataset.** CALMET is not used, but single station meteorological data in the form of AERMOD, AUSPLUME, CTDMPLUS and ISCST3 may all be passed directly into CALPUFF.

If good quality gridded, prognostic meteorological data are available. CALMET NOOBS mode is recommended as the preferred method for regulatory screen modelling. When run this way, CALMET uses gridded wind fields generated by one of the numerical prognostic models. The procedure permits the prognostic model to run with a significantly larger horizontal grid spacing than the diagnostic model. The 3D gridded data typically contains winds, vertical velocity, pressure, temperature and moisture parameters.

The essential benefits of running the model in NOOBS mode are:

- CALMET can be run on a much finer horizontal resolution than the prognostic model. The model will adjust the winds for the fine-scale terrain, and Land use of the CALMET model domain;
- Spatial variability in the horizontal and the vertical;
- Simplicity of the NOOBS run, fast and efficient;
- No additional data are required;

- Most of the decision-making by the user is eliminated; and
- No over-water data required to invoke the over-water boundary layer algorithm.

The HYBRID mode is considered an 'advanced simulation' since it combines the numerical prognostic model data in a gridded 3D format in conjunction with surface observation data. More work is required by the user to collect, format and quality control-check the data. In addition, the user must make specific model choices over various critical parameters pertaining to the distance weighting factors of the surface observations.

Finally, CALMET can be run in OBS-only mode. At a minimum CALMET must be provided hourly surface data from one or many stations as well as radiosonde data at intervals no more than 14 hours apart. This run requires significant effort by the modeller who needs to decide multiple choices pertaining to the station data, as well as managing the quality of the data and missing data.

There is a final choice to run CALPUFF with single-station meteorology of the form used to run AERMOD, ISCST3, AUSPLUME and CTDMPLUS. There are significant benefits of running CALPUFF with single-station meteorology compared to running a steady-state Gaussian model with the same meteorology. These are as follows;

- The time required for a plume material to reach a receptor (the causality effect) is accounted for in the puff transport, unlike the plume models where the plume extends to infinity even after 1 hour with a 1 m/s wind;
- CALPUFF has memory in that each hours emissions and meteorology are retained and may impact the concentrations during a subsequent hour; and
- CALPUFF is able to model calms, unlike regular plume models.

#### 3.4.5.2. SCIPUFF

SCIPUFF is a Lagrangian puff dispersion model that uses a collection of Gaussian puffs to represent an arbitrary, three-dimensional, time-dependent concentration field. The turbulent diffusion parameterisation is based on modern turbulence closure theory (Sykes, 1998). SCIPUFF can use several types of meteorological data for input, including

- Fixed winds where wind speed and direction are assumed constant;
- Observational input where time-dependent observations are combined from multiple surface stations and/or upper-air profiles; and
- Time-dependent 3-dimensional gridded input.

Planetary boundary layer turbulence is represented explicitly in terms of surface heat flux and shear stress using parameterised profile shapes. Turbulence data may be optionally specified as follows:

1. Planetary boundary layer - Vertical profiles of the boundary layer scale turbulent velocity fluctuations, heat flux and turbulence length scales can be provided as input by the user, or may be modelled based on boundary layer characteristics. Options for treatment of the boundary layer include “calculated”, “observed” or “simple diurnal”. Input requirements depend on the boundary layer treatment type.

2. Large-scale variability - For long-range transport, the mesoscale horizontal velocity fluctuations and turbulence length scale may be specified by the user, computed from a theoretical model or read from a meteorological observation file.

A Graphical User Interface (GUI) shown in Figure 3-19 assists SCIPUFF users in setting up the required meteorological inputs for the model.

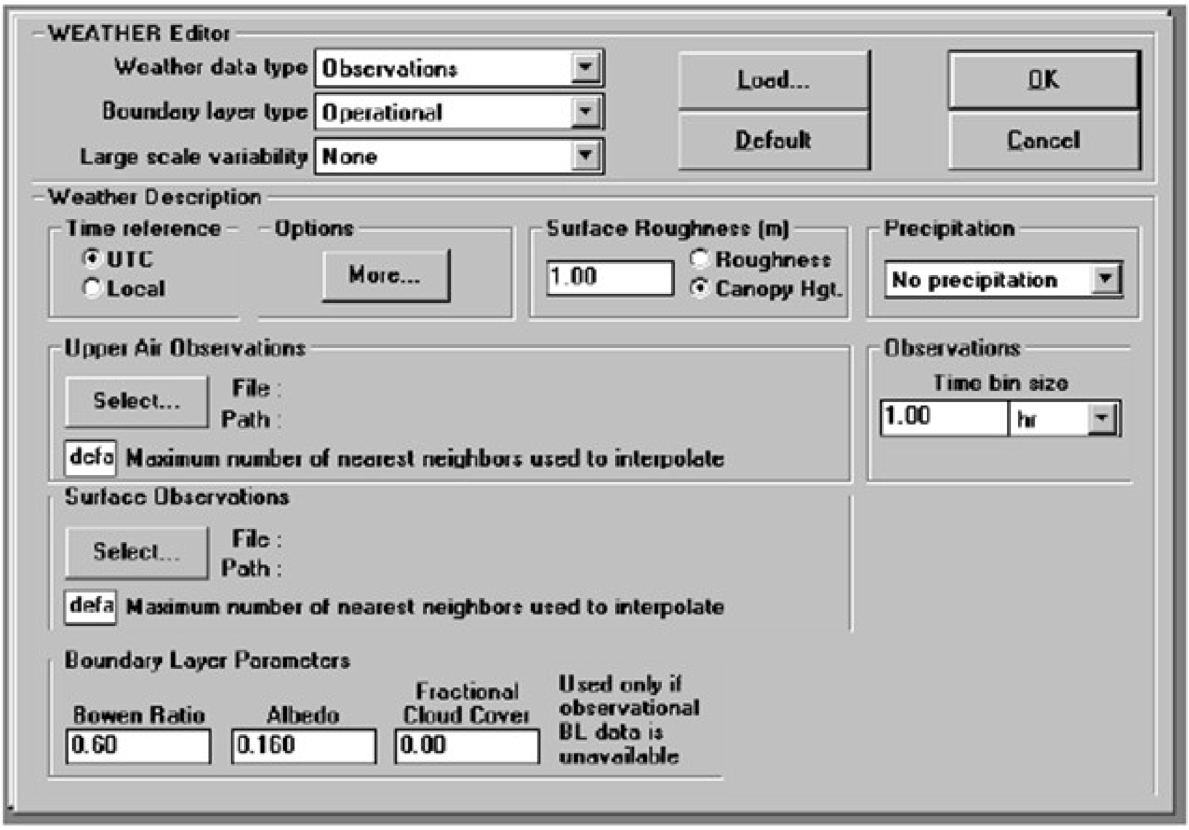



**Figure 3-19** SCIPUFF Graphical User Interface

Observational weather data files must follow formatting specific to SCIPUFF. Fixed wind information (10 metres above the surface) may be input directly. Gridded meteorology output from the WRF model can be read directly by SCIPUFF without the need for pre-processing with the MMIF program.

SCIPUFF calculates surface heat flux using a surface energy balance model. Boundary layer height is estimated from an evolution equation that models growth from convectively and mechanically-driven entrainment into the overlying stable air. The Bowen ratio, Albedo, and Cloud Cover parameters may be selected for use when observational boundary layer data are unavailable. Alternately, the daytime and nighttime inversion heights and sensible flux may be input directly. The surface roughness length and canopy height may also be selected by the user.

### 3.4.6. Lagrangian Particle-Puff Model – TAPM

The meteorological component of TAPM is an incompressible, non-hydrostatic, primitive equation model with a terrain-following vertical coordinate for three-dimensional simulations. The model solves the momentum equations for horizontal wind components, the incompressible continuity equation for vertical velocity, and scalar equations for potential virtual temperature and specific humidity of water vapour, cloud water/ice, rainwater and snow. The Exner pressure function is split into hydrostatic and non-hydrostatic components, and a Poisson equation is solved for the non-hydrostatic component. Explicit cloud microphysical processes are included. The turbulence terms in these equations have been determined by solving equations for turbulence kinetic energy and eddy dissipation rate, and then using these values in representing the vertical fluxes by a gradient diffusion approach, including a counter-gradient term for heat flux. A vegetative canopy, soil scheme, and urban scheme are used at the surface, while radiative fluxes, both at the surface and at upper levels, are also included.

## 3.4.7. Lagrangian Particle Models – SPRAY, AUSTAL (LASAT), LAPMOD and GRAL

### 3.4.7.1. SPRAY

SPRAY can be connected to different meteorological processors to acquire the three-dimensional fields of the average wind and air temperature and the variables related to particle dispersion. In particular, the most natural meteorological preprocessor for SPRAY is the mass-consistent diagnostic code SWIFT (Finardi et al. 1998), able to reconstruct, directly on the 3D grid needed by the dispersion code, wind and temperature fields over complex topography minimising the divergence of the flow. SWIFT considers data at discrete time steps, derived either from ground-level and vertical profiles measured at any point inside the computational domain, or considering a 3D grid of modelled data simulated at a coarser resolution. The code performs an initial interpolation phase in which all the available data are considered together and put on the target grid, followed by an adjustment phase during which the mass-conservation equation is applied to minimise the divergence field. During the adjustment phase, vertical velocities coupled with the underlying orographic profile are generated. This allows the SPRAY code to use wind fields generated at a relatively high resolution, down to less than a hundred metres, to describe meteorological fields in the presence of complex topographies. SWIFT can generate also 2D horizontal fields of the scaling variables describing the turbulence characteristics (such as the friction velocity $u_*$, the Monin-Obukhov length L, the convective velocity scale $w_*$ and the mixing-layer or stable-layer height) which depend on the horizontal structure of the land-use at the target resolution. These fields are then directly considered by the SPRAY code to generate the 3D fields of the variables related to the random particle movements through some embedded parameterisations. For the same purpose, the SPRAY code can be also coupled with the turbulence parameterisation code SurfPro (Silibello et al. 2006), which can also derive 2D time-dependent deposition velocities for the gaseous species or particulate matter to be considered in the dispersion simulation. SPRAY can be also connected with the output of the meteorological prognostic code RAMS (Pielke et al. 1992), using the preprocessing system named MIRS (Method for Interfacing Rams and Spray, Trini Castelli et al., 2000, 2014, 2017). This interfacing code generates directly the 3D fields of the variables related to the random particle movements on the target grid using the data generated by RAMS and applying some different parameterisations.

### 3.4.7.2. AUSTAL / LASAT

The German regulatory model AUSTAL, formerly known as AUSTAL2000, Federal Environment Agency, 2014) is designed to work in two modes: statistical calculations and "time series" calculations. In the second case, AUSTAL needs hourly data for wind speed, wind direction in 10-degree sectors and stability class according to Klug/Manier (or, alternately, Obukhov length scale). Meteorological data are usually provided in the form of an AKTerm file (meteorological time series in the format used by the German Weather Service). An AKTerm is a text file with one line of data for each successive hour of the year.

The internal boundary layer of AUSTAL is set up to assume a wind shear (Ekman spiral) with a height typical for central Europe. This must be considered when using AUSTAL in other countries. The wind shear can be switched off with the NOSTANDARD option NOSHEAR.

Klug / Manier is the default German classification scheme for atmospheric stability. The Klug

/ Manier Class ID is specified as: 1: Klug / Manier I (very stable), 2: Klug/Manier II (stable), 3: Klug / Manier III/1 (stable to neutral), 4: Klug / Manier III/2 (neutral to unstable), 5: Klug / Manier IV (unstable), 6: Klug / Manier V (very unstable). The Klug / Manier stability classes 1 to 6 correspond approximately to the Pasquill-Gifford classes F to A. In the time series file, the Monin-Obukhov length is specified as a more direct and detailed measure of the stability.

A diagnostic wind field model (TALdia) is integrated in the meteorological preprocessor and allows dispersion calculations in inhomogeneous terrain or in the presence of buildings. In articulated terrain, wind field libraries from prognostic models can be integrated into AUSTAL. In steep terrain, the limits of the diagnostic wind field model (TALdia) are reached. Flows around buildings can also be taken into account via the integrated diagnostic wind field model. However, if an assessment in the recirculation zone in the lee of buildings is necessary, prognostic wind field modelling has to be implemented in advance outside the model system AUSTAL.

#### 3.4.7.3. LAPMOD

The meteorological input of LAPMOD consists of three dimensional fields of wind and temperature and two dimensional fields of turbulent parameters as Monin Obukhov length, friction velocity, convective scale velocity, mixing layer height, etc. (Enviroware, 2022) LAPMOD reads directly the meteorological fields generated with CALMET (Scire et al., 2000), the diagnostic meteorological model also used in input by the CALPUFF dispersion model. LAPMOD is fully coupled with CALMET, up to version 6.5.0. CALMET also provides the geophysical variables required by LAPMOD, including terrain elevation, needed to calculate the concentration values, and roughness or the land use category, used to estimate deposition fluxes. LAPMOD can interpolate in time the meteorological output fields of CALMET with frequency specified in input by the user. For example, if the meteorological fields are provided with 1-hour time resolution, the user can specify to interpolate those fields every 10 minutes. Of course, LAPMOD can directly use high frequency time resolution when they are available (for example using CALMET 6.5.0). LAPMOD requires CALMET to be used with UTM (Universal Transverse Mercator) map projection, and all the “entities” (sources, receptors, etc.) in LAPMOD must be defined with those coordinates. The meteorological data needed by LAPMOD to perform a simulation may be within a single CALMET file, or within a series of files specified in chronological order (it may be useful, for example, to split the CALMET output over all the months of a year, when a single file could be too big).

CALMET is the preferred tool to provide meteorological data to LAPMOD because, for example, it is 3-dimensional and allows the use of high space resolution for the geophysical features. However, other two options are possible.

The first one consists in preparing the meteorological fields with a prognostic meteorological model such as MM5 or WRF, and then to post-process their output with the MMIF (Mesoscale Model Interface Program processor, US-EPA, 2021). LAPMOD reads directly the output of the MMIF processor, which can be contained in a single file or in a series of files specified in chronological order (as for CALMET). Since the map projection of MMIF is Lambert Conformal Conic (LCC), all the LAPMOD coordinates (domain, receptors, emissions) must be expressed with the same projection. MMIF, as CALMET, is 3-dimensional, but it typically does not provide information with the same spatial resolution, because it is based on the output of prognostic models.

Finally, the meteorological input file of LAPMOD may also be prepared with the LAPMET processor, which reads the AERMOD meteorological files and writes its output in CALMET format. The meteorological file prepared in this way derives from a single meteorological station, therefore it is not 3-dimensional as those prepared with CALMET or MMIF. In other words, for a specific time, the meteorological field is homogeneous along the horizontal direction. The variation along the vertical direction is determined using the information within the vertical profile input file of AERMOD and with the similarity theory. LAPMET is currently used for debugging purposes and for comparing LAPMOD and AERMOD results using the same meteorological data.

#### 3.4.7.4. GRAL – The GRAZ Lagrangian Model

In flat terrain, GRAL requires at a minimum the wind speed, wind direction, and stability class at a single point at any height. A power law as a function of the Obukhov length provides the vertical wind profile. The latter is derived from the stability class and the roughness length, which needs to be specified by the user and shall be representative for the whole modelling domain. Additional turbulence quantities, e.g. friction velocity or profiles of the standard deviation of wind velocity fluctuations, are mostly based on the well-known Monin-Obukhov similarity theory. GRAL also offers the possibility of using observed turbulent quantities (e.g. sonic anemometer observations) at a single location at multiple heights. In both cases, the input format is a simple text file.

Time series of meteorological data can either be used without any further data processing, or - in case that wind and stability data are used – can be binned into user-defined classes in order to enhance computational efficiency. In this way, simulations for an entire year can be sped up by about a factor of 10 in most cases. GRAL comes with its own graphical user interface (GUI) which is recommended for preparing and processing all of the model input data.

In the presence of either buildings or vegetation, GRAL automatically invokes a prognostic microscale wind-field model, which has been validated according to the German guideline VDI 3783-9 (Oettl, 2015a). Currently, only the 3D wind fields are used in the Lagrangian dispersion algorithm, because it was found that the usage of the turbulent kinetic energy does not improve results (Oettl, 2015b). The required input data for meteorology remains unchanged in the presence of buildings or vegetation.

In complex terrain, 3D wind fields are provided by the prognostic mesoscale model GRAMM (Oettl, 2020). In the simplest mode, GRAMM can use the same meteorological data as GRAL in flat terrain, namely a single point observation of wind speed, direction, and stability class. The initial wind profile in GRAMM is obtained in the same manner as for GRAL in flat terrain, while the initial temperature stratification is assumed to be neutral. The incoming solar radiation is directly linked to the stability class and wind speed. All initial meteorological fields are assumed to be horizontally homogeneous in GRAMM. Lateral boundary conditions are kept constant, while the surface energy balance is computed continuously by taking into account shading effects of the surrounding topography and by utilising a soil model with seven layers. The soil and land use properties, such as roughness length or thermal conductivity, are parameterised by using the CORINE land use classification scheme. With this methodology, quasi steady-state wind fields are simulated with GRAMM that can be used as input for GRAL.

Over the years, the methodology has been refined in order to improve the quality of the 3D wind fields. By developing the so-called ‘match-to-observation’ algorithm (MTO), the model’s performance could be greatly enhanced (e.g. Berchet et al., 2017). The basic principle of the MTO is the following: in a first step a large number (>2.000) of quasi steady-state wind fields for the domain of interest are computed with GRAMM using any possible combination of classified wind speed, direction, and stability. In a second step, the MTO selects for each hour of the year the best fitting 3D wind field comparing simulated and observed winds and stabilities at all available monitoring stations within the modelling domain. Note, that the MTO as well as GRAMM are fully integrated in the GUI. As the calculation of the wind fields can be very time consuming for large modelling domains (> 100 km x 100 km), specifically when using a high horizontal grid resolution (100 - 500 m), it is recommended to pre-compute such wind fields only once for a representative reference year.

Recent research focuses on coupling GRAMM with global reanalysis data such as ERA5 (Copernicus Climate Change Service, 2017). The main motivation is to improve the interaction of synoptic-scale flows with thermally-driven local flows (e.g. mountain-valley winds) in highly complex terrain such as the alps (e.g. Oettl and Veratti, 2021a; Oettl, 2021b).

## 3.5. Meteorological Data Evaluation and Reporting

Once the meteorological data set required for an odour dispersion analysis has been assembled, it is reasonable and proper to perform a few simple analyses of the data to be sure it is representative of the project site. These analyses may include: a determination of annual and monthly means of critical parameters; construction of annual and monthly wind rose plots; construction of simple plots or diagrams of atmospheric stability, mixing height, temperature, and precipitation over time; and perhaps an analysis of average vector wind speed and direction. This type of analysis and presentation of single-variable data can be included in the final modelling report and adds a level of confidence to any such report.

When meteorological data is extracted from a numerical model such as WRF, some additional statistical analysis of the data is required; the modelled data should be compared to observational data collected during the simulation period. This analysis will provide inferences about the differences between the two populations, that is, the modelled data versus observations data. These analyses typically will include: differences of the means of the populations; differences of the variances; the mean bias error; the root mean square error; the index of agreement; and other measures.

### 3.5.1. Single-Population Data Evaluation

As a first step, summarise the data fields to be used in the dispersion model by calculating the monthly means and standard deviations of scalar quantities such as surface temperature, mechanical and convective mixing height, precipitation, and sensible heat flux. These calculated values should be compared to long-term averages for the modelling domain to determine if the selected meteorology can be considered sufficiently representative. A few simple graphs such as given in Figure 3-20 can help to visualise the data over the modelling period.

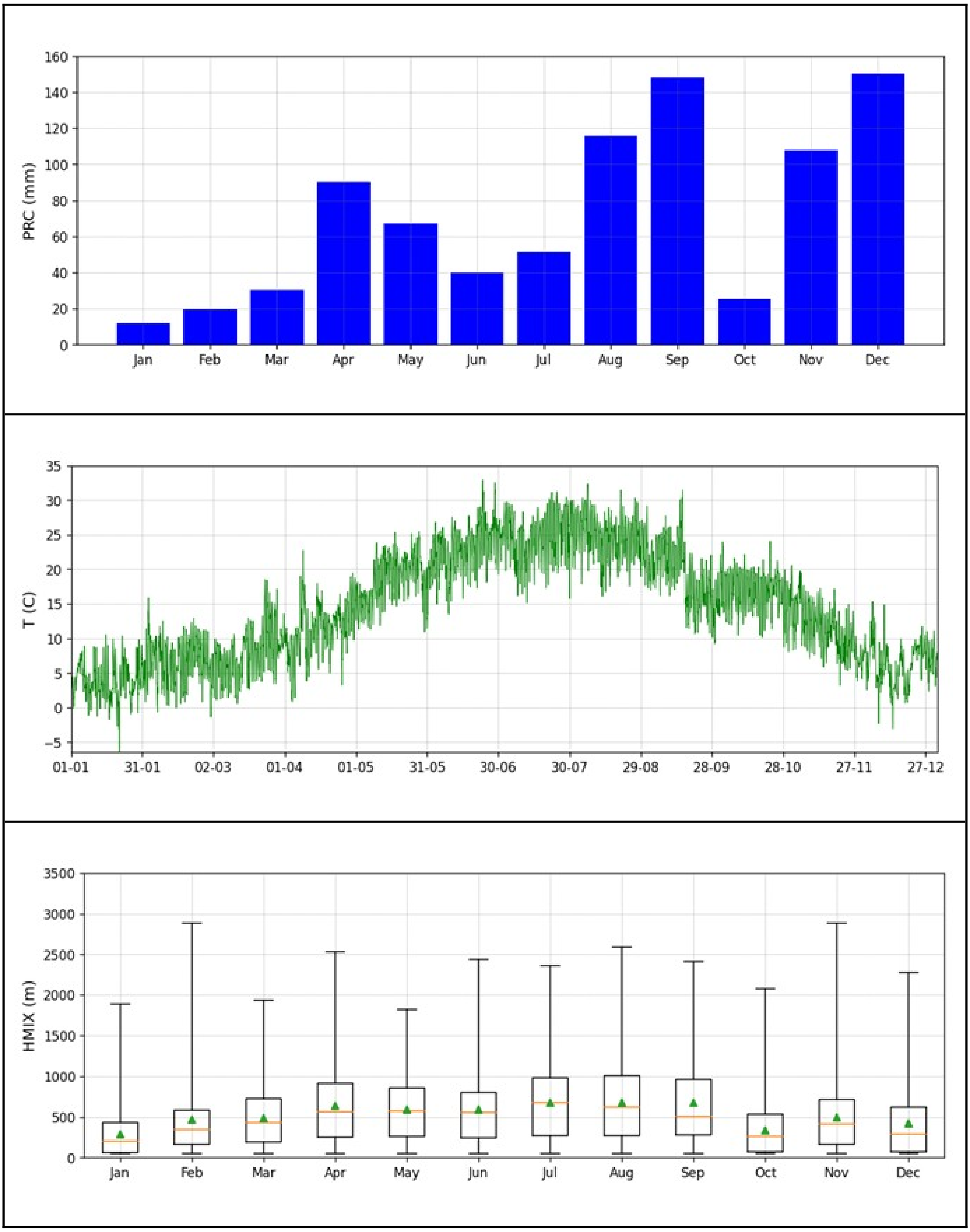
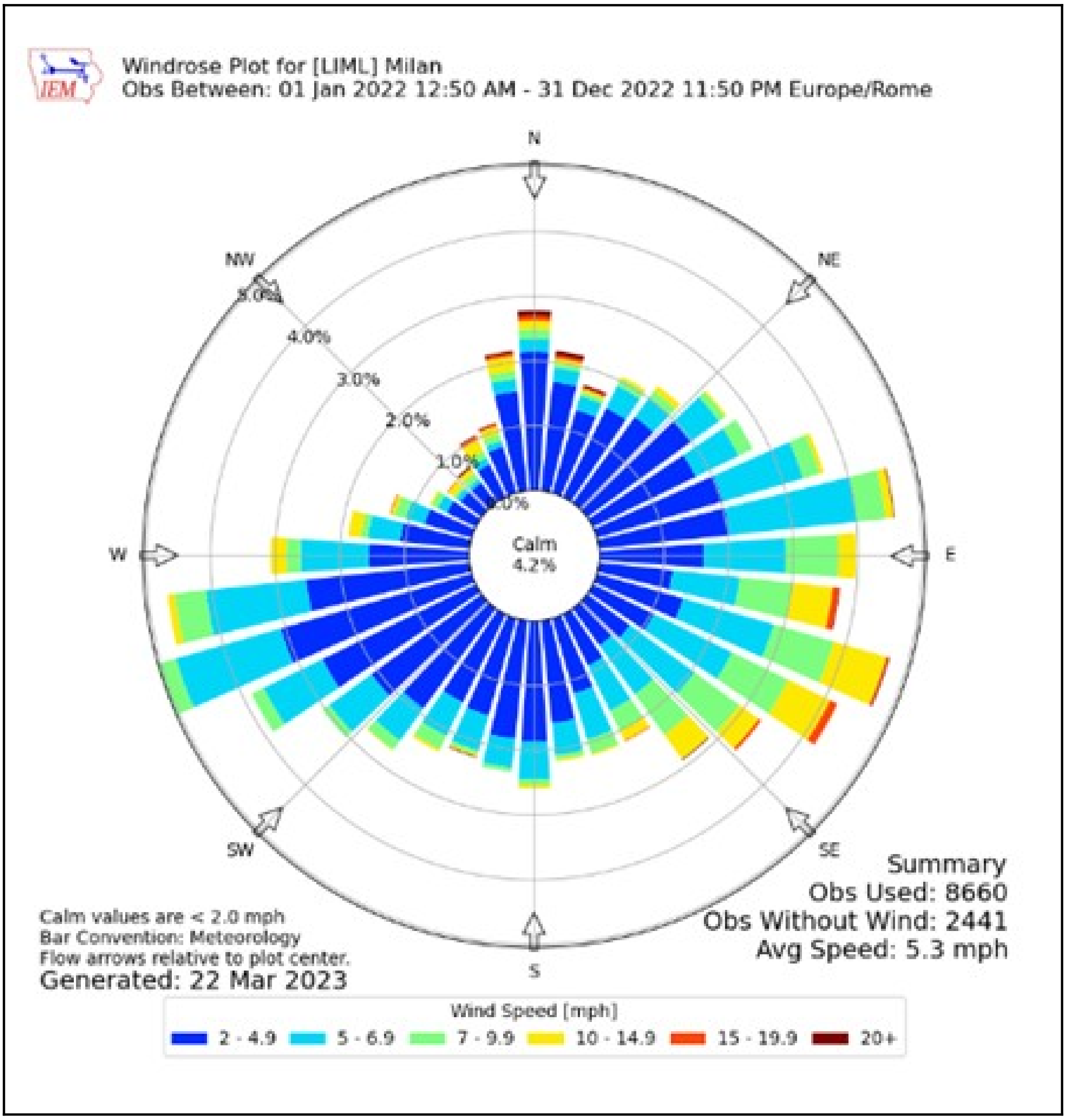



**Figure 3-20** Precipitation (top), Temperature (centre), and Mixing Height (bottom) plots (Courtesy of Enviroware)

Next create annual and monthly wind rose diagrams. Wind roses are graphical charts that characterise the speed and direction of winds at a location. Presented in a circular format, the length of each 'spoke' or 'petal' around the circle indicates the amount of time that the wind blows from a particular direction. Colours along the spokes indicate categories of wind speed. Wind roses are a very important evaluation method as they provide an easy-to-understand graphical output of many hundreds of hours of varying wind speed and wind direction. Figure 3-21 depicts example annual and monthly wind rose diagrams.



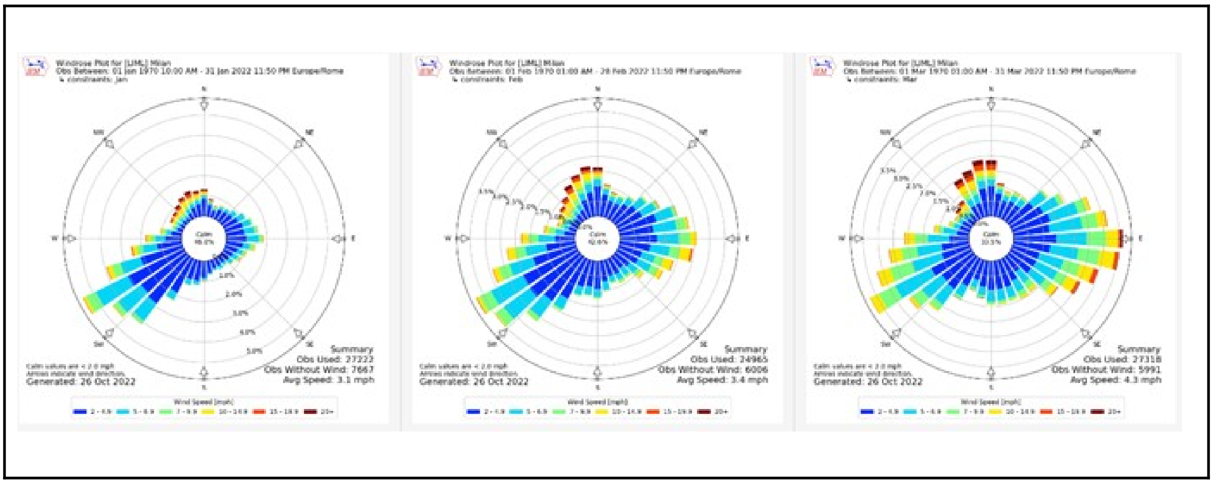


**Figure 3-21** Example Annual (top) and Monthly (bottom) Wind Rose Diagrams (Source: Iowa Environmental Mesonet, https://mesonet.agron.iastate.edu/)

Within the context of odour modelling, the monthly wind roses provide additional insight into critical periods of the year for receptors located across the modelling domain. Finally, daily wind roses can provide an additional check that any sea-land breeze is correctly reproduced by the meteorological data set. Appendix A includes links to several useful Tools including those which offer wind rose generators.

Conduct additional analyses for winds. Wind speed and direction are two components of the same quantity, i.e., wind is a vector with both magnitude and direction. While it is acceptable for a data user to calculate the arithmetic mean of wind speed (as a scalar quantity), this cannot be done for wind direction. The main issue arises because wind direction is usually reported as an angle in degrees, 0–360 (or 0-359) where 0 or 360 represents a wind blowing from a northerly direction. If the wind direction is blowing from the north and traverses the discontinuity at the beginning/end of the circular scale, and then the arithmetic mean is calculated, this will result in the average wind direction to be somewhere in the southern quadrant. This is clearly incorrect. To correctly deal with this scale discontinuity, trigonometric functions must be used to handle the angles (US EPA, 2000), (Grange, 2014).

Wind speed is expressed as the ratio of two different measures: distance and time. The harmonic mean is generally more appropriate than the arithmetic mean if the data values are ratios of two variables with different measures. For general wind analysis, however, the harmonic mean is rarely used. Both methods of calculation are shown here for completeness.

The scalar mean wind speed is:

$$\underline{u} = \frac{1}{N}\sum_{i=1}^{N} u_i \qquad \textit{(Equation 3-1)}$$

and the harmonic mean wind speed is:

$$\underline{u}_h = ¿ \qquad \textit{(Equation 3-2)}$$

where u_i is the wind speed at each time of observation. Note that the harmonic mean is not defined when the wind is null. This statistic is very sensitive to low winds.

These scalar wind speed calculations are quite simple to perform since the meteorological data set consists of columns of the various parameters which can easily be imported into a worksheet for manipulation.

Vector functions are used to average wind direction and can be used to compute a type of average wind speed which is different from the scalar average discussed above. The wind components Ve and Vn must be calculated as:

$$V_e = \frac{-1}{N} \sum_{i=1}^{N} u_i \left[ 2\pi \times \frac{\theta_i}{360} \right] \quad \text{(Equation 3-3a)}$$

$$V_n = \frac{-1}{N} \sum_{i=1}^{N} u_i \left[ 2\pi \times \frac{\theta_i}{360} \right] \quad \text{(Equation 3-3b)}$$

Where:

Ve = east-west component of the wind direction

Vn = north-south component of the wind direction.

ui is the wind speed at each time of observation, and

θ is the wind direction in degrees.

Since wind direction (θ) is in degrees, the units for the components are radians. There are two other things to note: (i) the wind components here are calculated along with wind speed (ui), that is, the vectors are weighted by their magnitude, and (ii) the negative sign negates the direction. This negation is because wind direction, by meteorological convention, is defined from where the wind is blowing from, while the vectors define the direction where the flow is heading to.

The vector average wind speed is then calculated as:

$$\underline{U}_{RV} = \left( V_e^2 + V_n^2 \right)^{1/2} \quad \text{(Equation 3-4)}$$

And the vector average wind direction as:

$$\theta_{RV} = \arctan\left( \frac{V_e}{V_n} \right) + FLOW \quad \text{(Equation 3-5)}$$

Where if:

ArcTan(Ve/Vn) < 180 then FLOW = 180

ArcTan(Ve/Vn) > 180 then FLOW = -180

One can easily use a worksheet to perform these calculations as shown in Figure 3-22. Note that in many programming languages the ArcTan function is available in two different forms, ATAN(Ve/Vn) or ATAN2(Ve,Vn).

| Date/Time (LST) | WD (deg) | WS (m/s) | 1/WS | _i | V_i | V_i |
|---|---|---|---|---|---|---|
| 07/12/2019 01:00 | 189 | 6.2 | 0.161 | 1 | 0.970 | 6.124 |
| 07/12/2019 02:00 | 186 | 5.7 | 0.175 | 2 | 0.596 | 5.669 |
| 07/12/2019 03:00 | 195 | 5.7 | 0.175 | 3 | 1.475 | 5.506 |
| 07/12/2019 04:00 | 202 | 6.7 | 0.149 | 4 | 2.510 | 6.212 |
| 07/12/2019 05:00 | 171 | 4.6 | 0.217 | 5 | -0.720 | 4.543 |
| 07/12/2019 06:00 | 215 | 6.2 | 0.161 | 6 | 3.556 | 5.079 |
| 07/12/2019 07:00 | 227 | 6.2 | 0.161 | 7 | 4.534 | 4.228 |
| 07/12/2019 08:00 | 205 | 5.7 | 0.175 | 8 | 2.409 | 5.166 |
| 07/12/2019 09:00 | 193 | 7.2 | 0.139 | 9 | 1.620 | 7.015 |
| 07/12/2019 10:00 | 198 | 7.7 | 0.130 | 10 | 2.379 | 7.323 |
| 07/12/2019 11:00 | 195 | 7.7 | 0.130 | 11 | 1.993 | 7.438 |
| 07/12/2019 12:00 | 176 | 9.3 | 0.108 | 12 | -0.649 | 9.277 |
| 07/12/2019 13:00 | 169 | 8.8 | 0.114 | 13 | -1.679 | 8.638 |
| 07/12/2019 14:00 | 156 | 9.3 | 0.108 | 14 | -3.783 | 8.496 |
| 07/12/2019 15:00 | 152 | 7.2 | 0.139 | 15 | -3.380 | 6.357 |
| 07/12/2019 16:00 | 173 | 7.7 | 0.130 | 16 | -0.938 | 7.643 |
| 07/12/2019 17:00 | 195 | 7.7 | 0.130 | 17 | 1.993 | 7.438 |
| 07/12/2019 18:00 | 199 | 7.7 | 0.130 | 18 | 2.507 | 7.280 |
| 07/12/2019 19:00 | 226 | 7.2 | 0.139 | 19 | 5.179 | 5.002 |
| 07/12/2019 20:00 | 246 | 6.2 | 0.161 | 20 | 5.664 | 2.522 |
| 07/12/2019 21:00 | 201 | 6.7 | 0.149 | 21 | 2.401 | 6.255 |
| 07/12/2019 22:00 | 195 | 5.7 | 0.175 | 22 | 1.475 | 5.506 |
| 07/12/2019 23:00 | 193 | 5.7 | 0.175 | 23 | 1.282 | 5.554 |
| 07/13/2019 00:00 | 197 | 5.1 | 0.196 | 24 | 1.491 | 4.877 |
| | | | | | | |
| | Scalar | 6.8 | | | 1.370 | 6.214 |
| | Harmonic | 6.6 | | ArcTan | 12.4 | |
| | Vector | 6.4 | | Vector | 192 | |

**Figure 3-22** Worksheet calculation for vector wind quantities

### 3.5.2. Technical Approach to Prognostic Model Evaluation

For both episodic and annual simulations, it is important that the observational databases to which the model outputs will be compared consist purely of routine surface and aloft measurements performed by individual countries' National Weather Service and other State agencies. The evaluation must focus on the ability of the meteorological prognostic model to correctly estimate surface and upper air wind speed, wind direction, temperature, mixing height and precipitation at pertinent time and space scales. All of the same parameters must be analysed as above, except that instead of using single population data, these statistics compare the two data populations: the prognostic model data versus observations.

Statistical procedures include scalar and vector mean wind speeds, standard deviations in measured and observed winds, errors of difference (total plus systematic and unsystematic components), two model skill measures, plus the Index of Agreement. Statistical measures for temperature, mixing height, and precipitation should include means, biases, gross errors, and the index of agreement.

Complementing the statistical measures are a variety of graphical displays which include state-variable time series plots, two-dimensional parameter fields, vertical profiles of predicted and observed variables, skew-T plots, scatter plots and wind roses.

For gridded 3-dimensional meteorological model predictions, evaluations could be both (a) subregional evaluations, and (b) limited time-period evaluations (e.g., monthly and seasonal). These evaluations are aimed at elucidating the model's ability to predict key processes at smaller time scales (e.g. coastal circulation regimes) as well as defining the model's ability to produce reliable air quality inputs at scales appropriate to odours from tall stacks that might disperse a reasonable distance.

All of the techniques in this Chapter have been employed extensively in other prognostic model performance testing after Doty et al (2002), Tesche and McNally (2001), Tesche et al (2002), Emery et al (2001). These evaluation procedures are endorsed by the US EPA (US EPA, 2000). A brief description of each statistic is given here; the reader is directed to the references and to general statistics texts for more detailed information.

## 3.5.3. Operational Evaluation of Surface Fields

### 3.5.3.1. Mean Statistics

Begin the evaluation by determining annual and monthly means and standard deviations of scalar variables in both populations as described earlier. For winds, follow the techniques for vector calculations.

### 3.5.3.2. Difference Statistics

Now begin the process of determining how similar the two populations are. For quantities that are continuous in space and time (i.e., wind speed, temperature, pressure, odour concentrations), difference statistics provide considerable insight into the model's performance, temporally and spatially. Difference statistics are based on the definition of a residual quantity, di. For instance a temperature residual, for example, is defined as:

$$d_i = c_e(x_i, t) - c_o(x_i, t) \qquad \textit{(Equation 3-6)}$$

Where di is the i-th residual based on the difference between model-estimated (ce) and observed (co) temperature at location x and time i. In the definitions that follow below, the letter c has been used to denote any continuous atmospheric variable (e.g., temperature, precipitation, etc).

Standard deviation of residual distribution (SDr). The standard deviation of the residual distribution is given by:

$$SD_r = \left\{ \frac{1}{N-1} \sum_{i=1}^{N} (d_i - MBE)^2 \right\}^{\square} \qquad \textit{(Equation 3-7)}$$

Where

Mean Bias Error (MBE) is the first moment, defined below. This statistic describes the dispersion or spread of the residual distribution about the estimate of the mean. The standard deviation is calculated using all estimation-observation pairs above the cut-off level. The second moment of the residual distribution is the variance, the square of the standard deviation. Since the standard deviation has the same units of measure as the variable (e.g., m/s for wind) it is used here as the metric for dispersion. The standard deviation and variance measure the average spread of the residuals, independent of any systematic bias in the estimates. No direct information is provided concerning sub-regional errors or about large discrepancies occurring within portions of the diurnal cycle although in principle these, too, could be estimated.

Mean Bias Error (MBE). The mean bias error is given by:

$$MBE = \frac{1}{N}\sum_{i=1}^{N}\left(c_e\left(x_i, t\right) - c_{o\left(x_i, t\right)}\right) \quad \textit{(Equation 3-8)}$$

Where N equals the number of hourly estimate-observation pairs drawn from all valid monitoring station data on the simulation period of interest. This is simply the average of the sum of the residuals. MBE is not a good estimator because MBE=0 does not necessarily indicate a good model, since many overestimations may be compensated by many underestimations.

There are other measures of error and all are based on this Mean Bias Error. They include:

- Mean Normalised Bias Error (MNBE), often just called the bias
- Mean Absolute Gross Error (MAGE)
- Mean Absolute Normalised Gross Error (MANGE)
- Root Mean Square Error (RMSE)
- Systematic Root Mean Square Error (RMSEs)
- Unsystematic Root Mean Square Error (RMSEu)

It is important that RMSE, RMSEs and RMSEu are all analysed. For example, if only RMSE is estimated (and it appears acceptable) it can consist largely of the systematic component. This bias might be removed, thereby reducing the bias transferred to the dispersion model. On the other hand, if the RMSE consists largely of the unsystematic component (RMSEu), this indicates further error reduction may require model refinement and\or data acquisition. It also provides error bars that may be used with the inputs in subsequent sensitivity analyses.

#### 3.5.3.3. Skill Measures

Index of Agreement (I). Following Willmott (1981, 1984) and Pereira et al. (2018), one index of agreement is given by:

$$I = 1 - \frac{\sum_{i=1}^{N}\left(P_i - O_i\right)^2}{\square} \quad \textit{(Equation 3-9)}$$

Where *P* and *O* are, respectively, the predicted and observed values

The Index of Agreement (I or sometimes IOA) condenses all the differences between the model estimates and observations into one statistical quantity. It is the ratio of the cumulative difference between the model estimates and the corresponding observations and the observed mean. Viewed from another perspective, the Index of Agreement is a measure of how well the model estimates departure from the observed mean matches, case by case, the observations' departure from the observed mean. Thus, the correspondence between estimated and observed values across the domain at a given time may be quantified in a single metric and displayed as a time series. The Index of Agreement has a theoretical range of 0 to 1, the latter score suggesting perfect agreement.

RMS Skill Error (Skille). The root mean square skill error is defined as:

$$Skill_e = \frac{RMSE_u}{SD_o} \quad \textit{(Equation 3-10)}$$

Variance Skill Ratio (Skillvar). The variance ratio skill is given by:

$$Skill_{var} = \frac{SD_e}{SD_o} \qquad \text{(Equation 3-11)}$$

Where SDe and SDo are the standard deviations of the model estimated parameter and the observed parameter, respectively.

There are several free software tools that can perform the statistical analyses described in this Section related to comparison of modelled data versus observational data. See Appendix A for more information.

#### 3.5.3.4. Benchmarks

There is a need for some benchmarks against which to compare new prognostic model simulations. In three studies (Tesche et al 2001, 2001b; Emery et al 2001), an attempt was made to formulate a set of mesoscale model evaluation benchmarks based on the most recent performance evaluation literature at the time. The purpose of the benchmarks is not to assign a passing or failing grade to a particular model application, but rather to put its results into a useful context. The following benchmarks listed in Table 3-3 may be helpful to modellers and model users in understanding how poor or good their results are relative to the range of other model applications.

**Table 3.3** Meteorological benchmarks

| | Wind speed | Wind direction | Temperature | Humidity |
|---|---|---|---|---|
| IOA | ≥ 0.6 | -- | ≥ 0.8 | ≥ 0.6 |
| RMSE | ≤ 2 m/s | -- | -- | -- |
| Mean Bias | ≤ ±0.5 m/s | ≤ ±10° | ≤ ±0.5 K | ≤ ±1 g/kg |
| Gross Error | -- | ≤ 30° | ≤ 2 K | ≤ 2 g/kg |

### 3.5.4. Graphical Evaluation Tools

Over the years a rich variety of graphical analysis and display methods have been developed to evaluate the performance of meteorological models. There are a number of procedures for graphically representing model results and observations that allow for direct comparison between them. In many instances, the differences in how modelled and measured quantities are treated in certain of these graphical techniques are more a matter of preference than correctness. Each graphical technique requires some assumptions that influence the outcome. However, by using a variety of graphical approaches it is possible to examine a model performance from different viewpoints and thus gain a clearer understanding of the results. Some of the well-known graphical displays include;

- the temporal correlation (time series) between point estimates and observations;
- the spatial distribution (gridded fields) of estimated quantities;
- the correlation among hourly pairs of estimates, observations, residuals and distributions;
- the variation in spatial mean, bias and error estimates as functions of time and space; and
- the degree of mismatch between volume-averaged model estimates and point

measurements.

### 3.5.4.1. Time series Plots

Time series analysis is extremely useful to observe how a given variable behaves / changes over time. For example, the plot below (Figure 3-23) shows the observed and predicted wind speed over a two week period in February 2015. In this example, the plot shows that the two time series are very well correlated, but that the predictions have a slight tendency to overestimate the observations.

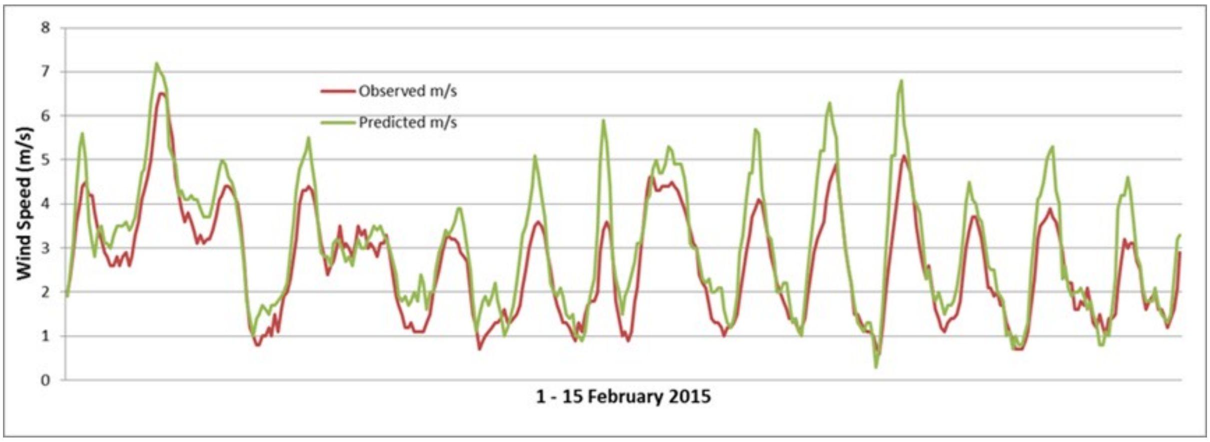



**Figure 3-23** Time series plot of observed and predicted wind speed over a two-week period from 1 - 15 February 2015 (courtesy of Atmospheric Science Global)

### 3.5.4.2. Spatial Distribution Plots

A spatial distribution in statistics is the arrangement of phenomenon across a portion of the earth's surface. A graphical display of such an arrangement is an important tool in environmental statistics. A spatial distribution map of winds, as shown in Figure 3-24, provides information on the spread of winds across a region whose effects might influence a location of key interest. Spatial distribution plots can be generated for most meteorological phenomena, such as temperature, wind speed and direction, mixing height, atmospheric stability etc. Spatial distribution plots provide information far beyond a single point of interest, and they can help validate the meteorology at a single point.

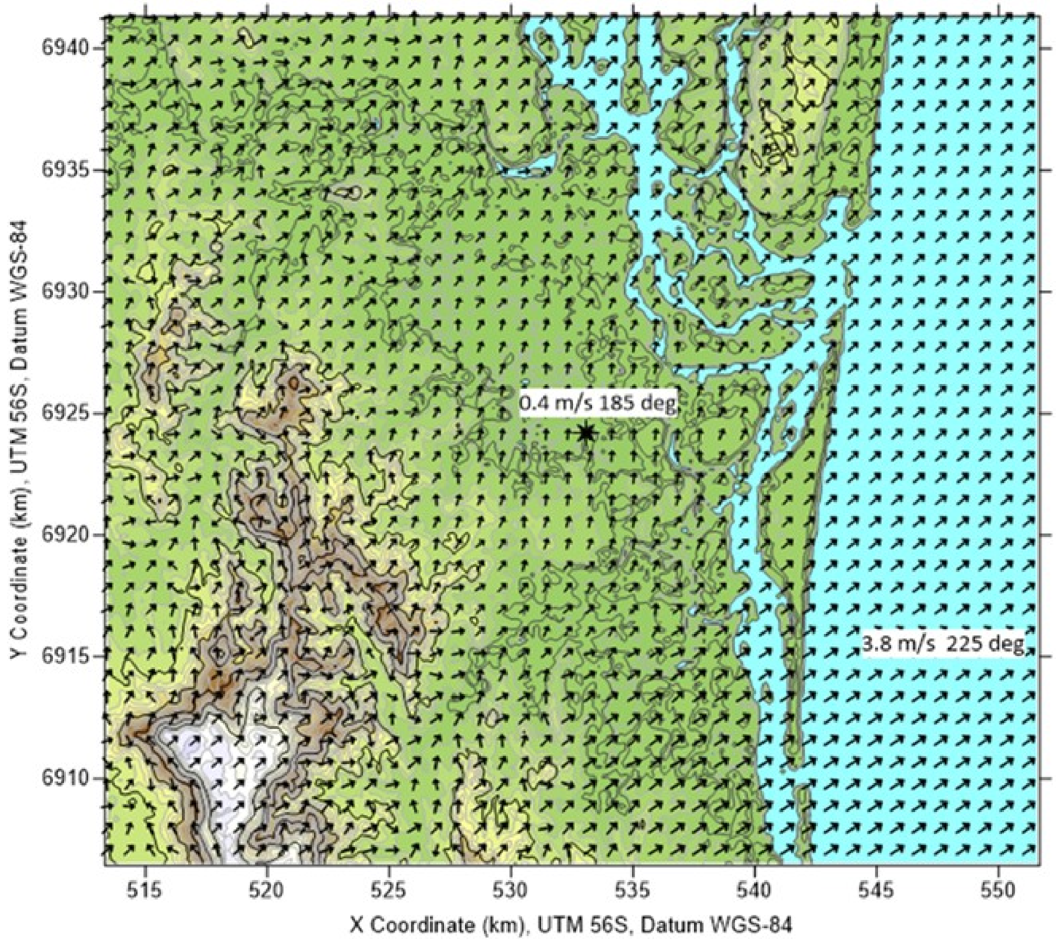



**Figure 3-24** Spatial distribution plot of wind field representing a snapshot of a single hour. (courtesy of Atmospheric Science Global)

Another type of spatial distribution plot is shown in Figure 3-25, which shows a spatial difference field of Bias in modelled minus observed surface wind fields over a 48 km grid domain.

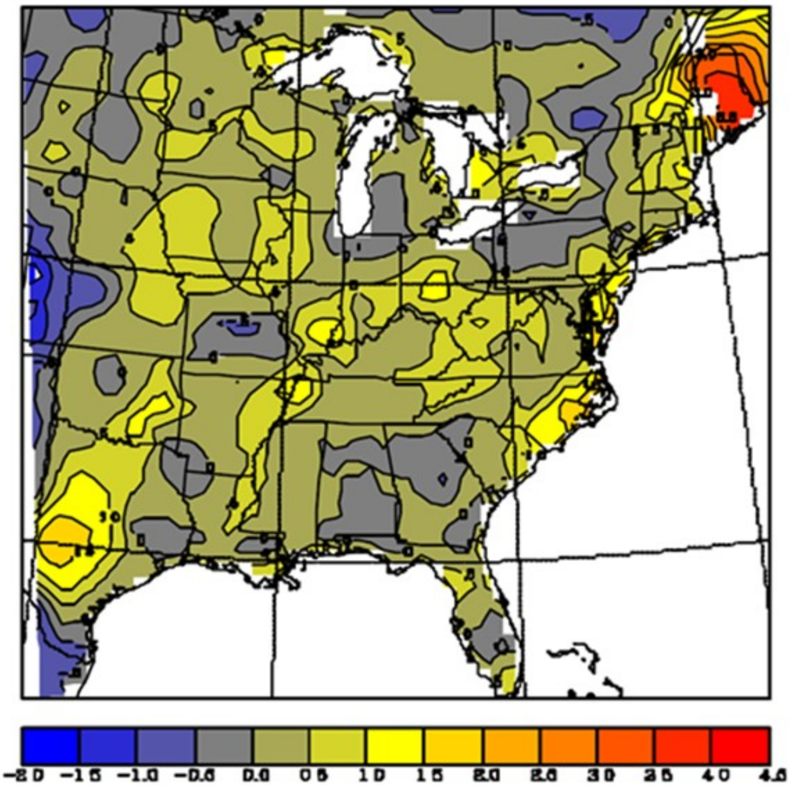



**Figure 3-25** Spatial distribution plot showing the model bias of wind fields over the eastern US during July 1995 (Doty et al., 2002).

### 3.5.4.3. Correlation Analysis

Correlation analysis is a useful technique in meteorology as it helps us determine the degree of relationship between variables. Correlations between variables indicate that changes in one variable are associated with changes in other variables, but this does not mean that the changes in one variable actually cause the changes in the other variable. Sometimes it is clear that there is a causal relationship.

Correlations are a useful evaluation tool as they can tell if two variables have a linear relationship, and the strength of that relationship. Figure 3-26 shows the graphical correlation relationship between observed and modelled winds. It is a simple measure to show the strength of a linear relationship between two meteorological variables.

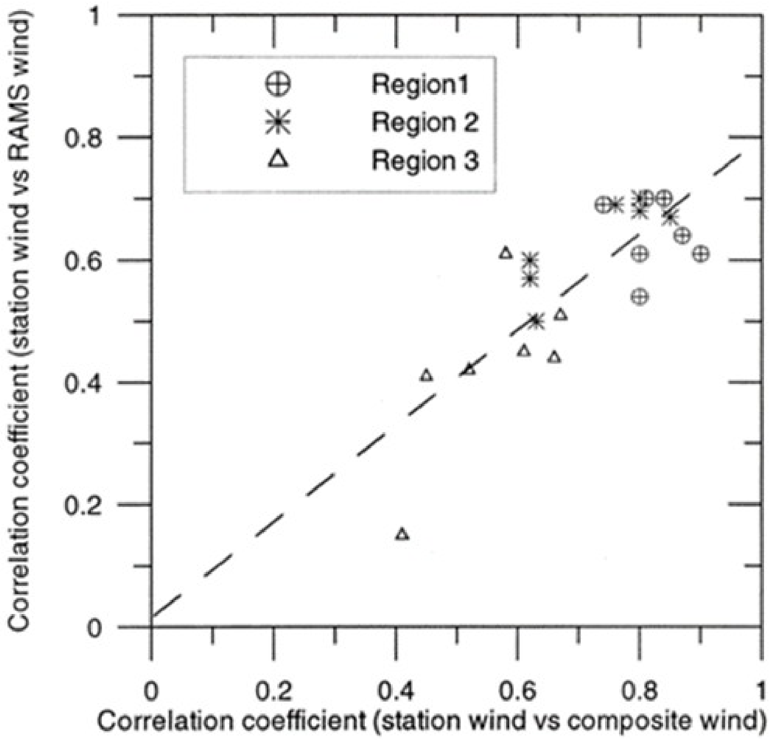



**Figure 3-26** Schematic plot showing the strong correlation relationship between observed and modelled winds (Weather and Forecasting 16, 5)

### 3.5.4.4. Wind Roses

Wind roses (discussed earlier) that are prepared from the modelled and observed data can be placed side-by-side for an easy graphical comparison of the two data sets. Figure 3-27 shows this technique.

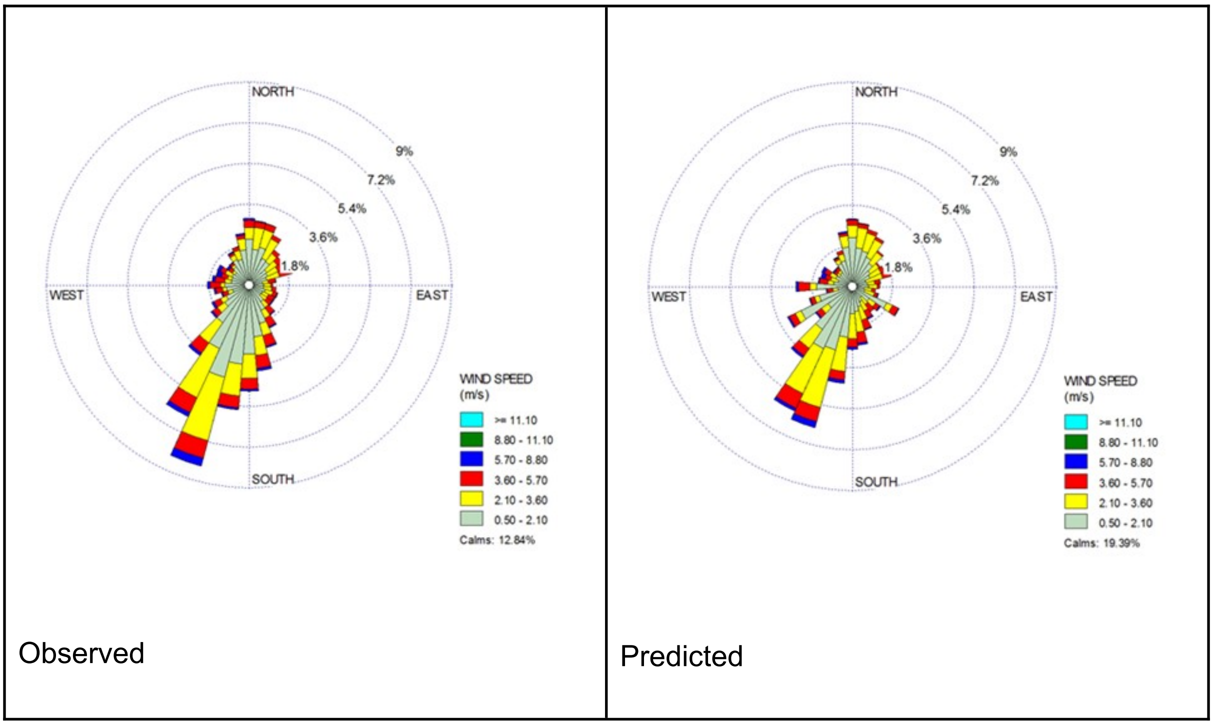


**Figure 3-27** Wind roses of observed and predicted winds (courtesy of Atmospheric Science Global)

### 3.5.4.5. Scatter Plots

Scatter plots are a type of data visualisation that shows the relationship between different variables. The data are typically shown by placing various data points between the x and y-axis. The scatter plot's primary uses are to observe and show relationships between two numeric variables. They can also show if there are any unexpected gaps in the data and if there are any outlier points. Scatter plots offer the following advantages:

- They identify correlation – they allow the comparison between two different variables
- They are nonlinear, easy to read and easy to create

Scatter diagrams do not measure the precise extent of the correlation and will only give an approximate idea of the relationship, they are a qualitative expression of the quantitative change. Figure 3-28 is an example of a scatter plot.

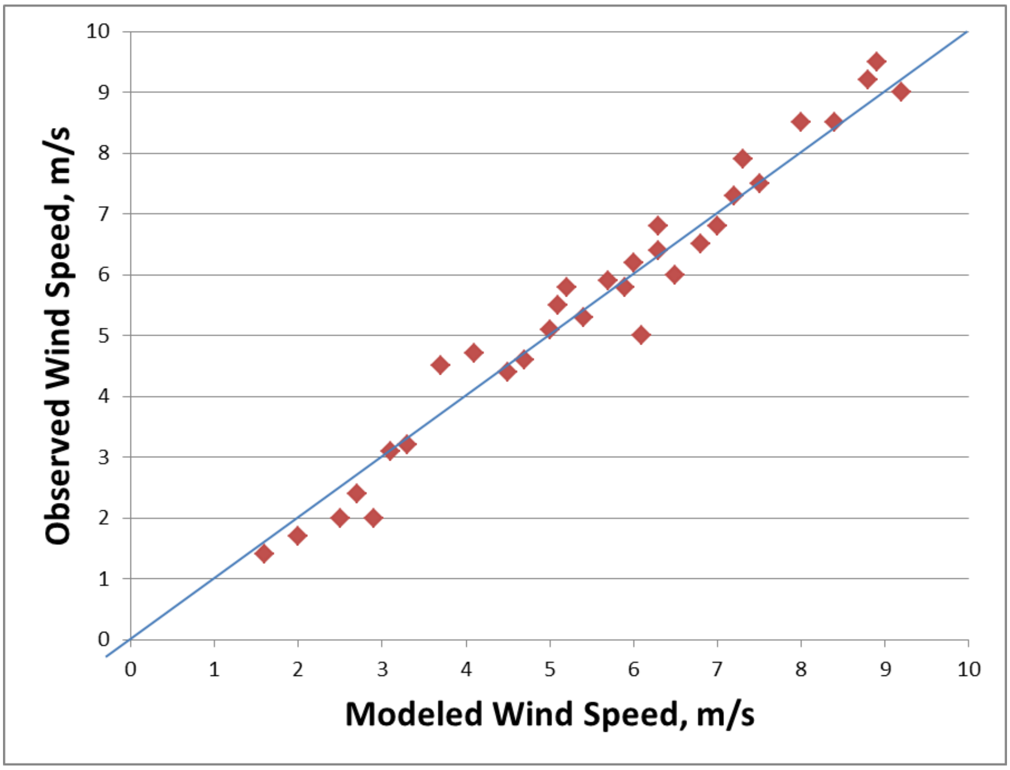



**Figure 3-28** Example scatter plot to compare observed versus modelled wind speed (courtesy of Atmospheric Science Global)

The following Figure 3-29 is a variation of a scatter plot which depicts all measured wind speeds by hour over the course of a one-year modelling period.

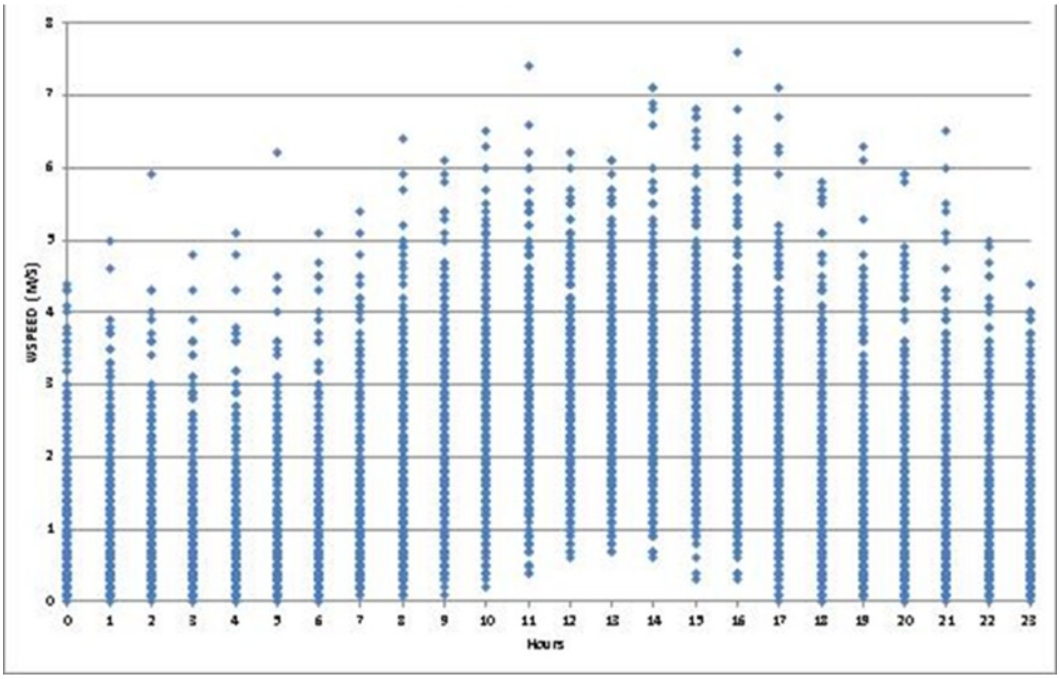



**Figure 3-29** A diurnal scatter plot of wind speed by hour over a full year (courtesy of Atmospheric Science Global)

#### 3.5.4.6. Quantile-Quantile Plots

A QQ plot is a probability statistic graph, which is a graphical method for comparing two probability distributions. The purpose of a QQ plot is to show if two data sets come from the same distribution. Plotting the first data set's quantiles along the x-axis and plotting the second data set of quantiles along the y-axis is how the plot is constructed. Figure 3-30 shows a QQ plot typically used to compare observed vs predicted distributions.

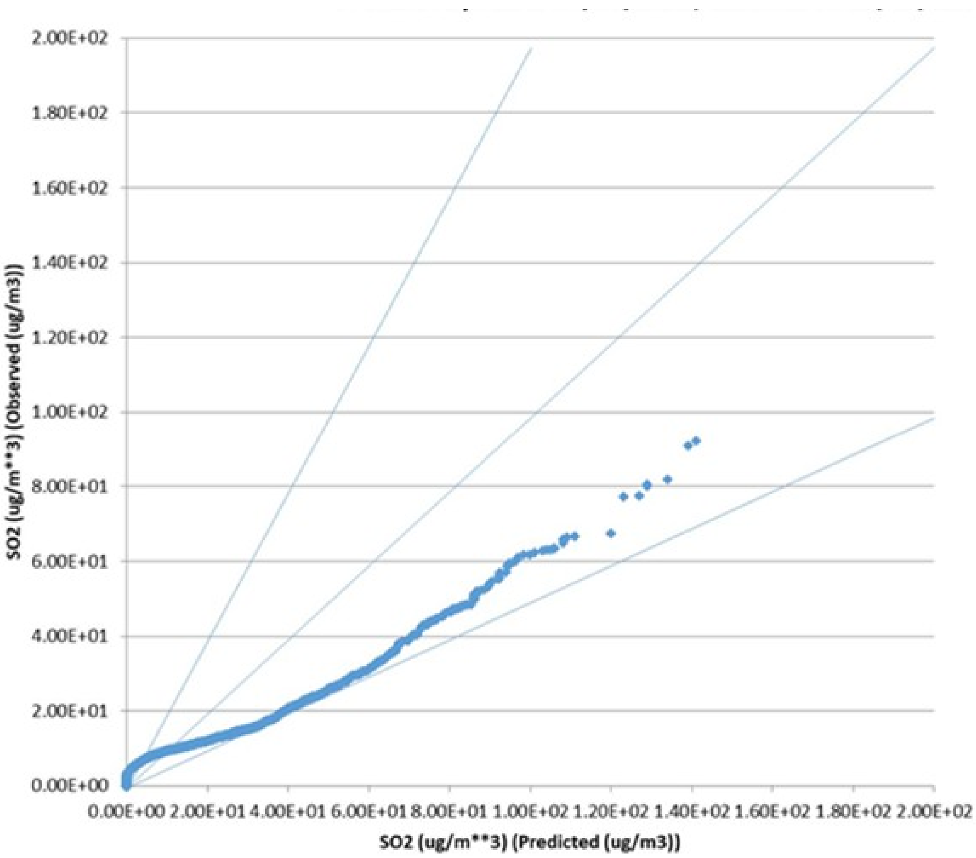



**Figure 3-30** Quantile-Quantile probability plot comparing observed (y-axis) vs predicted (x-axis) SO2 concentrations (μg/m3) (courtesy of Atmospheric Science Global)

### 3.5.4.7. Taylor Diagram

The Taylor diagram uses the law of cosines to represent in a single graph how the three most representative statistics of the performance of a model vary simultaneously, such as:

1. The mean square error, without taking into account the effect of the sign of the error (RMSE), which is very useful for checking the accuracy of the model.
2. The standard deviation (SD) makes it possible to check the variability in both data samples and see whether this variability is conserved or varies in the model concerning what is observed for the real data.
3. The Pearson Correlation Coefficient, r, which shows how close the linear relationship is between the pairs of data formed by the model and the real determinations.

It is challenging to measure odour in ambient air. Therefore, this kind of diagram is rarely used in odour modelling. The following Figure 3-31 shows an example comparing standard deviations.

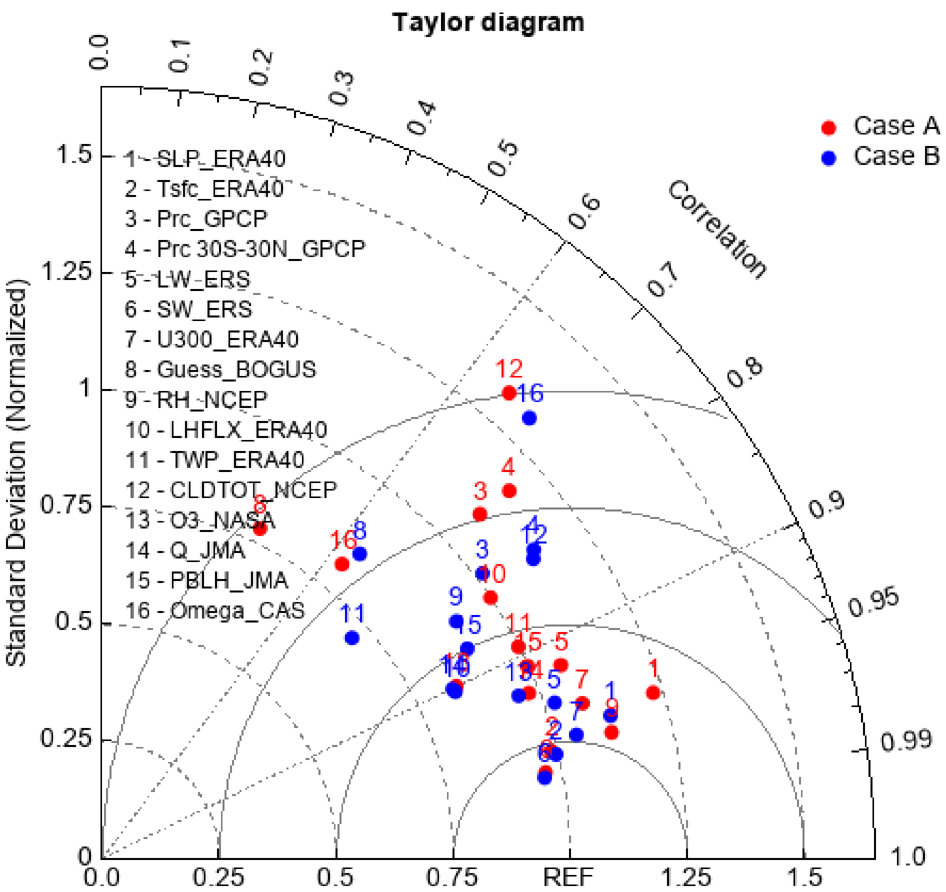



**Figure 3-31** Taylor Diagram for comparison of standard deviations (MeteoInfo, http://meteothink.org/)

### 3.5.5. Conclusion

A plausibility check of the meteorological simulation is recommended. This plausibility check should be performed with independent observations, that is observations not used in the meteorological assessment. These observations should be close to the location of the emission source and/or those most representative of the meteorology of the plant environment. It is recommended that, at least one of the series of observations used in the plausibility check, should contain data from vertical wind profiles.

The Guideline of good practices in the elaboration of dispersion models of the Basque Country, Spain, 2012 mentions that a meteorological plausibility check should include:

- A topographic map with the location of the meteorological stations used and the emission source(s).
- The wind roses estimated by the modelling at the location points of the selected meteorological stations and those obtained with the observations.
- Statistical metrics of at least wind, temperature and precipitation differences between observations and simulations (scatter plots of points, correlation coefficients, Taylors diagrams, etc.).
- Temporal wind sequences measured-simulated in selected periods (one or several weeks) within the year in question, coinciding with selected episodes of odour impact by one or several chemical species (subject to monitoring in the local network). The selected episodes and chemical species are at the discretion of the person in charge

of the evaluation, but must be justified.

- Discussion of the differences found, both in episodes and in statistics and wind roses, and how they might affect the dispersion calculations.

Taking into account the interannual meteorological variability, it would be ideal to use a temporal sequence of 5 complete years (not necessarily consecutive) to estimate the dispersion of the outbreak under evaluation. However, due to the difficulties associated with the preparation of a complete annual sequence of the non-stationary and three-dimensional meteorological fields of the target area, duly validated and with the necessary spatial and temporal resolution, the use of a 1-year time series is considered sufficient. According to the same guideline commented before, the choice of year should be adequately justified, in relation to at least two criteria:

1. Priority should be given to temporal proximity (recent years), normally better documented.
2. Representativeness in terms of intensity-frequency of pollution episodes in the selected simulation domain and year should be examined. A wet year (with many days with precipitation) or low frequency of pollution episodes (e.g. few situations with anticyclonic blockages) cannot be selected, with the sole justification of data availability.

In addition to justifying the selection made, it is recommended that the evaluation includes a discussion of what variations in impact estimates would be expected in those years with more adverse meteorology.

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# 4. Sources and emissions characterisation

## 4.1 Introduction

Odour sources can be classified from a geometrical point of view according to how they are treated within atmospheric dispersion models. In this classification, odour emissions may come from point, area, line or volume sources.

Odour annoyance may be due to the simultaneous emissions from multiple sources. For instance, a municipal waste treatment centre is characterised by several types of sources: area/volume sources (e.g., compost piles, waste stocks), point sources (e.g., biogas exhaust), and diffuse sources (e.g., leakage from buildings). Sources are often static but also in motion (e.g., trucks turning a compost pile over).

Special requirements for the modelling techniques are necessary to consider the interaction of different emission sources like point sources (e.g. stacks, exhaust air ducts), line sources (e.g. ventilation belts, roadways), area sources (e.g. slag beds, biofilters, clarifiers, manoeuvring areas) and volume sources (windows and gates distributed over an operation building, stockpiles).

In principle, all sources have to be specified, but sometimes criteria are introduced to neglect sources with odour emission rates or odour concentrations below specific thresholds. If there are many homogeneous sources, these are sometimes combined into a sort of equivalent source.

Another approach is to determine the odour flow rate after performing a field inspection (EN 16841 part 2) followed by a backpropagation use of the odour dispersion modelling (reverse modelling).

One important input variable of odour dispersion models is the *Odour Emission Rate* (OER), expressed in ou/s, or the *Specific Odour Emission Rate* (SOER), expressed in $ou/m^2/s$. The OER calculation needs first to collect and analyse the air sample to estimate its odour concentration and second to determine the air flow rate. Sometimes, the OER is not available, and the emission rate of odorants (e.g., $H_2S$) is expressed in mass per unit time (e.g., g/s). In these situations, the resulting concentration of each released odorant must be compared with its odour threshold to determine if it has been exceeded.

The characterisation of odour emissions is closely related to the type of source, in particular the geometry, whether passive or active areas or point (e.g. stacks) or fugitive (e.g. stockpile or building) sources. The specific objective of a study may also influence the method of sampling emissions from a source.

The sampling method will strongly influence the characterisation of the odour, and it is important to link the source parameters with the proposed sampling protocol. According to the applied technique, there are different ways to estimate the OER. The obtained value is strictly related to the specific technical details of the sampling and must be considered as a "relative" value. It means that another sampling protocol may give other values. Therefore, an OER of a source may be different due to the sampling method adopted. This will, in turn, affect the emission rate input and model predictions. For example, in paragraph 4.2.3.1, it is mentioned that using wind tunnels or flow chambers will condition the odour rate obtained.

Other important source data are needed for dispersion modelling, such as release height, exhaust gas temperature, exhaust gas velocity and surface area. This chapter aims to describe the inputs to the dispersion model that relate to the source characteristics and rate of odour emission.

# 4.2 Measuring odour emissions

## 4.2.1 Point sources

A point source, as defined in EN 13725, is a discrete stationary source releasing waste gas to the atmosphere via ducts of defined dimensions with a controlled or controllable volume flow rate. Stacks and vents are the most common examples of point sources.

The following geometrical and emission information defines a point source:

- Coordinates;
- Height above the ground of the release point;
- Cross-sectional area of the stack/duct at exit plane;
- Exit type (e.g., vertical, horizontal, tilted, with or without rain cap, …);
- Exit velocity of the effluent;
- Temperature of the effluent;
- Volume flow rate;
- Odour concentration within the flue gas.

Point sources vary in configuration and include simple stacks that discharge vertically to the atmosphere at various heights above the ground or surrounding buildings, and complex discharge arrangements such as goose-neck downward discharges, horizontal discharges and capped vertical discharges. Some representative examples of point source discharge configurations are shown in Figure 4-1, while Figure 4-2 represents an example of emission extraction from a piggery. The discharge geometry is an essential factor defining the point source as it may exert a controlling influence on the source's effective release height of odours.

According to EN 13725:2022, the OER is the number of odour units which crosses a given surface per unit of time. The OER is typically expressed in $ou_E$/s, but other units are sometimes used, for example, $ou_E$/min or $ou_E$/h. The OER is a quantity equivalent to the emission rate - typically expressed in g/s - in dispersion models used for air quality impact assessments.

**Figure 4-1** Examples of point sources. Vertical stack with free discharge (top left); vertical stack with rain-cap (top right); Y-shaped vertical stack with internal rain cap (bottom left); Horizontal stack (Bottom right). (Courtesy of Enviroware)

**Figure 4-2** Example of emission extraction from a piggery. (Courtesy of Air Environment)

#### 4.2.1.1. Synthetic description of sampling techniques for point sources

The odour concentration determined by olfactometry is the result of sensory measurements by selected panel members according to EN 13725:2022. The odorous gas is sampled in polymer bags at the source, and then the bag is connected to an olfactometer, where panel members conduct a sensorial analysis. Sampling introduces an additional uncertainty to that associated with dynamic olfactometry.

Different steps are taken to ensure the sampling is carried out correctly. For instance, the bag and the sampling line are verified to be odourless; the sampling line is connected to the exhaust gas to sample, and the bag is placed in a vacuum box / chamber. The exhaust gas is drawn into the bag by the vacuum in the box / chamber. The sample must have minimum contact with sampling materials. In some cases, a sample must be diluted in order to avoid condensation, or simply because the odour concentration is too high.

It is necessary to check if the gas contains particulates, and, if yes, it needs to be filtered because particulates are incompatible with olfactometer use. Temperature and humidity are also checked because the gas cannot be too hot, or too humid. A dilution probe with dry air or dry nitrogen can decrease humidity and then avoid condensation in the bag. Using nitrogen, the dilution rate can be easily verified by measuring oxygen level in the sample. Of course the dilution factor (generally between 5 to 10) at this sampling step must be included in the determination of the final olfactometry analysis results, also based on a dilution (dilution of the sample to determine its limit of perception). A pre-dilution of the sample can be carried out in the laboratory for highly concentrated samples. This action is necessary if the concentration of the sample is potentially higher than the dilution range of the olfactometer.

According to EN 13725, storage time between sampling and olfactory analysis should usually be at most 30 hours by convention. However, there needs to be more clarity in the literature to substantiate that degradation, adsorption and diffusion phenomena will be insignificant below certain storage times. Significant degradation of odour concentration in samples within 30 hours after sampling has been reported, for example, for odorants emitted from foundries and tobacco leaf processing. That is one of the reasons why the German standard on olfactometry VDI 3880 allows a maximum time of 6 hours between sampling and analysis.

## 4.2.2 Active area sources

These sources are characterised by odour emission from a surface with a volumetric flow or exit velocity greater than specific thresholds. According to EN 13725, active area sources are "*aerated with air gas that is driven through the matrix underneath the surface by mechanical ventilation*" such as, aerated composting. A typical example of an active area source is a biofilter, as shown in Figure 4-3.

EN 13725:2022 classifies active area sources as *sources with an exit velocity v > 0.008 $m^3/s/m^2$. Area sources with lower exit speeds are passive area sources*.

**Figure 4-3** Example of active source: biofilter surface (left panel); biofilter container open on the top (right panel) (Courtesy of Olfasense)

### 4.2.2.1. Synthetic description of sampling techniques for active area sources

For the measurement of active area sources with a minimum discharge velocity (e.g., biofilters, aerated compost heaps), a sampling hood with one m² surface is used to avoid disturbances of the air discharge with the atmosphere (Figure 4-4). Sampling takes place in the chimney of the sampling hood.

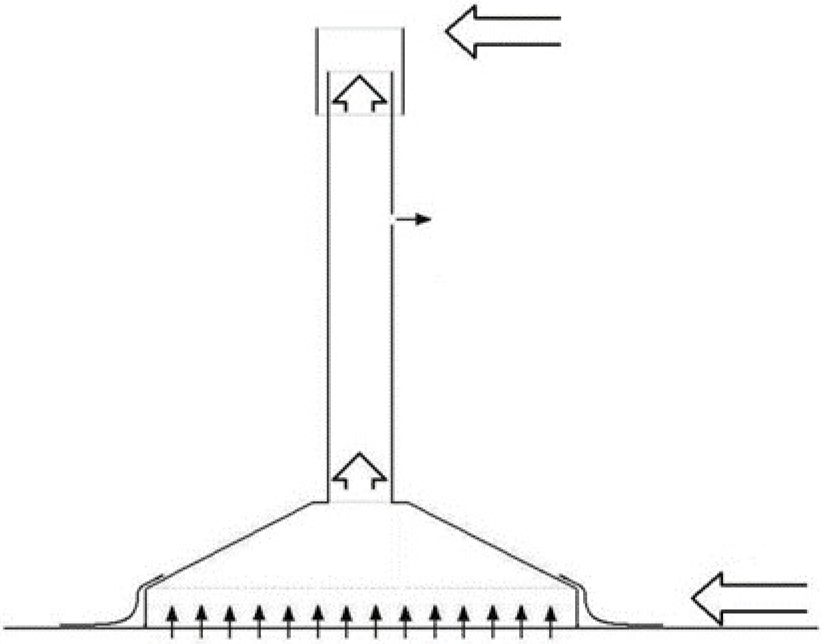

**Figure 4-4** Sampling hood, as defined in EN 13725:2022 and VDI 3880:2015 for active area sources.

Usually, due to the extent of the area sources, inhomogeneities must be checked and a sampling strategy must be defined. Sampling points are selected on the basis of representative source flow rates. Alternatively, a complete coverage of the area could be considered, as shown in Figure 4-5.

**Figure 4-5** Complete coverage of an active area source.

The product of the odour concentration of the sample bag ($ou_E/m^3$) and air velocity through the device (m/sec) gives the specific odour emission rate (SOER, $ou_E/m^2/s$). It is observed that the air velocity through the device is the ratio between the air flow rate ($m^3/s$) and the specific area $A_d$ ($m^2$) of the device. The odour emission rate (OER) is the product between the SOER and the area $A_s$ of the emitting surface.

### 4.2.3 Passive area sources

According to EN 13725:2022, passive area sources are areas with a*n exit velocity v < 0.008 $m^3/s/m^2$.* Passive area sources include waste landfills, fields after manure spreading, compost piles and open wastewater tanks. They emit through diffusion at the boundary layer between the source surface and the air. The emission depends on multiple variables, such as the material's humidity, atmospheric temperature and wind speed. Examples of area sources are shown in Figure 4-6.

**Figure 4-6** Different area sources: compost pile (left panel); aeration basin (right panel). ( Courtesy of Olfasense)

#### 4.2.3.1. Synthetic description of sampling techniques for passive area sources

For the passive area sources, the emission rate is estimated by simulating the flow through a ventilated hood (such as flux hoods and wind tunnels). The emission flow rate is then the hood's ventilation rate and is typically dependent on sampling conditions.

The SOER is estimated by covering a part of the surface with a ventilated hood with a defined flow rate, which can then be measured in the exit stack (VDI 3880:2015). The sampling plan shall ensure that the area sampled is representative of the total emission from the area source.

Different methods exist to measure the odour emission rate of these sources. The most common are wind tunnels (Figure 4-7) and flux hoods (Figures 4-8 and 4-9).

EN 13725:2022 recommends considering the following aspects when using a wind tunnel:

1. Sweep air fed into the inlet of the wind tunnel shall be odourless.

2. The flow regime of the sweep air inside the wind tunnel shall be laminar, not turbulent.

3. Since an increase in the sweep air flow rate produces a dilution effect that reduces the outlet odour concentration, in field conditions, the sweep air flow rate should be chosen low enough to get an outlet odour concentration higher than the field blank value. For this reason, a low sweep air velocity in the ventilation chamber is recommended.

4. To get a laminar flow regime of sweep air in the ventilation chamber and as much homogeneous air velocity as possible, air velocity in any point of the ventilation chamber, the design of the wind tunnel device upstream of the ventilation chamber is fundamental. Upstream of the ventilation chamber, a divergent and a parallel flow are recommended.

5. Design and materials of wind tunnel devices should prevent solar radiation from unnaturally increasing the air temperature in the ventilation chamber and the temperature of the emitting surface.

6. The above-listed parameters mainly affecting the mass transfer rate (in particular source temperature, sweep air humidity, and sweep air velocity) should be determined, recorded and reported.

a b

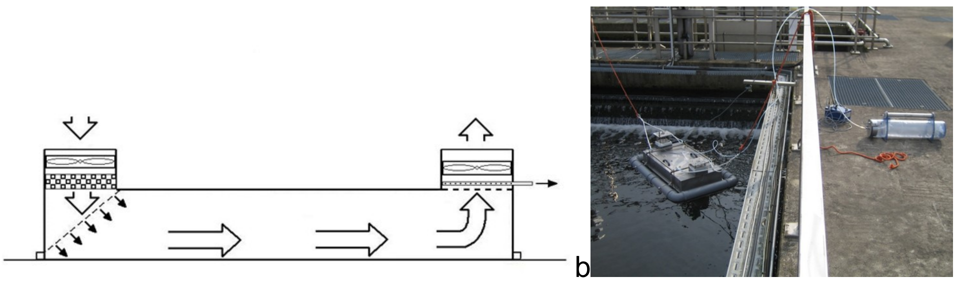

**Figure 4-7** Example of a wind tunnel: ventilated sampling hood, as defined in VDI 3880:2015. Schematic view (left panel); floating on a basin (right panel).(Courtesy of Olfasense)

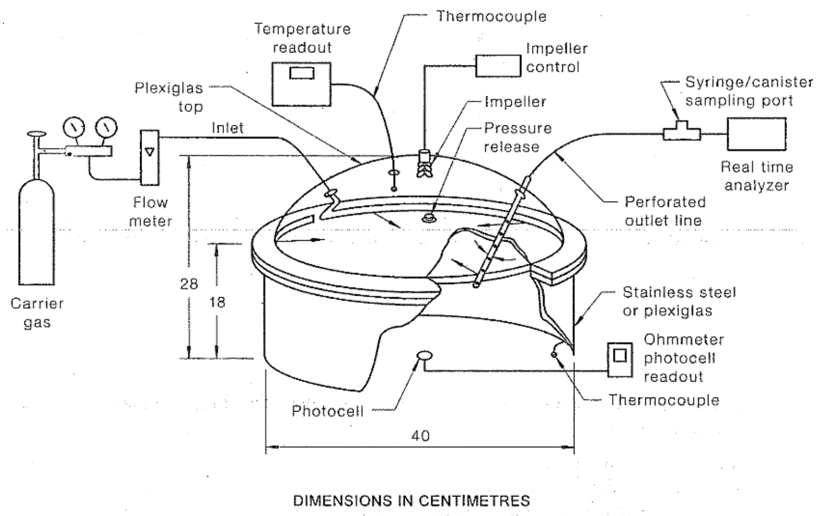


**Figure 4-8** Flux Chamber: Set up of the emission isolation according to US EPA 1986

**Figure 4-9** Flux chamber on a liquid source (left panel) and on a solid source (right panel)

Over the last 30 years, there has been a long-standing debate about the appropriateness and accuracy of wind tunnels versus flux chambers for quantifying area source emissions as the sampling devices give quite different results compared to each other and emission theory (e.g., Smith & Watts, 1994a; Smith & Watts, 1994b; Jiang & Kaye, 1996; Parker et al., 2013; Prata et al., 2018; Lucernoni et al., 2016). Therefore, verifying that they were collected using the same sampling method is essential when comparing emission data from different measurements.

An extensive comparison study was conducted in October 2013 in France (Guillot et al., 2014) to understand the differences in the results of the odour emission rates calculated from different sampling devices. The project aimed to test two types of devices: flux chambers (with low sweeping flows) and wind tunnels (with high sweeping flows). Liquid area sources and solid area sources were tested. Figure 4-10 shows the experiment's setting for a solid area source (composting pile), while Figure 4-11 shows the experiment's setting for a liquid area source (pond).

**Figure 4-10** Sampling flux chambers and wind tunnels in a composting pile. (Courtesy of JM. Guillot)

**Figure 4-11** Sampling flux chambers and wind tunnels in a pond (Courtesy of JM. Guillot)

Some of the devices tested with a low sweeping flow (flux chambers) are shown in Figure 4-12, while some of the devices tested with a high sweeping flow (wind tunnels) are presented in Figure 4-13.

**Figure 4-12** Devices with a low sweeping flow. (Courtesy of JM. Guillot)

**Figure 4-13** Devices with a high sweeping flow. (Courtesy of JM. Guillot)

The graphs in Figure 4-14 show the results for both types of devices.

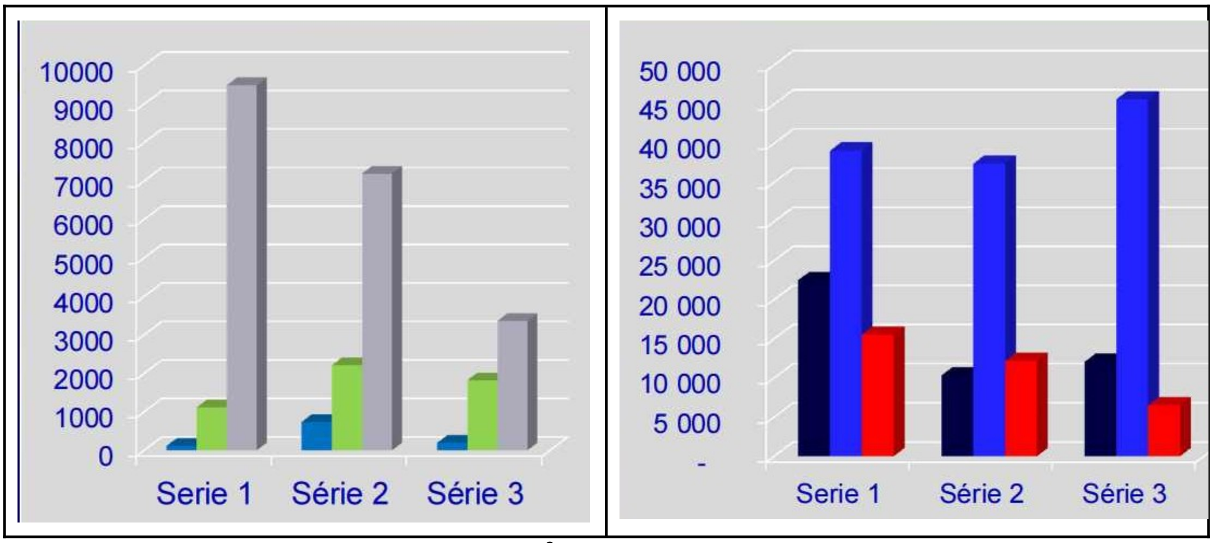


**Figure 4-14** Left panel: SOER in $ou_E/h/m^2$ for three different flux chambers (blue, green and grey) at different measurement periods. Right panel: SOER in $ou_E/h/m^2$ for three different wind tunnels (colours dark blue, blue and red) at different measurement periods. (Courtesy of JM. Guillot)

The project results showed that, for example, for measurement day 1 (Serie 1), flux chambers (left panel) showed significantly different SOERs between each other with differences of several orders of magnitude. Moreover, for the same measurement period (Serie 1), wind tunnels showed a much higher SOER, sometimes four times higher than the highest SOER obtained by a flux chamber. In the case of wind tunnels, the variability of the results was also relevant. This result demonstrates that odour emission from a static area source can only be compared to another if sampling conditions are similar.

Both methods lead to emissions at the boundary of the source. The link from odour concentration to emission rates is the diffusion coefficient. This factor might vary with different parameters such as atmospheric conditions.

A way to verify the impact of passive area sources is by performing a plume inspection. EN 16841-2:2017 describes two ways of measuring the impact of a source. With the impact measurements, the model results can be validated. The effective emission rate can be determined by using reverse modelling, see paragraph 4.4.2.

### 4.2.4 Volume sources

When the emissions are immediately spread over a 3D region, they can be modelled through volume sources. Examples of this type of source are industrial buildings with high gates and windows, open stall barns with natural ventilation, or portions of plants with fugitive emissions (i.e., unintentional losses) from items that are designed to be sealed (e.g., valves, flanges), passive ventilation apertures, leakage through building cladding (e.g., Figure 4-15).

These sources have no defined dimensions and no defined volume flow rate. Their description in an air dispersion model is challenging and highly dependent on every specific case.

**Figure 4-15** Example of diffuse emissions from an industrial building.

#### 4.2.4.1. Synthetic description of estimation techniques for volume sources

In the absence of a defined volume flow, sampling in a bag to estimate the emission rate (like for the point source) is not applicable. Moreover, it is challenging to sample due to the influence of weather on the source parameters (mainly temperature, humidity and flow). In some cases, emission rates could be derived using a source apportionment approach if a known indicator related to odour is available. For instance, Invernizzi et al. (2021) described a series of approximations to determine VOC emission rates.

When dealing with fugitive emissions, odour measurements must be performed at the receptor site (ambient air). Field inspection and *Reverse Dispersion Modelling* (RDM) is an appropriate and highly recommended approach.

Another methodology to measure diffuse / fugitive sources is the one proposed by *EN 17628* (Fugitive and diffuse emissions of common concern to industry sectors - Standard method to determine diffuse emissions of VOCs into the atmosphere), see paragraph 7.2.2. This standard specifies an array of methods to detect and / or identify and / or quantify VOC emissions from industrial sources. These methods include *Optical Gas Imaging* (OGI), *Differential Absorption Lidar* (DIAL), *Solar Occultation Flux* (SOF), *Tracer Correlation* (TC) and RDM. Additionally, the EN 15446:2008 standard includes guidance on how to perform a measurement for different specific items (e.g., valves, flanges, pump seals, compressor seals, …). It also specifies how to estimate the emission rates starting from the VOC concentration measurements in ppm.

An additional method to estimate the fugitive emissions of VOC is to make an inventory of the equipment (e.g., valves, flanges, etc.) by reading the P&IDs (Piping and Instrumentation Diagrams) of a plant, then applying the relevant emission factors for each item of equipment (e.g., Ng et al., 2017). The emissions depend on the equipment and on the characteristics of the flow through it, both in terms of composition and of phase (gas, liquid, 2-phase). This method is complex and time-consuming because some plants (e.g., refineries) may have hundreds of P&IDs describing thousands of pieces of equipment. For example, US-EPA (2005) reports an average number of valves greater than 7000 and an average number of over 12000 connectors for a typical refinery or chemical plant. Leak detection and repair (LDAR) programs have been promoted to reduce fugitive emissions (US-EPA, 2022a). VOC emission factors for many items are available, for example, from US-EPA (1995a).

As for the passive area sources, ambient air measurement may be used to derive emission rates for modelling (EN 16841). Additional details are given in paragraph 4.4.2.

### 4.2.5 Gas detector tubes

Gas detector tubes (GDTs), also called colour indicator tubes, are relatively simple tools to detect the presence of a specific chemical species or class of species in the atmosphere and their concentration. They are thin glass tubes containing a reagent powder that reacts with the specific gas generating a coloured stain. The length of the stain is read against a calibrated scale on the tube, indicating the concentration level. A hand pump - or an electronic pump - is used to draw the air sample into the tube. The volume amount of the air sample is typically 100 $cm^3$, but it may also be half of it (50 $cm^3$), and sampling usually takes less than one minute to complete. The datasheets of each tube contain tables with temperature correction factors to adjust the resulting concentration to the ambient temperature. Other adjustments may also be made for pressure.

The main advantage of the gas detector tubes is that they are very inexpensive compared to other measurement techniques (the cost of each measurement is approximately 10-15 USD). They are also simple to use and give immediate results. The disadvantage is that they are less accurate than other measurement techniques and indicate the concentration of odorants, not odour units of the composite gas, which may contain numerous odorants; they may also be relatively insensitive and not detect substances at levels close to the odour thresholds of the species present. However, in the odour field, odorant concentrations at emission sources are sometimes completely unknown, and gas detector tubes may be very useful to get initial indications. The use of GDTs for odour pollution studies is also described in the scientific literature (e.g, Tanaka et al., 2004; Ninh et al., 2007; Schmitt, 2017).

Each gas detector tube is specific for a gas or a class of compounds, and a given concentration range. Therefore the user must know the chemical species expected in their emissions and the order of magnitude of their concentrations. However, some tubes are capable of simultaneously determining multiple unknown substances in the sample.

GDTs are a useful method that could be easily employed at point and active area sources but probably less useful at the more difficult to characterise passive area sources and volume sources. Additional information about gas detector tubes can be found in Kawamura et al. (2021). Gas detector tubes are available from different brands worldwide, such as Dräger, Uniphos, Gastec, Sensidyne, RAE and Kitagawa.

### 4.2.6 Emerging methodologies

New methodologies for measuring odour emissions are emerging that are based on the simultaneous use of drones and Instrumental Odour Monitoring Systems (IOMS). For example, Burgués et al. (2022) present the results of a study that aimed to characterise and monitor odour emissions from a WWTP using a drone-based chemical sensor system. The study was conducted over a period of several weeks, during which time the researchers used a drone equipped with a chemical sensor to collect air samples at different locations within the plant. The results show that the airborne IOMS was able to detect and quantify different odorous compounds emitted from the WWTP.

According to the authors, the use of a drone-based IOMS provided several advantages over the gold standard odour monitoring method (dynamic olfactometry). The drone was able to collect air samples from hard-to-reach locations, which are not accessible by ground-based monitoring systems. Additionally, the drone-based system was cheaper, and was able to collect real-time data, providing a more accurate and comprehensive understanding of odour emissions from the wastewater treatment plant.

## 4.3 Modelling odour emissions

One of the first steps to be performed when dealing with complex plants, that may be characterised by the presence of tens of odour-emitting sources of any type (stacks, diffuse sources and fugitive sources), is to decide if all of them must be considered. The magnitude of the odour emissions from these sources may be very different, with some of them being important emitters, and some others being less important or even negligible. Since the preparation of data for all the sources within the dispersion model is a time-consuming process, it is important to understand if and when a source can be considered negligible. These considerations are typically based on specific thresholds on the OER and the odour concentration. For example, the odour guidelines of Region Lombardy (Italy), as described in DGR 3018/2012, state that all the sources characterised by an OER greater than 500 $ou_E/s$ must be considered in a study, excluding those characterised by a maximum odour concentration below 80 $ou_E/m^3$. In other words, sources characterised by OER below 500 $ou_E/s$ or concentration below 80 $ou_E/m^3$ can be neglected. A source with a variable OER, for example because it depends on meteorological variables, can be neglected only if the OER remains below 500 $ou_E/s$ for each time of simulation interval. Of course, there are no particular contraindications - excluding the additional time required for the study - to use all the sources in view of a conservative principle. Most importantly, other factors should be considered before excluding a source from a simulation, for example its proximity to a sensitive receptor or the particularly offensive hedonic tone of its emissions.

### 4.3.1 Point sources

Point sources are usually identified as vertical stacks that emit freely into the atmosphere. Stacks are characterised by a well-defined volume flow expressed in volume per unit time at a specific temperature. Typically volume flow is given at a temperature of 0°C, and is expressed in $Nm^3/h$ (normal cubic metres per hour).

The OER is calculated from the product of odour concentration ($C_{od}$) and volumetric flow on wet basis at a temperature of 20°C and pressure of 101.3kPa (EN 13725:2004). Then, if the volumetric flow of the stack $Q_S$ ($m^3/h$) is given at a different temperature $T_S$ (°C) and pressure $P_S$ (kPa), it must be transformed with the following equation:

$$Q = Q_S \frac{273.15+20}{273.15+T_S} \frac{P_S}{101.3}$$

For example, if a stack has $Q_S$ = 20000 $m^3/h$ at $T_S$ = 130°C and $P_S$ = 105 kPa, the volumetric flow at 20°C and 101.3 kPa is 15074 $m^3/h$, or 4.18 $m^3/s$. Therefore, if the flue gas of the same stack has an odour concentration $C_{od}$ = 5000 $ou_E/m^3$, the resulting OER is 20936 $ou_E/s$.

From a practical point of view, the emission temperature $T_S$ is always known because it is needed by the atmospheric dispersion models for calculating the plume rise parameters. On the contrary, the pressure $P_S$ within the stack is almost never known, therefore, in the above equation, the correction for pressure is often neglected (i.e., it is assumed that $P_S$=101.3kPa).

When exit velocity is not measured, it can be estimated by calculating the volume flow at the emission temperature and dividing by the exit area and by 3600 s/h. For example, considering again the stack described above, and assuming a diameter of 1.1 m (i.e., an area of 0.950$m^2$), the exit velocity is 5.85 m/s.

Temperature and exit velocity are important variables for calculating the plume rise. In some cases plume rise may be reduced due to the presence of a rain cap or due to the horizontal direction of the stack, as shown in the previous Figure 4.1. In these situations the vertical velocity of the plume is null, and the plume rise is due only to thermal buoyancy if the exit temperature exceeds the ambient temperature. Some atmospheric dispersion models contain algorithms to simulate this kind of emissions. For example, as reported in the 2021 British Columbia Dispersion Modelling Guideline (BC, 2021):

*"AERSCREEN and AERMOD can handle this situation explicitly through the selection of options, POINTCAP and POINTHOR for treating capped and horizontal plumes, respectively. The source parameters are input as if it were a vertically oriented stack and the model applies adjustments internally to account for these types of orientations. For plumes with little or no buoyancy, users can specify a stack gas exit temperature = 0.0 K, automatically setting the exit temperature to the ambient temperature.*

*CALPUFF can also handle these sources through the use of the adjustable vertical momentum flux factor (FMFAC) for point sources with constant emissions which* can assume only the values *1 (corresponding to a vertically oriented stack)* and *0 (corresponding to a horizontal or capped stack with no vertical momentum). If time-varying point source emissions are applied, in the PTEMARB.DAT file, set TIDATA(7) (the vertical momentum flux) = 0"*.

Other modern dispersion models may have algorithms to simulate releases from horizontal stacks or rain-capped stacks, and the users should adopt these algorithms when present. When the simulation is carried out with a dispersion model without specific algorithms for rain caps and horizontal stacks, the user may force the exit velocity to 0.001 m/s. It must be observed that higher emission velocities (e.g., 0.1 m/s) are not suggested because they may still result in significant momentum plume rise being calculated, as pointed out by the US-EPA Model Clearinghouse Memorandum dated July 9, 1993.

For vertical stacks with rain caps the stack tip downwash must not be activated, but their height must be reduced by three times their actual diameter, which means assuming the maximum effect of the stack tip downwash. If the atmospheric dispersion model adopts a parametric algorithm for the plume rise (e.g., the Briggs equations), an effective diameter must be calculated to maintain the volume flow and buoyancy. The equivalent diameter $d_E$ can be calculated as

$$d_E = d \sqrt{\square}$$

Where d (m) is the actual stack diameter, and v (m/s) is the actual exit velocity. For example, a capped stack with a diameter of 0.2 m and exit velocity 3m/s would have an equivalent diameter $d_E$ = 11.0m.

If the atmospheric dispersion model adopts a numerical algorithm for the plume rise, it solves a set of differential equations and needs the stack diameter as one of the initial conditions. The previous numerical example shows that the equivalent diameter may be - and often is - very large with respect to the actual diameter, therefore using the equivalent diameter in a numerical algorithm for the plume rise may give unrealistic results. In these cases, the actual stack diameter must be used, as suggested for example by the Iowa Department of Natural Resources (IDNR, 2014), or - as suggested by the AERMOD user guide (US-EPA, 2022b) - the initial radius must be assumed two times the actual stack diameter (i.e., the diameter must be multiplied by 4) to account for the interaction of the existing plume with the cap.

When dealing with horizontal stacks in dispersion models without specific algorithms to treat them, the stack tip downwash algorithm (if present) must not be activated, the exit velocity may be set to 0.001 m/s, and their actual height must be used.

Rarely, the stack tip is tilted and unobstructed. In these cases, the actual stack diameter and height must be given as input to the dispersion model, while the vertical component of the exit velocity must be used (IDNR, 2014). Unless the dispersion model has its own algorithm to simulate tilted stacks, the vertical component is calculated by multiplying the exit velocity and the cosine of the angle between the stack and the vertical. If the tilted stack is obstructed by a rain cap or any other equipment that suppresses the vertical momentum, the exit velocity may be set to 0.001 m/s as described previously.

Point sources may be affected by building downwash, which means that their plume can be captured in the building wake, increasing the ground-level concentration. As a general rule, a building may cause downwash to the stacks located within a distance of 5L, with L the minimum between the height and the width of the building. Sources within this distance lower than 2.5 the building height are subject to building downwash.

Some hybrid models, such as Eulerian/Lagrangian models or microscale Eulerian CFD models, can simulate building downwash without the need for any empirical methodology (Flassak et al., 2010; Oettl, 2015). However, for most atmospheric dispersion models used for regulatory purposes, the building downwash parameters to include in the input data may be determined with the Building Profile Input Program, BPIP (US-EPA, 1995c). Among the input data required by BPIP there are coordinates and the height of the buildings. These data may be obtained from plot plans of the industrial plant or, for some locations where the "3D Buildings" feature is available, from Google Earth with a good approximation.

### 4.3.2 Active area sources

As shown in Chapter 4.2.2, active area sources are characterised by their volumetric flow by unit of area. Therefore, their OER may be calculated by multiplying the volume flow at 20°C ($m^3/hm^2$) and the odour concentration ($ou_E/m^3$) by the total area of the source.

Within the dispersion model, an active area source can be simulated through an equivalent point source, which means a point source with equivalent area and the same volumetric flow. They typically emit at ambient temperature. Other times they are simulated through a series of point sources, for example, one in each vertex of the active area source (assuming, for instance, a rectangular shape). The sum of the volumetric flows of the point sources must be the total volumetric flow of the active area source.

According to EN 13725:2022, area sources with an exit velocity v > 0,008 m/s are, by consensus, active area sources and shall be sampled accordingly. Area sources with lower exit speeds are considered to be passive area sources.

### 4.3.3 Passive area sources

Emissions from passive area sources are typically governed by evaporation and diffusion. The concentration gradient provides the driving force for the transfer of odorants from solid or liquid surfaces to the air (Laor et al., 2014).

As discussed in paragraph 4.2.3, the specific odour emission rate (SOER) of passive area sources is determined by wind tunnels, or similar instruments, in which air flows with a known velocity (typically of the order of 0.3 m/s), and the SOER value depends on the flow velocity. This means that the actual emission from the source depends on the wind speed close to its surface. The OER due to a specific wind speed $v_S$ close to the emitting surface is calculated as (e.g., Lucernoni et al., 2016):

$$OER = A\,SOER\left(\frac{v_S}{v_R}\right)^k$$

where A ($m^2$) is the area of the passive source, $v_R$ (m/s) is the reference air speed within the wind tunnel during the measurement (e.g., 0.3 m/s) and k is a constant typically equal to 0.5. It is observed that Jiang and Kaye (1996) suggested k=0.63, but k=0.5 is most often used.

The wind speed over the emitting surface ($v_S$) can be calculated with a power law relation, even though other equations can be used, as described for example, by Ravina et al. (2020). The power law equation is:

$$v_S = v_h\left(\frac{z + z_{wt}}{h}\right)^p$$

Where h (m) is the height at which the wind speed $v_h$ (m/s) is known, z (m) is the height above the ground of the area source, $z_{wt}$ (m) is the half height of the wind tunnel, and p (unitless) is a power coefficient depending on the atmospheric stability and land use type (rural or urban). The values of the power coefficient p are shown in Table 4-1 (US-EPA, 1995b), even though different values have also been proposed (e.g., Arya, 1999; Scire et al., 2000).

**Table 4-1** Values of the power coefficient p

| Stability | Rural | Urban |
|---|---|---|
| A | 0.07 | 0.15 |
| B | 0.07 | 0.15 |
| C | 0.10 | 0.20 |
| D | 0.15 | 0.25 |
| E | 0.35 | 0.30 |
| F | 0.55 | 0.30 |

Considering the special case of emissions from liquid surfaces within tanks (e.g., wastewater tanks), the tank height above the ground is often used for z in the power law equation. When the tank is almost full, this approach is correct, while it can cause overestimated emissions when the tank is not completely full, because the wind speed at the tank top is higher than the wind speed close to the emitting surface, which may be well below the tank top. Bellasio and Bianconi (2022) proposed a possible solution to this problem with new equations in which emissions depend on the distance between the tank top and the emitting surface, the wind direction and the tank orientation (for rectangular tanks).

When the odour source is placed in a location partially protected from the wind (e.g., the presence of buildings and other structures), using the above equation for getting the OER as a function of wind speed may give overestimated emissions. However, even in those situations, the odour emission is related to the atmospheric motion close to the emitting surface. A possible treatment of these situations involves using an indicator of the mechanical turbulence in place of the wind speed $v_S$ close to the emitting surface. Therefore, the OER may be estimated as

$$OER = A\,SOER\left(\frac{u_{*}}{v_R}\right)^{0.5}$$

Where u* is the friction velocity (m/s), which may be obtained from the meteorological model.

The above equations apply to situations when the emissions depend on the “stripping” of odorous molecules from the surface. There are situations in which the emissions do not depend on wind speed. For example, the odour emissions from cultivated landfill areas (permanently covered waste) do not depend on wind speed because they are related to the biogas production from the old waste within the landfill. Capelli et al. (2018) pointed out that a variable SOER proportional to the square root of the wind speed results in an overestimation of about one order of magnitude of the landfill odour impact. Therefore, the landfill surfaces must be treated as a particular type of passive area source, not depending on the wind speed. On the contrary, the odour emissions from fresh waste within the front of the landfill may depend on wind speed and must be treated as described above.

## 4.3.4 Volume sources

### 4.3.4.1. Geometrical parameters

Three-dimensional sources such as the one shown in Figure 4-16 are typically described as volume sources within atmospheric dispersion models. These sources are used for simulating non-buoyant emissions from buildings or fugitive emissions from valves, flanges and other items.

The geometrical parameters needed to define a volume source within a Gaussian dispersion model (e.g., AERMOD) or a Lagrangian puff model (e.g., CALPUFF) are the height of the centre of the plume ($h_e$), the initial lateral dimension ($S_{y0}$), and the initial vertical dimension ($S_{z0}$). The initial dimensions can be determined as summarised in Table 4-2 (US-EPA, 1992)

**Table 4-2** Initial lateral and vertical dimensions of a volume source (US-EPA, 1992)

| Type of source | $S_{y0}$ | $S_{z0}$ |
|---|---|---|
| Surface-based ($h_e \sim 0$) | | Vertical dimension / 2.15 |
| Elevated source ($h_e > 0$) on or adjacent to building | Side length / 4.3 | Building height / 2.15 |
| Elevated source ($h_e > 0$) not on or adjacent to building | | Vertical dimension / 4.3 |

As an alternative, when the volume source is used for simulating fugitive emissions from a building, the New Zealand Ministry of Environment (2004) states that the initial vertical dimension ($S_{z0}$) may be estimated as a quarter of the building height. The initial lateral dimension ($S_{y0}$) may be estimated as a quarter of the building width (i.e., the minimum of the horizontal building dimensions).

In AERMOD, the initial lateral and vertical dimensions are used to reconstruct the volume source through two virtual point sources placed at an upwind distance such that at the volume source position, they have those horizontal and vertical dispersions. The positions of the two virtual point sources vary at each simulation time according to the wind speed and wind direction values.

When using volume sources in AERMOD, it is important to remember that receptors cannot be placed within the "exclusion zone", defined as a circle of radius R (m) equal to $R = 2.15 S_{y0} + 1$. Since AERMOD sets to zero the concentration values within the exclusion zone, it must be verified that the exclusion zone of each source does not extend outside the plant perimeter.

In a Lagrangian particle model, a volume source can be defined more precisely with the shape of the region characterised by the emissions, for example, a parallelepiped, a sphere or a hemisphere. The computational particles are released in random positions within the specified volume during the emissions. Then, particles released at higher levels of the volume source are transported and dispersed more effectively than those released at lower levels with weak wind.

#### 4.3.4.2. Estimation of OER and SOER

When dealing with volume sources, both OER and SOER may be difficult to define. Typically, what is available is a measure or an estimation of the odour concentration within the building or the region of interest. Then, there may be two alternatives: 1) the OER is calculated as the product between the concentration value and the volume flow rate through the building, or 2) the SOER is calculated as the product between the concentration value and a representative air speed over the area of interest. It is challenging to give specific universal equations to treat these situations because any case may require specific assumptions. Therefore, two examples are described below to illustrate the possible situations. They are only a starting point to elaborate on other situations.

##### Example 1: Fugitive emissions from refineries or chemical plants

Fugitive emissions may be simulated with volume sources because they affect large areas of the plant, both along the horizontal and vertical planes. Those emissions happen in areas with many obstacles, such as pipelines, buildings, racks, tanks and other structures. Therefore, wind speed cannot fully act within this industrial environment. However, it is reasonable to assume that the OER varies as a function of meteorological variables because both mechanical and convective parameters affect the emissions. For this reason, an equation for the OER variability should include the dependence on the friction velocity u* (representing the mechanical turbulence) and the convective velocity w* (representing the convective turbulence). If a representative odour concentration $C_{od}$ may be defined for the region of area A affected by fugitive emissions (e.g., with dynamic olfactometry, from scientific literature, from similar plants), the OER for each hour of simulation could be estimated as

$$OER = A\,C_{od}\,Max(u_{¿}, w_{¿})$$

##### Example 2: Emissions from livestock buildings

These buildings can be considered volume sources. When the odour concentration within a building has been measured or estimated, the OER can be calculated by multiplying it and the volumetric flow. For each hour of the simulation period, the volumetric flow Q ($m^3$/s) can be estimated considering a contribution due to the wind force ($Q_{wf}$) and a contribution due to the thermal buoyancy ($Q_{tb}$) as described, for example, by Angrecka and Herbut (2014):

$$Q = \sqrt{\square}$$

The contribution of the wind force ($Q_{wf}$) is calculated as:

$$Q_{wf} = E\,A\,v$$

Where E is a constant (E=0.35), A is the inlet area ($m^2$), and v is the wind speed (m/s) at a height above the ground representative for the inlet area, for example, half the opening height. The wind speed at the representative height can be estimated starting from the measurements at the anemometer height using the power law equation described in paragraph 4.3.3 about passive area sources or other tools (e.g., CFD models, when they are available). Of course, the measurements can be substituted by the predictions/reconstructions of meteorological models at the first level above the ground.

The contribution of the thermal buoyancy ($Q_{tb}$) is calculated as

$$Q_{tb} = \frac{C_d A}{3}\sqrt{\square}$$

Where $C_d$ is a constant ($C_d$=0.86), g is the acceleration due to gravity (9.81 m/s$^2$), H is the height of the openings (m), $T_i$ is the livestock building internal temperature (K) and $T_e$ is the external temperature (K). The internal temperature may vary over time and can be a function of the number and age of cattle within the barn.

During winter, curtains or other equipment may be used to protect the animals from excessive cooling. The presence of the curtains can be simulated, for example, by reducing the inlet area during the winter months.

Another example of estimating odour from livestock buildings is described by Rzeźnik and Mielcarek-Bocheńska (2022). In this publication, the volumetric flow, or ventilation rate, is calculated as a function of the number of cows, the amount of $CO_2$ produced by each cow, and the difference between the internal and external $CO_2$ concentrations. Additionally, the amount of $CO_2$ produced by each cow is calculated based on the heat flux needed to maintain vital functions, pregnancy and milk production. The final value is then corrected according to the internal temperature.

The OER resulting from the described procedures is time-dependent and varies for each hour of the simulation period. These examples may be applied, with due modifications, to other types of odour emissions from a building.

### 4.3.5. Temporal variation of emissions

The temporal variation of the odour emissions must be described as precisely as possible within the dispersion models. These variations may be due to the meteorological dependence of the odour emissions, for example, in wastewater tanks. They may also be due to the normal working processes, for instance, in the uncovered landfill front tip during the day hours and working days, and temporary cover during the closing hours and weekends.

Brancher et al. (2021) simulated the odour emission from a livestock building, assuming constant OER and hourly-varying OERs under different assumptions. Their results show that hourly OERs can improve the confidence in impact assessments compared to simulations driven by constant emissions.

In some situations, the odour emissions are regular over time, for example, when they happen N hours of the day every day. In other situations, for instance, when considering discharges from leachate vessels, the release is short and may happen at any time within the day when the pressure reaches a specific level. It is typically known, for example, that the release happens one hour a day, but not exactly when. For example, this kind of release must be simulated by activating it for a random hour each day.

Similarly, if the odour emission happens for N hours within a working interval of M hours (M>N), with the N hours unknown, they must vary randomly or cyclically within the dispersion model. In fact, considering the same N hours for all the days of the simulation may give unrealistic results, for example, because the wind always blows along a specific direction in those hours (e.g., sea/land breeze) or because the N hours are always within a time interval with maximum mixing height (e.g., close to noon), or minimum mixing height (e.g., early morning).

All the most advanced atmospheric dispersion models can define an emission time trend in their main input file when the trend is cyclic or by external files when variations are complicated or arbitrary.

When defining a precise time dependence of the odour emissions is impossible, the most unfavourable conditions must be considered in the atmospheric dispersion model (i.e., the highest OER must be used).

### 4.3.6. Future industrial plants

While for existing plants odour impact assessment (OIA) studies can be done using emission observations (e.g., volumetric flow, odour concentration, SOER), for future plants OIAs can only be done using the maximum authorised volumetric flow, and the odour concentration or SOER of similar plants or from the bibliography. Alternatively, the assessment might be based on a regulatory permit using the maximum allowable SOER as input data. This approach for future plants may not reflect the reality, but it typically gives overestimations.

Care must be taken when comparing the results of a study where a current scenario and a future scenario are analysed. Indeed, if the current scenario is simulated starting from the odour emission observations and the future scenario is simulated with the maximum authorised values, the difference between the results of the two scenarios will be unrealistically large.

### 4.3.7. Uncertainties

In atmospheric modelling, emission estimation is a complex process that involves many uncertainties. In odour modelling, these uncertainties are possibly even larger.

For example, the simplest situation would be the calculation of the OER of a stack, by the multiplication of the odour emission concentration and the volume flow rate corrected by temperature. However, the odour concentration within the stack is typically measured once and used for a long period of time, but the odour concentration may be a function of the level of production, which is not constant in time. In air quality studies, on the contrary, particularly in large plants, major stacks are often equipped with CEMSs, which measure pollutant concentration, temperature, flow rate and other variables in nearly real-time. Very different results have been obtained by using a constant OER or hourly-varying OERs with the same median value (Brancher et al., 2021).

Uncertainties in weather data, such as wind speed, temperature, and atmospheric stability, can significantly impact odour emission estimation. In fact, as seen in the previous paragraphs, excluding the conveyed sources (stacks), the meteorological variables play an important role in estimating the OER.

When emission factors are used for estimating the odour emissions, their inaccuracy reflects on the final calculations. The same is true when for a specific source there are no measurements or emission factors, and the emissions are estimated on the basis of similar sources.

Another source of uncertainty is related to the assumptions and the input values of the algorithm used to estimate odour emissions. For example, the calculation of the volumetric flow from a livestock building may be based on the internal temperature, which depends on the number of animals, their age, physical state and other variables. All these variables have their own uncertainties, as well as the algorithm that uses them to give the internal temperature of the building.

As commented in the previous paragraphs, different measurement techniques can lead to varying degrees of uncertainty in odour emission estimation. These uncertainties can also arise from inadequate sampling and analysis techniques, such as sampling duration or frequency.

Finally, odour assessment by panellists is subjective by its nature. Odour concentration results can be affected by the limited number of trained panellists available, the repeatability and reliability of their assessments.

It is important to keep in mind all these uncertainties - and possibly others not mentioned here but described in the scientific literature (e.g., Laor et al., 2014) - when carrying out OIAs.

## 4.4 Ambient air measurements: EN 16841

Odour flow rate may be determined after performing a field inspection (EN 16841) followed by a backpropagation use of the odour dispersion modelling (reverse modelling).

With the plume method according to EN 16841-2 (dynamic or stationary), one sniffing unit per cubic metre (su/m$^3$) is defined by panel members to express the odour concentration at the border of the plume (i.e., at a transition point). The sniffing unit is based on the recognition of the specific odour under analysis, not to the detection of any odour. It means that one sniffing unit (1 su/m$^3$) corresponds to an odour concentration from 1 to 5 ou/m$^3$. With this approach, the odour flow rate is usually expressed in su/s.

With the grid approach (EN 16841-1), no odour flow rate is estimated. This approach characterises odour exposure in a defined assessment area.

The plume (stationary and dynamic) method and the grid one (stationary) are briefly described in the following section. For a detailed presentation, reading EN 16841 standard and related papers is recommended.

### 4.4.1. Ambient air measurement to characterise odour exposure: grid method

**Grid inspection according to EN 16841-1** is used to derive the odour impact as the odour hour frequency of all emitting sources with detectable impact. This method is an efficient way to measure the impact in an odour-affected environment.

The grid method is a statistical survey method which is applied over a sufficiently long period of time, to provide a representative map of the exposure to recognisable odour and its spatial distribution over the assessment area. These grid measurements are used to determine the distribution of odour hour frequency for recognisable odour in ambient air, in an assessment area, under meteorological conditions that are assumed to be representative of local meteorology of about the last 10 years.

The odour hour frequency is an odour exposure indicator, and can be used to assess the exposure to recognisable odours originating from one or many specific odorant source(s) emitting in a particular area of study.

The odour hour frequency is determined for one or more “assessment squares”, configured as grid measurement points. The assessment area is defined as a known impact distance or minimum radius of a circle from the highest stack which equals 30 times the highest stack height. In the case of several installations, the area is combined from the circles from each source.

The assessment area is covered with a grid of equidistant points. The squares resulting from the joining of four measurement points are the assessment squares. A square size of 250 m should be initially chosen. Depending on the needs and the scope of the study, larger (maximum of 500 m) or smaller squares (e.g. 125 m, 100 m, 50 m) are possible. To reflect the decrease in odour exposure with increasing distance, adjacent assessment squares at different distances from the emitter should always be defined. An example is given in Figure 4-16.

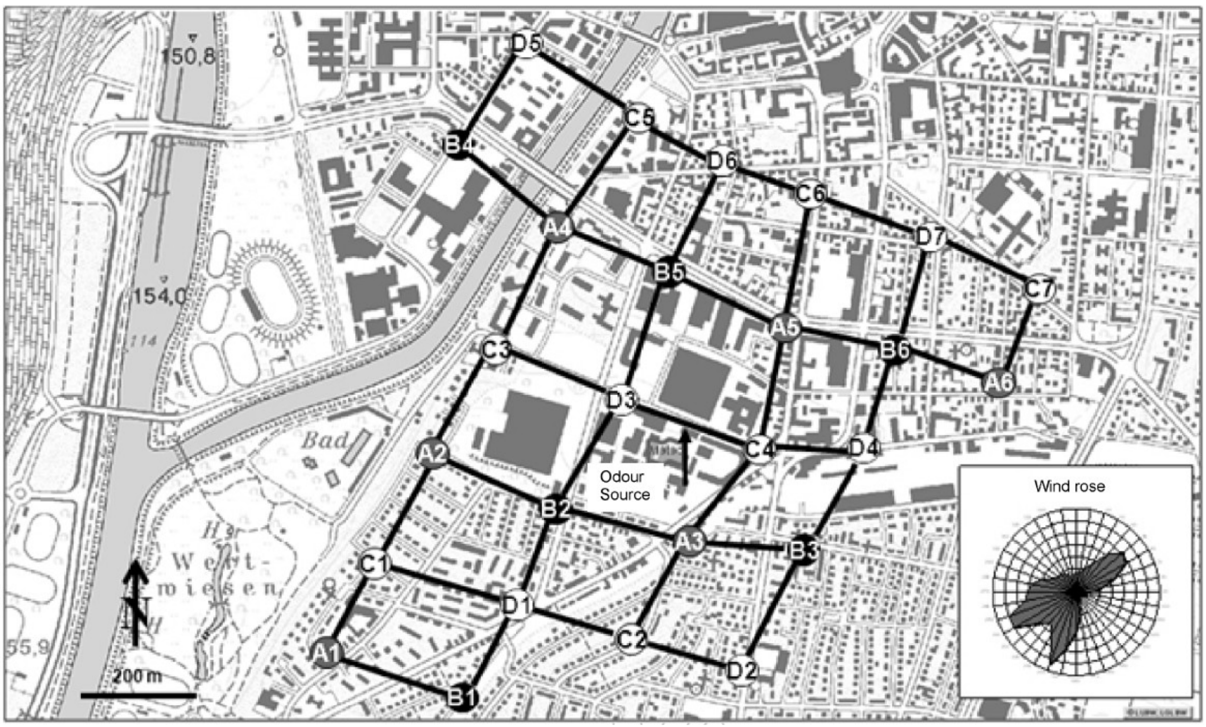

**Figure 4-16** Example for an assessment area in the vicinity of an odour source with assessment squares and measurement points (literature source: EN 16841-1:2017)

The measurement points are divided into four routes ( A, B, C and D in Figure 4-17). Each square is represented in a route with one point. The assessment takes place on 104 days in a year. Each day one of the routes is chosen, and after four measurements all four routes are performed. After 26 single measurements for each measurement point, the sum of all single measurements gives the result for the square.

A shorter survey duration can be planned for practical reasons, but the survey shall be at least six months, with a minimum scale of 52 single measurements for each assessment square. In this case, colder and warmer months shall be equally represented to denote an entire year.

The starting time varies from one measurement to the next. The measurement days should not be on consecutive days.

For statistical purposes, throughout the survey, all days of a week shall be roughly equally represented in the survey plan. The daily start of a survey should be changed and after four measurements all times of the day (morning, afternoon, evening and night) are covered.

The measurement is performed by a panel of at least 8 trained odour assessors.

### 4.4.2. Ambient air measurement of odours by using the plume method

EN 16841-2:2017 distinguishes two ways of capturing the outline of a plume: *stationary* method and *dynamic* method. The plume extent is determined with trained odour panellists.

Using the **stationary method**, the panel members are located at specific intervals along intersection lines perpendicular to the plume direction. Several panel members (minimum 5-panel members) are positioned at intervals along each intersection line to cover the estimated width of the recognisable plume.

At each measurement point, the panellists stay for 10 minutes. During this time, the panel member evaluates the perceived smell from the source every 10 seconds. So, each panel member determines the percentage odour time in the course of one single measurement.

If the result of a single measurement reaches a percentage odour time less than 10%, the odour is considered as being absent, while at higher values the odour is present. Single measurements at one intersection line are conducted simultaneously. Intersection lines at different distances from the source are assessed subsequently assuming that the relevant meteorological conditions remain the same.

At least one intersection line has to be at a sufficient distance to ensure that no recognisable odour is present at any measurement point to be able to determine the maximum plume reach estimate (Figure 4-17).

Parallel to the plume measurements the meteorological conditions such as wind direction, wind speed and parameters to determine turbulence are measured. This can be done for example with 3D-like ultrasonic devices.

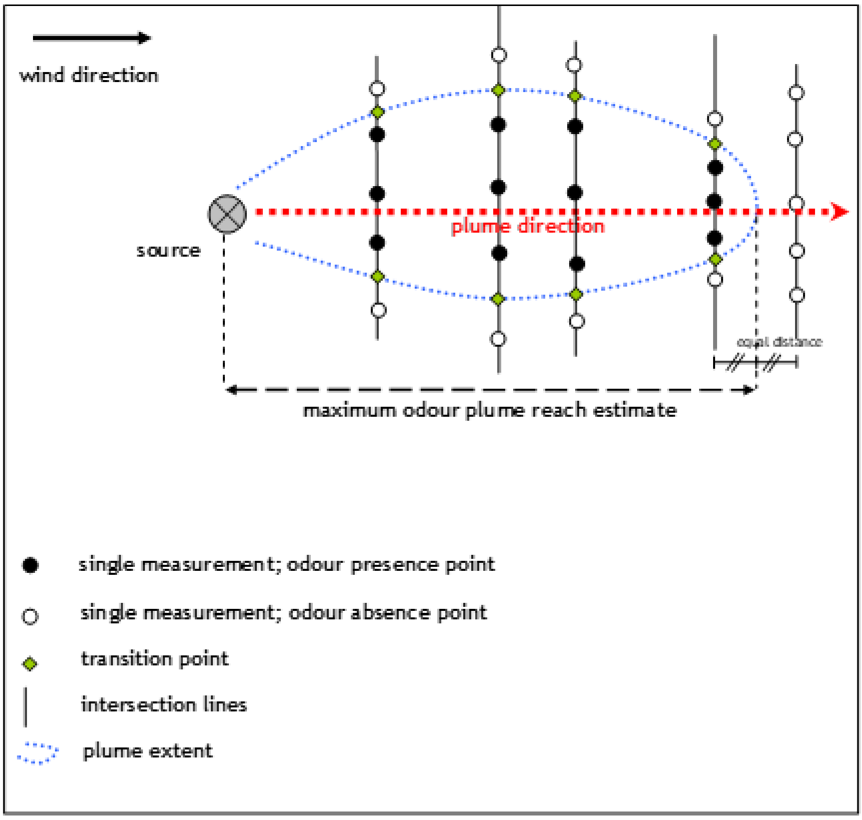


**Figure 4-17** Schematic diagram of an example of stationary plume measurement (EN 16841-2)

Using the **dynamic method**, the panel members cross the plume, while conducting single measurements at frequent intervals. At a minimum, two panel members are needed.

By successively entering and exiting the plume and in this way determining the transition between the absence and presence of recognisable odour, the extent of the plume is defined. This approach helps to avoid addiction to the recognisable odour. The plume direction is crossed at different distances from the source. This includes crossings at distances where no recognisable odour is detected. One measurement consists of two crossings: one moving toward the plume, and one moving away from the plume.

The maximum plume reach estimate is defined as the distance along the plume direction between the source and the point halfway from the furthest intersection line or crossing where odour presence points were recorded, and the first intersection line or crossing where only odour absence points were recorded. This equal distance between the two intersection lines/crossings is indicated as a green circle on the schematic Figure 4-18.

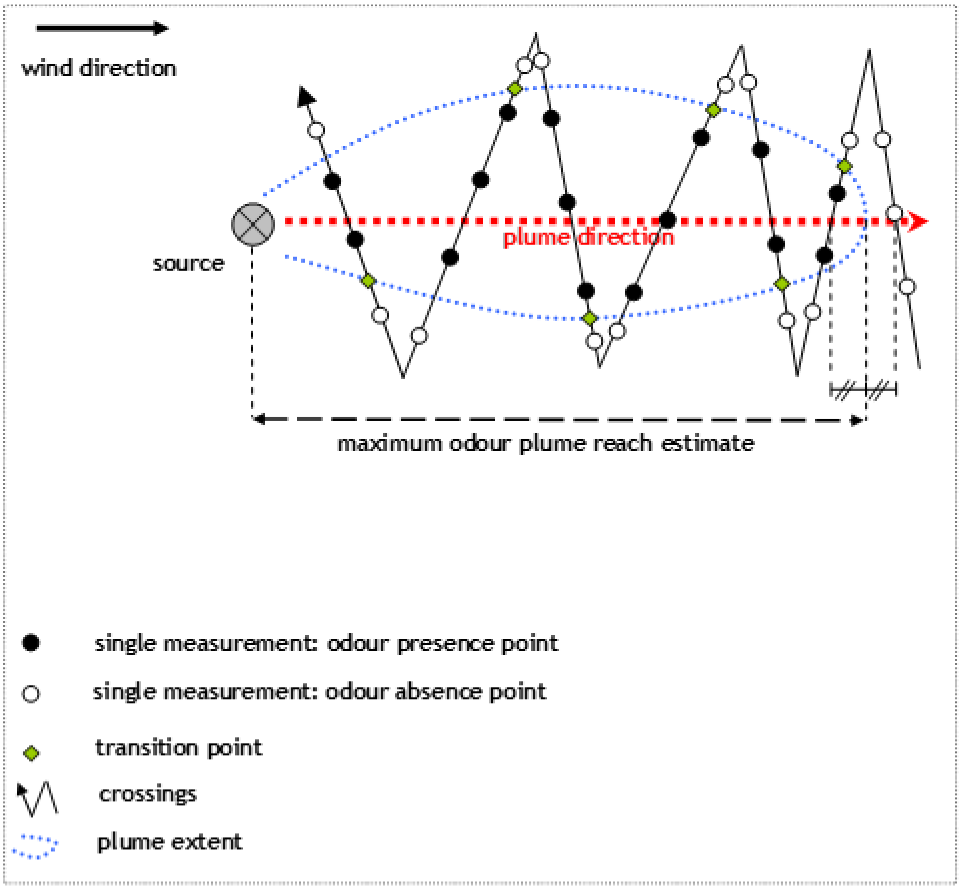


**Figure 4-18** Schematic diagram of an example of dynamic plume measurement (EN 16841-2)

Measurements with both methods are repeated several times, minimum of 10 plumes, with different meteorological conditions. Meteorological conditions characterised by variable wind direction should be avoided.

The plume extent derived from both methods can be used to validate model results. For this, the model is set up with the meteorological situation and an assumed emission rate. The plume extent for the situation is compared. From this comparison a suitable emission rate for the source can be determined. The methodology to calculate the odour emission rate of a source is described in paragraph 7.2.1.

## 4.5 The need for odour emission factors

The emissions of many air pollutants (e.g., $NO_X$, $SO_2$, $PM_{10}$, …) can be calculated starting from the knowledge of specific process or activity indicators, such as for example the amount of fuel used or the number of km travelled for a given vehicle. Many methodologies and collections of emission factors exist, for instance the European CORINAIR (EEA, 2019) or the US AP42 (US-EPA, 2023).

Concerning odour, many papers reporting emission factors or SOER for specific productions have been published (e.g., Frechen, 2004; Sironi et al., 2005; Sironi et al., 2007; Capelli et al., 2014; Mielcarek and Rzeźnik, 2015; Davoli et al., 2021), but they have not been homogenised and organised in a single collection.

For odour emissions, the use of a single activity indicator is not sufficient. For example, emissions from animal housing facilities show great variability over the course of the day and the year, which depends on the size of growth of the animals, the fluctuations of the ambient air temperature, animal activities, the housing system, and the management (Brancher et al., 2021). For modelling of livestock farms the use of emission factors is suitable (for instance emission factors per animal), which can be defined specifically for piggeries as the odour emission rate (ou/s) released to the atmosphere by a pig (Romain et al., 2013).

The emission factor method is the only one applicable for future projects but, even for existing livestock buildings, it is a convenient way of avoiding expensive measurements which could only be afforded for large units or production systems (Van Harreveld et al., 2001).

A comprehensive methodology to estimate odour emissions and a large collection of odour emission factors do not exist and should be developed. Such a methodology would be an important tool for atmospheric modellers to carry out odour impact assessments (OIA) when emission measurements are not readily available.

## 4.6 Conclusions

Sampling odours is challenging and it accounts for a large part of the uncertainties associated with the results of an air dispersion model.

OERs from point sources are reasonably well characterised, while those of area sources may vary depending on the device used for sampling and depending on the flow rate used. That means that, for the same area source, two different OERs can be obtained depending on the sampling device used. The most challenging activity is the characterisation of diffuse emissions. Field inspection is an appropriate approach, and it is highly recommended. Another possible way is to consider VOCs as odour proxy, and to use diffuse/fugitive VOCs measurement techniques as, for example, those proposed by *EN 17628*. Also, emissions factors for compounds related to odour (e.g., $NH_3$, VOC) exist for waste treatment activities (ADEME, 2012).

Depending on the kind of source that needs to be investigated, specific equipment is required and this investigation needs to be carried out according to specific measurement guidelines. This chapter did not detail these techniques: the reader should consider existing standards and reference works.

When the object of the odour impact assessment (OIA) is a future plant, dispersion models are the only tool that can be used. The OER or SOER can be obtained from similar existing plants or from the scientific literature. In these situations, a database of odour emission factors and a detailed methodology explaining their applicability would be very useful. A comprehensive database of odour emission factors nowadays does not exist.

Besides odour emission data, additional information is needed to assess odour exposure by means of air dispersion models. For example, when dealing with stacks, it is important to know the exit direction (vertical, horizontal, or tilted with a specific angle) and if a rain hat is present or not. The exit temperature is also important, both to determine the exit velocity and to calculate the volumetric flow at the same temperature at which odour concentration is specified. Additionally, when considering passive area sources, the OER is determined at every simulation hour starting from the measured SOER and evaluating how it varies according to the airspeed close to its surface. In order to determine this speed, the wind speed at the anemometer height (or first vertical model level), the atmospheric stability and the roughness length must be known.

This chapter did not consider the qualitative dimension of the odour. Indeed, in dispersion models, the main variable introduced into the software is the emission of odour whatever its nature (e.g., compost, chemical farm, coffee roasting, bakery, carcass rendering). There are many situations, especially in the case of multiple sources, where the character of the odour is important, but it is typically not considered when carrying out an OIA. The global odour emission rate cannot be determined by simple emission sampling and olfactometric measurements in the laboratory. This is particularly true for complex sites like, for example, landfills (e.g., Belgiorno et al., 2012), where odour is due to multiple sources, such as windrows turning, fugitive emissions, vehicles gas emissions and heterogeneous emissions surface. However, in recent years there have been some approaches to include the hedonic tone in the evaluations, as discussed in paragraph 7.4.

In order to approach the notion of nuisance (remembering the meaning of FIDOS), for which the hedonic tone is essential, it is ideally necessary to involve the residents in the evaluation, and to increase citizen participation. A resident-watchman survey becomes more accepted by the authorities and offers several advantages. The most important advantage is probably the restoration of the dialogue between the stakeholders (paragraph 5.9).

The correct characterisation of odour emissions and sources is an important step in OIAs carried out with modelling techniques. It requires time and may be expensive when samplings are required, but if it is not done with due diligence and following specific guidelines, the model results may be imprecise when not completely wrong.

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# 5. Dispersion Algorithms

## 5.1. Introduction

In everyday life, there are many contexts (industrial, agricultural, energy production, waste management, water treatment) in which the release of odorous substances into the atmosphere and the related nuisance that they can cause on the population play a very important role. Since the behaviour of odours depends crucially on the characteristics of the atmosphere, this is treated, similarly to what is supposed for other air quality issues, as a problem related to the transport and dispersion of gaseous substances in the turbulent atmospheric boundary layer. Atmospheric Dispersion Modelling is therefore considered, for various reasons, a fundamental support tool for the study and reconstruction of the odour impact. The knowledge of the characteristics of the available modelling technologies, or "Dispersion Algorithms", of their related advantages and limitations, allows a better choice among the different approaches and guarantees a better correspondence between the results of their application and the expectations of potential users.

In general, there are several reasons why dispersion modelling techniques are used in the field of odour impact assessment. Models are used to quantitatively predict the impact of pollution on air quality over relatively large geographical areas, potentially extending the information to a very high number of points compared to what is typically available from existing measurement systems, hence constituting a network of receptors at substantially zero cost. They are also necessary for the impact assessment of future plants or pollutant sources and allow, through source apportionment procedures, the separation of the contributions generated by different emission sources located in a certain area. They allow studying the effects of any mitigation measures on the emission sources, through a quantitative analysis of engineering solutions and the application of cost-benefit procedures. They are an essential part in the site planning process, as tools to minimise the impact of the emissions on the population. In fact, model simulations allow optimising the design of emission sources for a least-impact result, defining the possible insertion and correct localisation of buffer zones and fence lines, arranging any monitoring networks and designing the land use to minimise the pollutant exposure to the population.

They make it possible to objectify the impacts of odorous sources, helping to remove the "emotional" effect which is often associated with odorous nuisance. Models can directly address different aspects of the FIDOS process (Frequency, Intensity, Duration, Offensiveness and Sensitivity) and finally, they are the only tool capable of simultaneously taking into account aspects such as emissions, meteorology, and land use which are responsible, through a mutual and complex interaction, of the effects of odour annoyance on the population.

For all the reasons listed above, the use of dispersion modelling technologies is suggested, or in several cases explicitly required, by many guidelines or odour regulations/legislations in different countries around the world (see for example Bokowa et al. 2021), representing a widespread practice connected to the management of odour problems.

The purpose of this chapter is, therefore, to describe the dispersion algorithms and the available model implementations with sufficient details to support the choice of the various possible approaches that are offered and that are typically used in the field of odour applications. Given that the main objective of the document is to constitute a handbook, an attempt was made to orient the content of the chapter to a wide range of possible model users. In this sense, the chapter does not constitute an extremely detailed and completely exhaustive description from a technical point of view, which is possibly referred to both specific texts on dispersion modelling (e.g. Arya, 1998; Barrat, 2001; Zannetti, 2010), and on the dispersive structure of the Atmospheric Boundary Layer (e.g. Garratt, 1994; Stull, 1988). The topic covered in this chapter will be hence addressed taking into account many aspects of the modelling approach to odours, including a critical analysis of some well-known problems related to the use of the models in this field, which has distinctive characteristics posing some specific critical issues.

In particular, the chapter deals, in Section 2, with the topic of the role of the dispersion models in the specific field of odour applications, detailing the different aspects of the possible implementations and use related to the different phases of the planning or control of emitting sources.

Section 3 is devoted to a concise description of the various available modelling methodologies, starting from the simpler screening formulas, moving to stationary and homogeneous Gaussian formulations, the Lagrangian Puff/Segment or Stochastic Particle approaches and the Eulerian approach. Both the main theoretical and practical aspects of the different methodologies are described in order to give a general view of the topic.

These different methodologies for dispersion modelling represent a theoretical framework that has already been put into practice and implemented in modelling tools all over the world. They have a recognised name, often sponsored by national or worldwide recognised organisations as a possible standard or directly developed by private institutions and consequently present on the market. These models are, in the end, the tools to be applied by final users such as consultants or public agencies. Section 4 is hence devoted to describing a reasoned list of the dispersion modelling operational tools available and currently used in different parts of the world for odour applications. The list separates different models depending on the considered methodologies and gives the main characteristics and peculiarities of each model.

The adaptation of the use of the standard atmospheric dispersion models for the characterisation of odour impacts poses some specific problems compared to a more standard use related to air pollution simulations. In particular, it is well known that olfactory-related problems are perceived during short time intervals and in this respect it is necessary to model the “instantaneous” concentrations instead of time-averaged concentrations on time scales of the order of one hour, one day or one year as in a typical air quality framework. Since dispersion models are often developed to simulate concentrations averaged in time (typically of the order of one hour) or ensembles (over many realisations of the same statistical ensemble), some specific corrections have to be taken into account, such as the introduction of the Peak-to-Mean Ratio concept or the direct simulation of higher-order momentum for the statistical distribution of the concentration. Other problems are connected to the meteorological input that should be in principle able to reproduce this specific time variability particularly evident in low wind stable conditions, or connected to the description of the emissions, for example in the presence of diffuse, meteorology-driven sources. Section 5 is devoted to these issues, describing the current limits of each model technology and in some cases the way used to overcome them.

Once a categorisation of the different available models is given, Section 6 addresses the problem of the model suitability. Different complexities of the models must meet with different complexities of the faced problems. This section aims at giving support in choosing the different modelling technologies available, according to the different characteristics of the problems, such as the presence of homogeneous/non-homogeneous and/or stationary/non-stationary weather conditions, the presence or absence of complex topography, the spatial scale etc.

Section 7 is dedicated to the problem of model validation. Considering the use of the dispersion models in the frame of odour applications, there is a need for a specific validation framework and protocol, in order to verify the methodologies adopted to solve some of the existing problems such as, for example, the reproduction of peak concentrations. An overview of the available datasets and methods fitting this purpose is given.

A bridge towards the stakeholders is discussed in Section 8, in order both to address their needs in dealing with odour nuisance and to raise their awareness about the usefulness and necessity of using dispersion models, by widening their knowledge of the advantages offered by these technologies.

Finally, Section 9 contains a window opened on the current research regarding the atmospheric dispersion modelling approaches, particularly related to the scientifically advanced ways considered to overcome some of the problems cited above. These activities, including for example LES/DNS methods, PDF methods, two-particle Lagrangian Stochastic models, and Fluctuating Plume models, have not yet been able to provide standardised or commercially ready-to-use products, but contain many new helpful ideas that will lead to even more advanced modelling systems in the next future. This, even considering the development and diffusion of the High Performance Computing that is often required, is available in a form usable to produce simulations in a relatively standard way and in a reasonable time.

## 5.2. The role of dispersion models in the frame of odour applications

Atmospheric dispersion models are a useful mathematical tool for connecting an emission source to a receptor, simulating the behaviour of the substance (gas or aerosol) and predicting its fate. This is achieved by using a set of differential equations that describe the mechanisms of transport, turbulent diffusion, chemical transformation, and soil deposition (dry and wet) involving the substances emitted into the atmosphere. By integrating these equations numerically (or analytically in the simplest cases) in time and space, it is possible to quantify the concentrations that are generated around and away from the emitter source / s.

The difficulty of solving this process completely and correctly is well known due to the uncertainties and approximations present in the input data (acquisition of three-dimensional fields of meteorological variables, definition of source terms, characterisation of the territory) and to the intrinsic stochastic variability of the turbulent dispersion processes that typify the atmospheric medium. However, this "dynamic" method of calculating the impact of a source is the only one that can guarantee a valid result (given a correct description of the variables involved): simplified statistical methods of correlation between concentration measurements and polluting sources are not able to take into account the atmospheric non-linearity, such as the variation of the wind direction, the sudden transition from stable to unstable conditions, chemical transformations involving different substances, etc...

For the study of odour emissions, we currently have models with different levels of complexity, which provide simulations that can be used to ensure control of their dispersion and impact on the territory. The validation and routine use of these models is possible thanks to the availability of adequate computing resources and three-dimensional meteorological data with increasingly higher spatial and temporal resolution.

In detail, dispersion models can be applied in many contexts:

- ➢ they are indispensable tools of knowledge to predict the impact for project not yet built: according to the emissions generated, it is possible to calculate the concentrations at the ground, to study the spatial distribution around the plant and their temporal variation (day / night, weekday / holiday, seasonal, climatic trend); with these studies it is possible:
  - to verify compliance with the parameters and / or thresholds imposed by current legislation, if existing;
  - to predict possible nuisances for the resident population in the vicinity of the plant in critical meteorological / emission situations;
  - if the project is not acceptable, solutions can be simulated that involve a different configuration of emissions;
  - to define the optimal configuration for the system (height of chimneys, dimensions of area sources, fugitive, etc.);

- ➢ for a plant or emitting source already present and functioning, the use of the models can provide an estimate of their impact on the territory, continuously (hour by hour) or at fixed times (monthly or annual evaluations), using adequate meteorological data (from measurements or 3D modelled field) and available emission estimates; in this way it is possible to:
  - verify compliance with the legislation according to the variation in emissions that occur in the management of the plant or during the occurrence of meteorological situations not foreseen in the preliminary impact assessment phase;
  - in the event of odour nuisance, help to understand its origin: if it is due to high emissions, to unfavourable dispersion conditions, to a complex flow field generated by buildings for example, etc...
  - simulate the changes in the impacts as a consequence of necessary or required evolutions to the plant structure;
  - having weather forecasts available, a modelling system can be usefully exploited to predict in advance critical situations for the dispersion of odours: this allows optimal management of the system through the activation of

containment measures (if possible) or the displacement of planned works, particularly critical for odour emissions, in the most favourable hours from a dispersive point of view, so as to guarantee the least possible disturbance for the workers and the resident population;

- use the system also in accidental situations and provide impact maps in a short time, useful during emergency interventions.

The direct "dynamic" simulation of the evolution of odour emissions makes it possible to separate the contributions of the different sources on the territory and to evaluate their differentiated impact over time and space; in the event that an emission includes several odorous substances, the separation of the effects can be calculated immediately in the case of chemically non-interacting substances (at least over a short time); in the presence of significant chemical reactions it is necessary to use models with source apportionment algorithms. In the case of simulations referring to the odour unit, the separation of contributions is not easily derivable.

The dispersion models can also be used for the estimation of the source term, in case this is difficult to quantify or even unknown: using meteorological and concentration measurements of a tracer distributed on a territory, it is possible to invert the integration and estimate the quantity that generated these concentrations; the procedure, like all inverse operations, is very critical (in particular in the absence of information on the location of the source) and sensitive to uncertainties in the initial measurements (meteorological and chemical), but can give important indications in dangerous situations ( e.g. reports of intense and unexpected odours by the population).

The use of models to support experimental campaigns to verify the environmental compatibility of a plant should be noted: in fact, some measurement techniques relating to odorous substances (electronic noses) are still uncertain and subject to debate; furthermore, the measurements refer to a point and the sensors are often expensive and cannot be distributed in large numbers on the territory, so the impact maps obtainable with the models can be used in synergy with the measurements (and with assimilation techniques for example) to obtain spatialised information on the whole territory.

The flexibility of the models allows exploratory analyses to evaluate the stability of the results as a function of the approximations of the input variables, it is possible to perform comparative studies between different emission scenarios or even change the expected site of the plant under study to optimise its position to obtain the least foreseeable impact.

The distinctive characteristic of the use of dispersion models for odorous substances basically lies in the need to have an assessment of the peak concentration, unlike atmospheric pollution where the preferred scale is the hour: in the case of olfactory disturbance, the time scale of interest is considerably lower, essentially on the order of the duration of a respiratory act.

It is, therefore, necessary to have models capable of determining not only the average odour concentrations, but also the concentration fluctuations.

# 5.3. General synthetic description of the dispersion algorithms

## 5.3.1. Introduction

The dispersion of air pollution both in urban areas and rural areas is of great concern to the scientific community. In the last few decades, normal levels of air pollution and odour have increased and many countries have started to focus on regulation and monitoring. Air quality models are an important management tool as they are able to predict pollutants (gases and particles) in the atmosphere. There are many different types of models and their performance depends on many different variables. The classification of models may refer to the source type (point, line, area, volume), the adopted scale (small or large), the input type (deterministic or stochastic), the dynamic conditions (steady or unsteady state), and the pollutant sources (gases or particles).

Dispersion models vary on the mathematics used, but they all require the same input data that include:

- meteorological conditions such as wind speed and wind direction, the amount of atmospheric turbulence, the ambient temperature, mixing height, cloud cover and solar radiation;
- source term – the emission rate of the pollutant being released;
- source characteristics such as the source location, height, type of source, exit velocity and temperature;
- terrain elevations and land use type; and
- the location, geometry (mainly height and width) of any obstructions in the path of the emitted plume.

Many of the modern, advanced dispersion model programs include pre- and post-processors for the input of meteorological and geophysical data as well as statistical modules for the plotting and tabulating of the pollutant's impact over a geographical area.

Among the models used in the world today for odour assessments Gaussian plume models are largely used together with Lagrangian puff and particle models. Both are able to estimate the downwind ambient concentrations of air pollutants from different source types. Lagrangian models work well for both homogenous and stationary conditions over flat terrain, and inhomogeneous and non-steady state conditions over complex terrain, while Gaussian models are ideally suited for homogenous conditions in flat terrain. Despite their simplicity, Gaussian plume models are still widely used in atmospheric dispersion modelling around the world, and most often for regulatory purposes because of their easy implementation and their near real-time response.

The technical literature on air pollution dispersion is quite extensive and dates back to the 1930s and earlier. The basic formulations are discussed below.

## 5.3.2. Evolution of basic models

Because computational power was low, early air pollution models were simplifications which could only solve first approximations, and could only simplistically describe the dispersion of chemically unreactive substances from a point source in a time-stationary and horizontally homogeneous meteorological and turbulent environment. In the last decade of the last century, it became evident that the passive scalar assumptions of the early simplistic models were not representative of the convective planetary boundary layer (PBL) (daytime and sunny hours with low/moderate wind). This led to the development of semi-empirical, Hybrid models in which the main elements that characterise the convective PBL were introduced. This allowed a more realistic reproduction of dispersion in these situations. However, the complex characteristics of nocturnal and highly stable situations in which turbulence coexists and interacts with a myriad of wave motions and meandering was totally ignored in these early models.

A common feature of the early Gaussian plume and Hybrid models is that they both assumed quasi-stationary situations and horizontally homogeneous computational domains, and were a gross simplification of reality. It was inevitable that the simulations they produced were nothing more than a rough estimate of the mean concentration fields downwind of ideal sources that were essentially point-like in conditions far from high convectivity, and of medium-high stability. Today, these models are considered screening models and are suitable for providing the order of magnitude of the impact of a given source.

One of the early air pollutant dispersion equations was derived by Bosanquet, 1936. This early formulation did not assume a Gaussian distribution nor did it include the effect of ground reflection of the pollutant plume. However, by 1947, Sir Graham Sutton derived an air pollution plume dispersion equation (Sutton, 1947) which did include the Gaussian distribution assumption for the vertical and crosswind dispersion of the plume and also included the effect of ground reflection of the plume. This early Gaussian equation came at the time of the industrial revolution when there was a need to have numerical tools to simulate the dispersion of pollutants emitted in the PBL from industrial sources. Under the stimulus provided by the advent of stringent environment control regulations, there was a growth in the use of air pollutant plume dispersion calculations and early models from the late 1960s until today. The basis for most of these early models was the Gaussian equation which was considered the complete equation for Gaussian dispersion modelling of continuous, buoyant air pollution plumes provided in two well-known publications, (Turner, 1994) and (Beychok, 2005). The equation is:

$$C=\frac{Q}{u}\frac{f}{\sigma_y\sqrt{\square}_{\square}}$$

where

$f=\exp\left(\frac{-y^2}{2\sigma_y^2}\right)$ is the crosswind dispersion parameter

$g = g_1 + g_2 + g_3$ is the vertical dispersion parameter

$g_1=\exp\left[\frac{-\left(z-H_e\right)^2}{2\sigma_z^2}\right]$ is the vertical dispersion with no reflections

$g_2 = \exp\left[\frac{-(z+H_e)^2}{2\sigma_z^2}\right]$ is the vertical dispersion for reflection from the ground

$g_3 = \sum_{m=1}^{\infty} \exp\left[\frac{-(z-H_e-2mL)^2}{2\sigma_z^2}\right]$ is the vertical dispersion for reflection from an inversion aloft

C is the concentration of pollutant, in g/m$^3$, at any receptor located:

- X metres downwind from the emission source point
- Y metres crosswind from the emission plume centerline
- Z metres above the ground level

Q is the pollutant emission rate, in g/s

u is the horizontal wind velocity along the plume centreline, in m/s

$H_e$ is the height of the emission plume centerline above ground level, in m

$\sigma_z$ is the vertical standard deviation of the emission distribution, in m

$\sigma_y$ is the horizontal standard deviation of the emission distribution, in m

L is the height from the ground level to the bottom of the inversion aloft, in m

exp() is the exponential function

The above equation includes the upward reflection from the ground and the downward reflection from the bottom of the inversion lid present in the atmosphere.

The sum of the four exponential terms in $g_3$ converges to a final value quite rapidly. For most cases, the summation of the series with m=1, m=2 and m=3 provided an adequate solution.

$\sigma_z$ and $\sigma_y$ are functions of the atmospheric stability class, i.e., a measure of the turbulence in the atmosphere and of the downwind distance to the receptor. The classification of atmospheric stability was first presented by Pasquill (Klug, 1984) who proposed 6 atmospheric stability classes (describing atmospheric conditions from the most to the least dispersive) which are referred to as:

- A – extremely unstable
- B – moderately unstable
- C – slightly unstable
- D – neutral
- E – slightly stable
- F – moderately stable

The above Gaussian plume equation required the input of the pollutant plume centreline height above ground level $H_e$, which is the sum of $H_s$ (the actual physical height of the emission point) plus $\Delta h$, the plume rise due to the plume's buoyancy, if any. To determine

Δh many of the dispersion models developed between the late 1960s and the early 2000s used the ‘Briggs equations’ (Briggs, 1965). (Briggs, 1968) compared many of the plume rise models that were available at that time and in that same year he wrote a comparative analysis of plume rise algorithms in a publication published by the US Air Resources Laboratory (Slade, 1968). (Briggs, 1969) wrote a critical review of all the available plume rise literature. In this review Briggs proposed a set of plume rise equations which have become widely known as the ‘Briggs’ equations; these equations were subsequently modified by the same author (Briggs, 1971) and (Briggs, 1972). The ‘modified’ Briggs plume rise equations are still employed in many popular worldwide regulatory air pollution models.

### 5.3.3. Current form of Gaussian plume models

The current form of the standard Gaussian plume model is based on a simple formula that describes the three-dimensional concentration field generated by a point, volume or area source under stationary meteorological and emission conditions, and for concentrations on the ground is expressed by (e.g., (Zannetti, 1990), (Turner, 2020)).

$$C(x,y,0)=\frac{Q}{\pi\sigma_y\sigma_z u}\exp\left[\frac{-1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]\exp\left[\frac{-1}{2}\left(\frac{H_e}{\sigma_z}\right)^2\right]$$

Where C is the concentration of gas or aerosols (generally particles less than about 20 microns) at x, y, z=0 due to a continuous emission with an effective emission rate Q. $H_e$ is the height of the plume centreline when it becomes level, and is the sum of the physical stack height $H_s$ and the plume rise Δh. The following assumptions are made:

- The plume spread has a Gaussian distribution in both the horizontal and vertical planes with a standard deviation of plume concentration distribution in the horizontal and vertical of $\sigma_y$ and $\sigma_z$, respectively.
- The mean wind speed affecting the plume is u.
- The uniform pollutant emission rate is Q.
- The total reflection of the plume takes place at the earth’s surface, i.e., there is no deposition or reaction at the surface.

Figure 5-1 shows a schematic figure of a Gaussian plume. The effective stack height $H_e$ and the crosswind ($\sigma_y$) and vertical ($\sigma_z$) deviation of the profile are the key parameters of the model.

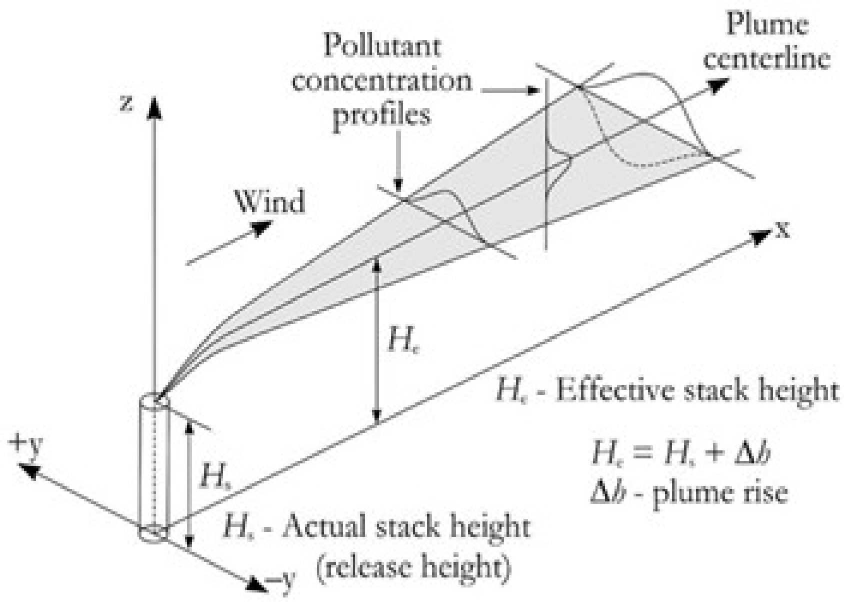



**Figure 5-1** Schematic figure of a Gaussian plume (Leelossy et al. 2014)

The main important assumptions of Gaussian plume models are:

- The horizontal meteorological conditions are homogenous over the space modelled. For each step modelled, the wind speed and wind direction, temperature and mixing height is constant.
- There is no wind shear in the horizontal or vertical plane.
- The pollutants are non-reactive gases or aerosols.
- The plume is reflected at the surface and aloft with no deposition or reaction with the surface.

## 5.3.4. Lagrangian models

### 5.3.4.1. Overview

Lagrangian models provide an alternative method for simulating atmospheric diffusion. They are called Lagrangian because they describe the fluid elements that follow the instantaneous flow. According to (Zannetti, 1990) the 'Lagrangian' term was initially used to distinguish between the Lagrangian box models that follow the average wind trajectory, from the Eulerian box models which do not move. Today, however, the term Lagrangian has been extended to describe all models in which plumes are broken up into segments, puffs or fictitious particles whose behaviour is followed along the mean flow.

$$C(r,t)=\int_{-\infty}^{t}\int p(r,t \vee r',t')S(r',t')\,dx'\,dt'$$

Where the integration in space is performed over the entire atmospheric domain, and

C(r,t) is the ensemble average[2] concentration at r at time t;
S(r',t') is the source term (mass volume$^{-1}$ time$^{-1}$);
p(r,t|r',t') is the probability density function (volume$^{-1}$) that an air parcel moves from r' at t' to r at t, where for any r' and t',

$$\int p(r,t \vee r',t')\,dr \leq 1$$

The expression above can be less than one when chemical or depositional phenomena are considered; otherwise, mass conservation always requires the value to be equal to one. For a primary pollutant, (pollutant emitted directly from a source), S(r',t') is greater than zero only at points where the pollutant is released (e.g., exit points of stacks). For a secondary pollutant (pollutant formed when primary pollutants react in the atmosphere), S(r',t') can be non-zero virtually anywhere. For both primary and secondary pollutants, however, the equation above which represents mass conservation must be satisfied.

The Lagrangian approach is more ideally suited to simulating diffusion and chemical reactions over short distances, e.g., tens of metres, (Scire, 2000b) from all source types, to very far downwind distances, e.g., hundreds of kilometres, (Lamb, 1979). Lagrangian models require no grid network, and can have as few or as many receptor points as required which can be arbitrarily distributed in any configuration over the area of interest. The absence of a grid network and of finite differencing schemes makes the computational process of modelling dispersion over elevated and complex terrain relatively simple. In addition, the Lagrangian approach is essentially free of the assumptions that hinder the plume model and they can explicitly account for wind shear, particle settling, deposition and resuspension, calm winds, and time and space variability in the meteorology or source emission conditions. The temporal evolution of the dispersion is also properly simulated, and complex Lagrangian models can treat chemical transformations. In addition, Lagrangian models can employ readily measurable Eulerian turbulence statistics such as the variances of the velocity fluctuations, or, use more common Lagrangian statistics like the sigma (σ) parameter.

#### 5.3.4.2. Particle vs Puff Lagrangian approach

Compared to Eulerian models discussed below, the Lagrangian approach is grid-free, and it follows at all scales, the motion of individual plume parcels, whose paths are modelled based on a random walk process. The Lagrangian approach describes all phases of dispersion with the same accuracy, and very importantly the near-field or near-source region, where most odour complaints generally occur. In Lagrangian particle models, the dispersion of the airborne pollutants is simulated through fictitious particles, each containing a small amount of the emitted tracer mass. These particles are small enough to move according to the smallest eddies and are also large enough not to be influenced by the viscosity. The local wind drives their mean motion and the diffusion is determined by velocities obtained as the solution of Lagrangian stochastic differential equations, providing the statistical characteristic of turbulent flows. Different portions of the emitted plumes can

[2] The ensemble average of a stochastic process (random variable) is analogous to an expected value. That is, given a large number of trials, it is the 'average' waveform that would result from a stochastic process. This means that an ensemble average is a function of the same variable that the stochastic process is.

experience different atmospheric conditions, allowing a realistic reproduction of the complex atmospheric phenomena that can occur in coastal and mountainous areas. The concentration is calculated by counting particles in a box. The Lagrangian particle model releases for each iteration a number of fictitious particles from any source within a model domain (see for example Figure 5-.2). The particles on the domain statistically represent the turbulent transport and simulate the pollutants' plume growth.

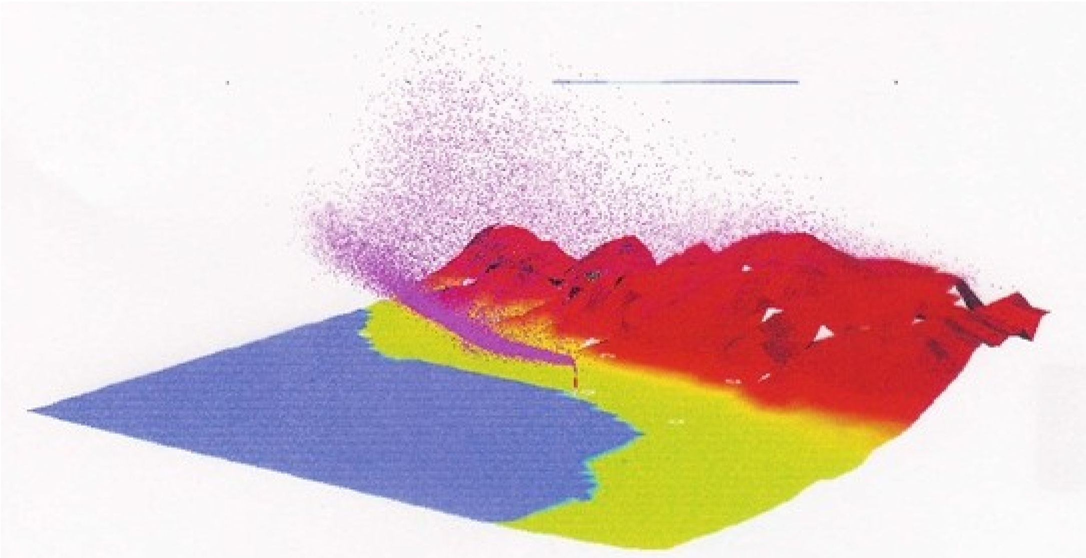


**Figure 5-2** Schematic figure of a Lagrangian particle dispersion model (courtesy of ARIANET).

Lagrangian puff models, on the other hand, represent a continuous plume as a number of discrete packets of pollutant material (see Figure 5-3). Most puff models (e.g. : (Ludwig, 1977), (van Egmond, 1983), (Peterson, 1986)) evaluate the contribution of a puff to the concentration at a receptor by a 'snapshot' approach. Each puff is 'frozen' at a particular time interval (sampling step). The concentration due to the 'frozen' puff at that time is computed (or sampled). The puff is then allowed to move, evolving in size, strength, etc, until the next sampling step. The total concentration at a receptor is the sum of the contributions of all nearby puffs averaged for all sampling steps within the basic time step, which is usually an hour.

The basic formulation for modern-day puff models which use an integrated puff sampling function can be explained in the equations below for the contribution of a puff at a receptor is:

$$C=\frac{Q}{\pi\sigma_x\sigma_y}g\exp\left(\frac{-d_a^2}{2\sigma_x^2}\right)\exp\left(\frac{-d_c^2}{2\sigma_z^2}\right)$$

$$g=\frac{2}{\sqrt{\square}}$$

Where
C is the ground-level concentration (g/m$^3$)
Q is the pollutant mass (g) in the puff,
$\sigma_x$ is the standard deviation (m) of the Gaussian distribution in the along-wind direction,
$\sigma_y$ is the standard deviation (m) of the Gaussian distribution in the cross-wind direction
$\sigma_z$ is the standard deviation (m) of the Gaussian distribution in the vertical direction
$d_a$ is the distance (m) from the puff centre to the receptor in the along-wind direction,
$d_c$ is the distance (m) from the puff centre to the receptor in the cross-wind direction,
$H_e$ is the effective height (m) above the ground of the puff centre,
g is the vertical term (m) of the Gaussian equation, and
h is the mixed-layer height (m).

The summation in the vertical term g accounts for multiple reflections off the mixing lid and the ground. It reduces to the uniformly mixed limit of 1/h for $\sigma_z$ > 1.6 h. In general, puffs within the convective boundary layer meet this criterion within a few hours after release. Therefore, for a horizontally symmetric puff with $\sigma_x = \sigma_y$, the equation reduces to:

$$C(s) = \frac{Q(s)}{2\pi\sigma_y^2(s)} g(s) \exp\left[\frac{-R^2(s)}{2\sigma_y^2(s)}\right]$$

Where R is the distance (m) from the centre of the puff to the receptor and s is the distance (m) travelled by the puff. The distance dependence of the variables is indicated, e.g., C(s), $\sigma_z(s)$ etc. Integrating this equation of the distance of puff travel, ds, during the sampling step, dt, yields the time-averaged concentration, $\underline{C}$ described below as

$$\underline{C} = \frac{1}{ds} \int_{s_0}^{s_0+ds} \frac{Q(s)}{2\pi\sigma_y^2(s)} g(s) \exp\left[\frac{-R^2(s)}{2\sigma_y^2(s)}\right] ds$$

Where $s_0$ is the value of s at the beginning of the sampling step. An analytical solution to this integral can be obtained if it is assumed that the most significant s-dependencies during the sampling step are in the R(s) and Q(s) terms.

The horizontal dispersion coefficient, $\sigma_y$ and the vertical term, g, are evaluated and held constant throughout the trajectory segment. At mesoscale distances, the fractional change in puff size during each sampling step is usually small, and the use of the midpoint values of $\sigma_y$ and g is adequate. This assumption reduces the number of times that the dispersion coefficients and vertical reflection terms need to be computed to one sampling step, but may not be appropriate in the near-field where the fractional puff growth rate can be rapid. These models have gotten around this by integrating the sampling function with receptor-specific values of $\sigma_y$ and g, evaluated at the point of closest approach of the puff to each receptor.

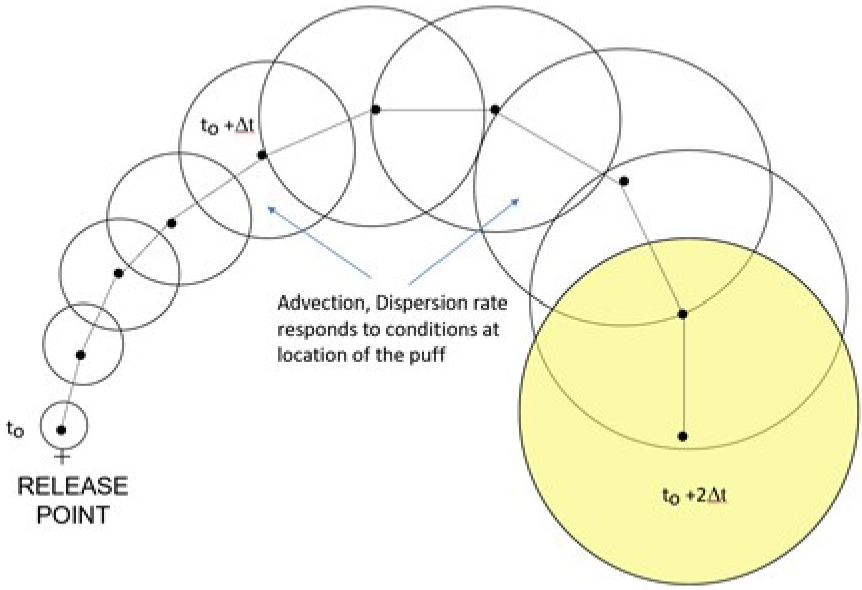



**Figure 5-3** Schematic figure of a Lagrangian puff dispersion model (Courtesy of Atmospheric Science Global).

#### 5.3.4.3. Particle-Puff Lagrangian approach

This approach typically uses a Gaussian puff solution in the terrain following horizontal direction and a particle solution for the vertical coordinate. The method allows a particle/puff to influence more than one horizontal grid point and so the total number of particles needed for a model run is reduced. The dispersion simulation still accounts for height-varying values of winds and turbulence in the same way as conventional particle models. There are not many models of this type and there is very little in the literature on their use in odour modelling. The main aim of these models was to reduce the number of particles, memory and computer time when compared to a regular particle model. It is understood that models of this type typically use an analytic puff solution of the Langevin equation for stationary, homogeneous, Gaussian turbulence, which agrees exactly with the full Langevin equation solution when these conditions on the turbulence are satisfied in the horizontal directions. The puff centroid is advected by the mean winds and is acted upon by the wind shear and turbulence in the vertical direction, but horizontal diffusion is included by assuming a lateral Gaussian concentration distribution with standard deviation $\sigma_y$. The approximation assumes horizontal wind shear is negligible, which is acceptable when the puffs are small, but is likely to break down as puffs increase in horizontal extent. Generally, these models do well in reproducing normal particle models in the convective boundary layer, except for where there is significant horizontal wind shear. In addition, (Hurley, 1994) found the Particle-puff approach has an advantage over puff models in that it can realistically handle the vertical structure of the atmosphere through the Langevin equation for the vertical coordinate, and does not require the complex vertical boundary conditions used by puff models to account for reflection at the ground and the mixing height. In particular, skewed turbulence can easily be accounted for in the convective boundary layer and well-mixed conditions in the vertical can be represented without complex Gaussian puff image sources. In addition, the particle/puff is able to handle vertical variations of wind and turbulence in the same way as existing particle models.

#### 5.3.4.3. Lagrangian models and odour

The Lagrangian approach is much more ideally suited to modelling odours than steady-state Gaussian plume models. They are ideally suited for modelling the very near field from a few tens of metres out to hundreds of kilometres. In addition, modelling dispersion around elevated and complex terrain is relatively simple, and they can model calm events which are usually the worst-case odour conditions. When linked to diagnostic and or numerical model-derived 3-dimensional meteorology they can produce very reliable model results for odour assessments.

Lagrangian particle models have been successfully used to calculate direction-dependent separation distances to avoid odour annoyance (Piringer, 2016) and to perform better in complex terrain environments (Baumann-Stanzer, 2015). The Lagrangian approach did much better reproducing the physical processes and generally calculated larger separation distances compared to the Gaussian model applied in their study. The Lagrangian approach is also routinely and successfully used for most odour assessments in Australia and New Zealand and is the preferred regulatory odour model in those countries, as limitations of the Gaussian plume model for odour assessments are generally well recognised.
Currently, Lagrangian models like Gaussian plume models also assume a 1-hour time-averaged distribution in the plume, which does not fully account for the turbulent odour concentration fluctuations, which is on the order of seconds, nor the meander of the plume from the mean direction. Similarly to Gaussian plume models, it has been normal practice around the world in odour assessments using Lagrangian models to apply Peak-to-Mean Ratios to try and account for the short-scale concentration fluctuations. Peak-to-Mean Ratios are a simple 'stand-alone' formula to estimate the concentration fluctuation intensity. They assume that the concentration fluctuation intensity completely defines a probability density function. Their use is required in different parts of the world (see for example Brancher et al., 2017), considering concentrations at different averaging time intervals from 1 hour to 1 second as in the assessment criterion in in New South Wales, Australia (NSW Approved Methods, 2022)

However, recent research by (Ferrero & Öttl, 2019) and (Ferrero et al., 2020) show that concentration fluctuation can be obtained directly from the Lagrangian approach. This new research is discussed in Section 7.8 (A window open on the research).

### 5.3.4. Eulerian models

Eulerian models (Figure 5-4) utilise a fixed reference grid, as opposed to the moving grid of the Lagrangian model, to describe the dispersion of emitting sources. The Eulerian models integrate the general form of the advection-diffusion equation following (Collett, 1997) and (Reed, 2005):

$$\delta < c_i > \frac{¿}{\delta t} = -U \vee . \nabla < c_i > - \nabla . < c_i ' U ' > + D \nabla^2 < c_i > + ¿ S_i > ¿¿$$

Where:
U = Windfield vector U(x,y,z), U = U| + U'
U| = average wind field vector
U' = fluctuating wind field vector

$c_i$ = concentration of pollutant for $i^{th}$ species, $c = \langle c \rangle + c'$
$\langle c \rangle$ = average pollutant concentration, where $\langle\ \rangle$ denotes average
$c'$ = fluctuating pollutant concentration
D = molecular diffusivity
$S_i$ = source or sink term (chemical reactions should be taken into account)

The terms $U|.\nabla\langle c_i \rangle$, $\nabla\langle c'_i U \rangle$, and $D\nabla^2\langle c_i \rangle$ represent the rates of advection, turbulent diffusion, and molecular diffusion, respectively. For most cases, the wind field vector U is considered turbulent and requires average and fluctuating wind field vector components. The previous equation is numerically solved on a fixed grid at discrete time steps to give the behaviour in time and space of the concentration of the $i^{th}$ species. Eulerian models can describe the fate of any pollutant, even if this is not directly emitted into the computational domain, considering the intrusion through the upper and lateral boundaries. Once the initial and boundary conditions are given, Eulerian models can describe the time and space behaviour of the air quality inside a certain volume, allowing in a relatively natural way to implement also chemical transformations involving all the species considered in a simulation. For this reason, Eulerian models are more often used as the computing core of air quality forecasting systems at a regional scale.

The difficulty of Eulerian models to describe the dispersion in the near field makes this approach not very suitable for odour assessments. In practice, this method is rarely used in this field.

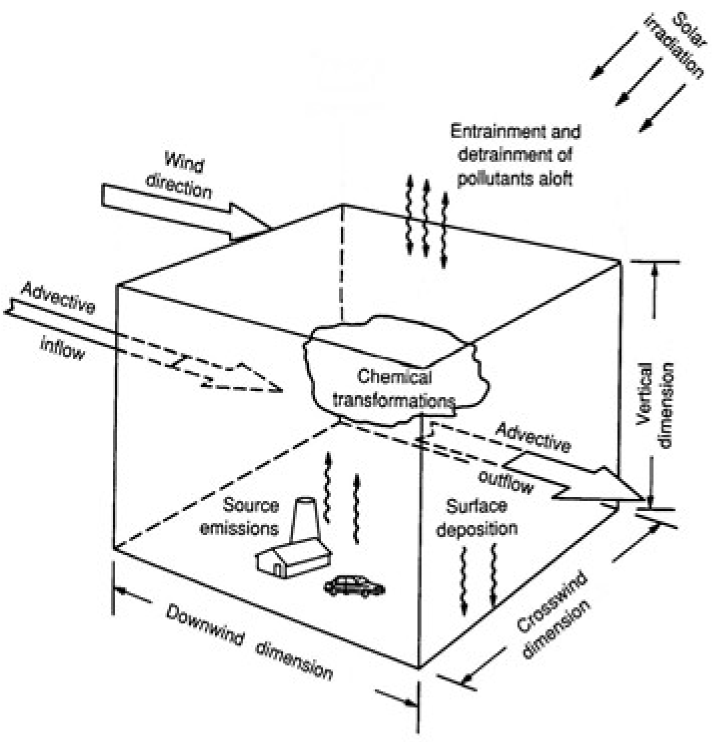



**Figure 5-4** Schematic figure of an Eulerian dispersion model (source: (NOAA, 2008)).

## 5.3.5. Computational Fluid Dynamic (CFD) Models

Computational fluid dynamic (CFD) models are becoming increasingly useful in the field of odour assessments (Lin, 2009). CFD models can predict how a fluid will flow in a given situation and can model airflow and pollutant dispersion in unstable and stable atmospheric conditions or where nearby structures cause localised turbulence. Odour facilities are frequently located in industrial areas or are themselves surrounded by structures, trees and commonly, hedges, popular with animal husbandry facilities. CFD models can calculate the properties such as flow patterns, pressure losses and temperature distribution, which are then used to predict how air pollutants will behave. CFD models are also becoming increasingly popular with complicated odour-producing facilities as they are ideally suited to very near-field modelling in adverse situations (Lin, 2007a). These models are especially useful in designing and optimising heating, ventilating and industrial extraction systems from large poultry and piggery barns. In addition, windbreaks have been found to improve odour dispersion and help reduce setback distances (Panofsky, 1984). According to (Lin, 2006) (Lin 2007b), a natural windbreak with an optical porosity of 35% reduced, on average, the maximum odour dispersion distance by 20% compared to a site without a windbreak.

CFD models (Figure 5-5) have advanced significantly in the last decade, primarily due to the advancing power of computational hardware and software. CFD simulations have the potential to yield more accurate solutions than other methodologies because they are a solution of the fundamental physics equations and include the effects of detailed three-dimensional geometry and local environmental conditions.

According to the US EPA (Huber, 2004), one of the key roles of CFD simulations for all air quality applications, including odour, is that CFD simulations should be shown to be comparable with simple proven air dispersion models which are being reliably applied today in routine air quality studies. (Huber, 2004) consider this critical to demonstrate that the complex numerical techniques part of CFD software are well-behaved under simple conditions. The US-EPA encourages users not to use CFD software to support studies where simple analytical studies are possible and instead to use CFD applications for complex conditions where the simple analytical solutions are not appropriate.

For odour applications, CFD models cannot be used as regulatory tools. These models are complex, easily influenced by user choice of boundary conditions, grid resolution and structure and can simulate just one atmospheric condition at a time.

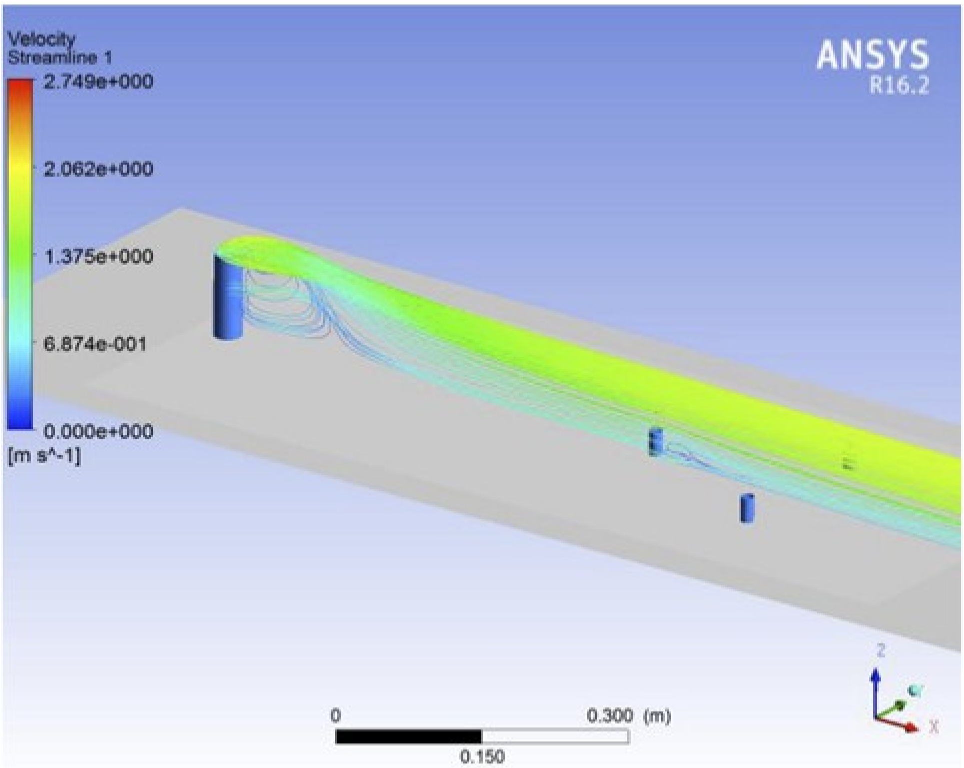



**Figure 5-5** Schematic figure of a CFD model (source: Brusca, 2008).

# 5.4. Operational existing models

## 5.4.1. Introduction

It is typical for the US, Europe and other countries to have preferred and/or recommended dispersion models for regulatory air quality assessments. These 'preferred' models are primarily used to determine compliance with a state or countries' National Ambient Air Quality Standards (NAAQS). It is normal for these air quality models to be used on both existing sources and new sources. These models are often associated with strict guidelines such as the 'Guideline on Air Quality Models' (US-EPA, 2017) in the US and the European Air Quality Directive (Denby, 2010). The guidelines themselves are periodically revised to ensure that any new model developments or expanded regulatory requirements are incorporated. These models are normally available from the regulatory site website or the developers' home website. Some of these models are open-source (users can view and access the code), and others are closed-source. In the US, 'open source' models are usually guideline models that have undergone a lengthy third-party review process. Typically, US guideline models:

- are pre-approved for designated uses in regulatory applications,
- have undergone an extensive, multi-year model assessment and evaluation process,
- have been evaluated relative to observations,
- are associated with free user access to all model documentation and codes,
- have undergone significant public review process at public hearings
- are associated with formal peer review committees created by the US EPA and other professional organisations such as AWMA, and private industry groups API and

EPRI

Because of this lengthy, costly and thorough process to become a guideline model, US EPA endorsed dispersion models quickly find themselves regulatory models in other countries who are comfortable with the significant effort put in by the US, where it can often take 20 or more years for a model to reach guideline status. In the US and in countries that employ US guideline models as their own tend to use these 'preferred' regulatory models regardless of whether they are inherently suitable for modelling odours or not. It is important that for regulatory applications in the US, there is a balance between the technology employed by the model and its ability to be utilised efficiently, cost-effectively, and be readily reviewed by the local authority. Many countries have followed this approach and as a result, the US regulatory models are routinely and much more frequently used for odour modelling all over the world, than any other model, regardless of their suitability. In Europe, Australia and New Zealand US guideline models do not carry as much weight in odour modelling where users are able to apply more sophisticated Lagrangian puff and particle models. In Europe, this might be multiple advanced country-specific developed particle models. A consequence of this is that these sophisticated 'odour' models are not as well known outside of Europe, and therefore are not widely used amongst the international odour community.

The following sections below discuss those dispersion models that are commonly used for odour assessments. These models range from simple screening models (AERSCREEN, ADMS-SCREEN, SMOD) to advanced Gaussian plume models (ADMS, AERMOD, ARIA Impact, AODM), to Lagrangian particle (SPRAY, AUSTAL, LAPMOD, GRAL, QUIC) and puff models (CALPUFF, SCIPUFF) and finally Eulerian and CFD models (CODE_SATURNE, FLOW 3D). Eulerian models are discussed, but in a limited sense, as there is little literature on their use in odour modelling. Discussion on CFD models is included as they have been very beneficial in assessing the impact of odours in adverse environments, such as complicated building structures (Tomasello, 2019), or in considering the effect of natural vegetation boundaries on odour (Jin, 2007a) and pollution (Santiago, 2019) dispersion.

Commonly used odour dispersion models are discussed in this next Section. For each model, there is a brief discussion provided on the evolution, development and key algorithms of the model, plus whether the model is regulated for odour assessments and who is using it. In addition, whether the model can manage odour units, concentration fluctuations, treatment of calms and odour concentration outputs, in so far as percentiles, exceedances, and comparison to odour criteria, is also considered.

## 5.4.2. Screening models – simple models and empirical equations

### 5.4.2.1. Screening Models

Screening models will typically produce estimates of 'worst-case' 1- hour concentrations for a single source without the need for an hourly year-long meteorological data set, detailed terrain or land use. Simple conversion factors usually allow estimation of 3-hour, 8-hour, 24-hour and annual concentrations. A principle key aim of screening models is that they are intended to produce concentration estimates equal to or greater than the estimates by a regulatory model with a fully developed set of meteorological and terrain data.

Typically, in the US, it is typical for a screening model to be a 'lighter' version of the main regulatory model. Examples of this are:

- AERSCREEN, the screening version of AERMOD
- CTSCREEN, the screening version of CTDMPLUS
- SCREEN3, the screening version of ISCST3

While the European Union (van Aalst, 1998) does not list a set of screening models, it does endorse the use of screening methods and says:

"*Particularly for first screening purposes, or in case of limited input information, the use of simple models may be appropriate… If initial screening leads to the conclusion that levels may be of the order of the limit values, more sophisticated models should be selected*".

In Annex 5.1 'Urban Dispersion models' found in the European Air Quality Directive, the EU provides a list of hand calculations to estimate: A. Area source model, B. Elevated point source, C. Street Canyon, and D a Highway. For each source type of A, B or C, the EU provides the equations for estimating the 1-hour average air concentrations at an arbitrary receptor using simplified expressions of the ATDL urban diffusion model after (Hanna, 1972) and (Gifford, 1973) for A and a simplified Gaussian relationship for B. These equations are to be used anywhere in Europe and are not site or country specific.

In addition, the EU has examples where local environmental agencies have recommended locally adapted dispersion tools in some geographical areas in combination with meteorological data for calculating odour concentration. This simplifies the application of advanced dispersion modelling because no specific meteorological knowledge is needed to run them. Examples of these simplified screening models include SMOD (Screening model for odour dispersion) used for planning and informative purposes of licencing procedures in the German province of North Rhine (Hartmann, 2007; Janicke, 2007). Another European screening model is the Gaussian plume model, V-STACKS (Steyn, 1978) model in the Netherlands, and in Manitoba, Canada (Manitoba, 2008) look-up tables have been recently developed based on AERMOD simulations. These screening methods are examples of an integral part of locally adapted solutions and are not easily transferred to other regions.

The US EPA currently supports several screening models; AERSCREEN, CAL3QCH, COMPLEX1, CTSCREEN, RTDM3.2, SCREEN3, TSCREEN, VALLEY and VISCREEN, but only one or two of these is of any use for odour assessments. Of these models, SCREEN3 is one of the oldest and most well-known screening models, written in 1995 and updated in 2013. Like other screening models, SCREEN can simulate a single source in short-term calculations. The model includes the effects of downwash and can estimate concentrations due to inversion break-up and incorporate the effects of simple terrain. SCREEN examines various meteorological conditions, including all stability classes and wind speeds. SCREEN is seldom used in the field, and there is no history or literature on its use in odour assessments. Many algorithms (building downwash and dispersion coefficients) have been superseded in advanced Gaussian models such as AERMOD. Therefore there is more likelihood that AERSCREEN will be used for odour assessments.

AERSCREEN (US-EPA, 2021), like SCREEN, is an interactive command-prompt application that interfaces with MAKEMET, which is a processor for generating a meteorological matrix, as well as interfaces to AERMOD's AERMAP (terrain processor) and BPIPPRM for processing building information. AERSCREEN will use user-defined single values for albedo, Bowen ratio and surface roughness and can model inversion break-up fumigation and shoreline fumigation. Like SCREEN3, the model does not contain input and output odour-specific information. AERSCREEN will build a matrix of meteorological hours based on the minimum wind speed and ambient minimum and maximum temperatures. This approach ensures that the model captures poor dispersion. The benefits of a screening model like AERSCREEN are that it can assess the potential worst-case impact of a known odour, such as naphthalene (ORION, 2019), where the emission rate is known. The model will compute the odour concentration at various discrete distances downwind, for instance, at the property boundary, the nearest off-site sensitive receptor, and the nearest residence. The model uses local terrain information and generated meteorological data to compute worst-case conditions. The model also assumes continuous emissions. If these results are generally below the appropriate short-term odour criteria levels, then no more work is usually needed. This saves time and money for a full-blow dispersion model assessment, likely producing lower results. However, screening models are unsuitable for complex odour emission scenarios, typical of most activities.

Another well-known Gaussian screening model is ADMS-Screen (CERC, 2021). ADMS-Screen models' dispersion from a single stack to calculate ground-level concentrations, providing rapid assessments of stack height. The model can compare predicted concentrations with air quality strategy objectives. The model has the option to include the effects of a single building. ADMS-Screen uses the ADMS dispersion code, including the ADMS Mapper, for GIS visualisation and editing. ADMS-Screen is used to assess the impact of point source emissions quickly.

A summary of AERSCREEN and ADMS-Screen is provided in Table 5-1. Both these models, whilst screening models, still require substantial input and are unsuitable for use in the field. These models are only recommended for a quick, 1-hour, worst-case assessment of a known odorant. They are not suitable for assessing a complex mix of odour compounds where the emission rate is largely unknown; they are also inappropriate for comparing the model output with odour criteria using percentiles. They are also not fit to assess exceedances of an odour impact criteria. They cannot assess concentration fluctuation internally and would require external processing to apply a PtMR, hedonic tone, or to compute a < 1-hour average. In addition, neither model allows odour-specific emission inputs and output odour concentration. In addition, there is little information in the literature concerning the use of screening models for odour assessments.

**Table 5-1** Well-known screening dispersion models, AERSCREEN and ADMS-SCREEN, used for odour applications

| Parameter | AERSCREEN | ADMS-SCREEN |
|---|---|---|
| Meteorology | Non-sequential meteorological data file representing a matrix of conditions derived from specific details concerning ambient minimum and maximum temperature, min wind speed (default 0.5 m/s) and anemometer height. Processor will generate approximately 300-400 hours. Wind direction is set at 270$^{o}$. | Standard ADMS format meteorological files or on-screen meteorological input. UK statistical met data suitable for screening modelling is available from CERC |
| Pre-processor | AERMINUTE, AERMET and AERMAP for terrain elevations | ADMS meteorological processors |
| Terrain and Land use | Interface to AERMAP for source and receptor heights, single value to characterise dominant land use | No land use inputs and assumes flat terrain |
| Surface characteristics | Single value for Bowen ratio, surface roughness, seasonal tables | None |
| Building downwash | Interface to BPIPPRM | Single building effects are considered |
| Receptors | Flagpole receptors, up to 10 discrete receptors in a user file, use terrain heights from AERMAP | Cartesian grid, specified discrete receptors |
| Dispersion | Turbulence based dispersion coefficients, urban/rural dispersion option | Turbulence based dispersion coefficients, urban/rural dispersion option |
| Boundary layer structure | h, $L_{MO}$ scaling | h, $L_{MO}$ scaling |
| Plume Rise | Briggs empirical equation | Briggs empirical equation |
| Concentration distribution | Gaussian | Gaussian |
| Partial Penetration | Plume fumigation due to inversion break-up | Plume fumigation due to inversion break-up |
| Coastal effects | Shoreline fumigation of plume | none |
| Source type | Point, area and volume source | Point source only |
| Odour unit inputs and outputs | no | no |
| Emission rate | Only in lb/hr or g/s. Odour emission rate will need to be modified to comply with model input requirements | Only in g/s. Odour emission rate will need to be modified to comply with model input requirements |

| Parameter | AERSCREEN | ADMS-SCREEN |
|---|---|---|
| Output | Plume centreline maximum ground level concentrations.<br>Not suitable to compute percentiles or exceedance data | Not suitable to compute percentiles or exceedance data |
| Averaging period | 1hr, 3hr, 8hr, 24 hr and annual | 1hr, 24hr, annual and percentiles |
| Concentration fluctuation | No | No |
| Pollutant type | Ideally suited to computing worst case concentrations from a known measurable odour such as $H_2S$, or a single odour chemical compound such as naphthalene | Ideally suited to computing worst case concentrations from a known measurable odour such as $H_2S$, or a single odour chemical compound such as naphthalene |

#### 5.4.2.2. Empirical Equations for assessing separation distances

There are other screening tools such as empirical equations (EQs) that are frequently used in Europe (e.g., Brancher, 2020a; Schauberger, 2012a) primarily for livestock buildings to determine separation distances between an odorous facility and nearby sensitive receptors. In Europe and elsewhere, separation distances are generally determined by two steps:

1. calculation of the odour exposure as a timeseries of odour concentrations using dispersion models, and
2. determining the separation distances through the evolution of the odour exposure by the odour impact criteria.

(Brancher, 2020a) noted that simple EQs deliver a unique, fixed distance circle around the source, while advanced EQs which include meteorological predictors such a wind frequencies and mean wind velocities within direction sectors, result in separation distance shapes that have been derived from regression analyses of dispersion model equations. (Brancher, 2020a) showed the difference between the German VDI (Schauberger, 2012a; VDI 3984, 2012) and Austrian (Schauberger, 2012b) shapes where the meteorology of the site is defined by wind statistics as determined by the frequency of wind direction for each 10-degree sector, compared to simpler EQs.  Another comparative analysis between the German and the Austrian empirical equations has been described by (Wu, 2019). Figure 5-6 shows the shapes of separation from five EQs for a livestock building of 22,500 ouE/s. The prevailing wind direction at the site was from the WSW and ENE. The comparison shows the impact of meteorology on the separation distances calculated by the EQs.  The German and the Austrian EQs, include the wind statistics from the site, the Belgian EQ (Nicolas, 2008) uses a rough parameterisation for the prevailing wind direction, the Purdue EQ (Lim, 2000) uses the wind frequency of 45-degree sectors, and the W-T EQ (Williams, 1986) does not consider the wind frequency as a predictor.  Australia (State of Victoria) (EPA Victoria, 2013) and New Zealand (Auckland City Council, 2012), set a minimum distance criterion for certain industry types. This has the same effect as the W-T EQ which sets a circle around the site. Figure 5-6 shows that the W-T EQ is unsuitable to describe the meteorological situation of the dilution and overestimates the separation distance for several wind directions.

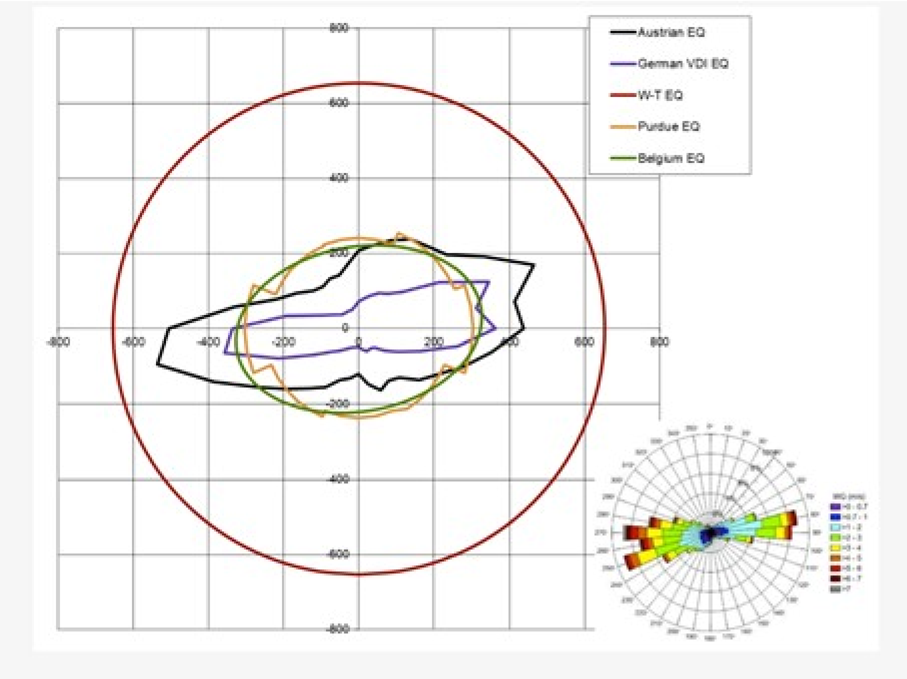



**Figure 5-6** Separation distances computed from empirical equations which are used as screening tools. The Austrian and German VDI EQs use 10-degree meteorological statistics whilst the Belgian and Purdue EQs use more coarse meteorological data. The W-T Scheme uses no meteorology. (Brancher, 2020a).

Figure 5-7 shows a schematic diagram that compares a full dispersion model simulation to calculate separation distances versus that of the screening tool empirical equations. The dispersion model can simulate many more physical processes than EQs and must be run with more complex input data. In the simplified scheme, both procedures begin with the odour emission rate and end with the direction-dependent separation distance. The red arrows show the simplification of the input parameters in the EQs.

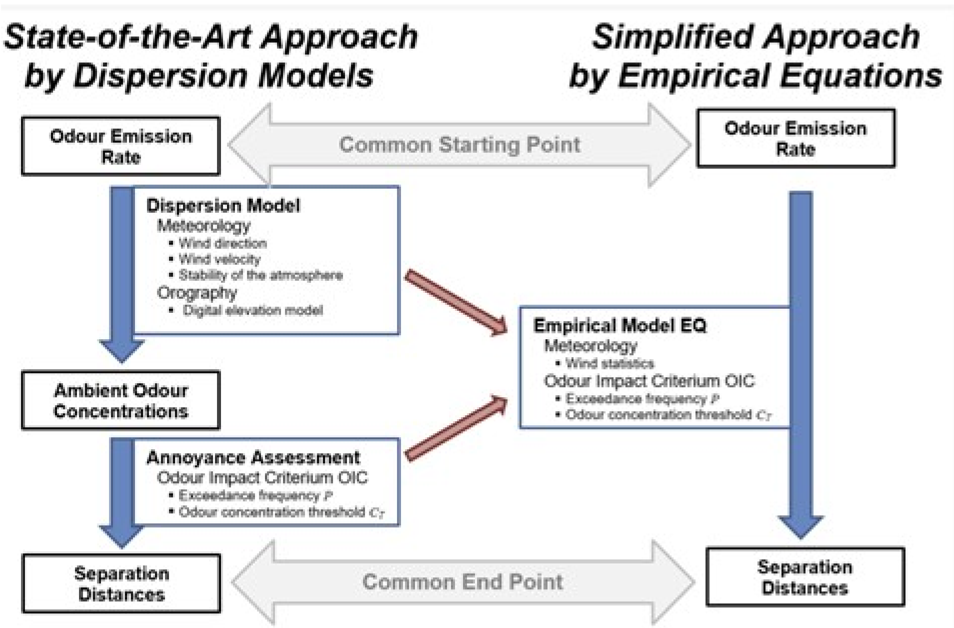


**Figure 5-7** Schematic diagram comparing screening empirical equations alongside dispersion modelling (Brancher, 2020a).

A major advantage of empirical equations lies in their simplified handling of the influence of meteorological input on separation distances. Separation distances from EQs are determined by the equation coefficient values which are derived from a statistical analysis of the time series of modelled ambient odour concentrations by the odour impact criteria. The EQ procedure includes implicit input of the exceedance probability to the empirical equations. This means that the two-step procedure of the state-of-the-art modelling methodology is reduced to a single step for EQs.

Table 5-2 shows some commonly used EQs employed internationally from livestock buildings and used primarily to determine separation distance. Note, Table 5-2 is not inclusive of all the empirical equations currently in use in odour assessments around the world. There are many that have not been included. Australia for example has several empirical equations for computing the separation distance required from livestock facilities. Western Australia has one such equation (Griffiths, 2013), while a second screening tool equation (Dairy Australia, 2008) is for estimating the separation distance for the pig and beef industries which takes into account the number of animals, site management practice, receptor type, local terrain and vegetation. Many screening methods like these are loosely employed and many do not have any local or regulatory status.

**Table 5-2** Odour-specific empirical equations used for computing separation distances

| | German VDI | Austria | Belgium | USA (Minnesota) | Purdue Setback Model | Australia (Victoria), New Zealand | Canada (Ontario) | Australia |
|---|---|---|---|---|---|---|---|---|
| **Reference** | Schauberger, 2012a; VDI 3984, 2012 | Schauberger, 2012b | Nicolas., 2008 | Jacobson, 2005 | Lim, 2000 | EPA Victoria, 2013; Auckland City Council, 2012 | Guo, 1998 | Meat and Livestock Australia Ltd 2012 |
| **Meteorology** | Wind direction frequency, exceedance probability | Mean wind velocity for each 10 degrees of wind direction, exceedance probability | Rough parameterisation for the prevailing wind direction Surface roughness protection level (zoning) | Not taken into consideration | Wind frequency for 45 degrees of wind direction, zoning, topography, | Not taken into consideration | Not taken into consideration | Not taken into consideration |
| **Building downwash** | no | no | no | no | Orientation and shape of building | na | na | no |

| | German VDI | Austria | Belgium | USA (Minnesota) | Purdue Setback Model | Australia (Victoria), New Zealand | Canada (Ontario) | Australia |
|---|---|---|---|---|---|---|---|---|
| **Terrain and Land use** | Flat terrain | Flat terrain | Surface roughness | no | Land Use factor for agricultural and pure residential areas<br>Topography factor for good ventilated area (flat terrain) and narrow valleys | na | na | Simple topography and land use factor |
| **Emission** | Odour emission rate ($ou_E\ s^{-1}$)<br><br>(500 - 50,000) | Odour emission rate ($ou_E\ s^{-1}$) | Number of animals, species, ventilation system, manure, feeding | All potential sources assigned an odour emission rate. OFFSET model can account for size, nature and range of odour | Odour emission rate ($ou_E\ s^{-1}$) | na | Species, number of animals, zoning, manure | Stocking intensity and management of beef feedlots |

| | German VDI | Austria | Belgium | USA (Minnesota) | Purdue Setback Model | Australia (Victoria), New Zealand | Canada (Ontario) | Australia |
|---|---|---|---|---|---|---|---|---|
| **Evolution of empirical equation** | Derived from dispersion modelling of 23 sites using (AUSTAL2000) Single point source from 5m | Derived from regression equations from dispersion models with minimum distance of 100m. Single point source from 6 sites | | Derived from dispersion modelling over 4 years and 85 farms | | Derived from review of empirical evidence of the performance of the recommended separation distances | | Derived from model predicted odour concentrations calibrated by receptor impacts |
| **Outcome** | Worst case outcome Shape determined by meteorology | Best fit approach Shape determined by meteorology | | Worst-case | | Worst case | Worst case | Worst case |
| **Separation Distance Shape** | Shape corresponds to wind frequency of 10 deg sectors | Shape corresponds to wind frequency of 10 deg sectors | Ellipse orientated in prevailing wind direction | circle | Shape corresponds to frequency of the wind direction for 45 deg sectors | circle | circle | circle |

#### 5.4.2.3. Summary

Screening tools are only useful if they greatly simplify the process of full dispersion modelling, provide reasonable yet conservative results and are fast and low cost to use. It is also important that they meet the requirements that the odour emission rate is quantitated in the same way as it is done for dispersion models and that separation distances are determined for odour impact criteria the same as for dispersion models. These constraints ensure a meaningful comparison of empirical equation separation distances against modelled separation distances. If the screening tools and models meet these criteria then there is no reason that they should not be usefully incorporated as screening level analysis tools in tiered regulatory odour assessment frameworks. A tiered framework recognises that tools such as simple power function-based equations may be sufficient to demonstrate that a proposal presents a low risk of impacting on amenities at nearby sensitive receptors and that if the criteria of the tier is met, then no more advanced work is necessary. But conversely if the screening level assessment does not pass then a more refined tool using dispersion modelling may be necessary. For some geographical areas local environmental agencies recommended locally adapted dispersion screening methods in combination with meteorological data for calculating such things as separation distances, this further simplifies the application of such tools as no specific meteorological information is compulsory to run them. These screening tools can work very well at the local level of regulatory control.

### 5.4.3. Steady State Gaussian Plume Models

There are multiple steady-state Gaussian models that are currently being used to model odours around the world. The most well-known and advanced model is the US EPA, regulatory model, AERMOD and the less used UK regulatory model, ADMS. Other Gaussian plume models used in odour assessments include: AODM, the Austrian odour regulatory model, and ARIA Impact, a widely used model in France, Italy and Brazil. Older Gaussian plume models, ISCST3, CTDMPLUS, AUSPLUME have been superseded by AERMOD, and are therefore not discussed further. Commonly used Gaussian plume models are discussed below.

#### 5.4.3.1. ARIA Impact

ARIA Impact is a simple and user-friendly modelling suite including CALPACT, a Gaussian plume/puff model, and AERMOD. It is developed and maintained by the French ARIA Technologies company and used in different countries. It can simulate the long-term dispersion of atmospheric pollutants (gaseous or particulate) from all types of emitting sources (point, surface, linear) in a simplified moderate topographic environment and calculate concentrations, and depositions (dry and wet) expressed as annual average or percentiles. The built-in Gaussian model switches from the plume dispersion algorithm to the puff algorithm in case of calm wind conditions, thus overcoming the inherent 1 m/s limitation of the plume approach. The software was developed to be used as a regulatory model to meet air quality criteria and can be used to evaluate the odour impact of a facility.

The software comes with a graphical user interface (GUI), allowing an easy import of both meteorological and topographic data and the definition of atmospheric emissions sources (constant, with cyclical temporal variation, or fully variable) with no limitation of the number of species or sources. A meteorological preprocessor helps calculating some needed derived variables such as stability categories, mixing height and surface layer parameters (u*, L, w*). The model is able to perform simple NOx to NO and NO2 conversions. It can take into account background pollution and includes a dust extraction module. The model can manage an extended range of deposition and concentration model output results such as percentiles, frequency of exceedance thresholds, values at specific points and output in multiple formats for further plotting. ARIA Impact can simultaneously treat multiple gas and particulate chemical species, radioactive pollutants as well as manage an odorous mix of chemicals expressed as an odour unit. Typical spatial scales of model application range from 5 x 5 $km^2$ to 30 x 30 $km^2$. Inputs also include hourly meteorological data from a single weather station and terrain data with knowledge of the dominant land use types.

Since the model is suitable in the near field, it may be a useful tool to assess the odour impact from the accidental releases of some species such as H2S and HCl. Although ARIA Impact can be strictly considered only partially as a regulatory tool, thanks to its simplicity of use and the presence of an efficient GUI it has found over time and still finds several applications in impact studies in France, Italy and Brazil, for both air quality and odour applications.

#### 5.4.3.2. ADMS

The ADMS model (Atmospheric Dispersion Modelling System) is an advanced steady-state Gaussian plume model for calculating ground level concentrations emitted from both continuous point, line, volume and area sources, or intermittent point sources. ADMS was developed by Cambridge Environmental Research Consultants (CERC, 2021b) of the UK in collaboration with the UK Meteorological Office, National Power plc (now INNOGY Holdings plc) and the University of Surrey. The first version of ADMS was released in 1993. Version 3 of the model was released in 1999, Version 5 was released in 2013, with a number of additional features and Version 6 was released in 2023. ADMS Version 6 contains a number of enhancements compared to ADMS Version 5, particularly in respect of modelling the effects of buildings, and modelling of time varying emissions factors.

ADMS includes algorithms which take into account: downwash effects of nearby buildings within the path of the dispersing pollution plume; effects of complex terrain; effects of coastline locations; wet deposition, gravitational settling and dry deposition; short term fluctuations in pollutant concentration; chemical reactions; radioactive decay and gamma-dose; pollution plume rise as a function of distance; jets and directional releases; averaging time ranging from very short to annual; and condensed plume visibility. The system also includes a meteorological data input pre-processor.

The model is capable of simulating passive or buoyant continuous plumes as well as short duration puff releases. It characterises atmospheric turbulence by two parameters, the depth of the boundary layer and the Monin-Obukhov length rather than the single parameter Pasquill Gifford classes.
The performance of the model has been evaluated against various measured dispersion data sets.

Users of ADMS include:

- Governmental regulatory authorities including the UK Health and Safety Executive (HSE)

- Environmental Agency of England and Wales
- Over 130 individual company licence holders in the UK
- Scottish Environmental Protection Agency (SEPA) in Scotland
- Northern Ireland Environment Agency
- Governmental organisations including the Food Standards Agency (UK)
- Users in other European countries, Asia, Australia and the Middle East

ADMS Version 3 is accepted by the US Environmental Protection Agency as an "Alternative" model (US-EPA, 2021b).

ADMS is used widely in odour assessments in the UK and uses the odour unit (ouE) as defined in the CEN standard (EN 13725:2003). One ouE is the mass of a pollutant that, when evaporated into 1 $m^3$ of odourless gas at standard conditions, is at the detection limit. The model allows the following odour release rates; ouE/s for point sources, ouE/m/s for line sources, ouE/$m^2$/s for area sources and ouE/$m^3$/s for volume sources. Output odour concentrations are in odour units (ou) defined as a ratio, and $ou_E$, as a mass measure.

Within the same modelling framework ADMS 5 includes a ‘fluctuations’ option. This option allows the user to take account of the variations in concentration caused by the ‘short’ time scale turbulence in the lower atmosphere and changes in meteorology. The technical formulation of the fluctuation module is described in depth in (Thomson, 1992; Thomson, 2017). The fluctuations module uses a probability distribution function (PDF) of concentrations and considers variations due to turbulence and changes in meteorology.

ADMS 5, like all steady-state Gaussian models, does not model calm wind events, which are often worst-case dispersion events for odours. By default, the model does not model hours when the wind speed is less than 0.75 m/s. However, the model has an optional capability for treating very low wind speeds via an ‘additional input file’ that allows lower wind speeds to be modelled. Since a key feature of low winds is that the wind direction is highly variable, ADMS 5 splits the dispersion into two types of plumes, the usual Gaussian plume aligned in the direction of the wind, and a radially-symmetric plume, with concentrations calculated as a weighted average of the two. The radially symmetric plume is modelled as a passive source with a source height equal to the maximum plume height from the standard plume rise calculations, and assumes an equal probability of all wind directions.

This scheme is similar to that used in AERMOD, which splits the plume into a coherent and radial plume for all wind speeds and is controlled through various LOWWIND options.

While ADMS is the default regulatory model in the UK, the Environmental Agency (UKEA) appears to be less strict regarding odour modelling (Pullen, 2007). The UKEA makes it clear that various models may be used in applications for authorisation and that the applicant must demonstrate that the model is fit for purpose. Although the UK Institute of Air Quality Management (Bull, 2014) says that odour assessments in the UK are almost exclusively undertaken using AERMOD and ADMS.

#### 5.4.3.3. AERMOD

AERMOD was established in 1991 through AERMIC, the American Meteorological Society/Environmental Protection Agency Regulatory Model Improvement Committee

(AERMIC), to introduce state-of-the-art modelling concepts into the EPA's own developed air quality models. AERMOD was developed to incorporate air dispersion based on planetary boundary layer turbulence structure and scaling concepts, including treatment of surface and elevated sources and simple and complex terrain. On November 9 of 2005, AERMOD was adopted by the EPA and promulgated as their preferred regulatory model, effective as of December 9 of 2005 (Federal Register, 2005). The developmental and adoption process took 14 years (from 1991 to 2005).

AERMOD is a steady-state plume model incorporating air dispersion based on planetary boundary layer turbulence structure and scaling concepts. AERMOD supports two input data processors; AERMET, a meteorological data pre-processor incorporating air dispersion based on planetary boundary layer turbulence structure and scaling concepts, and AERMAP, a terrain data preprocessor incorporating complex terrain.

The AERMOD model is an integrated system that includes three modules:

- A steady-state dispersion model designed for short-range (up to 50 kilometres) dispersion of air pollutant emissions from stationary industrial sources.
- A meteorological data pre-processor (AERMET) that accepts surface meteorological data, upper air soundings, and optionally, data from on-site instrument towers. It then calculates atmospheric parameters needed by the dispersion model, such as atmospheric turbulence characteristics, mixing heights, friction velocity, Monin-Obukhov length and surface heat flux.
- A terrain pre-processor (AERMAP) whose main purpose is to provide a physical relationship between terrain features and the behaviour of air pollution plumes. It generates location and height data for each receptor location. It also provides information that allows the dispersion model to simulate the effects of air flowing over hills or splitting to flow around hills

AERMOD is an advanced steady-state Gaussian plume model for calculating ground-level concentrations of pollutants emitted from both intermittent and continuous point, line, volume and area sources.

AERMOD includes new and improved algorithms (over ISC3, which it replaced) which take into account: the downwash effects of nearby buildings within the path of the dispersing pollution plume; effects of moderate terrain; dispersion in both the convective and stable boundary layers; plume rise and buoyancy; plume penetration into elevated inversions; computation of vertical profiles of wind, turbulence, and temperature; the urban night-time boundary layer, treatment of plume meander.

The model is capable of simulating passive or buoyant continuous plumes, and it characterises atmospheric turbulence by two parameters, the depth of the boundary layer and the Monin-Obukhov length rather than the single parameter Pasquill Gifford classes of the ISCST3 model.

AERMOD is the most widely used model in the world today, and is the US EPA recommended dispersion model for predicting air quality in the near field (up to 50 km). However, it is important to point out that in the United States, odour assessments are not limited by the requirements of 40 CFR 51, Appendix W rules and regulations. These guidelines only apply to criteria air pollutants (air pollutants with established air quality standards). Odours do not have federally enforceable air quality standards and are not regulated through the preparation of State Implementation Plans, New Source Review or Prevention of Significant Deterioration permit requirements (Barclay, 2019). However, despite the fact that odour assessments are not limited to the current US EPA model guidelines AERMOD's status as a guideline model means that most odour assessments are undertaken using AERMOD, regardless of whether it is suitable or not. Outside the US, many countries (Australia, Canada, New Zealand, Southern Africa) regulate odours where dispersion modelling is often a requirement. Many of these countries look to the US for regulatory models and guidance.

For modelling odours, AERMOD includes no option to input and output odour emission rates. The default emission rate units for AERMOD are g/s for point and volume sources and $g/s/m^2$ for area sources. By default, the model converts these input units to output units of micrograms per cubic metre ($\mu g/m^3$) for concentration.

Similarly to ADMS, AERMOD is unable to model calms (0.0 m/s) and will simply skip over these hours. The minimum allowable wind speed to define the boundary layer parameters is defined as $2^{1/2} * \sigma_{vmin}$ where $\sigma_{vmin}$ = 0.2 m/s or wind $speed_{min}$ = 0.28 m/s. This minimum is independent of the threshold wind speed which is 0.51 m/s. The restriction is based on the accuracy of the instruments. Sonic anemometers have no threshold limitations and therefore no wind speed threshold is imposed and the output AERMINUTE file can have winds lower than 0.28 m/s. By US EPA (and Australia) regulatory requirements, any data set that does not meet the 90% data coverage must use AERMINUTE which is a meteorological processor (or other method) to re-process the 1-10 minute automatic weather station readings to produce a new 1-hour average wind speed and wind direction which is different than the regular standard archived hourly data. The result of AERMINUTE is to generate a new meteorological data set that has fewer calm periods and more winds in the range 0.1 m/s to 1 m/s. The effect of AERMINUTE is shown in Table 5-3 which shows the number of calms for Danelly Fields met station in Alabama (US) with and without the use of AERMINUTE. The percentage of calms reduces from 27% of the data set to just 2% with its use, and the number of wind speeds increased from 0% in the range 0.28 – 1 m/s to 9.73%. Just how much AERMINUTE changes the 1-hour wind speed and wind direction pattern is shown in the annual wind rose (Figure 5-8) with and without the inclusion of AERMINUTE. However, it is observed that the ASOS 1-minute and ASOS 5-minute data needed to feed AERMINUTE may not be available in many countries outside of the US.

**Table 5-3** Wind speed statistics for Danelly Field, AL for 2011 with and without AERMINUTE

| Year | AERMET % | AERMET average wind speed (m/s) | AERMINUTE /AERMET (%) | AERMINUTE /AERMET average wind speed (m/s) |
|---|---|---|---|---|
| Danelly Field | Calms* = 27.2 | 5.02 | Calms* = 2.0 | 5.43 |

| | | |
|---|---|---|
| 2011 | 0.28 – 1 m/s = 0<br>1 – 2 m/s = 12 | 0.28 – 1 m/s = 9.7<br>1 – 2 m/s = 27.9 |

*Percentage calm based on threshold wind speed = 0.5 m/s

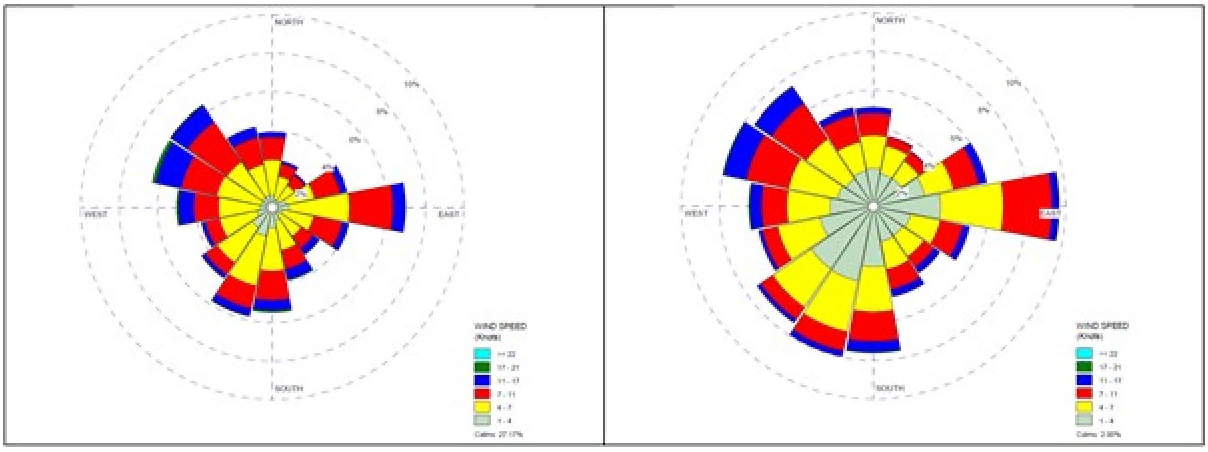
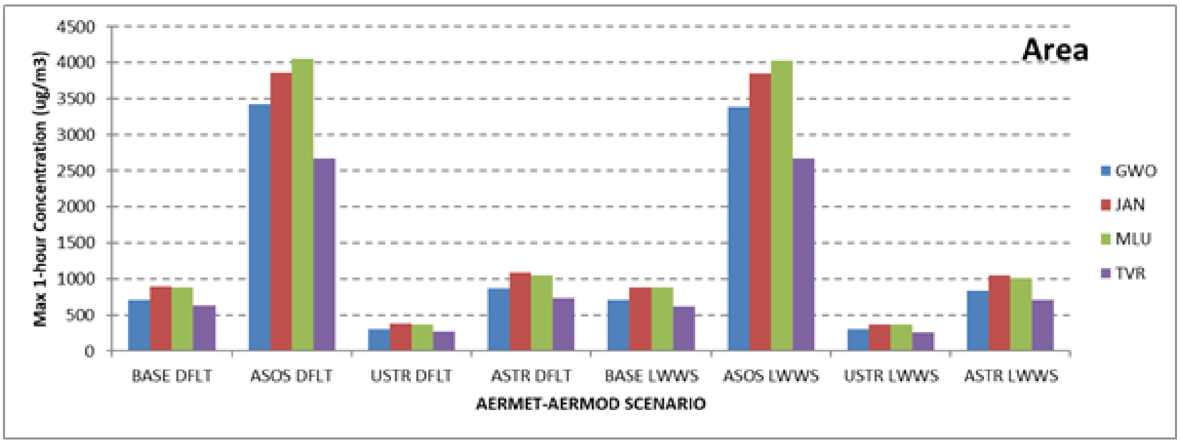



**Figure 5-8** Annual wind roses showing the effects of AERMET using hourly data and AERMET including a re-analysis of the 1-minute ASOS data using AERMINUTE (Barclay and Borissova, 2019)

However, while AERMINUTE solved one problem (i.e., reduced the number of calms in a data set and thereby increased the number of hours modelled to > 90%), increasing the number of very light winds created other problems such as AERMOD tendency to over predict in light winds (Connors, 2013), and its treatment of lateral plume meander, which is responsible for most of the horizontal plume dispersion in stable atmospheric conditions.

The US-EPA is continuously working on AERMOD and AERMET to improve their algorithms, for example those related to a better calculation of the friction velocity, or the treatments of calms.

The effect of these changes to AERMET and AERMOD from 2012 until the latest version of the model (ASTR LWWS) is significant for an area source as shown in Figure 5-9 for four nearby meteorological stations (GWO, JAN, MLU, TVR). AERMOD is especially sensitive to the re-analysis of 1 and 5 minute ASOS winds (ASOS DFLT, ASOS LWWS), where there is an order of magnitude difference from the pre 2012 (BASE DFLT) model. The most likely options for AERMOD outside of the US where 1-10 minute ASOS data may not be available is likely to be USTR LWWS, which takes into account the default Adj_u* option, default LOWWIND values and uses regular saved hourly data, which in the US, is representative of the last two minutes of wind speed and wind direction of each hour, and in Australia and New Zealand, the last ten minutes of the hour is the hour. As can be seen from Figure 5-9, USTR LWWS significantly underpredicts all the other combinations, including the pre 2012 BASE model. This will always be the case as long as there are 10% or more of the data set that contains calm winds. For odour assessments this is a significant concern. Odours will tend to accumulate and stagnate under calm conditions, but AERMOD will not model these conditions and therefore will most likely underpredict these worst-case episodes.




AERMET
BASE – hourly data, pre 2012 (before adj_u* and LOWWIND changes)
ASOS – re-analysis of < 1hour data (AERMINUTE), no adj_u* (2012)
USTR – hourly data (no AERMINUTE), adj_u*
ASTR - re-analysis of < 1hour data (AERMINUTE), adj_u*
AERMOD
DFLT – Default, no LOWWIND
LWWS – LOWWIND (since 2015)

**Figure 5-9** Ground level concentrations reflecting major US EPA changes for 4 meteorological stations for a single area source (Barclay and Borissova 2019)

It is important to note that AERMOD was not developed for odour modelling or accidental releases of pollutants, and therefore does not make allowance for modelling concentration fluctuations within the hour. Scaling of concentrations by a constant Peak-to-Mean Ratio or hedonic tone must be applied directly to the emission rate or the output concentration. The model will allow cyclical scaling of emission rates which are suitable for those peaks to mean ratios that might vary with stability and source type. AERMOD like most other advanced models will allow the computation of percentiles, a necessary criterion of most odour assessment criteria around the world, as well as provide plot files of ranked odour concentrations and number of hours exceeding such an odour criterion.

AERMOD has been used in odour studies all over the world, both in experimental capacity and regulatory assessments. The model's use and application in odour assessments is likely to grow.

#### 5.4.3.6. Summary

Table 5-4 is a summary of the most well-known, regulatory Gaussian plume models used in odour applications today.

**Table 5-4** Summary of key features of well known, regulatory steady-state Gaussian plume models used in odour assessments around the world today

| | ADMS-5 | AERMOD | ARIA Impact |
|---|---|---|---|
| Regulatory status for modelling odours | United Kingdom, Northern Ireland, Scotland | United States, Australia, New Zealand, Canada, Countries in Africa and Middle East | The suite includes two models: CALPACT, which is a non-regulatory model and AERMOD, whose regulatory status is described in the previous column.<br>Normally accepted in Italy, France, Brazil and everywhere as a derivation of the models suggested by US-EPA |
| **Meteorology** | | | |
| Pre-processor | In-built processors, allows flexible input met. data. Model also allows a user input file of light winds < 0.75 m/s | External processors.<br>AERMET and AERMINUTE. AERMINUTE to be used if >10% of data is calm. It is used to recompute the 1-hour average winds from 1–5-minute ASOS met data.<br>AERMET then computes surface parameters (h, w*, u*, L) from measured observations of cloud cover, wind speed and direction, temperature. | Internal meteorological processor computing surface parameters (h, w*, u*, L) and stability classes from measured observations of cloud cover and/or global and/or net radiation, wind speed and direction, temperature. |
| **Dispersion** | | | |
| Boundary layer structure | h, $L_{MO}$ scaling | h, $L_{MO}$ scaling | h, $L_{MO,}$ stability categories |
| Plume Rise | Advanced integral model using Runge-Kutta method | Briggs empirical equations | Briggs, Briggs small stacks, Anfossi equations and empirical equations. |
| Concentration distribution | Advanced Gaussian (PDF) | Advanced Gaussian (PDF) | Classical and Advanced Gaussian (PDF) |
| **Complex Effects** | | | |
| Buildings | ADMS building module | PRIME building module | |

| | ADMS-5 | AERMOD | ARIA Impact |
|---|---|---|---|
| Complex Terrain | Based on calculation of flow field and turbulence field by FLOWSTAR model | Interpolation between plume displaced by terrain height (neutral) and plume impaction (no vertical displacement, stable) | Use of a simplified terrain module |
| Calm winds | By default, does not model winds <0.75 m/s. 'Calms option' will allow additional input file for winds < 0.75 m/s, this invokes plume split into Gaussian plume aligned along wind and radially-symmetric plume to account for plume meander | Default low wind speed is 0.2828 m/s consistent with sigma v of 0.2. Users now have an option to set minimum wind speed, minimum sigma v and plume meander using alpha LOWWIND option.<br>Model will skip over 'zero winds'.<br>AERMINUTE recomputes the 1-hour average from ASOS stations | CALPACT with a Gaussian puff internally driven scheme during hours of "low wind speed" (wind speed < 1 m/s) |
| Plume Meander | | AERMOD plume meander is invoked for all wind speeds, not just when wind tending to 0.0<br>No plume meander for area sources | |
| | | | |
| Odour Input and Output units | yes | Input emission rate is g/s, output concentration is ug/$m^3$. For odours use emission factor of 1 that assumes input is ou/s and output odour concentration is ou/$m^3$ | Input emission rate in ou/s and output concentrations in ou/$m^3$[3] |
| Concentration fluctuations (built in Peak-to-Mean Ratio) | yes | No, must apply PtMR by scaling concentrations or emission rates | No, must apply PtMR by scaling concentrations or emission rates |
| Compute averaging times < 1-hour | No | No | Yes, with limitations |
| User-defined outputs | 1-hour to annual averaging<br>Percentiles<br>Exceedances | 1-hour to annual averaging<br>Percentiles<br>Exceedances | 1-hour to annual averaging<br>Percentiles<br>Exceedances |

## 5.4.4. Lagrangian Puff Models

### 5.4.4.1. CALPUFF

The CALPUFF model was developed by (Scire, 2000) using an integrated puff approach based on the MESOPUFF II model (Scire, 1984a; Scire, 1984b) with modifications for near-field applications.

The CALPUFF modelling system includes three main components: CALMET, CALPUFF and CALPOST and a large set of pre-processing programs designed to interface the model to standard, routinely-available meteorological and geophysical datasets. In simple terms, CALMET is a meteorological model that develops wind and temperature fields on a three-dimensional gridded modelling domain. Associated two-dimensional fields such as mixing height, surface characteristics, and dispersion properties are also included in the file produced by CALMET. CALPUFF is a Lagrangian puff dispersion model that advects 'puffs' of material emitted from modelled sources, simulating dispersion and transformation processes along the way. In doing so it typically uses the fields generated by CALMET, or as an option, it may use simpler non-gridded meteorological data from existing plume models such as ISCST3, CTDMPLUS, AUSPLUME and AERMOD. Temporal and spatial variations in the meteorological fields selected are explicitly incorporated in the resulting distribution of puffs throughout a simulation period. The primary output files from CALPUFF contain either concentrations or deposition fluxes evaluated at selected receptor locations. CALPOST is used to process these files, producing tabulations summarising the simulation results, and identifying the highest and second-highest 3-hour average concentrations at each receptor, for example. Any percentile or exceedance level can be obtained through its external post-processing tools.

CALPUFF was designated a US EPA Appendix A Guideline model in 2003 (Federal Register, 2003). Prior to the model promulgation to an Appendix A guideline model, CALPUFF, like the ISCST3 (US-EPA, 1995) model before it underwent rigorous testing, model evaluations and multiple peer reviews over more than a decade. This lengthy, dedicated, state-of-science and transparent process occurred under the scrutiny of the then Air Quality Management Group (AQMG) within the US EPA. In January 2017, CALPUFF was removed from the US EPA Appendix A as the preferred long-range transport model with no replacement (Federal Register, 2017), (Barclay, 2018). In the US, AERMOD is now the only dispersion model with guideline status and is the recommended US EPA dispersion model for use for all near-field applications out to 50 km (Federal Register, 2017). The US EPA-approved version of CALPUFF, Version 5.85 of the model (equivalent to the 2008 version with bug fixes, can still be found on the 'Alternative Models' web page. The model is now Version 7. The new wording in (Federal Register, 2017) points out that removing CALPUFF as a preferred model does not affect its use under the Federal Land Managers guidance regarding Air Quality assessments in National Parks, nor any previous use of the model as part of regulatory applications requiring Civil Aviation Authority. (Federal Register, 2017) also states that the use of CALPUFF in the near field as an alternative model for situations involving complex terrain and complex winds has not changed by removing CALPUFF as a preferred model. The US EPA further points out that it recognises that "AERMOD is limited" and that CALPUFF or another Lagrangian model may be more suitable in complex environments. Therefore, they have continued to provide the flexibility to use it. This last point is important as the EPA recognises that AERMOD is limited in complex, non-steady-state environments. This is especially important for odour assessments which are often located in complex meteorological environments, i.e., close to water bodies, such as WWTPs and in complex terrain environments such as Pulp and Paper Mills.

Unlike Gaussian plume models, Lagrangian models can model calm events. Calm periods in CALPUFF are determined when the puff transport speed is less than the user-supplied threshold wind speed of 0.5m/s. While CALPUFF has no special calm module, several adjustments are made to the normal algorithms. These adjustments alter how slugs are released, how gradual rise is addressed, how near-source effects are simulated, and how the puff size changes during each sampling step. These adjustments are consistent with the conceptual model in which fresh releases rise virtually straight up from a source and disperse as a function of time due to wind fluctuations about a mean of zero, while existing emission stagnate, and disperse as a function of time due to wind fluctuations about a mean of zero. Adjustments made to puffs that are released into a calm period include:

- Slugs are released as puffs
- All mass for the period is placed into one puff
- Distance to final rise is set to zero
- No building downwash effects are included
- Growth of σy and σz is based on time (not distance travelled) during the sampling step
- Minimum values of the turbulence velocities σv and σw are imposed

It is acknowledged that during calm conditions, estimates of the turbulence velocities σv and σw can be indeterminate, and CALPUFF relies on these velocities to grow puffs. Calm periods can be associated with very stable and convective boundary layers, with their distinctly different turbulent properties. Given these concerns, CALPUFF allows the use of stability-dependent minimum turbulence velocities.

A recent (2011) modification to CALPUFF, important for odour assessments over short time scales, was the capability of Version 6 of the model to allow sub-hourly temporal resolution of both source characteristics, input meteorological fields and output sub-hourly temporal resolution of modelled output fields. This included the introduction of sub-hourly time-varying structures that were designed and then implemented into CALMET Version 6. This included the introduction of a sub-hourly time step within the model for purposes of computing solar radiation, wind fields and boundary layer parameters and the modification of the structure of the output data file produced by CALMET to allow for hourly or sub-hourly time steps. This version of the model can accommodate input meteorological and overwater data with an arbitrary time resolution. This includes sub-hourly measurements of turbulence parameters (σv, σw) which are readily available from modern ultrasonic anemometers.

Figure 5-10 shows the difference in predicted ground level concentrations from CALPUFF using default hourly meteorology and computed dispersion coefficients under calm conditions compared to using 10-minute meteorology and measured 10-minute turbulence parameters. The first plot (lhs), when using model default options (minimum wind speed threshold of 0.5 m/s, hourly meteorology, computed turbulence coefficients) shows a typical 'bulls-eye' of ground level concentrations where the concentrations at the source are very high and plume dilution is a function of time. The second plot (rhs) shows the predicted ground concentrations for 10-minute meteorology and real measured 10-minute turbulence parameters σv and σw. The computed 1-hour turbulent dispersion coefficient (sigma v) and 10-minute measured sigma v corresponding to each isopleth plot is also shown.

The implications of directly using sonic anemometer data for local scale odour dispersion in a model equipped to use the data are apparent. Using site-specific winds and turbulent data on small temporal time scales may alleviate the need to apply any additional Peak-to-Mean Ratio. CALPUFF was compared using 15-minute meteorology and real measured turbulence parameters with the STAGMAP data set (Stagnation Model Analysis, Medford, Oregon 1991). In this study, $SF_6$ was released under true calm conditions. CALPUFF showed very good agreement with this data set (Barclay, 2008).

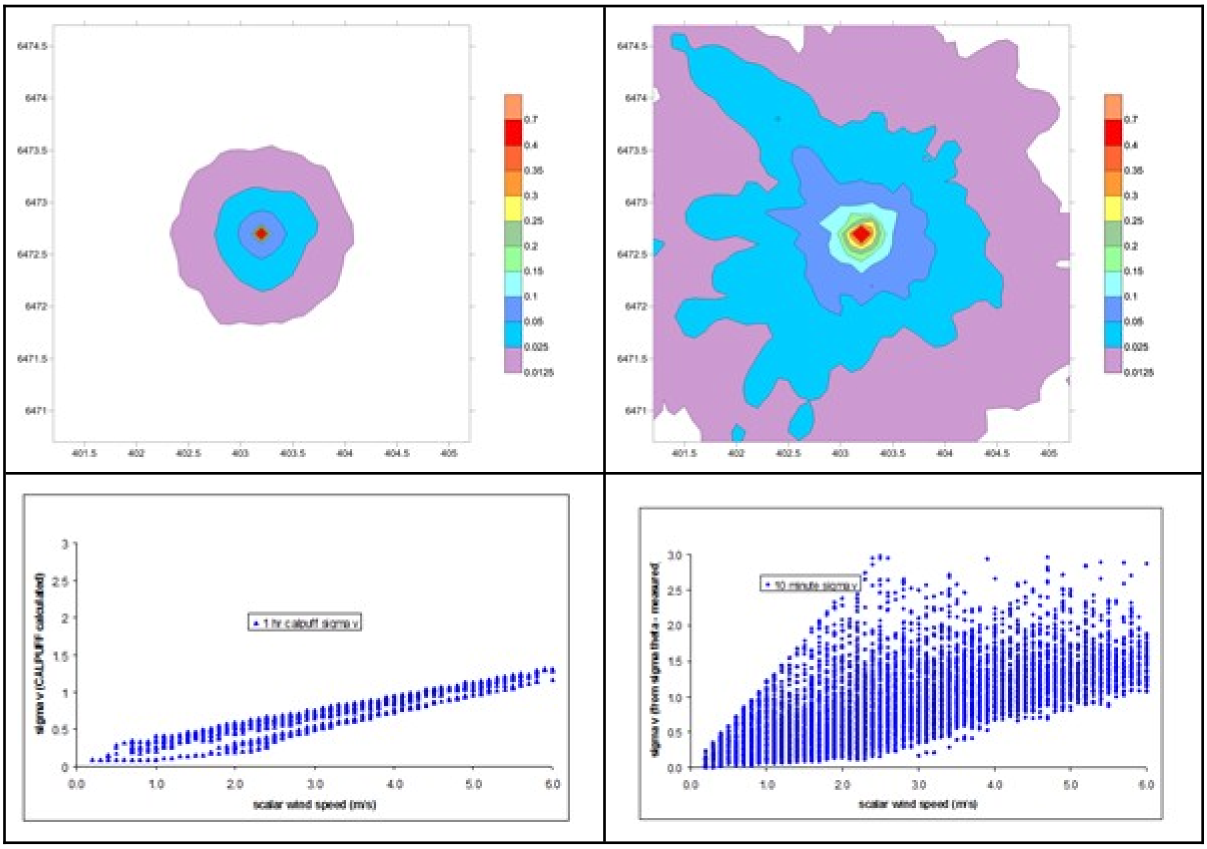



**Figure 5-10** Predicted ground level concentrations under calm conditions using model defaults (1-hour meteorology, calm wind speed threshold 0.5 m/s, minimum sigma v 0.5 m/s, computed turbulence parameters) on lhs, compared to 10-minute meteorology and measured 10-minute turbulence parameters (rhs). (Barclay and Scire 2011).

In 2014, CALPUFF Version 7.2.1 was updated to allow users to apply an averaging time factor to the lateral turbulence. This approach is suitable when sub-hourly meteorological data are available but no measured turbulence parameters. This allows users to apply an equivalent sub-hourly sigma-y value when using the default hourly turbulence dispersion coefficients or PG curves.

CALPUFF will directly allow the user to input odour emission rates into the model in the form of:

- Point, volume and line sources - Odour Unit * $m^3/s$ (vol. flux of odour compound), and

- Area sources - Odour Unit * m/s (vol. flux/$m^2$ of odour compound)

The model will output odour concentrations in odour units. The model will allow any percentile to be computed and will compute odour criteria exceedances.

Application of constant Peak-to-Mean Ratios can easily be applied to the model either through scaling the emission rate within the model control file, or in the post processing phase. In addition, scaling according to source type and stability category can also be done readily through the CALPUFF control file.

#### 5.4.4.2. SCIPUFF

SCIPUFF (Sykes, 1998) is a Lagrangian puff dispersion model that uses a collection of Gaussian puffs to represent an arbitrary, three-dimensional, time-dependent concentration field. The turbulent diffusion parameterisation is based on modern turbulence closure theory, specifically, the second-order closure model of (Donaldson, 1973) and (Lewellen, 1977), which provides a direct relationship between the predicted dispersion rates and the measurable turbulent velocity statistics of the wind field. In addition to the average concentration value, the closure model also provides a prediction of the statistical variance in the concentration field resulting from the random fluctuations in the wind field. The closure approach also provides a direct representation for the effect of averaging time (Sykes, 1997).

Shear distortion is accurately represented using the full Gaussian spatial moment tensor, rather than simply the diagonal moments, and an efficient puff splitting/merging algorithm minimises the number of puffs required for a calculation. In order to increase calculation efficiency, SCIPUFF uses a multi-level time-stepping scheme with an appropriately sized time-step for each puff. An adaptive multi-grid is used to identify neighbouring puffs in the spatial domain, which greatly reduces the search time for overlapping puffs in the interaction calculation and puff-merging algorithm. Static puffs are used to represent the steady-state phase of the plume near the source and are updated only with meteorology, also decreasing the number of puffs needed for the calculation.

SCIPUFF can model many types of source geometries and material properties. It can use several types of meteorological input, including surface and upper-air observations or three-dimensional gridded data. Planetary boundary layer turbulence is represented explicitly in terms of surface heat flux and shear stress using parameterised profile shapes. A Graphical User Interface (GUI) that runs on a PC is used to define the problem scenario, run the dispersion calculation and produce colour contour plots of resulting concentrations. The GUI also includes an online ‘Help’.

### 5.4.5. Lagrangian Particle Models

#### 5.4.5.1. AUSTAL

AUSTAL (previously known as AUSTAL2000 and AUSTAL2000g) is an atmospheric dispersion model for simulating the dispersion of air pollutants in the ambient atmosphere. It was developed by Ingenieurbüro Janicke under contract to the Federal Ministry for Environment, Nature Conservation and Nuclear Safety. AUSTAL was initially published in 1986 as a Gaussian Plume model (AUSTAL86), in 2002, the Lagrangian dispersion was implemented in AUSTAL2000, odour dispersion was added in 2004. It was recently modified primarily regarding boundary layer parameterisation, plume rise and wet deposition in accordance with the TA Luft 2021, resulting in the program AUSTAL.

Although not named in the TA Luft (Air Quality regulation in Germany), AUSTAL is the reference dispersion model accepted as being in compliance with the requirements of Annex 2 of the TA Luft and the pertinent VDI Guidelines. The program AUSTAL (starting with version 3) refers to the TA Luft 2021 and is the successor of the program AUSTAL2000 (ending with version 2), which refers to the TA Luft 2002. AUSTAL is provided by the Federal Environmental Agency as a free reference implementation.

AUSTAL is in compliance with the German guideline VDI 3945/3. For any model to be used under the TA Luft, it must follow this German Guideline. To date, there is no other model that follows the VDI 3945/3.

The dispersion model AUSTAL can be used to model the transport of passive trace substances in the lower atmosphere on a local and regional scale. The vertical dimension is up to about 2000 m with a maximum of 100 layers, the horizontal scale can reach tens of kilometers, with a maximum of 300 by 300 grid points. To cover larger areas, up to 6 nested calculation grids can be used (the grid resolution has to increase by factor 2 from one grid to the next). AUSTAL is a Lagrangian particle model, the dispersion of trace substances in the atmosphere is simulated utilising a random walk process. The physical processes that can be simulated include transport by the mean wind field, dispersion in the atmosphere, sedimentation of heavy aerosols, deposition on the ground (dry deposition) as well as washout of trace substances by rain and wet deposition. Thermal and mechanical plume rise is covered parametrically based on the German guidelines VDI 3782/3, or utilising the three-dimensional plume rise model PLURIS. For odorants, odour hour frequencies can be determined, with or without weighting factors based on hedonic tone. In flat and homogeneous terrain, the time dependent meteorological parameters are described by means of a one-dimensional boundary layer model that is based on simple parameters that characterise the weather situation. The sampling error can be reduced by increasing the number of particles released by the model. Emission sources of any number can be defined in form of point, line, area or volume sources. Most of the source parameters, especially emission rates, exhaust velocity, exhaust temperature and plume humidity can be specified as independent time series. The result of the dispersion simulation is the three-dimensional concentration field of the emitted trace substances averaged over successive time intervals, and the mass flow density of deposition into the ground. All substances regulated in the TA Luft (2021) are preprogrammed and the modelling results for each substance are post-processed, so that for each substance the respective impact values (daily average, yearly average, e.g.) can easily be assessed. In addition to that, inert substances or particles can be implemented to model missing substances in the default selection.

#### 5.4.5.2. LAPMOD

LAPMOD is a Lagrangian particle model whose development started more than 20 years ago (e.g., Bianconi, 1999). The model had different names in the course of its development, and for a short period it included a photochemical module (Zanini, 2002). During the years the model has been improved, validated (e.g., Bellasio, 2017; Bellasio, 2018; Haq, 2019) and enriched with some pre- and post-processors. According to the performance evaluation criteria proposed by (Chang, 2004) - based on FA2, NMSE and fractional bias - LAPMOD can be defined as a “good” model both in rural (Kincaid) and urban (Indianapolis) terrain. Anyway, model validation is a continuous process, and other tests are underway.

LAPMOD is not only a model but a modelling system, whose structure is summarised in Figure 5-11. The modelling system is open-source, its Fortran code and documentation can be downloaded at https://www.enviroware.com/lapmod/.

LAPMOD is used in Italy and Europe both for air quality (e.g., Ugolini, 2013) and odour (e.g., Pollini, 2015) applications. Moreover, LAPMOD is integrated into ARIES (Accidental Release Impact Evaluation System), the official Italian modelling system for nuclear emergencies (e.g., Bellasio, 2012), and in the AQWeb modelling system of the EPA of Emilia Romagna (one of the Italian regions). A recent paper (Bellasio and Bianconi, 2022) used LAPMOD to evaluate the results of different odour emission scenarios generated by a new method for calculating odour emissions from open-roof rectangular tanks. Finally, it has also been mentioned by the (US-EPA, 2020) among the models available for homeland security.

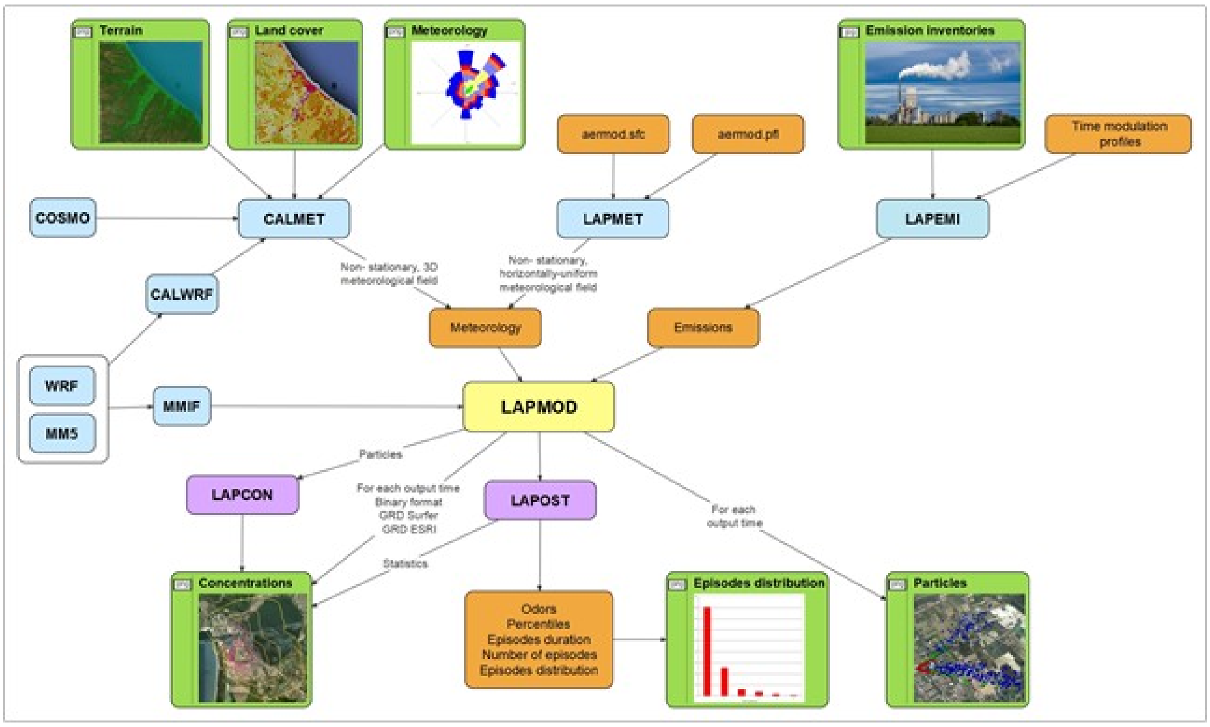



**Figure 5-11** Schematic Representation of the LAPMOD Modelling system (Courtesy of Enviroware)

Being a 3D non-stationary model, the most appropriate meteorological data should be prepared with the CALMET diagnostic meteorological model, which can be used with high spatial resolution. However, LAPMOD can also use the 3D meteorological data prepared with WRF and MMIF, typically with a lower grid resolution.

Many features of LAPMOD make it suitable for odour applications, as described for example in (Bianconi, 2011). For example, it allows simulating releases with arbitrarily time variable emission rates (up to a resolution of one second) from a number of source types: point sources without plume rise (e.g., stacks with rain caps), buoyant point sources (e.g., stacks), linear sources (e.g., road traffic), circular sources (e.g., tanks), spherical sources (e.g., dirty bomb), parallelepipedal sources (e.g., buildings) and area sources of arbitrary shape (e.g., any area source). Independently of the source type, LAPMOD requires the emission rates in terms of a specific variable X per unit of time, which means g/s for “classic” pollutants (e.g., NOX, PM10, …), Bq/s for radionuclides, and ouE/s for odour. The output unit is controlled by the user through a multiplication factor, for example, when the release rate is in g/s and the multiplication factor is 1, the output concentration is in $g/m^3$; on the contrary, if the multiplication factor is $10^6$, the output concentrations are in $\mu g/m^3$. The release units are not explicitly required by LAPMOD, but the user needs to know them in order to obtain correct results.

In a Lagrangian particle model each particle moves due to deterministic (mean wind field) and stochastic (turbulence) effects. Therefore, even in calm wind conditions, which are the worst situations for the dispersion of odour and any other pollutant, the model continues to work because the particles move according to the stochastic part of the trajectory equation. Numerical plume rise can be simulated for buoyant point sources with two different algorithms: JJ (Janicke and Janicke), and WT (Webster and Thomson). The main difference between the two algorithms is that JJ considers the presence of water vapour within the released plume (important for example for modelling emissions from dryers). Specific algorithms as stack tip downwash (i.e., the capture of the plume in the stack wake, resulting in an increase of the concentration values immediately downwind of the stack), partial plume penetration of elevated inversions (which depends on the combined effects of plume buoyancy, wind speed at stack height, difference between mixing height and stack height and strength of the inversion) and plume induced turbulence during plume rise (large close to the release, when the entrainment activity is maximum and the plume radius grows very quickly, while it reduces moving away from the source) are also available for buoyant point sources. Building downwash, which may be important when stacks are involved, is still under implementation. For many odour applications involving area or volume sources this is not an issue.

Atmospheric concentrations over regular and sensitive (discrete) receptors are calculated by LAPMOD starting from particle masses and the relative positions of particles and receptors by means of a kernel method (Vitali., 2006). Concentration fields calculated with kernel methods are less noisy than those calculated with the “classical” counting box method, based on the computation of the total mass within a specific volume of atmosphere. Moreover, kernel estimators require less particles.

Odour concentrations can be determined in two ways in LAPMOD. The first, is the calculation of the hourly concentrations and the application of a constant Peak-to-Mean Ratio (e.g., 2.3 as indicated by the Lombardy Region, Italy) in order to compute the peak concentration. The second, and most interesting way, to calculate the peak concentration is by determining the Peak-to-Mean Ratio dynamically as a function of atmospheric stability, distance from sources and age of the particle (e.g., Schauberger, 2000; Mylne, 1992a; Mylne, 1992b; Smith, 1973). An example of application of LAPMOD with this second method for calculating odour concentrations has been described by (Invernizzi, 2020). The same paper contains an intercomparison against the results of two other atmospheric dispersion models.

The LAPOST processor can be used to estimate some of the FIDOS parameters (Frequency, Intensity, Duration, Offensiveness and Location), except offensiveness which depends on the odour mixture and has subjective characteristics. Concerning frequency (F) for example, LAPOST calculates the number of exceedances of an odour threshold specified by the user. Intensity (I) is represented by means of the maximum hourly concentration or with the 98th percentile of the peak concentration. Duration (D) is calculated by LAPOST for each point and each odour episode. The episode indicates the time for which concentration remains consecutively above the odour threshold. LAPOST also determines the number of exceedance episodes, which coincides with the number of exceedances only when each exceedance lasts for a single hour. A specified percentile of episode durations can also be calculated for each output receptor. The location (L) is automatically determined by LAPOST because all the results are associated with precise coordinates.

#### 5.4.5.3. GRAL

The Graz Lagrangian Model – GRAL (Oettl, 2020a) - was initially developed in 1999, and has been used extensively in regulatory assessments and scientific studies. The model is used worldwide by more than 1,000 authorities and research institutes. Over the years the capabilities of GRAL have been extended, and the current version of the model can simulate the following:

- Dispersion of chemically non-reactive pollutants.
- Computation of odour-hours based on a concentration-variance model (e.g., Oettl and Ferrero, 2017).
- Dry and wet (only in transient mode) deposition and sedimentation.
- Dispersion from road tunnel portals. GRAL fulfils the requirements of the Technical Guideline RVS 04.02.12 in Austria (e.g., Oettl, 2002).
- Dispersion over the full range of wind speeds, in particular low-wind-speeds (e.g., Oettl, 2005; Anfossi, 2006), and for all stability conditions.
- Dispersion in built-up areas, including building downwash effects (e.g., Oettl, 2015a; Oettl, 2015b).
- Dispersion of stack emissions, taking into account temperature and exit velocity (e.g. Oettl, 2020a).
- Dispersion in complex terrain, allowing for the effects of buildings (e.g., Oettl 2015c).
- Decay rates (e.g. bacteria die off, radioactive decay)
- Flow and dispersion within vegetation layers
- The model can handle steady-state (standard mode) as well as transient simulations (e.g. puff releases) (e.g., Petrov, 2019)

The effect of buildings and vegetation on dispersion is taken into account using a micro-scale flow-field model. This is fully integrated into the GRAL code and is automatically launched whenever buildings or vegetation layers are added to the model domain. In the case of complex terrain, GRAL can be coupled with the prognostic, meso-scale wind field model GRAMM (‘Graz Mesoscale Model’; (Oettl, 2020b)). Both GRAL and GRAMM are parallelised and can be run on both Windows and Linux operating systems. The models can be operated through a graphical user interface (GUI) which has been thoroughly tested for Windows operating systems. Since 2017 a LINUX version for the GUI is available, though it is not as intensively tested as the Windows version. There is no limit to the number of separate emission sources that can be included in a GRAL simulation. The lower bound for the horizontal grid size is 2 m, and there is no upper bound. The scale of application ranges from individual streets (e.g. street canyons) to urban agglomerations that are several tens of kilometres across. At all scales the effects of buildings and/or topography (e.g. cold air drainage flows) on dispersion are taken into account.

GRAL allows the usage of odour emission rates in M OU/h and offers two different methods for odour impact assessments. The first, is the calculation of user-defined percentiles (e.g. 98 percentile of mean-hourly odour concentrations at a receptor). In this case, the model outputs are odour-concentration maps for the specified percentile. The second, is based on the computation of odour hours, whereby the Peak-to-Mean Ratio can either be calculated by a spatially and temporal constant value (adjustable by the user), or by using the concentration-variance model by (Oettl, 2017). The concentration-variance model simulates the Peak-to-Mean Ratio (i.e. the ratio of the 90th percentile to mean) in dependence on the three-dimensional structure of the plume(s) and spatially inhomogeneous atmospheric turbulence. The model outputs when using this assessment method are maps showing the frequencies of odour hours. The contribution of each odour source can be assessed by defining source groups in GRAL. For each source group, individual temporal varying emission rates can be defined. An evaluation of GRAL regarding odour assessments has been carried out in, for example, Oettl (2020a), Invernizzi (2020), Brancher (2020a).

Quality assurance is central to the ongoing development of GRAL, based on these fundamentals:

- Regular reports detailing the model physics, and the publication of results in international peer-reviewed scientific journals.
- Comprehensive documentation of the software, with version control.
- A handbook for the GUI that includes hints and recommendations for good practice.
- Validation of every update using 30 different data sets (field experiments, wind tunnel experiments, air quality measurements), as published in the GRAL documentation.

The model (binaries) and the complete documentation is available via: https://gral.tugraz.at/. The GRAL code is available under the GNU/GPL 3 licence: https://github.com/GralDispersionModel.

#### 5.4.5.4. SPRAY

SPRAY is a Lagrangian stochastic particle model designed to perform dispersion simulations in complex terrain (Tinarelli, 2000). The early Version 1 of the code was based on a three-dimensional form of the Langevin equation for the random velocity with coupled non-gaussian random forcing following (Thomson, 1984) which was subsequently improved by (Tinarelli, 1994), was able to satisfactorily reproduce locally to regional scale dispersion both over flat (Brusasca, 1989) and complex terrain (Nanni, 1996) taking into account the emission from single or multiple sources, and low-wind stable conditions (Brusasca, 1992). Version 2 introduced a better-based theory (Thomson, 1987) covering the further demand of more complex regional scale simulations taking into account longer periods (of the order of entire years) with a variety of emissions of different kinds (i.e., main roads, industrial or urban areas). Version 3 of the SPRAY code currently released includes some improvements, enhancing the description of turbulence parameterisations, introducing building downwash effects and improving the time response characteristics for long simulations. In addition, specific developments for odour applications have been introduced, allowing the calculation of a longitudinal Peak-to-Mean Ratio, based on the original work of (Mylne, 1991) and (Mylne, 1992). Two more recent developments have been recently released, allowing more advanced calculations of the Peak-to-Mean Ratio considering respectively a simplified form of the variance transport equation and a Micromixing Model. (Tinarelli et al.,2022).

SPRAY can be linked to the output of different meteorological models able to reconstruct 3D fields of the meteorological flow over complex terrains, such as the diagnostic code SWIFT or the prognostic codes RAMS or WRF.

A more comprehensive version of the SPRAY code, allowing simulations at the microscale (horizontal resolution of the order of 1 m, explicitly considering the effects of buildings or obstacles to the atmospheric flow) and implementing a sophisticated MPI parallelisation scheme has been introduced. This version, named PSPRAY, is part of the PMSS modelling suite (Oldrini, 2017), maintained by ARIA Technologies and ARIANET, including the PSWIFT diagnostic meteorological code, working at the microscale.

#### 5.4.5.5. QUIC

The QUIC fast-response urban dispersion modelling system computes the three-dimensional wind patterns and dispersion of airborne contaminants around clusters of buildings. The system is comprised of a wind model, QUIC-URB; a Lagrangian dispersion model, QUICPLUME; and a graphical user interface, QUIC-GUI.
QUIC-URB uses empirical algorithms and mass conservation to estimate the wind velocities around buildings.

The QUIC-PLUME dispersion model is Lagrangian, that is, it tracks the movement of particles as they disperse through the air. QUIC-PLUME utilises the mean wind fields computed by QUIC-URB and produces the turbulent dispersion of the airborne contaminant using random walk equations. QUIC-PLUME has been specially adapted to account for particle reflection on building surfaces and for the additional dispersion due to horizontal inhomogeneities in the turbulence field. QUIC has been also used for applications involving odours, see for example, Pettarin et al. (2015) and source location, see Gunawardena et al. (2021).

### 5.4.6. Summary of Lagrangian Puff and Particle Models

Table 5-5 summarises the key features of Lagrangian puff and particle models.

**Table 5-5** Summary of key features of well-known regulatory Lagrangian Puff and Particle models used in odour assessments around the world today

| Description | CALPUFF | SCIPUFF | SPRAY | AUSTAL \ LASAT | GRAL | LAPMOD |
|---|---|---|---|---|---|---|
| **Dispersion** | | | | | | |
| Dispersion coefficient (σy, σz) options | -direct measurements of σv and σw<br>-estimated values of σv and σw based on similarity theory<br>-PG dispersion (rural areas)<br>-McElroy-Pooler (urban areas)<br>-CTDM (neutral/stable) | Employs second-order closure turbulence schemes | | | | Hanna et al. (1982) for stable and neutral conditions.<br>Hurley and Physik (1993) for convective (i.e. unstable) conditions. |
| **Special features for odour modelling** | | | | | | |
| Odour input and output units | Input -point and volume sources ou . $m^3$/s<br>Input – area sources ou . m/s<br>Output units in odour units (ou/$m^3$) | | | | | Suitable multiplication factors in LAPMOD or its post processor allow to use any emission unit |
| Output statistics for odour | Percentiles, exceedances, ranked, isopleth, exceedance plots | Percentiles, exceedances, ranked, isopleth, exceedance plots | Percentiles, exceedances, ranked, isopleth, exceedance plots | Percentiles, exceedances, ranked, isopleth, exceedance plots | Percentiles, exceedances, ranked, isopleth, exceedance plots | Percentiles, exceedances, ranked, isopleth, exceedance plots |
| Sub-hour capability | Version 6 of the model allows sub-hour meteorology including measured sub-hour turbulence coefficients | 1-hour time step | 1-hour time step | 1-hour time step | 1-hour time step | Theoretically up to 1 second |

| Description | CALPUFF | SCIPUFF | SPRAY | AUSTAL \ LASAT | GRAL | LAPMOD |
|---|---|---|---|---|---|---|
| Adjustments to <1-hour averaging periods | 1-hour averaging period is minimum with 1-hour meteorological data, which means <1-hour assessment criteria must apply external power law equation. Otherwise, averaging time will be same as meteorology time step, i.e., 10-minute meteorology means a 10-minute averaging time | | | | | The best option is to use a high frequency meteorological field (e.g., CALMET output with 10-minute time step). |
| Concentration fluctuations<br>(built in Peak-to-Mean Ratio) | CALPUFF 1st-order closure integrated puff model<br>User must apply PtM factor when using 1-hour meteorology. Otherwise use sub-hour meteorology and turbulence parameters in place of PtM factor. | SCIPUFF is a 2nd-order closure integrated puff model. Velocity fluctuations might be obtained without external application of PtMR, but requires modelling the turbulence | | | | Possibility to use a constant PtMR, or a dynamic PtMR based on stability conditions and time from release |
| Treatment of calms | Yes, user-defined min wind speed (def 0.5 m/s).<br>Model switch from distance to time dependent sigma's, no downwash, slug model, no gradual plume rise.<br>Puff will diffuse with time but not be advected anywhere | Yes | Yes | Yes | Yes | Yes |

## 5.4.7. Particle-puff Lagrangian models

Some Lagrangian models employ a Particle-puff approach, described in 5.3.4.3. Hurley (1994) found that particle numbers, memory and computer time requirements were significantly reduced compared to a regular particle model. This is because fewer particles were needed as turbulence only needs to be resolved vertically, and each particle influences any concentration grid points horizontally. There is little literature on applying Particle-Puff models and their use or evaluation in odour assessments. However, these models are expected to return similar results to standard Lagrangian particle and puff models and are more computationally efficient than full particle models.

### 5.4.7.1 TAPM

Australia's Lagrangian model, The Air Pollution Model (TAPM) (Hurley, 1994; Hurley, 2002), is different to typical air pollution models that rely on semi-empirical/analytic approaches based on Gaussian plumes or puffs. TAPM solves approximations to the fundamental fluid dynamics and scalar transport equations to predict meteorology and pollutant concentration for a range of pollutants important for air pollution applications. TAPM consists of coupled prognostic meteorological and air pollution concentration components, eliminating the need for site-specific meteorological observations. Instead, the model predicts the flows important to local-scale air pollution, such as sea breezes and terrain-induced flows, against a background of larger-scale meteorology provided by synoptic analyses.

The meteorological component of TAPM is an incompressible, non-hydrostatic, primitive equation model with a terrain-following vertical coordinate for three-dimensional simulations. The model includes cloud microphysics. The model includes a vegetative canopy, soil scheme and urban scheme, which are used at the surface, while radiative fluxes at the surface and at upper levels are also included. The air pollution component of TAPM, which uses the predicted meteorology and turbulence from the meteorological component, consists of four modules. The Eulerian Grid Module solves prognostic equations for the mean and variance of concentration and the cross-correlation of concentration and virtual potential temperature. The Lagrangian Particle Module can accurately represent the near-source dispersion model (Physick, 1994). The plume rise module (Hurley, 1995) accounts for plume momentum and buoyancy effects for point sources. The building wake module is based on PRIME (Schulman, 2000) and allows plume rise and dispersion to include wake effects on meteorology and turbulence. TAPM also includes gas-phase photochemical reactions based on the Generic Reaction Set, gas- and aqueous-phase chemical reactions for sulphur dioxide and particles, and a dust mode for total suspended particles (PM2.5, PM10 and PM20). Wet and dry deposition effects are also included. The output of TAPM will allow the extraction of time series, profiles and summary statistics of pollution. A built-in graphical user interface allows the user to see colour-shaded maps of concentration statistics, which are also easily exported into a spreadsheet. Time series of pollution can be easily viewed. TAPM does not allow odour input emission units or output in odour units. The model will output concentration as either µg/m3 or ppb for all model heights. The model will also process the percentiles (90th – 99.9th) level. Scaling factors, such as a 3-minute averaging time or PtM factors, would need to be applied to the predicted ground-level concentrations after TAPM has been executed in a spreadsheet.

TAPM is widely used in Australia and New Zealand, primarily to develop upper air data as single or multiple vertical profiles or as gridded data. This data is commonly used as input to the CALMET diagnostic meteorological model, on which CALPUFF is then executed. TAPM includes routines to single output 1-dimension meteorological data for AUSPLUME and\or 2-dimensional meteorological data in AERMOD and CALMET format for any location over its model domain. In addition, TAPM can output gridded 3D data at typically 1 km resolution or larger.

In summary, although TAPM is not used exclusively in odour applications within Australia and New Zealand, it is an essential and frequently used model in most odour assessments that require dispersion modelling.

# 5.5. General well-known problems/limitations/solutions

## 5.5.1 General introduction

This section aims to give a general picture of the main problems presented using the different model types described in the previous paragraphs, both in general terms and specifically for the odour assessment applications. Different descriptions are reported for each model type, even though some problems may be familiar to different models.

## 5.5.2 Gaussian models

### 5.5.2.1 Overview

Meteorological conditions are horizontally homogeneous within the modelling domain. This means that meteorological variables such as wind speed and direction, mixing height, temperature, humidity, and turbulence variables such as surface friction velocity (u*), convective velocity scale (w*), Monin-Obukhov length (L), have the same value at a specific time over the domain.

Meteorological conditions are assumed constant over the time needed for the plume to reach each receptor; also, source characteristics, including emission rates, are constant.

Finally, each hour is separate and independent of other hours: there is no memory of pollutant location or emissions from other hours (see Figure 5-12).

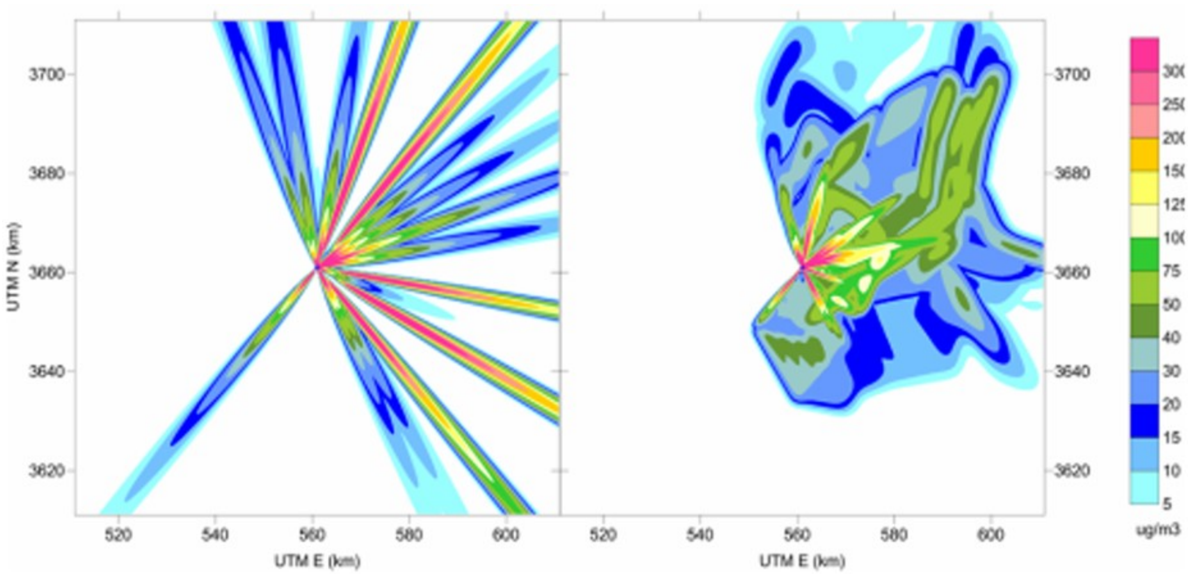



**Figure 5-12** Comparison of Steady-state Gaussian plume model (left) vs Lagrangian puff model (right) for 24-hour simulation over flat terrain (Courtesy of Atmospheric Science Global)

### 5.5.2.2 Complex environments where the Gaussian plume model is not applicable

Sea breezes, thermal internal boundary layer (TIBL) fumigation, inversion break-up fumigation, terrain channelling effects, stagnation and retention events, causality effects, horizontal and vertical wind shear effects are all complicated 3-dimensional features that require sophisticated meteorological models in order to simulate these events realistically. These phenomena are significant everyday occurrences affecting all source types, from ground-level-based odour sources to those released from tall point sources such as pulp and paper mill factories.

The only way to capture these phenomena is to use sophisticated diagnostic and numerical meteorological models. Interfacing gridded 3D wind fields from traditional weather-type models with a fine resolution diagnostic meteorological model such as CALMET allows regional flows to be captured with the added benefit of including multiple observation stations. In many instances, gridded 3D numerical model data (e.g., WRF and ECMWF) is more useful than a single observation site typical of Gaussian plume models which:

A. tend to be representative of conditions in their immediate vicinity,
B. frequently suffer from missing or loss of data and,
C. are limited to just the surface.
D. unable to capture the 3D signal in the atmosphere.

Precipitation, gridded cloud cover and detailed sea surface temperatures are additional significant advantages of using numerical meteorological data in regulatory modelling.

The procedure of combining sophisticated numerical 3D gridded data into a diagnostic meteorological model permits the prognostic model to be run with a significantly larger horizontal grid spacing and different vertical grid resolution than that used in the diagnostic model, which can then be run at a much finer resolution (< 250m) incorporating fine-scale terrain and Land Use data. This allows the three-dimensional features of the flow field, such as the sea breeze circulation with return flow aloft, which may not be captured in the surface observational data, to be introduced into the diagnostic wind field results.

Gaussian plume models such as AERMOD and ADMS, which are limited to one surface meteorological site and an upper air profile, do not know the three-dimensional flow and therefore produce spatially uniform meteorology across all receptors. This is a major drawback of the steady-state assumption. Usually, the winds are derived from a single point measurement from a nearby site, such as an airport which does not necessarily reflect the flow in the valleys. Steady-state models do not adjust the winds to reflect the terrain effects, and the net effect is that the steady-state flow field does not reproduce the terrain-induced spatial variability in the wind fields. In addition, the plume model's straight-line trajectory assumption cannot handle the curved flow associated with terrain-induced deflection of channelling.

Figure 5-13 shows the results of 3 individual sources and their related plumes from AERMOD vs that from a Lagrangian puff model, CALPUFF. In a complex terrain simulation, the plumes from the simple plume model blow directly across the valley, regardless of the terrain. In this scenario as well as the plumes going in the wrong direction, they also give unrealistically high concentrations on the terrain features, and they do not model the cumulative impact as they do not overlap.

Gaussian models should not be used in complex flow situations (i.e., conditions where steady-state criteria are not met). Examples of complex flow situations are:

- Complex terrain
- Coastal regions/ land-water boundaries
- Overwater transport
- Inhomogeneous dispersion conditions
- Land use/land cover variation
- Distance (> 10 - 20 km)
- Stagnation
- Light wind speed dispersion, calm conditions
- Flow reversals
- Land-sea breeze
- Upslope/downslope, valley flows
- Recirculation

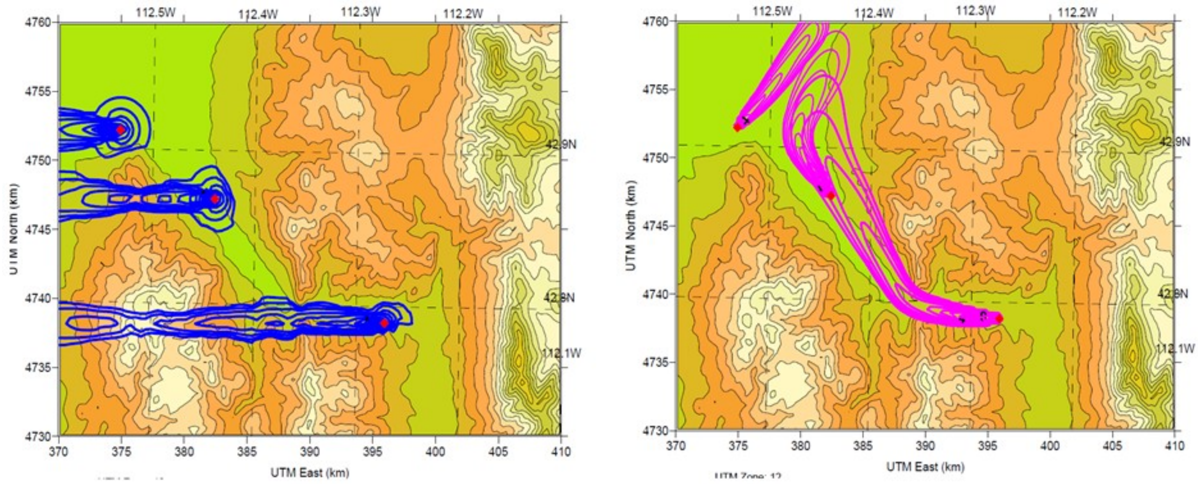



**Figure 5-13** Cumulative impacts and terrain channelling effects from three sources using AERMOD (left) vs CALPUFF (right). The spatially varying wind flow produced by CALPUFF is shown in the figure on the right, where winds are channelled through the main valley, generating a cumulative impact. AERMOD on the other hand has a uniform wind field and is unable to produce terrain channelled effects, hence the three sources do not overlap (Barclay and Borissova 2013).

#### 5.5.2.2 Light winds, calms and lateral plume meander

Light winds, calms and lateral plume meander are important because:

- Odours can reach their highest levels
- They are difficult to model – models struggle to capture the generation of turbulence by mesoscale motions
- All models rely on advection
- Plume models (e.g., AERMOD, ADMS) have inverse wind speed dependency therefore cannot handle calms
- Turbulence diffusion never completely vanishes (never strictly laminar), but the turbulence diffusion can be extremely slow
- Flow tends to be terrain driven, in combination with heating and cooling of near-surface air
- Very strong inversions develop under clear skies
- Flow in stable hours usually downslope but can be multi-layered due to different potential temperatures of different contributory flows
- Cloud shadow – immediate negative heat flux which sets up turbulence suppressing stratification near the ground

Gaussian plume models, such as ADMS and AERMOD, are unable to model calm winds and will simply skip over these hours. In AERMOD, the minimum allowable wind speed to define the boundary layer parameters is defined as $2^{1/2} * \sigma_{vmin}$ where $\sigma_{vmin}$ =0.2 m/s (then the minimum wind speed is about 0.28 m/s). This minimum is independent of the threshold wind speed, which is 0.51 m/s. The restriction is based on the accuracy of the instruments. Sonic anemometers have no threshold limitations; therefore, no wind speed threshold is imposed, and the output AERMINUTE file can have winds lower than 0.28 m/s. ADMS has a low wind speed threshold similar to AERMOD and is currently set at 0.3 m/s. If the wind speed is lower than 0.3 m/s (including 0.0 m/s), ADMS will increase the wind speed to 0.3 m/s and adjust the friction velocity and surface heat flux. However, it is essential to note that the minimum wind speed at 10 m is 0.75 m/s.

By US-EPA (and Australia) regulatory requirements, any data set that does not meet the 90% data coverage must use AERMINUTE, which is a meteorological processor (or another method) to re-process the 1-10 minute automatic weather station readings to produce a new 1-hour average wind speed and wind direction which is different than the regular standard archived hourly data. AERMINUTE generates a new meteorological data set with fewer calm periods and much more wind in the range of 0.1 m/s to 1 m/s. However, while AERMINUTE solved one problem (i.e., reduced the number of calms in a data set and thereby increased the number of hours modelled to > 90%), increasing the number of very light winds created other problems, such as AERMODs tendency to over-predict in light winds, and its treatment of lateral plume meander, which is responsible for most of the horizontal plume dispersion in stable atmospheric conditions. AERMOD, similarly to ADMS, accounts for the lateral meander of plumes in the stable boundary layer by interpolating between two concentration limits, the coherent (wind direction determined) plume limit, and the random plume limit which assumes an equal probability of any wind direction.

As the wind speed approaches zero, plume transport and dispersion changes from a “coherent” plume (Gaussian shape) advected in a single direction to a random or “pancake” plume dispersing radially in all directions.

This scheme in AERMOD was understood to apply to situations when the wind speed was near zero, but it actually applies to all wind speeds. AERMOD concentrations are thus a sum of the Coherent Plume and Random Plume (see Figure 5-14) according to

$$\text{Conc (final)} = \text{F(Random)} * \text{Conc(Random)} + (1 - \text{F(Random)}) * \text{Conc (Coherent)}$$

Where F(Random) is the fraction of plume removed from the main (coherent) plume and distributed in circular 360-degree rings around the source, including upwind of the source.

Mass is removed in all conditions, not just light wind speeds. Under some convective conditions, a large amount of mass (40 to 67%) is removed from the main plume, which is thus depleted. The effect of the random plume is potentially large concentrations located upwind of each source that may even exceed plume concentration downwind under some conditions, such as hilly terrain upwind of the source.

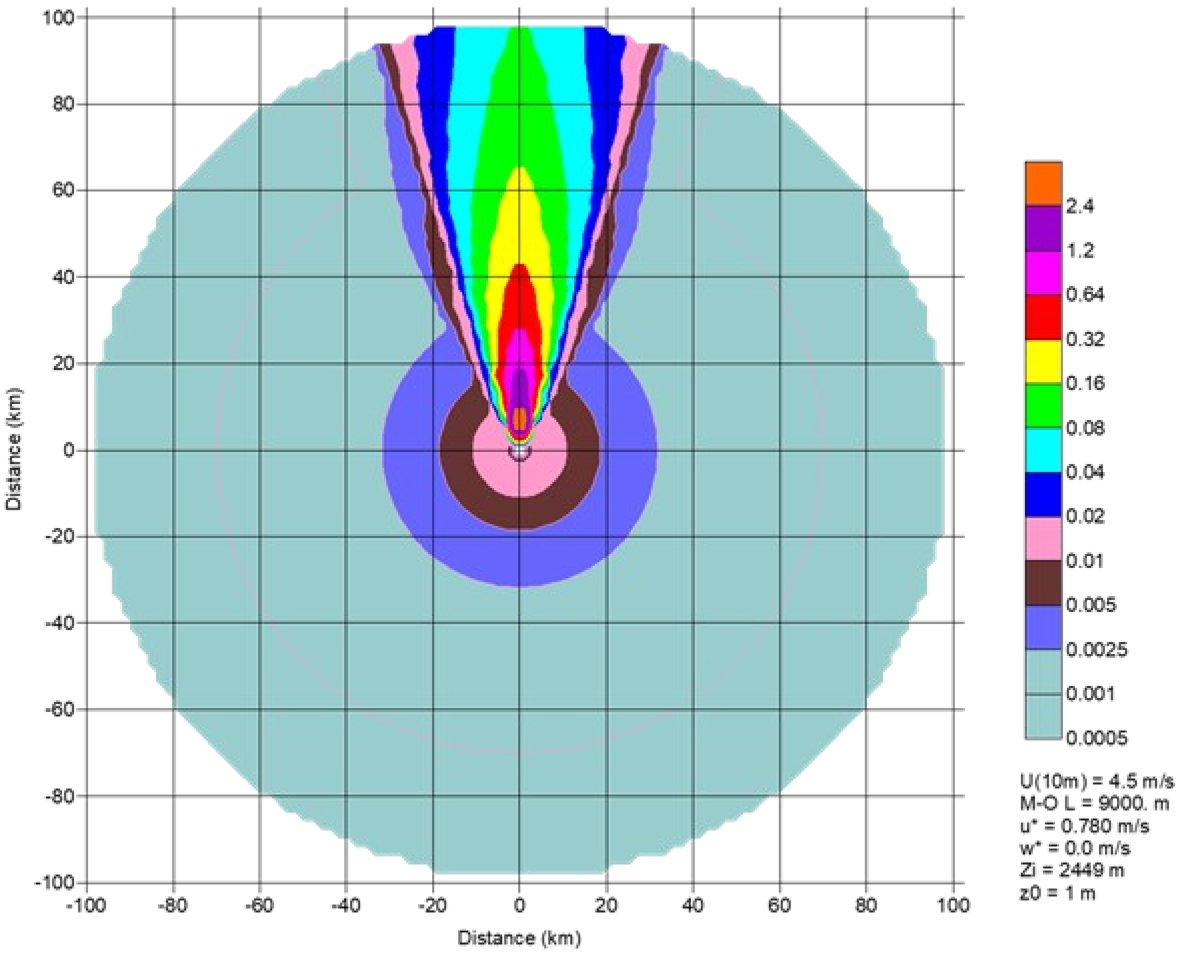



**Figure 5-14** AERMOD predicted concentrations for steady 4.5 m/s wind and neutral stability. Concentrations occur upwind due to the random plume effect (Courtesy of Atmospheric Science Global)

Figure 5-15 shows the significant amount of mass removed from the main coherent plume and placed into the random plume for a light wind situation in convective conditions (40% to 65%) and under a steady wind in neutral conditions (6% - 16%). In moderate terrain applications, the concentration can be higher upwind of the source than downwind, and in many instances, this has led to concentration under predictions downwind. As a result, major changes have been made to AERMET and AERMOD since 2012 to try and improve AERMOD's predictions in light winds. These changes are still ongoing today. These modifications, which affected both AERMET and AERMOD, are summarised below.

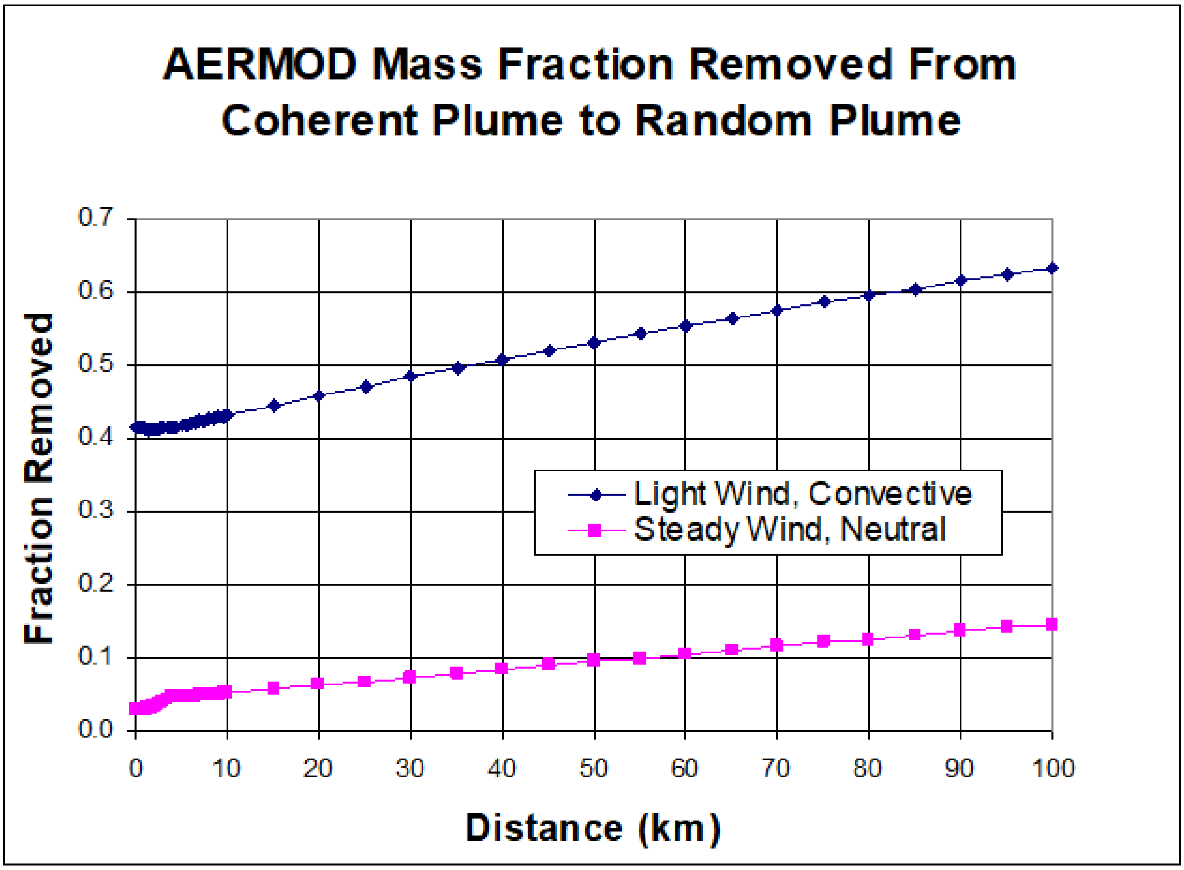



**Figure 5-15** AERMOD Mass fraction removed from coherent plume to random plume (Courtesy of Atmospheric Science Global)

Since 2012 until 2018, the US EPA underwent significant major changes to AERMET (points 1, 2 below) and AERMOD (points 3, 4, 5 below) which included:

1. Development of AERMINUTE in order to recompute the hourly average from 1 and 5-minute ASOS data. The effect of this was to increase the number of light winds in the category 0.1 – 0.5 m/s and increase the number of modelled hours to 90% or more.
2. Adjustment to the friction velocity (Adj_u*)
3. Introduction of 4 LOWWIND options
4. FRAN (adjustments to the random\pancake plume)
5. Adjustments to the minimum value of $\sigma_v$

At the 2012 10th EPA Modelling Conference, modifications were made to AERMOD V12345 called the 'beta ADJ_u*' option for a revised u* formulation under stable conditions and two different low wind speed options in AERMOD (Jeffrey et al., 2013). It was found that AERMOD was routinely under-predicting u* during stable boundary layer conditions under low wind speeds. This had the effect of underestimating the mixed layer height, leading to the overestimation of concentrations trapped within the mixed layer. However, the effect of Adj_u* sent the model back to under-predicted concentrations. Therefore, it was realised that changes were needed for AERMOD and AERMET.

Between 2012 and 2018, the US EPA developed 4 LOWWIND (US EPA LOWWIND White

Paper) options; each option was mutually exclusive, non-default beta options focused on the minimum value of sigma-v (lateral turbulence intensity). Further, each of these options included changes to the default plume meander. The LOWWIND options were briefly;

LOWWIND1 (V12345) increased minimum σv of 0.2 m/s to 0.5 m/s; turned off the horizontal meander component altogether, and eliminated upwind dispersion, whereas;

LOWWIND2 (V12345) increased the minimum σv of 0.2 m/s to 0.3 m/s, incorporated meander with an adjustment on the default upper limit of the meander factor (FRAN) from 1.0 to 0.95. It included upwind concentrations due to horizontal meander and an adjustment to the meander component, e.g., 12 hours is used for BIGT (time scale where mean wind information at source is no longer correlated with plume location) instead of 24 hrs).

LOWWIND3 (V16216) increased the minimum σv of 0.2 m/s to 0.3 m/s, consistent with LOWWIND1, but used the FASTALL approach that matches centreline concentration for LOWWIND2, based on an effective σy. This scheme eliminated upwind dispersion – the effect of this is to potentially cause higher concentrations for receptors near the plume centreline than LOWWIND2.

Alpha LOWWIND (V18081) allowed the user to adjust the minimum σv (default 0.2m/s) within the range 0.01 - 1.0 m/s, the min wind speed value from 0.01 - 1.0 m/s (default 0.2828 m/s) and, the meander factor within the range of 0.0 - 1.0 (default 1.0). [Note. Alpha options are for 'experimental' use only and are not to be used for regulatory applications].

The US EPA subsequently then removed the LOWIND1, LOWIND2 and LOWWIND3 options. The current version of the model now includes the adjust u* option (ADJ_u*) and the alpha LOWWIND option, which was designed to aid in further exploring potential improvements in model predictions under low wind conditions. However, since there is virtually no literature on how variations of these parameters perform, plus alpha options are experimental only, most users worldwide continue to use the model default options.

ADMS, similarly to AERMOD, treats the plume's lateral meander in light wind conditions through a radial solution. The default wind speed is 0.5 m/s (unless specified in an external input file), and when the wind speed data is below this, the model will calculate the radial plume only and not the coherent plume. The approach used for calm conditions > 0.5 m/s is to calculate the concentration as a weighted average of a normal Gaussian-type plume ($C_g$) and a radially symmetric plume ($C_r$), where the weighting depends on the wind speed at 10 m. The radially symmetric plume is modelled as a passive source with a source height equal to the maximum plume height from the standard plume rise calculations. It assumes an equal probability of all wind directions. The model calculates Cr only for winds less than the threshold (0.5 m/s or as specified in an external file).

In addition, area sources in AERMOD currently do not experience any lateral meander. In the latest US-EPA (2021) LOWWIND White Paper, the EPA looks for "considerations for updates in the AERMOD model system" and "welcomes input from the community on the possible implementations of meander for area sources". The lack of plume meander for area sources means that area sources will most likely be significantly under or over-predicting ground-level concentrations. This has serious consequences for many odour sources, which are largely ground-based area sources, such as, for example, evaporating and wastewater ponds, clarifiers, composting, and biofilters.

## 5.5.3 Lagrangian models

### 5.5.3.1 Lagrangian puff models

Lagrangian puff models describe a continuous emission as a series of discrete packets (i.e., puffs) of pollutant material which move independently (Scire et al., 2000). The centre of each puff moves by advection according to the “local” wind field. The “local” wind field may be, for example, the wind at the height where the larger puff mass is located or the average wind speed and direction along the vertical size of the puff.

The effect of atmospheric turbulence is to increase the puff size as it moves. Some formulations are available to describe the puff growth; they depend typically on the standard deviation of the wind components, the travel time of the puff and the Lagrangian time scales. The standard deviation of the wind components may be estimated in different ways depending on the atmospheric stability conditions.

Puffs are typically spherical; however, sometimes, they may be stretched along the wind direction. They are named “slugs” in those cases. In near-field applications, when the wind field is rapidly varying, using slugs is important because it assures the correct calculation of the concentration fields.

The vertical wind shear across a single puff, when significantly extended along the vertical, is typically managed by splitting the original puff into smaller puffs by conserving the mass. This procedure is called “puff-splitting”. Actually, puff splitting may be both along the vertical and along the horizontal direction (http://www.src.com/calpuff/FAQ-answers.htm). Horizontal puff splitting is needed when the puff becomes very large and covers several meteorological grid cells. In such a case, a single huge puff would not respond correctly to the cell-to-cell meteorological variability; therefore, it must be divided into more small puffs. The application of this procedure is important both in long-range simulations and in simulations over smaller domains, typical for odour impact studies when the meteorological grid size is kept small to reconstruct terrain features as precisely as possible. Applying the puff splitting procedure increases the number of puffs and, therefore, the computational resources required for the simulation.

Lagrangian puff models have many advantages with respect to the Gaussian plume models. The main one is the possibility of using three-dimensional time-varying meteorological data to obtain more realistic concentration fields. Additionally, these models can handle calm or low-wind conditions, which are important while evaluating odour pollution. For example, considering the Lagrangian puff model CALPUFF, puffs are not advected by the model during calm hours. However, they continue to increase their size due to atmospheric turbulence.
Puff models can simulate a large variety of sources. Considering the sources of interest in odour applications, they can simulate point sources (e.g., stacks), area sources (e.g., biofilters, tanks, and landfill portions) and line sources (e.g., transportation of malodorous substances and polluted water channels). When point sources are modelled, plume rise

algorithms are activated.

Concentrations at each receptor are due to the sum of the contributions of each puff (e.g., De Visscher, 2013; Zannetti, 2013). CALPUFF (Scire et al., 2000), probably the most used Lagrangian puff model, includes a simple averaging-time scaling factor to estimate short-term peak concentrations needed in odour modelling. The first method includes a scaling factor (through the input variable AVET) to adjust the lateral dispersion coefficient, which means acting on plume meandering. The second method uses the scaling factor directly on the output concentrations (in CALPOST or any other post processor). In both cases, the scaling factor used in CALPUFF is constant, depending on a 1/5 power law of the time ratios (e.g., 60 minute of the output concentration or the Pasquill Gifford averaging time of the lateral dispersion coefficient, and 1 minute for the averaging time of interest to get the peak value). This scaling factor of CALPUFF does not depend on the stability conditions or the puff travel time.

One of the drawbacks of Lagrangian puff models with respect to Gaussian plume models is the longer time needed to carry out simulations. These additional computational resources are due to the inherent complexity of the model and the high number of puffs that must be released to get good concentration fields. The number of puffs may also increase during the simulation due to puff-splitting, as mentioned above. Additionally, computational times are longer when area or line sources are used, with respect to emission scenarios involving only stacks.

The use of a Lagrangian puff model requires additional resources with respect to a Gaussian plume model, both in terms of computational time, both in terms of knowledge (more input data and variables required). Additionally, even though such models can be used with a single point meteorology as AERMOD or the old ISC3, the best results are obtained only using a three-dimensional meteorological model (e.g., CALMET), therefore, the user is required to know how to use it. Also, diagnostic models as CALMET may be fed by the output of complex prognostic meteorological models (e.g., WRF), which are very difficult to use, and require huge computational resources (indeed they often require to hire cloud computational resources, as for example AWS, Amazon Web Services). All this additional complexity must be justified. Using a Gaussian plume model may be a reasonable choice when the simulation must be carried out over an almost flat domain with practically no calms.

As mentioned, an additional difficulty in using Lagrangian puff (and particle) models is related to preparing the meteorological field. Practical problems must be faced and solved. For example, the user must decide which grid resolution can describe the terrain features within a complex terrain domain without requiring many computational points. A practical suggestion in these cases is to describe each terrain feature with 5/10 grids (e.g., http://www.src.com/calpuff/FAQ-answers.htm). For example, if the width of a valley is 2 km, the user should use a meteorological grid size ranging from 400 m to 200 m.
Of course, once the domain and grids of the meteorological model are defined, the average terrain elevation over each grid must be determined. The original (raw) terrain data must have a spatial resolution equal to or higher than the grid resolution. For example, the SRTM (*Shuttle Radar Topography Mission*) data may be used for practically any domain in the world (https://srtm.csi.cgiar.org/srtmdata/). The same operation must be performed for the land use data. The land use over each grid must be defined as the prevailing one, not the

average one as for terrain. For example, the original (raw) land use data for the European territory may derive from the CORINE Land Cover project (https://land.copernicus.eu/pan-european/corine-land-cover). A final check must be done to evaluate the correctness of the gridded values of terrain and land use, for example, using tools such as Google Earth. An example of a terrain map averaged over the grids of a simulation domain and superimposed on Google Earth is shown in Figure 5-16. Similarly, Figure 5-17 shows the general land use over the same domain.

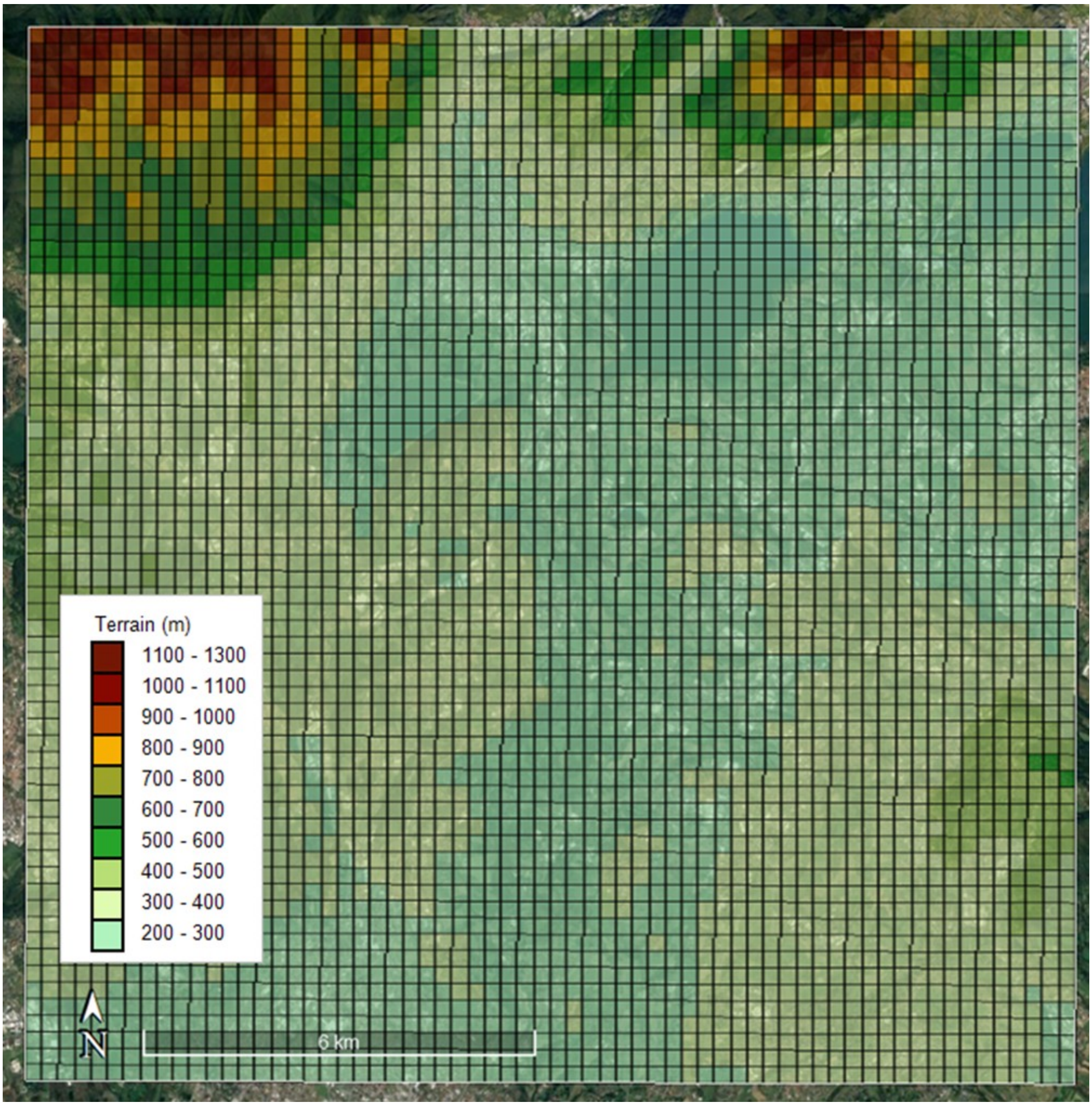



**Figure 5-16** Example of average terrain elevation over a 16x16 km$^2$ domain with 250 m grid size (Courtesy of Enviroware).

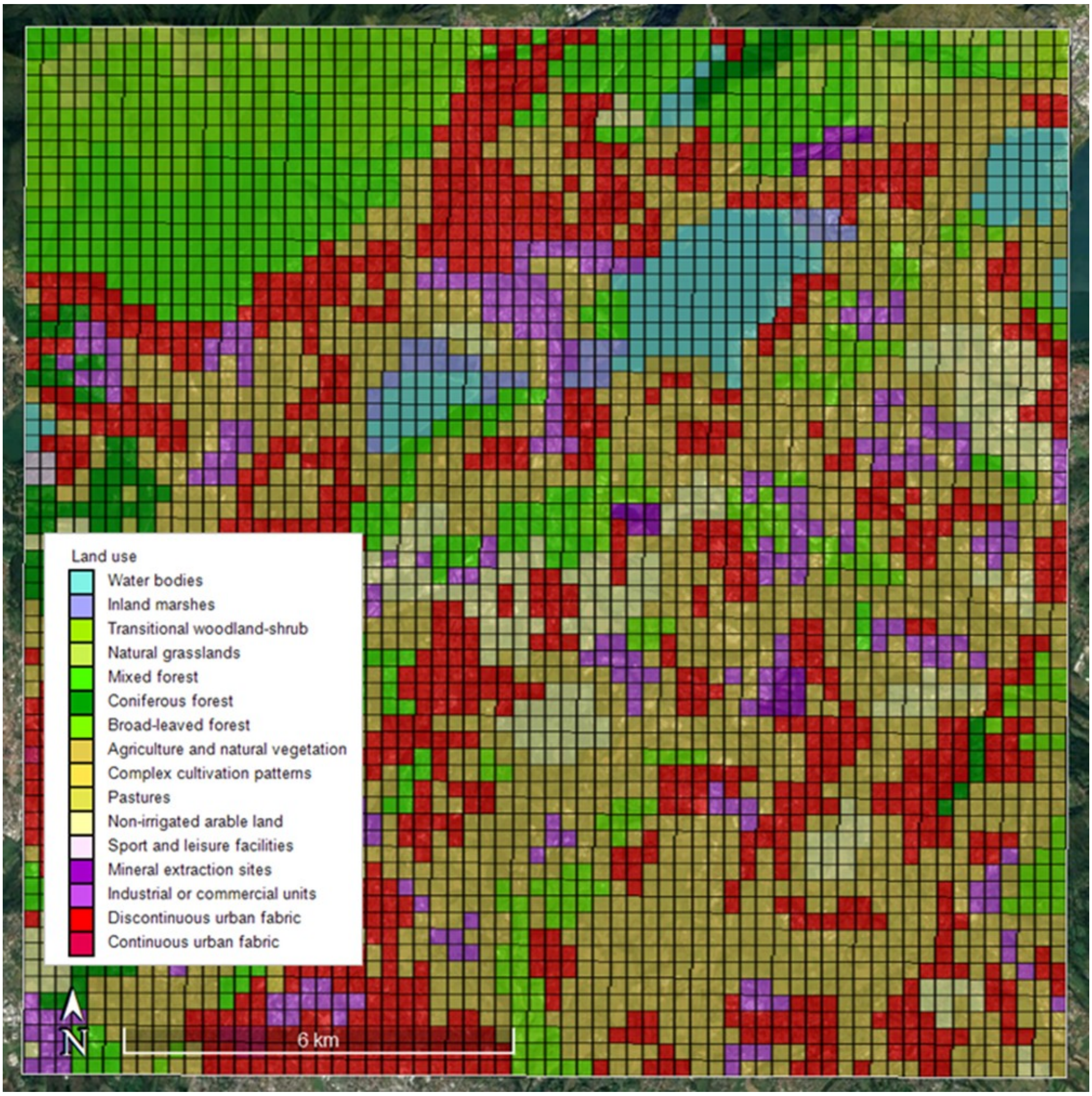



**Figure 5-17** Example of prevailing land use over a 16x16 km$^2$ domain with 250 m grid size (Courtesy of Enviroware).

When preparing the meteorological field with a diagnostic model such as CALMET, particular attention must be paid to the quality of the surface and upper air input data quality. For each hour of simulation (assuming for simplicity simulations with 1-hour resolution), each meteorological variable must have a valid value at least in one surface station; otherwise, the model stops the simulation with an error message. This means that the user must check the quality and validity of the input data and, if needed, define a procedure to recover the missing values. When missing values are sparse, scalar variables (e.g., temperature, precipitation, relative humidity) may be recovered simply by averaging the values containing the missing data, or by repeating the last valid value.

The same procedure may be adopted for wind speed and direction, even though the situation is a bit more complicated (for example, it must be decided if a scalar or a vector average must be performed). When the missing values are continuous for a relatively long time, if there are no other stations with valid data for that period, a possible option is to create a pseudo station, possibly close to the borders of the simulation domain, starting from the output of a prognostic model such as WRF.

The situation is even more difficult when the missing data involve vertical profiles. Vertical profiles are typically available twice daily, and a single upper air station is often used in simulations. Sometimes a full vertical profile is missing, and it could be replaced, for example, by the vertical profile of the same time of the previous day. When the output of a prognostic model is used in the input, the vertical profile issue is automatically solved.

#### 5.5.3.2 Lagrangian particle models

Lagrangian Particle Dispersion Models (LPDMs) offer some general advantages compared to Gaussian Plume and Puff models but show at the same time some specific shortcomings that should be taken into account. The main advantages are related to their intrinsic capability to describe pollutant dispersion three-dimensionally. Particles can move with continuity throughout the computational domain, and the three-dimensional distribution of the particles allows, in principle, a detailed description of the dispersion phenomena everywhere in the PBL. This capability overcomes all previously described spatial problems for the Gaussian Plume and Puff Models (e.g., the need to activate puff splitting procedures when the puff becomes too big).

On the other hand, this evident advantage requires a detailed description of the meteorological conditions necessary to drive a dispersion simulation, particularly turbulence. The difficulties related to preparing three-dimensional non-stationary meteorological fields are the same described for the Lagrangian puff models in the previous paragraph.

Some of the turbulence variables required by LPDMs, such as Lagrangian time scales, are difficult to measure and are not directly calculated by the closure schemes of the turbulence used by the meteorological driving models. Another critical point of LPDMs is related to the statistical dependence of their results. The implementation of the stochastic differential equations inside such models implies the use of random numbers and the use of discrete numerical samples from theoretical distributions. This sampling methodology, typical of all the Monte-Carlo methods, tends to generate final results in terms of concentration fields that are not strictly unique. A different sequence of numbers extracted from the same distribution generates different results in a way that could be erroneously assimilated to the statistical behaviour of the atmospheric turbulence, being instead a consequence of the numerical sampling. This implies a greater difficulty in the operations of a simulation setup to minimise this problem with respect to simpler models involving analytical formulations. This implies finding a tradeoff between the number of particles used to discretise the source emissions and the quality of the simulation. Sometimes, this can be in contrast with the available computational tools. Nowadays, this problem is minimised by the wide availability of parallel computers and the possibility of finding parallel operational LPDMs easily.

Finally, LPDMs share the same problem with other modelling methodologies. Being only able to describe the trajectories of independent particles, they can only deal with average ensemble concentrations, showing an intrinsic difficulty in describing peak values. Ad-hoc algorithms need to be added as post-processing tools to compute Peak-to-Mean Ratios to be applied to the expected results of such models.

## 5.5.4 Eulerian models

### 5.5.4.1 Eulerian grid models

Eulerian grid models suffer the disadvantage that their resolution is confined by the spatial discretisation of the mesh on which they are solved. The use of the mesh is computationally expensive and requires some form of optimisation to achieve any degree of efficiency. As the focus of odour analysis is mainly in the near-field of the source, this approach is not generally applied for odour modelling purposes.

Eulerian grid models have the following limitations for odour assessments:

- Odour sources cannot be adequately described due to their mesh size. The pollutant is immediately spread in the whole grid containing the source, and this is not acceptable for odour, which is typically a short-range problem.
- Due to the typical size of their grid cells, Eulerian models struggle to form a continuous plume in the near field, and odour assessments are mostly near-field issues.
- They do not include near-field algorithms like building downwash or stack tip downwash.
- They are computationally inefficient and slow, especially in complex terrain areas where small grid cells are required to capture the resolution of the terrain.
- They only provide mean concentrations and cannot consider concentration fluctuations, which is important for odour.

### 5.5.4.2 CFD models

In principle, CFD models could be reliable tools to assess odour pollution due to the ability to take into account the impact of many types of obstacles such as buildings, plant structures, and trees on a micro-scale explicitly. However, due to the following drawbacks, CFD models are more commonly used in research rather than for regulatory purposes:

- The preparation of the computational grid can be challenging and requires considerable time.
- The computational time of the simulation is significantly higher than for other, less complex models.
- They are typically used to assess a specific meteorological situation (e.g. neutral atmospheric conditions, a specific wind direction, or a given temperature value).
- The application of a modelling tool is finalised to calculate concentration percentiles over a whole year.
- The model set-up is complex, and the user choice of boundary conditions and grid resolution can easily influence the outcome.

In some cases, the wind field near the source is modelled using CFD. This micro-scale wind field is then inserted into a Lagrangian model to assess the odour dispersion in the impact area. This has the advantage of short computational time, and the meteorological conditions can be better estimated by a specific situation for a small area compared to modelling the whole impact area.

# 5.6. Which model or type of model is suitable for odours?

## 5.6.1 General Introduction

This paragraph briefly summarises the types of air dispersion models which are more suitable for odour assessment. According to what has been written, Eulerian grid models are not commonly used and suitable  for odour assessment in few situations. Additionally, while on the one hand, CFD models are a powerful tool to describe odour dispersion in a complex environment for a specific meteorological situation, on the other hand, they cannot be applied for regulatory purposes (i.e., a minimum of a 1-year long simulation) due to their high-demanding computational resources. Therefore, only Gaussian models (e.g., AERMOD, ADMS, ISCST3, CTDMPLUS, AUSPLUME, SCREEN) and Lagrangian models (e.g., CALPUFF, SCIPUFF, SPRAY, AUSTAL, LAPMOD) will be considered in this paragraph.

## 5.6.2 Key features affecting odour dispersion and model types

A summary of the key features affecting odour dispersion for each model type (Gaussian and Lagrangian) is reported in Table 5-6.

### 5.6.2.1 Time and space causality effects due to the meteorology, including land use effects, recirculations, coastal or mount/valley breeze

Gaussian plume models do not consider causality effects, and their plumes immediately extend in a straight line to infinity (see, for example, Figure 5-1). Lagrangian puff and particle models allow full causality effects; they allow curved and variable trajectories. In principle, Lagrangian particle models are even better than Lagrangian puff models because they do not need the activation of particular algorithms (e.g., puff splitting) to follow precisely the atmospheric flow along the vertical or the horizontal direction.

### 5.6.2.2 Spatial characteristics of the surface

Gaussian models can partially consider the surface variability of the domain. For example, AERMET, the meteorological processor of AERMOD, uses values of geophysical variables averaged along different directions up to a certain distance from the surface meteorological station. The AERSURFACE processor determines these average values.

Additionally, AERMOD can carry out simulations in moderately complex terrain but can only simulate the impingement of the plume on the ground. At the same time, the flow is not affected by the terrain features.

On the contrary, the meteorological processor of the three-dimensional Lagrangian models contains information about terrain elevation and land use (then geophysical variables) in each grid cell (as shown, for example, in Figure 5-16 and Figure 5-17).

### 5.6.2.3 Calm winds and mass accumulations

Odour nuisance may be maximum under calm wind conditions; therefore, it is essential to describe those situations as precisely as possible. Gaussian models cannot handle wind speeds tending to zero because, as previously shown, they have wind speed at the denominator in their basic formulation.

Lagrangian puff and particle models can handle calm wind situations. For example, CALPUFF switches from distance-dependent to time-dependent sigmas at user-defined minimum wind speed.

#### 5.6.2.4 Obstacles/buildings (explicitly simulated or parameterised)

CFDs can treat the presence of obstacles explicitly and modify the atmospheric flow. However, as written above, they are not suitable for regulatory purposes.

Gaussian models can treat obstacles (buildings and other structures opaque to the wind) in a parameterised way. This is the case, for example, of the building downwash algorithms. Some Lagrangian particle dispersion models have been developed to work at the microscale, considering a horizontal resolution of a few metres and explicitly treating the presence of obstacles. This is the case, for example, of PMSS, QUIC, GRAL and LASAT.

#### 5.6.2.5 Short-range/ Long range Simulations

Odour assessment is typically a short-range issue. Both Gaussian and Lagrangian models have features capable of describing short-range effects, such as, for example, building downwash, stack tip downwash and plume-induced turbulence.

**Table 5-6** Key features which affect odour dispersion by model type

| Feature | Gaussian Plume Models | Lagrangian Puff and Particle Models |
|---|---|---|
| Causality effects considered | No causality effects, plumes extend in a straight line to infinity immediately | Full causality effects, allows curved and variable trajectories |
| Spatial variability of surface characteristics (land use) | Land use variability allowed in wind sectors centred over the met station | Land use and parameters (Bowen Ratio, Zo, albedo) vary with each grid cell across model domain |
| Spatial variability of meteorological variables (wind speed, wind direction, temperature) | None, single station and uniform meteorological variables | Full spatial variability of meteorological and turbulence variables |
| Ability to treat calm winds | Cannot handle a zero-wind speed, minimum wind speed must be set else model will skip over calm hours | Models can handle calms. [e.g., CALPUFF switches from distance-dependent sigmas to time-dependent sigmas at user-defined minimum wind speed] |
| Mass accumulation under stagnation conditions | Unable to handle stagnation or accumulation of pollutant mass | Retains previous hours emissions and will allow accumulation under stagnation events |

| | | |
|---|---|---|
| Memory of previous hours emissions or meteorology | No memory, each hour and emission rate are treated independently of previous hour | Full memory |
| Coastal effects, and recirculation | None, or very limited | These more advanced models are linked to advanced 3D diagnostic and prognostic meteorological models so include the ability for TIBL calculations and 3D sea and land breeze |

## 5.7. Model validation in the frame of odour applications

Model validation is a fundamental phase in developing and using mathematical models – both analytical and numerical - because it allows for determining the model's reliability. In principle, validation can be divided into three steps:

- Theoretical validation, which means to verify if all the physical and chemical equations needed to describe a specific problem have been considered in the mathematical model.
- Validation of the implementation phase (or code verification), which means verifying if possible approximations or simplifications introduced in the original equations to solve them (analytically or numerically) are acceptable. In the case of a non-analytical solution, the numerical method must guarantee accuracy and a reduced numerical error. Finally, the correct implementation of the resulting model into a computer code must be evaluated and tested. The correct implementation can be verified by accessing the code and checking how the model algorithms are written (for open-source models). Testing can be done by applying the so-called sensitivity analysis, which evaluates if model output varies in agreement with model input. Sensitivity analysis can also be used to implicitly verify the model implementation when its code is not accessible.
- Comparison of model predictions against observations. Typically, the term “validation” or “plausibility check” is used only for this phase, even though – strictly speaking - it must include the previous two.

Validating an atmospheric dispersion model requires handling at least three sets of data:

1. concentration and deposition time series at specific receptors of known coordinates,
2. source and emission characteristics and
3. meteorological fields.

For air quality (AQ) applications, many datasets are available for validating models in different conditions: almost flat terrain (e.g., Kincaid, 1983), complex terrain (e.g., Martin’s Creek, (Dresser, 2011)), and urban environment (e.g., Indianapolis, (Murray, 1988)).

Datasets that provide information on varying source terms (e.g., Oklahoma City, (Allwine, 2004) and the case studies of (COST ES1006, 2015a) to validate time-dependent features are also available for AQ models. These datasets for validating the AQ models are often based on the release of SF6 (sulfur hexafluoride), as in the Kincaid and Indianapolis experiments. The SF6 environmental background is very low because it is produced industrially; it does not exist in nature. For those field experiments, concentration time series at several receptors are available. On the contrary, when the pollutant of interest is odour – not an odorous pollutant such as H2S, but the odour – concentration time series are not available since odour measurement in the field is a complicated task (e.g., Bax, 2020; Conti, 2020; Capelli, 2013), and detailed emissions are practically never available. An additional problem with the validation of odour dispersion models is that odour is ubiquitous (e.g., Chacko, 2020), and its measurement at a specific position cannot be associated with the emission of interest, particularly when the distance from it increases. Another challenge is that odour at the emission level is typically measured using human panel members, and therefore the measurement is associated with great variation (e.g., Klarenbeek, 2014; Hansen, 2016). Indeed, due to the physiological nature of odour measurements with dynamic olfactometry, even with trained panel members, the results are not as precise (i.e., repeatable) and reproducible (i.e., they may have high inter-laboratory variance) as they would be with an analytical measurement technique. A great help in odour field measurements could arrive from IOMSs (e.g., Borowik, 2020), but additional work must be done to consider them reliable operational devices.

Concerning the second point (emissions), validation data for AQ models are often related to a stack's emissions, and source characteristics and emissions variables are precisely measured, even for relatively long periods. For example, emission rates, exit temperature and exit velocity may be available with a 1-hour time resolution for several days. On the contrary, odour concentrations (in terms of $ou_E/m^3$) within a stack are not measured continuously; in practical applications, a single observation must be used for emissions related to relatively long periods. Additionally, quite often, the odour source is not a stack but (e.g.) a pond, a tank, or a building (e.g., a stable), and the emission rate is a function of meteorological variables as well as other variables (e.g., the internal temperature of the stable, see for example (Angrecka, 2014).

Further general difficulties of field experiments include obtaining data that characterise the site's meteorological conditions and the results' limited statistical representativeness due to the changing boundary conditions, such as wind speed and direction. On the other hand, nowadays, the meteorological data needed to feed a dispersion model should not be a problem. In urban areas, where odour-related problems may be important due to their impact on many inhabitants, weather stations are often available (even if not always representative). In any case, even in rural areas and without weather stations, the meteorological fields needed to validate the model can be reconstructed with great accuracy using modelling chains, such as, for example, WRF-CALMET (e.g., Skamarock, 2008; Scire, 2000a). Even the (US-EPA, 2017) recognises the possibility of the "use of prognostic meteorological data for areas where there is no representative NWS (National Weather Service) data, and it is infeasible or prohibitive to collect site-specific data".

Considering what has been reported above, and adding that the time interval of odour concentrations is very short (i.e., the time of a single breath, about 10 s) when compared to

AQ concentrations (typically 1 hour), it is clear that validating an odour dispersion model is quite complicated and presents several uncertainties. However, validation remains a task to be done in many cases.

Datasets based exclusively on the release of inert tracers (e.g., SF6) will not be discussed in the following chapters because they are essentially those used for AQ model validation, briefly mentioned above. Additional information about those experiments can be found in (Capelli, 2013) and (Onofrio, 2020).

### 5.7.1. Examples of validation with odour measurements

A dataset available for validating odour models is the one related to the Uttenweiler (Germany) field experiment (Bächlin, 2002; Bächlin, 2003; Aubrun et al., 2004; Souza et al., 2014; Oettl, 2020a). The dataset has been used by Brancher et al. (2020b) to evaluate three approaches to predict sub-hourly odour peak concentrations, from a simple constant Peak-to-Mean Ratio to more complex ones. As Brancher et al. (2020b) described, the dataset has been obtained by releasing odour and SF6 from a point source within a pig farm. The site is almost flat, with cultivated fields surrounding the farm and a small forest north of the barn. The barn comprised two buildings, respectively, 7.65 and 10.65 metres high. The smaller one had two stacks of 8.5 metres of height connected to the internal ventilation systems. Only one of the stacks was used in the experiment. Two releases have been carried out, one in December 2000, and one in October 2001, for 14 valid trials. Small volumes of SF6 tracer and odorant gas were released in parallel during each experiment. Odour levels were measured with a 10-minute sampling time by up to 12 persons with certified odour perception capabilities positioned in one or two lines perpendicular to the wind direction. At the same time, 10-minute SF6 concentrations were measured. Moreover, fast response concentration measurements (0.1 Hz) of SF6 were performed at two receptors at the position of two persons breathing odour. A sonic thermo-anemometer made measurements of temperature, wind speed and direction every 10 seconds. All experiments had enough cloud coverage to prevent turbulent conditions, and the wind speeds were sufficiently high.

(Hoff, 2006) performed a field experiment by measuring the odour released from a deep-pit swine finishing facility located in Iowa (USA) in a rural environment characterised by flat terrain. Meteorological variables were simultaneously measured using an on-site weather station. From June to November 2004, odour emission and concentration data downwind from the source were collected in three intensive sessions characterised by twelve atmospheric conditions. They placed two panel members at the four grid points at different downwind distances. Each panellist used a Nasal Ranger field olfactometer. Moreover, both at source and at grid points, two 10-litre Tedlar bags were collected for dynamic dilution olfactometry. Each measure was characterised by two 10-minute samplings 15 minutes apart.

(Yu, 2011) described the application of a *Livestock Odour Dispersion Model* (LODM) and its comparison against field measurements collected by the University of Manitoba (Zhang, 2005) from June to August 2004. The measurements were performed around two swine farms in Manitoba (Canada) in a flat cropland with a roughness length of 0.1 m. Both two farms were characterised by ventilated barns. Along with the odour field measurements, odour emission rates were also measured. The field measurements were done by fifteen trained sniffers positioned on a three-row grid at 100 m, 500 m and 1000 m downwind from a fixed point. Measurement sessions were 10 minutes long, and the odour was sniffed for 10 seconds. A total of 129 measurement sessions were conducted, 100 during the daytime. During each session, weather data were also collected at 2 m above ground level with a time resolution of one minute.

(Ranzato, 2012) used the CALPUFF dispersion model and the field inspection technique (VDI 3940, 2006) to quantify the odour impact due to the operation of a municipal solid waste (MSW) plant located in northeastern Italy. Even though their intention was not to validate the model but to highlight the differences between the two methods to evaluate odour impact, their results gave useful information about the model's performance. The frequency of odour episodes was evaluated over the same 6-month period (July 2009 - January 2010) with the model and field inspection. An inspection grid was defined starting from citizen complaints and prevailing wind; it was composed of 48 measurement points with a distance of about 250 m, one from the other. Fourteen trained assessors conducted a series of visits to the inspection grid, and each grid point was visited 26 times by different assessors. At each point, the assessor sniffed the ambient air every 10 s over 10 min and recorded the perceived odour. In this way, odour hours (when the odour is perceived for at least 10% of its duration according to (VDI 3788, 2000) were defined with field inspection. With CALPUFF, odour hours were determined as those where the peak concentration (i.e., the value obtained by multiplying the 1-hour average concentration by the Peak-to-Mean Ratio) was higher than one $ou_E/m^3$. The frequencies of odour hours were then compared both qualitatively and quantitatively. The qualitative comparison was made by observing the frequency isolines obtained with the two methods. In contrast, the quantitative comparison was made at the discrete receptors (i.e., field inspection points) through different statistical parameters (Nash-Sutcliffe model efficiency, mean absolute error, root mean square error, mean absolute relative error). The authors found a satisfying agreement between model results and field inspection data. However, while the spatial extension of the odour was similar according to the model and observations (qualitative comparison), the frequency of odour episodes was sometimes different (quantitative comparison). For example, CALPUFF underestimated the peak concentrations close to the plant, possibly due to missing fugitive emissions among its sources.

(Yeo, 2020) simulated with a CFD (computational fluid dynamics) the odour emitted by a pig farm in South Korea within an area of complex terrain. Odour samples were conducted simultaneously at different locations using a portable air sampler inside and outside the pig houses. All measuring devices were located 1.5 m high from the ground surface. Four sampling locations were used outside the pig houses, the first one positioned at the farm's boundary and the farther one at 140 m from it. The distance between each sampling location was about 40/50 m. Odour sources (ventilation from the pig houses) and emissions are described in the paper; therefore the data could be used for model validation.

### 5.7.2. Data from physical modelling experiments

Data obtained from physical experiments, such as from wind tunnels, may be important to create datasets for odour model validation. Data obtained from those experiments must be converted to full scale in order to be used. The advantages of physical experiments are the controllable boundary conditions and the statistical representativeness of the results. For example, (Aubrun, 2002) replicated the work of (Bächlin, 2002) (Bächlin, 2003) with neutral tracer gas experiments within a 1:400 scale physical model in a wind tunnel. Several parameters influencing odour dispersion were varied during the experiment: presence/absence of terrain, different wind directions, different ratios between the velocity of the ventilation stack and reference wind speed, and two stacks working independently or simultaneously. Concentrations were measured at a height corresponding to 1.6 m full scale. Time series were collected for over 33 hours with a frequency of 1.25 Hz (both full-scale). The objective of these researchers was to generate a dataset that should be now available on the website of Hamburg University. These data have been used by de (Melo, 2012) to compare CALPUFF and AERMOD results.

### 5.7.3. Data from social participation

The validation of odour dispersion models can also be done using odour observations recorded by residents about a specific plant, and the odour emissions estimated for such a plant. As a minimum, this type of validation allows the evaluation of the ability of a model to predict odour in specific locations and at specific times, although the evaluation of odour intensity could be more difficult. An example of this kind of validation is described in (Sironi, 2010).

(Nimmermark, 2005) considered seven livestock farms (swine, cows, turkeys) located in Minnesota (USA) and compared the predictions of the Gaussian puff model INPUFF2 and the observations of odour intensities at twenty neighbourhood residences. In order to characterise the emissions, odour samples were collected from each animal housing facility and each manure storage unit at each farm. The neighbourhoods were trained to identify odour intensity on a 5-level intensity scale, from “none” to “extreme”. After removing the odour observations not in agreement with wind direction, 309 valid observations remained. There was a good agreement between predicted and observed odour intensity. The frequency of odour episodes was not considered in this study.

(Haeger-Eugensson, 2014) evaluated allergens and odours emitted by horse stables with forced ventilation in Sweden. 102 persons of different ages were randomly selected near the riding school stable to evaluate the presence of odour. They simulated the ammonia emissions from the stable using the ADMS model (Carruthers, 1993), where ammonia was used as a tracer for odour. The authors found that the ammonia concentration was well below its odour detection threshold at all distances where people sensed odour. They concluded that odour could be due not only to ammonia but also to the presence and combination with other odorous species.

More recently, (Zhang, 2021) described the application of the CALPUFF model (Scire, 2000b) for simulating odour emissions from a Waste Water Treatment Plant (WWTP) located in the region of Tianjin (China). A total of 126 persons randomly selected from the residential areas around the plant were interviewed to gather information about the influence of the WWTP odour emissions on their life. They were asked questions about the degree of perceived odour intensity, degree of perceived odour annoyance, time of occurrence, and season. The questionnaires provided discrete results. For example, odour intensity was on a 6-point scale (0 for no odour, 1 for very faint strength, …, 5 for very strong strength), while annoyance was on a 5-point scale (0 for not annoyed, …, 4 for extremely annoyed). The results of the questionnaires were related to the CALPUFF odour estimations through binomial logistic regression models, and statistical parameters evaluated the predictive ability.

Diaz et al. (2016) compared the results of the odour impact of an animal by-product rendering plant predicted with CALPUFF using WRF meteorology forecast data with those of real citizen observations. Previous data analysis of this plant using this technology did not show a good agreement (Cartelle et al. 2014). Therefore, the aim was to examine different approaches to improve the results. After 10 months, the results showed that the optimum level to consider a forecasted result as an odour incident was 2.1 $ou_E/m^3$. The system was able to adequately forecast only 41.2% of the incidents. The use of peak-to-mean ratios improved the results. The use of a higher WRF resolution did not have any effect on the results.

### 5.7.4. Evaluation of model performances

The model results and the evaluation measures selected for model validation depend on the investigated model and the available validation data set. Various modelling results, such as odour concentration, various percentiles, frequency, duration, and separation distances, can be considered for model validation.

Commonly used performance measures and acceptance criteria for AQ models are described, for example, in (Chang, 2004) and (Mosca, 1998). The comparisons apply qualitative as well as quantitative methods to evaluate the ability of AQ models to reproduce the observations. A scatter plot of the measured vs modelled results is a common qualitative comparison to evaluate model performance. The following primary quantitative measures are typically applied for model evaluation:

Fractional mean bias:

$$FB = \frac{2\left(\overline{C_o} - \overline{C_p}\right)}{\overline{C_o} + \overline{C_p}}$$

Normalised mean-square error:

$$NMSE = \frac{\overline{\left(C_o - C_p\right)^2}}{\overline{C_o}\,\overline{C_p}}$$

Geometric mean:

$$GM = \exp\left(\overline{\ln\left(C_o\right)} - \overline{\ln\left(C_p\right)}\right)$$

Geometric variance:

$$GV = \exp\overline{\left(\ln\left(C_o\right) - \ln\left(C_p\right)\right)^2}$$

Fractions within a factor of two:

fraction where $0.5 < \frac{C_p}{C_o} < 2$.

In the formulae above $C_p$ represents the model predictions and $C_o$ the observations. (Hanna, 2012) provide separate acceptance criteria for AQ models for rural and urban settings. Further, less commonly applied model evaluation measures for AQ models, such as the correlation coefficient, factor of exceedance, index of agreement, normalised absolute difference and figure of merit in space, can be found, for example, in (COST ES1006, 2015b). These performance measures and their criteria can be applied to time-averaged and time-dependent dispersion characteristics.

Many of the above-mentioned and further statistical parameters used for AQ models can also be applied to odour models when both estimated and observed values are available. For example, (Wu, 2019) applied root mean square error, relative absolute error (Benett, 2013) and the Nash-Sutcliffe model efficiency (Nash, 1970) to evaluate the performance of AERMOD (Cimorelli, 2003) and (VDI 3894-2, 2012) to predict separation distances.

### 5.7.5. Final remarks

Validation is a fundamental phase to estimate an atmospheric dispersion model's reliability and gain confidence in it. It is a complicated task for air quality dispersion models and, for the reasons explained in this paragraph, an enormous effort for odour models. Notwithstanding its complexity and cost, preparing reliable datasets, including meteorological data, emission characterisation, and ambient odour concentrations, would be important for odour modelling science. As mentioned at the beginning of the paragraph, many such datasets are freely available for validating air quality models, but no datasets are available for validating odour models. Two noticeable exceptions are the datasets of (Bächlin, 2002) and (Aubrun, 2002), but the datasets are not openly available and accessible on the Internet.

## 5.8. A window open on the research

One of the main problems connected with using dispersion models to describe the odour impact is related to the intrinsic characteristic of the odour itself. The sensation of olfactory nuisance occurs during normal respiratory activity. Without going into details, the respiratory act of an individual periodically conveys air taken from the external environment into his respiratory system and puts it in contact with the human olfactory system. The latter analyses the air from the external environment and determines its hedonic degree, which can be pleasant or unpleasant. In the latter case, we are faced with a sensation of smell sensation, an olfactory nuisance. Since any human respiratory act occurs at a relatively high frequency, approximately every less than 5 seconds, it follows that the sensation of olfactory nuisance represents an event that needs, in principle, to be described at such a high frequency. It is hence necessary to have available dispersion algorithms able to describe events occurring in a way close to being “instantaneous” or, in other words, representing the peak events represented by peak concentrations.

All the dispersion algorithms and models previously described in this chapter and currently used for odour applications have mainly been derived and designed for their application in the frame of air quality. For this purpose, the request to describe peak concentrations was not very stringent except for specific cases (dispersion of toxic or potentially explosive substances, for example). On the other hand, standard dispersion models are built to obtain average concentrations. To tackle this issue, some ad-hoc algorithms have been developed to parameterise or derive from the average concentration the peak values needed to better describe the odour impact. These parameterisations are often part of the dispersion tools used for odour applications and justify their use in this framework. At the same time, the research is currently moving to study and develop new tools to address the problem more directly and physically better. The scope of this section is to give a general description of the new methods under development, opening a window on what could be the core of the new dispersion algorithms that could be adopted in the future. This is not meant to be a detailed description but only a general touch to solicit the possible interest of the reader and to give the flavour of each new modelling approach, leaving the details inside the associated cited bibliography. Although in many cases well developed and accompanied by a substantial bibliography, all these new methods do not yet find direct applications and development in widely used and consolidated models.

The following four different approaches are taken into account:

1. Dissipation of the concentration variance
2. Fluctuating plume
3. Micromixing model
4. Two Particles Lagrangian Dispersion Models

Each method describes concentration peaks, either directly calculated or statistically derived from the moments of the concentration distribution simulated by the equation of the adopted scheme. What follows is a general description of each approach, together with some useful references to get all the related details.

### 5.8.1. Dissipation of the concentration variance

Supposing that the instantaneous concentration C can be described as:

$$C = \underline{C} + c$$

Where $\underline{C}$ represent any possible average (time or ensemble) value and c a fluctuation, it is possible (Stull, 1988; Sorbjan, 1989; Tampieri, 2017) to write an Eulerian differential equation for the conservation of the average concentration

$$\frac{\partial \underline{C}}{\partial t} + \underline{U}_j \frac{\partial \underline{C}}{\partial x_j} = S_C - \frac{\partial \underline{U_j C}}{\partial x_j}$$

where $S_C$ represents the source term for the concentrations.
From this differential equation and other considerations related to a Reynolds decomposition for both the flow and concentrations, the following differential equation, which describes the spatial distribution and temporal evolution of the variance of the concentration fluctuation,

can be written

$$\frac{\partial \overline{c^{2}}}{\partial t}+\overline{U}_j\frac{\partial \overline{c^{2}}}{\partial x_j}=¿-2\overline{u_j c}\frac{\partial \overline{C}}{\partial x_j}-\frac{\partial \overline{u_j c^2}}{\partial x_j}-2\epsilon_c ¿$$

This last equation could be, like the previous one, directly numerically solved considering both specific methods for the closure and appropriate initial and boundary conditions, leading to a complex model that is requiring a too big computational effort in the typical simulation conditions required for odour applications. The idea is to find suitable approximations of the equations to be adapted inside relatively standard modelling tools such as Gaussian plume and Lagrangian Particle dispersion models. Once a simplified solution for $\overline{c^{2}}$ is given, it is possible, supposing a given form of a statistical distribution for C described by the first two moments (such as a Gamma or Weibull), to estimate any other moment or percentile. A definition of the peak concentration can be derived from the higher percentiles of the distribution, such as the 95th or 98th.
References for the application of such methods inside Gaussian plume models can be found in Wilson et al. (1982a,b, 1985) and in Lofstrom et al. (1995). In these works, the spatial and temporal distribution of the concentration variance for a gaseous substance is represented as an equivalent diffusion process from the “source of variance” characterised by a certain emission rate.

The implementation inside a Lagrangian Particle Dispersion model of the computation of the concentration variance can be found in Manor (2014), Ferrero et al. (2017) and Oettl and Ferrero (2017). More recently, this methodology has also been implemented into the SPRAY Lagrangian Particle Dispersion Model, as presented at the NOSE 2020 international conference.

### 5.8.2. Fluctuating plume

Suppose to consider the emission of a passive substance, in this case coloured in violet, as documented in the photographic sequence reproduced in Figure 5.18.

**Figure 5-18** Emission of a passive substance 15 s (left) and 55 s (right) after the release. Side view (above) and view from behind (below) (from Long et al., 2010)

As can be seen, when a passive substance is emitted from a source (for example a point source), instantaneous plumes are generated in succession, different from each other and having an irregular shape that, only on average, can be described as the usual regular plume characterised by a progressive widening with the distance downwind, proportional to the turbulence present in the air. If we focus our attention on a single instantaneous plume, we notice that in the first phase of dispersion, close to the source, the plume is coherent and relatively narrow and meanders from one side to the other, mainly horizontally but also vertically, even if to a lesser extent. The meandering of the plume is more pronounced near the source, progressively reducing with the distance, until it disappears. As we know, this is due to the fact that the meandering of the plume is inversely proportional to its characteristic size. This phenomenological evidence inspired the Fluctuating Plume Model proposed by Gifford (1959), which was originally formulated more as a conceptual way than a quantitative model. With this conceptual model, the dispersion is described by the superposition of independent Gaussian plumes characterised by dispersion parameters describing the “instantaneous dispersion”. Each Gaussian plume considers a different position of its centroid, described by a stochastic variable given that the coordinates of the position of the centroid derived from the stochastic nature of the turbulent vortices present in the PBL. These vortices have a characteristic dimension not less than the dimension characteristic of the entire plume at the considered leeward distance. In practice, if one samples at the receiving point of coordinates (x, y, z) with a high frequency (i.e. at successive instants very close to each other), what would be obtained is a sequence of instantaneous concentration values c_i, each corresponding to a very precise position of the centroid i. Since the meandering of the centroid is a stochastic process driven by turbulent vortices present in the PBL and larger than the characteristic dimension of the instantaneous plume, the instantaneous concentration values $c_i$ will be realisations of the stochastic process "concentration at the point (x, y, z) ".

After a period of a few decades in which the Gifford model constituted only a conceptual method useful for interpreting the experimental evidence, some works describing an implementation into modelling realisations appeared in the scientific literature, such as Högström (1972), Mussio et al. (2001) and Yu et al. (2011). More recently, the work of Marro et al. (2015), on the basis of the availability of measurements systematically collected in the wind tunnel (Sironi et al. 2015) must be cited. The intrinsic limit of this type of realisation lies in the fact that the Gaussian Plume modelling can be considered sufficiently realistic only in situations in which there are no orographic problems and in which the meteorology is relatively homogeneous and not highly convective.

To overcome these problems, the most natural way to concretise Gifford's conceptual model is to formulate it in a completely Lagrangian context, as was done in part in the work of Marro et al. (2015) subject of the previous point. The description of some Lagrangian implementations can be found in Luhar et al. (2000), Cassiani and Giostra (2002), Franzese (2003) and Mortarini et al. (2009), in addition to the clear synthesis made on this subject by Ferrero and Mortarini (2014).

### 5.8.3. Micromixing model

A micromixing model (or PDF model) views the intrinsically continuous PBL as a geometric space in which a very large number of air particles, each fully detectable, are uniformly distributed. Each of them is completely characterised at a generic instant t by:

- a position in space **X**(t),
- a velocity fluctuation **u**(**X**,t) with respect to a mean (Eulerian) field of motion **U**(**X**,t);
- by a concentration of the interested pollutant C(**X**,t)

At each instant t prior to an initial instant $t_0$ all particles (initially uniformly distributed in space) possess a concentration $C(t<t_0) = 0$. At a given initial time $t_0$, some of these particles will transit through the source (e.g. a point source) and will acquire mass from it and, therefore an initial concentration of $C_0(t_0)$ while all the others will continue to keep zero concentration. From the instant $t_0$ onwards, the model will begin to simulate the dispersion of all the particles (both those with non-zero concentration and those with zero concentration), that is, both all their different stochastic trajectories and their mutual interaction. This interaction is constituted by a mass exchange of the pollutant between a generic particle and the adjacent particles, a mass exchange induced by molecular diffusivity and driven by the turbulence that is present locally in the PBL. In practice, the model will simulate the trajectory of all particles using the laws of a normal Lagrangian one-particle model with the practical problem related to the huge number of particles whose trajectory and mass exchange must be simulated.

In a micromixing model, the pollutant exchange among close particles is modelled, for simplicity, through a bulk law describing, for each particle, such mass exchange with the adjacent external environment, seen as a continuous fluid characterised by an average concentration C. In practice, for the p-th particle, this exchange is described by the micromixing relation that simulates the action of molecular diffusivity:

$$\frac{dC^p(X_p,t)}{dt} = \frac{-C^p(X_p,t) - \overline{C^p(X_p,t)}}{\tau_m}$$

Where $\tau_m$ represents the so-called micromixing time scale. Some particles will decrease in concentration (those passing through the source) while others (those that constitute the surrounding air) will increase it.
Assuming to divide the entire computational domain into cells, at the end of the time step, there will be $N_k$ particles in the k-th cell, each with its own concentration. The average characteristic concentration of the cell can be computed as

$$\underline{C_k}(t) = \frac{1}{N_k}\sum_{p=1}^{N_k} C^p(t)$$

while the second moment can be computed as

$$\underline{C^2_{k□}}(t) = \frac{1}{N_k}\sum_{p=1}^{N_k} ¿¿$$

and finally, the concentration variance can be computed as

$$(\sigma^2_c)_k = \underline{C^2_{k□}}(t) - ¿$$

To overcome the problem of simulating a huge number of particles, Cassiani (2013) proposed the Volumetric Particle Approach (VPA), a model that can initially be seen as a drastic simplification of a generic micromixing model. However, as pointed out by Ferrero et al. (2020) and Cassiani et al. (2020), the simplified two-particle model proposed independently by Kaplan (2014) coincides exactly with the VPA model, which, therefore, can also be considered a simplified Lagrangian two-particle model (described in the following section). Some of the practical aspects related to this model, in particular, the derivation of the micromixing time scale τ_m, are described in Dixon and Tomlin (2007), Cassiani (2013) and Marro et al. (2018).

### 5.8.4. Two-Particles Lagrangian Dispersion models

As already seen in this chapter, a Lagrangian Particle Model can be used to describe operationally the average dispersion of a passive substance (chemically non-reactive) emitted in the turbulent PBL. Basically, this consists in assuming that portions of fluid which are emitted from the source move independently, each constituting a distinct and independent statistical realisation. The velocity u and the position x of each particle together constitute a continuous Markov process and will be obtained by integrating a system of stochastic Langevin differential equations. The ensemble mean concentration field is obtained from the set of trajectories of the different particles. A model that operates in this manner is called the One Particle Lagrangian Model.

The independence among emitted particles prevents us from describing the concentration fluctuations. In order to describe this last, it is, in fact, necessary to take into account the correlation between the various emitted particles conditioning their motion. Basically, the movement of an emitted particle is not independent of the motion of the other particles. In principle, the correlation between particles decreases with time until it disappears at great distances from the emission point. By taking this effect into account, it is possible to reconstruct the statistics of the motion of the particles and, therefore, the concentration statistics, including the concentration variance.

Thomson (1990) has formulated a method, named Lagrangian Two-Particle Model, considering the emission not only of independent single particles, but of pairs of particles in which each of the two particles is conditioned by the presence of the other one. The proposed model, together with the reconstruction of the average concentration substance, is also able to determine the concentration variance. The limitation of this model lies in the fact that it is valid only in homogeneous and isotropic conditions. To try to extend the model to situations characterised by non-stationary, non-homogeneous and non-isotropic turbulence, Du (2001) has proposed a heuristic and reasonable extension. One of the main difficulties that this approach is still having resides in the difficulty to find good parameterisations of the statistical properties of the turbulent atmosphere related to the movements of coupled particles in order to feed the model operationally in a way similarly adopted by commonly used One Particle Lagrangian Models.

## 5.9. A bridge towards the stakeholders

The concern about the odour nuisance is increasing in the population and among stakeholders. The first questions they ask for answers are: From where does such 'disgusting' odour come? Is it dangerous for health?

As described in previous sections, numerical models can certainly support tracking and detecting the possible sources of odour nuisance. To contribute to responding to these specific questions, their development and improvement should be *application-oriented*, and in this context, the interaction with decision-makers and stakeholders and with their needs becomes a fundamental aspect.

It is thus important to address some basic issues, such as the following ones, which can drive the integration of numerical models in nuisance-response procedures and protocols.

- *What do the stakeholders need and desire to know for handling the problem of odour nuisance*
- *What scientists are nowadays able to provide, what is yet unknown*
- *What is the gap between science and response and what can be done to fill it*
- *What is the meeting point between scientists and stakeholders in dealing with odour problems*

Environmental protection agencies and decision makers need tools that may support them in identifying the source of the odour nuisance, possibly during its occurrence, in order to collect measurements timely and in the right place, then to analyse the samplers in a convenient time frame. As a follow-up, tracking the origin of the emission allows taking the needed countermeasures to avoid further releases from the same source.

Alert systems, also involving citizens who may send complaints about odour nuisance episodes, are increasingly developed nowadays. Numerical models may be integrated into the response system to track back the possible odour source using the alerts' distribution as receptors. The main open issues related to the appropriate modelling of the odour dispersion in the air have been discussed in previous sections, and they represent the actual scientific limits that still need to be overcome. Traditional dispersion models need to be modified to adapt their application for the simulation and prediction of atmospheric transport of odours and the characterisation of their nuisance. Atmospheric dispersion modelling systems can also be used to define regulatory frameworks for odour emissions from industrial, agricultural and sanitary activities. The assessment of the impact of odour emissions may support the definition of the criteria and measures to control and regulate the releases.

In this context, the dialogue and cooperation between scientists, stakeholders and decision-makers is essential. The practical problems that responders have to face and the final goals they need to achieve should be part of the guidelines for model development and improvement. A proper balance between the complexity, efficacy and usability of models is to be pursued to guarantee their applicability in alert systems. Based on odour reporting provided by the stakeholders, a comprehensive analysis framework beyond the model simulation, has to be established to identify the odour source, to assess the impacted areas and provide useful indications for the protection intervention. The *citizen-science* approach should be promoted and sustained, involving and training the population, since it is a unique opportunity to get distributed information in space and time, which can be fruitfully used as input for the model simulations.

The cooperation between scientists, stakeholders and decision makers should thus entangle all aspects, from the modelling system conceptual approach, to its development, implementation and maintenance, from the training of the operators to the design of the guidelines for the use of the results and outputs.

Responding to the above questions - as in the following - clarifies that air quality experts may be ascribed to be the bridge between the scientific community developing the models and the final decision makers. Air quality experts are expected to have a good knowledge about running dispersion models for odour assessments, even when not directly involved in the scientific development of the models themselves.

- *What the stakeholders need and desire to know for handling the problem of odour nuisance*

In general, air quality experts working for the local authorities would need information about available modelling tools and corresponding training. The establishment of national guidelines on odour assessment is a key element for developing harmonised and comprehensible methods. Assembling working groups where scientists are involved in the development of guidelines would be indeed extremely valuable.

- *What scientists are nowadays able to provide, what is yet unknown*

Great advances have been accomplished in the field of applicable complex numerical models for regulatory purposes. Nowadays, it is possible to account for buildings, vegetation, topography and complex odour sources using coupled Lagrangian dispersion models and Eulerian flow field models. Two major issues for which scientific progress remains to be pursued are: (i) the establishment of dose-response relationships between odour annoyance and any kind of odour impact criteria (e.g. odour hours, concentrations), and (ii) the development of flow-field models that are able to account for the interaction between synoptic flows and local thermal flows at high horizontal resolutions (< 500m).

- *What is the gap between science and response, and what can be done to fill it*

The air quality experts must possess a good knowledge about the legislative requirements for odour assessments. In most Countries, the legislation stays quite vague in this regard. Therefore, legislative terms like “a neighbour must not be annoyed in an unacceptable manner” or “any health risk is unacceptable” need to be rendered into quantifiable terms such as limit values that can be assessed by dispersion models or field inspections (e.g. EN 16841).

- *What is the meeting point between scientists and stakeholders in dealing with odour problems*

The meeting point between scientists and stakeholders are likely the air quality experts employed at the regional and national governments. Fostering the interaction between air quality experts and the scientific community by establishing e.g. conferences, communication platforms would be a step forward for harmonising and accelerating the development of applicable guidelines and models.

In conclusion, promoting the cooperation between model developers, model users, stakeholders and decision makers is the most efficient pathway to provide fit-for-purpose modelling tools also in the framework of odour nuisance assessment and response.

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# 6. Output dose-response

## 6.1. Introduction

Of the five senses, the sense of smell is the most complex and unique in structure and organisation. While human olfaction supplies 80% of flavour sensations during eating, the olfactory system plays a significant role as a defence mechanism by creating a natural aversion response to malodours and irritants. Human olfaction protects from potential illness or infection caused by tainted food and matter, such as rotting vegetables, decomposing meat, and faecal matter.

Two concepts are used interchangeably within the odour impact assessment framework and, often, incorrectly: odour and odorant. Further, there needs to be clarification between the stimulus of odorant(s) concentration and the effect, which is the odour sensation. Further, there is a need to link odour sensation to odour nuisance.

Figure 6-1, illustrates how an odorant creates the odour perception. The term odour refers to the perception experienced when one or more chemical substances in the air come in contact with the various human sensory systems and when the stimuli are sufficient to trigger perception.

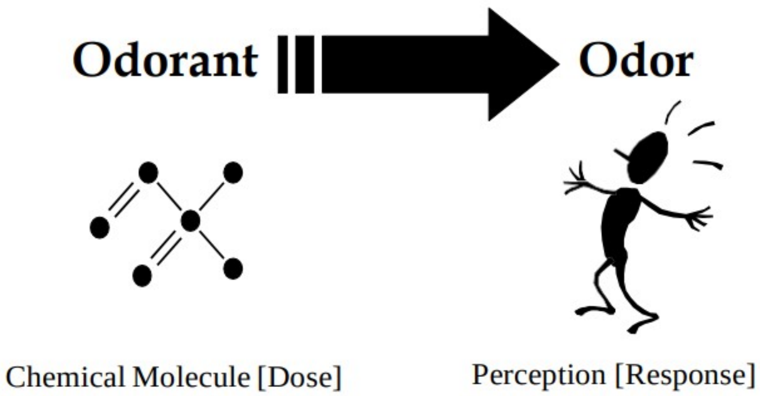


**Figure 6-1** Chemical Odorant versus Odour Perception (courtesy of St. Croix Sensory)

The term odorant refers to any chemical in the air that is part of the perception of odour by a human (odorant is a chemical). Odour perception may occur when one odorant (chemical substance) is present or when many odorants (chemical substances) are present.

An analogy that helps to understand what is happening with odour perception in the olfactory system is envisioning the receptor nerves like keys on a piano. As a single chemical odorant hits the piano keyboard (the olfactory epithelium), a tone is played (odour perception). When multiple chemical odorants are present and hit the piano keyboard, the result is a chord (odour perception). For example, if keys 1, 3, and 7 are hit by three different odorants, the brain may perceive earthiness. Likewise, if keys 4, 6, and 12 are hit by three different odorants, the brain may perceive sewer. The greater the number of odorant molecules present (higher concentrations), the louder the chord is played. The loudness of the chord is analogous to the intensity of the odour perception.

Perception of odours depends not only on the sensitivity of each individual or community but also on the number of times this odour occurs, how intense it is, how unpleasant it is, and the duration of the odour episodes once they are perceived. Odour perception also varies depending on the recipient's experience, expectations, motivation and degree of alertness.

## 6.2. The FIDOS factors

A range of factors influence the impact of the odour experienced by a community, the most relevant being *Frequency*, *Intensity*, *Offensiveness*, *Duration* and *Sensitivity* (FIDOS).

It is possible to find in the literature (Bokowa et al. 2021; H4 Odour Management, 2011) the terms FIDO, FIDOL (L stands for Location) and FIDOR (R stands for Receptor). In this text, we have preferred to use the term FIDOS to give a more meaningful name to that factor related to the odour impact, not covered by frequency, intensity, duration and offensiveness.

The following chapters will describe each of these FIDOS factors in detail.

### 6.2.1 Frequency

The frequency of odour exposure simply refers to how often odour events occur. It is a function of the variations of odour emissions over time and of the meteorological conditions in the area around an odour source. The frequency of odour events is generally greatest in areas most often downwind of the source, especially under light wind and stable atmospheric conditions (provided that the odour is not emitted at a significant height above the ground).

Although the frequency of odour events is a prime determinant of the likelihood of nuisance occurring, the timing of events can also be important. There are times of the day, for example, when there may be a greater likelihood of people being exposed to any ambient odour, such as in the morning period around breakfast or around the evening mealtime. At other times, the likelihood of being away from the home, or asleep or simply inside with windows and doors shut may reduce the likelihood of being affected by odours that are present in the ambient air.

The dispersion models are relevant, as they allow the calculation of the odour concentration at certain receptor points (immission), allowing estimating the odour supply frequencies as a function of the modelled time.

Exposure to odour is usually quantified in terms of a frequency of occurrence of mean hourly concentrations of a certain odour above a defined limit concentration. Considering that the criteria of maximum hourly impact, or most unfavourable condition, are not representative of a permanent exposure condition synthesised in a year due to the variation of the seasonal meteorological state of a certain place, the use of the percentile criterion is recommended. which allows you to view the percentages of hours in which the value defined for the 8,760 hours of the year is exceeded (this is the relationship between frequency and percentile).

What are Percentiles?

A percentile is a descriptive statistic that can be used to describe the distributional characteristics of a dataset. To arrive at percentile values, data must be rank ordered, i.e. arrayed in order of decreasing or increasing magnitude, to form a frequency distribution. In this case, data would, for example, be hourly odour concentration data for a year and a specific location. The 98th percentile represents the concentration value for which 98% of the data points are less than or equal to this value. Other percentiles can be used as well. For example, the 50th percentile or median is the variable's value that has an equal number of data points on either side. The range enclosed by the 1st - percentile and 99th percentile provides an indication of the data range. When time series data are used, the nth-percentile value may be used as a criterion representing the value that may be exceeded only (100-n) % of the time, i.e. (100-n)% × 8760 hours over a full year.

Why are Percentiles Used in Odour Assessment?

Understanding the reasons for the use of percentiles in odour assessments requires a brief discussion of the history of odour research. Early odour research found that measured instantaneous odour nuisance and modelled hourly odour concentration are weakly but significantly correlated. In other words, the reported nuisance increased with increasing odour concentration levels. However, stronger and linear correlations were found between (long-term) nuisance surveys and the logarithmic 98th-percentile and 99.99th-percentile (i.e. maximum) values of the modelled annual hourly odour concentration (e.g. Verschut et al., 1991; Walpot et al., 1991). This relationship was particularly clear for high odour concentrations ($C_{98\ 1\ hr}$ exceeding roughly 10 ou/m³). This better correlation with higher percentiles compared to other descriptive statistics (e.g. mean, mode, median, etc.) may be explained by the fact that the relatively rare hours with high concentration levels are more critical in causing nuisance than the majority of hours when the concentration is relatively low (or zero).

Another important finding was that no single unambiguous relationship between nuisance and absolute odour concentration level could be established. This means that for one type of industry, an odour nuisance threshold in terms of the proportion of people annoyed may be significantly higher (e.g. $C_{98\ 1\ hr}$ = 10 ou/m³) than for another type of industry (e.g. $C_{98\ 1\ hr}$ = 3 ou/m³). This is due to the complexity of odour nuisance. The actual odour nuisance that is experienced depends on several factors such as type of components (hedonic value), place of occurrence, time of occurrence (frequency, time of exposure) and personal experience (Australian Pork Limited, 2003).

In subsequent research, Miedema (1992) found a correlation between community odour annoyance and percentiles of odour concentration for five different types of odour sources, including a pig farm. The 99.5th percentile was found to be a somewhat better indicator of odour impact across a range of sources than the 98th percentile. It was suggested that this is because people base their annoyance judgement on the hours of maximum concentration. It was found that a single curve can describe the linear relationship between log(C99.5 1 hr) and annoyance for all types of odour sources. This research suggested that different characters (in terms of “offensiveness” or “pleasantness”) of odour did not play an important role with respect to nuisance. The research also found that the level of annoyance in the community due to an odour source did not depart from baseline levels until the $C_{99.5\ 1\ hr}$ odour level exceeded about 10 ou. In summary, the better correlation between percentiles and community nuisance levels compared to other descriptive statistics (e.g. between the mean and nuisance levels) explains the use of percentiles in odour assessments. The actual relationship between percentiles and community nuisance levels in absolute terms will depend on many factors, including odour quality (hedonic value), place of occurrence, time of occurrence and personal experience.

On the other hand, and complementing the aforementioned, Miedema et al. (2000) developed a model for predicting the percentage of individuals who are highly annoyed in the surrounding community (%HA). This model is expressed as follows:

**Equation 6-1** $\%HA = 9.55 \times$ ¿¿

%HA : the percentage of individuals who are highly annoyed in the surrounding community.

$C_{98}$ : 98th percentile concentration.

In addition, it was found that the accuracy of the prediction of the percentage of individuals who are highly annoyed in the surrounding community is improved if both the pleasantness of odour and odour concentration is taken into account (Miedema et al., 2000).

## 6.2.2 Intensity

The perception of intensity of an odour is how strong an odour is perceived to be. Odour intensity describes the relative magnitude of an odour sensation as experienced by a person. The perception of intensity of an odour in relation to the odour concentration follows a logarithmic relationship (the same relationship occurs for other human senses, such as hearing and sensitivity to light). Therefore, to understand the concept of intensity, we must first define the concept of odour concentration. According to EN 13725 the odour concentration is “the number of European odour units per cubic metre under normal conditions”. Odour concentration is measured in European odour units and its symbol is $ou_E$.

The logarithmic nature of odour perception is important for all odour sources. It means that decreasing the concentration of an odour (as determined by olfactometry) by 10-fold will only decrease the intensity by a much smaller amount (see Figure 6-2). Intensity can be assessed in many ways.

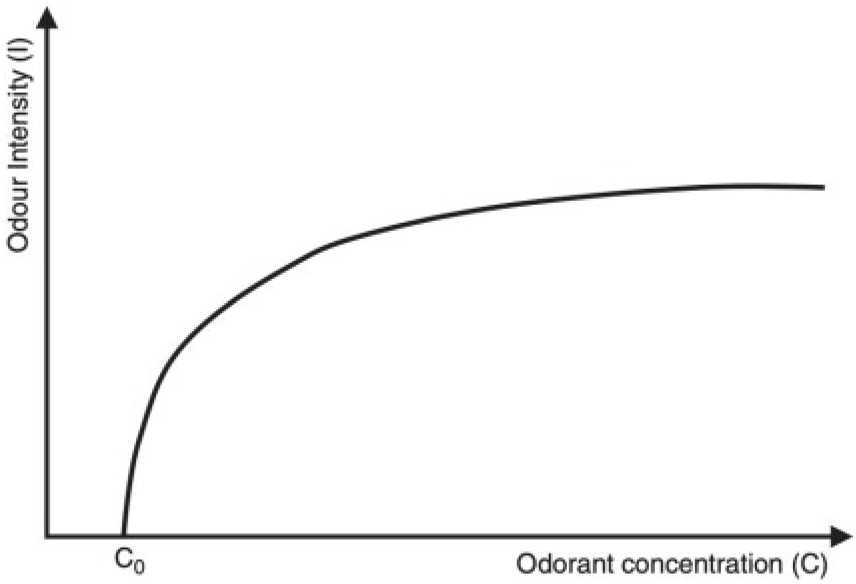


**Figure 6-2** Logarithmic relationship between intensity and concentration

An assessment of odour impacts from the sources using an odour intensity criterion approach recognises the fact that the same concentration (stimulus) of different odorants does not elicit the same perception of intensity (response) in people. This approach may be advantageous to activities that emit odorous substances that exhibit low intensity at relatively high concentration.

Odour concentrations above the detection threshold are not direct indicators of perceived odour intensity. For each odorant, its odour intensity is a non-linear function of its concentration and the perceived odour intensity can be described using a mathematical equation (Stevens Law or the Weber-Fechner Law). The Weber Fechner law can be expressed by the equation:

**Equation 6-2** $S = k_w \times \log$ ¿¿

Where,

S = perceived intensity of sensation (theoretically determined).
I = physical intensity (odour concentration).
$I_o$ = threshold concentration (1 $ou_E$).
$k_w$ = Weber-Fechner coefficient.

Odour intensity can be categorised according to the German Standard method VDI 3882/1, Olfactometry - Determination of Odour Intensity, Part 1, 1992, into odour intensity in categories described as not perceptible, very weak, weak, distinct, strong, very strong and extremely strong and assigned corresponding numerical values, 0 to 6. The seven-point intensity scale is defined as shown in Table 6-1.

**Table 6-1** Odour Intensity Categories

| Odour Strength | Intensity Level |
|---|---|
| Extremely strong | 6 |
| Very strong | 5 |
| Strong | 4 |
| Distinct | 3 |
| Weak | 2 |
| Very weak | 1 |
| Not perceptible | 0 |

Solving the experimentally established Stevens Law or Weber-Fechner equations at a particular intensity level for odours characteristic of an individual facility yields a corresponding odour concentration value. The approach requires a considerable amount of initial work by a proponent or industry group to establish the intensity versus concentration relationships for a particular odour type.

This method requires an odour intensity study to determine the relationship between odour concentration and odour intensity, in order to specify the odour concentration equivalent to the intensity level of “weak”. The method for determining odour concentration and intensity must follow the procedure and standards internationally validated, for example: Australian and New Zealand Standard (AS/NZS 4323.3:2001) and the German Standard VDI 3882/1. The samples collected from the source will be analysed simultaneously in the laboratory for odour concentration and intensity, using odour panels and dynamic olfactometry equipment. By doing this, it is possible to develop a relationship between them and determine the odour concentration equivalent to the intensity level of “weak” or "strong".

### 6.2.3. Duration

#### 6.2.3.1 Fundamentals

Odour nuisance is known to be closely linked to short-term odour-concentration peaks, as these may reach levels well above the recognition threshold causing immediate annoyance. In the past decades, dispersion models have become a standard tool for air quality assessments, which are based mostly on the prediction of hourly-mean concentrations. Typically, dispersion models are not designed for providing concentrations for time intervals well below one hour. Different approaches have been developed for implementation in regulatory models. These could be split into two groups: (1) methods providing short-term concentrations based on predicted hourly-mean concentrations of a dispersion model, and (2) methods that additionally account for the sensitivity of persons. The methods are usually strongly related to odour regulations set up by local or national authorities. In the following, only approaches are outlined which are in use for regulatory purposes, while models/methods currently discussed in the scientific literature but are not yet applied in practice will not be discussed subsequently.

#### 6.2.3.2. Methods for assessing peak concentrations

A basic concept relating short-term $C_p$ to long-term concentrations $C_m$ was suggested by Smith (1973):

**Equation 6-3**

$$\frac{C_p}{C_m} = \left(\frac{t_m}{t_p}\right)^n$$

$\frac{C_p}{C_m}$: constant Peak-to-Mean Ratio.

$\frac{t_m}{t_p}$ : the ratio of the long- and short-term intervals, and *n* is an empirical exponent.

Often a constant exponent n is used, ranging from 0.18 to 0.68 (Beychock, 1994; Venkatram, 2002). For instance, the U.S. EPA regulatory model CALPUFF (Scire et al., 2000) as well as the Australian regulatory model AUSPLUME (Lorimer, 1986) set *n* equal to 0.2. Table 6-2 lists countries and regions applying a constant Peak-to-Mean Ratio in the odour regulations.

**Table 6-2** List of countries using a constant Peak-to-Mean Ratio (Brancher et al. 2017)

| **Country** | **Region** | **$t_p$** | $\frac{C_p}{C_m}$ |
|---|---|---|---|
| Canada | Quebec<br>Ontario<br>Manitoba | 4 min<br>10 min<br>3 min | 1.9<br>1.65<br>2.3 |
| Denmark | - | 1 min | 7.8 |
| Italy | Lombardy, Puglia | Not defined | 2.3 |
| Australia | Victoria | 3 min | 1.82 |

It can easily be deduced from the widely accepted K-theory

$$\overline{u'c'} = K_i \frac{\partial \bar{c}}{\partial x_i}$$

**Equation 6-4**

$\overline{u'c'}$ : the turbulent flux.

$\frac{\partial \underline{c}}{\partial x_i}$ : flow mix in atmosphere

$K_i$ :the exchange coefficient that expresses the turbulent structure of the atmosphere.

that the turbulent flux $\underline{u'c'}$ of any quantity becomes zero in case that it is well mixed within the atmosphere, i.e. $\frac{\partial \underline{c}}{\partial x_i}=0$. This is approximately the case far downwind from a source, or in the case that multiple and/or large extended odour sources cause overlapping plumes. It follows, as the turbulent velocities $u' \neq 0$ in the atmosphere, that c' must be close to zero, and that the corresponding Peak-to-Mean Ratio $\frac{C_p}{C_m}$ approaches one in such circumstances. Apparently, besides the distance from the source and the shape of (overlapping) plumes, the turbulent structure of the atmosphere, expressed by the exchange coefficient $K_i$, also exhibits an influence on the turbulent flux, and thus on the Peak-to-Mean Ratio.

The method developed by Piringer et al. (2015) takes into account two of the aforementioned influences: atmospheric stability and distance from a single point source:

$$\frac{C_p}{C_m} = 1 + \left(\left[\frac{C_p}{C_m}\right]_0 - 1\right) e^{-0.73\frac{T}{T_L}}$$

**Equation 6-5**

*T* : stands for travel time.
$T_L$ for the Lagrangian time scale.

$\left[\frac{C_p}{C_m}\right]_0$: the initial Peak-to-Mean Ratio

$\frac{C_p}{C_m}$ : Peak-to-Mean Ratio

Both the initial Peak-to-Mean Ratio $\left[\frac{C_p}{C_m}\right]_0$ and $T_L$ depend on atmospheric stability. Brancher et al. (2020) pointed out that the approach tended to underestimate Peak-to-Mean Ratios (expressed as the 90$^{th}$ percentile in their study) caused by the rapid exponential decrease of $\frac{C_p}{C_m}$ with a downwind distance.

Table 6-3 lists countries that are using variable Peak-to-Mean Ratios in their regulations. As can be seen, the majority applies ratios depending on atmospheric stability classes (Pasquill-Gifford-Turner). However, in some regions in Australia Peak-to-Mean Ratios vary also with distance from the source as well as inside or outside wake-affected zones.

**Table 6-3** List of countries using a variable Peak-to-Mean Ratio $\frac{C_p}{C_m}$ ( Brancher et al. 2017)

<table>
<tr><th>Country</th><th>Region</th><th>t<sub>p</sub></th><th colspan="2">$\frac{C_p}{C_m}$</th></tr>
<tr><td>Israel</td><td>-</td><td>10 min</td><td colspan="2">PGT stability classes<br>A, B: 2.45<br>C: 1.82<br>D: 1.43<br>E, F: 1.35</td></tr>
<tr><td>Hong Kong</td><td></td><td>5 s</td><td colspan="2">PGT stability classes<br>A, B: 45<br>C: 27<br>D: 9<br>E, F: 8</td></tr>
<tr><td rowspan="3">Australia</td><td rowspan="2">New South Wales</td><td rowspan="2">1 s</td><td>PGT classes A, B, C, D<br>Far field: 2.3<br>Near field: 2.5<br>Wake-free Point: 12</td><td>PGT classes E, F<br>Far field: 1.9<br>Near field: 2.3<br>Wake-free Point: 25</td></tr>
<tr><td colspan="2">Volume, wake-affected point: 2.3</td></tr>
<tr><td>Queensland</td><td>1 s</td><td colspan="2">Wake-affected point, and all ground-based sources: 2<br><br>Wake-free point: 10</td></tr>
</table>

Oettl and Ferrero (2017) developed the concentration-variance method in which the hourly-mean concentration is calculated with any suitable dispersion model, while the concentration variance is estimated by neglecting the advection and diffusion terms in the time-dependent governing equation for the concentration variance.

**Equation 6-6**

$$\frac{\partial \underline{c}'^2}{\partial t} = 2\sigma_{ui}^2 T_{Li} \left( \frac{\partial \underline{C}}{\partial x_i} \right)^2 - \frac{\underline{c}'^2}{t_d}.$$

$\sigma_{u}^2$: variance of wind speed fluctuations

$t_d$: dissipation time scale for the concentration variance

$\underline{c}$: hourly-mean concentration computed by a dispersion model

One of the main advantages of using Equation 6.6 is that it can be computed in post-processing mode, and thus, is independent on the dispersion model applied for calculating the mean concentration field. The simulated concentration variances are used in combination with a slightly modified two-parameter Weibull probability distribution function to get the Peak-to-Mean Ratio expressed as the 90$^{th}$ percentile of the cumulative frequency distribution. Figure 6-2 displays modelled Peak-to-Mean Ratios using Equation 6.6 for a single point source (upper) and multiple point sources (lower) in neutral atmospheric stability. Contrasting the simpler models outlined before, the method suggests strongly varying Peak-to-Mean Ratios. While the ratios expectedly decrease with increasing distance to the source, secondary maxima are visible at the edge of the plume, which is in agreement with observations (e.g. Yee et al., 1994). Overlapping plumes significantly affect Peak-to-Mean Ratios as can be seen from the lower frame of Figure 6-2. Recently, Brancher et al. (2020) compared the concentration-variance method with the one used in Germany (constant factor of 4) and the model suggested by Piringer et al. (2015) outlined before. They concluded, by comparing Peak-to-Mean ratios with observations near a pig shed in Germany, that the concentration-variance approach provided the most realistic ratios.

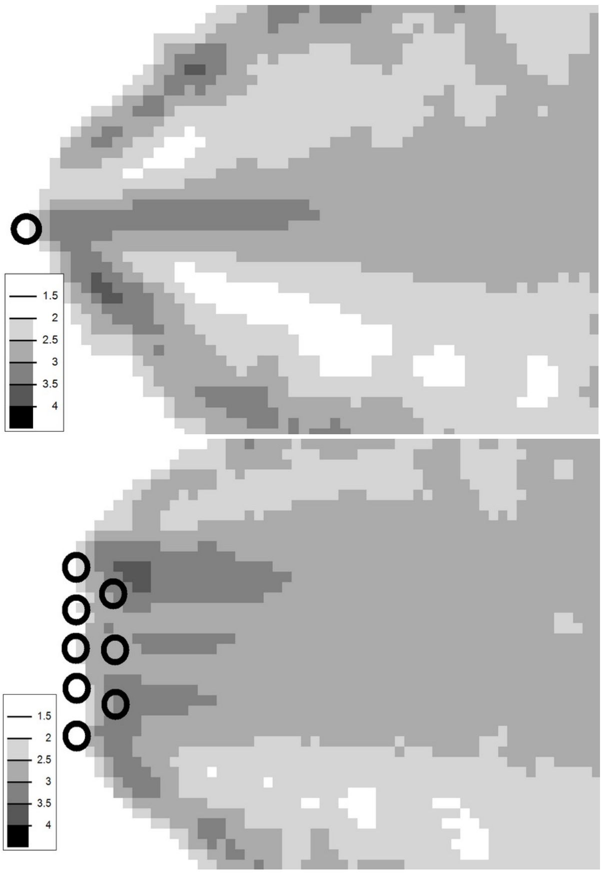


**Figure 6-2** Modelled Peak-to-Mean Ratios using Equation 6.6 near a single point source (upper) and multiple point sources (lower) indicated by the circle and wind from the left. (courtesy of Öttl Dietmar)

### 6.2.3.3. Methods additionally accounting for the sensitivity of persons

Janicke and Janicke (2004) did not only consider the concentration fluctuations themselves, but took into account the probability $P_0$(c) of qualified panel members to recognise a certain type of odour dependent on its concentration. This is expressed in the definition of the so-called “odour hour” in the German guideline VDI 3788 (2015) by the following function:

$$\kappa = \int_0^\infty P_0(c) f(c) \mathrm{dc},$$

**Equation 6-7**

$f(c)$ : the probability density function of odour concentrations at some observational point for an hourly interval.

$P_0(c)$: the probability of qualified panel members to recognise a certain type of odour dependent on its concentration.

$\kappa$ : odour hour

An odour hour is defined by $\kappa \geq 0.9$, i.e., in 10% of the time odour will be detected by the qualified panel members. Janicke and Janicke (2004) demonstrated that for an assumed log-normal distribution for $P_0(c)$:

$$P_0(c) = 0.5\left[1 + erf\left(\frac{\ln\left( c/c_{OT} \right)}{\sqrt{2}\alpha}\right)\right]$$

**Equation 6-8**

$P_0(c)$: the probability of qualified panel members to recognise a certain type of odour dependent on its concentration.
$\alpha$ : scale parameter.
*erf :* the error function
*c :* the odour concentration
$c_{OT}$ : the odour concentration detected by 50% of qualified panel members

For $\alpha$ > 1 an almost constant Peak-to-Mean Ratio of about 4 is obtained, practically independent on the shape of $f(c)$. This is the very reason why in Germany a constant factor of four is prescribed as Peak-to-Mean Ratio for computing an odour hour.

The value of $\alpha$ can be determined by means of dynamic olfactometry however. Oettl et al. (2021) analysed more than 1000 datasets covering a wide range of odour types, and found a median for $\alpha$ of 0.6. In this case, the shape of $f(c)$ becomes important and needs to be taken into account in odour assessments. Oettl et al. (2018) implemented the concentration-variance model outlined in the previous section in the Lagrangian Particle Model GRAL

(Oettl, 2020), which is widely used in Austria for odour assessment studies though the model is not mandatory. It could be demonstrated that computed odour-hour frequencies using GRAL, in the vicinity of a pig shed, agreed well with observed frequencies based on the European standard EN 16841-1 (2017). It should be emphasised that the main advantage of using odour hours in assessment studies over the widely used limit values based on percentiles of hourly-mean odour concentrations (e.g. Brancher et al., 2017), is the possibility of using either dispersion modelling or field inspections in odour assessments. Recently, Brancher et al. (2020) linked the concentration-variance model with the German Lagrangian Particle Model LASAT (Janicke Consulting, 2019).

### 6.2.4 Offensiveness

Offensiveness is the character related to the “hedonic tone” of the odour, which may be pleasant, neutral or unpleasant.

According to the German guideline VDI 3882 Part 2, the methodology uses a nine-point scale, ranging from -4 (extremely unpleasant) to +4 (extremely pleasant), being 0 an odour that is perceived neither as pleasant nor unpleasant (Figure 6-3).

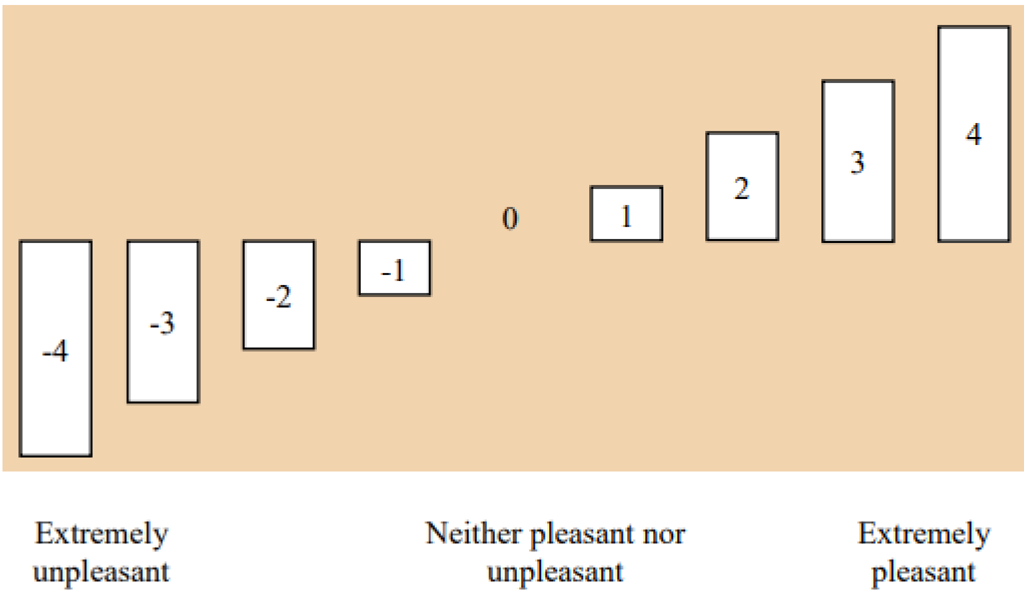


**Figure 6-3** 9-level hedonic tone scale - ref. VDI 3882

The same scale from +4 to -4 is used in the Dutch standard NVN 2818:2019. Odour quality - Sensory determination of the hedonic tone of an odour using an olfactometer.

Although the VDI 3882 Part 2 and NVN 2818:2019 use the same scale, these standards differ in 2 main points:

1. The VDI standard prescribes at least 16 panellists to measure the hedonic tone, while the NVN standard only needs a minimum of 6.
2. The dilution series presented to the panellists is random in the VDI and increasing in

the NVN.

This parameter is a subjective measure of the acceptability of an odour and a key element in estimating odour annoyance. As with most parameters, the hedonic tone is not an independent quality of a volatile compound, and it depends on the intensity, concentration, duration and frequency of the odour exposure. Moreover, the hedonic tone also differs widely from person to person, and it is strongly influenced by previous experiences, emotions and other circumstances.

Odour character is what the substance smells like. However, because individuals perceive odour individually, the same chemical may be described quite differently among people. Odour character can also change with concentration. For example, butyl acetate has a sweet odour at low concentrations but smells like banana at higher concentrations.

With the potential evolution of the odour with the concentration, the hedonic tone itself can be affected. Even a pleasant odour can become unpleasant if the concentration is too high. It can be the case for perfumes but also very often with the food industry. So offensiveness must be considered at the level of odour exposure without extrapolation of potential evolution for lower or higher concentrations. The global feeling (with all the factors) is for offensiveness, the perception for one level in the concentration range and this aspect is covered by intensity description.

### 6.2.5. Sensitivity

Sensitivity (of individuals to odours in one environment) is individuals' sensation and emotional responses to an odorous atmosphere at one time of their daylife/life and the location where the odour is perceived.

Four basic factors affect the sensitivity of individuals:

- Experience.
- Expectations.
- Motivation and
- Degree of alertness of the receiver.

From this point of view, as none of these parameters is included in the equations of the dispersion algorithm, it is difficult that just by using dispersion modelling a modeller will be able to calculate the odour impact of a facility.

When assessing odour impact, and above all when dealing not only with individuals but also with a group of people, other factors affect the sensitivity of a population. A first approach was described by (Rossi et al. 2015). This author describes the following factors affecting sensitivity:

1. The population affected (large city, town, scattered houses, etc.).
2. The use of the land where it is located (industrial, rural, hospital, school, etc.),
3. The housing uses (a continuous, occasional, fortuitous, repeated passage, etc.),

4. Type of protection that the impacted area may have (historical site, natural site, etc.).

The IAQM Guidance on the assessment of odour for planning (Bull et. al. 2018) proposes another approach. This Guidance differentiates between receptors with high, medium and low sensitivity according to the following table:

| | |
|---|---|
| High sensitivity receptor | Surrounding land where:<br>● users can reasonably expect enjoyment of a high level of amenity; and<br>● people would reasonably be expected to be present here continuously, or at least regularly for extended periods, as part of the normal pattern of use of the land.<br>Examples may include residential dwellings, hospitals, schools/education and tourist/cultural. |
| Medium sensitivity receptor | Surrounding land where:<br>● users would expect to enjoy a reasonable level of amenity, but wouldn't reasonably expect to enjoy the same level of amenity as in their home; or<br>● people wouldn't reasonably be expected to be present here continuously or regularly for extended periods as part of the normal pattern of use of the land.<br>Examples may include places of work, commercial/retail premises and playing/recreation fields. |
| Low sensitivity receptor | Surrounding land where:<br>● the enjoyment of amenity would not reasonably be expected; or<br>● there is transient exposure, where the people would reasonably be expected to be present only for limited periods of time as part of the normal pattern of use of the land.<br>Examples may include industrial use, farms, footpaths and roads. |

The weighting of receptor sensitivity can be carried out using traditional *psychometric tools*. In this case, values or quantity are attributed to psychological conditions and other phenomena so that, in this way, it is possible to compare the psychic characteristics of different people and to work with objective information. An example of such methodology is the German standard VDI 3883 which to date it is divided into 4 parts. Each of the parts deals with a different psychometric approach. Part 1 of this standard, for example, describes a method for assessment of odour nuisance by means of the questionnaire technique as well as for estimation of whether and to which extent odour nuisance is present in an area.

Other psychometric tools used traditionally are

1. Interviews (telephone, face-to-face)
2. Surveys, Questionnaires
3. Odour diaries
4. Analysis of records of complaints

In addition, there is a fifth psychometric tool being used nowadays:

5. Mapping odours by using citizen science approaches

These psychometric tools are very much used in contexts related to the evaluation of odour impact.

The following subchapters will deal with each of these psychometric tools.

#### 6.2.5.1 Measuring sensitivity with Interviews

Interviews can be carried out door to door. Another way of carrying out interviews is by phone, provided that a phone book is provided.

In the following example a telephone survey was carried out by the Belgian company VITO, after selecting phone numbers corresponding with different addresses, at different distances from a waste treatment plant.

A total of 17 people living less than 400 metres from the plant answered the phone call. Of those 17 people, 11 answered that the odour was not annoying, whilst the other 6 answered that they were seriously annoyed.

Different people at different distances from the plant were also interviewed, the following Figure 6-4 shows the results of all the people that answered the phone call (100 people in total).

| | Number of respondents | | |
|---|---|---|---|
| distance [m] | not/hardly hindered | (serious) hindered | Total |
| 0 - 400 | 11 | 6 | 17 |
| 400 - 500 | 18 | 3 | 21 |
| 500 - 550 | 16 | 0 | 16 |
| 550 - 600 | 20 | 2 | 22 |
| > 600 | 24 | 0 | 24 |
| **totaal** | **89** | **11** | **100** |

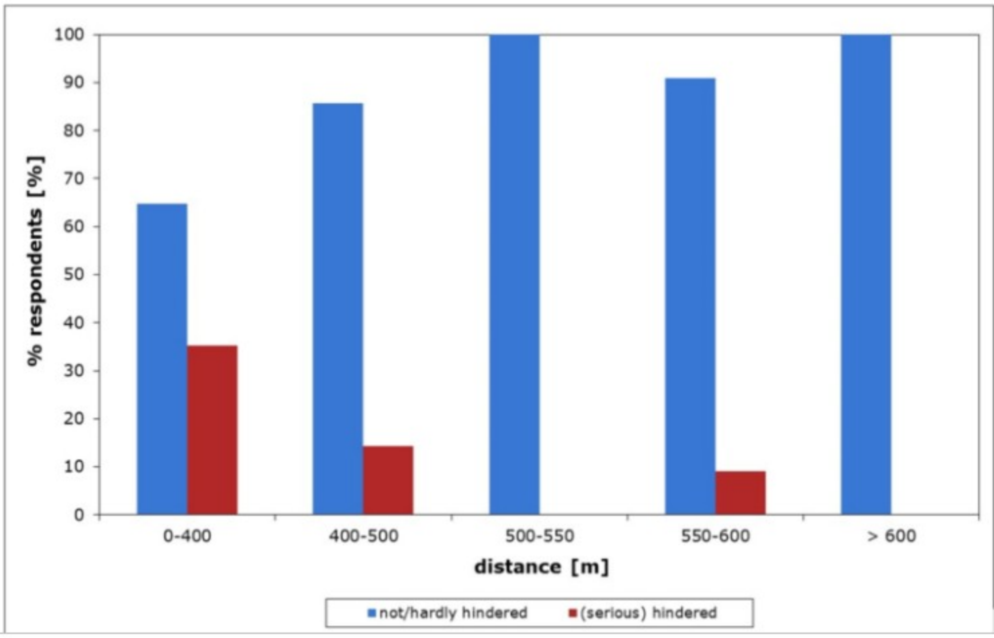


**Figure 6-4** Comparison of results from interviews by phone to citizens at different distances from a waste treatment plant. Red bars show the percentage of respondents that were annoyed and blue bars show the percentage of respondents that were not annoyed (Courtesy of VITO, Belgium).

### 6.2.5.2 Measuring sensitivity with Surveys/Questionnaires.

Surveys and questionnaires are very useful for dose-response studies. There are numerous studies that link health with odour impact in the literature such as Aatamila et al. (2011); Baldwin et al (2004); Dalton et. al. (1999); Dalton et. al. (2003); Government of Alberta (2017); Heany et. al. (2011); Helene et. al. (2020): Miedema et. al. (2000); Oiamo et. al. (2015); Ragoobar et. al. (2016); Rethage et. al. (2007); Shiffman et. al. (1995); Schiffmann et. al. (2004); Shusterman et. al. (1991); Steinheider et. al. (1993); Sucker et al. (2001); van Harreveld et al. (2002).

Most of the studies aforementioned relied on surveys and questionnaires in order to find sensitivity in a population. There are in fact a couple of German standards dealing with the use of questionnaires. Those are:

- VDI 3883 part 1:2015-09 Effects and assessment of odours - Assessment of odour annoyance - Questionnaires

- VDI 3883 part 2:1993-03 Effects and assessment of odours; determination of annoyance parameters by questioning; repeated brief questioning of neighbour panellists

The difference between these 2 standards is that part one deals with one single questionnaire and part 2 deals with a questionnaire repeated a few times along the period of study.

These 2 standards are key, as they can be used when a dispersion model is showing no impact, but the citizens are still complaining about the situation of a plant. The following snapshot (Figure 6-5) shows some of the questions asked in part 1.

| | |
|---|---|
| Questions 1+2: | Questions on the general pollution situation and sensation of annoyance |
| Question 3: | The intensity and frequency of odours are graded with verbal descriptions |
| Question 4: | Annoyance reactions to odours and noise are to be given on a so-called thermometer scale. The advantage of this answer scale is that it is non-verbal, i.e. no verbal description of the investigated situation is necessary. |
| Question 5: | As a control, the same situation is recorded as in Question 4 but in this case with a verbal description |
| Question 6: | This is the question on the state of annoyance, i.e. on the emotional assessment, in the extreme range |

**Figure 6-5** Example of questions made according to VDI 3883 part 1

Respondents are also asked to mark in a thermometer how much annoyed they are, which is a very graphic way to measure annoyance.

German standards are not only used in Germany, but in many other parts of the world. For example, in some parts of Colombia these standards (transposed as the NTC 6012 part 1 and part 2 Colombian standards) are used to take a decision on requiring an odour emitting activity to take additional measures in order to solve a situation of odour conflict.

For example, the Government of the Colombian region of the Valle del Cauca (CVC) has in place several protocols to deal with odour impact based on questionnaires.

- Guide: Field planning and data processing - psychometric assessment of odour nuisances of odour nuisance. CVC (2018)
- Guide: Field guide for Interviewer - odour complaints. CVC (2018)
- Technical instructions: methodological route for determining potential nuisance due to intense odorous substances due to intense odorous substances. CVC (2016)

A typical path in Germany and other parts of Europe could be the following.

1. A dispersion model is carried out
2. If there are still complaints, the plant is asked to whether carry out the grid method according to EN 16841 part 1 or to take corrective actions
3. If there are still complaints, the plant is asked to carry out a VDI 3883 or take corrective actions.
4. If the results of the VDi 3883 show that there is impact, then the plant must take corrective actions.

### 6.2.5.3 Measuring sensitivity with odour diaries

Odour diaries are a very important tool to understand odour impact. When performed correctly, this psychometric technique can deliver very interesting results. For example, on many occasions citizens have some confusion with the type of smells that they perceive, and odour diary may serve to a consultant to check whether it is always the same odour character perceived or not.

Odour diaries are much used all over the world. For example, the Agency for Toxic Substances and Disease Registry of USA has, in its website, very comprehensive information on the topic. EPA Victoria of Australia has also a guideline (2021) dealing with the use of odour diaries.

### 6.2.5.4 Measuring sensitivity with an analysis of records of complaints

Unfortunately, an unstructured analysis of records of complaints will have several limitations for a consultant. Usually complaints are addressed to several organisms and just a few citizens will be available to carry out this task. That means that complaints are just the tip of an iceberg, as usually there are many citizens who do not complain, but are also impacted by odours.

Better results can be achieved if there is a protocol to deal with complaints with a structured set of questions asked to the citizen who is doing the call. A couple of German standards on the topic are:

- VDI 3883 part 3:2014-06 Effects and assessment of odours - Conflict management in air pollution abatement - Fundamentals and application to ambient odour
- VDI 3883 Blatt 4:2017-06 Effects and assessment of odours - Processing odour complaints

A simple search on the internet will show many guidelines on how to carry out an odour complaint. For example, the Government of the Colombian region of the Valle del Cauca (CVC) has a Guide on recommendations for visit report - odour complaints (2016). Other authorities with protocols for odour complaints are Metrovancouver (Canada), several councils in UK. NSW EPA (Australia), etc.

#### 6.2.5.5 Measuring sensitivity with citizen science

Citizen science involves the participation of communities in recording the frequency, intensity and type of the odour. The data obtained from social participation may be associated with other parameters, such as meteorological data recorded during the same study period, allowing its integration and comparison to dispersion models.

Citizen science does not provide odour concentration in $ou_E/m^3$, which is only measured by the do at emission-level.

There are two main limitations that affect the traditional four psychometric methodologies mentioned beforehand. First, the timestamp of the odour complaint is usually not very accurately recorded. Second, the location of the odour complaint is also usually registered, but again not very accurately.

Nowadays there are apps in smartphones that are able to register very accurately the time and location of an odour observation. In fact, these apps are able to, not only register an odour observation, but also register where the odour came from, by using meteorological data or even better, reverse modelling. At this stage, a standard on this new methodology is being prepared by the Spanish Standardisation Agency UNE (Izquierdo et. al. 2021). A large *Horizon 2020* European Project has been carried out.

Following this new methodology, a better approach could be taken by comparing odour observations performed by citizens and comparing them with the results of dispersion models to calculate the correct odour concentration value that triggers an odour observation.

In other words, sensitivity adjustments can be carried out by adding a factor that establishes the actual odour nuisance of an activity at the closest receptors (Díaz et al. 2021).

## 6.3. Limitations on dose-response curves

Unfortunately, it is challenging to set a proposal on maximum allowable levels because, as mentioned before, in the end, it will all depend on the sensitivity of the receptors. A perfectly fine FIDOS setting might fit in a community, while the same FIDOS levels can fail to prevent odour impact due to the different degrees of perception of the sensitive receptors.

An odour modeller is supposed to apply best practices, such as the ones proposed in this handbook. However, the final result will usually not be right or wrong, as it will depend on many factors, being one of them the sensitivity of the receptors.

Percentiles 98 or 90 and odour concentrations of 1 odour unit  or 3 odour units should not be taken as the absolute truth. In some cases, there will still be odour complaints.

When there is evidence that the odour modelled does not correspond with the real situation in the area, other tools can be used. The most common approach is the use of the grid method proposed by EN 16841 part 1 (NCh 3533 in Chile). This approach requires six months to 1 year of data and involves a number of measurements carried out by a group of assessors.

The grid method described in EN 16841 part 1 is a statistical survey method which is applied over a sufficiently long period of time, to provide a representative map of the exposure to recognisable odour, spatially distributed over the assessment area. These grid measurements are used to determine the distribution of the so-called, '*odour hour*' frequency for recognisable odours in ambient air in an assessment area under meteorological conditions that are assumed to be representative of the local meteorology (e.g. the last ten years). An *odour hour* is obtained by a single measurement when the percentage odour time reaches or exceeds 10 % by convention.

One *odour hour* should not be confused with one $ou_E/m^3$. The first one is based on a *recognition* threshold (supra-threshold) measurement and the second one is based on a *detection* determination (threshold).

*Odour hours* obtained using EN 16841 part 1 and *odour concentrations* obtained using dispersion modelling should not be compared unless any sort of transformation is carried out to take into account the differences in the nature of both units.

The grid method does not measure sensitivity. In cases where EN 16841 part 1 shows that there is no impact, but there is still reasonable evidence that odour impact is occurring, other methods can be used.

If there are still odour complaints after carrying out an odour campaign according to EN 16841 part 1, other approaches can be taken, for example, based on the psychometric tools commented in chapter 7.

## 6.4. A window open to research

For several years, approaches have been based on FIDOS factors (Frequency, Intensity, Duration, Offensiveness, Sensitivity). This approach, which shows the multifactorial impact of odour complaints, needs to be improved.

There is a need to identify the subjective parameters linked to odour exposure (and nuisance) based on the FIDOSs scheme and to verify that they are sufficient.

The approach must be validated on the basis of data (experimental). For that, there is a clear need for more dose-response studies coupled with modelling in order to evaluate the dose appropriately.

The *International Commission on Biological Effects of Noise* (ICBEN) meets regularly at conferences every 3-4 years. In these events, epidemiologists around the globe meet to discuss the different impacts that vector noise produces on people (and nature in general). Odour is an environmental stressor very similar to noise. Unfortunately, there is not such an event to study the impact of odours on health, so there is a need for many more dose-response studies to understand the effects of this environmental vector better and for an organisation similar to ICBEN to take the lead on this topic. Some authors (Guadalupe-Fernandez et al., 2021) mention that there is a need for higher quality studies, especially concerning study design (e.g., using panel studies), exposure assessment (e.g., using dispersion models), and outcome assessment.

## 6.5. Conclusions

The FIDOS factors commonly provide the basis for jurisdictional odour criteria. The concentration threshold of a standard odour modelling criterion is related to the intensity dimension of FIDOS. The percentile compliance parameter may be alternatively expressed as a frequency of exceedances or the number of allowed exceedances of the threshold within a given period, thus aligning with the frequency factor of FIDOS. These parameter values may be adjusted in criterion frameworks to account for variations in the FIDOS factors of odour offensiveness and receptor sensitivity.

It can be noted that all factors strongly influence global perception. However, the way to estimate factors can be different. It is possible to just consider qualitative values that represent the perception of one factor (for example, Low/high for frequency), or typically, if a percentile is defined, the factor is then considered quantitative because a scale with time recording is introduced.

The form of evaluation of the FIDOS protocol is linked to the odour standards or regulations established in each country, which vary in compliance values, odour measurement unit, methodology to assess nuisance, etc. Therefore, it is challenging to define a single way, procedure or criterion in the applicability of the FIDOS protocol.

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EN 13725:2003: Air Quality – Determination of Odour Concentration by Dynamic Olfactometry, Comité Européen de Normalisation (CEN)

Venkatram, A. (2002) Accounting for averaging time in air pollution modelling. Atmos. Environ., 36, 2165-2170.

UNE-EN 16841-1:2017, Ambient air - Determination of odour in ambient air by using field inspection - Part 1: Grid method.

van Harreveld AP, Jones N, Stoaling M. Environment Agency. Assessment of Community Response to Odorous Emissions, R&D Technical Report P4-095/TR, ISBN 1 857059 247. (2002)

Yee, E., R. Chan, P. R. Kosteniuk, G. M. Chandler (1994) Experimental Measurements of Concentration Fluctuations and Scales in a Dispersing Plume in the Atmospheric Surface Layer Obtained Using a Very Fast Response Concentration Detector. J Appl Meteorol, 33, 996-1016.

# 7. Other approaches

## 7.1. Introduction

Using dispersion modelling is not limited to only calculating odour isoconcentration curves at different percentiles. Dispersion modelling can be used for many other purposes, such as

1. Calculating odour emission rate by using *Reverse Dispersion Modelling* (RDM);
2. Estimating the location of odour sources by using back trajectory analysis;
3. Source Term Estimation (STE);
4. Calculating odour impact by balancing the hedonic tone of multiple sources;
5. Calculating odour impact from intermittent sources and non-static receptors;
6. Calculating odour impact by using tracers; and
7. Forecasting odour impact.

The following sections will present these topics.

## 7.2. Calculating odour emission rate using reverse modelling

There are a few standards dealing with using RDM to determine the odour emission rate from an unknown source.

a) Annex G of EN 16841 part 2 that deals with "Calculation of the odour emission rate by reverse modelling. Dynamic plume measurement"

b) Chapter 8.2.3 of the EN 17628 dealing with "*Reverse Dispersion Modelling* (RDM) to determine diffuse emissions of VOCs into the atmosphere";

c) EN 15445:2008 fugitive and diffuse emissions of common concern to industry sectors - qualification of fugitive dust sources by reverse dispersion modelling.

d) VDI 3788 part 2 Environmental meteorology – Dispersion of odorants in the atmosphere - Reverse modelling.

RDM can be done in any case, provided that there are adequate meteorological “Gaussian-like” conditions, but there are some main limitations:

- Calculation of emission rate is not possible when there are multiple odour sources (except VDI 3788 part 2);
- Calculation of the relative contribution of different sources with similar odour character in the same plant is not possible;
- When the terrain is not accessible for measuring odour or odorants;

- When the meteorological conditions are not adequate. For example, carrying out RDM during calm winds is not possible.

### 7.2.1 EN 16841 part 2

As explained in chapter 4.4.2, EN 16841 part 2 is divided into two parts: the *dynamic* and *static plume* methods.

In the *dynamic approach*, the assessors walk (or go by bike) in zigzags through the plume getting either closer or far away from the source, whilst, in the *static method*, the assessors do several transects across the plume. Both techniques should give similar outputs, although, to date, no study has been published comparing the results of both methods.

Figure 7-1 shows a schematic overview of the dynamic plume method and how this method looks in reality (Capelli et al., 2012).

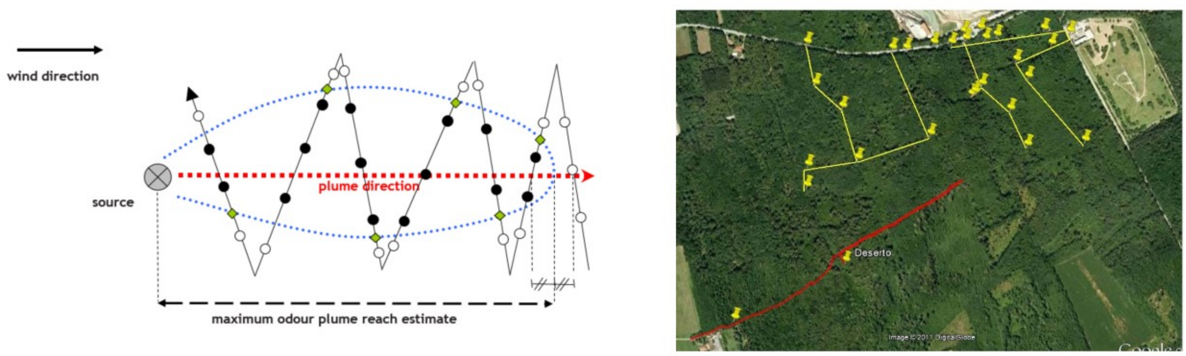


**Figure 7-1** Schematic of the dynamic (left) and a real measurement (right) (Capelli et al., 2012)

The natural result of the dynamic plume measurement is the extent of the odour plume. This result can be used to estimate the total odour emission rate using reverse dispersion modelling.

The calculation of the odour emission rate for the dynamic method using RDM is included in one of the annexes of EN 16841 part 2; that is, it is not part of the “normative” part.

The method described in this annexe has been used in Belgium for over 20 years and can easily be applied in other countries. The Flemish odour policy uses these measurements as one of the main techniques to calculate the emission rate and the impact of an odour source (Van Broeck et al., 2001; Van Broeck, 2003; Van Elst, 2016). The method is standardised in a Code of Good Practice (Bilsen et al., 2008; Bilsen & De Fré, 2009).

The odour emission rate of the source under study is calculated based on the recorded plume extent, the source characteristics and the local meteorological conditions during the plume measurement.

The odour emissions calculated based on the plume measurement are expressed as *sniffing units* per second (su/s) instead of *odour units* per second. A fundamental difference with the European odour unit is that sniffing units are determined by recognising the odour. In contrast, European odour units are determined by detection, not necessarily by identifying the odour type. Typically 1 su/m$^3$ corresponds with a concentration of 1 $ou_E/m^3$ to 5 $ou_E/m^3$.

One sniffing unit per cubic metre can be defined as the odour concentration at the border of the plume. This means the odour concentration can be determined at every transition point as 1 su/m$^3$. Quantifying higher concentrations (e.g. 5 su/m$^3$) by field observation is not possible.

The method of reverse modelling is applied as follows: In the first step, the plume extent is determined as described above. In this step, a sonic anemometer records wind speed/direction along the process.

In the second step, a dispersion model calculates the average odour concentrations on ambient air in the surroundings of the odour source under investigation. This is done based on the source characteristics (emission rate, height, temperature and flow, among others) and the local meteorological data (wind speed, wind direction and stability class) recorded during the measurement. Since the odour emission rate is unknown, a fictitious emission rate of, for example, 5000000 ‘model units’ per second is assumed. The calculated odour concentrations on ambient air are expressed in model units per m$^3$.

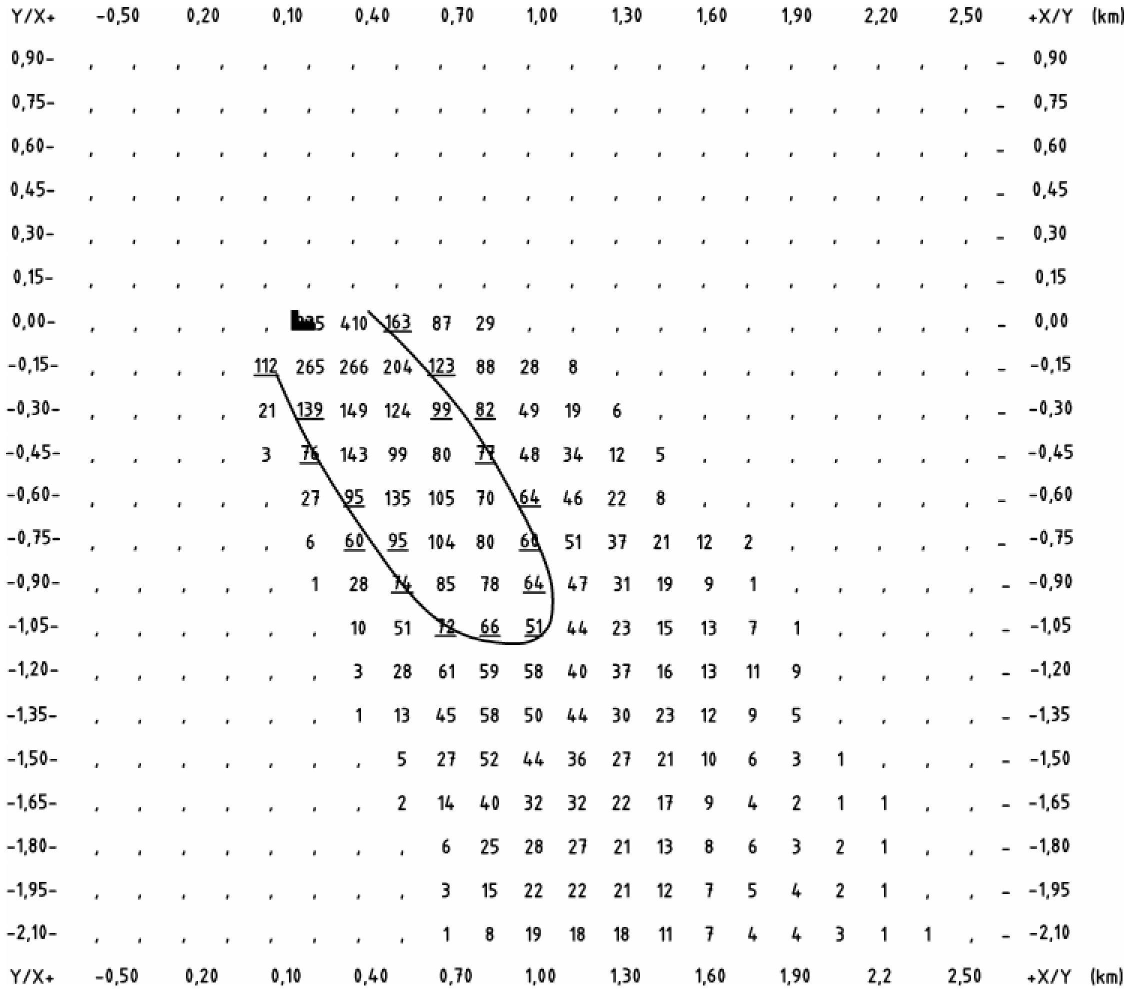


**Figure 7-2** Example of reverse modelling calculation according to EN 16841

After calculating the concentrations in ambient air (in model units per m³), the plume extent recorded during the plume measurement is put on the calculated odour distribution grid, and the grid points on the edge of the plume are ticked. By definition, the odour concentration at these edge points equals one sniffing unit per m³ (su/m³). The average of the concentrations in ambient air (in model units per m³) of all edge points is calculated. In this case:

(117+139+75+95+60+95+74+72+66+51+64+61+64+77+82+99+123+163)/18 = 87.4.

In this example, the average odour concentration with an emission of 5 000 000 model units per second at the edge points is 87,4 model units per m3. Thus, the real odour emission rate of the source would be:

5 000 000 / 87.4 = 57 254 sniffing units per second.

This type of calculation makes sense when there is just one odour source or when there are fugitive emissions all over a building. In complex cases, with multiple sources of odour present, assigning the odour emission rate to a specific source is challenging. This is a well-known limitation, not only using this methodology but for any other reverse modelling approach.

### 7.2.2 EN 17628

This standard deals with fugitive and diffuse emissions of common concern to industry sectors and describes several standard methods to determine diffuse emissions of VOCs into the atmosphere.

One of the methods proposed in the EN 17628 standard is using RDM to calculate diffuse emissions of VOC. In this case, a portable VOC monitor (such as FID/PID) is used to quantify VOC concentration in ambient air. Later, this data is used with meteorological data to calculate OER at the source.

### 7.2.3 EN 15445

EN 15445:2008 deals with quantifying dust emissions by using RDM.

The implementation of the procedure involves several steps. First, emissive areas, measuring points, and receptors are identified and geo-referenced. Then, in the same way that EN 16841 part 2, a hypothetical value of emission flow is set, and meteorological parameters are defined.

These data are given as input to an air quality dispersion model that calculates dust concentration in each receptor. Finally, least squares regression between concentrations and measured concentrations is applied to obtain an optimised value of dust emission flow.

### 7.2.4 VDI 3788 part 2

VDI 3788 part 2 is still a draft at the time of writing of this handbook. This standard takes EN 16841 part 2 plume static method and calculates the OER of multiple sources by RDM.

This standard is based on a preprocessing tool named *esofin*, built upon the German dispersion model *Austal.*

*Esofin* does an interactive run on the emission to retrieve the measured odour frequencies. The iteration ends when the difference model - measurement at each measurement point in the plume is at a minimum.

At this stage, the working group dealing with this new standard discusses the limits of the iteration process and the retrieved emissions. In addition, the group is working on the quality measures for the plume inspections.

The interesting point of this *esofin* module and the *VDI 3788 part 2* is that, unlike the previous methodologies, it can calculate the odour emission rate from *multiple* sources. The iterations are made by testing simultaneously different combinations of OER for different sources.

For this, all known sources are defined in the model with their emission rates. The unknown sources are described in the technical parameters as size and location. The iteration process will find the odour emission rate for the unknown source, which is needed to retrieve a high correlation to the modelled to the measured impact. The quality of the results depends on a good knowledge of the investigated site and the situations during the plume inspection. The meteorological measurements during the field inspection need high-resolution 3D-turbulence measurements. The measurements should be synchronised with the odour impact measurements.

The current work of the VDI group is testing with various data sets from plume inspections with corresponding sampling.

## 7.3. Calculating the origin and type of odour sources

### 7.3.1 Use of wind data to get preliminary information on the origin and type of a source

The correlation of meteorological variables – mostly wind direction and speed - with levels of air pollution is the most straightforward technique to estimate the potential origin of an odour. These data can be combined with other data, such as odour concentration, to know where a source is located. Also, they can be useful in finding out the type of source.

These approaches rely on simple calculations not considering topography or land use. The methodologies described in this chapter cannot be used when neither of these factors is important.

#### 7.3.1.1 Wind direction

Meteorology, particularly wind direction and intensity, has been widely used to assess the source of odour nuisance. A German standard deals with this topic: The *VDI 3883: Part 4*.

VDI 3883 part 4 deals with the effects and assessment of odours, particularly with processing odour complaints. The following picture shows a scheme of the simplest case considering only one source of odours.

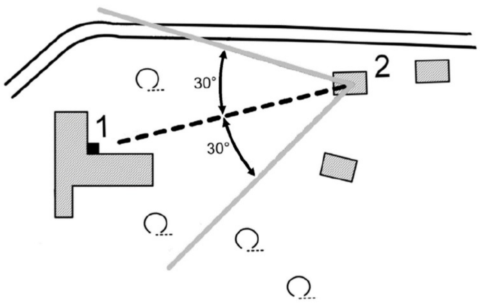


**Figure 7-3** Schema to identify the origin of an odour source according to the German standard VDI 3883 part 4

In Figure 7-3, the receptor (2) is exposed to a single-point source (1). The wind direction of exposure is determined by connecting the two points with a line (dashed line). A 30° angle is drawn on each side of the connecting line from where the impact occurred.

In this example, the area in between is the exposure sector, which contains wind directions from 228° to 288° (southwest to west-north-west). If the wind direction is within this range, the odour observation is plausibly attributed to that source.

More complex cases dealing with *multiple sources*, *area sources* and *fugitive sources* are addressed in this standard.

#### 7.3.1.2 Pollution Roses

More specifically, this correlation is often carried out using *pollution roses*. These roses are helpful tools to characterise air masses that represent direct anthropogenic influences nearby. A pollution rose is similar to a wind rose, but it uses the concentration level of a specific pollutant in place of the wind speed. It may give important information about the presence and the approximate position of important emission sources.

Pollution roses can be misleading in areas where pollution levels are due to the transport and transformation of pollutants over long distances. However, this is not the case with odour pollution. Indeed, as pointed out by *Fleming et al.* (2012), in short-range transport, the airflow pathway is more influenced by emission source areas than in long-range transport, where various processes, such as advection, dry and wet deposition, chemical reactions and physical losses, have more influence on the composition at the receptor location. The wind rose method often tracks local wind influences (the last 2 or 3 hours before reaching the station), but it can often be misleading in the longer term.

Two examples of pollution roses are reported below. The graph on the left of Figure 7-4 represents the pollution rose of the average concentration along each wind direction. The chart has been created starting from a 1-hour time resolution concentration of *non-methane hydrocarbon* available for a whole year. The higher average values are associated with winds blowing from WSW, SW and S. The graph on the right of Figure 7-4 plots the pollution of the 90th percentile of concentration values along each direction. This graph shows that higher values are associated with winds blowing from WSW.

In order to get an idea about the statistical significance of the results, this kind of pollution roses must be associated with the information about the number of data used to calculate the average, or the percentile, along each direction. For example, the number of data used in each direction for the two charts reported below goes from a minimum of 114 (SSE) to a maximum of 1117 (W).

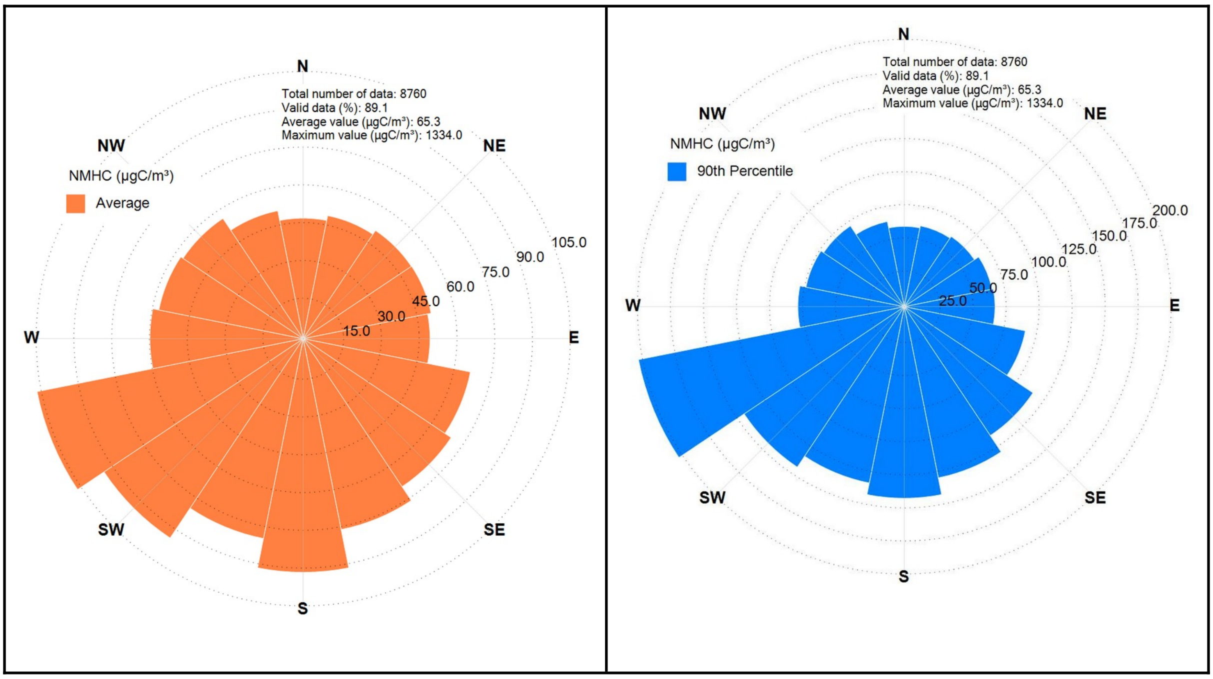


**Figure 7-4** Pollution rose, representing the average concentration along each wind direction (left), and Pollution rose, representing the 90th percentile of concentrations along each wind direction (right). (courtesy of Enviroware)

Another type of *pollution rose* is the *percentile rose*. The percentile roses are useful for showing the distribution of pollutant concentrations related to the wind direction. The percentile rose can help to identify different sources, e.g. those that affect high percentile concentrations (Carslaw & Ropkins, 2012). Figure 7-5 is an example that explains how percentile values vary by season and hour of the day. In this figure, $NO_2$ concentrations are higher in winter and when the wind is from the southeast. $NO_2$ concentrations are higher during nighttime than in winter daylight hours.

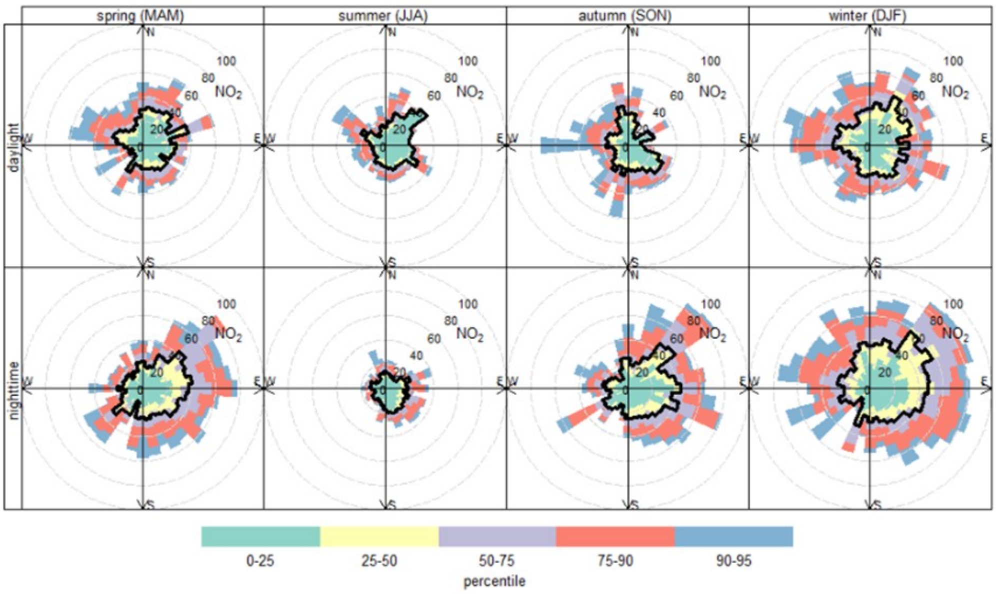


**Figure 7-5** Pollution rose, representing the 90th percentile of concentrations along each wind direction (Courtesy of the Israel Ministry of Environment)

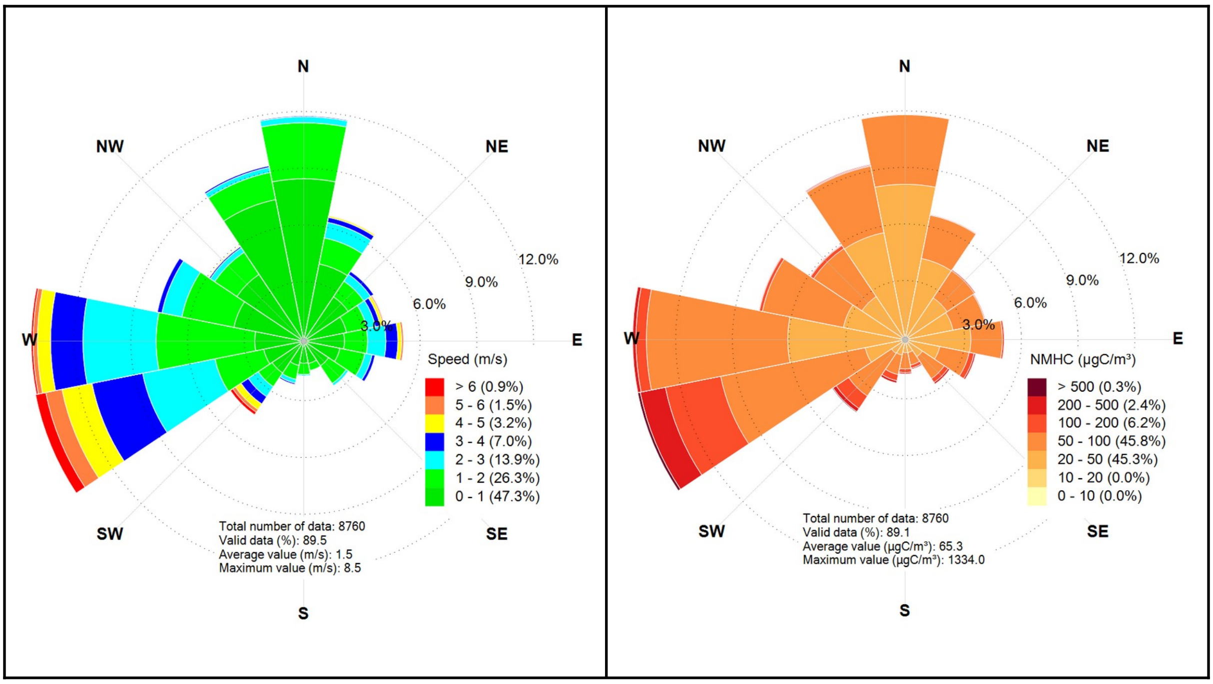


**Figure 7-6** A wind rose (left), and concentration rose (right) for the same site (Courtesy of Enviroware).

Figure 7-6 shows a wind rose (left) and a pollution rose (right) created from the data of the same monitoring station and during the same time interval. These are the same data used for preparing the previous Figure 7-6. The pollution rose has been created considering concentration intervals along each direction, in the same way, a wind rose is created considering speed intervals along each direction. The shape of the two charts is identical:

the longest “arms” of the pollution rose are associated with the prevailing wind direction, not with the directions associated with the highest average concentration (or to the highest percentile). In this sense, a pollution rose, as shown in Figure 7-6, is not as helpful as one of the previous two figures because it gives information already given by the wind rose. Indeed, concentrations are also visible by different colours along each direction. However, their role is not always well understood (e.g., typically, the highest concentrations are shown by a narrow strip).

#### 7.3.1.3 Wind speed

Wind speed is important because it gives useful additional information not given by the wind direction.

For example, high-level emissions, such as those of a high stack, may be observed near the source only for high wind speeds. This happens when *Stack Tip Downwash* (STD) plays a role: for large diameter stacks and relatively low momentum releases (i.e., $w_S/U < 1.5$, with $w_S$ emission speed and U wind speed at the height of release), the plume is captured within the downwind side of the stack, causing high concentration values at the ground. On the contrary, the concentration due to low-level emissions decreases while wind speed increases.

By applying considerations similar to those reported by Mensink and Cosemans (2005) for PM2.5, it is possible to state that the concentration of odour emitted by a source can be described by $C = \alpha\ OER/U$, where U is the wind speed, OER is the odour emission rate and $\alpha$ incorporates the terms of the Gaussian solution. Then, when OER is constant, C decreases as U increases. On the contrary, considering, for example, the emissions of a passive odour source, OER is proportional to the power of the wind speed (the power is 0.63 according to Jiang and Kaye, 1996, or 0.5 according to Region Lombardy, 2012). Therefore, the odour concentration should go as $C = \beta\ U^{0.5}/U = \beta/U^{0.5}$, where $\beta$ incorporates $\alpha$ and other constant emission terms. These two different behaviours - qualitatively represented in Figure 7-7 help in estimating the possible origin of odour:

- If the odour concentration decreases inversely as the wind speed increases, it is likely that the source is a stack or any other emitter, not depending on wind speed.
- If odour concentration varies more or less as the inverse of the square root of the wind speed, it is likely that odour derives from a passive source whose OER depends on the wind speed.

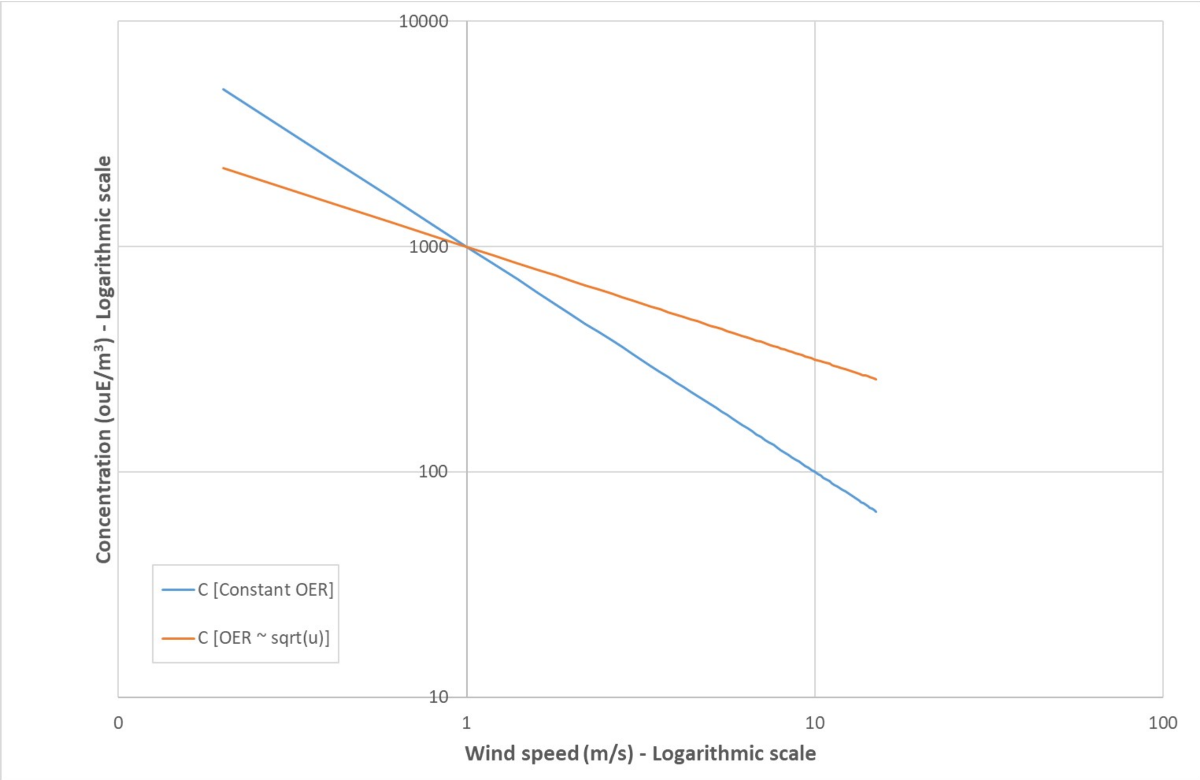


**Figure 7-7** Odour concentration as a function of wind speed for a source with constant OER and a source whose OER goes as the square root of wind speed. Both axes are on a logarithmic scale. (Courtesy of Enviroware)

#### 7.3.1.4 Three-variable plots (Ternary plots)

When wind data and odour levels, or concentration levels of odorous species, are available at the same time, resolution, speed, direction and concentration can be represented in a single ternary plot. In this kind of plot, the concentration level is represented by symbols (e.g. circles) of different colours and/or sizes, which are placed at a radial distance given by the wind speed and at an angular coordinate given by the wind direction. This plot may help in estimating the presence of essential sources. The drawback is that many points of different colours may be superimposed, and some plot characteristics must be better visible. The number of points may be reduced by selecting to show only some values of concentrations, for example, the higher ones. An example of a ternary plot is shown in Figure 7-8, which indicates the presence of a source WSW from the measuring point.

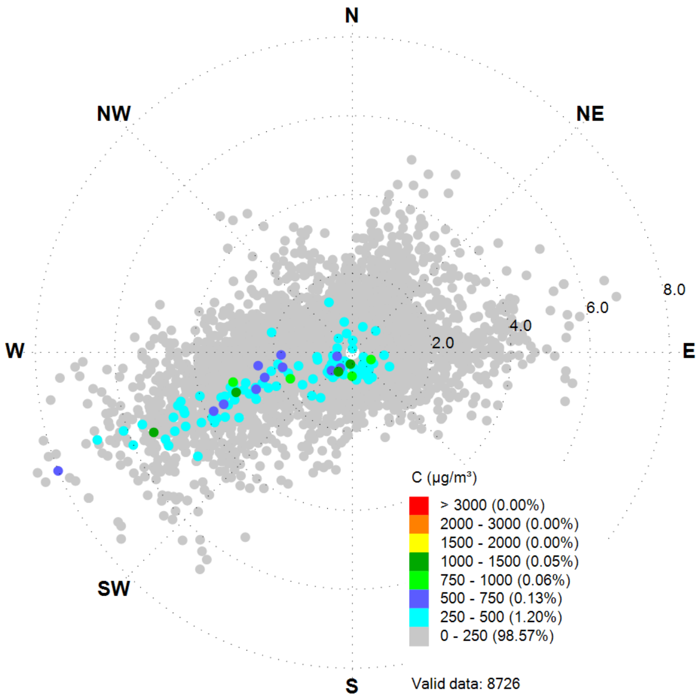


**Figure 7-8** Example of a ternary plot showing the presence of a source WSW from the measuring point (Courtesy of Enviroware)

#### 7.3.1.5 Non-parametric analysis

Another useful representation can be obtained by applying the non-parametric regression, which is a method to estimate the value of a dependent variable (concentration) starting from the values of one or more independent variables (wind speed and direction) without any a priori functional relation between the dependent and the independent variables. Examples of applications of this analysis are shown in (e.g., *Henry et al.*, 2002; *Yu et al.*, 2004). The average concentration of a pollutant for a given couple of *wind directions* (wd) and *wind speed* (ws) is calculated as a weighted mean of the measured concentrations in a window centred on (wd, ws). The window size is determined by the *Full Width at Half Maximum* (FWHM) of the kernel functions used in the weighted mean. Such size is the unique input value of a non-parametric regression. For example, an FWHM of 10 degrees can be used for the wind direction, and an FWHM of 2 m/s can be used for the wind speed. Typically, the Gaussian kernel is used for the wind direction, and the Epanechnikov kernel is used for the wind speed (Yu et al., 2004). For example, Figure 7-9 shows the relation between concentration and wind direction.

It is noticed that the considerations reported in this paragraph may be more frequently applied to the concentrations of odourous substances than to odour levels.

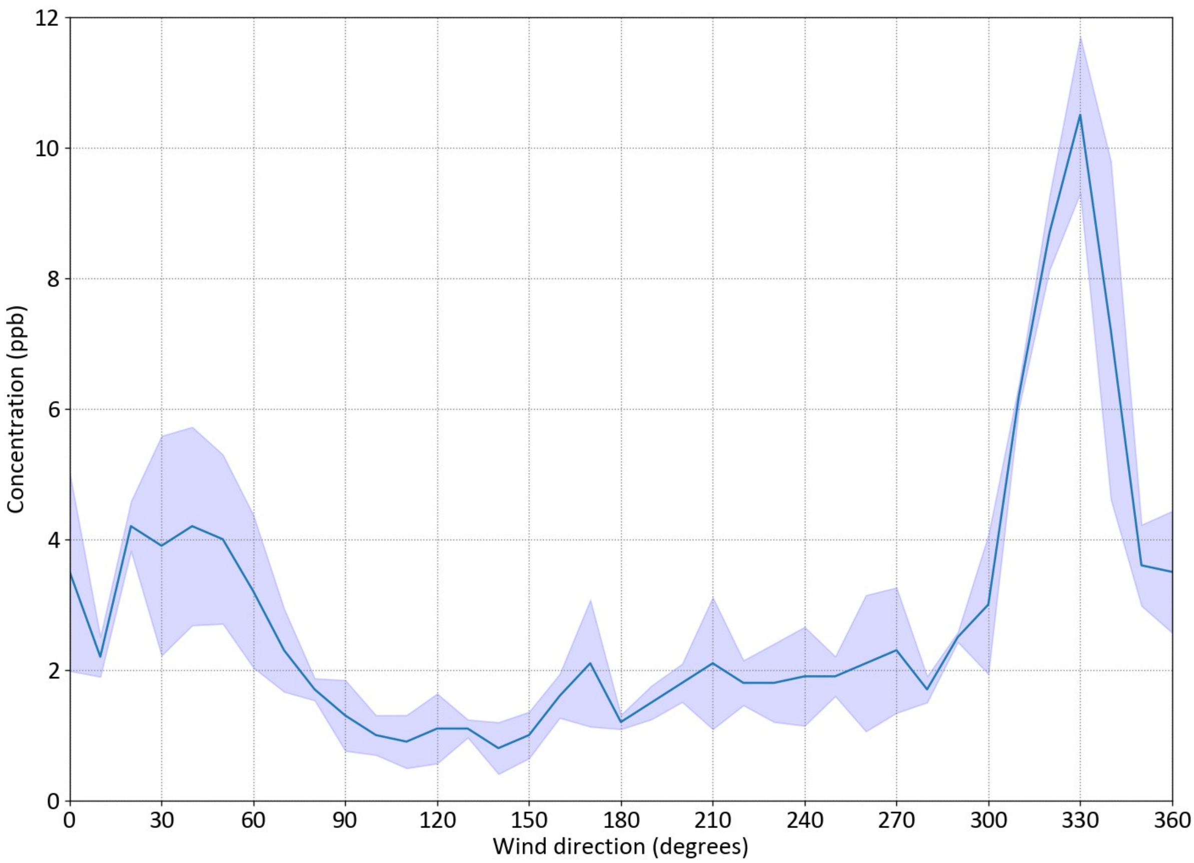


**Figure 7-9** Example of a chart that can be obtained with the non-parametric analysis (Courtesy of Enviroware)

### 7.3.2 Numerical modelling approaches for back-trajectories and backward plumes.

Numerical models are useful and used tools to trace back in time the trajectories of an airborne substance released in the atmosphere. As similarly done in forward-mode applications, they employ meteorological fields to drive the motion of airborne parcels, but back in time. In the frame of this approach, the determination of the origin of an odour event can be carried out by using numerical models provided the following information is available:

- Date and time of odour observation of the event
- Location of the odour observation of the event

Starting from such information at the known “receptor”, it is possible to determine the areas where the potential “source”, originating the odour nuisance, is located. The simplest way to generate back trajectories consists of calculating the deterministic path of a tracer parcel by appropriate interpolations of the wind field provided by an atmospheric model. Typically, Lagrangian models (see Chapter 5.5.3 Lagrangian models) of increasing complexity, from the mean-trajectory approach to boxes, puffs and particles, can be adopted for more advanced approaches. Their applicability depends on the time and spatial scales of interest and the degree of approximation that can be acceptable at such scales. In the simplest mean-trajectory models, the parcel motion is determined considering only the mean wind velocity and neglecting the turbulent diffusion. Examples are *FLEXTRA*, (Stohl & Seibert, 1998), *HYSPLIT* trajectory version (Stein et al., 2015); *TRAJ2D*, (Exponent, 2023) and *LAGRANTO*, (Sprenger & Wernli, 2015). Such simplification can be accepted for long-range dispersion, which means synoptic and planetary spatial scales from weeks to months. When considering the typical scales of the odour dispersion in the atmosphere, from minutes to some hours and for distances up to a few km, more advanced models capable of accounting for local circulations and turbulence, such as the stochastic Lagrangian particle dispersion models, are needed (*FLEXPART*, Pisso et al. 2019; HYSPLIT, Stein et al. 2015; SPRAY, Tinarelli et al., 2000; *LAPMOD*, Bianconi et al. 1999; LASAT, Janicke Consulting 2019). Here, the local wind determines the mean motion of ‘virtual’ particles containing a mass of pollutant or odour units. The diffusion is given by velocities obtained as a Lagrangian stochastic differential equations solution. The pathway of the plume or puff of particles is thus tracked in backward mode.

Back-trajectory and backwards-plume approaches can be used when only qualitative information, such as citizens’ notifications, reveals the odour nuisance occurrence. With this method, it is, therefore, possible to trace the atmospheric pathways the parcels followed before arriving at the receptor and identify their potential source's origin. Backward trajectories were applied to define the origin areas of various types of tracers, not only odour, including Saharan dust (Chiapello et al., 1997), radioactive pollutants (Pudykiewicz, 1998; Hourdin & Issartel, 2000) and $CO_2$ peaks (Ferrarese & Trini Castelli, 2019).

In order to identify the origin and the most plausible source of the odour release, in particular when a quantitative estimation of the odour event is available, such as measured concentration of a substance typifying the odour nuisance, more advanced model configurations and additional processing of the model outputs are necessary, in a way similar to the reconstruction of the source term and the emission rate based on pollutant concentration measurements.

### 7.3.3 Source Term Estimation Methods using backward modelling approaches

Identifying the source generating the disturbance can be challenging due to the presence of

- many potential sources in a complex industrial area
- unknown sources.

S*ource term estimation* (STE) algorithms can predict a possible release location with specific emission characteristics, such as the time and amount of release of material or odorous emissions. These algorithms are often based on the use of local concentration measurements (either chemical species or odour units) given as input to dispersion models applied in a configuration capable of solving the inverse problem of the dispersion.

An inverse dispersion model can be derived, in principle, from different standard forward-in-time dispersion models, from simple Gaussian, Lagrangian (puff or particles) up to Eulerian dispersion models, by appropriately modifying the formulation of the dispersive section and considering the advective section backwards in time.

Examples of this modelling approach are retroSPRAY (Armand et al., 2013), the inverse of the standard Lagrangian particle dispersion model SPRAY, but other examples can be found in literature, such in Sofiev et al. (2005) and Flesch et al. (1995). Similar techniques can also be used with the inverse version of Eulerian dispersion models, as in Hourdin and Talagrand (2006), Elbern et al. (2007), Corazza et al. (2011), and Thompson et al. (2014). Recently, Hutchinson et al. (2017) published a paper containing a useful and comprehensive review of STE methods using dispersion models to describe the inverse source-receptor relationship and considering different types of models. Platt and Deriggi (2012) showed the results from a comparative activity involving different STE algorithms and backward dispersion models.

Applying a backward dispersion model using the concentration measured at given points as sources cannot determine all the desired information alone. The backward dispersion starting at locations and times of observed pollutant concentration values composes ‘back-concentration’ fields, which define areas where possible emitting sources reconstruct the measured concentrations, provided that a good estimate of meteorological fields, particularly the mean wind, is available. Similarly, in the presence of observations with zero values, back concentrations starting from those locations (or values compatible with a possible environmental background) can define exclusion areas and times, identifying where the pollutant source cannot be located. Due to the intrinsic uncertainty of the dispersion phenomena, the mean wind reconstruction, the measured concentration data and the model formulation itself, backward dispersion patterns obtained from different measuring points may describe relatively large and sometimes non-overlapping or inconsistent areas. In this respect, a postprocessing phase of the backward simulations is needed to find a statistically congruent area, integrating all the available information and giving a unique final view of the emission regions, together with an indication of both the emission rate and time and their related uncertainties. Different methods are considered to implement these postprocessing schemes. Among them, a Bayesian approach (Rajaona et al., 2017), statistical approaches counting the maximum overlap of retro-plumes or applying variational methods to minimise the values of an objective function (Tinarelli et al., 2018) can be cited.

An approach - which is not backward modelling but can be used as STE - consists of producing a set of simulations by varying the location and the release duration of a potential source – placed within a candidate region - and evaluating the concentration at a specific receptor where concentrations have been measured, or complaints received. The analysis of the simulation results allows the estimation of the source position and its release duration in probabilistic terms. The two functionalities, i.e., execution of several simulations and analysis of their results, have been implemented, for example, in the LAPMOD_SA simulation tool (Bonafè et al., 2016), which is based on the LAPMOD Lagrangian particle model. The tool has been applied to understand the origin of a sudden peak of fine particulate matter rich in ammonium nitrate observed in Bologna (Italy) on February 16, 2012. The candidate emission area was placed in the northern part of the Po Valley, where manure spreading, responsible for ammonia emissions, was possible (the southern part was covered by snow). The result of the application was several areas characterised by specific probabilities to contribute to the impact at the receptor point.

### 7.3.4 Tracing the origin of odour nuisance by integrating citizen-science and modelling approaches

This chapter briefly summarises three examples of applying the back-trajectory technique to estimate the origin of odour nuisance. The first example is an application in Tarragona (Spain), the second one is an application in Sicily (Italy), and the third is in operation in Israel by the Ministry of Environment.

#### 7.3.4.1 Tarragona (Spain).

Tracing the backward course of an air mass is very interesting when using advanced psychometrics tools, such as citizen science approaches (Gallego et al., 2008; Roca et al., 2008; Chunrong et al., 2021).

Ramos et al. (2017) presented the case of a small town near Tarragona, Spain, that had suffered from odour impact from two waste treatment plants. In 2016, the citizen science app ©*Nasapp* was given to a set of several citizens in this town. As a result, 213 citizen observations were recorded over six months. Figure 7-10 shows the results obtained.

A close analysis of this figure shows

1. Two sets of *Back-Trajectories* (BT) that go through to the plants involved
2. Other BTs whose paths do not cross the plants.

In the example above, it was possible to calculate the attribution of the odour observations. After six months, 63% of the BTs were attributed to one of the plants, 26% to the other plant, and 11% could not be attributed to any of the plants due to:

1. Errors in the calculation made by the algorithm.
2. Odours perceived by the citizens but not attributed to the plants.
3. False/biassed observations made by citizens.

In the case of false/biassed observations, using back-trajectories is very useful as citizens reporting repeated wrong odour observations are very easily detected, and their results can be automatically discarded.

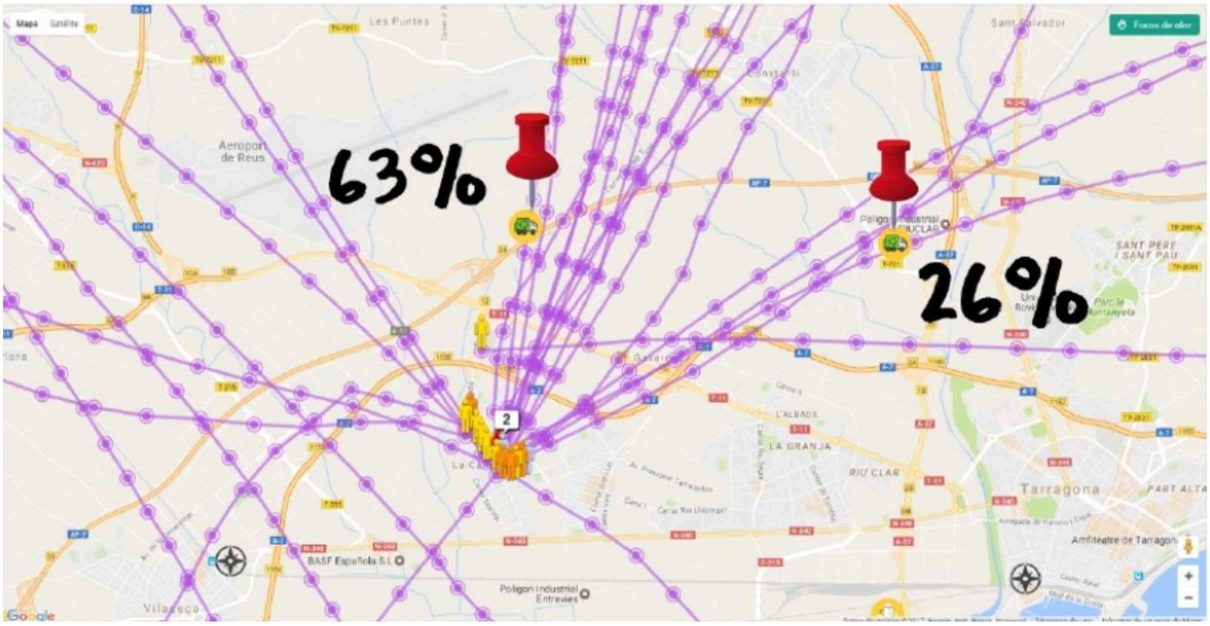


**Figure 7-10** Results of 6 months of BTs drawn from citizens' observations in a town close to Tarragona, Spain, impacted by two waste treatment plants (Ramos et al., 2017)

More accurate back-trajectories will be obtained with higher temporal/space resolutions and at lower altitudes close to the receptor level.

In the example above, BTs were used to identify two sources separated by a distance higher than that of the spatial resolution of the model. In these cases, an identification between two sources can usually be carried out. However, for sources very close to each other, BTs will not be adequate. BTs are not a suitable tool to find out which of the processes of a plant is responsible for an odour event, as usually, these sources are separated by a distance lower than the spatial resolution of the model.

#### 7.3.4.2. Sicily (Italy)

Odour nuisances are often a source of justified complaints from the population. Thanks to the widespread availability of web apps, it is nowadays possible to collect and manage these complaints in a structured way, allowing a fast visualisation of the areas most affected by odour nuisance. In this respect, the information collected by such a tool can represent, in principle, a sort of adaptive receptor network centred on the impact event and moving with it. Using odour observations as moving “receptor points” and applying a backward dispersion model can support localising the odorous sources. The idea is to use the STE algorithms previously described limiting the expected information to identify the emitting area. This, due to the unavailability, for example, of real observed concentrations, which would give the necessary input to reconstruct an emitting flow rate. An example of this approach is the NOSE - *Network for Odours Sensitivity* (https://nose-cnr.arpa.sicilia.it/) web application, developed by CNR-ISAC and ARPA Sicilia and aimed at tracking episodes of odour nuisance through a citizen-science approach. The meteo-dispersive modelling suite SMART (Spray-Moloch Atmospheric Regional Tool, Bisignano et al., 2020; Trini Castelli et al., 2021) is coupled to the NOSE web app. A new and original approach was developed for the SMART dispersion module, where the SPRAY Lagrangian stochastic particle model was integrated with the version that includes the backwards-mode option, RetroSPRAY. The main challenge lies in using the signals from citizens in place of observed concentrations as input receptors for RetroSPRAY. The warnings received through the NOSE Web App are sparse in space and time, yet they are considered moving in the space/time receptor grid. A three-phase approach was established. A clustering of the warnings is elaborated to generate proper ‘receptors’ for the back-trajectories. Then, simulations with RetroSPRAY are performed by releasing  a series of retro-puffs from cells containing the identified receptors at each time interval, during which a significant number of signals are collected. Finally, the back-concentration fields generated by the retro-puffs are statistically combined at emission and receptor times. Through such a process, maps are produced, describing the region where possible sources can be located. This version of SMART modelling system has been applied to different odour nuisance events notified by the NOSE web app, providing reliable results in detecting the potential source, in one case identified after a dedicated measuring campaign.

#### 7.3.4.3. Israel

The *Ministry of Environment* of Israel uses an operational web system to identify potential sources of odour nuisance in a real-time calculation. The system calculates back trajectories and shows the airflow path on a map from the complainer’s location (Figure 7-11). The system considers all the meteorological data from all stations in the analysis area and interpolates the stations’ data using Cressman equations. The number of stations participating in the analysis is not limited, and their impact varies according to their distance from the point of calculation. Forward trajectories can verify a potential pollution source or compute an odour nuisance event trajectory in real-time (Figure 7-12). When the system is activated for a real-time event persistence or forecast mode, the trajectory can be calculated in *perseverance mode* according to the last wind data at each station. This is done using a half-hour wind data before the odour event starts and proceeding with the last wind data at each station).

This system helps regulatory authorities and industry plan a response to an air pollution event and identify the pollution source  (developed by  *Meteo-Tech* European Patent 3339855, Israeli Patent 249780).

**System Components**

To establish the method proposed here, the following infrastructures are required:

- meteorological station network
- command centre

**Meteorological Network**

- The meteorological network enables calculating the wind field at any given time over the grid covering the "area of interest".
- Analysis and computation of the meteorological grid are done using *Cressman's method (Cressman, 1959)*.
- The system computes the meteorological grid values as an average of the last 5 minutes' data (Wind Speed and Direction).
- The wind field calculation is based on data from several available meteorological stations in the area of interest

**Methodology for calculation of the airflow trajectories**

• Meteorological data – the system collects real-time data (wind speed and direction, 5 minutes averages) from available meteorological stations.

• Interpolation – the calculation of the airflow trajectory is based on the data from all meteorological stations. The closer the station - the greater its influence on the calculated trajectory.

• The model uses the Cressman algorithm to calculate the wind speed and direction (5 minutes averages) at each grid point, relying on data from the meteorological stations.

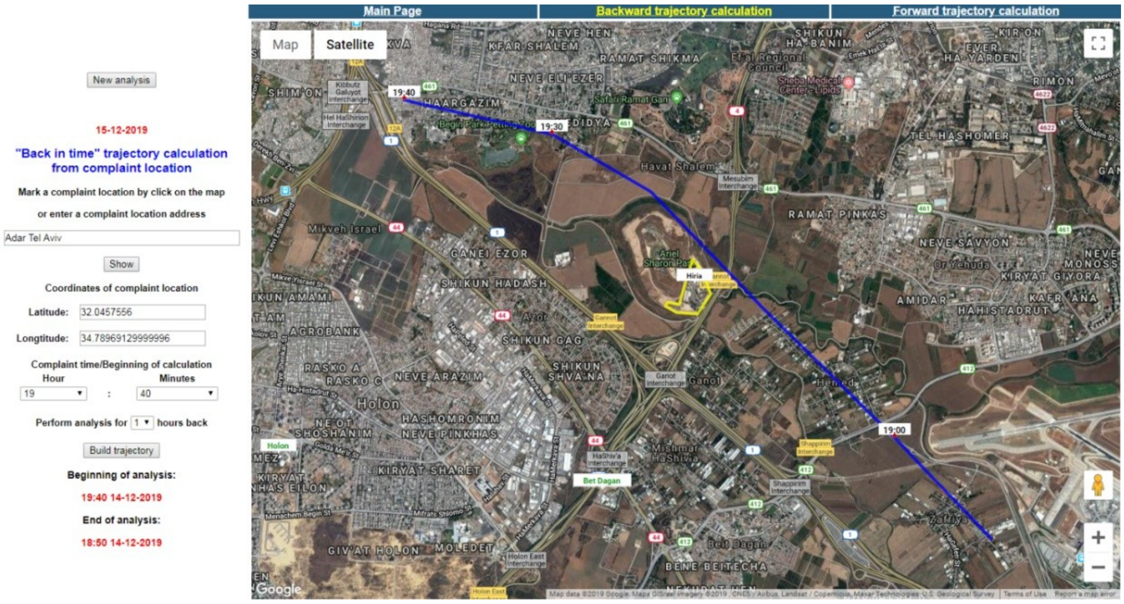


**Figure 7-11** Example of backward trajectory from Adar Street Tel Aviv, input data (on the left side) including the address of the complaint, start hour and date (Courtesy of Israel Ministry of Environment)


**Figure 7-12** Example of forward trajectory from Hiriya Recycling Park (Courtesy of Israel Ministry of Environment)

The Haifa Bay industrial area is close to sensitive receptors, characterised by a complex topography that includes Mount Carmel (~400 metres), a flat area and the Mediterranean Sea. The following example will describe a trajectory analysis of odour nuisances in the Haifa area near the shoreline. The complainant's location is marked in Figure 7-13a (Complaint place at 9:00 AM) when several met stations are used from different heights (marked by a blue circle). The back trajectories (Figure 7-13a) indicated a possible source on the coastline (at 5:30 AM, red triangle), and indeed at this time in this area, there were unusual emissions from port containers. On the other hand, when one meteorological station at Carmel Mountain was used (Figure 7-13b) for the same event, the back trajectory path points to a possible source in the sea. When a met station on the coast was chosen (Figure 7-13c), a possible source of the odour nuisance was in the mountain area.

In this case, identifying the odour nuisance source was incorrect when a single meteorological station was used.

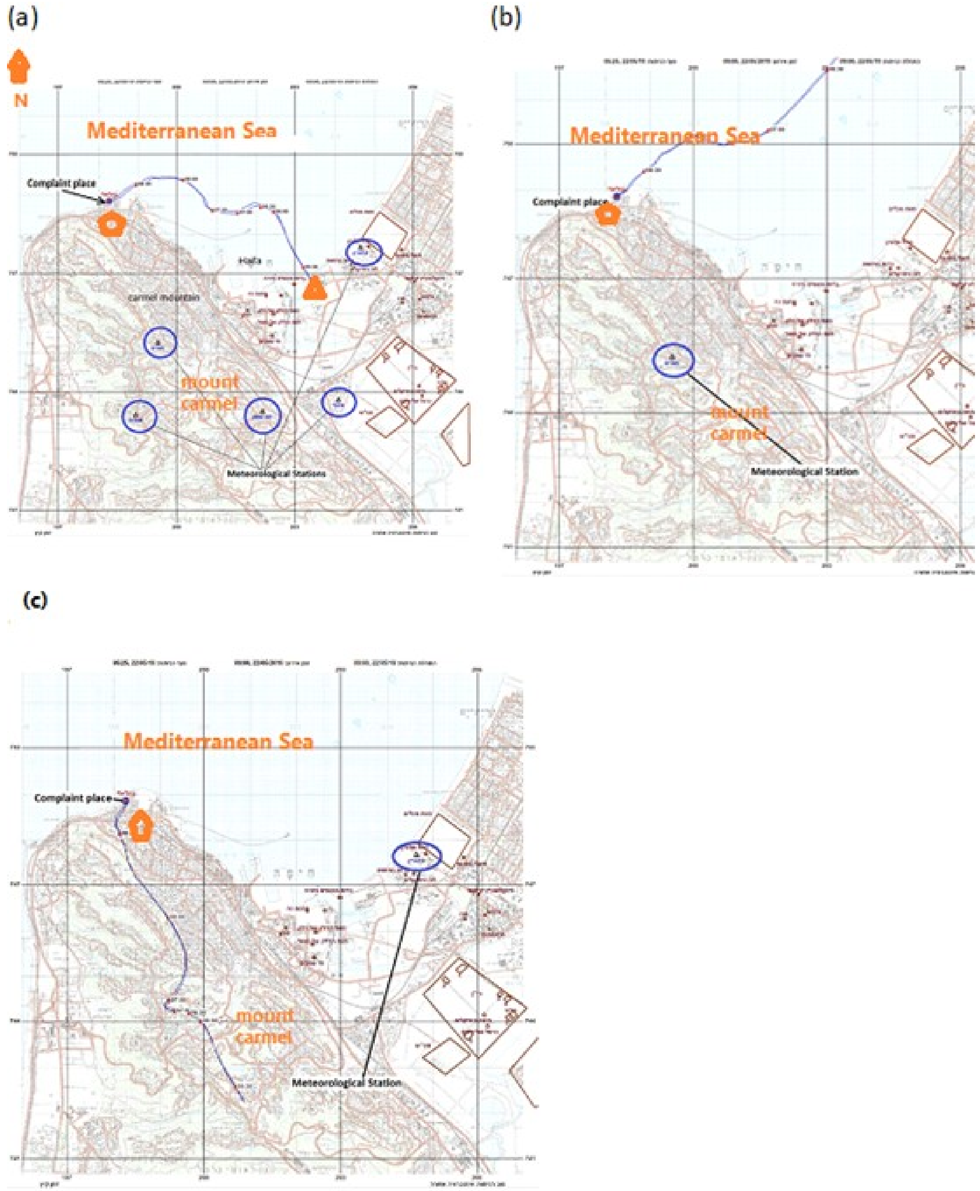


**Figure 7-13** Airflow back trajectories calculated from the complaint site at *Bat Galim* neighbourhood in *Haifa* from 09:00 AM to 05:25 AM on 22.05.2019. The calculations were based on: (a) all the meteorological stations in the area, (b) the mountain meteorological station, and (c) the coast meteorological station. (Courtesy of Israel Ministry of Environment).

## 7.4. Calculating odour impact by balancing the hedonic tone of multiple sources

Source apportionment of odour rate from multiple sources is traditionally addressed by calculating the contribution of different odour emission rates of each source. Usually, this contribution is measured by calculating the number of odour units released per unit of time for each source.

This approach is correct when the odour sources have a similar hedonic tone. However, the calculated contribution of each source to the overall odour impact can be challenging when different hedonics are involved.

Whilst calculating the odour concentration in a lab is a *threshold* measurement, the hedonic tone is considered a *suprathreshold* measurement. In addition, the calculation of odour concentration usually involves four assessors and sometimes up to 8-10, whilst calculating the hedonic tone involves a larger group of assessors.

That said, evaluating the hedonic tone is a valuable tool to calculate the contribution of each odour source to the overall odour impact. Sources with an equal odour concentration but with different hedonics will impact differently.

The hedonic tone is usually measured in the lab with scales, such as the one indicated in Chapter 6.2.4 based on the German Standard VDI 3882 part 2. The Dutch standard NVN 2818:2019 details the same scale.

**Table 7-1** Scale for the hedonic tone of the Dutch standard NVN 2818:2019

| Hedonic Tone | Verbal description |
|---|---|
| -4 | Extremely unpleasant |
| -3 | Moderate unpleasant |
| -2 | Unpleasant |
| -1 | Slightly unpleasant |
| 0 | Neutral |
| 1 | Slightly pleasant |
| 2 | Pleasant |
| 3 | Moderate pleasant |
| 4 | Extremely pleasant |

Hedonic tone can also be measured on the field (*VDI 3940 part 5*).

A different measurement of the hedonic tone of an odour sample can be carried out using the so-called polarity profiles (Kwiatkowski et al., 2021).

There is a relationship between the odour concentration and the hedonic tone. For example, the following graph extracted from *Li et al. (2017)* shows the variation of the hedonic tone with the odour index for the case of ammonia. The odour index is directly related to the odour concentration.

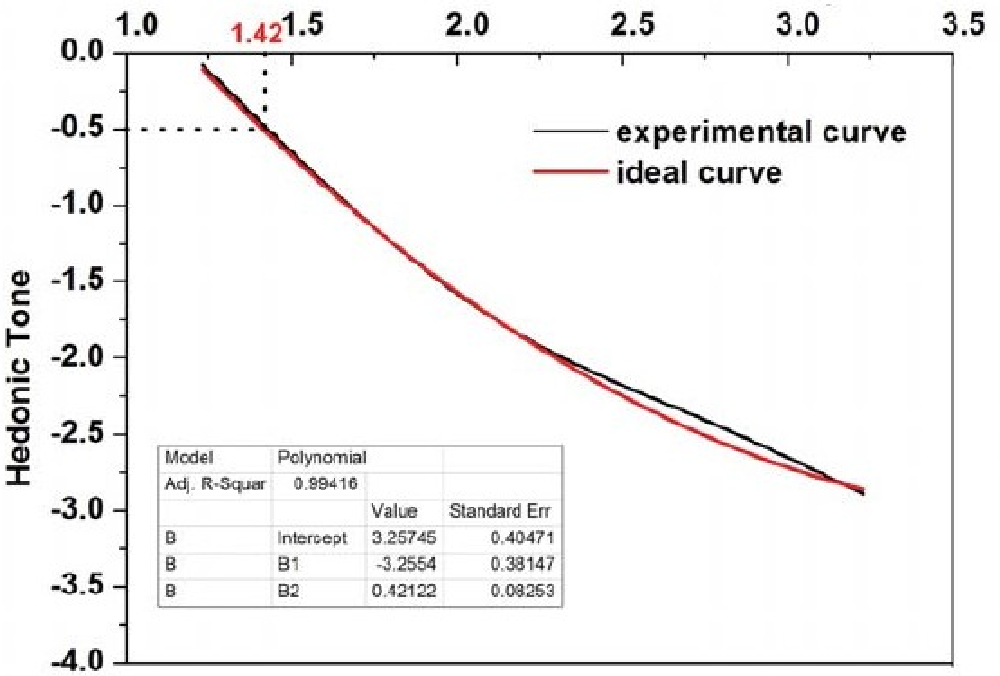


**Figure 7-14** Relationship between odour concentration index (X) and hedonic tone (Y) for ammonia (Li et al., 2017)

The behaviour curve of the hedonic tone as a function of *odour concentration index*[3] for ammonia was studied by *Li et al., 2017*. These authors observed a significant decrease in the hedonic tone when the odour concentration index increased. When the absolute value of the hedonic tone was lower than 0.5, the odour was considered neutral, neither pleasant nor unpleasant. Figure 7-14 above shows that when the hedonic tone is -0.5, the corresponding concentration index is 1.42 (odour concentration approximately 26 ou/m$^3$). For concentration indexes lower than 1.42, the ammonia smell will not be unpleasant.

The odour threshold value of ammonia is 1062 µg/m$^3$ at 20ºC (https://www.odourthreshold.com/). That means that ammonia odour will be unpleasant at concentrations of 1062 X 26 = 27612 µg m$^{-3}$.

However, the hedonic tone is not consistently decreasing with increasing odour concentrations. The following graph shows a concentration-hedonics relationship for several chemicals (Li et al., 2019). In this case, dimethyl sulfide and butyl acetate follow the same pattern. However, in the case of limonene, the hedonic tone increases when the concentration increases and then decreases sharply. Figure 7-15 below shows three distinct categories of odorants concerning hedonic tone:

- *Unpleasant odorants* (e.g., dimethyl disulfide, hydrogen sulfide, ammonia, methyl mercaptan): the odour at each dilution factor is unpleasant to all the assessors, and the aversion gradually diminishes as the dilution increases.
- *Divergent odorants* (e.g., butyl acetate, methyl isobutane, propionaldehyde): At the

3The odour concentration index is a measurement of odour concentration used in Japan, China and Korea to measure odours. It is numerically equal to the Log of the odour concentration. For example, with reference to Figure XX, $10^{1.42}$ = 26.3.

same odour concentration, a minority of the assessors find the odour pleasant, while the remaining find it unpleasant. The resulting hedonic tone remains negative at all the concentration values.

- *Pleasant odorants* (e.g., limonene, ethyl acetate, vanillin): The odour is pleasant at lower concentration values but becomes unpleasant when the concentration values increase.

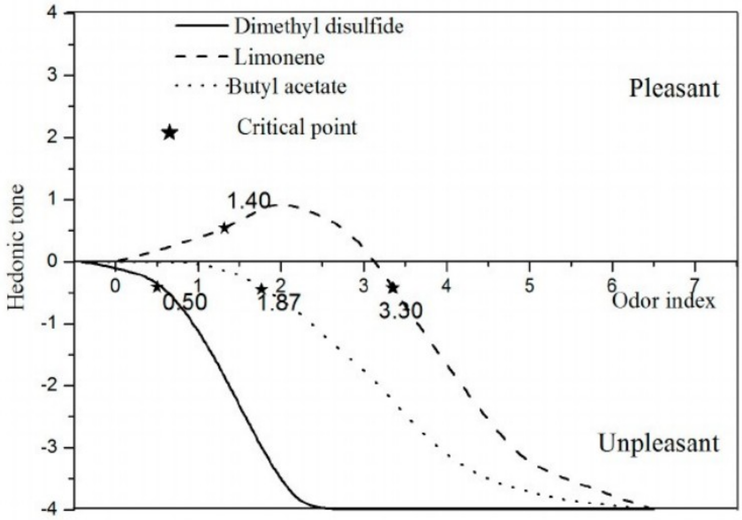


**Figure 7-15** Relationship between odour concentration index and hedonic tone for dimethyl disulfide, limonene and butyl acetate (Li et al., 2019)

### 7.4.1 Example of hedonic tone weighting

The hedonic tone is used in many provinces of the *Netherlands* to balance odour impact following the Dutch standard NVN 2818. *Brancher et al. 2017*, mention a practical example of the legislation in the province of *North Brabant*.

The regulation of *North Brabant* uses the hedonic value H = -1 (slightly unpleasant, see previous Table 7-1). Before the ambient air level is calculated using a dispersion model, the odour emission rates first need to be corrected numerically by the hedonic value associated with the source. Calculations are based on a "*hedonic weighted $ou_E$ per unit of time*", expressed as $ou_E(H)\ h^{-1}$. For instance, if a source has an odour emission rate of 630 $Mou_E\ h^{-1}$ and an odour concentration of 7 $ou_E\ m^{-3}$ at H = -1, then the *hedonic weighted odour emission rate* is 90 $Mou_E\ h^{-1}$ (as a result of dividing 630 $Mou_E\ h^{-1}$ by 7 $ou_E\ m^{-3}$). Therefore, dispersion modelling results are expressed as $ou_E\ m^{-3}$ and compared against the criteria set for North Brabant.

These hedonic weighted odour units can be very well used to identify sources with a similar concentration inside a facility but with different offensiveness.

## 7.5. Calculating odour impact from intermittent sources and non-static receptors

If there are situations where particular meteorological or emission conditions occur relatively infrequently, special consideration should be given to whether the result of odour impact obtained is a good and representative environmental indicator of a nuisance. Some examples of situations where an expert assessment of representativeness would be required are as follows:

a) **Intermittent sources:** If a source produces short-term peaks in odorant emissions at a particular time of the day, this may lead to a significantly higher odour exposure that occurs only during that limited period of the day at specific locations. Even though the exposure criteria are met, there could be significant complaints due to a high odour concentration during a short period.

b) **non-static receptors**: When regular wind patterns during the day exist, as can be the case in coastal land-sea breezes, the situation can arise that a particular location is exposed predictably and with higher probability at a particular time of the day (typically in the early morning or evening, when the wind direction reverses). These exposure events are, therefore, more likely to correlate with periods when people return home from work and would like to enjoy leisure time. Therefore, The exposure criteria may underestimate the potential for nuisance impact on residents at that location.

### 7.5.1 Calculation of odour exposure by intermittent / discontinuous / seasonal sources.

Sources are considered Intermittent when they produce:

1. Short-term peaks in odorant emissions at a particular time of the day (for example, because of loading/unloading or cleaning operations) or
2. Odorant emissions a few hours every day (e.g., plants operating 6 hours a day) or in certain seasons (e.g., fisheries).

In these cases, calculating odour exposure might be challenging because most odour criteria are based on hourly percentiles of a year, considering that the odour source emits continuously throughout the time.

Therefore, different approaches could be taken, the main ones:

1. To model odour exposure as a percentile of the hours of the year
2. To model odour exposure as a percentile of the working hours
3. To calculate odour load/dose and compare it with the odour load/dose of a regular plant working 24/7/365.

The first approach has a few limitations as plants that emit short-term high-odour emission rates will produce impact provided the right conditions, independently of the source working only a few hours.

The following Figure 7-16 shows the odour impact of an animal byproduct rendering plant located in Spain that operated only 6 hours daily, usually during the morning. This plant had a record of many years of odour complaints.

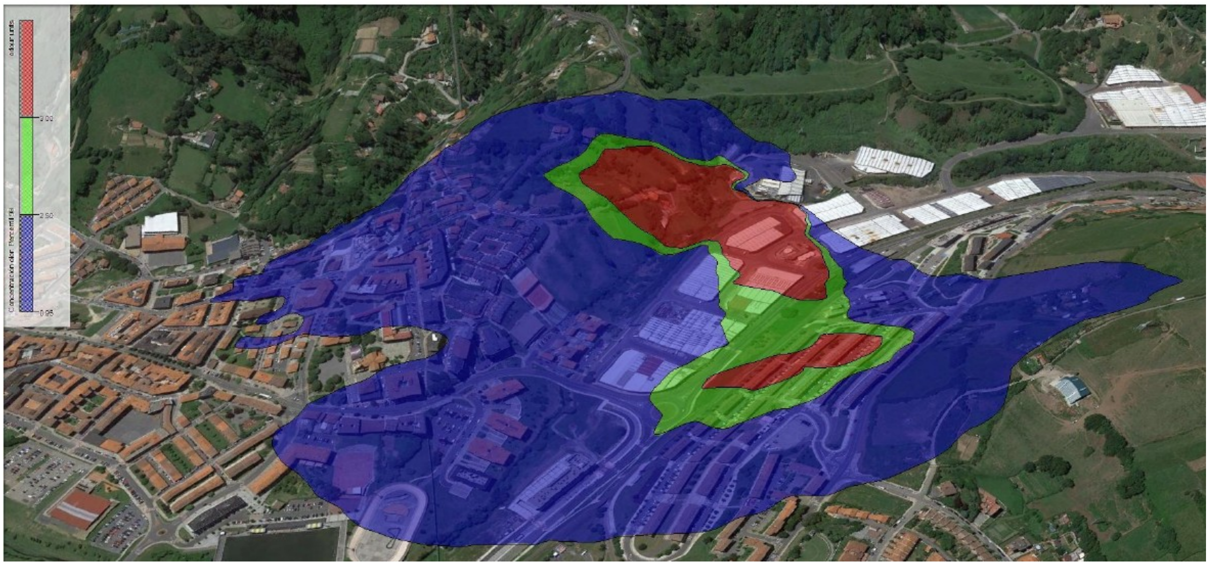

**Figure 7-16** P98 Odour isopleths of a year of an animal by-product plant when modelling 6 hours of emissions daily (175 hours of the 8760 hours of the year) (Courtesy of Ambiente et Odora).

The contours showed no impact by calculating the percentile 98 of the year's hours. The model used in this case was CALPUFF. The blue, green and red area shows a $P_{98}$ of 1, $ou_{E}$.

Thus, the first approach of modelling odour exposure as a percentile of the year's hours did not reflect the reality of the complaints at that time. This plant still had a record of many years of odour complaints.

Therefore a second approach was taken. That is, the modeller used only the 6 hours of the morning the plant was working. The result is shown in the following Figure 7-17.

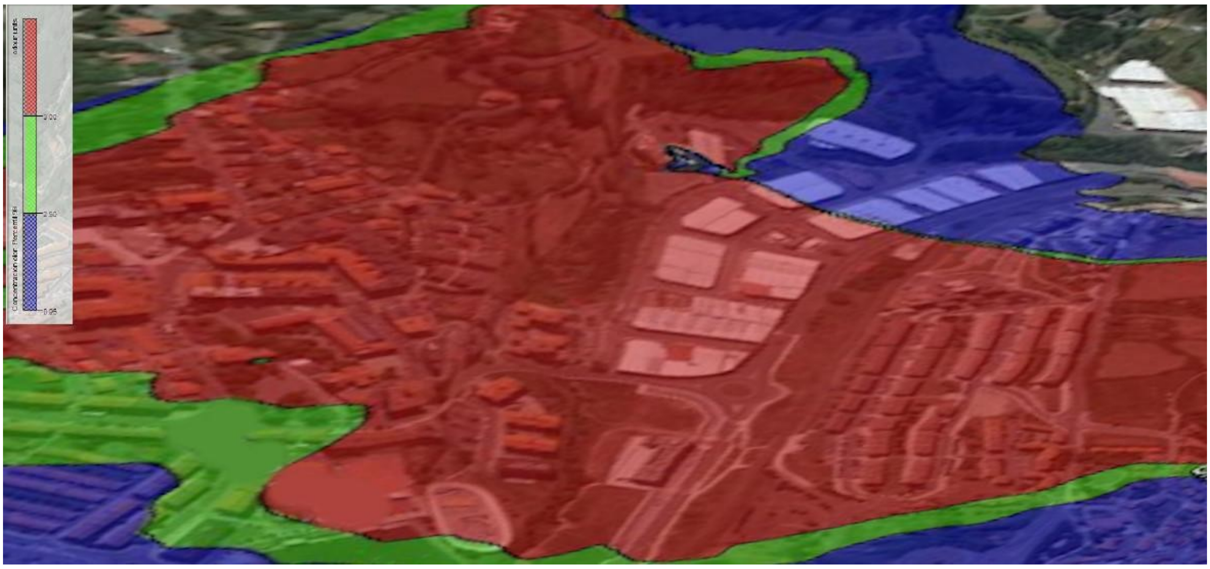

**Figure 7-17** Odour isopleths of an animal by-product plant when modelling 6 hours of emissions daily and calculating the P98 of these 6 hours of emission (44 hours of 2190 hours of the year) (Courtesy of Ambiente et Odora)

The impact, in this case, is shown as much higher.

Unfortunately, the odour impact criteria set for different legislations are based on hourly percentiles of the year. Therefore the results of this exercise could not be compared with any existing level set in any guideline or regulation, as they are all based on continuous emitting sources.

This is the main limitation of modelling only a few hours of the day.

In addition, percentiles have many limitations, reflecting only a set of maximum concentrations at a given number of hours a year.

Intermittent sources, like the one of this animal byproduct plant, will produce impact even though a certain percentile shows that it does not.

The concept of *odour load* or *odour dose* is being discussed in the working group revising the Dutch standard NTA 9065 (Diaz et al., 2020). The way to express the odour load is through diagrams of frequency distributions such as the one below (Figure 7-18).

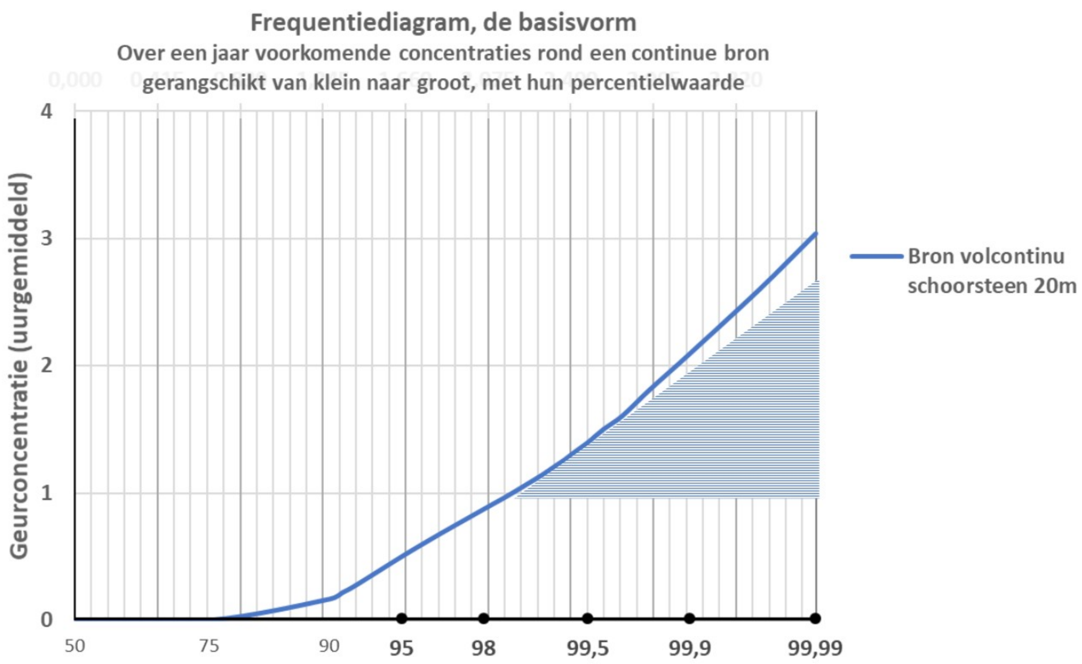


**Figure 7-18** Odour dose as obtained representing the odour concentration (Y-axis) at different percentiles (X-axis) in a receptor (Courtesy of Hugo van Belois).

The *odour dose or load* would correspond with the yearly total number of hours X with an odour concentration Y above the detection value.

The Y axis shows the odour concentration on a linear scale. The X-axis shows the total number of hours of the year represented in the form of percentiles. For example, 95, 98, 99.5, and 99.9 percentiles correspond with the maximum concentrations above one odour unit obtained considering 438, 175, 44 and 9 hours of the year, respectively.

The total odour load would be the area of the graph corresponding with the odour concentration above the detection limit (1 odour unit).

# 7.7. Online calculation of odour impact

## 7.7.1 Real time odour plumes

In principle, a “real-time” atmospheric modelling system tailored for a specific plant needs the definition of these components: a simulation domain, an emission scenario and meteorological information. Strictly speaking, “real-time” could be a wrong term because acquiring data and using them to perform calculations requires time, even though a short one. It should be better to use the term *nowcasting*, which refers to predictions in the very near future (i.e., minutes).

The extension of the simulation domain is defined once for the worst impact expected from the plant, and the geophysical information is processed and stored within the system. For example, a simulation system based on CALMET/CALPUFF (Scire et al., 2000a, 2000b) must include, at minimum, topography and land use for each meteorological grid. This information must not be renewed at any simulation; it is part of the system setup. The specification of sensible receptors must also be done in the setup phase.

Concerning the emissions, they include both static and dynamic information. Static information includes source coordinates, stack heights, diameters and geometrical variables of other source types. This information does not vary with time unless new sources are added, or existing ones are modified or removed. The dynamic information is related to the emissions. Major stacks within large plants typically mount *Automatic Measuring Systems* (AMS), which are composed of hardware (e.g., gas analysers, sampling systems, thermometers) and software for data acquisition and storage.

AMSs provide in real-time volume flow rate, emission temperature, and concentration of each pollutant of interest. Among the pollutants monitored by AMSs, there could be some odorants, such as H2S, VOC or other compounds such as $CH_4$, that is odourless, but it is often related to the odour emission of a landfill. In other cases, the signal provided by an IOMS might also be used.

Meteorological information may derive from a monitoring station – or more stations – installed within or near the plant. Moreover - even though this paragraph describes “real-time” applications - sometimes it is useful to adopt a prognostic regional model such as WRF (Skamarock et al., 2008) to get the current hour meteorological data. Indeed, the data forecasted by the prognostic model a few hours ago (the past) are used for the current hour (the present), they are not used for the next hours (the future). Therefore, the model is not used to forecast the odour plume. Meteorological fields obtained from WRF or other prognostic models can be spatially refined through diagnostic models (e.g., CALMET). Adopting prognostic models for real-time simulations is particularly useful when there are no representative meteorological stations close to the plant, in particular vertical profiles able to represent the atmospheric flow at upper levels.

These three components (domain, emissions, meteorology) must communicate through a suitable software system, often a web-based one. The results will be the concentration values at the sensitive and gridded receptors.

When emissions do not arrive from stacks (e.g., fugitive emissions from flanges, valves, etc., of a refinery or tanks of a WWTP), and/or a specific pollutant cannot be measured by an AMS (e.g. an odorant) or by an IOMS (odour), the situation is more complicated. Emissions may depend on the meteorological variables, such as wind speed and/or wind direction (e.g., Bellasio and Bianconi, 2022). The simulation system may include a sort of feedback in order to improve the quality of the simulation. For example, an IOMS may be placed downwind over the plant fence line and measure an odour concentration equal to $C_{EN}$. If the model concentration corresponding to the position of the IOMS and calculated with an initial emission E is $C_M$, the model must run again with a new emission equal to $E_{NEW} = E * C_{EN}/C_M$. This is the simplest situation when a single source is present; the real situations may be more complicated.

Uvezzi et al. (2022) conducted a short review of real-time odour dispersion modelling. They identified three main scientific works on the topic: Chirmata et al. (2015), Giveleta et al. (2012) and Burgués et al. (2021). Chirmata et al. (2015) applied their methodology to an Agadir (Morocco) industrial plant. They integrated the data of six IOMSs and those measured by some meteorological stations; odour concentration maps in real-time were obtained using the AERMOD dispersion model. Givelet et al. (2012) applied their system to a Waste Methaisaation Facility in Montpellier (France). The system was composed of dedicated sensors and IOMSs, together with an air dispersion model, allowing to get the odour map in real-time. The software generated warning messages when the odour concentration exceeded a specific threshold. Finally, the system of Burgués et al. (2021) is based on small drones specifically designed for real-time odour monitoring. The system was applied to a WWTP facility in Spain. The drones were equipped with more than twenty different sensors; the signal was sent in real-time to a base station, and the data were visualised both as text and as an odour concentration map.

There is also some commercial software available for real-time odour dispersion simulation. For example, AMS, Atmospheric Modelling System (Enviroware srl), Nose Vision 360 (Arianet), Prolor (Ambiente et Odora), EnviroSuite (Envirosuite Ltd), Meteosim (Meteosim), Total Odour Management System, TOM (Osmotech srl) and SmartPlume (The Synergy Group).

### 7.7.2 Forecasting odour impact

This tool could be useful for industrial activities provided that they can control their emission using operative actions, such as a decrease or delay in the production of a unit or an increase of the efficiency of the odour abatement system. This can be done, for example, by using more chemicals or increasing the fan's speed to favour the plume's dispersion.

Odour forecasting requires the same system components needed for determining real-time odour plumes. On the one hand, odour forecasting is even simpler than nowcasting because, for example, the feedback procedure to adjust emissions is not required since it cannot be done. On the other hand, while nowcasting could be done by “simply” using the data of a meteorological station, forecasting odour impact necessarily requires using a prognostic meteorological model such as WRF. For example, a modelling system for odour forecasting has been described by Cartelle et al. (2016). Thanks to wind speed and direction availability, these systems also allow forecasts of wind-dependent odour emissions (e.g., Bellasio and Bianconi, 2022) and use them to feed the dispersion model.

## 7.8. Role of electronic olfaction devices to test the performance of odour dispersion models.

There is a need to investigate the role of Electronic Olfaction devices, better known as *Instrumental Odour Monitoring Systems* (IOMS), in evaluating model performance. However, it is unclear if, at this stage, these devices are reliable enough to serve as monitors of odour in ambient air.

IOMSs work better when located near odour sources (Bax et al., 2020) or at the fenceline (Bax et al., 2021; Cangialosi et al., 2021) due to the high odour concentrations usually found there. Unfortunately, they cannot be used to evaluate the performance of a dispersion model. Commercially available IOMSs may struggle at distances over 1 km from the source. Odour concentration in ambient air is usually tens to a few hundred European odour units. At those relatively low odour concentrations, IOMS performance is limited.

Although many IOMS manufacturers claim that their devices can measure odours, there is a need to standardise those claims. The *European Committee on Standardisation* (CEN) have tried to standardise the use of these devices, but no text has been produced (Harreveld, 2022). Some national Standards on IOMSs include the Dutch NTA 9055:2012, the German VDI/VDE 3518 Part 3 or the Italian UNI 11761:2019.

In addition, there are other developments related to IOMSs, such as the three initiatives carried out by IEEE: IEEE P2520.2.1 Standard for Machine Olfaction Devices and Systems Used for General Outdoor Odor Monitoring, IEEE P2520.4.1 Standard for Performance of Machine Olfaction Devices and Systems for Chemical Manufacture, and IEEE P2520.1 Standard for Baseline Performance for Odor Analysis Devices and Systems.

More research is needed to compare the results of a dispersion model with that measured with an IOMS.

### 7.8.1 Evaluation of performance according to EN 16841 part 1

EN 16841 part 1 deals with the measurement of odours using the so-called grid method. This methodology uses assessors brought to different points in a grid to determine if odours are present in those points (see Chapter 4.4.1. Ambient air measurement to characterise odour exposure: grid method).

The unit of measurement of odours is the “odour hour” .

According to EN 16841 part 1, the odour hour is obtained by a single measurement when the percentage of the odour time reaches or exceeds 10% by convention.

At the end of a minimum of 6 months of data collection, there will be 13 measurements at each point of the grid. After a year, there will be 26 measurements. At each measurement point, an assessor inhales every 10 seconds and records if he/she perceives an odour. After 10 minutes, there will be 60 observations. If in 6 of these 60 observations (10%) an odour is detected, the result is expressed as one odour hour.

Therefore, for 6 months, there will be 13 recordings of the presence/absence of odour (of a certain quality) for 10 minutes. That is, of the 4830 hours of a half year, there will be only 13 that will be used in each point of the grid after 6 months. Or, to be more precise, of 26280 packages of 10-min data, only 13 packages will be used to check model performance.

This is not much data to check model performance, so it is difficult that EN 16841 part 1 could be used to evaluate model performance.

### 7.8.2 Evaluation of performance according to EN 16841 part 2

Evaluation according to EN 16841 part 2 is more suitable for checking dispersion model performance. Part 2 of this standard deals with measuring odour in ambient air using the plume method (for more details, see Chapter 4.4.2. Ambient air measurement of odours by using the plume method).

One of the important points of this methodology is that it needs Gaussian-like conditions to carry out the plume measurement. That means that model performance can be carried out with the plume measurement but only with constant turbulence conditions (no changing dispersion class) during one measurement cycle. The atmospheric stability is specified by indicating the Monin-Obukhov length LM, which can be measured by a 3D ultrasonic anemometer. EN 16841 part 2 prescribes that the Monin-Obukhov length (LM) shall be under -150 m or above 250 m. Also, turbulence classes should be slightly stable, neutral or slightly unstable (for example, Pasquill C or D or part of B and E).

Unfortunately, odour impact usually occurs when there are calm or low wind conditions (Diaz et al. 2014), so model performance will not be carried out under these conditions using EN 16841 part 2.

A typical example of using the plume method for assessing dispersion modelling performance is the Uttenweiler experiment mentioned in Chapter 5.7.1. Examples of validation with odour measurements.

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# 8. Reporting

## 8.1. Introduction

An odour modelling report aims to show the potential impact on a certain area, including at sensitive receptors, of the emissions from an odour source or sources.

The methodology and results in an odour report should be presented in a way that can be understood by the reader, which could include plant managers, regulators or complainants. Several publicly available guidelines exist and these set out minimum requirements for dispersion modelling, data analysis, and reporting. Example guidance documents include those from regulatory authorities such as UK EA 2021, EPA NSW 2022, Eusko Jaurlaritza 2012, Oregon 2022, NZ ME 2004 and SEA 2023.

Minimum information in a report can include a location map, a list of odour emission sources, a summary of applicable odour regulations, an explanation of the meteorological data and dispersion model used, emission rates and parameters adopted, modelled domain, receptors, surface characteristics, and terrain and building treatments.

Some guidelines require other, more detailed specific information in the report, such as estimating the model uncertainty or performing a sensitivity analysis. Additional requirements can include model input parameters and settings or sometimes text outputs of input files as an appendix.

While there is general information detailing the requirements for general air quality assessment reports, some differences make reporting odour challenging. For example, examining model uncertainty is challenging when odour concentration in ambient air is usually below the threshold of the reference methodology for measuring odours in a laboratory (dynamic olfactometry). Other standards dealing with measuring odour in ambient air (EN 16841) either do not have a significant number of odour records (EN 16841 part 1), or they use modelling the other way around to calculate the odour emission rate of a source by using reverse modelling (EN 16841 part 2), as explained in chapter 7.2.

In addition, Instrumental Odour Monitoring Systems (IOMS) are not, at this stage, suitable for evaluating model performance.

The following sections will describe the minimum and recommended information to be considered when preparing a report assessing odour exposure using dispersion modelling.

## 8.2. Report structure

### 8.2.1 Cover Page

The cover page should include the Project Title, the author(s) of the report, the version number and the date that the report was issued. The cover page should also include the name of the company or person the report was prepared for.

The report's index (Table of contents) should be included immediately after the cover page. A list of Figures, Tables, metrics of conversion and Acronyms and Abbreviations can also be included if required.

### 8.2.2 Introduction

The introduction should give a general description of the facility, such as the company name, proponents involved in the project, the proposed use or modification to that use, including activities on site that may emit odours, and the potential receptors of odour impact. Data that could be included are shown in Table 8-1 below.

The introduction should include information on the selection of the methodology and the scenarios implemented.

**Table 8-1** Requirements to be described in the introduction

| Elements | Description |
|---|---|
| Project Name | The title of the facility or proposed project must be stated |
| Proponents | The name of the entities or individuals involved during the entire phases of the project (e.g., corporation, partnership, single proprietorship, etc.). |
| Project Location | The location where the site is situated. Include the geographical coordinates and location map. |
| Project Type | Project classification defined during implementation that specifies essential project attributes. |
| Status of the operation | Specify if the project is new, or an expansion of the existing plant. |
| Dispersion Model Type | The considerations in selecting the dispersion model must be briefly justified (e.g., Gaussian-based, Lagrangian-based, etc.) |
| Contact person and details | The name of the responsible person must be included here and necessary contact information. |

### 8.2.3. Regulatory requirements

The report should summarise the regulations, documents or guidelines used as references to perform the assessment. The requirements could include local or international legislation, policies, guidelines or technical specifications.

Table 8-2 below provides a list of elements that could be reported.

**Table 8-2** Elements to be considered in reporting

| Elements | Description |
|---|---|
| Definition of the law, guideline, ordinance, etc. | This element has to briefly report the scope, aims and general provisions. Moreover, implementing rules and regulations (IRR) must also be included. |
| Responsible authorities | The relevant government agencies must be introduced, which can be at the regional level, state, country and/or an internationally recognised organisation. |
| Parameters or variables regulated | This includes some specific needed parameters such as peak concentrations and the method suggested to calculate them starting from modelling results, if not directly available (by, for example, applying a peak to mean ratio). The extent of applicability of the law must be emphasised, particularly to the parameter being regulated. If a specific law or guidance does not apply to the facility, an indication of the most appropriate best practice guidelines should be included. |
| Odour Impact Criteria (OIC) | OIC selected for the project. |

### 8.2.4. Project description

This section should present all of the information about the project that is relevant to the assessment of odour emissions and their potential impact on the surrounding area. In particular, information should be provided about the nature and type of activities performed at the facility and how the emissions are generated, released and dispersed from the facility.

The section should be organised into subsections, each including the elements detailed below.

#### 8.2.4.1. Site location and affected area

This subsection should provide a site location map and details of the area in which the project is located. The subsection should:

- identify sensitive receptors in the area of the project and within the potential zone of impact;
- describe the topography near the site and the land uses in the surrounding areas; and
- describe ambient air quality and other potential odour sources in the immediate vicinity of the site and consider the risks of cumulative impacts within the potential zone of impact.

A scale location plan should be provided which shows:

- layout of the site which clearly shows all relevant odour sources;
- site boundary;
- relevant sensitive receptors; and
- topography.

#### 8.2.4.2. Facility, plant, and process description

This subsection should describe the plant activities and the processes performed at the facility. In particular, the details of the activities performed and how they may affect the release of emissions and their dispersion in the atmosphere should be included. As a minimum, a description of the site's operations in simple language should be included.

Table 8-3 presents a list of process information that could be included in this subsection.

**Table 8-3** Requirements to be considered in the discussion of the facility

| Elements | Description |
|---|---|
| Process flow diagram | This should clearly show all unit operations carried out |
| Production data | Details of batch and/or continuous processes to be presented to include duration of operation for each distinct cycle where relevant |
| Production rate | The rate of material processed (tonnes/hour), rate of items processed per hour for general manufacturing processes or other indicators of process activity should be stated. |

| | |
|---|---|
| Operating information | The operational hours and consideration of any seasonal variations in activity should be stated. |
| Odour sources | The report should include odour emitting sources including area and stationary sources. A description of each source including what the source does should be included. Commentary should also be included if specific assumptions relating to management measures are required, for example equipment failure and or maintenance requirements. |
| Treatment and abatement of emissions | If proposed or required, the report should include details of odour control systems and essential operating information for these systems. This could include a description of the control system, with particular regard to any fugitive emission capture (e.g. hooding, ducting), treatment (for example, scrubbers, bag filters) and discharge systems (for example, stacks). Any performance guarantees or other information regarding the performance of the systems which the report relies upon should be included. |

All potential sources of odour, including the source type (point, area, diffuse, passive, etc.), the physical and location features and dimensions and the emission characteristics of each identified source should be provided. There should be sufficient information provided to allow a reader to reconstruct the assessment or at least understand what occurs on site.

### 8.2.5. Model selection and setup

This section should present all of the information about model selection and its application.

The section could be organised into subsections, each bearing the elements described below.

#### 8.2.5.1. Dispersion model selection and assumptions

This subsection shall include details of the modelling methodology, including reasons for the selection of the dispersion model. The section should identify any specific local, regional or national regulatory and/or best practice requirements. For example, in some countries, the Regulatory Authority may have a preferred or recommended model for specific assessments, which should be identified if relevant in the report. If the recommended model is not being used, the reasons for this choice and for selecting the model that has been applied should be explained.

#### 8.2.5.2. Dispersion model application

**Assessment scenarios**

This section should report and describe the scenarios that are investigated. For example, a study may consider specific sources of odour emissions at a facility, such as the wastewater treatment plant or specific active sources, which could include a particular process at a site which may only operate for a limited period each day.

The section should describe what scenarios were assessed and the reasons for selecting those scenarios.

**Topographical and terrain data**

This section should describe the topographical features of the site and the surrounding area in terms of a description of data sources and/or graphical representations. The applicability of the dispersion model should be discussed having regard to the local terrain. The subsection could include a review of the relevant information that may have been obtained during site assessment (e.g., mapping, field surveys, odour sampling) to generate data presented through topographical maps, aerial photographs, 3-dimensional contour plots, 2-dimensional cross-sections between odour sources and receptors. GIS software can be a useful tool to present this information especially where cadastral information is required to be included.

**Simulation Domain**

This section should describe the position and extent of the computational domain, with the identification and location of possible sensitive receptors inside, receptor grid location and resolution. Justifications should be included for any receptors that are not included in the assessment.

The domain could be described in terms of its extent and coordinates, and/or graphically.

**Meteorological Data**

This subsection should describe the type and location of data sources for meteorology, which can include data from meteorological stations or meteorological models.

Justifications should be provided with regard to representative local data, any software used for the processing of meteorological data, and the representative wind rose. Justifications should be provided as to why the year(s) modelled are representative of meteorology in the area.

The meteorological data at the site should be fully described, including:

- description of the techniques used to prepare the meteorological data into a format for use in the dispersion modelling;
- detailed discussion of the prevailing dispersion meteorology at the site. The report should include wind rose diagrams and an analysis of wind speed, wind direction, stability class, mixing height and ambient temperature. If rainfall or other parameters

influence emissions, these should also be discussed; and

- a description of the results of model switches and settings, quality assurance and quality control checks on the meteorological data used in the dispersion modelling.

It is important that the meteorological data are either a representative set of measurements or that prognostic model results are validated against nearby weather station data. While not always required, the input files can be provided as an annex to the report, or the report can offer to make the input and outputs available for peer review if required.

**Emission Data**

This section should describe the characteristics of each emission source. A table of the required input data to allow the emissions to be estimated construction and execution of the dispersion model should be included.

The emission inventory data should include the following information:

- A detailed discussion of the methodology used to calculate the expected odour emission rates for each source with references to the source of the information and the methodologies used for sampling and measurement;
- a table showing source release parameters (for example, temperature, exit velocity, stack dimensions and emission rates);
- Subject to the source type, a summary that includes:
    - the hours of operation of the facility,
    - whether the process or activity is batch or continuous in nature,
    - whether emissions vary as a function of process conditions (e.g temperature, pressure etc.), production rate, the hour of the day, week, month or season, meteorological variables (e.g. wind speed, ambient temperature, humidity, atmospheric stability class and rainfall), feedstock, and animal age or feed type.

### 8.2.6. Presentation of the odour impact assessment results

Odour impact reports should, as a minimum, include odour contours with the applicable criteria and also receptor concentrations predicted using discrete receptors. For figures, it is preferable to include a caption that details the scenario, model used, criteria adopted, averaging time, percentile and the author.

The post-processing of relevant percentile values has to be reported, with the addition of the local level of background odour concentration from other sources, when these concentrations are required by local legislation. For example, in Germany, a maximum allowable odour level of 2% of the background concentration is allowed for new activities (TA-Luft, 2021).

The results of odour dispersion modelling shall be interpreted using the necessary air quality objectives or other relevant criteria, guidelines, and standards. The results should be explained in a concise manner that can be easily understood by the reader. If the contours are inconsistent with terrain information, the cause of this should be discussed. For example, a tall stack that emits above a valley.

Elements that could be included in a report are detailed in Table 8-4 below.

**Table 8-4** Elements in reporting the results of odour dispersion modelling

| General | Possible elements to report |
|---|---|
| | Supporting data for the input parameters and the factors affecting the variations |
| | A summary of receptor concentrations for each scenario |
| | Explanation of the accuracy and the limitations of the assessment (if relevant) |
| **Presentation of Maps** | **Criteria** |
| | Overlay the odour contours on a good quality base map. |
| | Clear perspective, scale, and content of the results, including sufficient contours to enable a reader to interpret the contours. |
| | Clear labels and/or legends |
| For Thematic Maps: | Present a clear legend that indicate the extent of odour pollution at various colour scale |
| For Isopleths Maps: | Appropriate number of concentration contours |
| **Presentation of Tables** | **Criteria** |
| | Key data in the report i.e. receptor concentration at specified averaging time and percentile<br><br>Large datasets as appendix |
| **Model Analysis and Interpretation** | **Criteria** |
| | Locations of the high concentrations |
| | Consistency of high odour concentrations with meteorological conditions |
| | Robustness of the simulation with respect to important conditions, especially when using non-steady state meteorology |
| **Estimation of model error and accuracy** | **Criteria** |
| | Identify the reducible (input data and the model implementation) and inherent uncertainty (limitations of the selected model or approach) |
| **Impact Assessment and Programs** | **Criteria** |

| General | Possible elements to report |
|---|---|
| | Compliance with the relevant environmental standards |
| | The environmental and health impacts |
| | The mitigation measures for the identified impacts |
| | The different phases of the activities |
| | The documentations and other related reports |

In the following section, suggestions on the criteria to be adopted for the presentation of the results are provided.

### 8.2.6.1. Odour impact assessment criteria - Data elaboration criteria

As mentioned in Chapter 6, one way to quantitatively and qualitatively estimate an odour impact is by considering annoyance factors related to the *frequency, intensity, duration*, *offensiveness* of the odour emitted and the receptor's *sensitivity* (FIDOS).

These factors usually lead to or are reflected in the definition of exposure limit values, a concept composed of the following aspects:

- **A limit concentration or threshold [C]: (intensity factor)** for different types of sources. Different limit concentrations are usually defined depending on their hedonic tone (offensive factor). Different limiting concentrations may also be defined for different land use types, such as industrial, commercial or residential (sensitivity factor).
- **A criterion of compliance with the limiting concentration over time** usually expressed as a percentile [p] (frequency factor). Different percentiles may be defined for different types of land use (sensitivity factor).
- **A criterion related to the average assessment time [t] (duration factor).**

These three variables result in the following exposure limit values: C, p, t, where:

**C: threshold concentration**, usually given in odour units [$ou_E/m^3$].

**p: percentile of compliance.** For example, the 98th percentile means that the threshold concentration is met 98% of the time. That is, if the time is one year, this concentration is exceeded 175 hours per year.

**t: assessment time,** typically between 0.1 s and 60 min. An average value for one hour is usually considered according to the possibilities offered by modelling tools.

### 8.2.6.2. Criteria for odour exposure maps

There are usually two ways of expressing odour exposure, by means of isopleths of concentration and by using frequencies of perception.

Approach 1) Quantification according to odour isoconcentration curves

The modelling work allows the generation of graphs corresponding to maps that represent the odour dispersion phenomenon associated with emission events and meteorological conditions in the territorial context of the potential receptors (see Figure 8-1); these illustrate lines that indicate the same odour concentration in the corresponding units ($ou_E/m^3$).

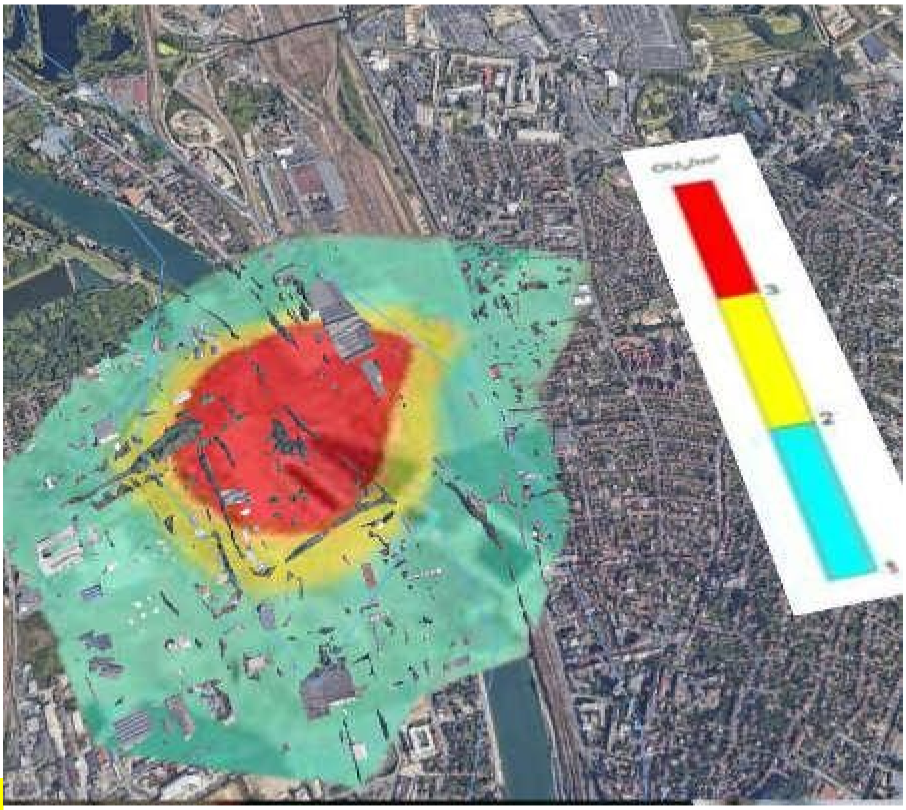


**Figure 8-1** Representation of odour concentration isopleths for a 98th percentile (courtesy of Ambiente et Odora)

Approach 2) Quantification of odour perception frequency

Odour exposure is usually quantified in terms of the frequency of occurrence of hourly average concentrations of a given odour above a defined threshold concentration.

The criteria of maximum hourly impact, or worst-case condition, is not representative of the total odour exposure at a receptor. A better approach is to use high percentiles, such as the 90th or 98th percentiles, at a specific odour concentration. This methodology allows visualising the percentages of hours in which the value defined for 8,760 hours of a year is exceeded. Figure 8-2 illustrates a graphical example.

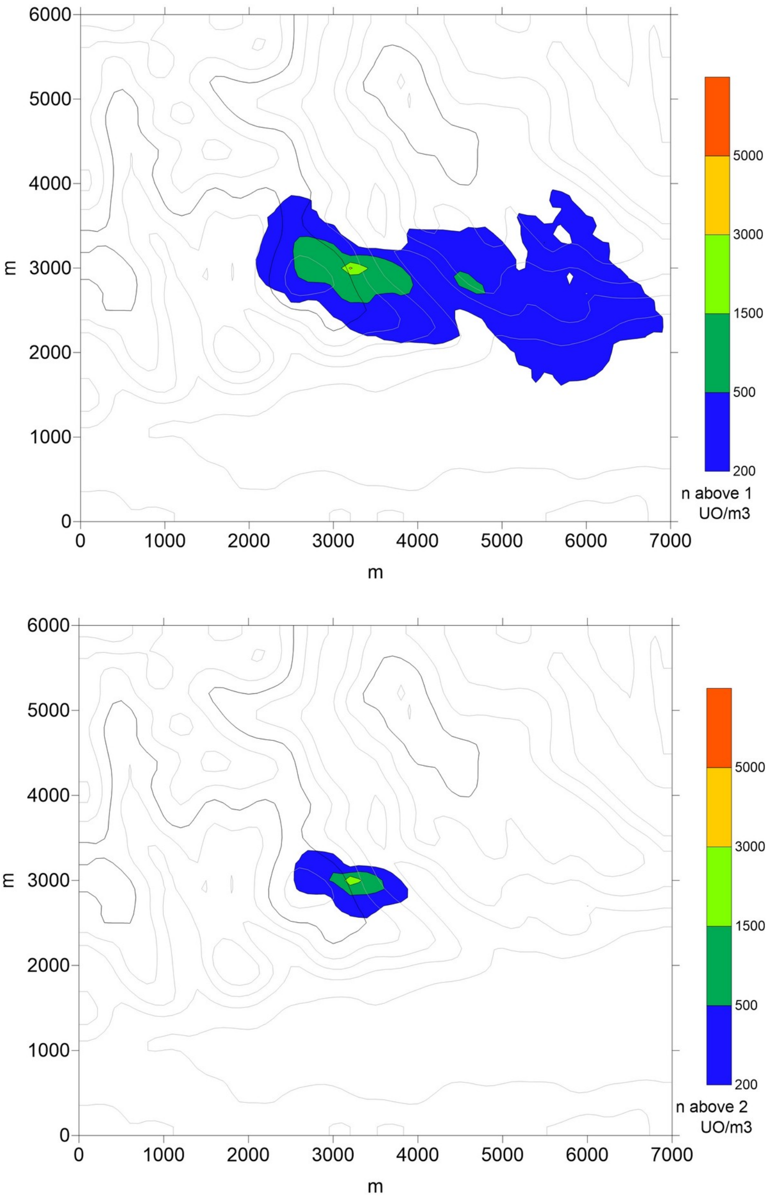


**Figure 8-2** Example of representation of odour hourly frequencies, number of cases above 1 $ou_E/m^3$ (above) and above 2 $ou_E/m^3$ (below) during one year (courtesy of ARIANET)

### 8.2.6.3. Criteria for quantification of odour exposure at receptors

Deciding on the sensitive receptors that may be affected by odour impact is essential. In some countries like Australia receptors are residences and workplaces. For example see NSW EPA (2022) or DEHP (2021).

There are two approaches to selecting the relevant receptors:

**Approach 1)** Directly ask the potentially odour-impacting activity which receptors are the most sensitive.

**Approach 2)** Try to determine using an aerial photo, taking into account either the wind rose or the outline of the odour isopleth contour, which receptors are the most relevant.

The first approach is interesting because usually, the plant operators know where the odour complaints come from. However, there is a risk that due to a conflict of interest, some receptors that may be relevant are not given to the modeller, so they do not appear in the report.

Approach 2 is interesting because it allows an unbiased assessment of which receptors may be most exposed to odour impact. However, this methodology does not consider the sensitivity of the receptors, which is much better known by local people.

Carrying out both approaches is suggested. The report should include a sentence describing which approach has been used by the modeller to select the different receptors.

This handbook has defined the concepts of “receptor” and “sensitive receptors”. Both concepts, though related, are different.

The *Institute of Air Quality Management* (IAQM) published in 2018 Guidance on the assessment of odour for planning. A series of matrices, similar to environmental impact matrices, are defined in this document to try to identify the most relevant sensitive receptors. However, this methodology has the same limitations as any impact matrix: it is subject to the personal judgement of the technician who prepares it and is therefore exposed to a usually high degree of subjectivity.

In any case, it is advisable to set receptors in high-sensitivity areas. For example, the *Recommended Procedures for Air Quality Dispersion Modelling* recently published by the *Department of Environmental Quality* of the *State of Orego*n in 2022 recommends that discrete receptors should be placed in *sensitive areas such as schools or other child exposure areas*.

The odour exposure at the receptors shall be indicated in a table; an example of a table is given below.

**Table 8-5** Example of table with the location of receptors and odour concentrations calculated

| Receptor | X UTM coordinate (m) | Y UTM coordinate (m) | Odour Concentration at P98 ($ou_E/m^3$) |
|---|---|---|---|
| Fenceline 1 | 250891 | 4239606 | 2.4 |
| Fenceline 2 | 250892 | 4139448 | 1.4 |
| Industrial plot | 250890 | 4140006 | 1.1 |
| Scattered houses | 250893 | 4139880 | 1.3 |
| Town 1 | 250891 | 4138769 | 0.9 |

Unless a regulatory document states otherwise, the odour concentration in ambient air should only specify one decimal place when detailed at the receptors. Odour concentration in stacks and other emission sources should never contain decimals.

Using tables helps indicate written values of odour concentration at receptors. However, when assessing compliance with a given odour impact criterion, using graphs can be more informative. An example is provided below in Figure 8-4.

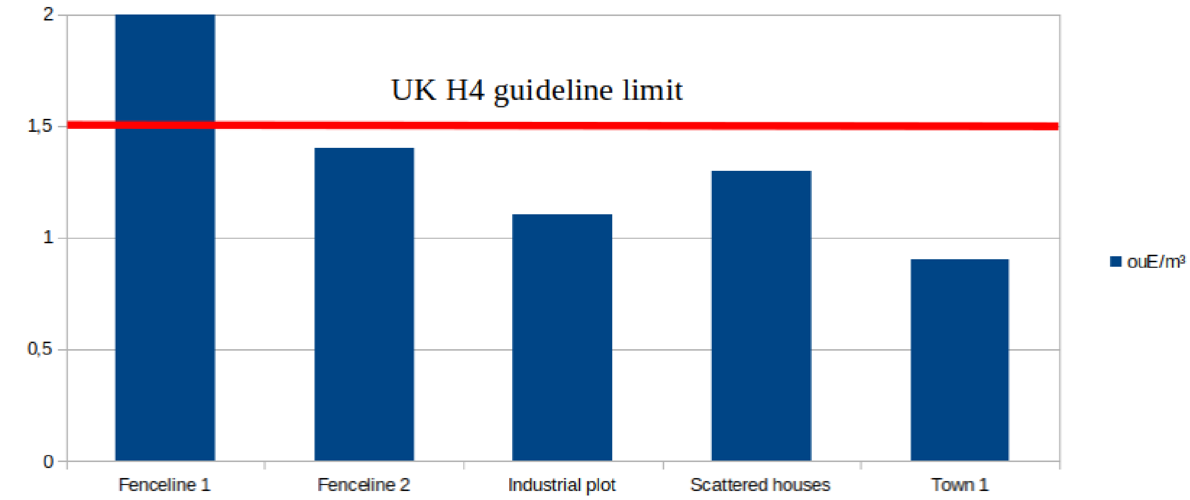


**Figure 8-3** Concentration at receptors and exposure criteria taken as reference (Courtesy of Ambiente et Odora)

There are other ways to express odour exposure at the receptors. For example, a graph showing odour dose, such as the one in Chapter 7.5, could be adequate for intermittent receptors.

There are other ways to evaluate the impact on receptors. The following graph (Figure 8-4) was carried out by plotting discrete receptor results using an AERMOD post-file with a one-hour time interval during a year.

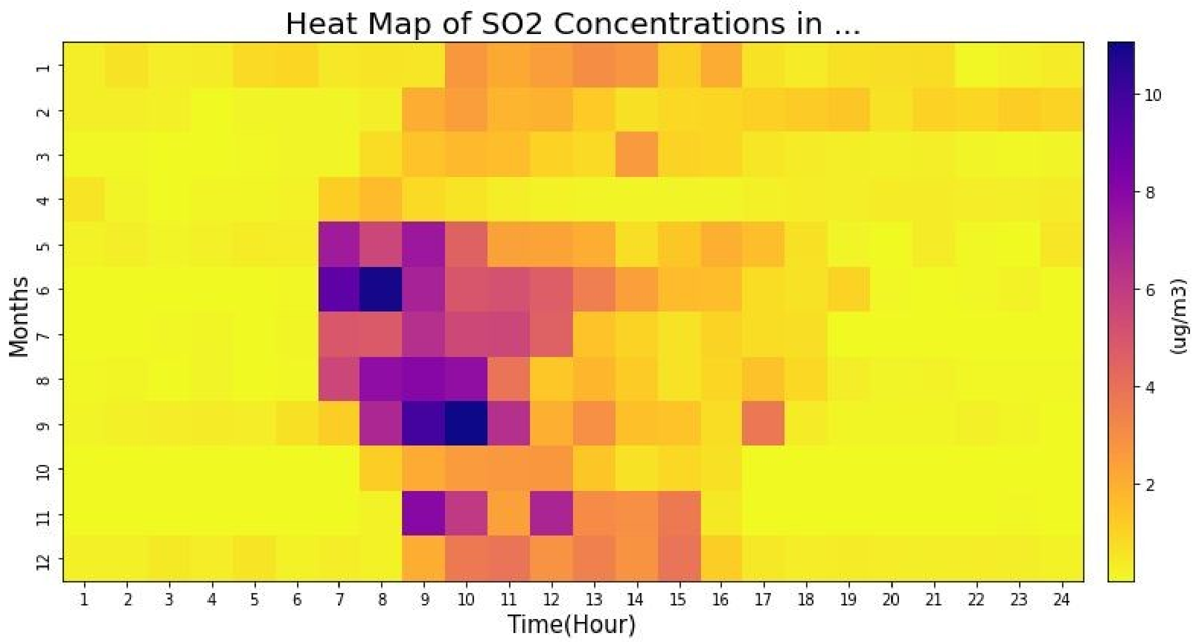


**Figure 8-4** Hourly odorant $SO_2$ concentration of a year in a receptor close to an oil refinery. (courtesy of José Junco, Epalife)

The graph above shows the months and hours of the year when the odorant impact is more significant at a specific receptor.

## 8.3. References


EN 16841-1: 2017-03 Ambient air - Determination of odour in ambient air by using field inspection - Part 1: Grid method; German version EN 16841-1:2016.

EN 16841-2: 2017-03 Ambient air - Determination of odour in ambient air by using field inspection - Part 2: Plume method; German version EN 16841-2:2016.

DEHP (2021) Guideline: Odour Impact Assessment from Developments. Queensland Department of Environment and Heritage Protection, Brisbane.

DWER, 2019: Odour emissions, Department of Water and Environmental Regulation (DWER), June 2019

EPA NSW, State of New South Wales and the Environment Protection Authority. Approved Methods for the Modelling and Assessment of Air Pollutants in New South Wales, 2022, ISBN 978 1 922778 45 1

Eusko Jaurlaritza 2012, Guidance on Good Practice Guide for the development of dispersion models, June 2012. Basque Government. Department of the Environment, Territorial Planning, Agriculture and Fisheries. Directorate of Environmental Planning

IAQM, 2018 Guidance on the assessment of odour for planning, Institute of Air Quality Management (IAQM), 2018

NZ ME, 2004. Ministry for the Environment. New Zealand, Good practice guide for atmospheric dispersion modelling, June 2004

Oregon 2022, Recommended Procedures for Air Quality Dispersion Modelling. March 2022. Air Quality Division Technical Services, Department of Environmental Quality, State of Oregon.

SEA 2023, Guideline in the use of air quality models in the SEIA, Servicio de Evaluación Ambiental, Second Edition, Santiago, Chile, February 2023

TA Luft. Technical Instructions on Air Pollution Control. 18 August 2021.

UK EA 2021, UK Environment Agency and Department for Environment, Food & Rural Affairs. 2021. Environmental permitting: air dispersion modelling reports 1–8.

# Appendix A

Note: All the URLs reported in this Appendix have been accessed on March 30, 2023

## A. Raw meteorological data

Free meteorological data are made available in different countries, with different formats that may require some processing to be used in dispersion models. The data listed below are collected, managed and stored by different agencies or private citizens. Some quality control operations are always suggested before using the data. The list is of course not complete, because many other agencies may provide meteorological data, particularly at the local level. Most of the links provided below refer to surface data (typically measured at 10 m above ground level). The last two links refer to vertical profile data.

**NOAA ISD (Integrated Surface Database)**

Global hourly and synoptic observations compiled from numerous sources into a single common ASCII format. Over 35,000 stations worldwide. Over 14,000 "active" stations are updated daily. Data available since 1901 (few stations initially). Numerous parameters included (e.g., wind speed and direction, wind gust, temperature, dew point, cloud data, sea level pressure, altimeter setting, station pressure, present weather, visibility, precipitation amounts for various time periods, snow depth, and other parameters). The WBAN/USAF codes of the station(s) of interest must be known (see NOAA NCEI below).

https://www1.ncdc.noaa.gov/pub/data/noaa/

**NOAA ISD Lite**

These data have been designed to be an easier-to-work-with subset of the larger ISD dataset. They are represented with a modified timestamp which corresponds to the nearest hour of actual observation. Sub-hourly observations present in the ISD have been removed.

Each file contains eight meteorological variables represented in fixed-width format: Air temperature (°C, multiplied by 10), Dew point temperature (°C, multiplied by 10), Sea level pressure (hPa), Wind direction (degrees), Wind speed (m/s, multiplied by 10), Total cloud cover (described by a code, see format documentation), One-hour accumulated liquid precipitation (mm), Six-hour accumulated liquid precipitation (mm).

https://www1.ncdc.noaa.gov/pub/data/noaa/isd-lite/

**NOAA NCEI (National Centers for Environmental Information)**

Meteorological data for the whole world. Stations can be graphically selected from a viewer, then available data can be downloaded. This viewer is useful to identify the WBAN/USAF codes for surface stations

https://www.ncei.noaa.gov/maps/hourly/

**SCRAM (Support Center for Regulatory Atmospheric Modelling) - USA**

Available only for the USA and for the time interval 1984-1992. Useful for analysis of past events. Available as .zip files containing *.dat ASCII files.

https://www.epa.gov/scram/scram-surface-meteorological-archived-data

**Iowa Environmental Mesonet (IEM)**

Automated Surface/Weather Observing Systems (ASOS/AWOS) data for the whole world.

http://mesonet.agron.iastate.edu/request/download.phtml?network=MN_ASOS

**Meso West (USA)**

Meteorological data measured in the USA. Directly downloadable from the web site. API service also available.

https://mesowest.utah.edu/

**Weather Underground**

Thousands of stations are located around the world. Beware that many of these stations are managed by private citizens, therefore data must be critically checked before using in a dispersion model.

https://www.wunderground.com/wundermap

**ASOS 1-minute**

Data consist of running 2-minute average winds, reported every minute. The maximum 5-second wind speed and the corresponding direction are also reported. Available from the year 2000 only for the USA.

https://www.ncei.noaa.gov/pub/data/asos-onemin/

**ASOS 5-minute**

Wind data, cloud cover and other variables. Available from the year 2000 for the USA. The 5-minute data consists of the 2-minute wind speeds reported every 5-minutes.

https://www.ncei.noaa.gov/pub/data/asos-fivemin/

**NDBC (National Data Buoy Center)**

Measurements carried out by automatic buoys or by ships. Available for the current hour and for the past 12 hours. Both meteorological and waves-related variables are available.

https://www.ndbc.noaa.gov/

**GeoSphere Austria Data Hub (Austria)**

National meteorological data for Austria. The data can be accessed freely via the web portal.

https://data.hub.zamg.ac.at/

**The Global Wind Atlas**

The Global Wind Atlas is a free, web-based application with data to identify high-wind areas for wind power generation virtually anywhere in the world, and then perform preliminary calculations. The downloadable datasets are free. Users can also download high-resolution maps of the wind resource potential, for use in GIS tools, at the global, country, and first-administrative unit (State/Province/etc.) level in the Download section. Information on the datasets and methodology used to create the Global Wind Atlas can be found in the Methodology and Datasets sections. The resource is also very useful for good graphical representations of wind conditions in specific areas and has uses beyond the wind-energy sector for which the tool was developed. Includes a link to the Global Solar Atlas where information about solar irradiance is available.

https://globalwindatlas.info/en/about/introduction

**Online Environmental Data for State of Styria (Austria)**

Meteorological data from stations operated by the Regional Government of Styria, Austria plus elevation data can be downloaded freely here.

https://www.umwelt.steiermark.at/cms/ziel/2060750/DE/

**Chilean Meteorological Directorate - Climate Services (Chile)**

Freely download one-minute data by month for automatic stations.

https://climatologia.meteochile.gob.cl/application/index/menuTematicoEmas

**China Meteorological Data Service Centre (China)**

Fee-based service for surface and upper air station data throughout China.

https://data.cma.cn/en

**Copernicus Climate Data Store**

This is a huge data repository operated by European Centre for Medium Range Weather Forecast (ECMWF). Reanalysis data as well as land use and topographical data can be obtained from this site. Must register for free to obtain access.

https://cds.climate.copernicus.eu/#!/home

**MeteoNet (France)**

MeteoNet is an open meteorological dataset created by METEO FRANCE, the French national meteorological service. Their goal is to provide a clean and ready-to-use dataset for Data Scientists who require weather data. The data spans over 3 years, 2016 to 2018, and covers two geographical areas : the north-western and south-eastern quarters of France.

https://meteofrance.github.io/meteonet/english/data/summary/

**Climate Data Center - CDC (Germany)**

The Climate Data Center of the German Meteorological Service (Deutscher Wetterdienst - DWD) offers open access to a wide range of climate data.

https://www.dwd.de/DE/klimaumwelt/cdc/cdc_node.html

**Met Eireann (Ireland)**

Met Eireann is the Irish Meteorological Service. Good datasets are available for a fee but the data has to be processed to a usable input format for dispersion models. There is also a lot of free historical data for the various weather stations, including wind roses, rainfall, temperature etc.

https://www.met.ie/

**Israel Meteorological Service - IMS (Israel)**

Data for all of Israel may be obtained freely from this meteorological database. API service available.

https://ims.gov.il/en/data_gov

**Yr.no (Norway)**

Yr.no is a website and a mobile app for weather forecasting and dissemination of other types of meteorological information hosted by the Norwegian Broadcasting Corporation in collaboration with the Norwegian Meteorological Institute. Datasets are free but have to be processed to get to usable data for dispersion modelling.

https://yr.no

**State Meteorological Agency (Spain)**

In Spain, meteorological data generally is not free. A manual petition must be made to the State Meteorological Agency (Agencia Estatal de Meteorologia or AEMET). To get hourly and sub hourly data from the 800 plus meteorological stations visit:

https://sede.aemet.gob.es/AEMET/es/GestionPeticiones/nuevaSolicitud

**Open Data Euskadi - Basque Country (Spain)**

In some other regions of Spain you may find free online meteorological data. For example, here is data from the Euskadi region.

https://opendata.euskadi.eus/catalogo/-/estaciones-meteorologicas-lecturas-recogidas-en-2023/

**Agroclimatic Information Network of Andalusia - RIA (Spain)**

The region of Andalusia offers free data from its 122 stations, but a manual petition is required (no fee).

https://www.juntadeandalucia.es/agriculturaypesca/ifapa/riaweb/web/inicio_estaciones

**Agrometeorological service of Galicia (Spain)**

Meteorological data for numerous stations in Galicia,Spain.

http://servizos.meteogalicia.gal/agroMeteo/index.action?request_locale=es

**Swedish Meteorological and Hydrological Institute (Sweden)**

Here you may freely download meteorology, hydrology, and oceanographic data. Meteorological observation station data includes hourly temperature, precipitation, wind, air pressure, lightning, solar radiation, cloud cover and more.

https://www.smhi.se/data/meteorologi/ladda-ner-meteorologiska-observationer#param=airtemperatureInstant,stations=core

**Federal Office of Meteorology and Climatology MeteoSwiss (Switzerland)**

SwissMetNet, the automatic measurement network of MeteoSwiss, comprises about 160 automatic stations with a full measurement program. Data access is fee-based.

https://www.meteoswiss.admin.ch/weather/measurement-systems/land-based-stations/automatic-measurement-network.html

**ARPA Lombardia (Italy)**

Meteorological data measured in Region Lombardy (Italy). They are delivered in your mailbox a few minutes after the request. They are easily-readable (CSV format) and available in different time-aggregations (daily, hourly, sub-hourly).

https://www.arpalombardia.it/Pages/Meteorologia/Richiesta-dati-misurati.aspx

**ARPA Emilia Romagna (Italy)**

Meteorological data measured in Region Emilia Romagna (Italy). They are delivered in your mailbox a few minutes after the request. They are easily-readable (CSV, XLS, PDF formats) and available in different time-aggregations (daily, hourly, sub-hourly).

https://simc.arpae.it/dext3r/

**ARPA Puglia (Italy)**

Meteorological data measured in Region Puglia (Italy). Data available for selected years and stations in CSV format.

http://www.webgis.arpa.puglia.it/meteo/index.php

**Mareografico (Italy)**

Meteorological data measured along the coastline of Italy.

https://www.mareografico.it/

**MeteoHub (Italy)**

Meteorological observations coming from many regional networks plus forecast model data with spatial resolution up to 2.2 km distributed as open data. The download is available in BUFR and JSON format for observed data and in GRIB format for forecast data to registered users.

https://meteohub.mistralportal.it/app/datasets

**National Meteorological Service of Slovenia (Slovenia)**

Meteorological data measured in Slovenia. Directly downloadable from the web site. Easily readable (CSV format). Available in different time-aggregations (daily, sub-hourly, more), hourly not available.

http://meteo.arso.gov.si/met/en/app/webmet/

**IGRA (Integrated Global Radiosonde Archive)**

Radiosonde observations for standard, surface, tropopause, and significant pressure levels. Over 2,700 stations worldwide. Over 1,000 "active" stations are updated daily. Data are available since 1905 (only a few stations initially). Parameters include: pressure, temperature, geopotential height, relative humidity, dew point, wind direction and speed, elapsed time since launch.

https://www.ncdc.noaa.gov/data-access/weather-balloon/integrated-global-radiosonde-archive

**RAOBS (NOAA/ESRL Radiosonde database)**

The RAOBS site is an alternative to IGRA to get upper air meteorological data. It might be used, for example, to download short time periods.

http://esrl.noaa.gov/raobs/

# B. AERMOD-ready meteorological data

AERMOD is one of the preferred and recommended air quality dispersion models of the US EPA. It is also widely used both in the US and in many countries of the world. The preparation of reliable input meteorological data for AERMOD requires the use of other tools (e.g., AERMET, AERSURFACE), the availability of raw meteorological data, and may be time consuming. For all these reasons Table A.1 summarises many pre-processed meteorological data prepared by regulatory agencies in the US and Canada. A link is provided for each state or province. In some cases data can be directly downloaded from the link, while in other cases they must be requested.

**Table A.1.** USA States and Canadian Provinces that provide AERMOD-Ready meteorological data

| EPA Region / State | Air Agency Web Address | Availability |
|---|---|---|
| **Region 1** | | |
| Connecticut | https://portal.ct.gov/DEEP/Air/Modeling/Dispersion | Download |
| Maine | https://www.maine.gov/dep/air/meteorology/metdata.html | Request |
| Massachusetts | https://www.mass.gov/how-to/air-quality-modeling-submittal-aq-mm | Request |
| New Hampshire | https://www.des.nh.gov/air/state-implementation-plans/modeling | Request |
| Rhode Island | https://dem.ri.gov/environmental-protection-bureau/air-resources/air-permits | No |

| EPA Region / State | Air Agency Web Address | Availability |
|---|---|---|
| Vermont | https://dec.vermont.gov/air-quality/permits/construction/impact-evaluation | Request |
| **Region 2** | | |
| New Jersey | https://dep.nj.gov/boss/ | Request |
| New York | https://www.dec.ny.gov/chemical/281.html | Request |
| **Region 3** | | |
| Delaware | https://dnrec.alpha.delaware.gov/air/ | No |
| District of Columbia | https://doee.dc.gov/air | No |
| Maryland | https://mde.maryland.gov/programs/Air/Pages/index.aspx | Request |
| Pennsylvania | https://www.dep.pa.gov/Business/Air/ARMDivision/Pages/default.aspx | No |
| Virginia | https://www.deq.virginia.gov/air/air-quality-monitoring-assessments/air-assessments | No |
| West Virginia | https://dep.wv.gov/daq/planning/Pages/AirModelingGroup.aspx | No |
| **Region 4** | | |
| Alabama | https://adem.alabama.gov/programs/air/emissionsModeling.cnt | Request (fee) |
| Florida | https://floridadep.gov/air/air-business-planning/content/aermet-datasets-map | Download |
| Georgia | https://epd.georgia.gov/air-protection-branch-technical-guidance-0/air-quality-modeling/georgia-aermet-meteorological-data | Download |
| Kentucky | https://eec.ky.gov/Environmental-Protection/Air/Pages/Modeling%20and%20Meteorology.aspx | Download |
| Mississippi | https://www.mdeq.ms.gov/air/nsr-air-quality-modeling-2/met-data/ | Download |
| North Carolina | https://deq.nc.gov/about/divisions/air-quality/air-quality-permits/modeling-meteorology/meteorological-data | Download |
| South Carolina | https://gis.dhec.sc.gov/aermod/ or https://scdhec.gov/environment/air-quality/air-dispersion-modeling-data | Download |
| Tennessee | https://www.tn.gov/environment/program-areas/apc-air-pollution-control-home/apc/air-quality-modeling.html | Request |
| **Region 5** | | |
| Illinois | https://www2.illinois.gov/epa/topics/air-quality/Pages/default.aspx | Request |

| EPA Region / State | Air Agency Web Address | Availability |
|---|---|---|
| Indiana | https://www.in.gov/idem/airquality/modeling/ | Download |
| Michigan | https://www.michigan.gov/egle/about/organization/air-quality/modeling-meteorology | Download |
| Minnesota | https://www.pca.state.mn.us/business-with-us/aermod-ready-meteorological-data | Download |
| Ohio | https://epa.ohio.gov/divisions-and-offices/air-pollution-control/reports-and-data/aermet-output-files-for-aermod-model-input | Download |
| Wisconsin | https://dnr.wisconsin.gov/topic/AirPermits/Modeling.html | Download |
| **Region 6** | | |
| Arkansas | https://www.adeq.state.ar.us/air/permits/files.aspx | Download |
| Louisiana | https://deq.louisiana.gov/subhome/air | No |
| New Mexico | https://www.env.nm.gov/air-quality/modeling-publications/ | Download |
| Oklahoma | https://www.deq.ok.gov/divisions/aqd/ | Request |
| Texas | https://www.tceq.texas.gov/permitting/air/nav/datasets.html | Download |
| **Region 7** | | |
| Iowa | https://www.iowadnr.gov/Environmental-Protection/Air-Quality/Modeling/Dispersion-Modeling | Download |
| Kansas | https://www.kdhe.ks.gov/333/Air-Permit-Modeling | Request |
| Missouri | https://dnr.mo.gov/air/business-industry/permit-modeling | No |
| Nebraska | http://dee.ne.gov/NDEQProg.nsf/AirHome.xsp | Request |
| **Region 8** | | |
| Colorado | https://cdphe.colorado.gov/air-emissions/air-quality-modeling-guidance-for-permits | Request |
| Montana | https://deq.mt.gov/Air/ | No |
| North Dakota | https://deq.nd.gov/AQ/Modeling/ | No |
| South Dakota | https://danr.sd.gov/Environment/AirQuality/default.aspx | No |
| Utah | https://deq.utah.gov/air-quality/emissions-impact-assessment-guideline-preface | Download |
| Wyoming | https://deq.wyoming.gov/aqd/new-source-review/ | Request |
| **Region 9** | | |
| Arizona | https://www.azdeq.gov/node/2127 | Download |

| EPA Region / State | Air Agency Web Address | Availability |
|---|---|---|
| California | https://ww2.arb.ca.gov/resources/documents/harp-aermod-meteorological-files | Download |
| Hawaii | https://health.hawaii.gov/cab/ | Request |
| Nevada | https://ndep.nv.gov/air | Request |
| **Region 10** | | |
| Alaska | https://dec.alaska.gov/air/air-permit/aermod-met-data/ | Download |
| Idaho | https://www.deq.idaho.gov/permits/air-quality-permitting/ | Request |
| Oregon | https://www.oregon.gov/deq/aq/cao/Pages/CAO-Risk-Assessment-Resources.aspx | Request |
| Washington | https://ecology.wa.gov/Air-Climate | No |
| **Canadian Province** | | |
| Alberta | https://www.alberta.ca/meteorological-data-for-dispersion-models.aspx | Purchase |
| British Columbia | https://www2.gov.bc.ca/gov/content/environment/air-land-water/air/air-quality-management/modelling | No |
| Manitoba | https://www.gov.mb.ca/sd/environment_and_biodiversity/air_quality/air-emissions/index.html | No |
| New Brunswick | https://www2.gnb.ca/content/gnb/en/departments/elg/environment/content/air_quality.html | No |
| Newfoundland and Labrador | https://www.gov.nl.ca/ecc/env-protection/ics/ | No |
| Northwest Territories | https://www.enr.gov.nt.ca/en/services/air-quality | No |
| Nova Scotia | https://novascotia.ca/nse/air/ | No |
| Nunavut | https://www.gov.nu.ca/environment | No |
| Ontario | https://www.ontario.ca/page/map-regional-meteorological-and-terrain-data-air-dispersion-modelling | Download |
| Prince Edward Island | https://www.princeedwardisland.ca/en/information/environment-energy-and-climate-action/air-quality-permit | No |
| Quebec | https://www.environnement.gouv.qc.ca/air/criteres/index.htm | Download |
| Saskatchewan | https://environment-saskatchewan.hub.arcgis.com/datasets/aermod-input-file-download-by-location-/explore?location=54.329076%2C-105.748273%2C6.20 | Download |
| Yukon | https://yukon.ca/en/doing-business/permits-and-licensing/get-air-emissions-permit | No |

## C. Geophysical data

Geophysical data are important for using meteorological and dispersion models. The most important variables are terrain elevation and land cover. Other variables, such as roughness length, albedo and Bowen length may be determined from the land cover type. Typically dispersion models have their own processors to manage these data. For example, AERMOD manages elevation data through AERMAP and land cover data through AERSURFACE. Similarly, the CALMET/CALPUFF system manages these data through the processors TERREL, CTGPROC and MAKEGEO. Some geophysical data providers are listed in Table A.2.

**Table A.2. Geophysical data providers**

| Web site | URL | Contents |
|---|---|---|
| Earth Explorer | https://earthexplorer.usgs.gov/ | Terrain elevation, land cover and many other data. Requires a free account. |
| ESA/CCI[1] | http://maps.elie.ucl.ac.be/CCI/viewer/index.php | Land cover data at global level |
| MRLC[2] | https://www.mrlc.gov/viewer/ | Land cover data for US |
| ESA Climate Data Dashboard | https://climate.esa.int/en/explore/access-climate-data/ | Land cover and several climate data |
| CORINE Land Cover | https://land.copernicus.eu/pan-european/corine-land-cover | Land cover data for Europe |
| USGS National Map | https://apps.nationalmap.gov/ | Terrain elevation and many other data for US |
| ALOS Global Digital Surface Model | https://www.eorc.jaxa.jp/ALOS/en/dataset/aw3d30/aw3d30_e.htm | Terrain elevation data (1 arc-second). Requires a free account. |
| National Lidar Dataset | https://en.wikipedia.org/wiki/National_Lidar_Dataset_(United_States) | Terrain elevation data for US |
| US Interagency Elevation Inventory | https://coast.noaa.gov/inventory/# | Terrain elevation data for US |

| | | |
|---|---|---|
| CGIAR-CSI Consortium for Spatial Information | https://srtm.csi.cgiar.org/srtmdata/ | Terrain elevation data |
| Vito | https://lcviewer.vito.be/download | Land cover |
| RCMRD GeoPortal | https://geoportal.rcmrd.org/ | Land cover for the Eastern and Southern Africa regions |
| Open Topography | https://portal.opentopography.org/dataCatalog | Terrain elevation data, tools, and software |

# D. Tools

The following tools may be useful to manage the geophysical and meteorological data listed in the previous sections.

**Scripting and File Translation**

The most useful tools are probably scripting languages such as Perl (https://www.perl.org/) and Python (https://www.python.org/). They allow you to ingest a huge quantity of data and to process them as desired.

GDAL (https://gdal.org/) is a translator library for raster and vector geospatial data formats.

Some useful tools in R (https://www.simularia.it/simulariatools/). They are licensed as open source software and freely available on CRAN as R package or on GitHub at: (https://github.com/Simularia/simulariatools).

**NCL (NCAR Command Language)**

An open source collection of scripts and tools for scientific data analysis. Supports NetCDF 3/4, GRIB 1/2, HDF 4/5, HDF-EOS 2/5, shapefile, ASCII, binary.

https://www.ncl.ucar.edu/

**Metview**

Metview is a meteorological workstation application distributed by ECMWF that can take input data from a variety of sources, including: GRIB, BUFR, MARS (ECMWF's meteorological archive), ODB, ASCII, and NetCDF. Metview has excellent graphing capabilities.

https://confluence.ecmwf.int/display/METV/Metview

**GIS Mapping Programs - Open Source**

These are all free and open source geographic information systems which run under Windows, Linux, or Mac OS/X. They allow users to load many layers of data and reproject them as needed. Many plugins are available to carry out specific operations.

**QGIS**

https://qgis.org/en/site/

**uDig**

http://udig.refractions.net/

**GeoDa**

http://udig.refractions.net/

**OrbisGIS**

http://orbisgis.org/

**SAGA - System for Automated Geoscientific Analyses**

https://saga-gis.sourceforge.io/en/index.html

**GRASS GIS**

https://grass.osgeo.org/Grass

**Coordinate Converters**

Many online tools are able to perform coordinate transformations, such as between geoids or to/from UTM and Latitude-Longitude.

http://rcn.montana.edu/Resources/Converter.aspx

https://mygeodata.cloud/cs2cs/

https://epsg.io/transform#s_srs=4326&t_srs=32616&x=-85.7284000&y=38.2546700

https://www.earthpoint.us/convert.aspx

https://www.ngs.noaa.gov/NCAT/

https://twcc.fr/en/#

**Grid Reference Finder (Ireland)**

This site is a useful grid reference finder and co-ordinate inter-converter for Ireland. Datasets and access are free.

https://irish.gridreferencefinder.com/

And finally, here is one coordinate converter to download and run on a local computer

https://proj.org/about.html

## Mapping Data and Viewers

### Copernicus Climate Data Store

A useful set of tools for plotting and analysing maps and data

https://cds.climate.copernicus.eu/cdsapp#!/toolbox

### Earth Data

A global multi-data source, requires free registration

https://www.earthdata.nasa.gov/

### Tailte Eireann (Ireland)

Tailte Eireann is a newly established Irish state agency which includes mapping and geodetic data for Ireland. There are fees payable for digital or paper mapping resources.

https://www.tailte.ie/

### The National Parks and Wildlife Service - NPWS (Ireland)

The NPWS mapping section offers a detailed mapping resource for ecologically sensitive sites in Ireland. Datasets are free.

https://dahg.maps.arcgis.com/apps/webappviewer/index.html?id=8f7060450de3485fa1c1085536d477ba

### The Irish Environmental Protection Agency (Ireland)

The Irish Environmental Protection Agency mapping website presents a significant mapping resource for environmental professionals in Ireland. Datasets are free.

https://gis.epa.ie/EPAMaps/

### MICRODEM (download)

A useful mapping program to work with DEM, Land Cover, GeoPDF and other GIS data.

https://www.usna.edu/Users/oceano/pguth/website/microdem/microdem.htm

## Wind Rose Generators

**cli-MATE**

Multiple data type access, free account required

https://mrcc.purdue.edu/CLIMATE/

**Iowa Environmental Mesonet (IEM)**

https://mesonet.agron.iastate.edu/sites/locate.php

**iWindsurf**

Some simple wind data freely available, but more with a subscription

https://wx.iwindsurf.com/search/Victoria%20AU

**Downloadable Excel wind rose generator**

https://maps.cise.jmu.edu/public/wind/NewSBALPmapWebsite/Documents/WindRoseInstructions.pdf

## E. Prognostic Model Information

The following are some of the more important meteorological models in use globally. Model information and numerical data are available from their webpages.

**North American Mesoscale Forecast System (NAM)**

Developed and operated by the U.S. National Centers For Environmental Prediction (NCEP).

https://www.ncei.noaa.gov/products/weather-climate-models/north-american-mesoscale

**Global Forecast System (GFS)**

Developed and operated by the U.S. National Centers For Environmental Prediction (NCEP).

https://www.ncei.noaa.gov/products/weather-climate-models/global-forecast

**Rapid Refresh (RAP)/Rapid Update Cycle (RUC)**

Developed and operated by the U.S. National Centers For Environmental Prediction (NCEP).

https://www.ncei.noaa.gov/products/weather-climate-models/rapid-refresh-update

**High Resolution Rapid Refresh (HRRR)**

Developed and operated by the U.S. National Centers For Environmental Prediction

(NCEP).

https://rapidrefresh.noaa.gov/hrrr/

**European Centre for Medium-Range Weather Forecasts - ECMWF (IFS)**

Developed and operated by ECMWF.

https://www.ecmwf.int/en/forecasts/documentation-and-support/changes-ecmwf-model

**Consortium for Small-Scale Modelling (COSMO)**

Developed and operated by Germany, Switzerland,Italy, Greece, Poland, Romania, Russia, and Israel.

https://www.cosmo-model.org/

**HARMONIE**

Developed and operated by a consortium of meteorological institutes from Sweden, Norway, Denmark, Iceland, the Netherlands, Ireland, Spain, Estonia and Lithuania.

https://www.smhi.se/en/research/research-departments/climate-research-at-the-rossby-centre/harmonie-1.135580

**Unified Model (UM)**

Developed and operated by Met Office UK.

https://www.metoffice.gov.uk/research/approach/modelling-systems/unified-model

**WRF Model**

The WRF model was developed collaboratively by the National Center for Atmospheric Research (NCAR), the National Oceanic and Atmospheric Administration (represented by the National Centers for Environmental Prediction (NCEP) and the Earth System Research Laboratory), the U.S. Air Force, the Naval Research Laboratory, the University of Oklahoma, and the Federal Aviation Administration (FAA). It is operated by the University Corporation for Atmospheric Research (UCAR). WRF is the leading global numerical model, is in the public domain, and anyone may freely download the source code here:

https://www.mmm.ucar.edu/models/wrf

**WRF Portal**

As indicated earlier in the Handbook, running the WRF model requires extensive computing resources (typically under Linux), thus the model is not realistically accessible for everyone. For those that do install and use the WRF model, the following portal is available to assist in program setup and execution:

https://esrl.noaa.gov/gsd/wrfportal/

**WRF Users Page**

A Users Group has been established to facilitate an open exchange between users regarding questions and issues with the model:

https://www2.mmm.ucar.edu/wrf/users/

**Input Data to Initialise the WRF Model**

**NCAR Research Data Archive**

https://www2.mmm.ucar.edu/wrf/users/download/free_data.html

**NOAA - NCEP Central Operations**

https://www.nco.ncep.noaa.gov/pmb/products/

**Model Evaluation Tools**

**The Atmospheric Model Evaluation Tool (AMET)**

The AMET tool facilitates the evaluation of meteorological and air quality models. AMET is designed to work with standard output formats of the Weather Research and Forecasting (WRF) model (Dennis et al., 2010).

https://www.epa.gov/cmaq/atmospheric-model-evaluation-tool

**MODEL EVALUATION TOOLS (MET)**

MET is a highly-configurable, state-of-the-art suite of verification tools. It was developed by the United States Air Force, the National Oceanic and Atmospheric Administration (NOAA), and the National Center for Atmospheric Research (NCAR) using output from the Weather Research and Forecasting (WRF) modelling system, but may be applied to the output of other modelling systems as well.

https://dtcenter.org/community-code/model-evaluation-tools-met

**BOOT and ASTM Evaluation Procedures**

The BOOT statistical model evaluation software package and a link to the ASTM procedure are available from the website of The Initiative on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes (HARMO). These two approaches to statistical evaluation of models are discussed by Chang and Hanna (2004) and Olesen and Chang (2010).

https://www.harmo.org/kit.php

[1] CCI: Climate Change Initiative

[2] MRLC: Multi Resolution Land Characteristics Consortium