Dispersion Modelling in an Uncertain World

• Probability, Uncertainty and Risk
• Meteorological Uncertainty and Ensembles
• Uncertainty in Dispersion Predictions
• Understanding and Communicating Uncertainty
Introduction: Probability, Uncertainty and Risk
What is “probability”?

A simple illustration – tossing a coin

• Formally a Bernoulli process …

\[ P(X = x) = \begin{cases} 
  p, & x = \text{HEADS} \\
  1 - p, & x = \text{TAILS} 
\end{cases} \]

But what is \( p \)?

\[ p = 0.5 \text{ IF COIN IS FAIR (and tossed fairly!)} \]
What is “uncertainty”?  

• Oxford English Dictionary

uncertainty *noun* (plural uncertainties)  
the state of being uncertain

uncertain *adjective*  
not able to be relied on; not known or definite

• Wikipedia

Uncertainty is a term used in subtly different ways in a number of fields, including physics, philosophy, statistics, economics, finance, insurance, psychology, sociology, engineering, and information science. It applies to predictions of future events, to physical measurements already made, or to the unknown.
Uncertainty in models

• For a perfect model (i.e. one which is known to precisely replicate the underlying process):
  - uncertainty (if any exists) is through stochastic randomness of events (or ‘chance’)
  - model probabilities provide a true estimate of likelihood

• In practice, complex models are not perfect and additional ‘layers’ of uncertainty are present:

<table>
<thead>
<tr>
<th>‘random chance’</th>
<th>• on the choice of model parameters and inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>limited knowledge</td>
<td>• on the structure and design of the model (and</td>
</tr>
<tr>
<td>and/or ‘known unknowns’</td>
<td>confidence in the underlying science)</td>
</tr>
<tr>
<td>‘unknown unknowns’</td>
<td>• on the suitability of the entire model to resolve an event</td>
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</tbody>
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Probability and Uncertainty

• Model predictions of probability are **conditional** on the assumptions underlying the modelling.

• Actual probabilities of the associated real-world events will be different.

• Important to state the modelling assumptions.

• What if these assumptions are wrong?
Probability and Uncertainty

Uncertainty = level of confidence/understanding

qualitative ‘expert’ judgement based on amount of evidence (observations, models, underlying theory, etc.) and its level of agreement

quantitative assessment

Use quantitative probabilities for assessing risks, etc. only when justified by a sufficiently high level of confidence [Risbey and Kandlikar]

Or

qualitative assessment

Selection of possible outcomes, “what if?” scenarios, etc. when confidence is low
Meteorological Uncertainty and Ensembles
NWP and forecast production
Uncertainty in weather forecasting

**NWP models are not perfect!!**

- approximation (→ errors) in dynamics, numerics, physics
- model resolution (explicitly-resolved dynamical scales versus parametrised sub-grid scales)
- initialisation (observation errors, data assimilation errors → analysis errors)
- model spin-up and edge effects

**Examples:**

- synoptic scales (cyclogenesis, blocking, trough disruption)
- mesoscale (development of convection, sea breezes, local terrain effects (drainage flows, etc.))
Acknowledging uncertainty

Uncertainty assessment gives us ...

• degree of confidence in the forecast
• range of possible outcomes
• extreme forecast solutions

Can we give quantitative measures of uncertainty?
Ensemble approaches

1. Multi-model forecast comparisons (or “poor man’s ensemble”)
Poor man’s ensemble

Example of forecast
Ensemble approaches

1. Multi-model forecast comparisons
   (or “poor man’s ensemble”)

2. Time-lagged ensemble for a single model
   (temporal consistency)
Time-lagged ensemble

Example of forecast
Ensemble approaches

1. Multi-model forecast comparisons (or “poor man’s ensemble”)

2. Time-lagged ensemble for a single model (temporal consistency)

3. Ensemble Prediction System (EPS)
Uncertainty in both initial conditions and forecast model represented by an ‘ensemble’ of forecast realisations with each forecast member starting from a perturbed initial state and evolving using perturbed physical schemes.

Ensemble usually designed such that each forecast member has an equal likelihood of occurrence – allowing quantitative measures of uncertainty in the forecast evolution.
Ensemble Prediction System

Example: 2-day forecast of heavy rain
Ensemble approaches

1. Multi-model forecast comparisons (or “poor man’s ensemble”)

2. Time-lagged ensemble for a single model (temporal consistency)

3. Ensemble Prediction System (EPS)

4. Multi-model ensemble
Multi-model ensemble

Example of forecast
Met Office Global and Regional Ensemble Prediction System

MOGREPS

For short-range forecasts up to 2 days ahead

- helps to assess risks from severe events (rapid storm development, windstorms, heavy rain and snow, etc.)

- regional ensemble over North Atlantic and Europe nested within global ensemble for lateral boundary conditions

- Ensemble Transform Kalman Filter (ETKF) perturbations and stochastic physics

- 18 km NAE resolution, 24 members

- Direct use of ensemble members in downstream decision-making systems
For medium-range forecasts at 3 to 15 days

- global ensemble run twice daily at ECMWF
- initial condition perturbations based on singular vectors
- stochastic physics
- 40 km resolution, 51 members

Also a 15-day version of MOGREPS now being run operationally at ECMWF
Uncertainty products
a.k.a. “How to see the wood from the trees”

Postage stamp plot for overview of ensemble
Uncertainty products
a.k.a. “How to see the wood from the trees”

Probability forecasts
Uncertainty products
a.k.a. “How to see the wood from the trees”

Percentile products ("EPS-grams")
Uncertainty products
a.k.a. “How to see the wood from the trees”
Uncertainty in Dispersion Predictions
Uncertainties in dispersion modelling

A deterministic approach is often adopted in dispersion applications:

• emergency-response modelling
• impact assessment studies

… but …

Uncertainty in dispersion predictions caused by:

• errors and limitations of dispersion models
• uncertainty in the inputs to these models

Consider plausible sources of uncertainty – can these be quantified in a realistic way?
Uncertainties in dispersion modelling

**Meteorology** – synoptic-scale; meso-scale; local effects (e.g. topography, buildings)

**Source term** – source strength; release height; release nature (e.g. buoyant or dense gases); species mixture (chemistry, radiological properties)

**Dispersion model limitations** – model formulation, resolution, advection-diffusion scheme, model physics (deposition, convective mixing, etc.), transformations (chemistry, radiological, etc.)

**Fluctuations at short-range** – response time (averaging time) of “receptor”; nature of release (explosive/flammable substances; impacts on toxicity, chemical reactions; biological agents)
Uncertainties in dispersion modelling

Ensembles provide one way to represent uncertainties

- multiple solutions sample the phase-space of possible evolutions
- can provide a probabilistic approach to the dispersion problem (but with care – probabilities are contingent on assumptions!)
- ensembles used for many years in weather prediction – how can we learn from that experience?
Handling uncertainty in dispersion modelling

1. Simple inter-model and intra-model comparison (multi-model or time-lagged)
Model comparisons: inter-model, intra-model or against obs

Ash cloud predictions from 3 VAAC models for Eyjafjallajökull eruption

- London
- Montreal
- Toulouse

Valid at 12 UTC on 10 May 2010
Model comparison with satellite

Ash cloud prediction from London VAAC for Eyjafjallajökull eruption
Valid at 12 UTC on 10 May 2010
Handling uncertainty in dispersion modelling

1. Simple inter-model and intra-model comparison (multi-model or time-lagged)

2. “Poor man’s ensemble” (multi-model or time-lagged)
Poor-man’s ensemble technique: multi-model and/or time-lagged

Exercise 16 — Agreement on threshold level for time-integrated concentration of H31
Date and time: 2005-05-14 06:00 UTC (+45 h after release start)
Threshold level = 0.001 g/m²

Release from Cernavoda [Romania]
Location: 28.65 E 44.015 N
Start: 2005-05-12 05:00 UTC
Duration: 4 h

Node(s) (delta mean/delta scan)
ATL members:
UK1 [-5h/0m/+3h35m]
DE1 [-5h/0m/+3h35m]
FR1 [-5h/0m/+3h30m]
US1 [-5h/0m/+11h21m]
DK3 [-5h/0m/+2h4m]

Ensemble (crosshatch): none
UK1 [-5h/0m/+105h14m]

Projection: LambertAzimuthal
Created by user axjones on 2005-06-07 12:57:26 UTC

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Handling uncertainty in dispersion modelling

1. Simple inter-model and intra-model comparison (multi-model or time-lagged)

2. “Poor man’s ensemble” (multi-model or time-lagged)

3. EPS-based dispersion modelling
EPS-based dispersion modelling
EPS-based approach to dispersion modelling

Scale of dispersion problem

- met ensemble should represent uncertainties at the scale of interest
- ECMWF EPS (global-scale EPS) for long-range transport (3+ days)
- MOGREPS (regional-scale EPS) for regional transport (days 1 - 2)

Efficient use of EPS

- running dispersion model on full ensemble (ECMWF = 51 members, MOGREPS = 24 members) can be expensive!
- high data volume for transfer, processing and storage
- new parallelised version of NAME code will help
- clustering may be promising option for efficient use of EPS
Uncertainty in source term

Example: Buncefield fire

- stable atmosphere with suppressed vertical mixing
- elevated plume above boundary layer (~3km)
- clear day → plume visible from aircraft and on satellite imagery
Uncertainty in source term

Example: Buncefield fire

Vertical wind shear → fan-like plume
- model outputs used with satellite imagery to estimate plume height
- good agreement with aircraft reports

Other source term uncertainties
- emission rates (~50 kg/s PM10?)
- composition - pollutants
- emission temperature
- heat flux
- time variation due to firefighting
Uncertainty in source term

• height of release is often uncertain (esp. in early phase of an incident)

• can be dominant factor in certain meteorological conditions (e.g. is release above b.l.?)

• do we know the nature of the release and the quantity of material?

Buncefield fire, Dec 2005

Reproduced courtesy of Meteo France
Communicating uncertainty

• A better understanding of uncertainty can help us to make better-informed decisions

• No unique approach to communicate risk – adapt message to user needs and level of understanding
  • scientists / modellers
  • decision makers / emergency responders
  • public / media

• Need to present information in a balanced way

• Subjective perception of risk
Communicating uncertainty in dispersion predictions

How to communicate uncertainty to a decision-maker? Don’t they just want a ‘yes-no’?

• what is the benefit of ensemble products (percentiles, probabilities, etc.) over a conventional deterministic approach?

• generates much more information – how to manage this and reconcile any differences?

• can we really quantify the true risks? or better to use qualitative judgment of uncertainties?

• may be useful approach for defining clear areas (evacuation zones, safe approach routes, etc.)
Developing ensembles for atmospheric dispersion

Ensemble products

- ‘deterministic-type’ products ("a single answer")
- probabilistic products (quantifying risk)
- other uncertainty products (summarise our confidence)

Probabilistic validation

- Brier score, reliability diagram, ROC, rank histogram, etc.
- needs many cases – difficult!

New approaches

- DACE (Univ of Southampton/DSTL/Met Office)
EPS-based dispersion modelling

Uncertainty products

NAME III / ECMWF EPS: PMCH Dosage at 0 m (g/s/m^3) T+75h

DT 00Z on 23/10/1994
VT 03Z on 26/10/1994
NAME volcanic ash predictions using ECMWF EPS forecasts

Only represents large-scale meteorological uncertainties in the dispersion problem

NO ACCOUNT OF OTHER UNCERTAINTIES, ESP. IN THE VOLCANIC ERUPTION!

N.B. meteorological uncertainty only!
Site-specific products

Risk category for threshold exceedence

Probability concentration exceeds black

Air Concentration From FL000 - FL200
25/10/2010 18:00:00

Probability of threshold exceedence

3-hourly time series of concentration

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Communicating uncertainty

Some general hints …

• use ‘out of’
  e.g. ‘80 out of 100’ or ‘80% out of 100%’

• avoid use of negatives
  e.g. don’t say ‘60% chance that it will not rain’

• graphical/pictorial representations are often easier to understand than numbers!

• take care when presenting ‘worst-case scenarios’ – are the underpinning assumptions realistic? or too precautionary?

• aim to use ensemble members in full modelling chain for consequence assessments, etc.
Summary

Acknowledge uncertainty – be open and honest about it!

Quantifiable risk (probabilities) vs uncertainty

Mature use of NWP ensembles for assessing uncertainty in meteorological forecasts – how can dispersion modellers learn from this experience?

Uncertainty in dispersion predictions due to limitations of dispersion models and incomplete input to those models (meteorology, source, consequences, etc.)

Dispersion ensembles (multi-model, EPS-based, etc.)

Communication of uncertainties is important
Questions and answers