Health effects of agricultural emissions of ammonia:
A focus on the UK with global implications

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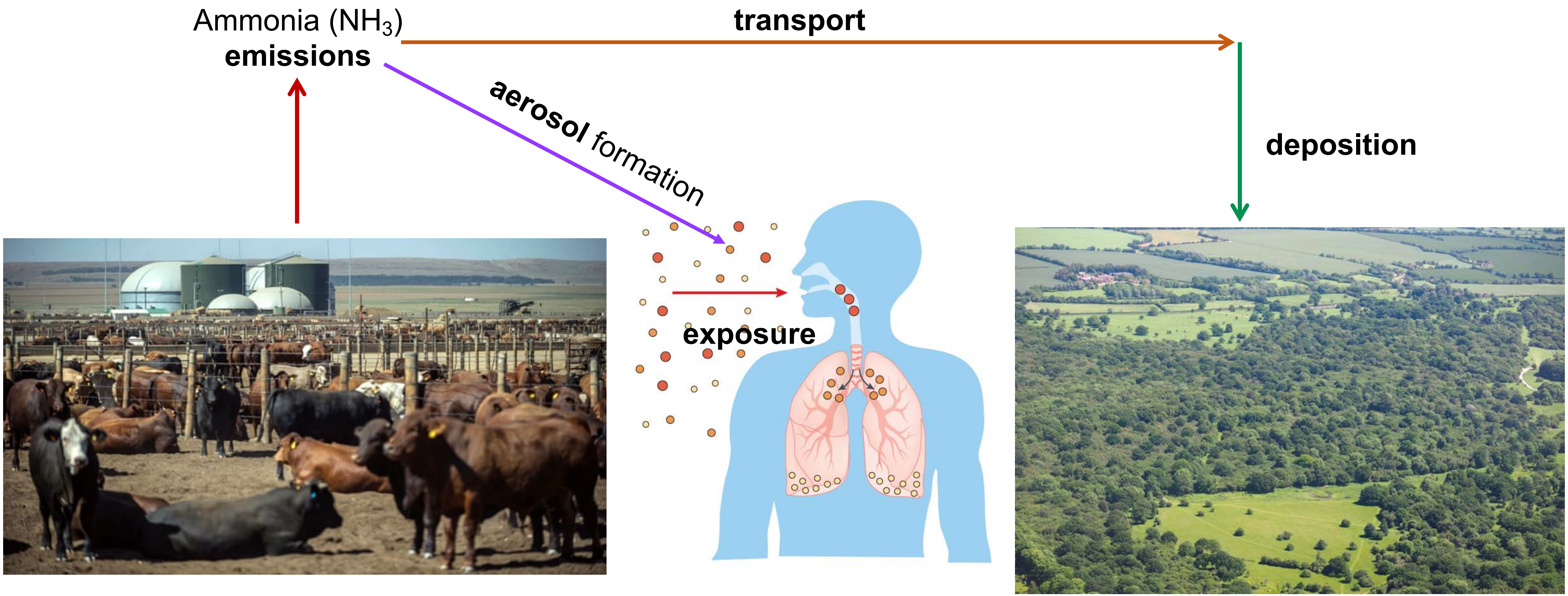
U. Edinburgh Seminar

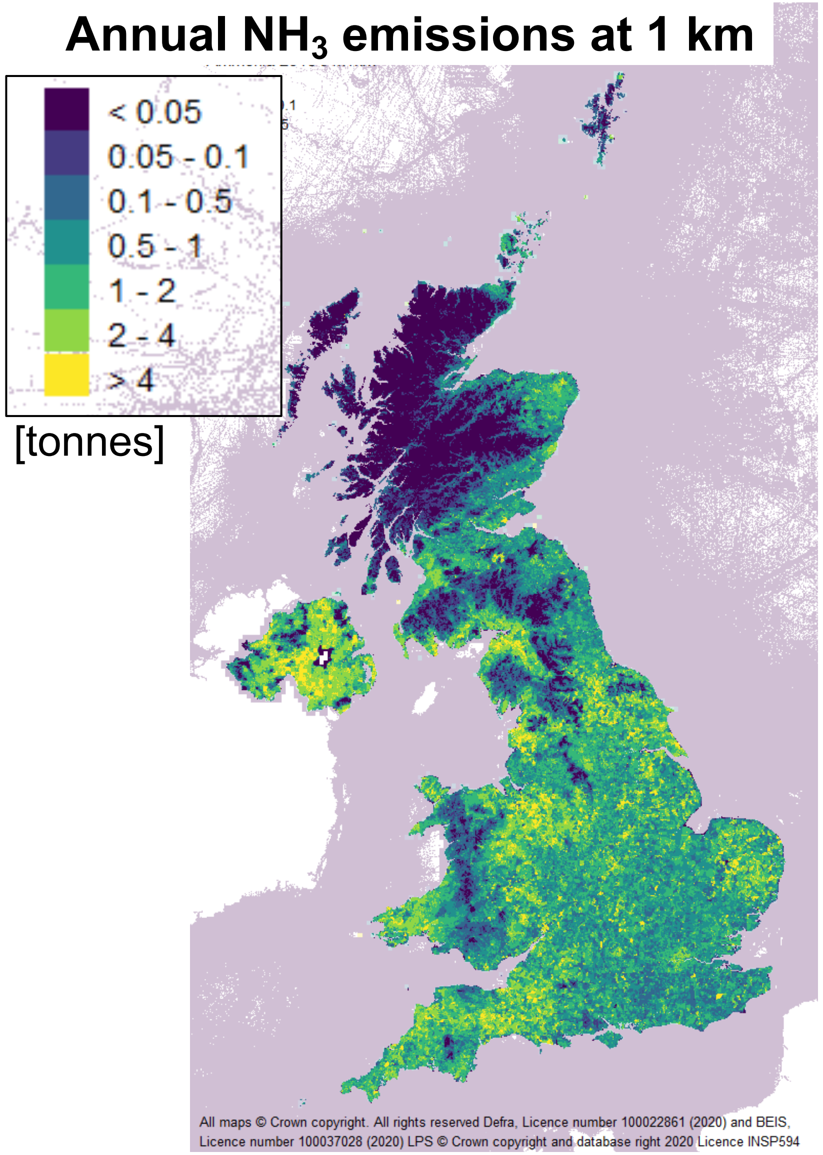
30 November 2022

Ammonia pathway leading to adverse health outcomes



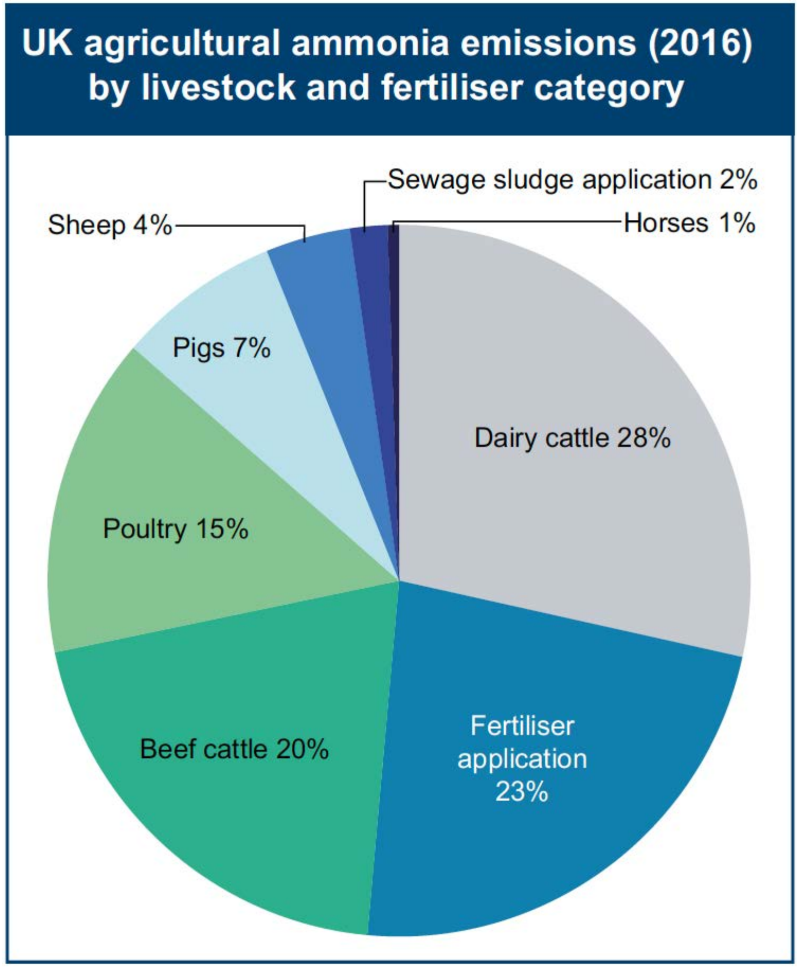
Ammonia emissions in the UK: the bottom-up perspective

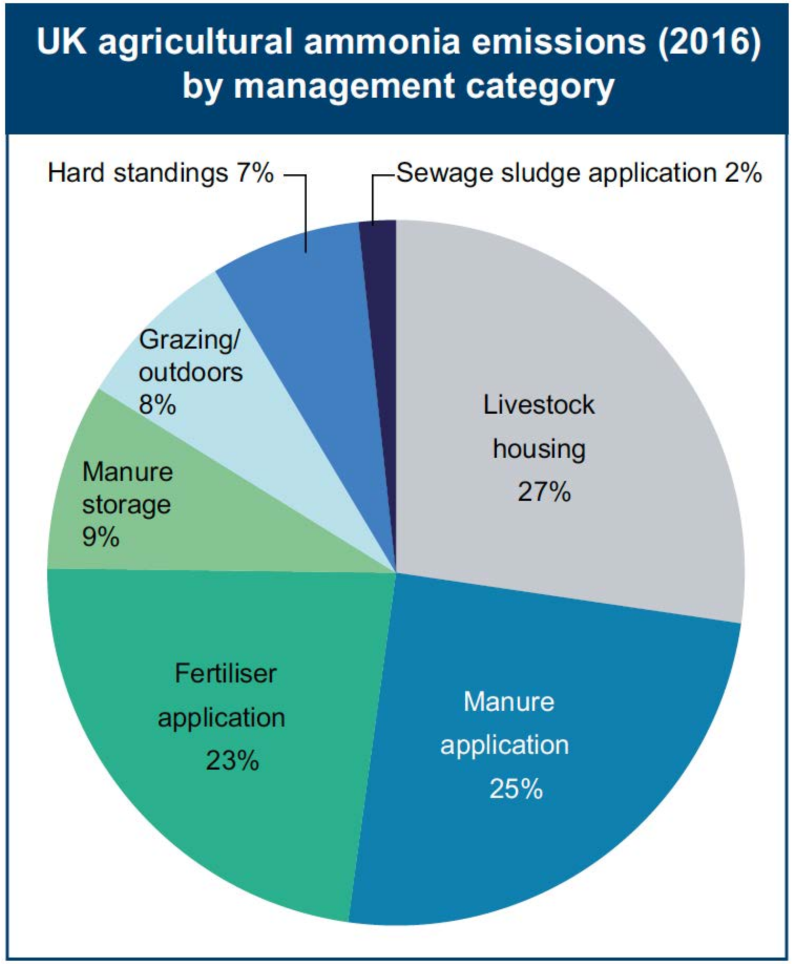
Emissions Spatial Variability



[*Adapted from* https://naei.beis.gov.uk/data/]

Contributions of activities to ammonia emissions



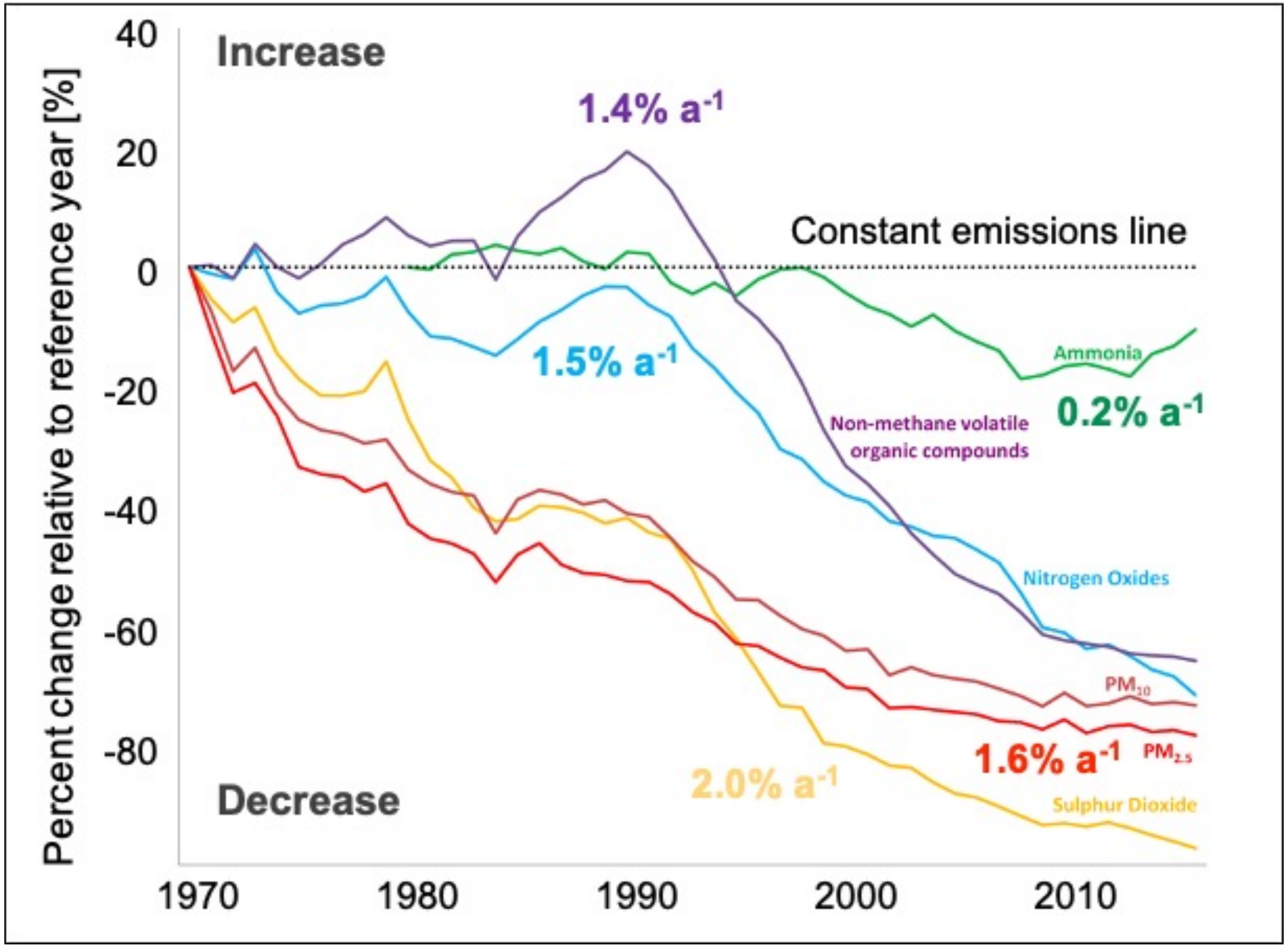


[UK Clean Air Strategy, 2019]

Beef, dairy, and fertilizer use dominate

Ammonia emissions in the UK: the bottom-up perspective

Temporal (Time) Variability in Emissions



Green: ammonia

Purple: non-methane volatile organic compounds

Blue: nitrogen oxides

Orange: Coarse particles

Red: Fine particles

Yellow: sulfur dioxide

[*Adapted from* Defra, 2018]

Successful decline in all primary $PM_{2.5}$ sources and precursor emissions, except ammonia (NH_3)

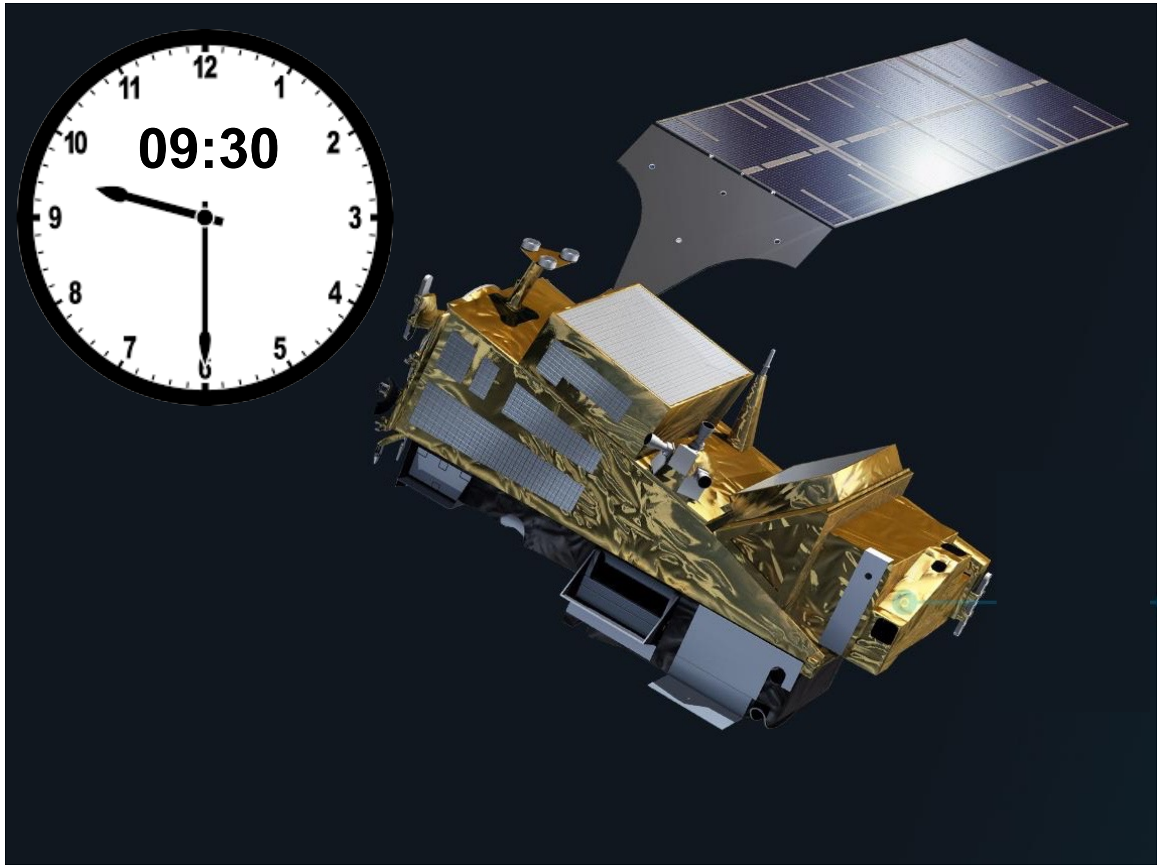
Assess national inventory estimates of ammonia emissions with satellite observations

Published in JGR: Atmospheres:
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2021JD035237

Engineering and Physical Sciences Research Council
Natural Environment Research Council
Department for Environment Food & Rural Affairs

Instruments in space measuring NH_3 column densities

IASI: Infrared Atmospheric Sounding Interferometer



CrIS: Cross-track Infrared Sounder

<u>Resolution:</u> 12 km at nadir

<u>Swath width:</u> 2200 km

<u>Launch date:</u> 2006 (2012, 2018, 2024, 2031, 2038)

<u>Years used</u>: 2008-2018

<u>Resolution:</u> 14 km at nadir

<u>Swath width:</u> 2200 km

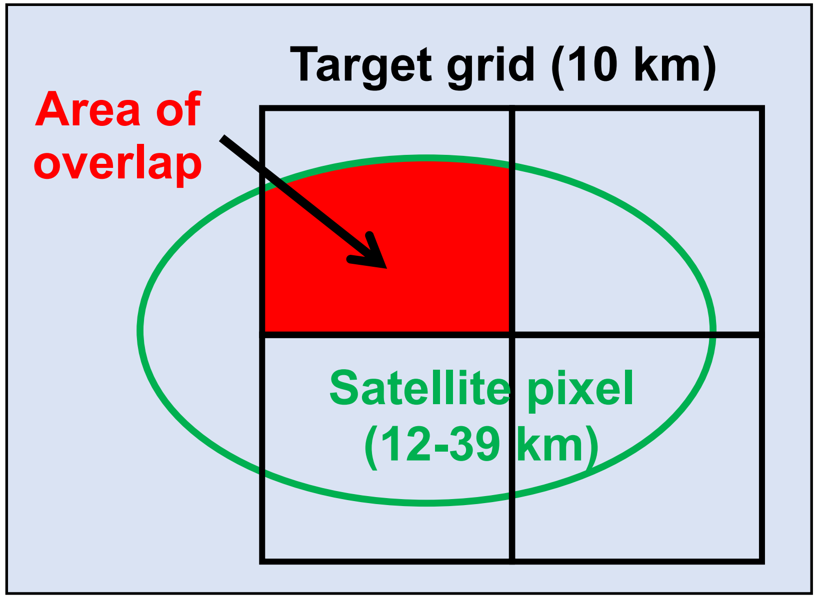
<u>Launch date:</u> 2011 (2017, 2022, 2027, 2032)

<u>Years used</u>: 2013-2018

Fine-scale regridding of satellite observations by oversampling

Enhance the spatial resolution relative to the native resolution of the instrument by oversampling

Oversampling Technique

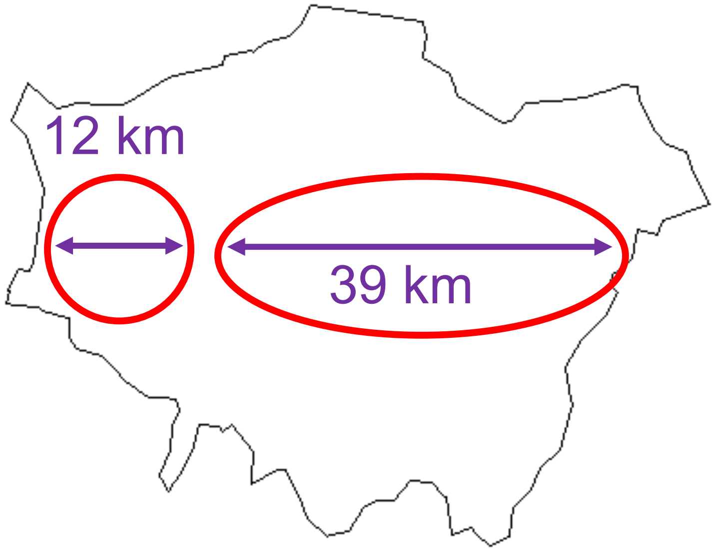


Weights each IASI NH_3 pixel by area of overlap and the reported uncertainty

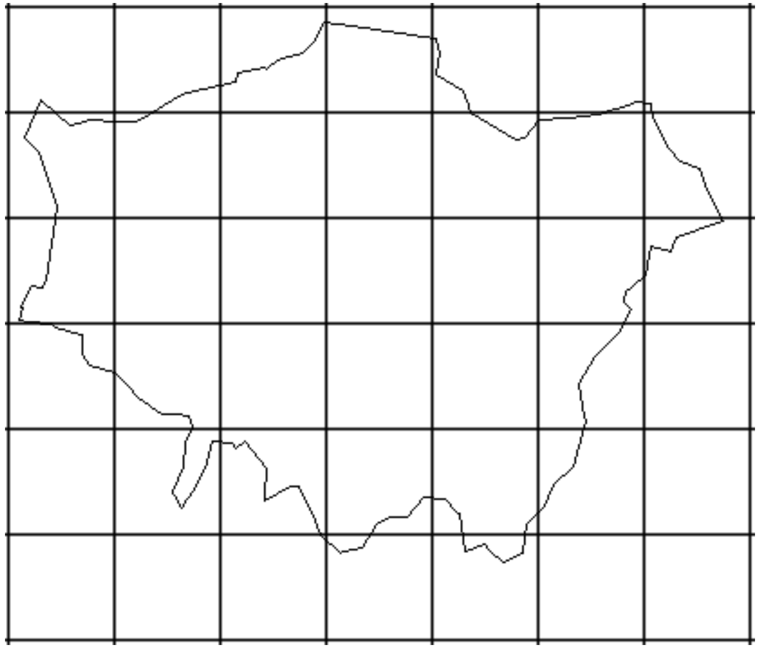
<u>Oversampling code</u>: L. Zhu, SUSTech (Zhu et al., 2017)

Oversampling technique over London

IASI ground pixel



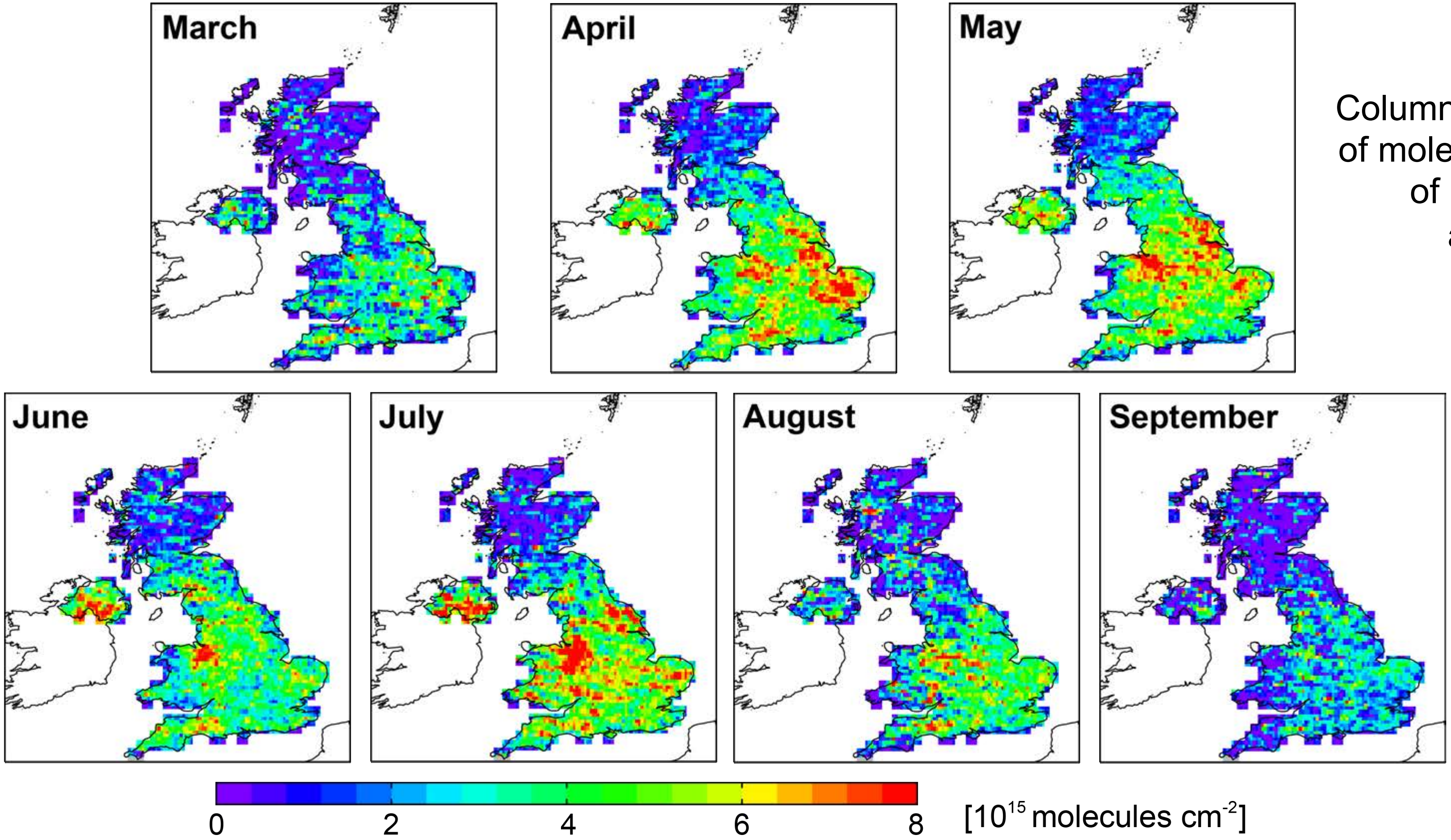
0.1° x 0.1° (~10 km) grid



Lose time (temporal) resolution; gain spatial resolution

Multiyear means from the IASI (morning overpass) instrument

Multiyear (2008-2018) monthly means for warmer months of the year



Column densities: number of molecules from surface of Earth to top of atmosphere

Climatological mean to be consistent with bottom-up ammonia emissions

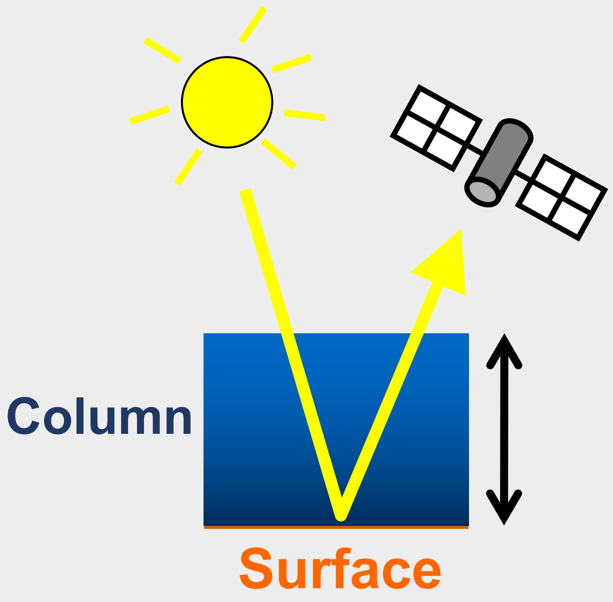
Top-down estimate of ammonia emissions

Employ simple mass balance approach:

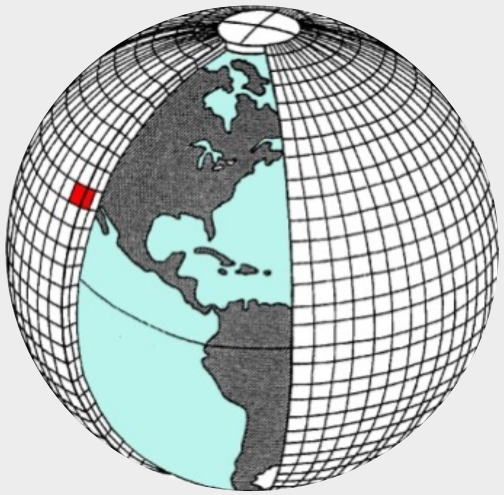
Convert atmospheric **column concentrations** to surface **emissions** by relating the two with a **model**

ABUNDANCES → **Conversion Factor** → **EMISSIONS**

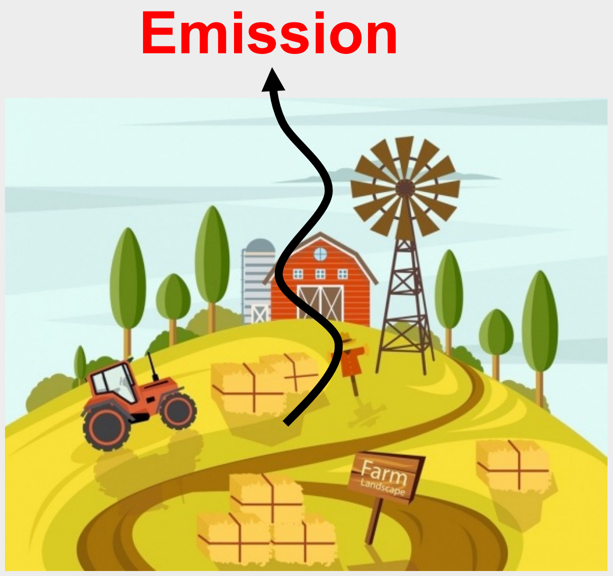
Satellite column densities



Model Concentration-to-Emission Ratio



Satellite-derived Surface Emissions



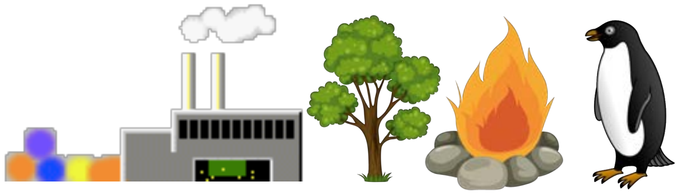
This approach possible as NH_3 has a relatively short lifetime (2-15 hours) at or near sources

Modelled concentration-to-emissions-ratio from GEOS-Chem

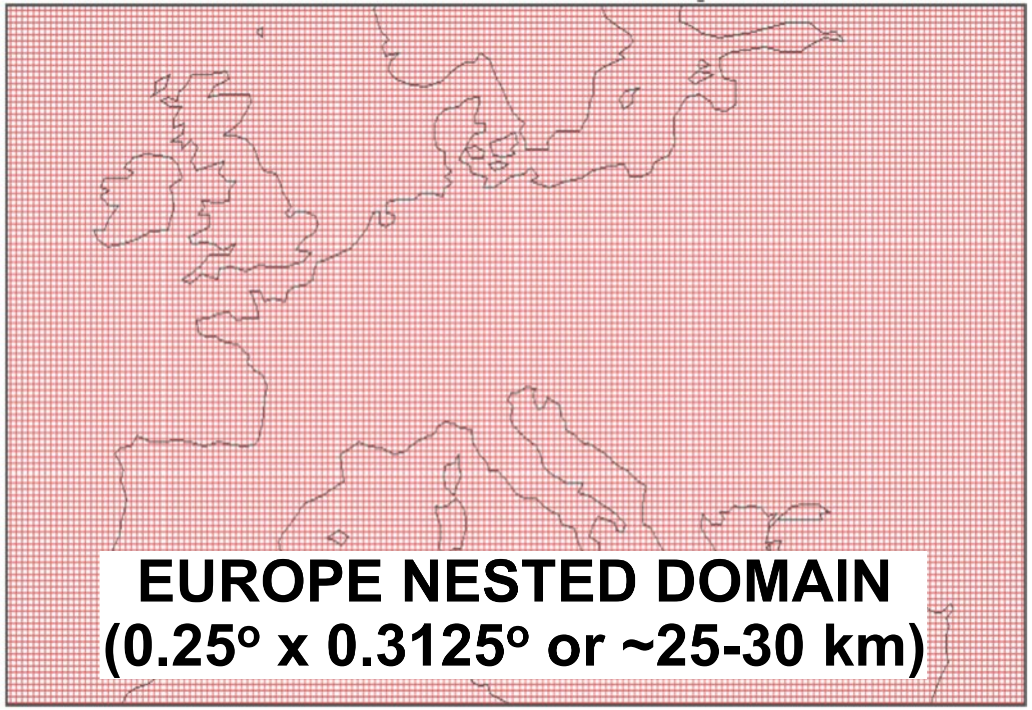
GEOS-Chem

3D Atmospheric Chemistry Transport Model

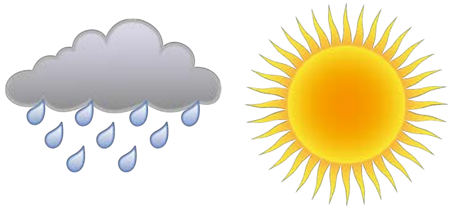
Emissions (natural/human)



UK NAEI emissions
(with temporal information)



Offline assimilated meteorology



NASA GEOS-FP for 2016

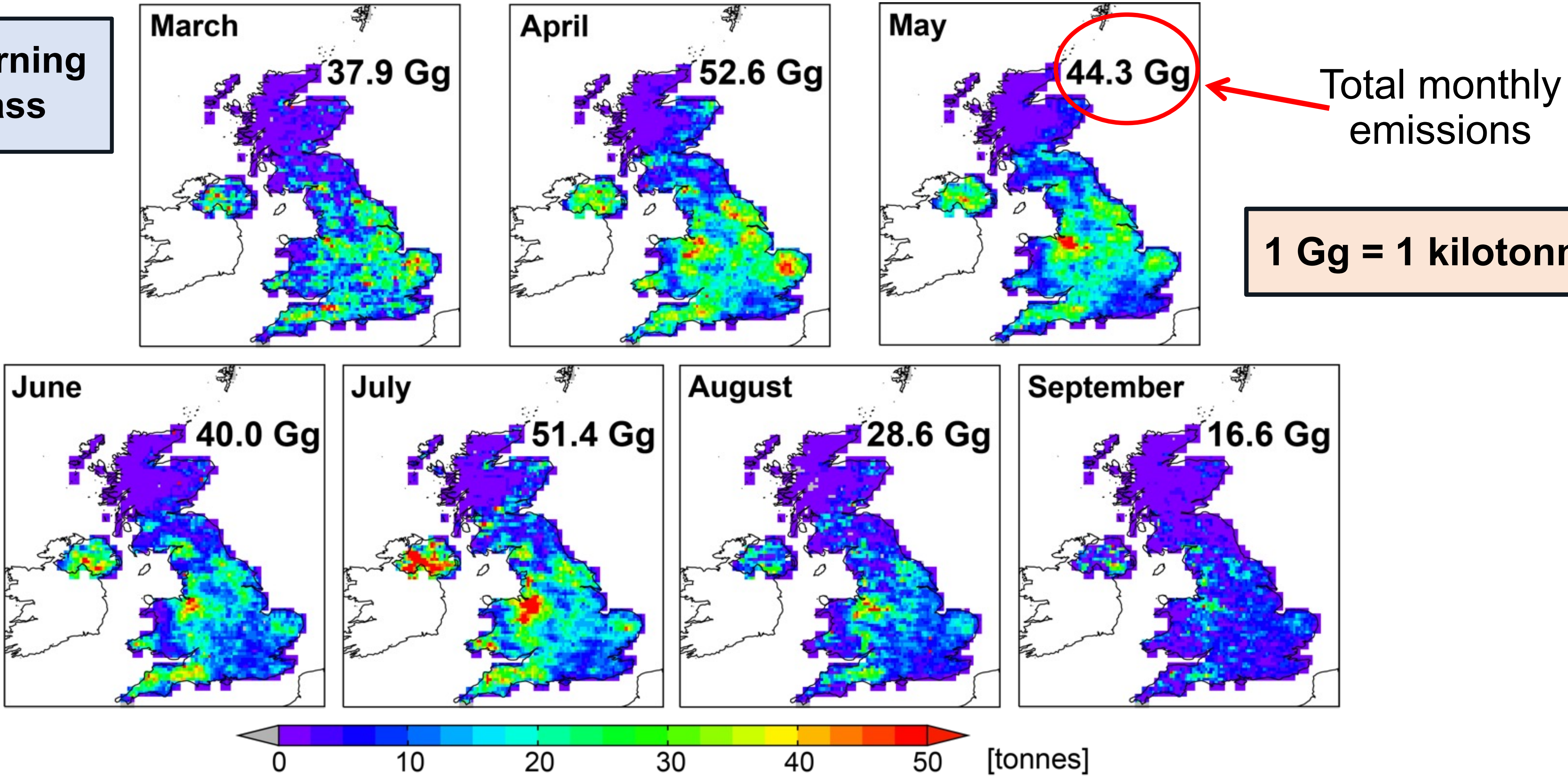
Gas phase and heterogeneous chemistry
Transport
Dry/wet deposition

GEOS-Chem **version 12.1.0** (doi:10.5281/zenodo.1553349)

IASI-derived multiyear (2008-2018) monthly mean NH_3 emissions

Focus on **Mar-Sep** when warm temperatures and clearer conditions increase sensitivity to surface NH_3

IASI: morning overpass

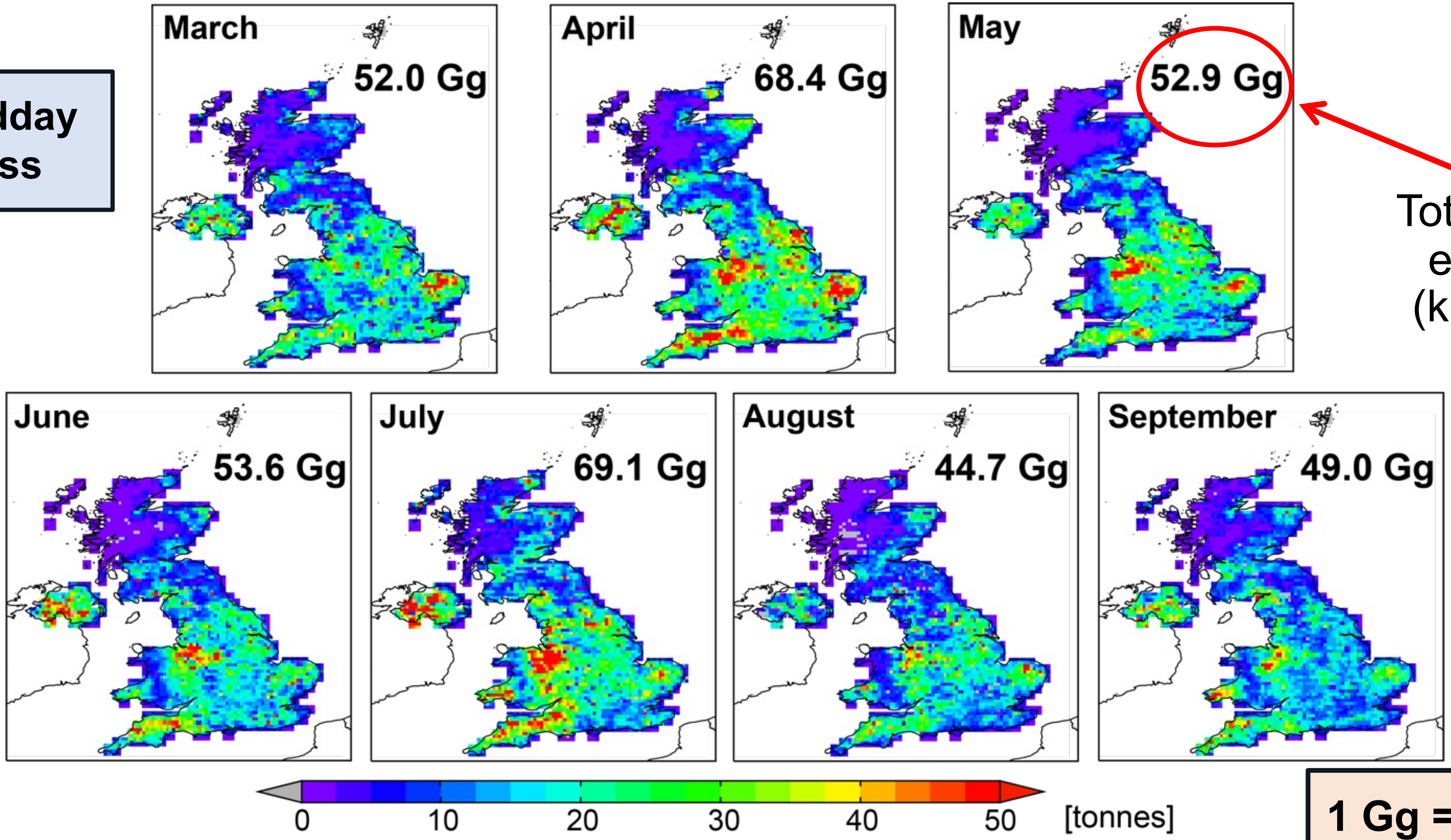


1 Gg = 1 kilotonne

Monthly emissions for March-September from **IASI**-derived estimates sum to **271.5 Gg**

CrIS-derived multiyear (2008-2018) monthly mean NH_3 emissions

CrIS: midday overpass



Total monthly emissions (kilotonnes)

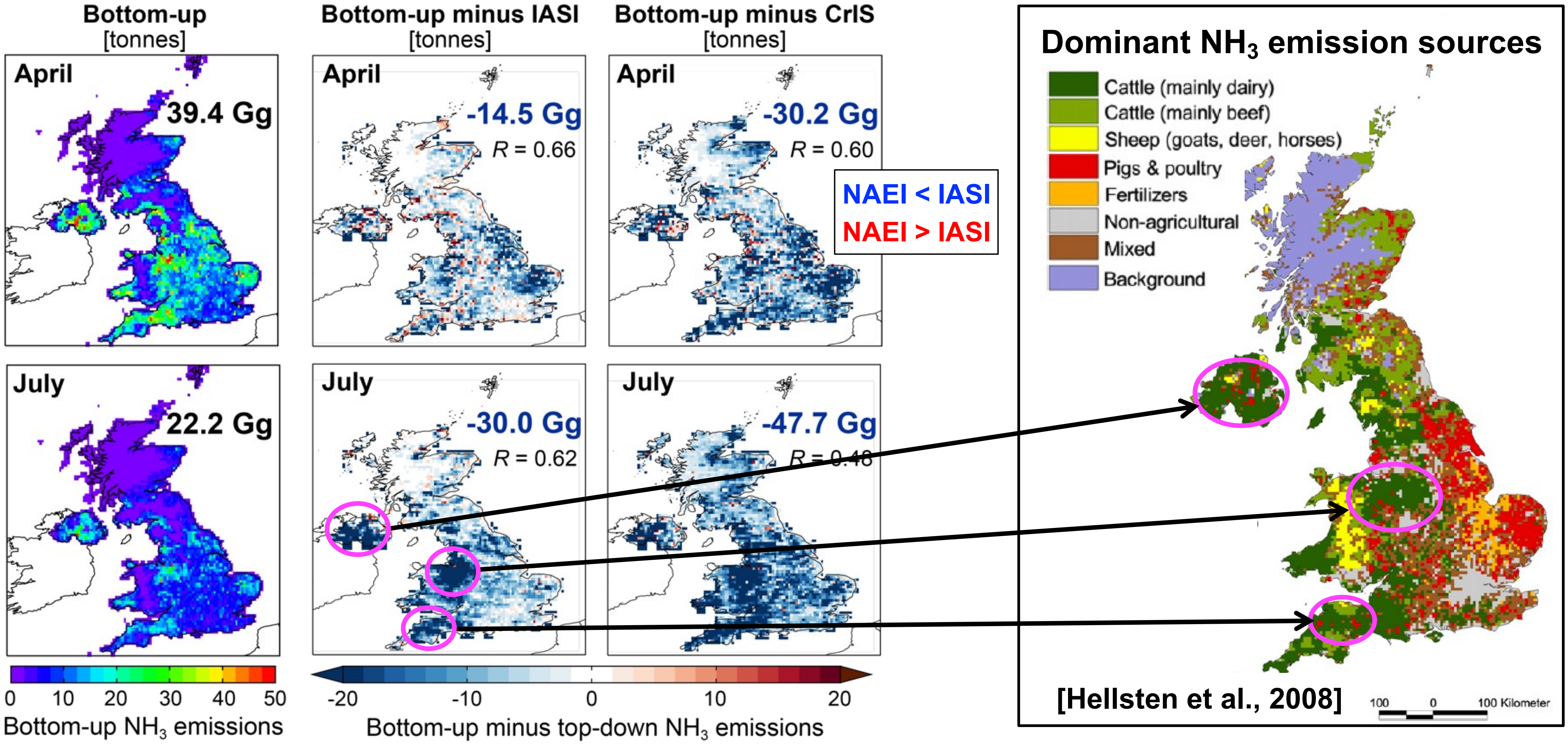
1 Gg = 1 kilotonne

Monthly emissions for March-September from **CrIS**-derived estimates sum to **389.6 Gg**

CrIS is 43% more than IASI. Largest difference of >a factor of 2 in September.

Satellite vs inventory NH_3 emissions: spatial distribution

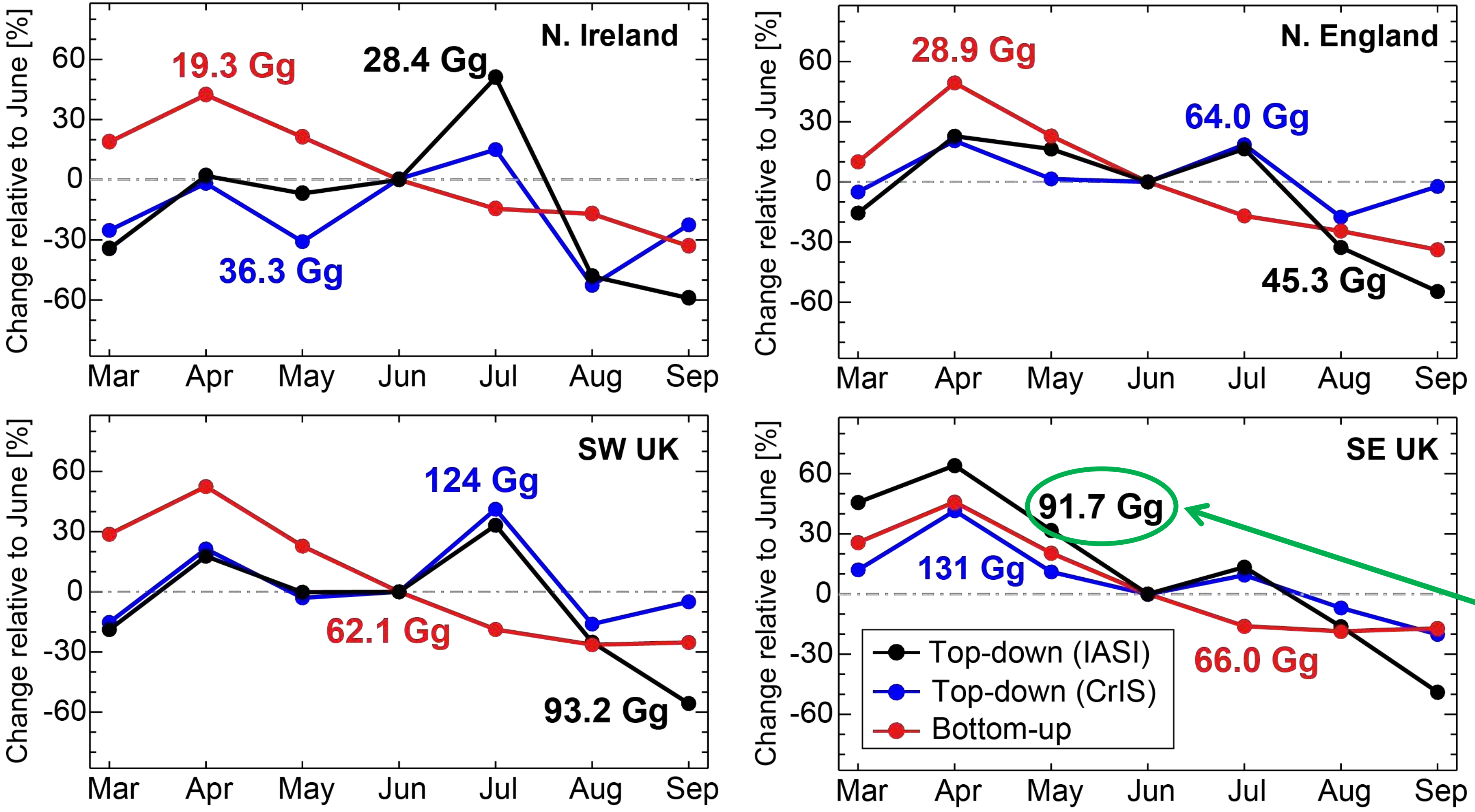
Comparison of months with peak emissions according to IASI and CrIS (April and July)



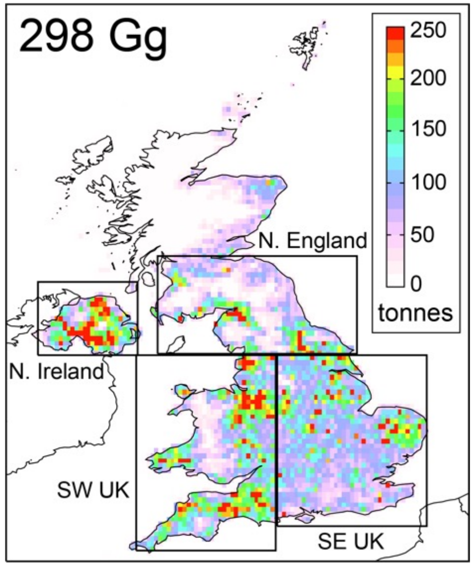
Large July difference over locations dominated by dairy cattle. Inventory is 27-49% less than the satellite values.

Satellite vs inventory NH_3 emissions: seasonality

Seasonality shown as emissions in each month relative to June



Regions and annual inventory emissions



Mar-Sep emission totals in each region

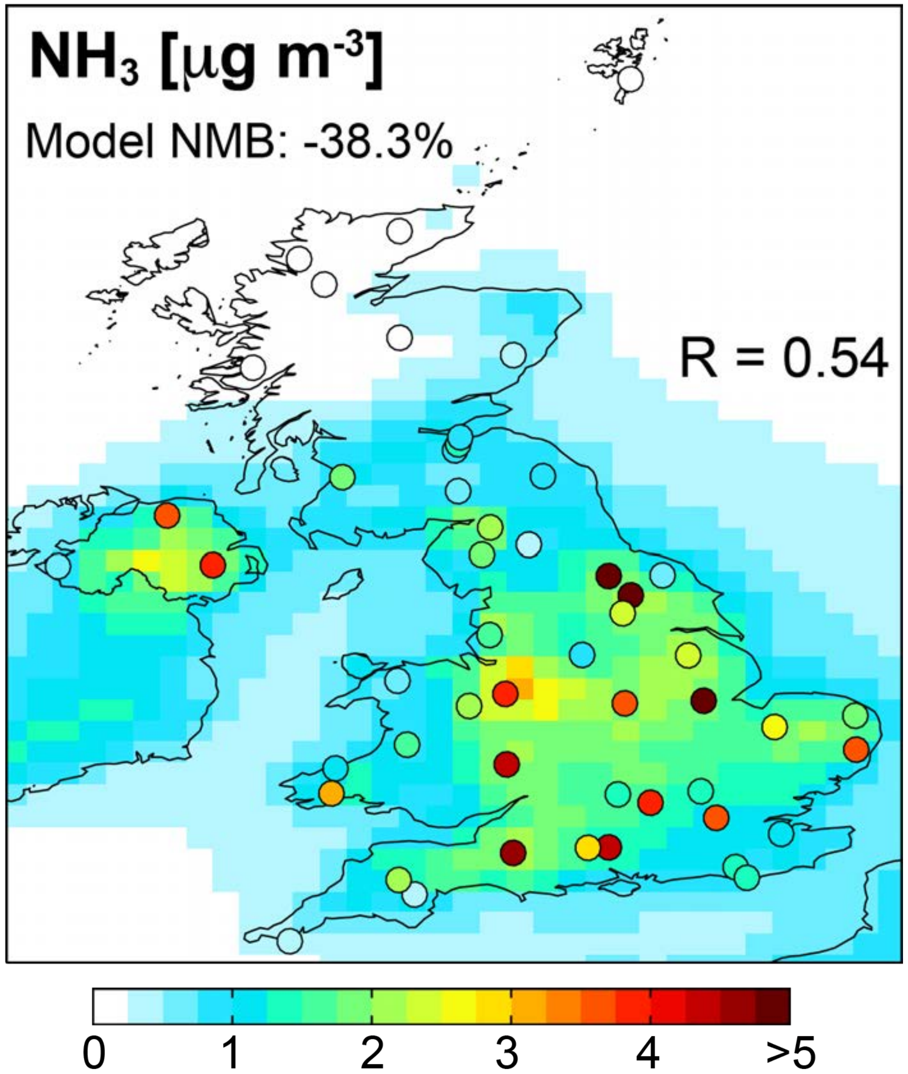
1 Gg = 1 kilotonne

All reproduce spring April peak (fertilizer & manure use). Only the satellite show summer July peak (dairy cattle?).

The increase in emissions in September in CrIS is spurious.

Surface network observations corroborate top-down results

Network (points) and model (background) surface NH_3 in Mar-Sep



Points are for DELTA instruments (blue circles)

DELTA instruments support model underestimate (**NMB = -38%**)

So do passive low-cost ALPHA instruments (yellow triangles) (**NMB = -41.5%**)

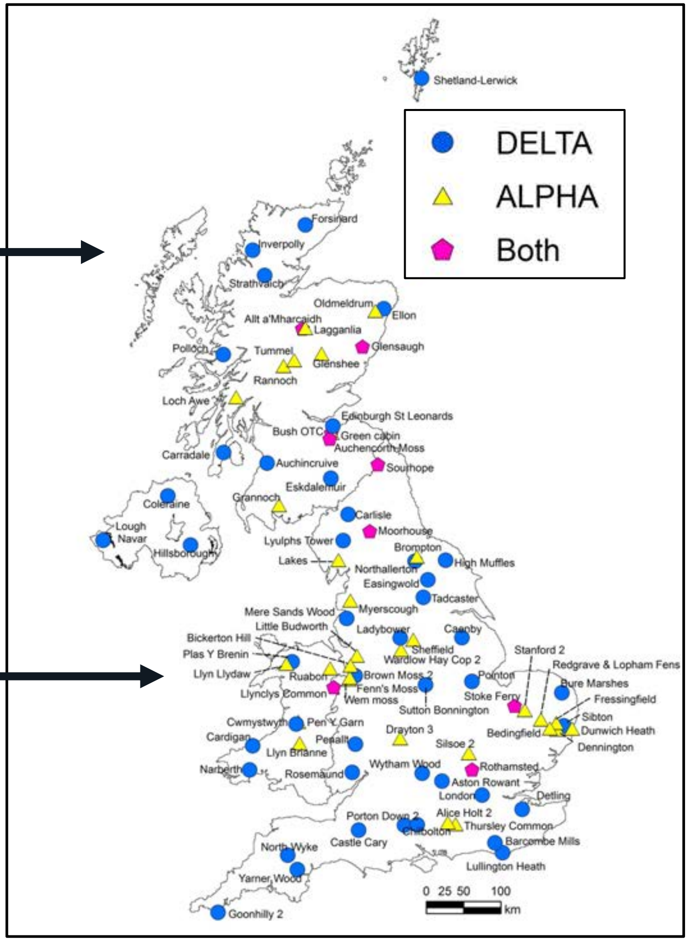


Image source:
http://www.pollutantdeposition.ceh.ac.uk/content/ammonia-network

GEOS-Chem underestimate in surface NH_3 driven with the NAEI corroborates results from IASI

Rural ammonia emissions influence on fine particles ($PM_{2.5}$) in UK cities

J. Kelly et al., 2022, *under review*

Engineering and Physical Sciences Research Council

Natural Environment Research Council

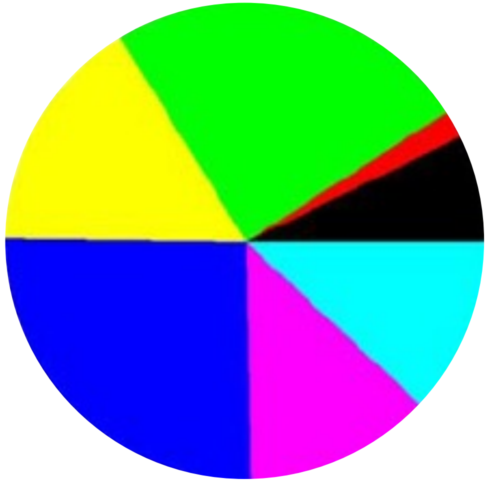
Department for Environment Food & Rural Affairs

Particles are a mix of components that persist for days

Direct emission of $PM_{2.5}$ **(primary)**

Emission of gas-phase precursors **(secondary)**

$PM_{2.5}$ includes a mix of components



Black carbon primary

Sulfate
Nitrate
Ammonium
} secondary

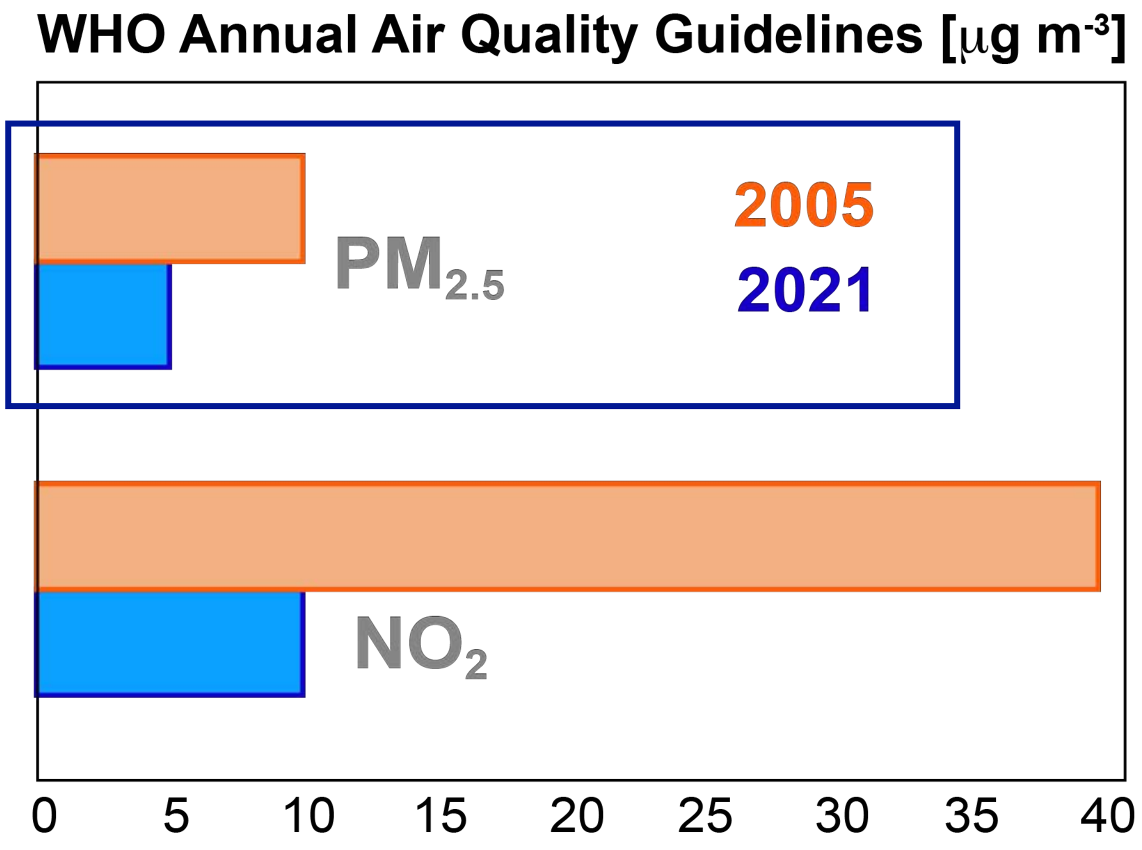
Other inorganics

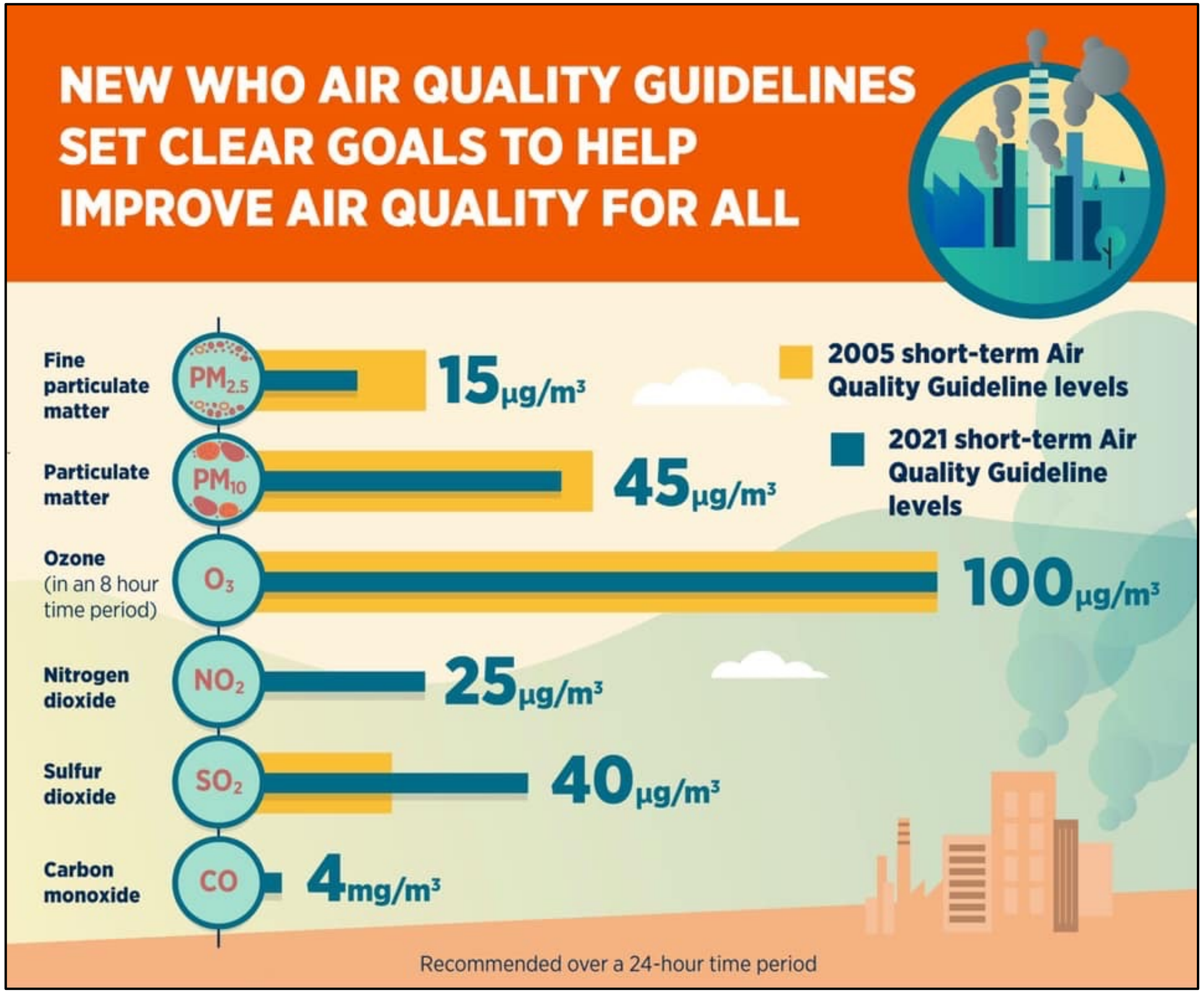
Organic aerosols primary+secondary

$PM_{2.5}$ challenging to regulate, as includes many sources and has a long atmospheric lifetime (2-3 weeks)

Stricter World Health Organization (WHO) Guideline

(https://apps.who.int/iris/handle/10665/345329)



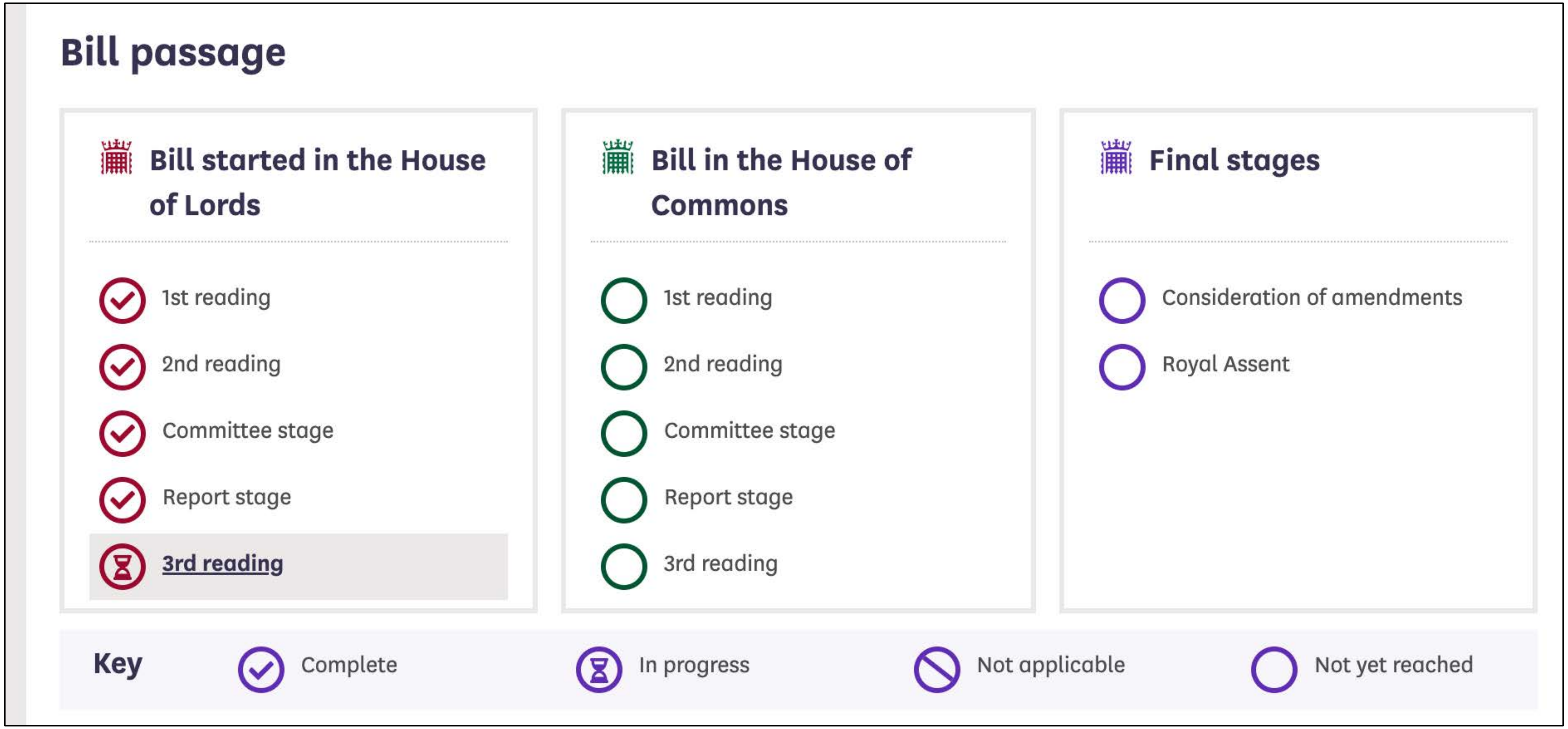


Source: WHO Facebook page

UK air pollution targets making its way through parliament

Pretty meek target: "$PM_{2.5}$ to be less than or equal to 10 µg m^{-3} by 1 January 2030."

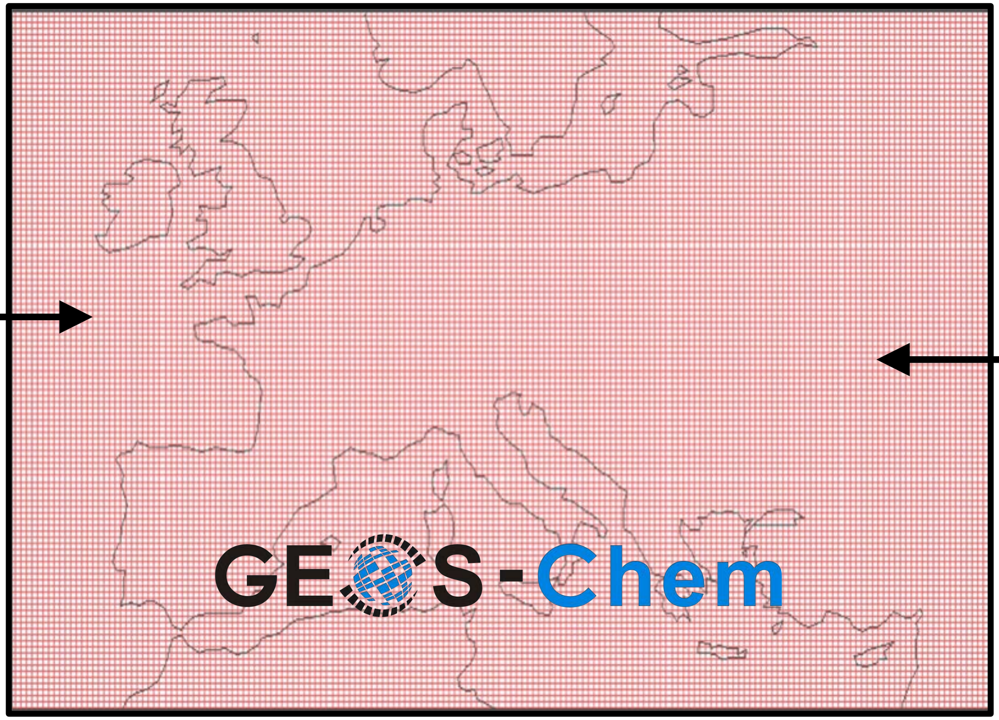
Status at 9am yesterday (https://bills.parliament.uk/bills/3161)



Simulate $PM_{2.5}$ with GEOS-Chem

3D Atmospheric Chemistry Transport Model

Ammonia emissions updated
(based on previous work)



Chemistry, transport, loss processes

NASA Meteorology

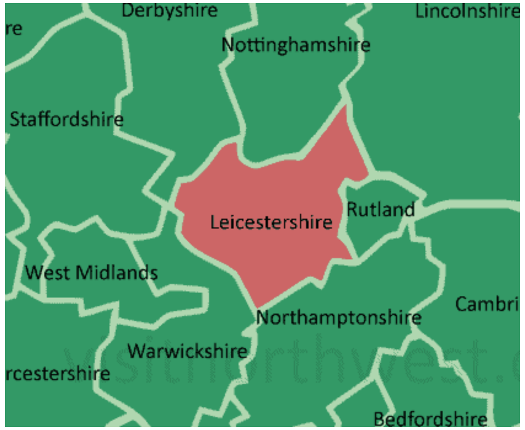
$PM_{2.5}$ from all but one source

GEOS-Chem manual: http://acmg.seas.harvard.edu/geos/

Test Contribution of Potentially Influential Sources

Local

City



County

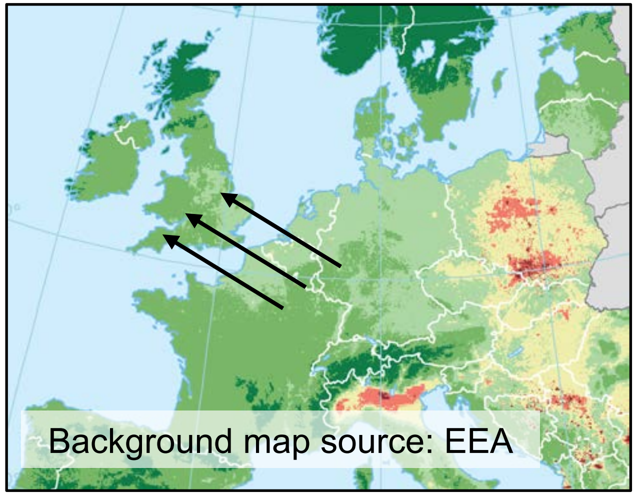
National

Nearby large cities

Transport

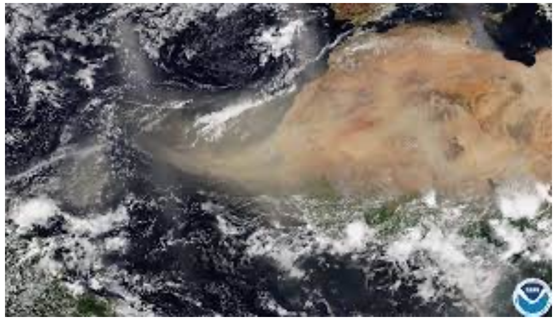
Agriculture

Regional



Mainland Europe

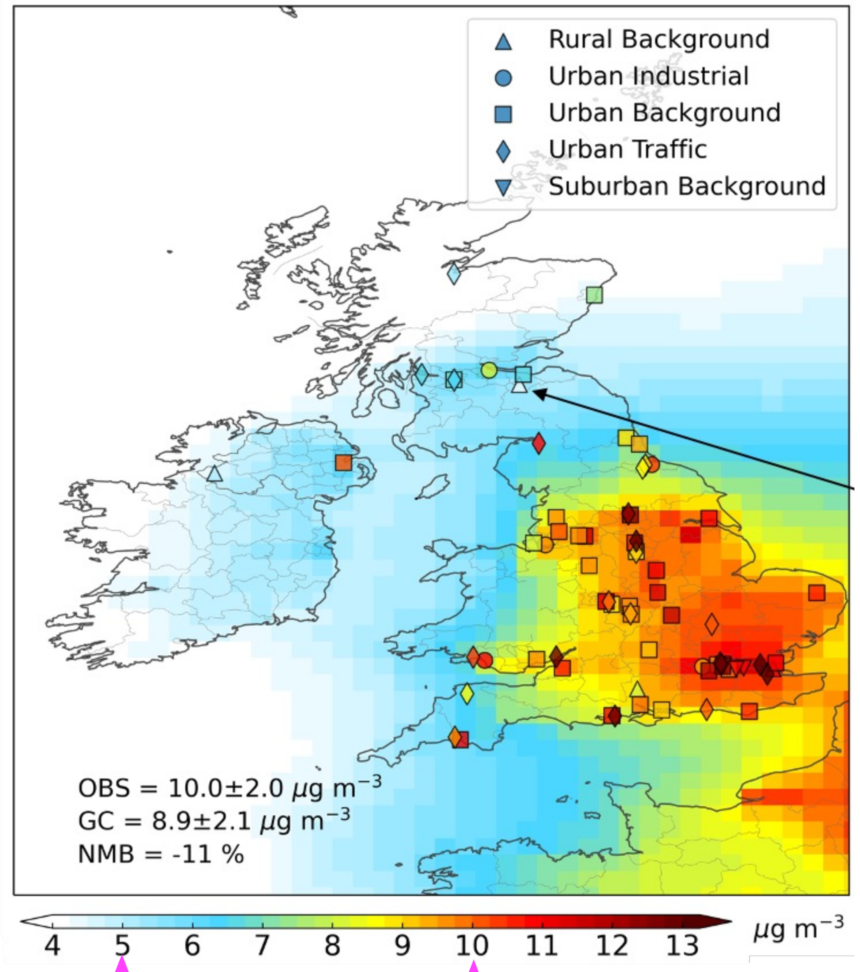
Global



Desert Dust

Assess Validity of Model using Permanent Networks

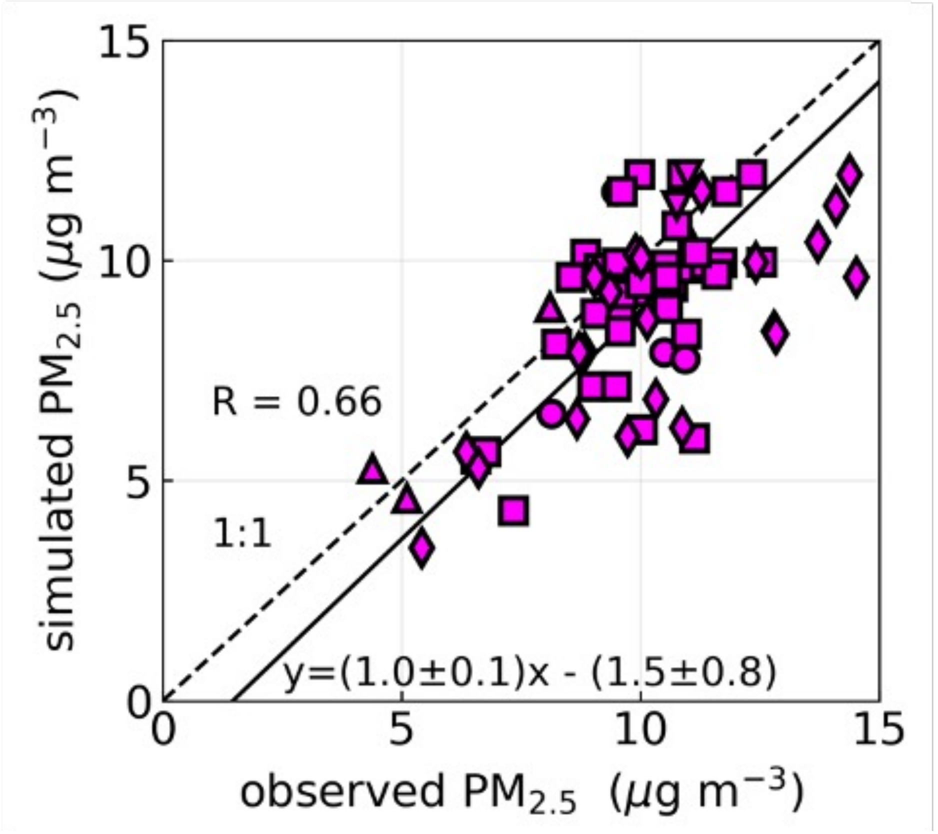
Use total $PM_{2.5}$ observations from the Automatic Urban and Rural Network (AURN) to assess model



WHO (2021) **WHO (2005), new UK target**

74% of UK exceeds updated WHO guideline

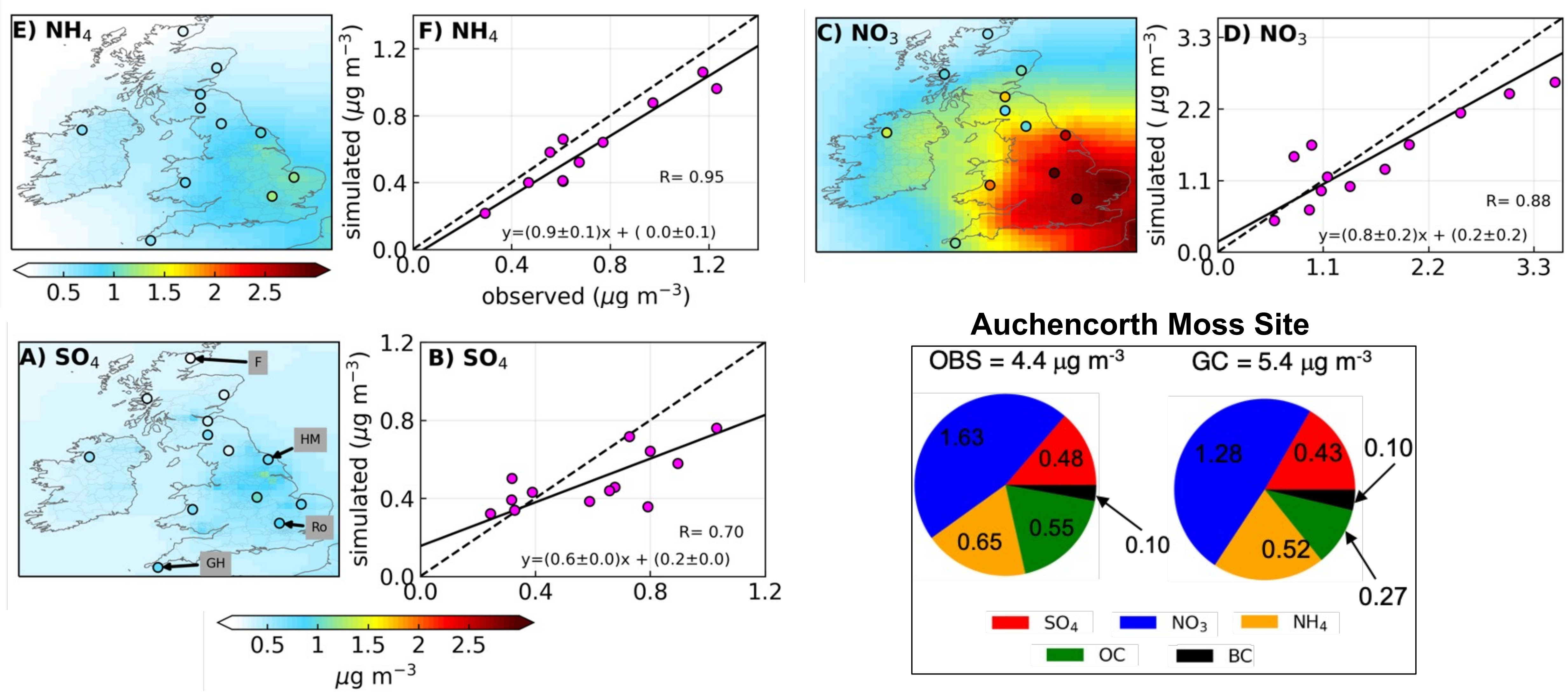
Compare annual mean surface concentrations of $PM_{2.5}$ for 2019



Consistent spatial pattern (**R = 0.66**) and variance (**slope = 1.0**). Model **11% less** than observations

Assess Validity of Model using Permanent Networks

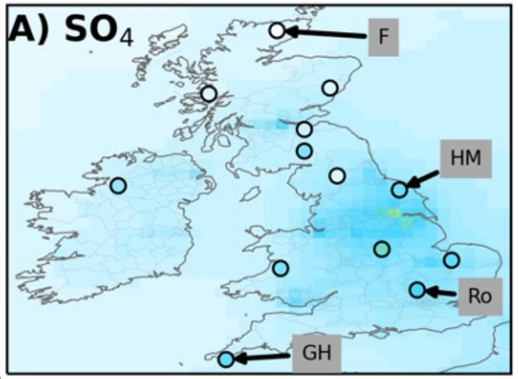
Use $PM_{2.5}$ composition measurements from UKEAP and EMEP sites to assess model



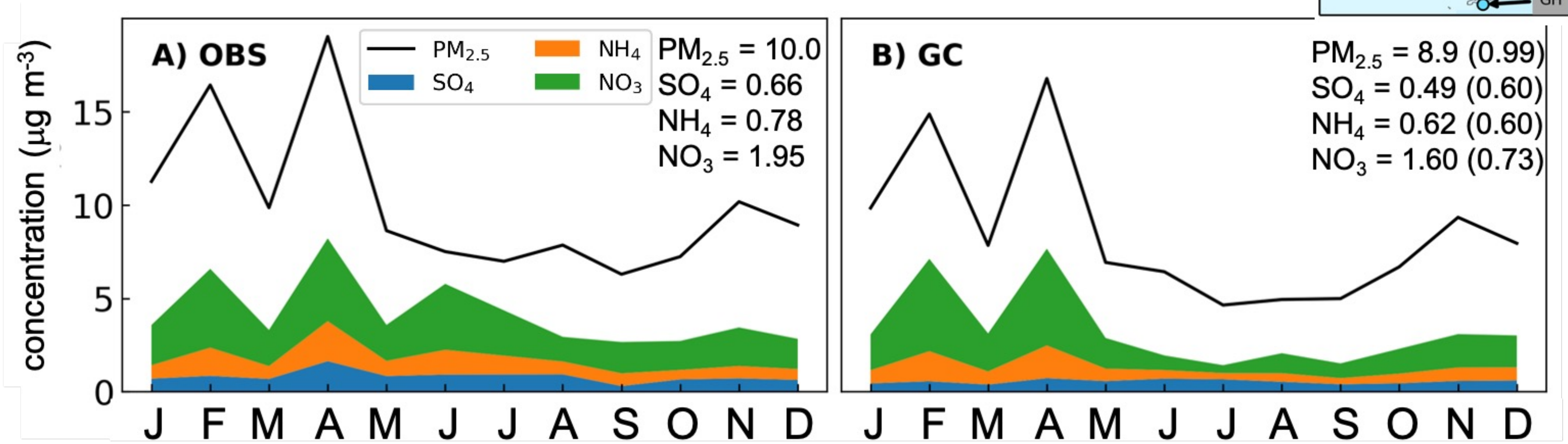
Model underpredicts observed (sulfate, nitrate, ammonium) and possibly overpredicts unobserved (dust) components. Model captures variance of components from NO_x (nitrate) and ammonia (ammonium)

Assess Validity of Model using Reference Monitors

Also evaluate model skill at reproducing observed seasonality in $PM_{2.5}$

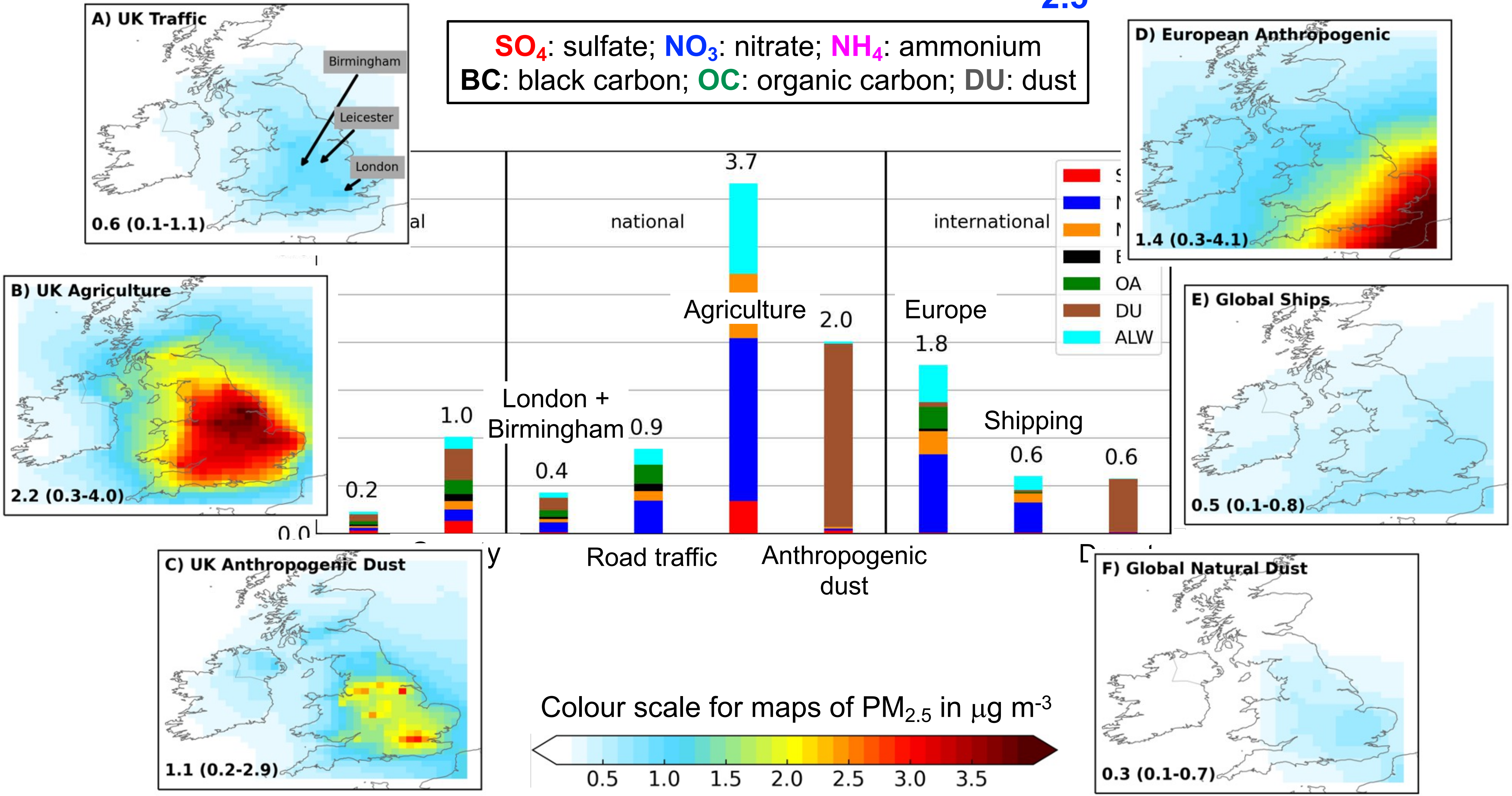


SO_4: sulfate; NO_3: nitrate; NH_4: ammonium



Enhancements in cold months and when ammonia emissions from agriculture peak due to application of synthetic fertilizer in March-April

Contribution of Sources to annual $PM_{2.5}$ in Leicester



Support for Small Local Contribution to $PM_{2.5}$

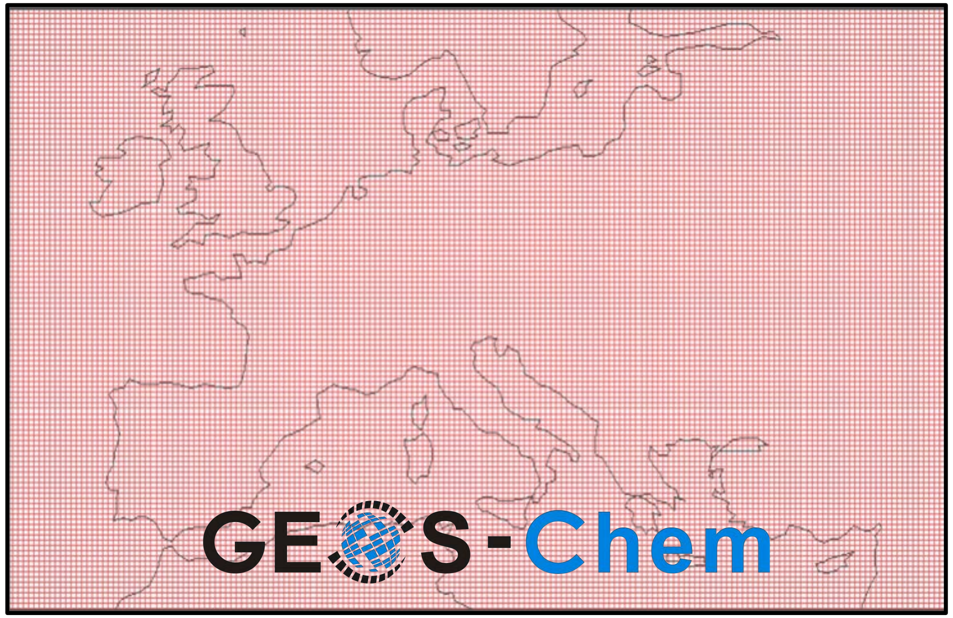
Low-cost network of Zephyr® sensors distributed throughout Leicester since November 2020

AURN network

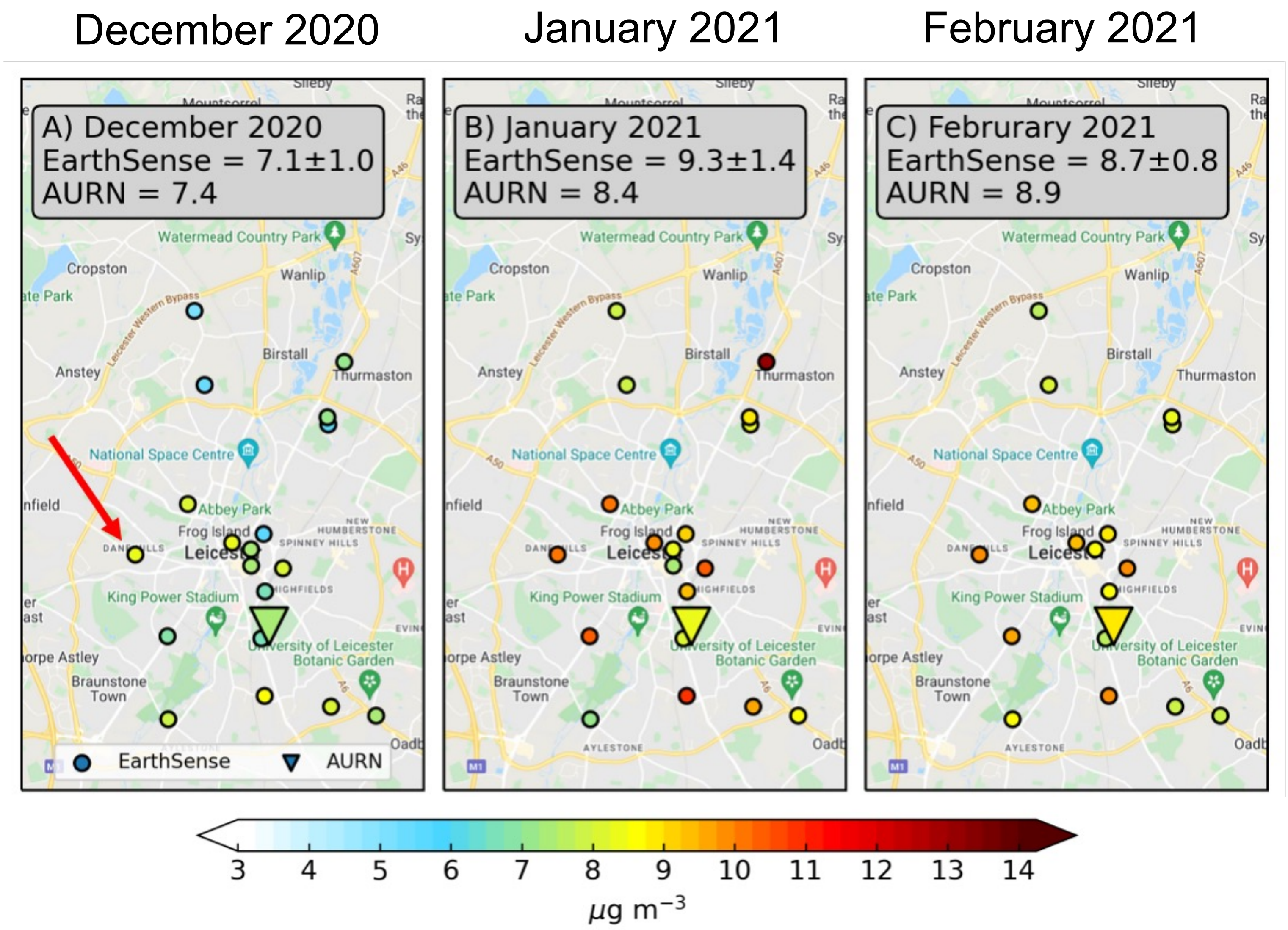
GEOS-Chem model

EarthSense low-cost sensors

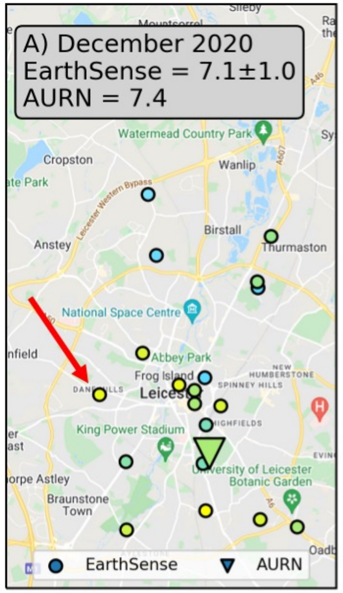
Jan 2019 | Jul 2019 | Jan 2020 | Jul 2020 | Jan 2021 | Present



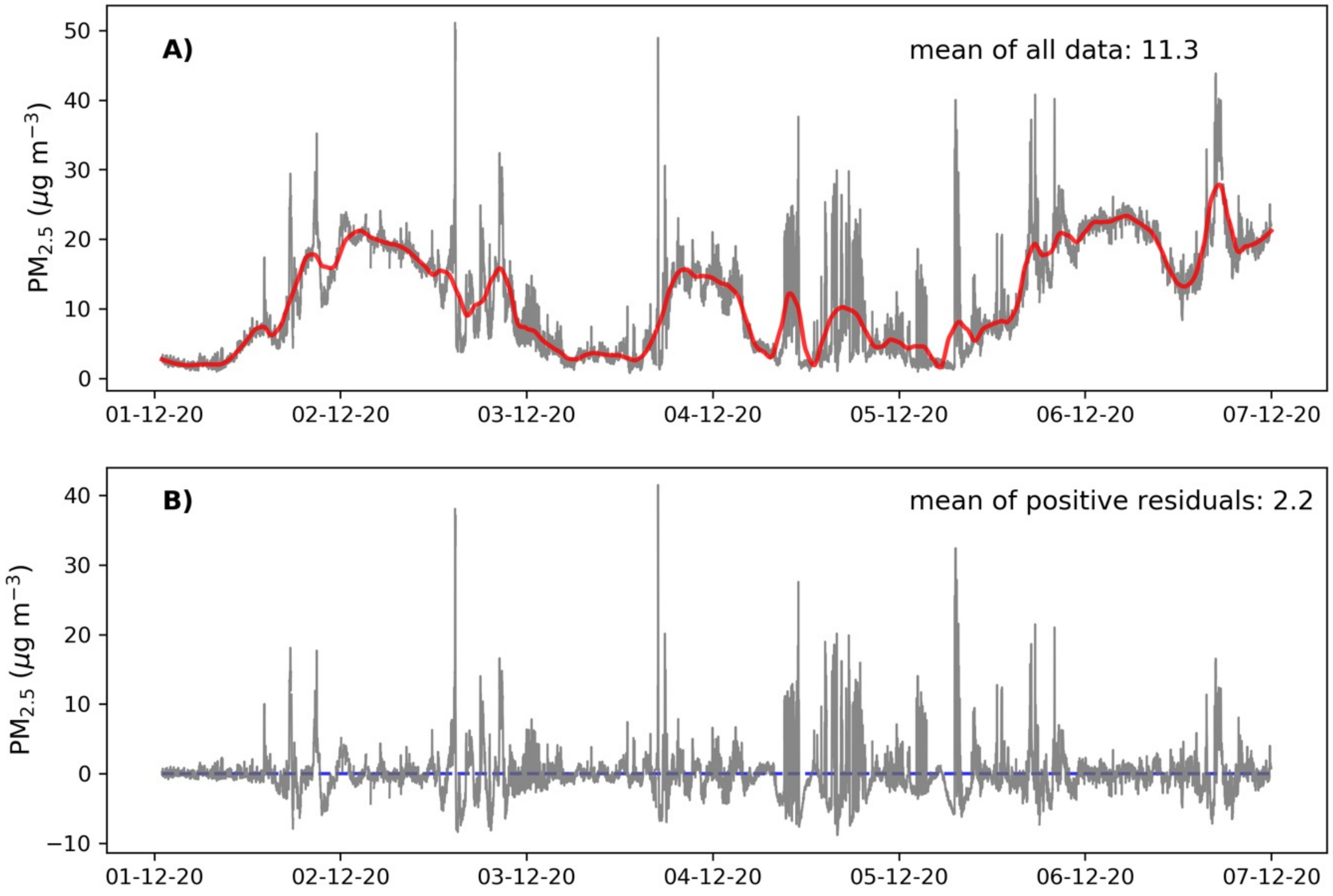
Zephyr Low-Cost Sensor Network Across Leicester



Zephyr Low-Cost Sensor Network Across Leicester



Decompose data into local and background contributions

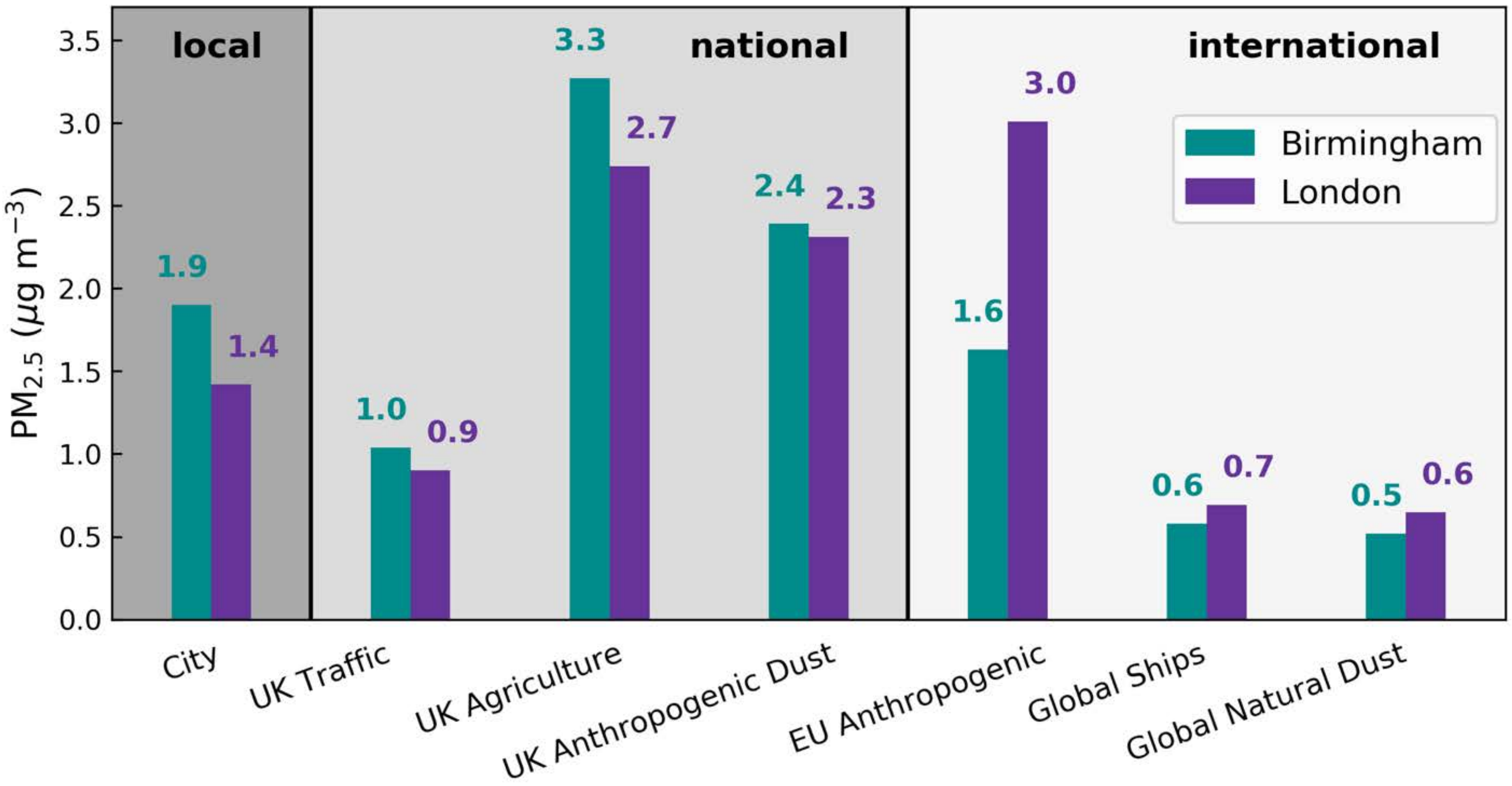


Red: Background

Residuals > 0: Local

According to low-cost sensors, local sources contribute **4-10%**. Small like the model (**2%**)

Results for Large Cities like London and Birmingham



London: 1,600 km^2

Birmingham: 270 km^2

Leicester: 70 km^2

Lower local than rural agricultural ammonia contribution consistent with Leicester

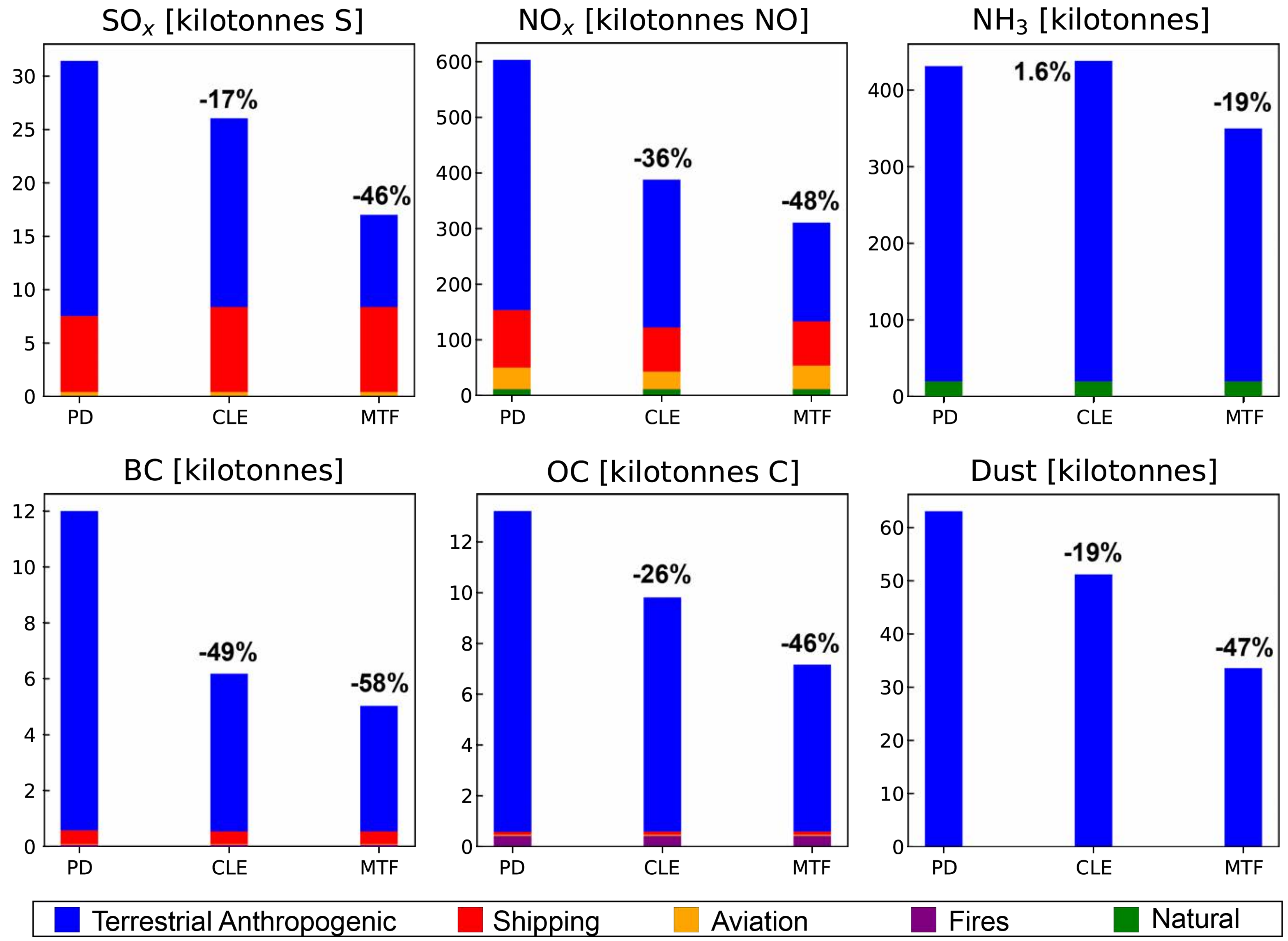
Air quality and health benefits of current legislation vs technically feasible solutions

Engineering and Physical Sciences Research Council

Natural Environment Research Council

Department for Environment Food & Rural Affairs

$PM_{2.5}$ precursor emissions for implementation in GEOS-Chem



PD: present-day (2019)

Future (2030) emissions:

CLE: current legislation

MTF: max. technically feasible

NH_3 leading to aerosol ammonium (NH_4) increases under current legislation

Technically feasible solutions include low nitrogen feed, covered manure storage, improved manure spreading, air filters and scrubbers, and move from urea-based fertilizer

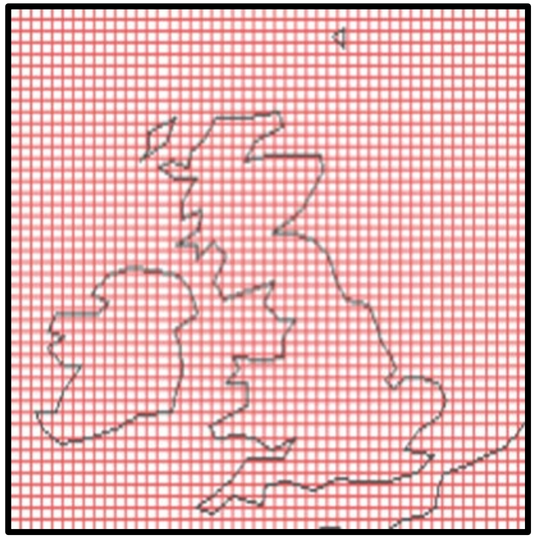
Model emissions impacts on $PM_{2.5}$ and nitrogen deposition

Emissions

Scales to match present day and future options

GEOS-Chem

3D Atmospheric Chemistry Transport Model



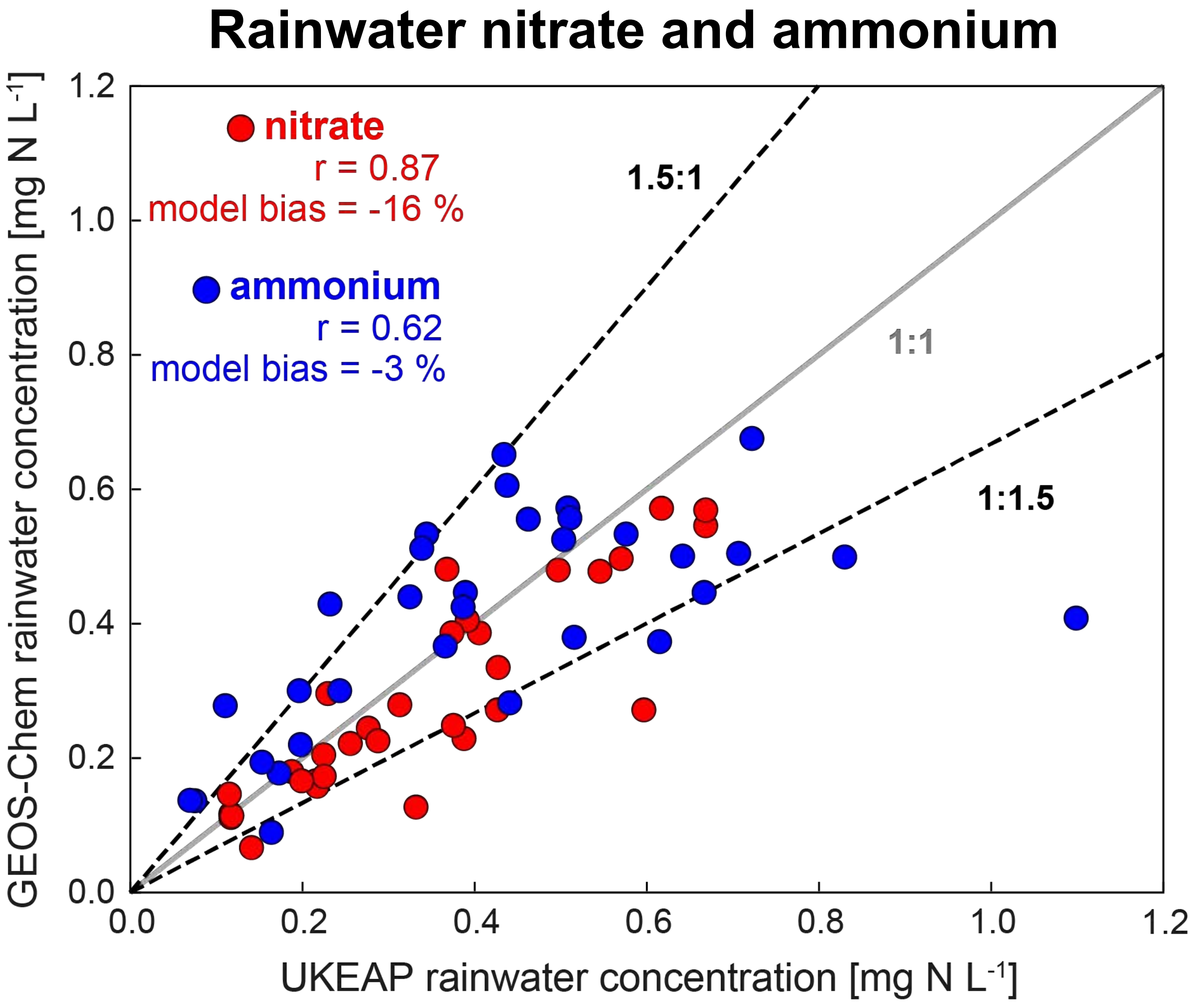
Chemistry, transport, sinks

NASA GEOS-FP Meteorology

Surface $PM_{2.5}$

Nitrogen wet and dry deposition

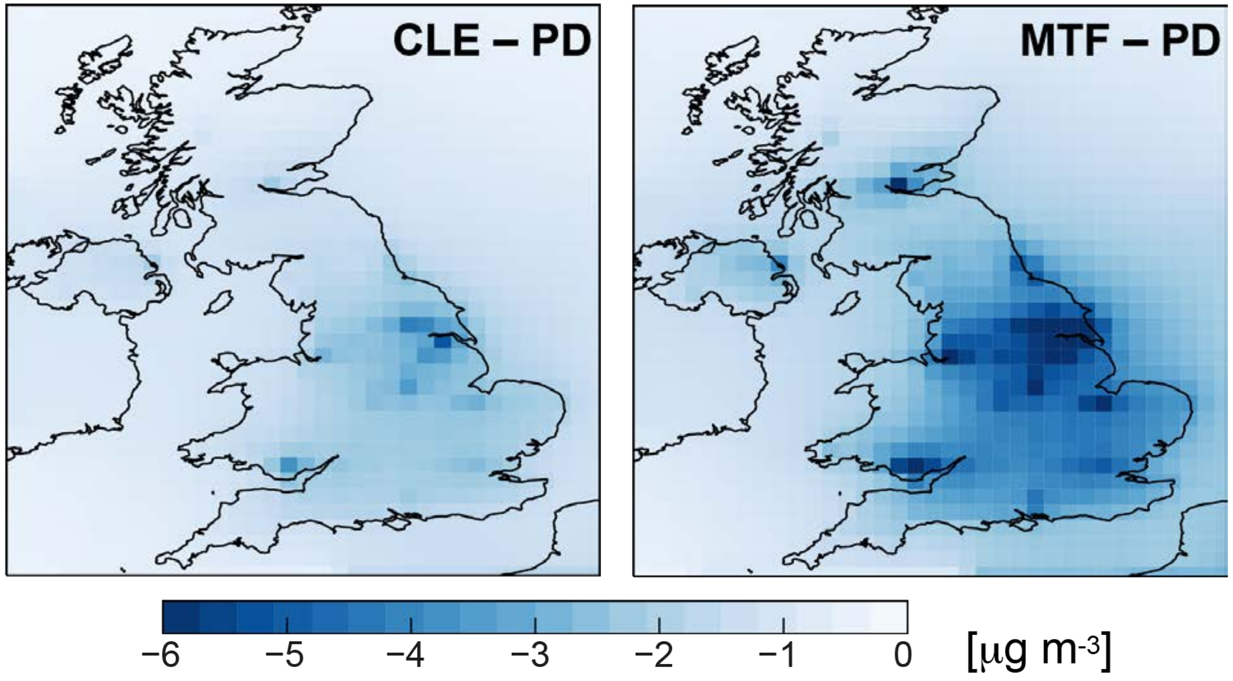
Assessment of deposition



Includes correction to model (GEOS-FP) underestimate in rainwater volume

Air Quality Impacts of Future Mitigation Measures

Change in $PM_{2.5}$ relative to the present-day due to emission controls



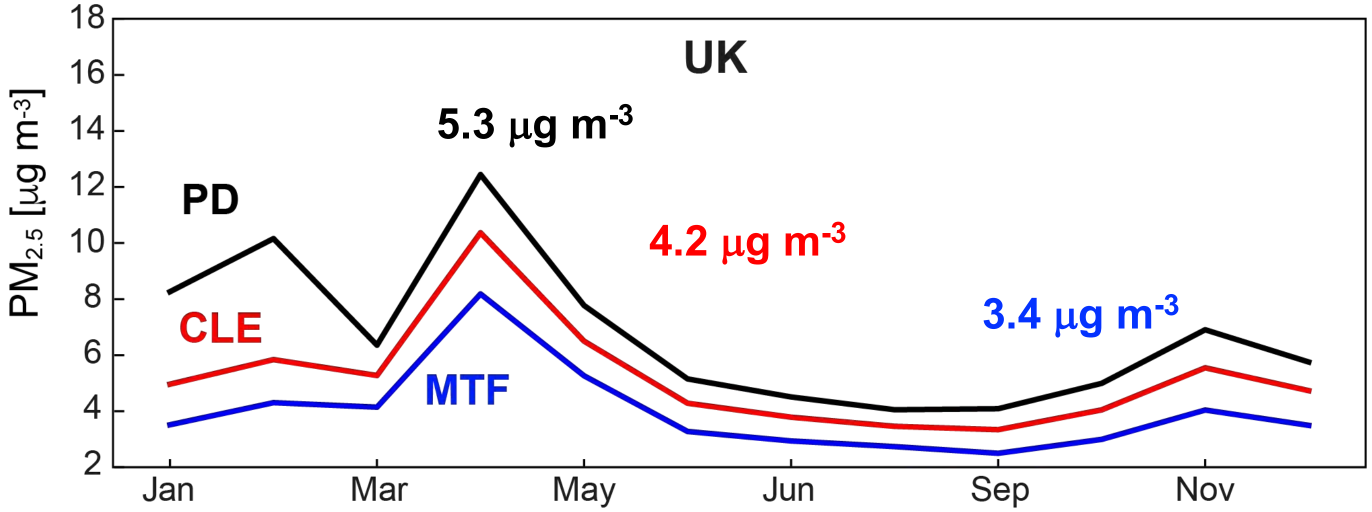
Average decline in $PM_{2.5}$ in the UK of 21% with current legislation and 36% with maximum technically feasible options

Decline greatest over densely populated urban areas and North Yorkshire (coal-fired power plants)

Percent UK grids above the updated WHO guideline (5 μg m^{-3}) decreases from 48% in PD to 32% for CLE, and 2% for MTF

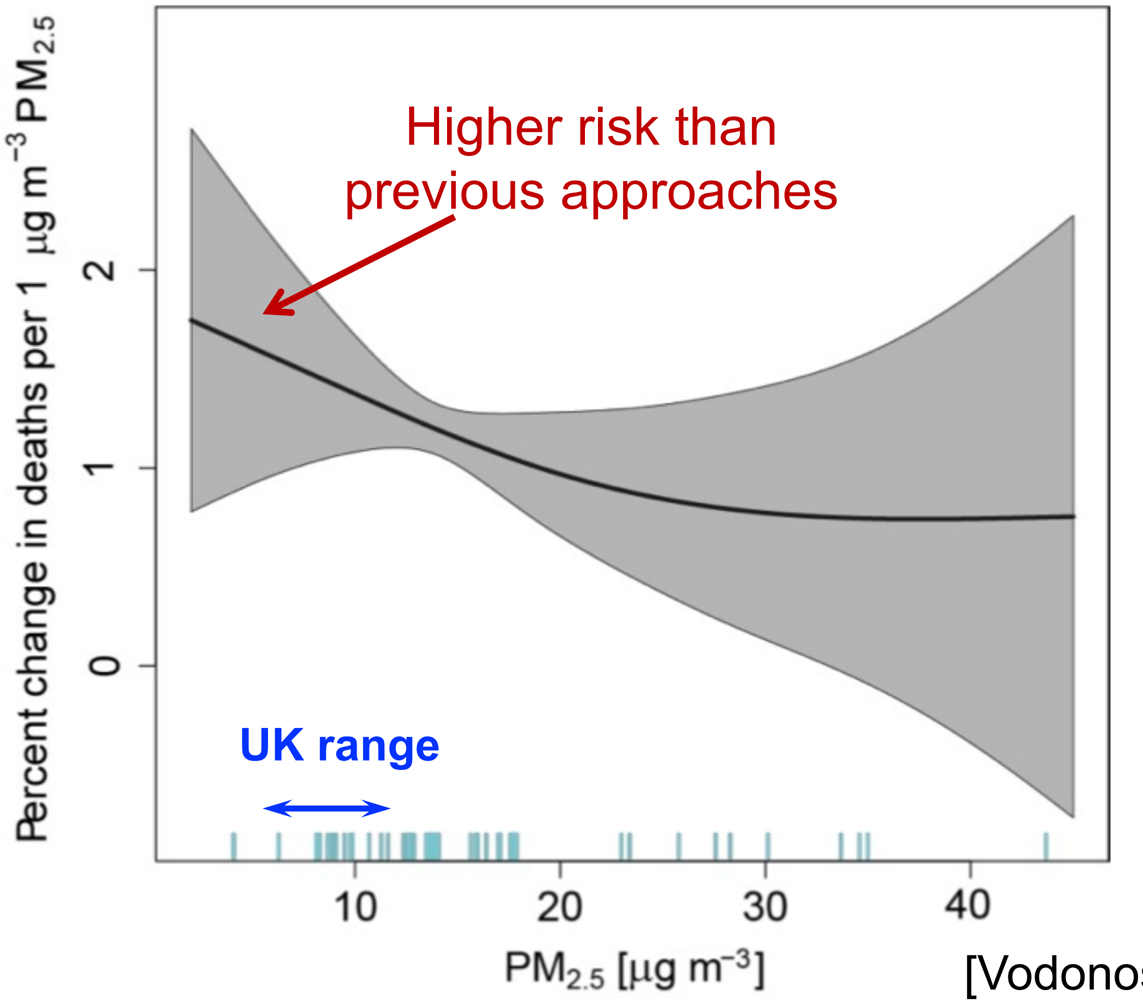
Similar decline in $PM_{2.5}$ in all months, except Jan-Feb.

Reduces vulnerability to interannual variability in meteorology (dry, stable conditions)



Public Health Impacts of Future Mitigation Measures

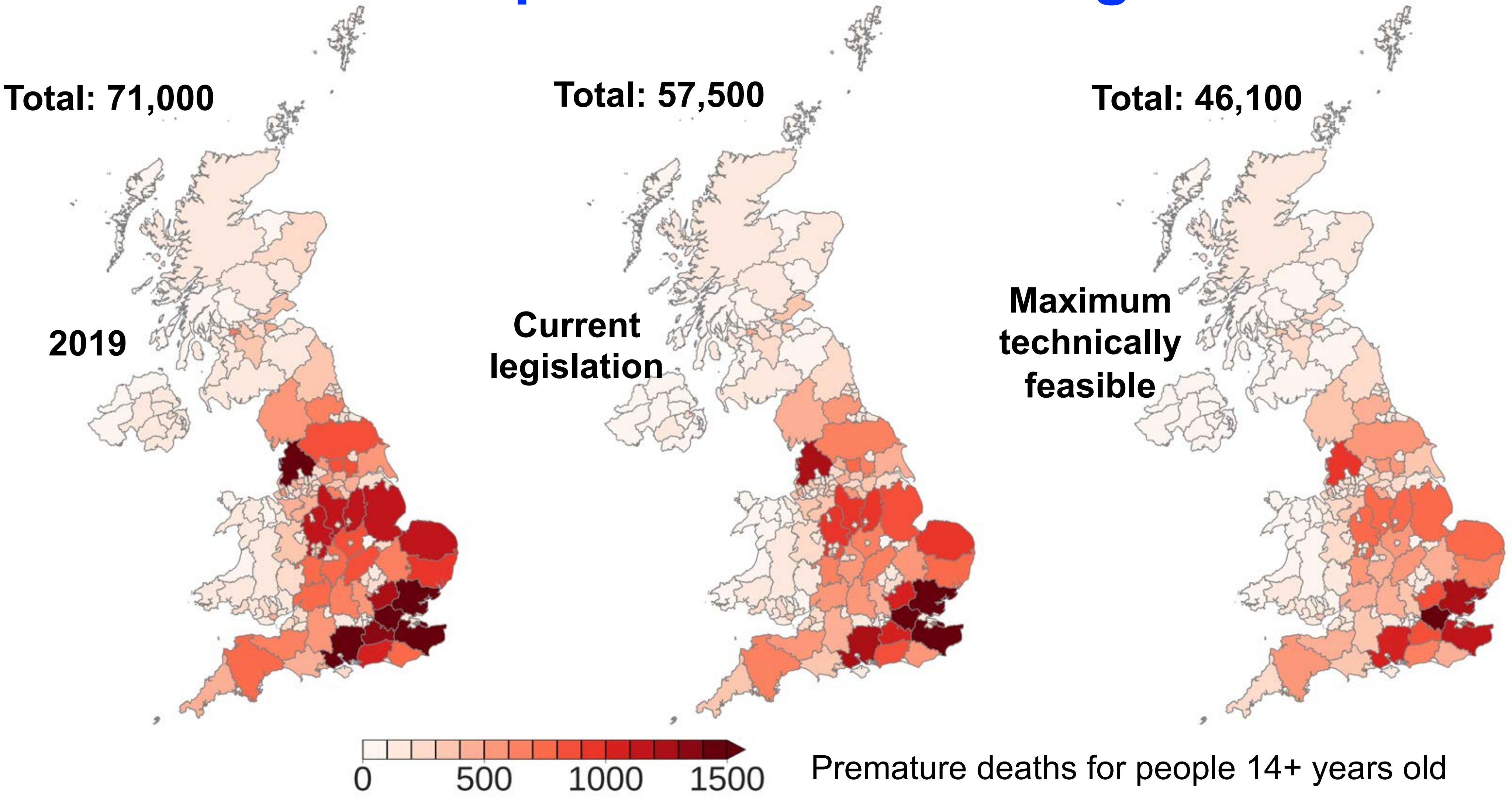
Health risk curve used in this study



[Vodonos et al., 2018]

Yields more excess deaths than Public Health England 2014 study due to differences in relative risks

Public Health Impacts of Future Mitigation Measures

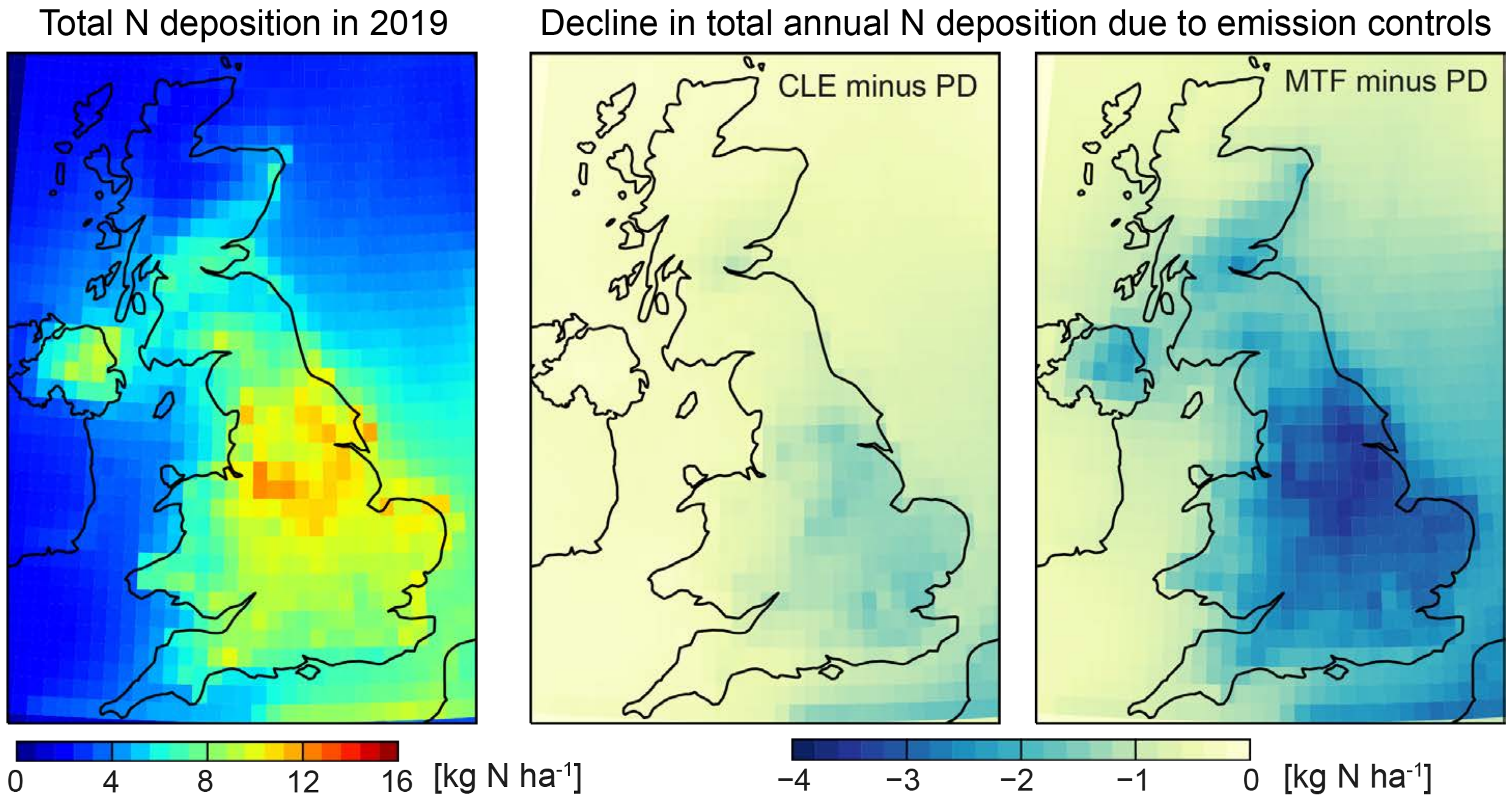


Excess deaths from $PM_{2.5}$ in 2019 of ~71,000 (PHE report for 2010 was ~29,000).

Avoided deaths of ~13,000 for current legislation and of ~25,000 if adopt best solutions available

Ecosystem Impacts of Future Mitigation Measures

Reduced (ammonium) and oxidized (nitrate) nitrogen deposition today and likely in the future



Total: **429 Gg N**
Ammonium (NH_x): **252 Gg**
Nitrate (NIT): **177 Gg**

48 Gg decrease in total
5 Gg increase in NH_x
53 Gg decrease in NIT

116 Gg decrease in total
42 Gg decrease in NH_x
74 Gg decrease in NIT

Concluding Remarks

- Satellite columns effective for estimating top-down ammonia emissions
- Suggest underestimate in dairy cattle ammonia emissions in summer; support springtime peak from fertilizer application
- Discrepancy in dairy cattle ammonia emissions needs to be resolved
- Rural ammonia emissions dominant contributor to $PM_{2.5}$ in all UK cities
- City sources make modest contribution to urban $PM_{2.5}$, supported by network of low-cost sensors, so local solutions alone insufficient
- Current legislation only marginally effective at reducing $PM_{2.5}$
- Adoption of maximum technically feasible solutions yields health burden reductions 2-times greater than current legislation
- Potentially large ecosystem benefits too, though still to quantify exceedances of nitrogen critical load