National Physical Laboratory

Uncertainties in greenhouse gas emissions: accounting for covariance

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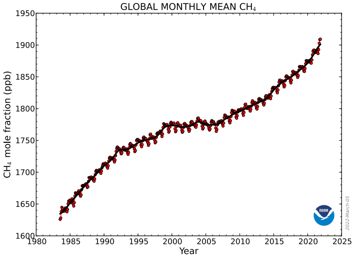
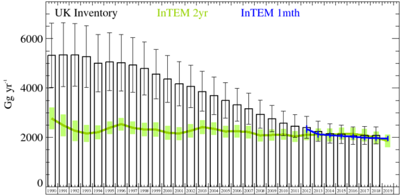
Measurement uncertainty in meteorology and climatology

Background

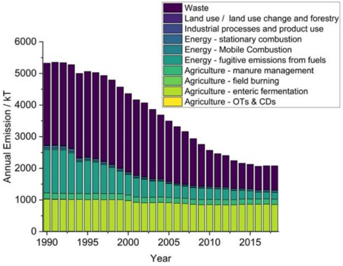
- NPL project: effect and management of error covariance structures in climate data records
- This work part of one case study in that project
- Other case studies include
  - Re-gridding: from data on source grids in different frames of reference to common grid to facilitate calculations of derived quantities
  - Sea-level rise data analysis from altimety (Emma Woolliams)
- Emphasize clear provision and communication of uncertainties (standard, expanded, relative, ...) and covariance/correlation matrices
- Concentrate on fundamentals

GHG CH_4 global and UK emissions





- DECC annual report 2020
- InTEM: UK Met Office's inversion modelling system



- Uncertainties highly relevant when estimating trends and accelerations
- Key factor: investigation of possible covariance

National GHG emissions' inventories

- Compiled according to IPCC Guidelines
- Each year updated to include latest data available
- Inventory includes the seven direct GHGs under the Kyoto Protocol:
  - Carbon dioxide (CO_2)
  - Methane (CH_4)
  - Nitrous oxide (N_2O)
  - Hydrofluorocarbons (HFCs)
  - Perfluorocarbons (PFCs)
  - Sulfur hexafluoride (SF_6)
  - Nitrogen trifluoride (NF_3)
- Three largest GHG contributors: CO_2, CH_4, N_2O
- Bulk of uncertainty from Agriculture, Land Use and Waste sectors
- CO_2, CH_4, N_2O contribute 86 % of the uncertainty in total inventory emissions

Bottom-up calculation of emissions

Total GHG emission for a given sector, geographic area and time period:

$$E = \sum_i F_i A_i G_i$$

F_i	emissions' factor for given pollutant from source category i
A_i	activity rate for source category i
G_i	100 year Global Warming Potential (GWP) to convert emissions of various gases to 'CO_2 equivalents (CO_2e)' GWP100 conversion factors: CO_2: 1 CH_4: 25 N_2O: 298

743 emission factors and $>$ 1700 emission sources

European and other countries moving towards metrological assessment of current uncertainty quantification including accounting for effect of correlated quantities

Critical review of current calculations

Agriculture sector data: contributions from use of two fuels

Activity rate data and emission factors with expanded uncertainties U (95 % confidence)

[UK National Atmospheric Emissions Inventory site]

No uncertainty attributed to the G_i (can 'add' it afterwards)

Fuel	Gas	$A/(\mathrm{TJ})$	$U(A)/\%$	$E/\mathrm{kt\,TJ}^{-1}$	$U(E)/\%$
Gas oil	CO_2	0.020 438	38.6	2.0438×10^{-2}	2.7
Gas oil	CH_4	0.020 438	1.6	3.5368×10^{-6}	80.0
Gas oil	N_2O	0.020 438	1.6	3.0984×10^{-6}	216.3
Petrol	CO_2	67.19	50.7	1.9127×10^{-2}	4.8654×10^{-5}
Petrol	CH_4	67.19	1.6	4.8654×10^{-5}	80.0
Petrol	N_2O	67.19	1.6	3.3578×10^{-7}	216.3

What do you notice?

Agriculture sector data

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Commonality: perceived correlation!

Further, question whether uncertainty attributed to the G_i can be ‘added’ afterwards

Uncertainty propagation under independence

Let $A_1, \ldots, A_6$ denote the activity rate data values and $F_1, \ldots, F_6$ the corresponding emissions' factors in the order given in table

Measurement model for total emissions: $$E = \sum_{i=1}^{6} E_i, \qquad E_i = A_i F_i G_i$$

Apply GUM (JCGM 100):
$$E = 4282\,\mathrm{kt\,CO_2e}$$
$$u(E) = 835\,\mathrm{kt\,CO_2e}$$
$$u_{\mathrm{rel}} = 19\,\%$$

Above assumes independent inputs

Dependence since two groups (red and blue) of 3 identical A_i (perceived common source)

How to cater for perceived common sources?

Accounting for perceived correlation associated with the A_i

Reparametrize $\implies$ change measurement model parametrically

A_1, A_2, A_3 identical numerically: suspect common origin — same quantity

Similarly for A_4, A_5, A_6

Replace A_1, A_2, A_3 by A_{GO} (GO = Gas Oil) and A_4, A_5, A_6 by A_{P} (P = Petrol) Apply GUM (JCGM 100):

Apply GUM (JCGM 100):

$$E = 4282\,\mathrm{kt\,CO_2e} \qquad \text{(as before)}$$
$$u(E) = 846\,\mathrm{kt\,CO_2e}$$
$$u_{\mathrm{rel}}(E) = 20\,\% \qquad \text{(negligible increase — was 19 %)}$$

Although increase very small, important principle here

Waste Incineration sector data

- Above approach repeated for Waste Incineration sector data
- Again, little change in $u(E)$ when accounting for correlation
- If result applied to all subsectors — and when subsectors combined to give total emissions — assumption of independence would be verified
- Difficulty in sourcing data with known provenance to say one way or other
- If, as above, various contributors provide parts of inventory, likely to be analyzed *independently*
- To make the point forcibly that covariance can make a difference, need instance where it makes meaningful change
- Examined influence of GWP100 factors, the G_i, making similar assumptions as above

Global warming potential (GWP)

Index defined as the cumulative radiative forcing between the present and a future time horizon caused by a unit mass of gas emitted now, expressed relative to that of CO_2

'The uncertainty of the GWP values for the six main GHGs is estimated to be $\pm 35\,\%$ for the $90\,\%$ confidence interval ($5\,\%$ to $95\,\%$ of the distribution)' [IPCC Fourth Assessment Report]

Under normality assumption, standard deviation of normal distribution characterized as above is $21.2\,\%$, taken as standard uncertainty associated with the GWP100 (100 y) conversion factors

IPCC notes the GWP uncertainty but seems not to take strong account of it

> *Companies that choose to quantify inventory uncertainty may include the uncertainty of GWP values in their calculations.* [World Resources Institute]

Waste incineration: simple calculation to quantify effect

Dominant contribution in waste incineration calculations is from CO_2

Replace the model used by one just involving CO_2, obtaining the emissions due to CO_2 as

$$E_{\mathrm{CO_2}\,e} = (F_1A_1 + F_2A_2)G \qquad \text{Correlation-based model}$$

$$E_{\mathrm{CO_2}\,e} = F_1A_1G_1 + F_2A_2G_2 \qquad \text{Correlation-free model}$$

F_1, F_2	chemical & clinical waste emissions' factors	Estimates, std. uncs. given
A_1, A_2	corresponding activity rates	
G, G_1, G_2	100 year GWP	

	$E_{\mathrm{CO_2}\,e}/\mathrm{kt}$	$u(E_{\mathrm{CO_2}\,e})/\mathrm{kt}$	$u_{\mathrm{rel}}(E_{\mathrm{CO_2}\,e})/\%$
Uncorrelated	245	47	19
Correlated	245	58	24

Makes a meaningful difference

Conclusions

- Carefully consider origins of data
- However, difficult to source *raw* data from reputable sources
- Look for commonalities, perceived correlations, ...
- Be transparent and state assumptions
- Fundamental principles of covariance and correlation in EMUE compendium http://empir.npl.co.uk/emue/wp-content/uploads/sites/49/2021/07/Compendium_M36.pdf
- Perceived correlation: $\boxed{E = (F_1A_1 + F_2A_2)G}$ versus $\boxed{E = F_1A_1G_1 + F_2A_2G_2}$
- Compare sum of quantities with equal uncertainties: quadrature and additive
- Use of multivariate LPU in matrix form (JCGM 102) simplifies computations
- Monte Carlo used to confirm calculations modulo involved uncertainties

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