Reviewing Issues Associated with Modelling Atmospheric Dispersion in Changing Meteorological Conditions

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Changing Meteorological Conditions – Time Scale / Spatial Scale

- Focus on the effects of **temporal** changes in meteorological conditions on pollutants when travelling between source and receptor

- Time scale
  - Time to travel from source to receptor
  - Time scale of impact
    - 1h-average
    - 24h-average
    - Annual average

- Spatial scale
  - Distance from source where impact is relevant – vary with type of application
    - Short-range
    - Long-range
  - Spatial variability (meteorology, landuse,...)

Spatial Scale / Changing Meteorological Conditions

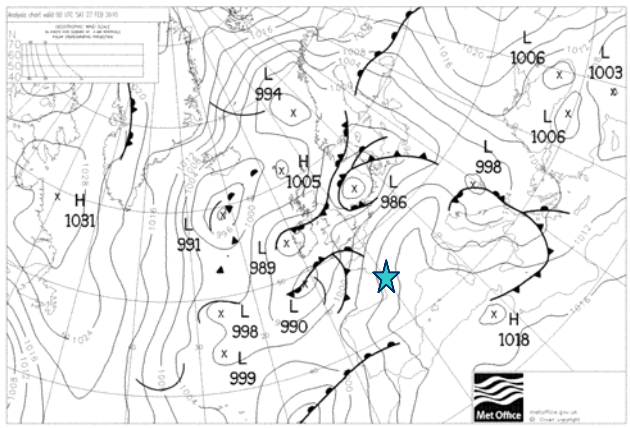
- Atmospheric dispersion modelling covers a large range of applications
  - Local scale (less than 1km) : Toxic spills, accidental releases
  - Short-range (1 to 20km); Regulatory applications
  - Long-range (more than 50km): Wide-spread fires, volcanic eruption, Chernobyl accident
- Changing meteorological conditions can be tackled also at different scales
  - Mesoscale (i.e. fast track moving low pressure)
  - Micro-meteorological parameters changing locally

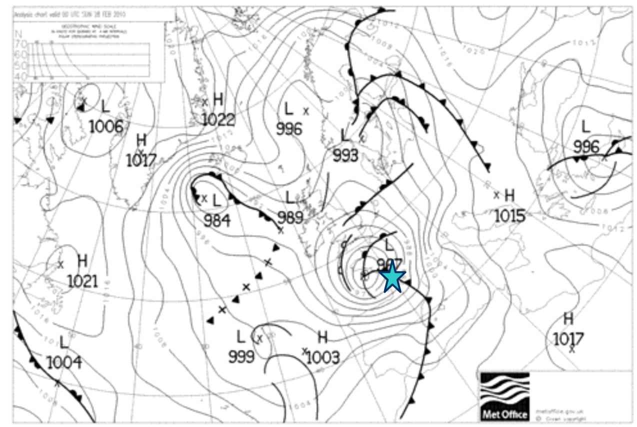
Example Large Scale - Fast Moving Low Pressure

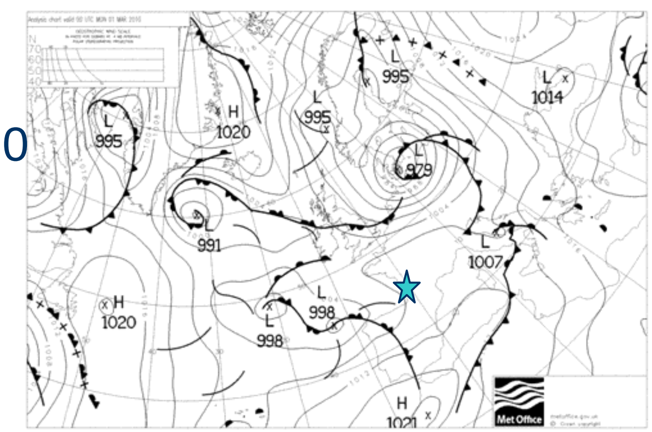
☆ South west coast of France

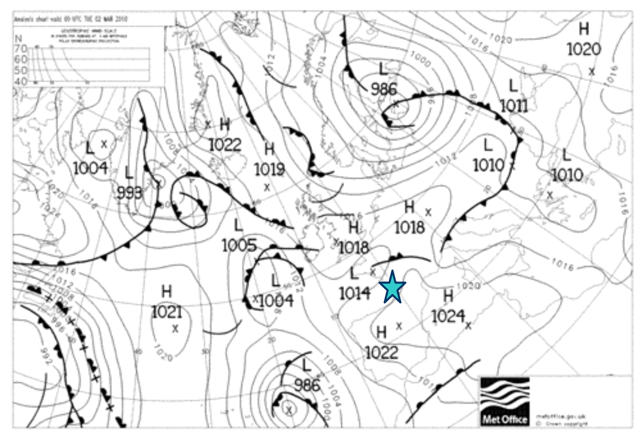
Eulerian view
Passage of low pressure

Fast moving low pressure over
A 4-day period
27Feb – 2Mar, 2010





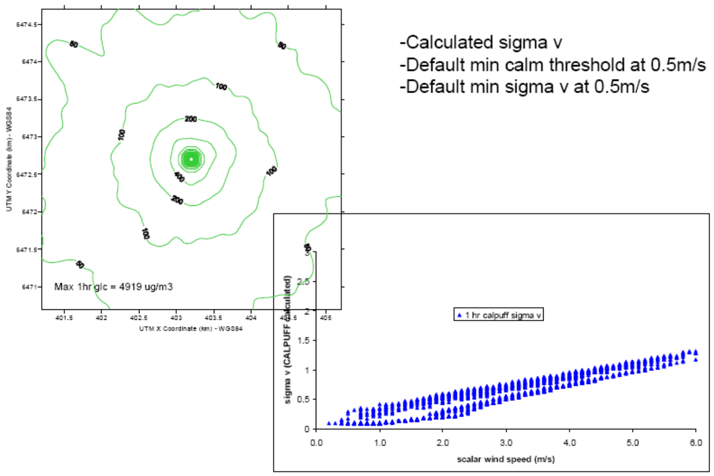




(from Met Office)

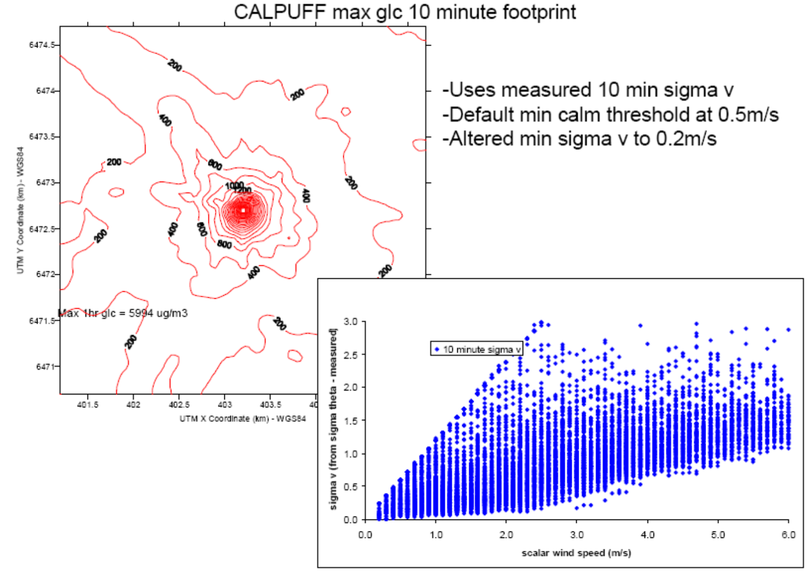
Example Local Scale – 1h / 10 minutes Meteorological Data – H2S Impact

CALPUFF max glc 1-hr footprint using model defaults



-Calculated sigma v
-Default min calm threshold at 0.5m/s
-Default min sigma v at 0.5m/s

CALPUFF max glc 10 minute footprint



-Uses measured 10 min sigma v
-Default min calm threshold at 0.5m/s
-Altered min sigma v to 0.2m/s

1-hour peak H_2S concentration
Hourly Meteorology
Internally computed turbulence parameters

10-minute peak H_2S concentration
10-minute Meteorology
Real-time turbulence parameters

(From Barclay, 2008)

Changing Meteorological Conditions – Non-Steady-State Situations

- Other Non-steady-state factors in atmospheric dispersion modelling
  - Chemistry
  - Type of sources
    - Variable emission rates
    - Variable emission temperature, exit velocity
    - Moving sources
  - Terrain effects
  - All are important but not part of this review

Identify Changing Meteorological Conditions

- Atmospheric dynamic
  - Highs, lows
  - Front passages
  - Thunderstorm and squall lines
- Thermally induced circulations
  - Land-sea breeze
  - Anabatic/katabatic winds
  - Radiation temperature inversions
  - Urban heat islands
- Combination of the above – complex atmospheric system
- For each, examples exist in literature of possible adverse impact on atmospheric pollution

Which Meteorological Parameters Changes are Important for Atmospheric Dispersion?

- Wind speed and/or wind direction
- Wind shear
- Stability class
- Temperature (chemistry involved) or buoyancy related
- Mixing height (fumigation; temperature inversion)
- Precipitation (for deposition)

Passage of a Weak Gust Front

Local rapid change in meteorological conditions

Illustrate local perturbation in meteorological parameter

Low wind speed and high fluctuation before front

Increase in wind speed and decrease variability as front pass

(from Bowen, 1996)

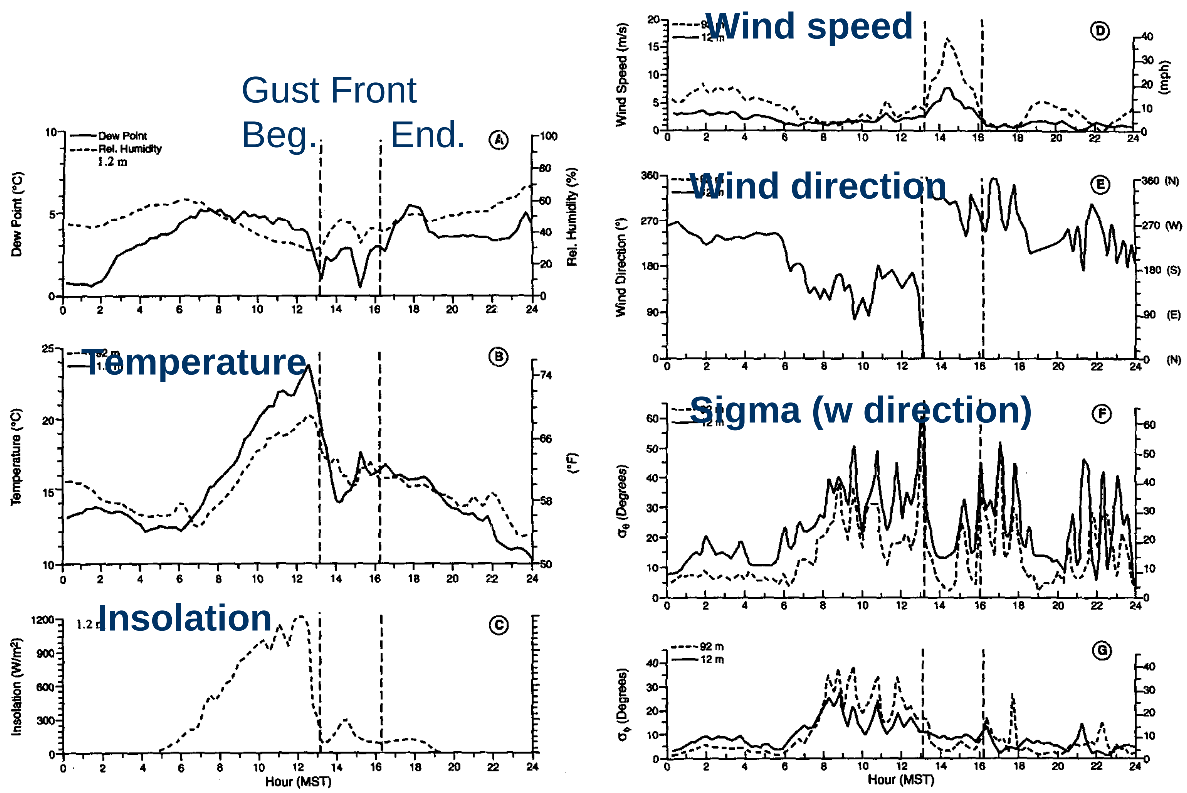


FIG. 2. Tower measurements during thunderstorm flow on 9 June 1991. Analyses include 15-min averages of (a) dewpoint and relative humidity, (b) temperature, (c) insolation, (d) wind speed, (e) wind direction, (f) standard deviation of wind direction (σ_θ), and (g) standard deviation of vertical wind direction (σ_ϕ). Measurement levels above ground are shown in upper-left corners of each plot. Vertical dotted lines indicate estimated onset and cessation times of outflow.

Passage of a Weak Gust Front (continued)

12.30 LST -------
14.00 LST ____

Calm wind conditions follow by gust front – Impact on a source emitting in 120m layer at this location – accumulation follow by transport (non-steady-state)

(from Bowen, 1996)

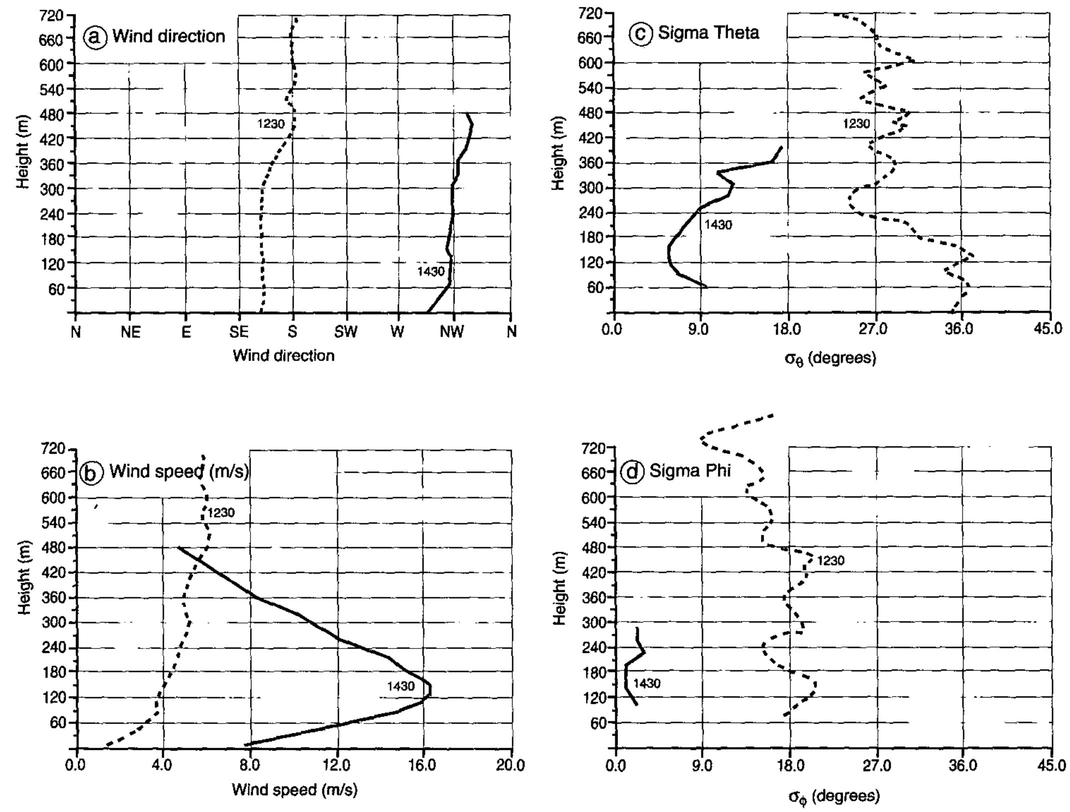


FIG. 3. Vertical profiles of (a) wind direction, (b) wind speed, (c) σ_θ, and (d) σ_ϕ measured by sodar before (1230 LST) and after (1430 LST) gust front passage on 9 June 1991.

Changing Meteorological Conditions Which Can Induce Significant Impact on Pollution

- Sub-hourly wind fluctuations
  - Calm wind conditions – anti-cyclonic
- Recirculation / flow reversal
  - Land-sea breeze
  - Valley/slope flows
  - Urban heat island effect
- Change in mixing height
  - Coastal fumigation
  - Temperature inversion at night follow by a breakup in the morning
- Front passage
  - Sudden rain
  - Passage of depression
- Squall lines, thunderstorm, tornado, hurricane, severe weather....

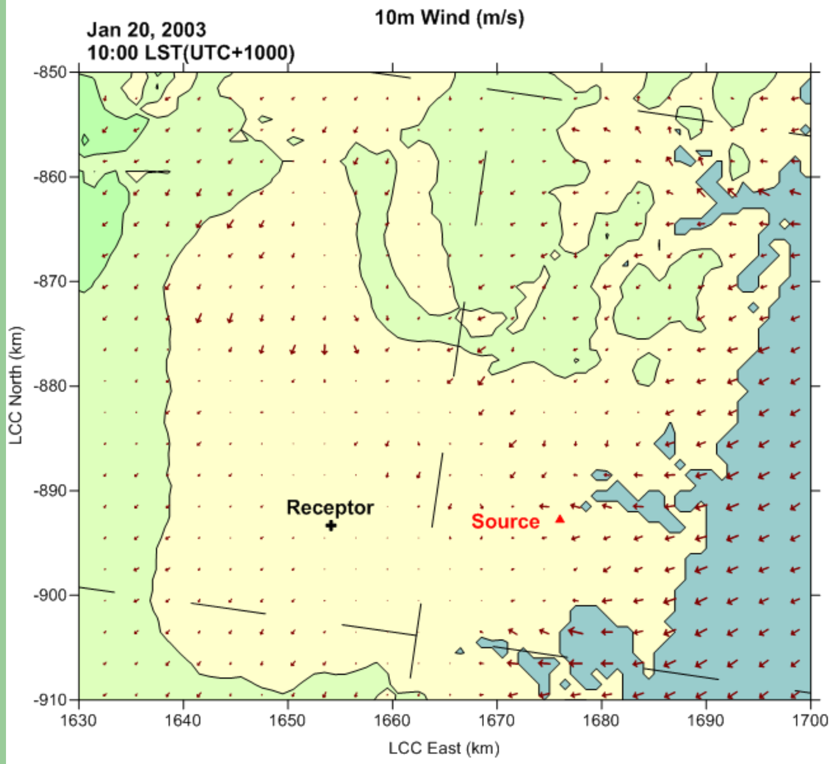
End Points of Interest for Modelling?

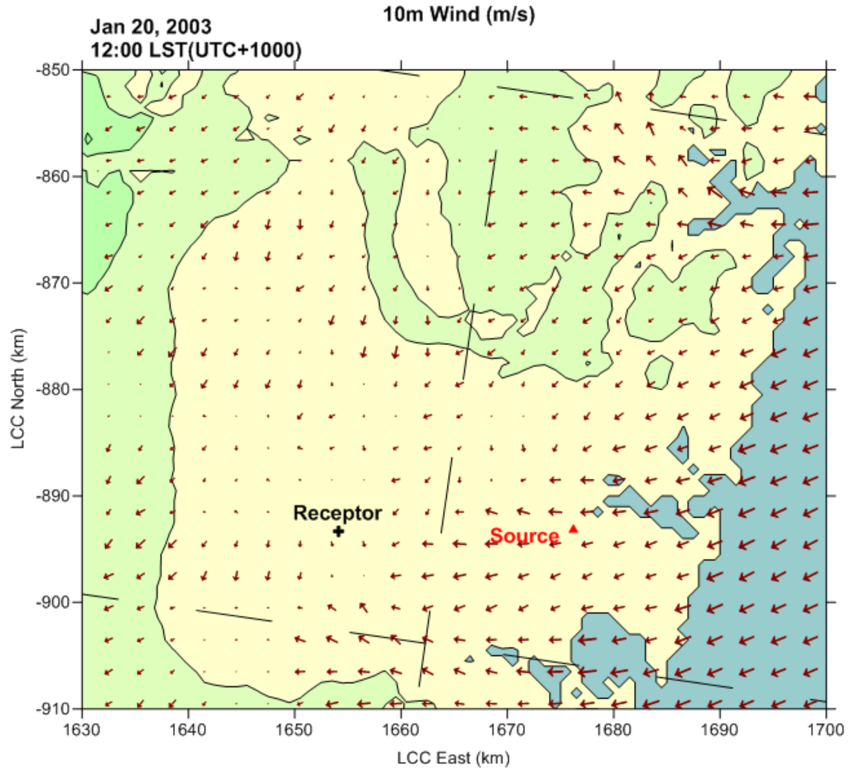
- Compliance with ambient standards
  - Regulatory impact assessment
    - different time scale (short-range, long-range)
    - Importance of concentration
    - Independent of location
- Determine worst-case scenario
  - Risk assessment (design safety zone)
    - Importance of concentration
    - Independent of location
- Determine the location, time and concentration of plume impact
  - Odour modelling
  - Accidental release (short-range, long-range)
  - Operational real-time and forecasting
    - Importance of both: concentration and path

Possible Effects of Changing Meteorological Conditions?

- On path of pollutant between source and receptor
  - Change the location of impact
    - distance from the source
    - direction

Example of Change in Meteorological Conditions Between Source and Receptor





Sea breeze - Winds at source are different from winds at receptor
During the two day period - Steady-state model would show an impact at receptor, Non-Steady-state model would not show impact at receptor – (non-steady-state situation)

Possible Effects of Changing Meteorological Conditions?

- On pollutant concentration
  - Accumulation
  - Recirculation
  - Dilution
  - Removal by wet/dry deposition

Example 1 - How Changes in Meteorological Conditions Can Affect Pollution

Inversion layer breakup
(non-steady-state conditions)

Correlation vertical
profile of temperature
and vertical profile
of ozone
(from Zhang and Rao, 1999)

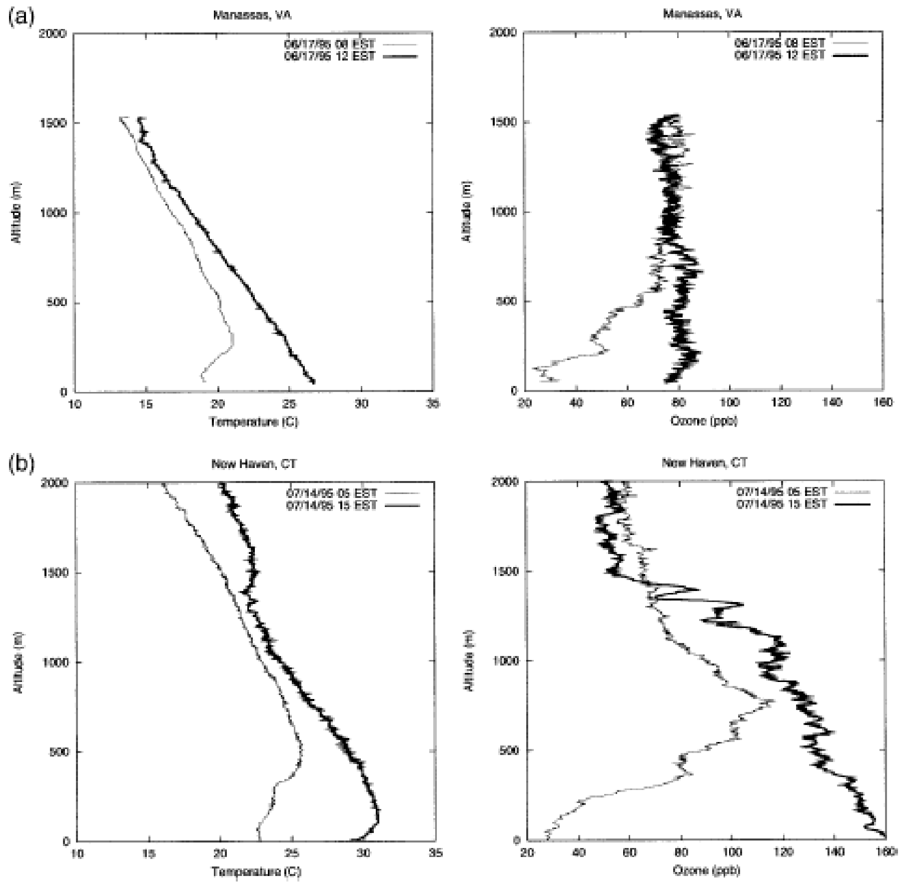


FIG. 8. Aircraft measurements of temperature and ozone profiles at (a) Manassas, Virginia, on 17 June 1995 and (b) New Haven, Connecticut, on 14 July 1995.

Example 2 - How Changes in Meteorological Conditions Can Affect Pollution

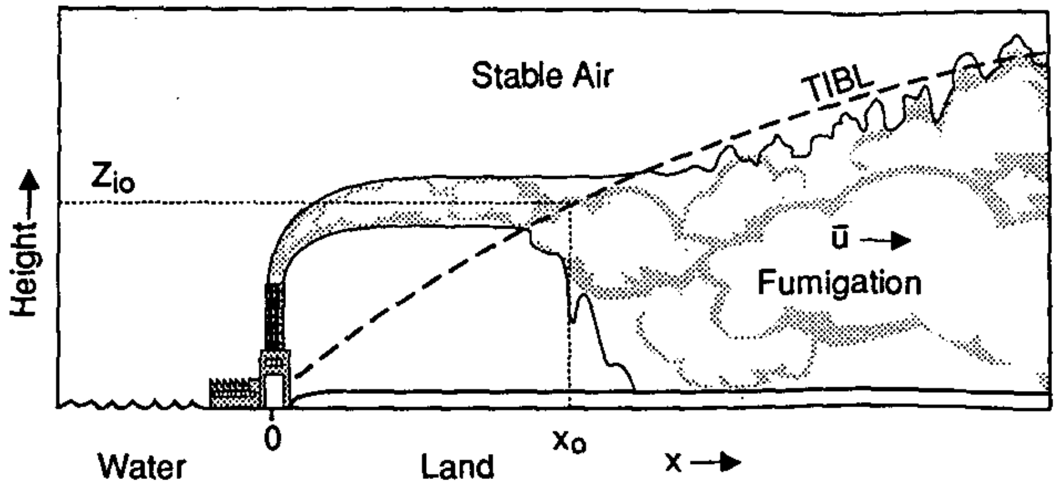


FIG. 1. Illustration of the coastal fumigation phenomenon. The TIBL is shown by a dashed line.

(From Luhar and Sawford, 1995)

Atmospheric Dispersions Models

- Simple plume steady-state models
  - Examples: SREEN, R91
- Advanced plume steady-state models
  - Examples: AERMOD, ADMS, OCD, ISC3
- Non-steady-state models
  - Lagrangian
    - puff models (i.e CALPUFF, UDM, SCIPUFF)
    - particle models (i.e. Met office NAME), MicroSpray)
  - Eulerian (i.e.: CMAQ, CAMx, EMEP Unified model)
  - Hybrid
    - Eulerian/Lagrangian (TAPM)
    - hybrid single-particle (HYSPLIT)
- Other models
  - CFD models (i.e. FLUENT, MERCURE)
  - Design of accidental release of dense gas, toxic gas (i.e. HGSYSTEM, SLAB, DEGADIS)

Steady-state Assumptions in Plume Models

- Straight line trajectory
- Assume non-zero wind speed
- No causality
  - Does not account for travel time between source and receptor
- Conditions do not change within a time step (i.e 1h)
  - Meteorological conditions are assumed the same on the entire modelling domain
  - Over the time period needed for the plume to reach receptor, the meteorological conditions are assumed to be constant
  - Constant source characteristics
- Each hour is separate and independent of previous hours
  - No memory of pollutant location or emissions from previous hours are required

Non-Steady-State Models Assumptions

- Allow 3-Dimensional meteorology
  - Meteorological conditions not steady-state
  - Spatial variability to winds and turbulence fields
- Allow variable/curved trajectories
- Allow spatial variability of terrain/landuse
- Retain information of previous hours emissions
- Allow calm and low wind speed conditions
- Include causality effects

Differences Steady State Model versus Non Steady State Model

ANIMATION COMPARISON OF 24H SIMULATION OF
STEADY_STATE MODEL VERSUS NON-STEADY_STATE MODEL

Examples of Options in Steady-State Models to Adjust to Non-Steady-State Situations

- ADMS
  - Calm wind module
  - Terrain effects
  - Coastal fumigation
  - Land-use variability
- AERMOD
  - Steady-state fumigation (constant wind and TIBL)
- OCD (Offshore and Coastal Dispersion Model)
  - Boundary layer option to model coastal fumigation

When Does The Use of Steady-State Models Become Questionable?

- Will depend on the application
- Use of single meteorological field not enough to characterize flow between source and receptor
- The changes in meteorological conditions too fast for steady-state model relative to end points impact requirements
- Memory of pollutant build-up from hour to hour is important for application
- Spatial inhomogeneity between source and receptor
- Receptor – Source Distance?
  - Are causality effects important for application (steady-state plume model reach infinity in direction of flow)

Applications/Local Conditions Which Can be Impacted by Changing Meteorology

- Regulatory applications; odour modelling; risk assessment
  - Time scale (1h-average, 24h-average)
  - Stagnation - calm wind conditions
  - Recirculation – land/sea breeze
  - Fumigation – coastal / morning temperature inversion
- Accidental release
  - Location of the impact is important
  - Any changes in wind direction on the path of pollutant
  - Distance from source
- Long-range application
  - A number of changes in meteorological conditions occurs on the pollutant path
  - Impact on endpoints of interest most likely to be different
  - Example Accidental Release with long-range impact such as Chernobyl, volcanic eruption
- Less important for long-term (annual) averages impact

How to Decide if Steady-State Models are Suitable of Not?

- A number of Questions should be asked and answered
  - What is the distance between source and receptor (short, long?)
  - What type of application?
    - What type of impact requires?
    - Is the path important or concentration important, both?
  - Can changes in meteorological conditions bring significant dispersion changes on the path?
  - Are meteorological conditions slowly changing?
  - Frequency of changes in meteorological conditions along the path
  - Time Scale of impact (long-term averages, short-term averages)
  - Local physical characteristics (complex terrain, landuse type inhomogeneity,...)
  - Compute a steady-state index

Steady-State Index

- Three parameters
  - wind speed as surrogate for dilution and plume rise, causality
  - wind direction as surrogate for advection
  - Stability class as surrogate for rate of dispersion

- Frequency of match of these parameters between source and receptor
  - Change in wind speed (1m/s or 25% whichever is greater)
  - Change in wind direction (within 22.5 deg sector)
  - Change in Stability class (category must match)

- If frequent enough (match all 3 parameters over time) – steady-state conditions apply

- Define where (distance from source) conditions become non steady-state and where non-steady-state model would be recommended

(From Scire, 2009)

Are Results Significantly Different if Steady-State or Non-Steady-State Models are Used?

- Previous statements are qualitative
  - Evaluate when a discrepancy can occur
  - Discuss if it can be significant or not
- Need to quantify the difference
  - Lack of quantitative assessment whether steady-state model assumptions are violated in a given application
- Most near-field comparisons/evaluations previously performed are in steady-state conditions
- Availability of dataset for comparison steady-state models and non-steady-state models in changing meteorological conditions

Types of Available Datasets

- Dense gas and toxic gas accident releases
  - Short-term emissions usually non constant
  - Receptors up to 6-10km from source
  - Steady-state conditions

- Near-field tracer experiments
  - Buoyant gas, continuous emissions
  - Flat terrain or simple terrain features
  - Receptors up to 10-20km from source
  - In general, steady-state conditions

- Long-range tracer experiments
  - Buoyant gas
  - Short-term emissions or continuous emissions
  - A few days or annual monitoring
  - Non-steady-state conditions

- Others
  - Urban area field experiments
  - CFD experiments
  - Meteorological only datasets
    - No emissions or monitoring
    - Non-steady-state conditions

Availability of Datasets for Non-Steady-State Situations

- Near-Field Experiment
  - Kwinana coastal fumigation study (emissions, meteorology and pollutant monitoring)
  - ISB52 – developed to study Improved Air Forecasting (meteorology)
  - Tracy power plant, Nevada – morning temperature inversion
- Calm wind conditions
  - Cardington, UK (instrumentation site)
- Long-range experiment
  - ACURATE tracer experiment (emissions, meteorology and pollutant monitoring)

Proposed Sensitivity Studies

Test	Dataset	Change in Met. Conditions	Time Scale	Distance from Source	Comments
1	Kwinana	Shoreline fumigation	Short-term (1h-, 24h-average)	Near-field (within 10km)	Coastal location under sea breeze conditions
3	Tracy power plant	Morning fumigation	Short-term (1h-average)	Near-field (within 10km)	Complex Terrain study – not exactly strictly variation due to meteorology
2	Cardington, UK	Low wind speed conditions	Short-term (1h-average)	Near-field (within 10km)	Only meteorological data available
4	ISB52	Passage of a front / Precipitation	Short-term (1h- 24h-average)	Near-field (10km)	Only meteorological data available
Additional Possible studies					
5	ISB52	Morning fumigation	Short-term (1h-average)	Near-field (10km)	Only meteorological data available
6	ACURATE	Varied - Sequential/Statistical	Long-term (annual)	Long-range (100km)	Long-range, extend outside boundaries of possible steady-state application -

Why Non-Steady-State Sensitivity Studies?

- These types of studies not common – not done before
- What to learn from these sensitivity studies?
  - Compare results from plume steady-state models (AERMOD or ADMS) and non-steady-state models (CALPUFF or NAME)
  - Quantify the discrepancy when steady-state models rather than non-steady-state models are used in non-steady-state situations
    - Leading to pollutant accumulation
    - Leading to curved trajectory
  - Determine how receptors of interest are impacted
    - Pollutant reaching or not the receptor
  - Determine if it can affect the results/conclusion of the application
- Testing Steady-State Index

Additional Points to consider

- Meteorological data availability (validity of data – representativeness of data)
  - 1D-meteorology
  - 3D-meteorology
  - Statistical meteorology
- Computer Time / Computer resources
  - Size of domain, resolution, number of grid cells, number of receptors, number of sources,....
- Expertise
- Accuracy versus conservatism (type of applications)
- Averaging Time (short-term, long-term)
- Uncertainties due to model parameterisations, meteorological measurements, source characteristics, all input data
- Type of Sources
  - Elevated sources are more sensitive to change in meteorological conditions than ground sources

Conclusion

- Each type of application should be treated differently
  - Local meteorological conditions (frequency of changes)
  - Situation of source (coastal, release near sunrise, mountain area,...)
  - Compute a steady-state index
  - may help to determine if steady-state model is suitable or not

- Distance of impact from the source
  - Near-field (local situations need to be investigated)
  - Long-range (non-steady-state models recommended)

Conclusion

- Time scale of the outcome at receptors
  - Annual averages concentration (less sensitivity to non-steady-state conditions)
  - Short-time scales (hourly or daily averages concentrations)
    - Slowly changing meteorological conditions (steady-state model may be adequate)
    - Fast changing or importance of input from previous hours (non-steady-state models recommended)

- End Points of interest
  - Worst-case scenario (local situations need to be investigated)
  - Path and concentration (non-steady-state models may be recommended)

- Sensitivity Studies
  - Give an indication if steady-state models are suitable or not in the situation studied
  - Cannot provide a general evaluation results – would be valid only in the case studied

Thank You

Acknowledgement:

We are grateful to all reviewers for providing useful comments and suggestions