The successes, limitations and uncertainties of estimating emissions from measurements

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Why estimate regional or country emissions from observations?

- As part of the UNFCCC (United Nations Framework Climate Change Convention) each developed country has to report its annual anthropogenic emissions of a range of greenhouse gases (GHG).
  - CO_2, CH_4, N_2O, HFCs, SF_6, PFCs
- Traditional **inventory** approach ('bottom-up').
  - Combines **Activity Data** (activities that result in the emission of a GHG e.g. landfill waste) and **Emission Factors** (links a specific activity to an emission).
  - Sum emissions per sector (industry, agriculture, energy, waste, etc) per gas to estimate an annual country GHG emission total.
- Emissions from observations: **Inversion modelling** ('top-down').
  - Challenge traditional emission inventories.
  - Independent.
  - Best practice for Kyoto Protocol although not mandatory.
- Both bottom-up and top-down methods have uncertainty.

Inversion modelling

- Information required:
  - How emissions dilute in the atmosphere as they travel from a source region to an observation point.
    - Atmospheric transport (dispersion) model underpinned by meteorology.
  - Precise observations preferably at high temporal resolution.
- Output:
  - Spatial distribution and magnitude of emissions.
- Challenge:
  - Maximising the match in concentration between the modelled (estimated given an emission map) and measured (truth) time-series.

Comparing measured and modelled time-series of concentration

- Inversion Model
  - Uses a grid of emissions, fixed within a time frame (emission map).
  - Estimates the contribution each grid makes to an observation.
  - Sums contributions from each grid to estimate modelled time-series of concentration.
  - Searches for the emission map that produces a model time-series that has the best statistical match to the observed time-series.
- Statistical Match
  - What statistical function to use to measure the quality of the fit?
  - Common functions (there are many more): root mean square error (*RMSE*), correlation coefficient (*r*), fraction within a factor of two (*FAC2*)
  - Each statistic has strengths but also some weaknesses.

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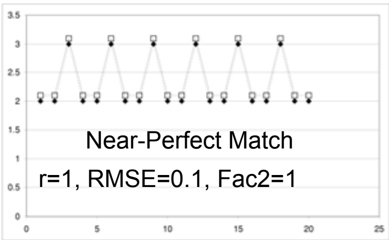
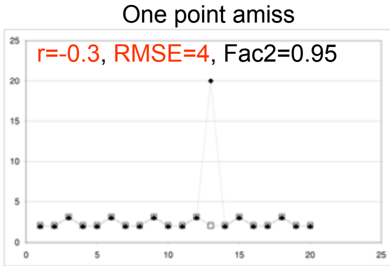
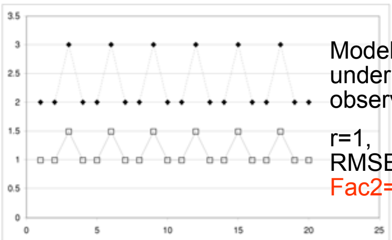
Simple artificial examples of statistical measures



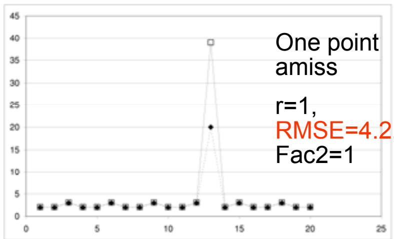
One point amiss





Model just under half observations

r=1, RMSE=1.2, Fac2=0



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Additional knowledge can help the inversion

- Inversion models can use additional information to better constrain the emission map.
  - E.g. knowledge about how the emissions are distributed (*a priori*).
- An emission map is penalised for moving away from the *a priori.*
  - I.e. the benefit in terms of a better time-series fit needs to outweigh the penalty of an emission map more distant from the *a priori*.
- How to price the distance from the *a priori* solution relative to the statistical fit of the modelled time-series to the observations?
  - related to the perceived quality of the *a priori* (subjective).
  - Usually defined relative to the *a priori* solution, e.g. 100% uncertainty.
  - New or unexpected sources or those significantly different from the *a priori* estimate struggle to be seen in the inversion.
- A good *a priori* estimate can significantly improve the robustness of the final solution. A poor one is detrimental.
- If inventory data used in *a priori* then inversion solution is not independent.

Transport (dispersion) model

- Critical component of inversion system.
  - Describe how emissions dilute with distance and where they go.
- 2 components: Meteorology and Dispersion.
- 3-D wind, temperature and boundary layer information on a grid from Numerical Weather Prediction (NWP) models.
  - Use short-term forecast 0-3 hours corrected for by observations.
  - Resolution varies between models (25-80 km globally up to 1.5 km country scale).
  - NWP models do not 'see' everything. Sub-grid features not represented, i.e. sharp changes in orographic features e.g. steep mountains, valleys or coasts. NWP 'sees' average flow in grid.

Location of measurement station matters

- Flat terrain sites are usually ideal as the flow well represented by NWP.

Cabauw Tower

The Netherlands

Photo: Alex Vermeulen

Location of measurement station matters

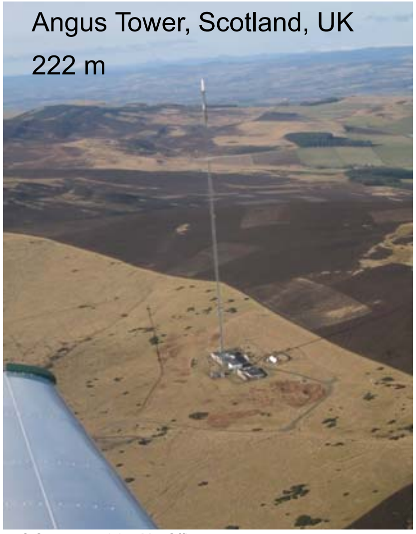
- Coastal stations are affected by (sub-grid scale) land-sea breezes but benefit from a ‘clean’ well mixed sea sector.

Mace Head

West coast Ireland

Photo: Simon O’Doherty

Location of measurement station matters



- Elevated observations (tower) more representative of grid average.
- Ground is heterogeneous and thus complex.
- Potentially difficult to decide whether measurement within Boundary Layer (BL) or not (profile of observations valuable for this).
  - BL notoriously difficult to estimate in NWP models.

Photo: John Moncrieff

Location of measurement station matters

Stations in mountainous areas are very challenging!

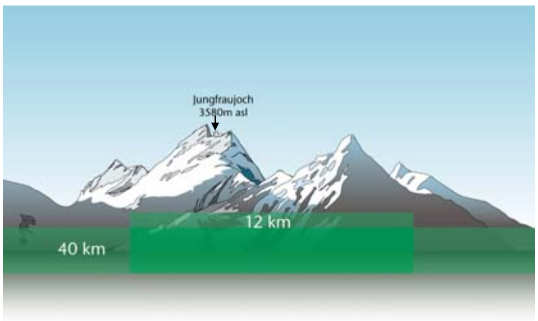
Jungfraujoch station in the Swiss Alps.

Photo: Stefan Reimann

Where is the measurement station?

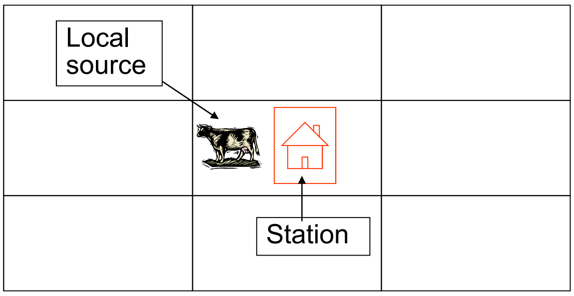
- Which point in 3-D model atmosphere is most representative of the observed air?

- Surface station at Jungfraujoch in the Alps (3580 m asl).
  - On saddle between two mountains with valleys on either side.
  - UK global model 40 km: ground level = 1760 m asl.
  - UK regional model 12 km: ground level = 2110 m asl.



Resolution of inversion solution

- Inversion emission map has a defined horizontal grid and a specified time window. During this time emissions are assumed constant in each grid.
- Intermittent emissions or large sources near to the monitoring station will cause problems for inversion.
- Incorrectly placed emissions will lead to over- or under- estimates.



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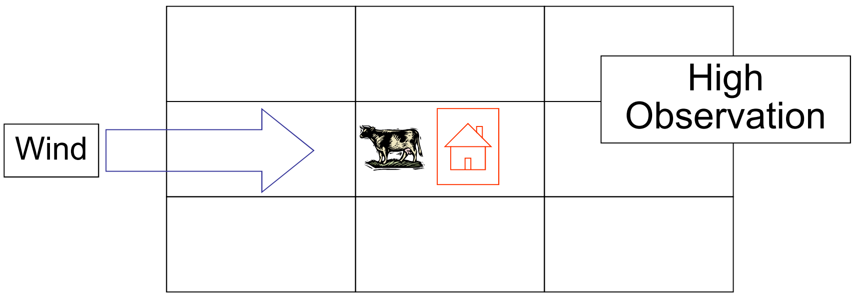

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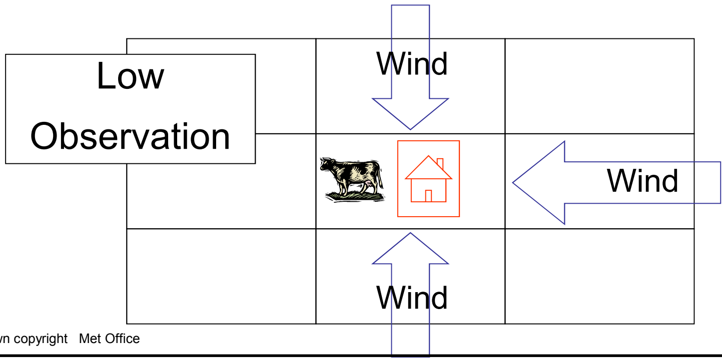

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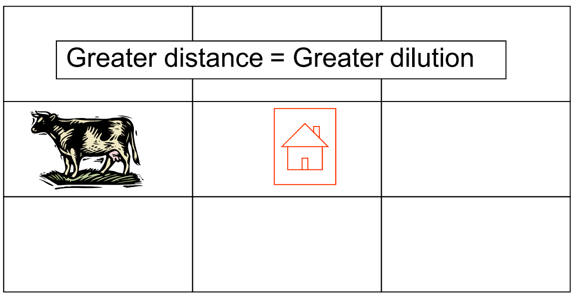
Larger emission estimated further from station



Selecting the observations to use in the inversion

- Increasing the number of observations can help the inversion model (better triangulation).
  - Flask (weekly) to high-frequency (hourly).
  - Observations from multiple measurement stations.
  - Improves knowledge about the distribution and magnitude of sources.
- Multiple stations – Are the observations inter-comparable? Would both instruments measure the same value if side by side?
- Removing observations that maybe too challenging to model e.g.
  - low wind speed conditions (local sources dominate).
  - day time values in mountainous areas (flow complex).

Uncertainty in inversion models

- Sources of uncertainty:
  - Observation,
  - Modelled meteorology,
  - Transport and dilution of pollution.
  - Inversion method (statistical fit)
- Difficult to assess the total uncertainty but vital to try. Possible ways to test robustness of inversion solutions:
  - Randomly perturb or randomly sub-sample observations,
  - Use multiple NWP models (ensemble),
  - Use multiple inversion methods (inversion ensemble),
  - Change uncertainty level when using *a priori* information.
- However Inversion Modelling is useful!

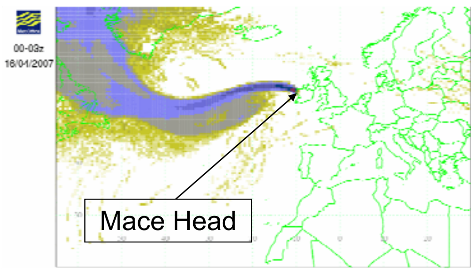
UK verification of UNFCCC inventory submission

- NAME-inversion method (No apriori):
  - Methane (CH_4)
  - Nitrous oxide (N_2O)
  - HFC-134a
  - HFC-152a
  - HFC-125
  - HFC-32
  - HFC-143a
  - HFC-365mfc

NAME-inversion method

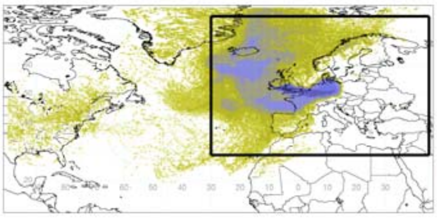
- NAME model (Lagrangian particle dispersion model).
- Uses 3D meteorological data from UK Met Office NWP and ECMWF models (40-80 km resolution).
- Derive air history map for Mace head for a 3-hour period:
  - Combination of tens of thousands of trajectories.
  - Darker shade means greater contribution from that area.
  - All surface sources within previous 12 days of travel that contribute to an observation during a 3-hour period are recorded.

Maps generated for each 3-hour period:
- 1994 onwards



NAME-inversion technique

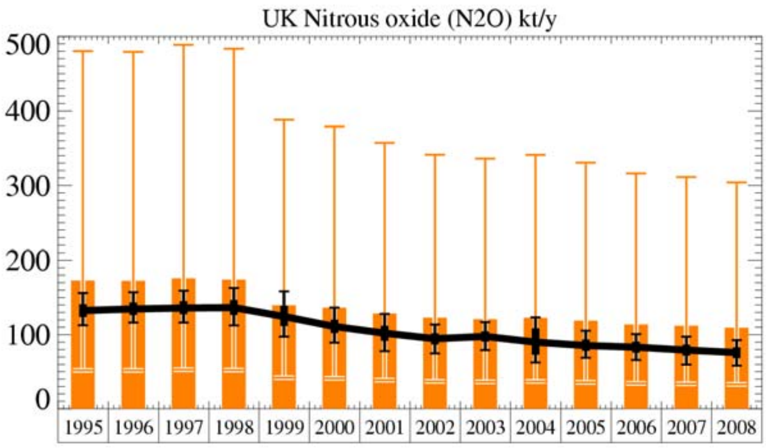
Air Origin Map = Matrix **A**
(Nº times x Nº grids)



Measurement - Baseline = **m**
Emission Map = **e** (the solution)
Relationship: **A e** = **m**
Problem: Minimise **m** - **A e**

- Remove observations that have a strong **local** influence.
- Scale emissions (**iteration**) to obtain **best-fit** statistical match between model time-series and observations.
- No prior information – **Random** initial guess.
- Solve for each **3-yr** period iterating monthly e.g. Jan'05 – Dec'07, Feb'05 – Jan'08, …
- Repeat **multiple** times, each time start from different random initial guess.
- Apply random **'noise'** to observations (different for each inversion).

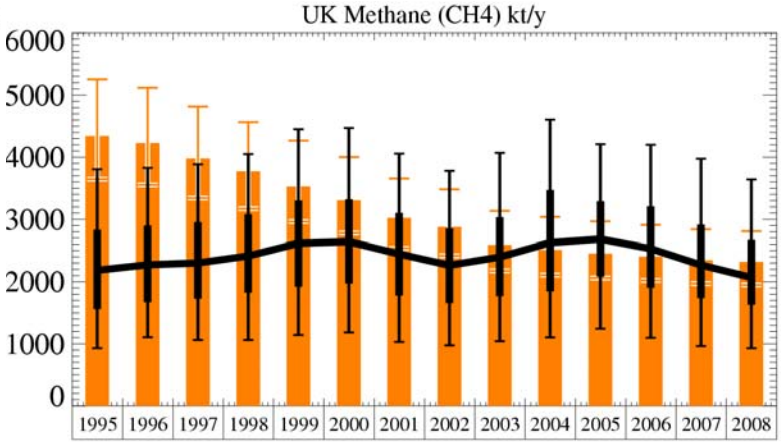
N_2O emissions: UK



NAME-inversion estimates with uncertainty

Inventory estimates (UNFCCC 2009) (30% - 278%)

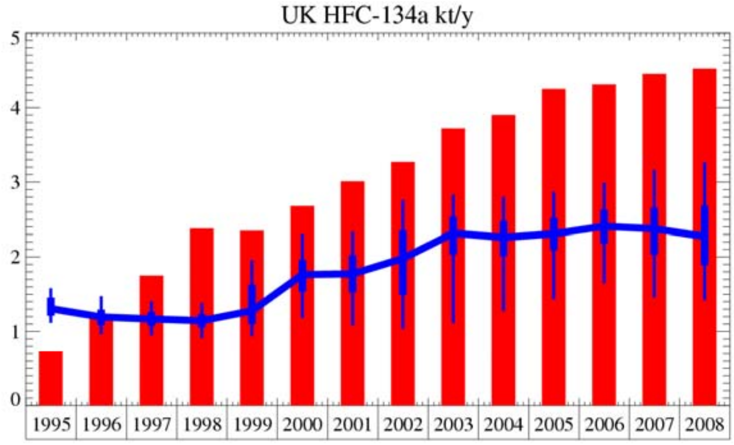
CH_4 emissions: UK



NAME-inversion estimates with uncertainty

Inventory estimates (UNFCCC 2009) (84%-121%)

HFC-134a emissions: UK



NAME-inversion estimates with uncertainty

Inventory estimates (UNFCCC 2009)

HFC-152a emissions: UK

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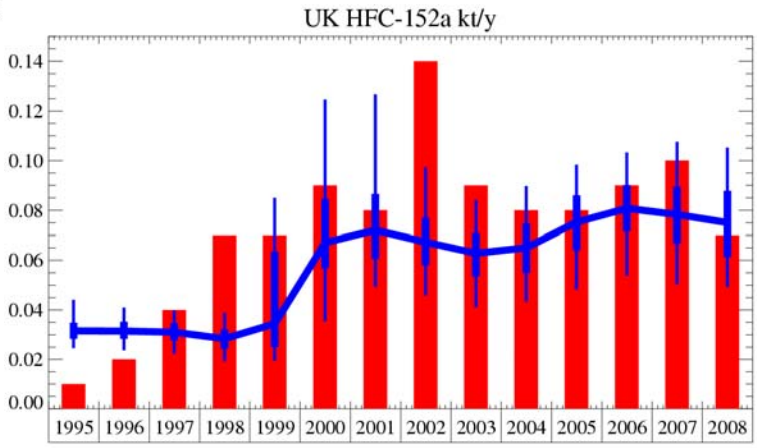


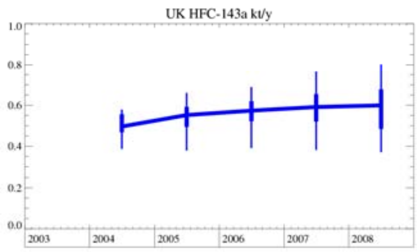
NAME-inversion estimates with uncertainty

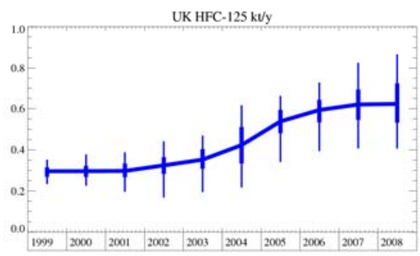
Inventory estimates (UNFCCC 2009)

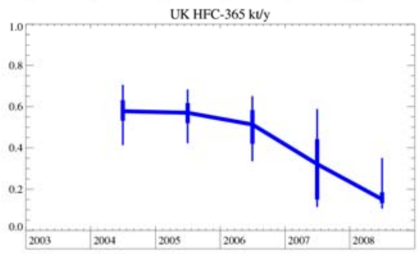
Other HFC emissions: UK

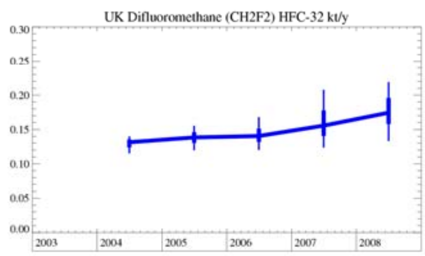
Met Office

NAME-inversion estimates with uncertainty









Conclusions

- Inversion models can be used to estimate regional emissions.
    - Compare with existing inventories.
    - Investigate compliance (verification).
- Important issues to consider:
    - Statistical measures, a priori knowledge, dispersion and meteorological models, location of measurement station, local emissions, observations data selection.
    - Uncertainty in methodology.
- More observations are needed to improve resolution and coverage of inversion models