Greenhouse gAs Uk and Global Emissions (GAUGE): Quantifying UK anthropogenic GHG emissions

GAUGE objective: Quantify UK GHG budget, in the context of European and global scales, to underpin the development of effective emission reduction policies.

Challenge: Development of a comprehensive, multi-year and interlinked measurement and data analysis programme.

http://www.greenhouse-gases.org.uk/

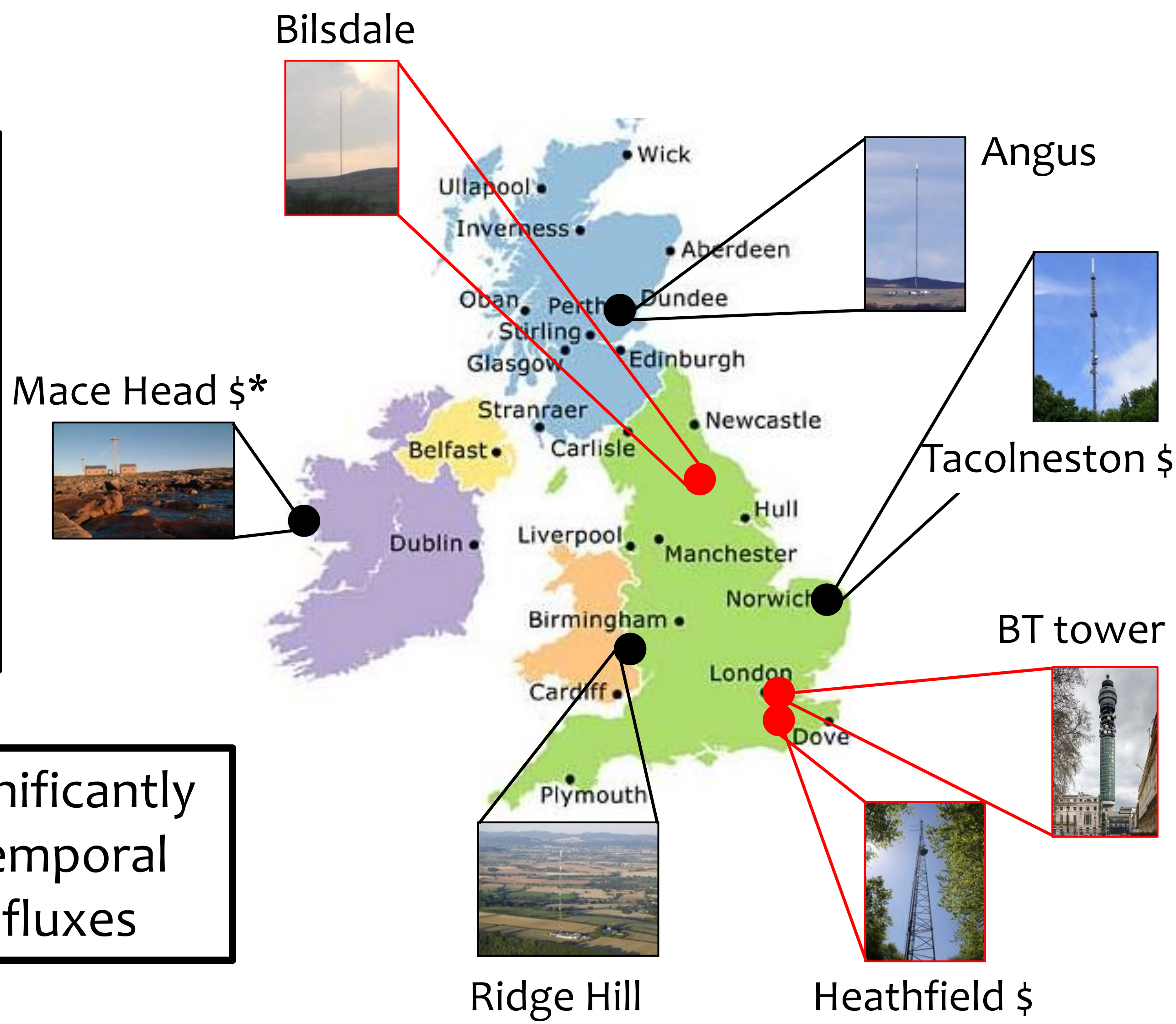
Tall towers: enhancing existing measurement network

DECC and GAUGE tall towers:

1) CO_2, CH_4, N_2O, CO + additional tracers

2) $ denotes ™3CH_4 and ⊗14C_{CO2}

3) * denotes N_2O isotopes



Enhanced network significantly improves the spatial/temporal resolution of the GHG fluxes

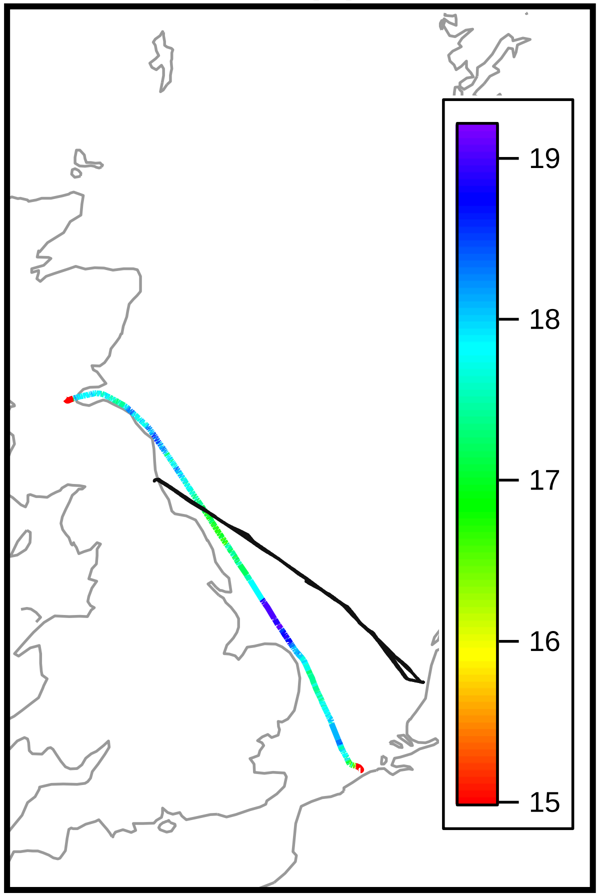
Aside: TT site at Divis, NI, run by Airbus Defence and Space/NPL since 9/13

Sampling UK outflow from the North Sea

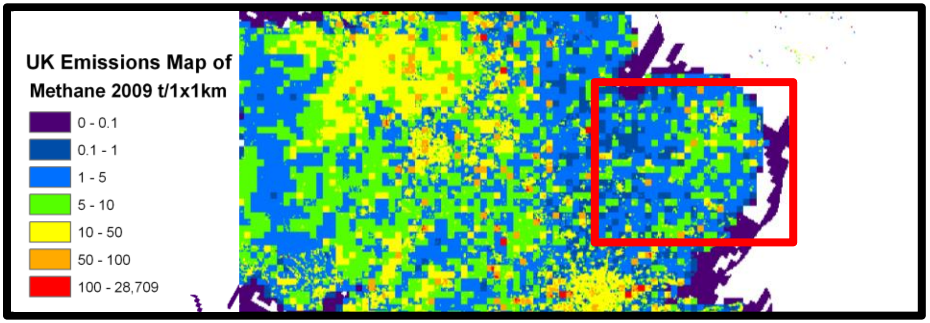
Rosyth to Zeebrugge freight vessel

Mobile laboratory in a shipping container

/100 ppb

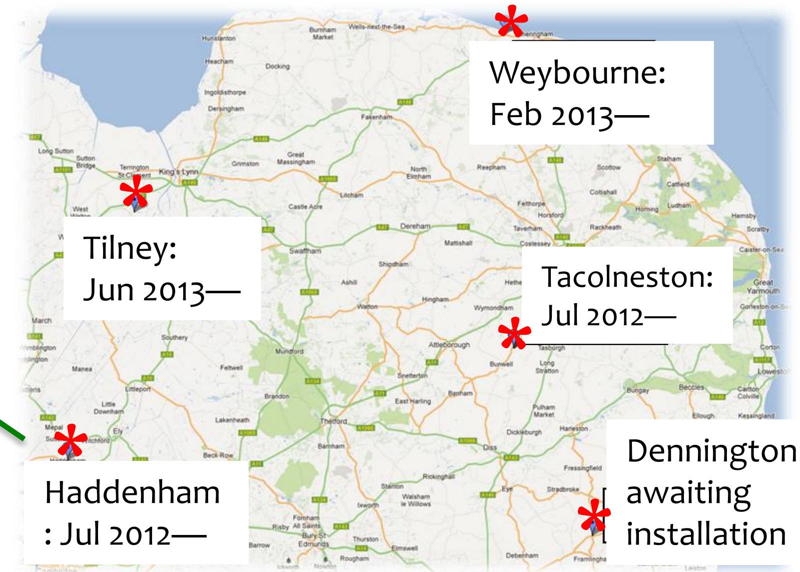


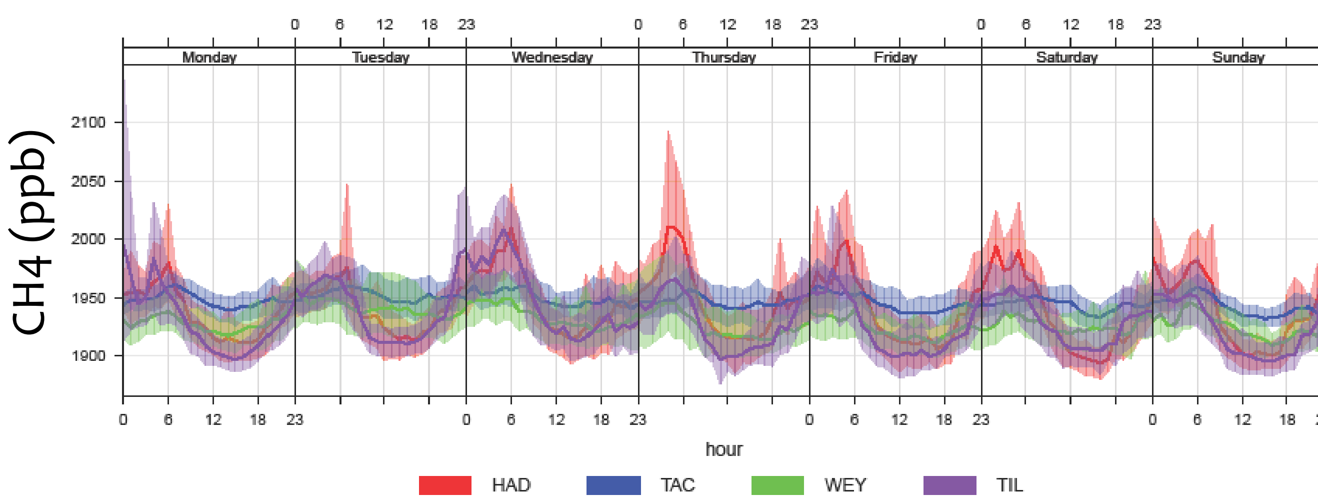
•Sails 6 times/week (23 hours) at different times.
•Provides continuous sampling of continental outflow over the North sea for 36 months.



Working with local communities: quantifying agricultural emissions of CH_4 and N_2O

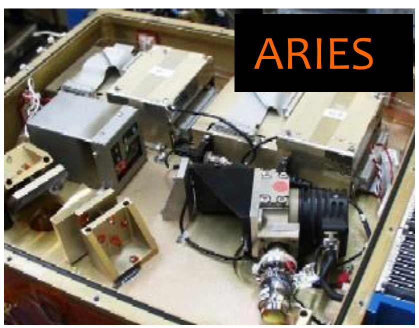
St Mary's Church, Haddenham

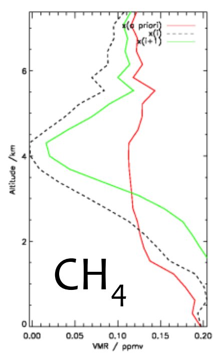




Using the UK research aircraft to linking across scales

UKMO remote sensing instrument



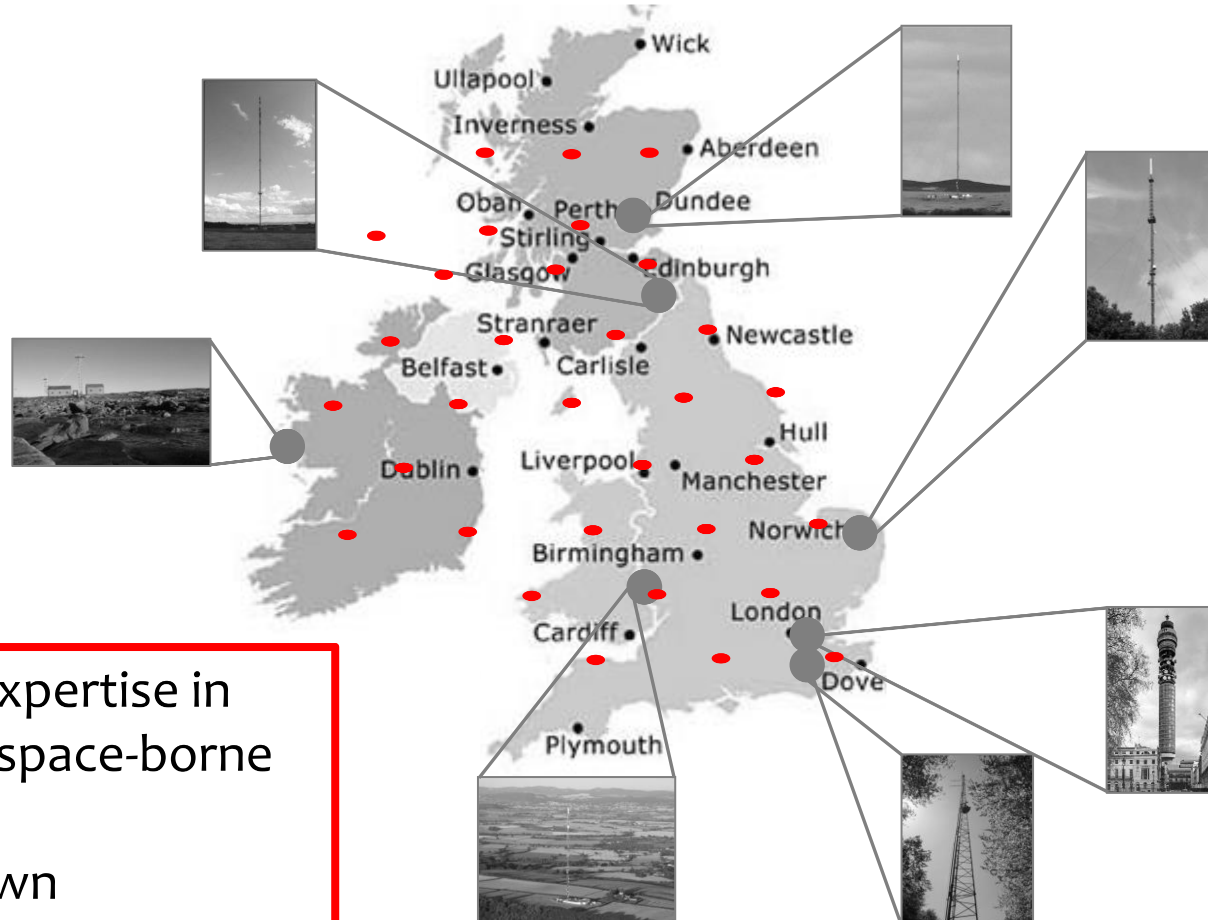


Links across spatial scales, measurement platforms, and validate satellites

- Campaign mode: summer (2014 and/or 2015, ~60 hours)
- Piggyback mode on FAAM flights (~200 hrs/yr)

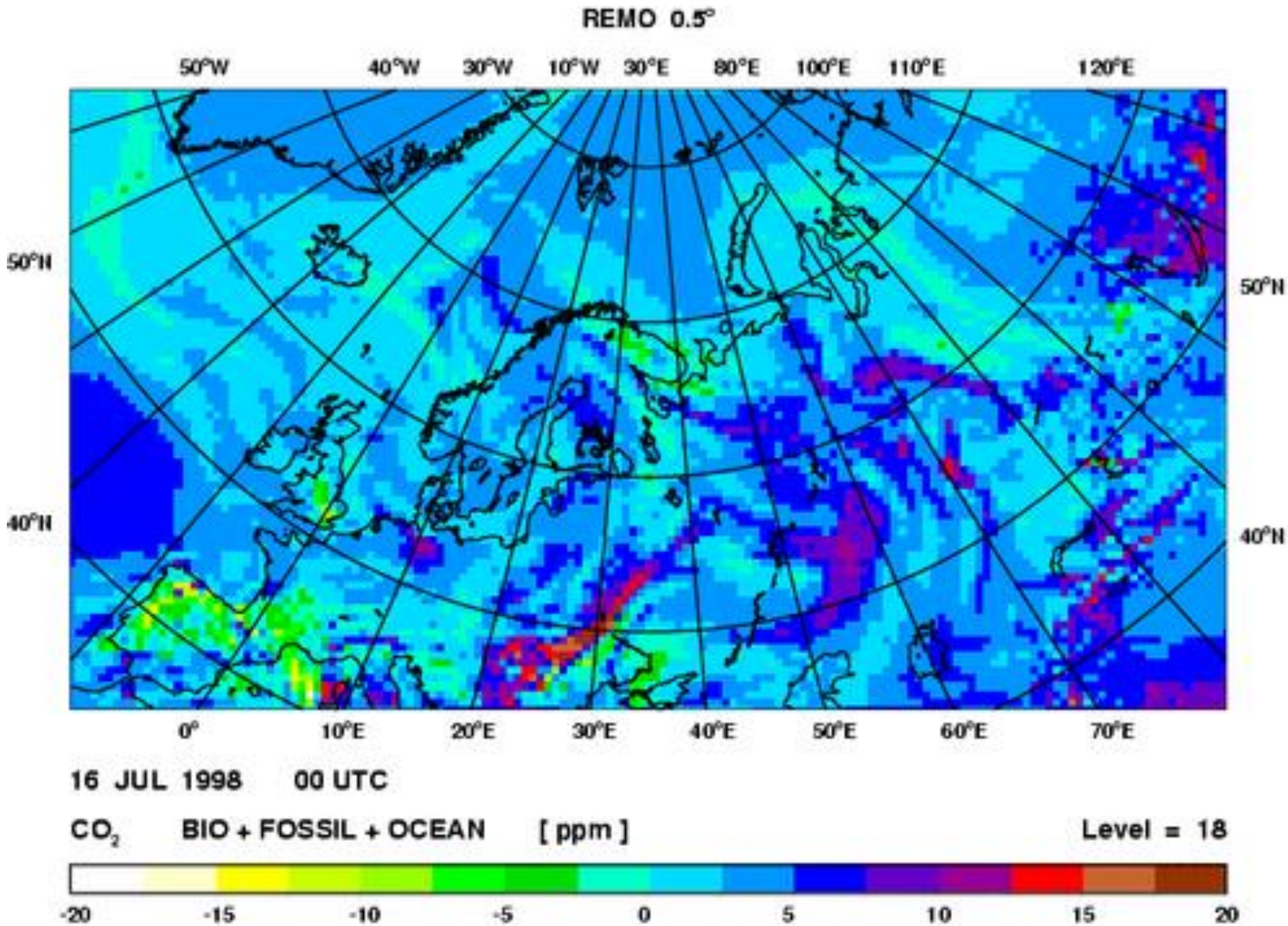
Space-borne data links UK work to larger scales

Using NASA, ESA, and Japanese instruments



- Exploiting existing NERC expertise in retrieving and interpreting space-borne data
- Global, continuous top-down constraints.
- GAUGE is developing UK-specific products (e.g., partial cloudy retrievals.)

The signals

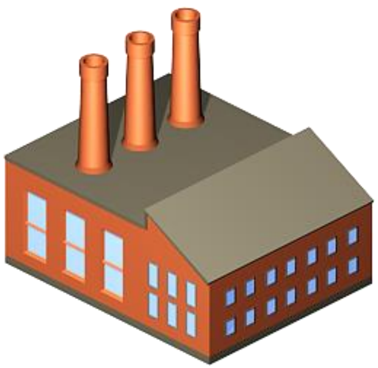


Courtesy U. Karstens / M. Heimann

Synthesis- 3 approaches

First (standard) approach

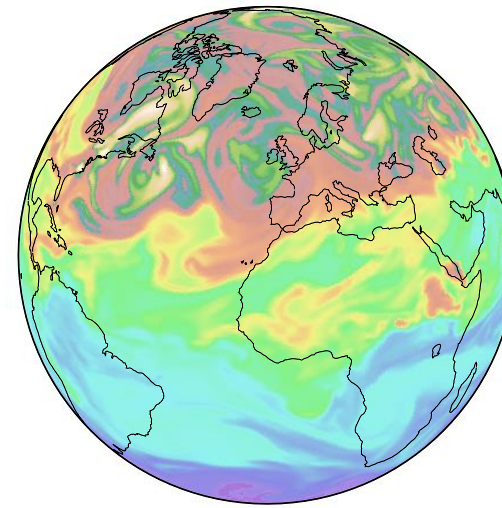
Fluxes

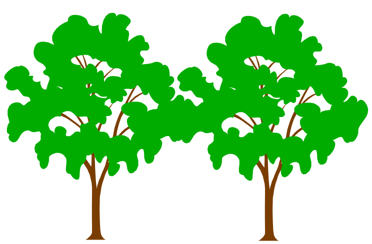


Prior flux estimates

Atmospheric transport model

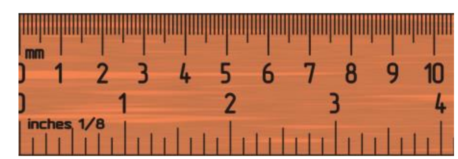
4-D atmospheric concentrations





“inverse” model

$$P(A \mid B) = \frac{P(B \mid A)P(A)}{P(B)}$$

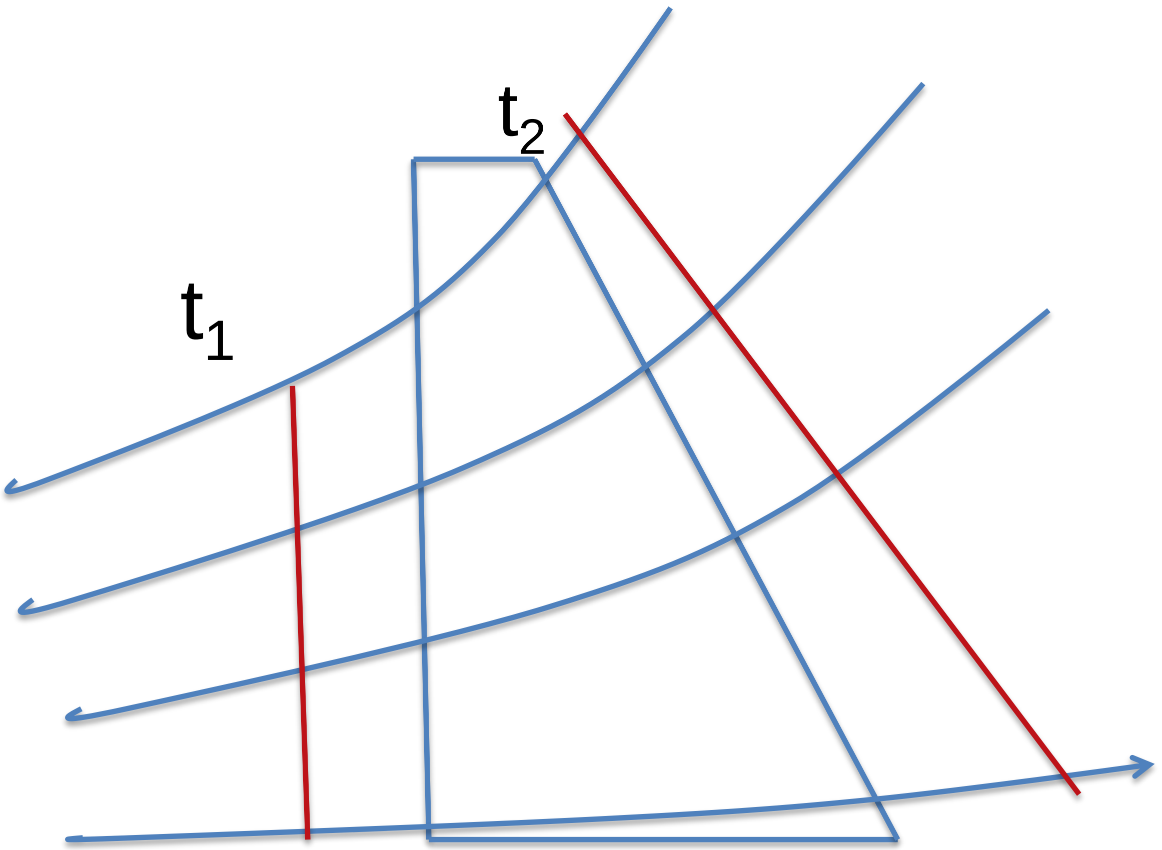


Posterior flux estimates

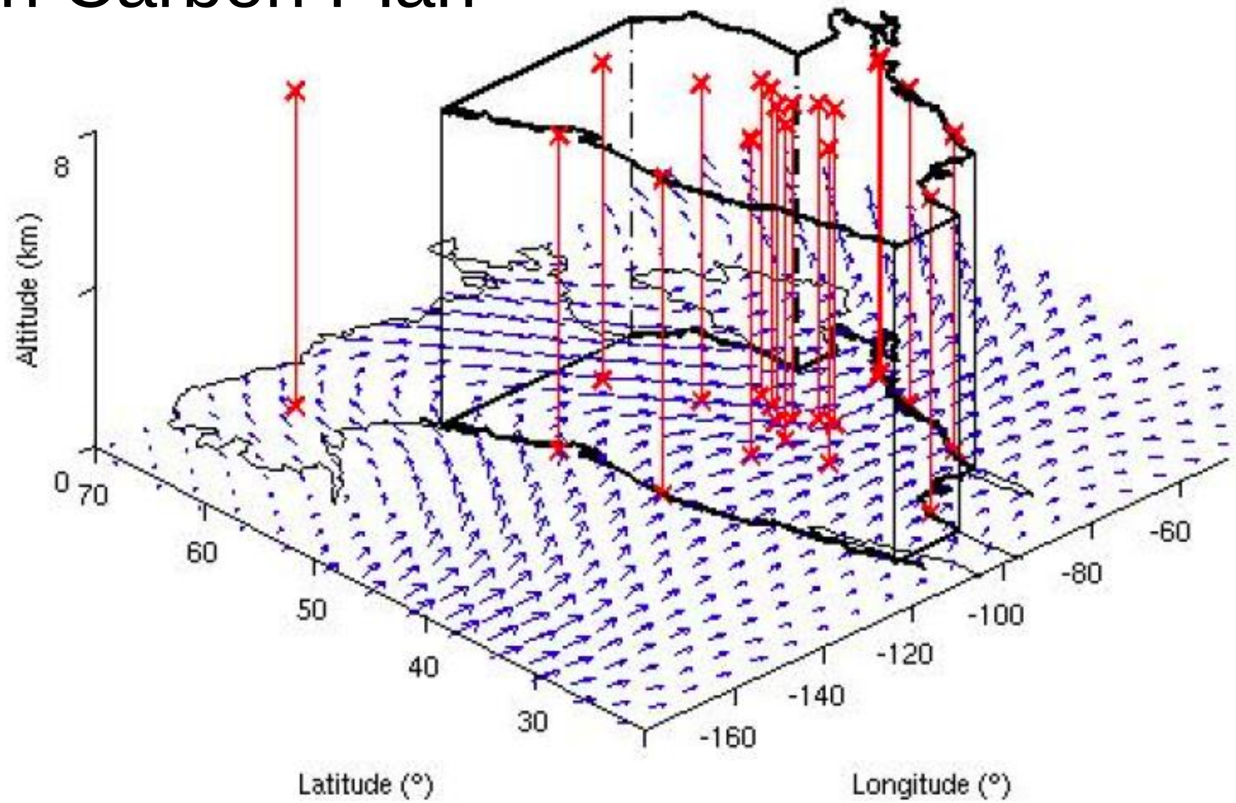
Ensemble Kalman Filter with a 3-month lag window

Measurement and uncertainties

Second Approach: Lagrangian mass balance (e.g. STILT, Gerbig, Lin, Wofsy)



Third approach: Eulerian Budget – example North American Carbon Plan

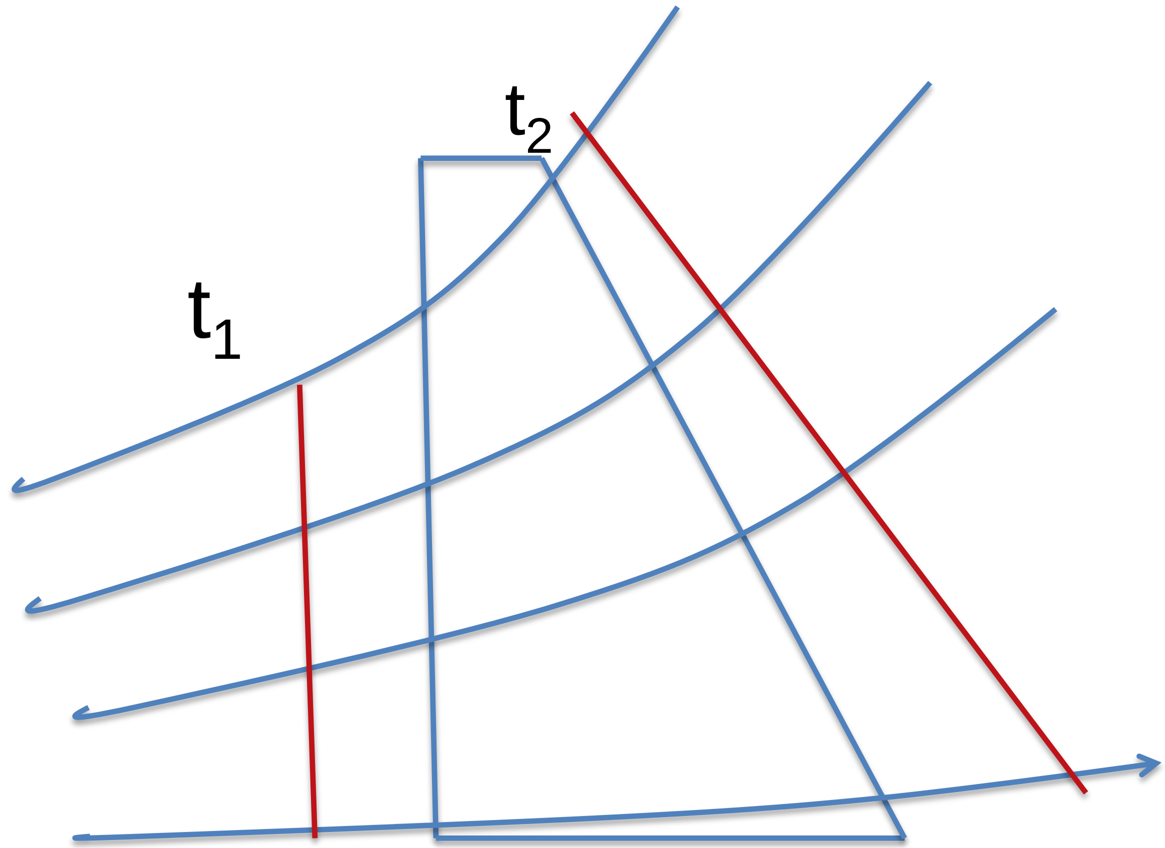


Method

$$\left.\frac{\partial C}{\partial t}\right|_V = \frac{\partial}{\partial t}\iiint_V \rho\chi dV = -\iint_S \rho\chi \mathbf{u}.\mathbf{n} dS + \left.\frac{\partial C}{\partial t}\right|_{vertical} + F_{surf}$$

Need to interpolate concentration field -> e.g. Kriging

Signals



$$f \approx \frac{m_C}{m_{air}} \frac{\int_{surface}^{12\,km} \rho_{air}\left(c_{CO_2}(t_2) - c_{CO_2}(t_1)\right)dz}{\Delta t} \quad (kgC\; m^{-2}\; s^{-1})$$

Currently UK annual fossil fuel emissions are approximately 0.13 PgC yr^{-1}

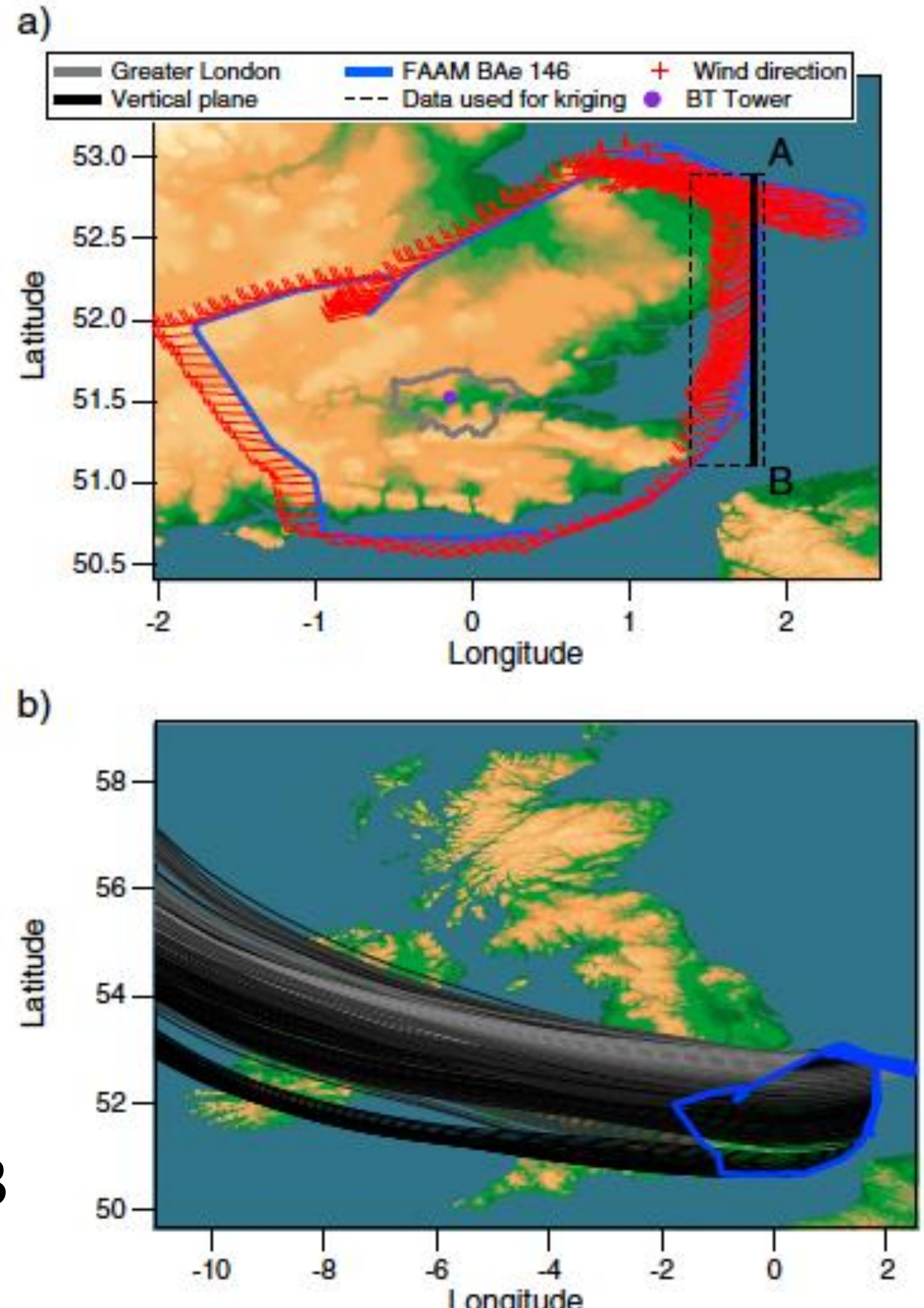
Consider Southern UK: area a, is on the order of 50’000 km^2 and assume air travel time from West to East coast ~ 0.5 d. The fossil flux from this region then causes approximately a signal of

$$dc_{CO2,FF} \text{ » } 4\,ppm$$

For estimation of fossil fuel emissions accuracy of measurements is thus NOT the main obstacle

This is not true in global inversions – because areas involved are much larger and signals smaller

Grant Allan and his team from Manchester University and FAAM (NERC) research airplane



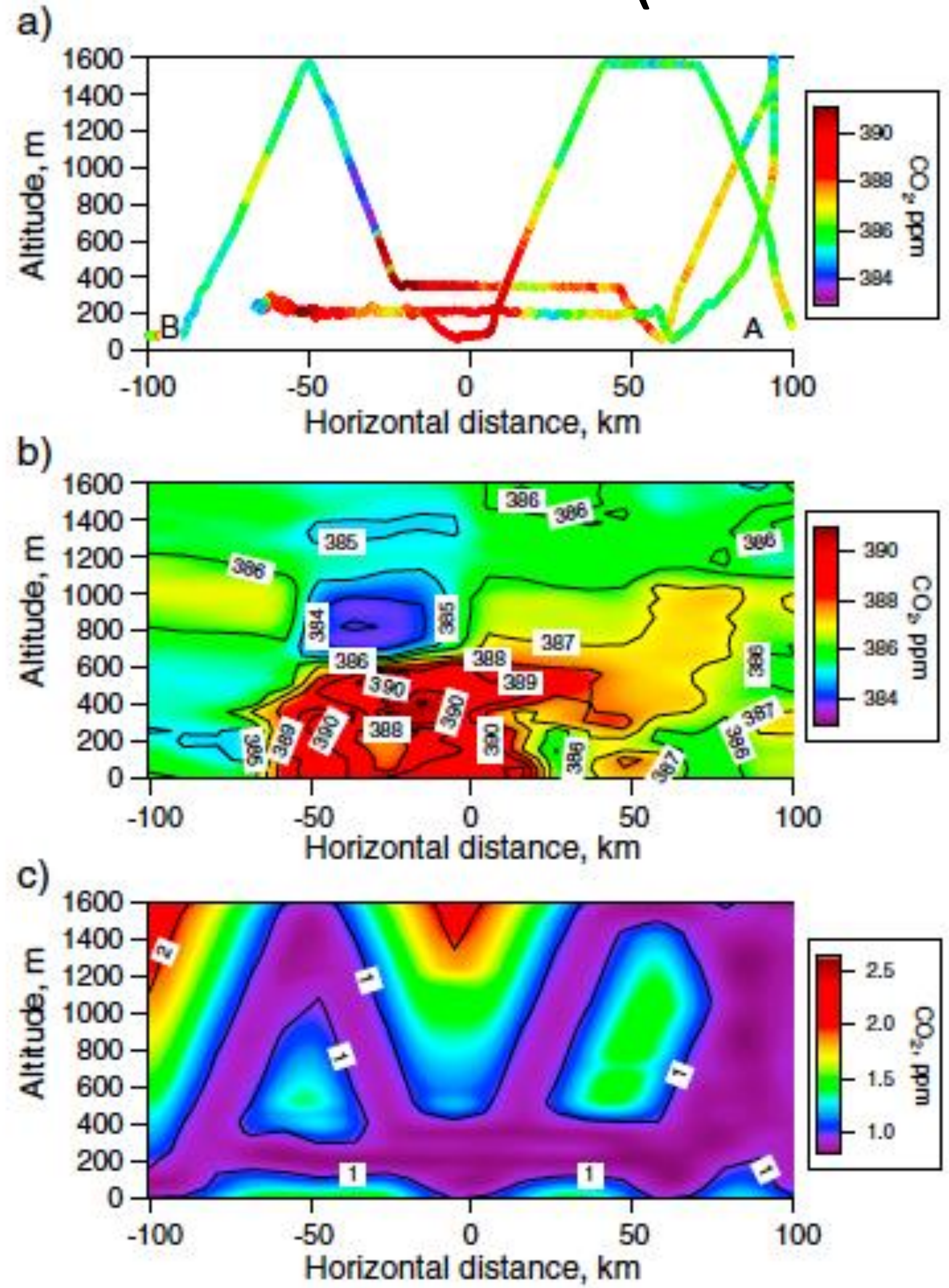
O'Shea et al., JGR 2013

CO_2 measurements downwind of London (Plane A-B)

In-situ measurements

Data interpolated using Kriging

Uncertainties



Inter-calibration

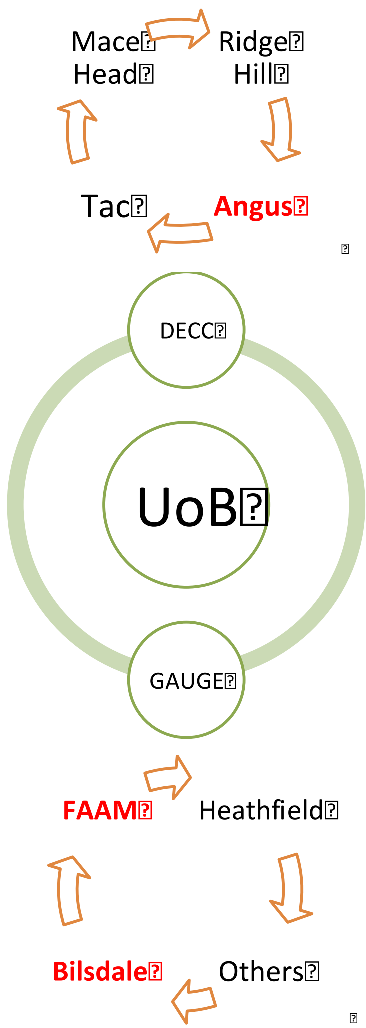
Based on round-robins to all labs and sites

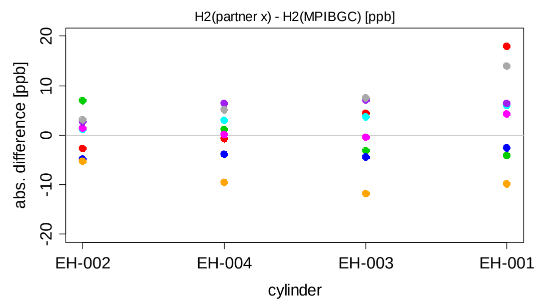
Issues:

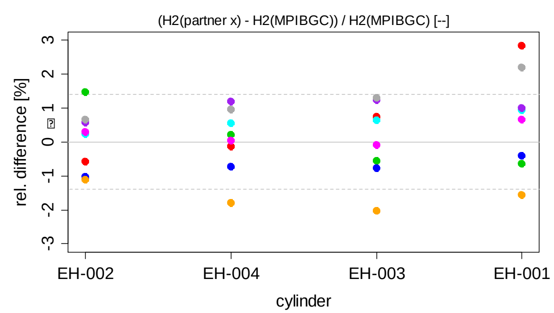
- Takes quite a while to get certified gas tanks from providers
- For global inverse modelling small errors in measurements leads to large errors (order of 1PgC ppm^{-1})

synthetic gas maybe problematic – very careful anchoring with NOAA needed

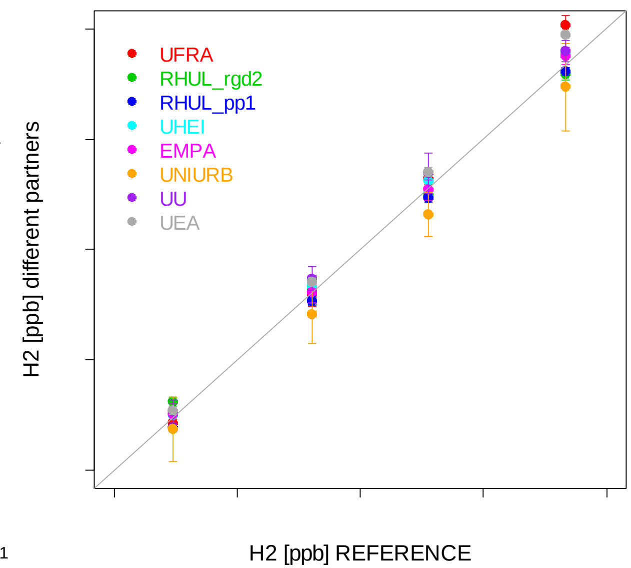
Round robin circulation







Distribute 3 cylinders (calibrated at Max Plank, Jena)

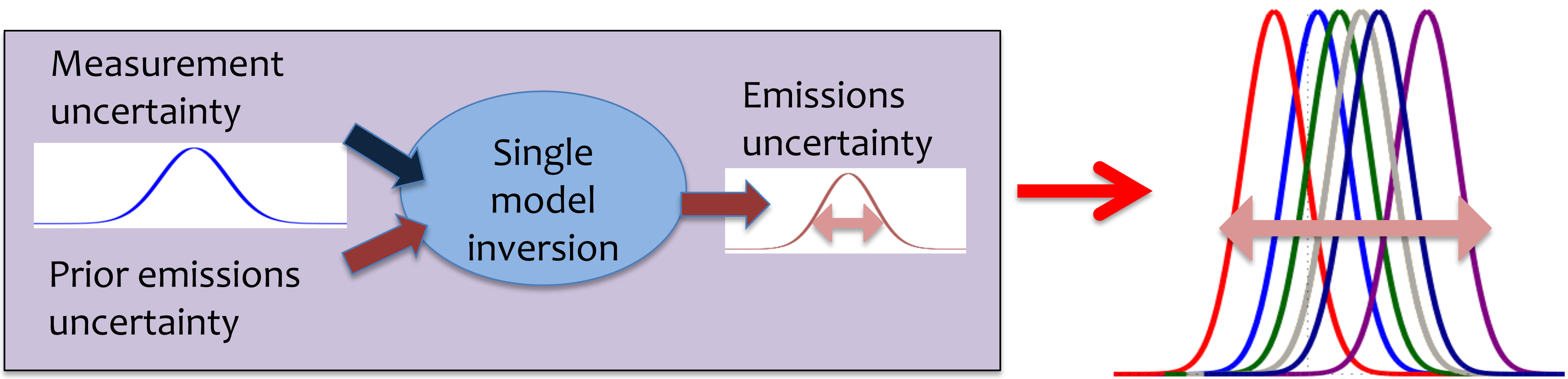


NPL tank comparison

	NPL	Bilsdale Picarro	Δ%
CO2	400.68 ± 0.40 ppm	400.45 ± 0.01 ppm	0.06
CH4	1804.20 ± 1.80 ppb	1802.30 ± 1.20 ppb	0.10

NPL provided a reference gas mixture (CO_2 and CH_4 in synthetic air)

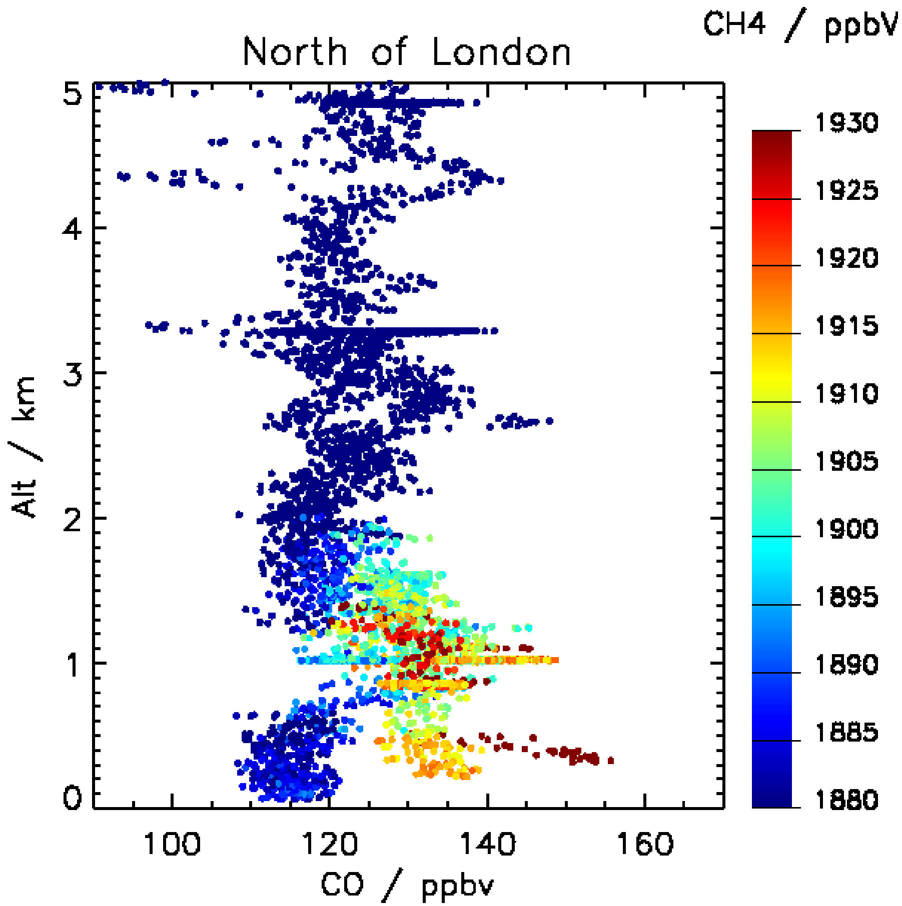
GAUGE will deliver robust regional flux estimates of CO_2, CH_4 and N_2O

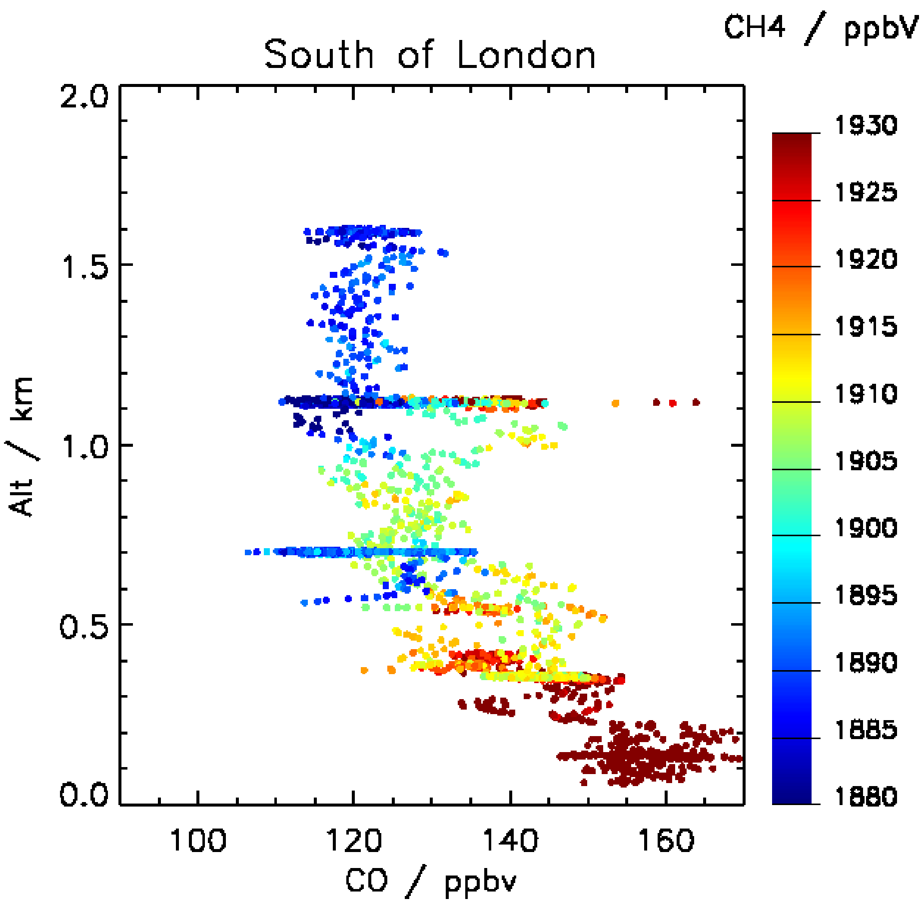


Ensemble of emission estimates provides better estimates uncertainty

- Different transport models
- Different methods to infer the fluxes
- This approach will lead to more robust results
- Regional emission estimates and uncertainties will be freely available

B725 – 9 August 2012 – polluted case





- Urban increment CO of 40 ppbv in PBL,
- 50 ppbv CH4

Courtesy G. Allan

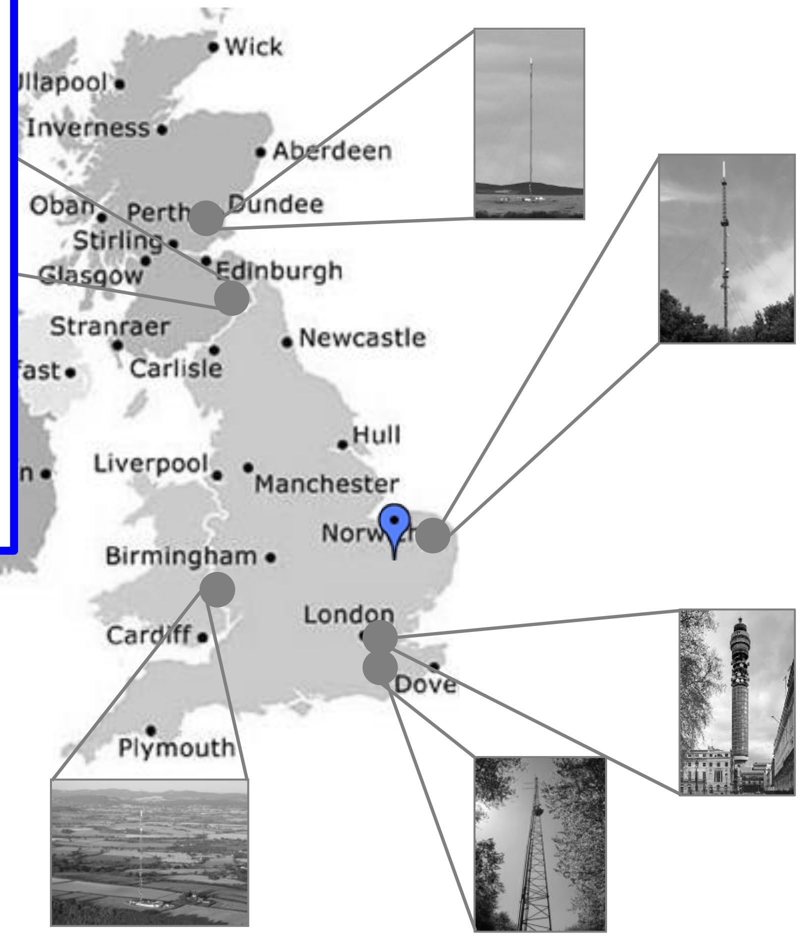
Testing emerging technologies for measuring GHGs

- CO_2/CO sondes
- mobile FTS (CO_2, CH_4, N_2O, CO, $^{13TM}C_{CO_2}$)

•A laser instrument ($^{13TM}C_{CO_2}$)

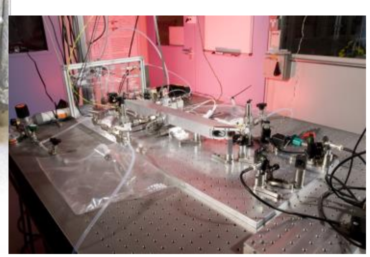
Inter calibrated with more established instruments.

Developing post-2016 measurement activities.

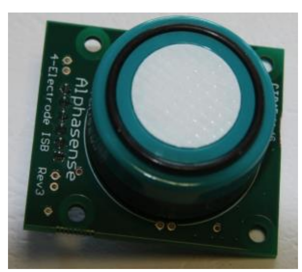


Mobile FTS

RAL laser system



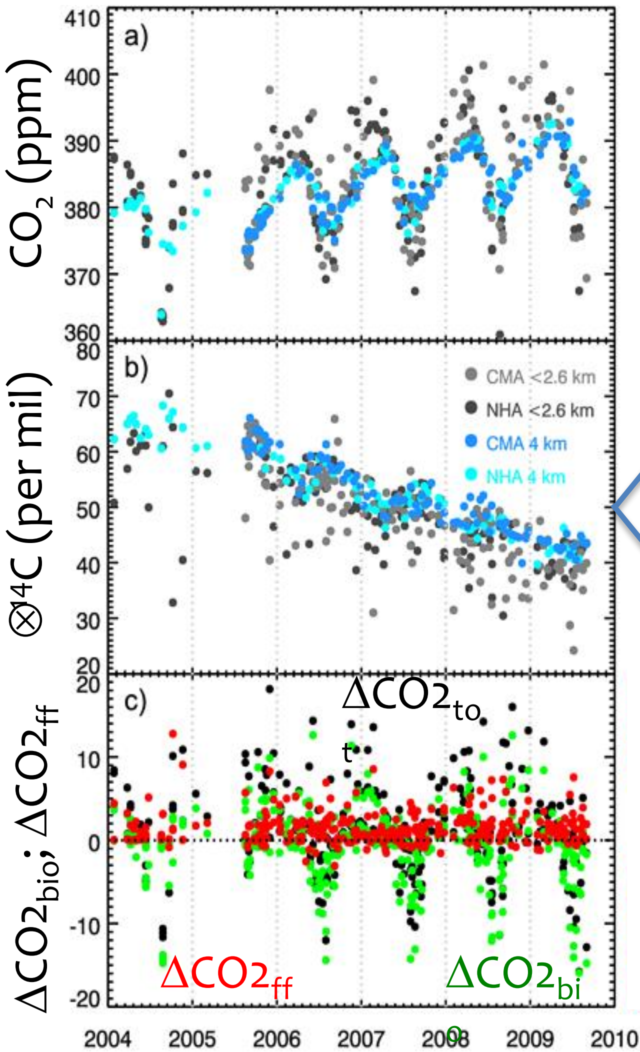
CO_2 sondes



Isotopes helps to identify the source of GHGs from fossil fuels

Samples: ™13CH$_4$, ⊗14CO$_2$; Sensors: N$_2$O (™15N, ™18O, dalpha-15N), 13™C$_{CO2}$

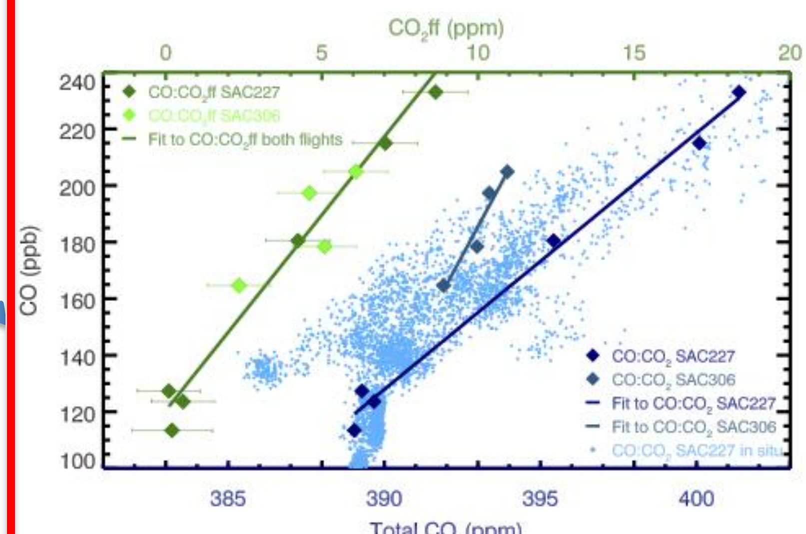
E.g., ⊗14C



Miller et al, JGR, 2012

Exploit observed relationships between CO$_2$ and ⊗14C in a Bayesian inference scheme to estimate anthropogenic CO$_2$ emissions

"Calibrate" CO/CO$_2$ff to estimate anthropogenic CO$_2$ emissions from GAUGE CO measurements



Turnbull et al, ACP, 2011

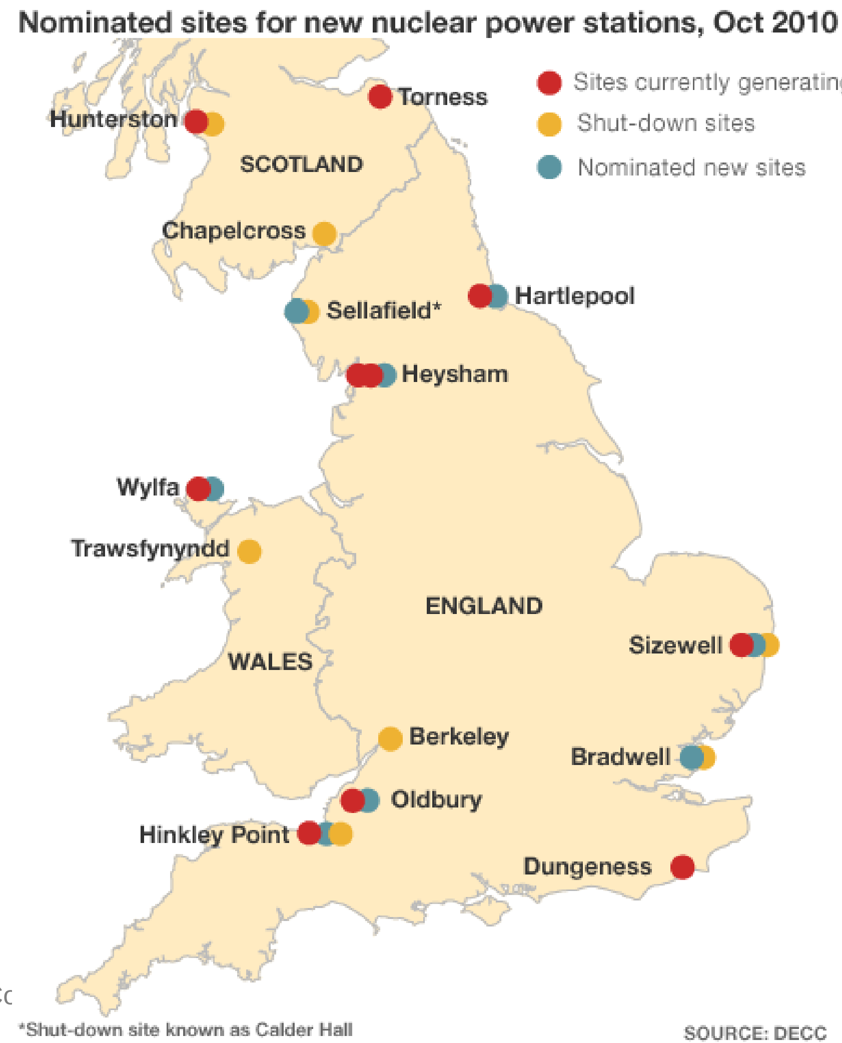
NOAA Isotopes

Compound	Facility	Precision	Cost/sample (£ total)	Estimate number of samples	Sample Turnaround time
$\Delta^{14}C_{CO2}$ (‰)	INSTARR	±1.8	$250 (£80,000)	500	1-2 weeks
$\delta^{13}C_{CH4}$ (‰)	INSTARR	±0.04	$100 (£23,680)	500*	1 month
$\delta^{13}C_{CO2}$ (‰)	INSTARR	±0.01	$50 (£11,840)	500*	1 month
$\delta^{18}O_{CO2}$ (‰)	INSTARR	±0.03		500*	1 month
CO_2 (ppm)	MAGICC	±0.03	$90(£21,312)	500*	1-2 weeks
CH_4 (ppb)	MAGICC	±1.2			
CO (ppb)	MAGICC	±0.3			
SF_6 (ppt)	MAGICC	±0.03			
H_2 (ppb)	MAGICC	±0.4			
N_2O (ppb)	MAGICC	±0.4			

GAUGE ⊗$^{14}CO_2$ Isotopes

Sampling strategies:

- Mace head and Tacolneston TTs
- BAe-146 (profiles) and downwind of Sellafield reprocessing plant
- Other reprocessing plants compromise surface measurements?



Assuming a systematic bias δ$X_{CO2=}$in X_{CO2} causes a difference δf in the flux estimate of

$$d f = \frac{m_C}{m_{air}} \frac{\int_{surface}^{12\,km} r_{air}\, dc_{CO_2}\, dz}{Dt}$$

Assuming a travel time of 0.5 days for the air-parcel and an exponentially declining air density profile with scale height H=10km, we obtain

$$\frac{d f}{dc_{CO2}} » 30 gCm^{-2} yr^{-1} ppm^{-1}$$

Assuming a systematic bias $\delta X_{CO2=}$in X_{CO2} causes a difference δf in the flux estimate of

$$\delta f = \frac{m_C}{m_{air}} \frac{\int_{surface}^{12\,km} \rho_{air}\, \delta c_{CO_2}\, dz}{\Delta t}$$

Assuming a travel time of 4 days for the air-parcel and an exponentially declining air density profile with scale height H=10km, we obtain

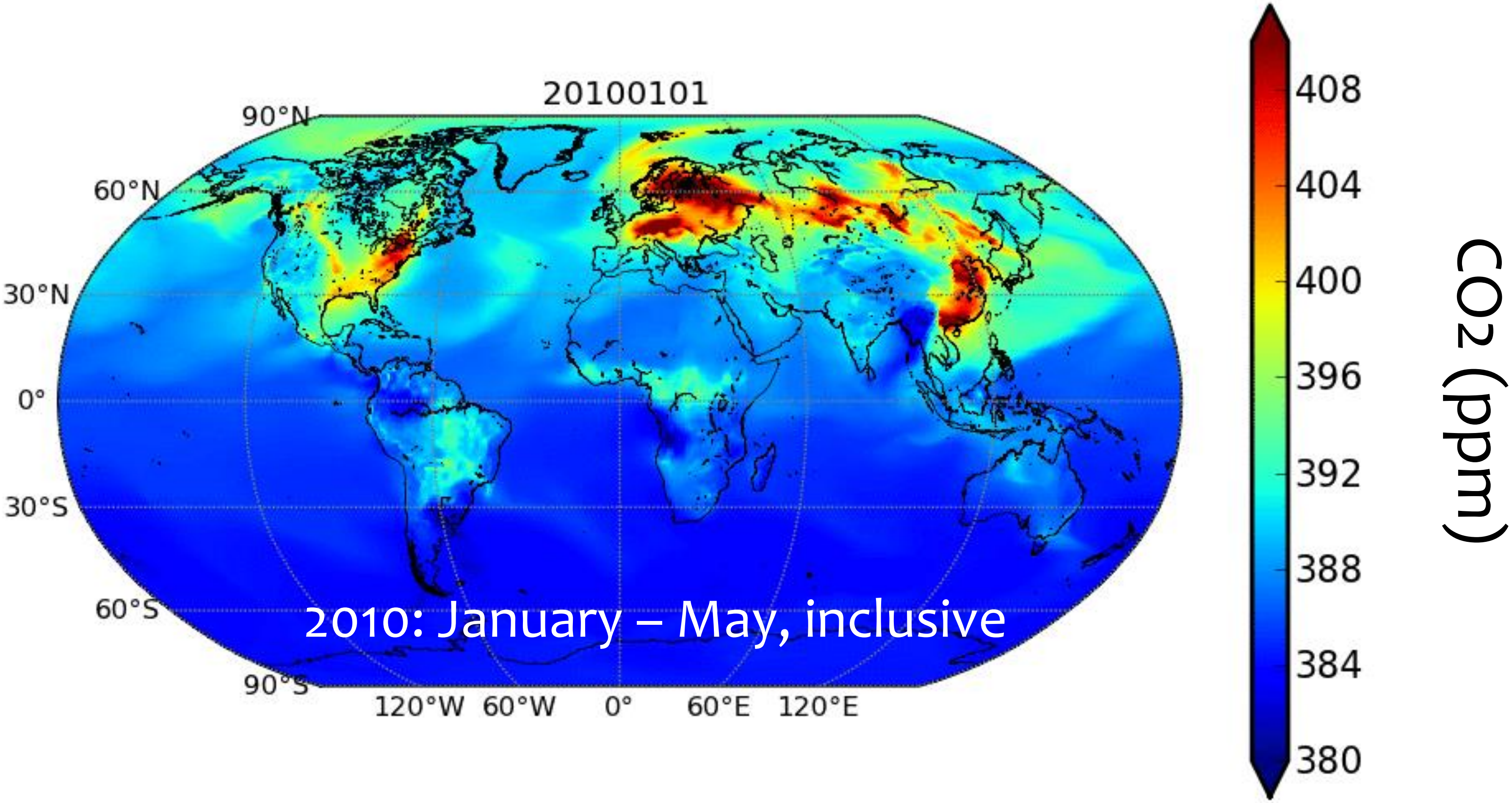
$$\frac{\delta f}{\delta c_{CO2}} \approx 250\, gC m^{-2} yr^{-1} ppm^{-1}$$

For Rio Branco the region of influence, a, is on the order of 50’000 km^2. The change in the flux F=a*f estimated for this region is

$$\frac{dF}{dc_{CO2}} \text{»} \frac{1 * PgCyr^{-1}}{1ppm}$$

Currently annual fossil fuel emissions are approximately 9 PgC yr^{-1}
The global land vegetation sink is approximately 2 PgC yr^{-1}

Using numerical models to integrate data



- Use prior information for emission inventories
- Model can help attribute observed variability to sources and regions
- We sample the model as observed by a particular instrument.

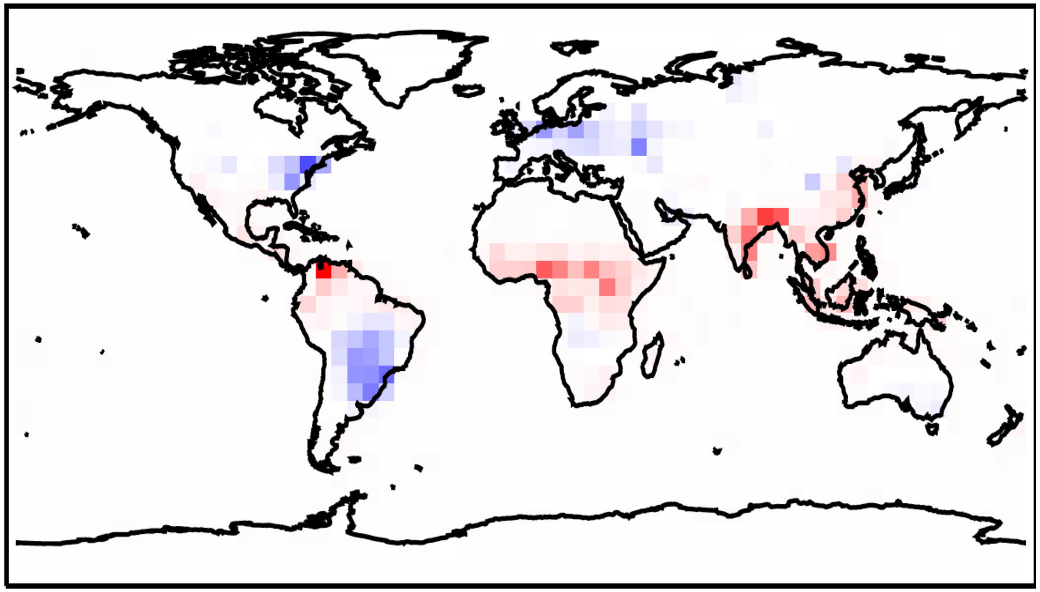
Leeds – two/three possible (planned) GHG flux estimation approaches

1. 4D Var system – inversion of atmospheric transport - global
2. Eulerian mass balance
3. Lagrangian balances of FAAM aircraft

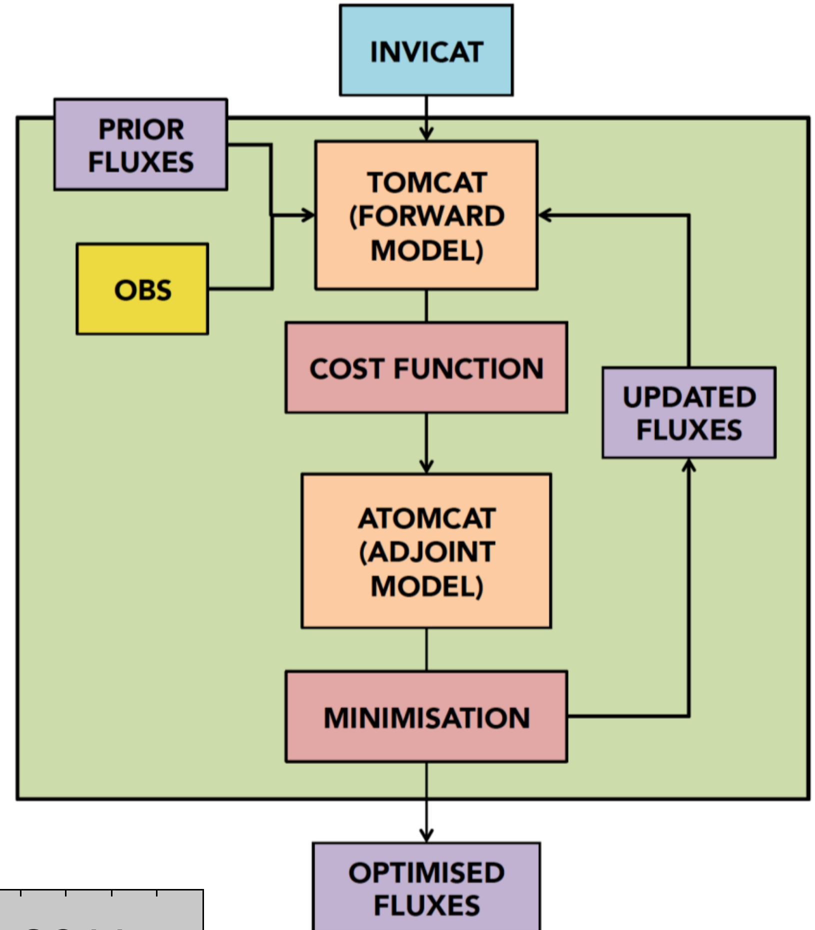
Leeds– focus CH_4 (but flexible)

Inverse modelling in TOMCAT

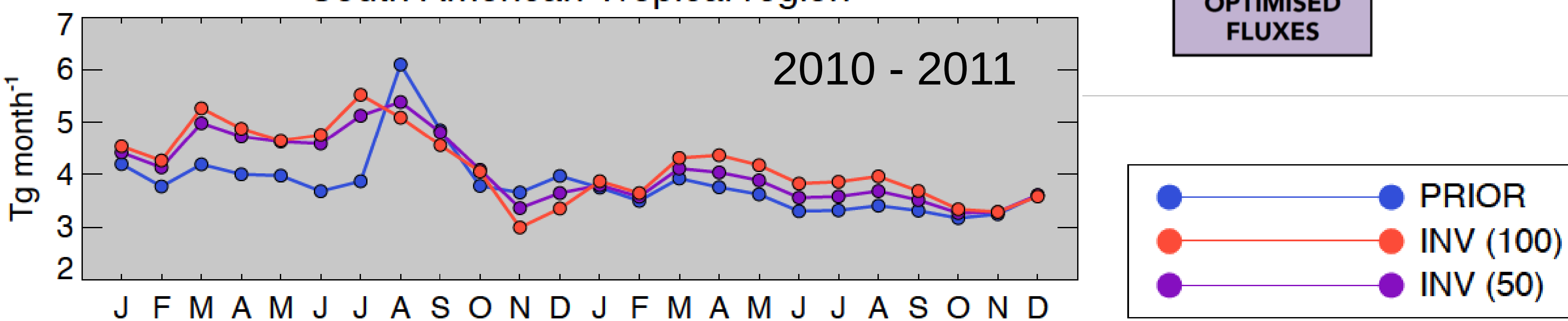
Change in CH_4 fluxes (post – prior)



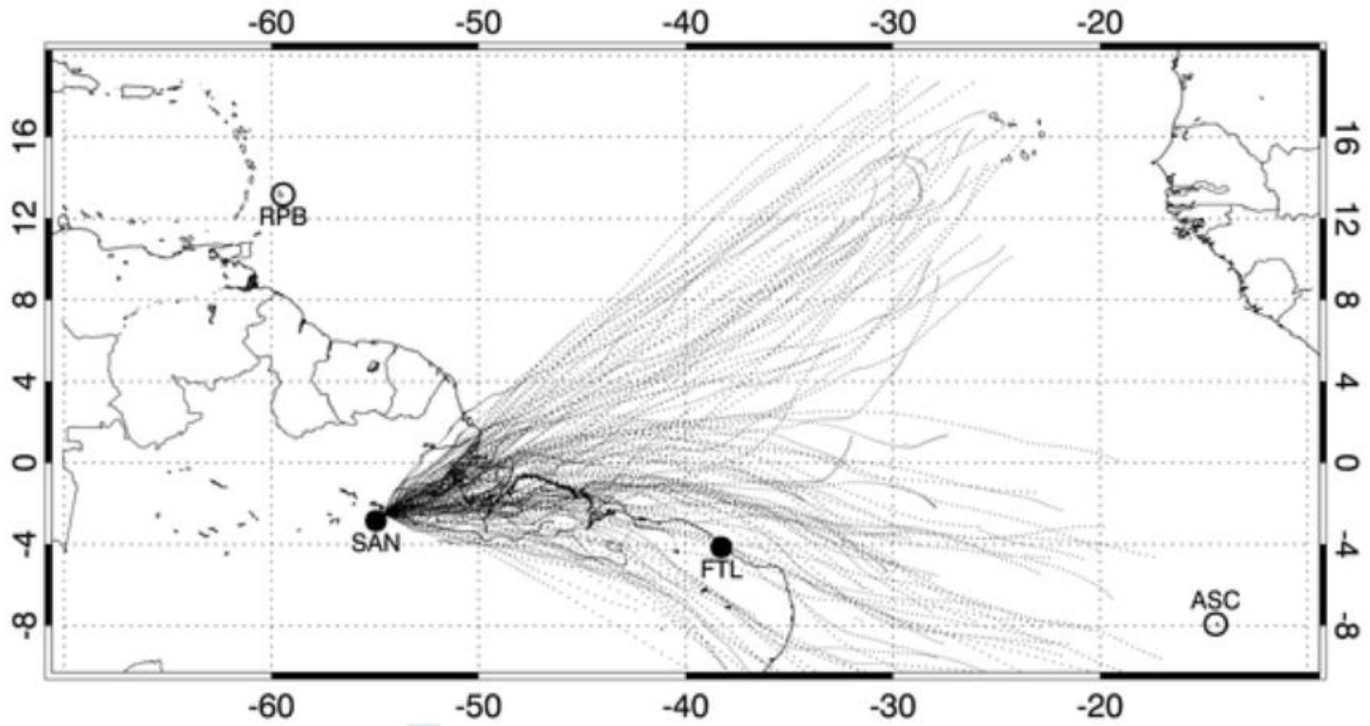
4D-Var inverse model (INVICAT)



South American Tropical region



Signal to noise – Carbon flux estimation

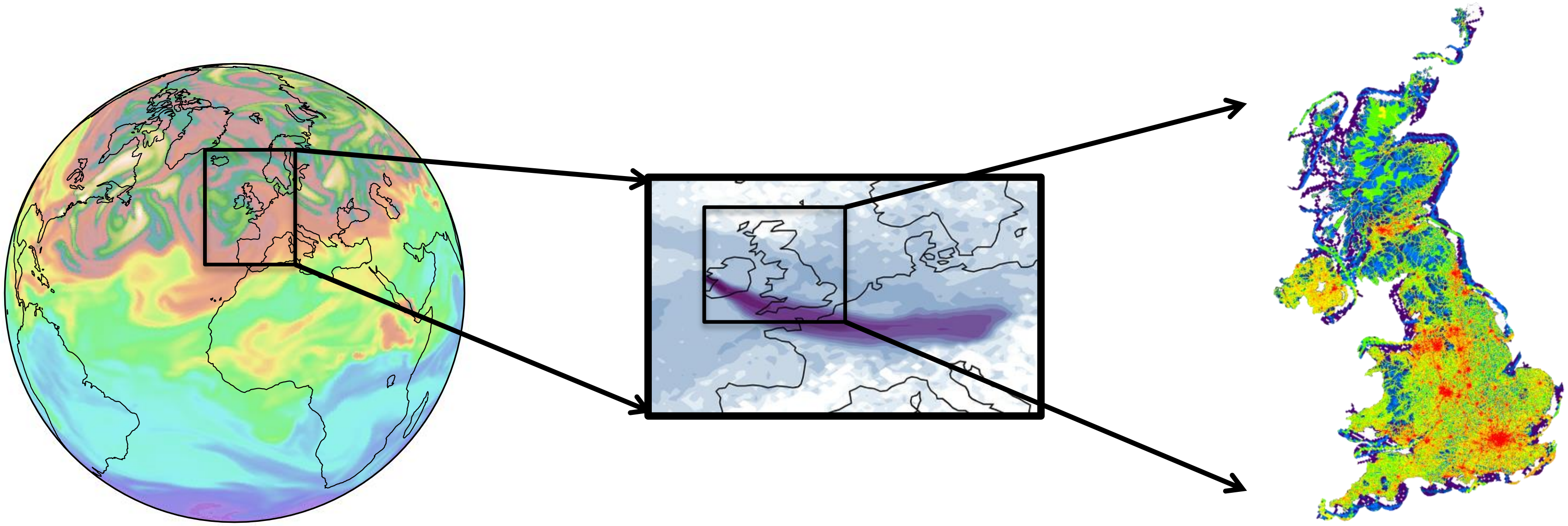


$$f \approx \frac{m_C}{m_{air}} \frac{\int_{surface}^{12\,km} \rho_{air} (c_{CO_2,site} - c_{CO_2,Atl.Coast}\, dz)}{\Delta t} \quad (kgC\ m^{-2}\ s^{-1})$$

Assuming a travel time of 0.5 days for the air-parcel and an exponentially declining air density profile with scale height H=10km, we obtain

$$\frac{f}{Dc_{CO2}} \approx 30\,gCm^{-2}yr^{-1}ppm^{-1}$$

Using different models to address different scales

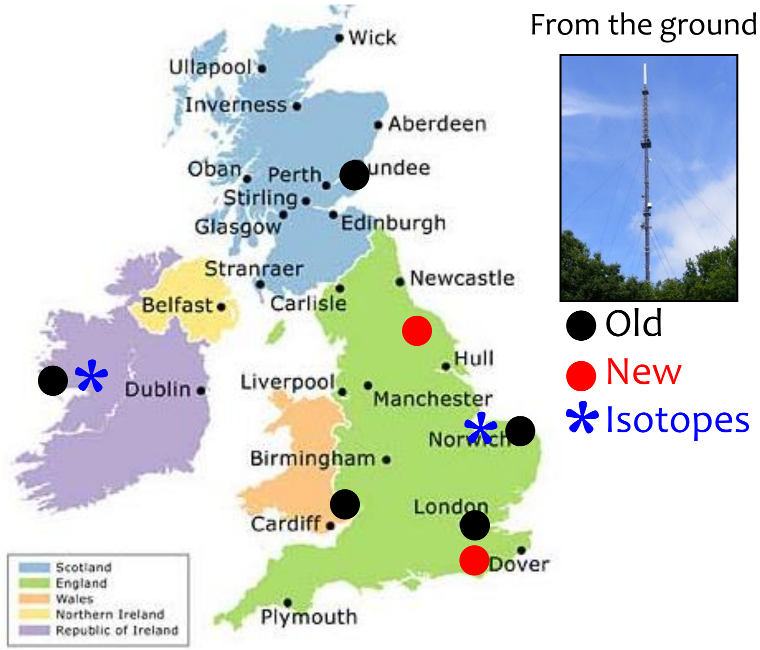


1,000 km | 100 km | 10 km | 1 km

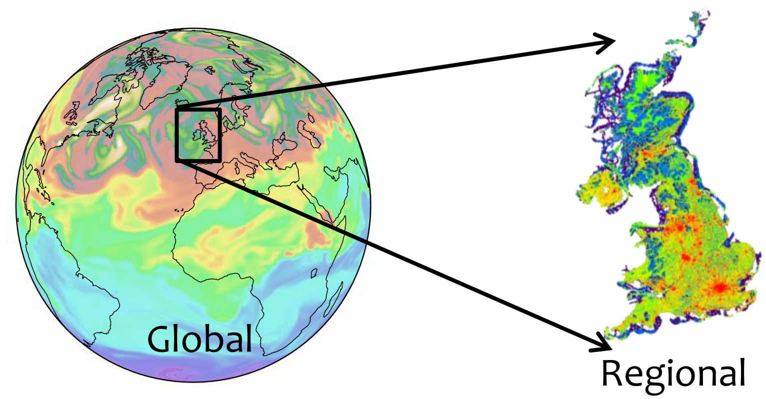
Satellites | Tall towers | Aircraft | Ship | Regional intensive | BT tower

Greenhouse gAs Uk and Global Emissions (GAUGE): Quantifying UK anthropogenic GHG emissions

Inter-calibrated atmospheric GHG measurements

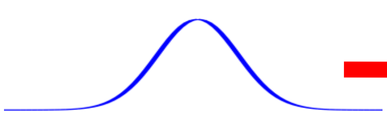


Cutting-edge models of atmospheric transport



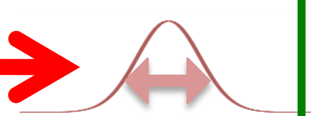
Using the world-class meteorological analyses and the latest prior emission inventories

Estimating posterior emissions by combining measurements and models



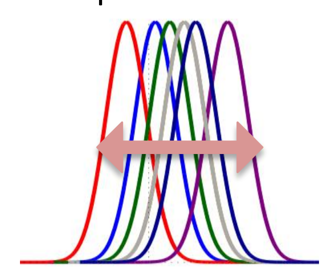
Inputs: 1) Measurements and uncertainty and 2) prior emissions uncertainty

Single model inversion



Output: Posterior emission estimates and uncertainty

Facilitating better decisions: ensemble of emissions estimates provide uncertainty



$$\frac{dc_{CO2}}{dF} \approx \frac{100\,ppm}{PgCyr^{-1}}$$

$$\frac{dF}{dc_{CO2}} \approx 1PgCyr^{-1}ppm^{-1}$$

$$dc_{CO2,FF} \approx 4\,ppm$$

Currently UK annual fossil fuel emissions are approximately 0.13 PgC yr^{-1}

Consider Southern UK: area a, is on the order of 50’000 km^2. The fossil flux F=a*f estimated for this region is thus

$$\frac{dF}{dc_{CO2}} \text{»} \frac{0.01 * PgCyr^{-1}}{1ppm}$$

thus for this region the fossil fuel signal is

$$dc_{CO2,FF} \text{»} 4\,ppm$$

GAUGE: integration into international activities

UK/European Collaborators

- Natural Environment Research Council
- National Centre for Atmospheric Science – Natural Environment Research Council
- National Centre for Earth Observation – Natural Environment Research Council
- CEH
- esa
- ICOS – integrated carbon observation system
- InGOS – Integrated non-CO_2 Greenhouse gas Observing System

International Collaborators

- GEIA – Global Emissions InitiAtive
- NOAA – National Oceanic and Atmospheric Administration, U.S. Department of Commerce
- Global Carbon Project
- NDACC – Network for the Detection of Atmospheric Composition Change – Exploring the Interface between Changing Atmospheric Composition and Climate
- NASA
- ipen
- JAXA – Japan Aerospace Exploration Agency
- USP
- Massachusetts Institute of Technology – 1861 – Mens et Manus
- AGAGE

Stakeholders

- ECMWF
- Department of Energy & Climate Change
- defra – Department for Environment Food and Rural Affairs
- Met Office
- DFDS Seaways