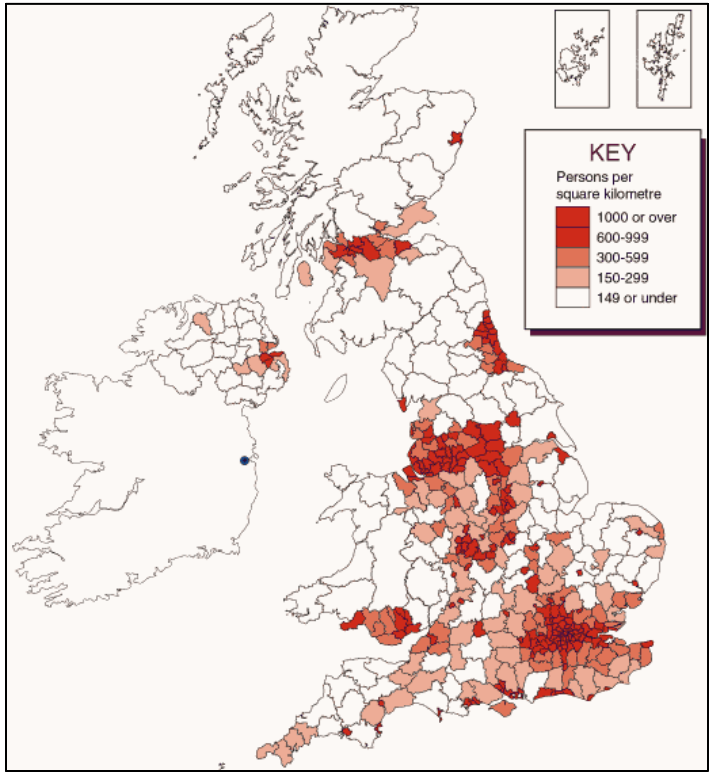
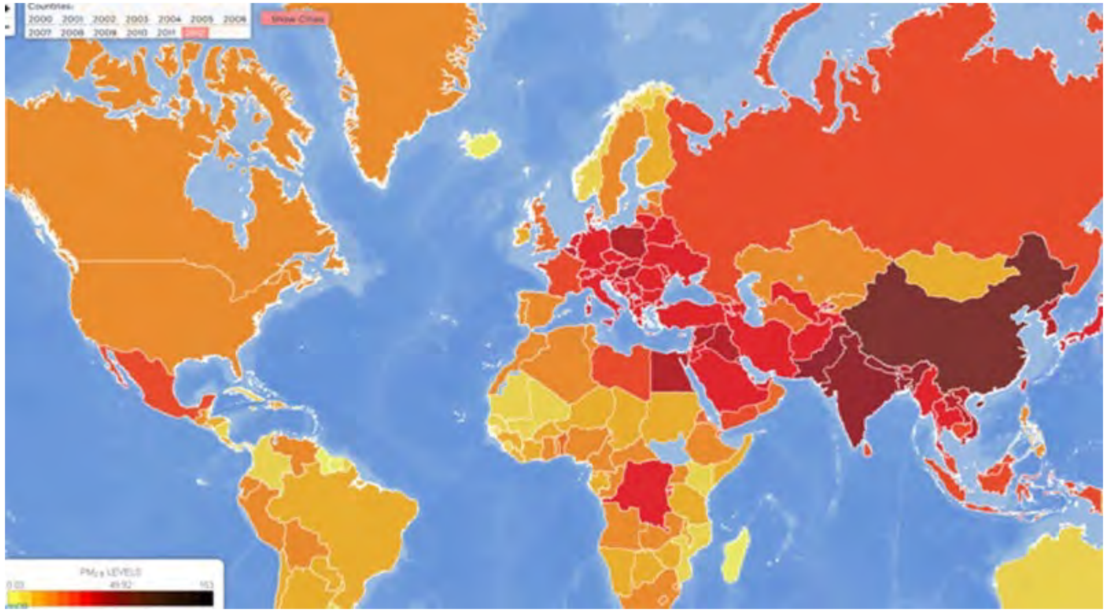
Use of Chemical Transport Models to Motivate and Inform Air Quality Policies at Local, National and Global Scales





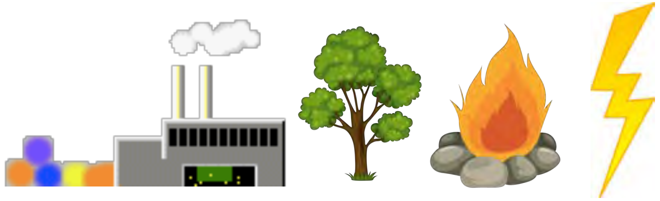
Eloïse Marais **ERC HEAL Workshop** 7 July 2022 e.marais@ucl.ac.uk

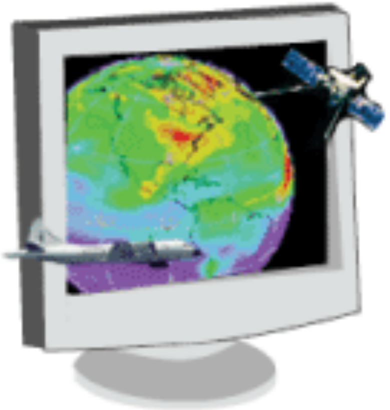
Lab: https://maraisresearchgroup.co.uk/; **Profile**: https://www.geog.ucl.ac.uk/people/academic-staff/eloise-marais

The GEOS-Chem Chemical Transport Model

GEOS-Chem

Emissions (natural/human)





Offline meteorology (NASA GMAO)

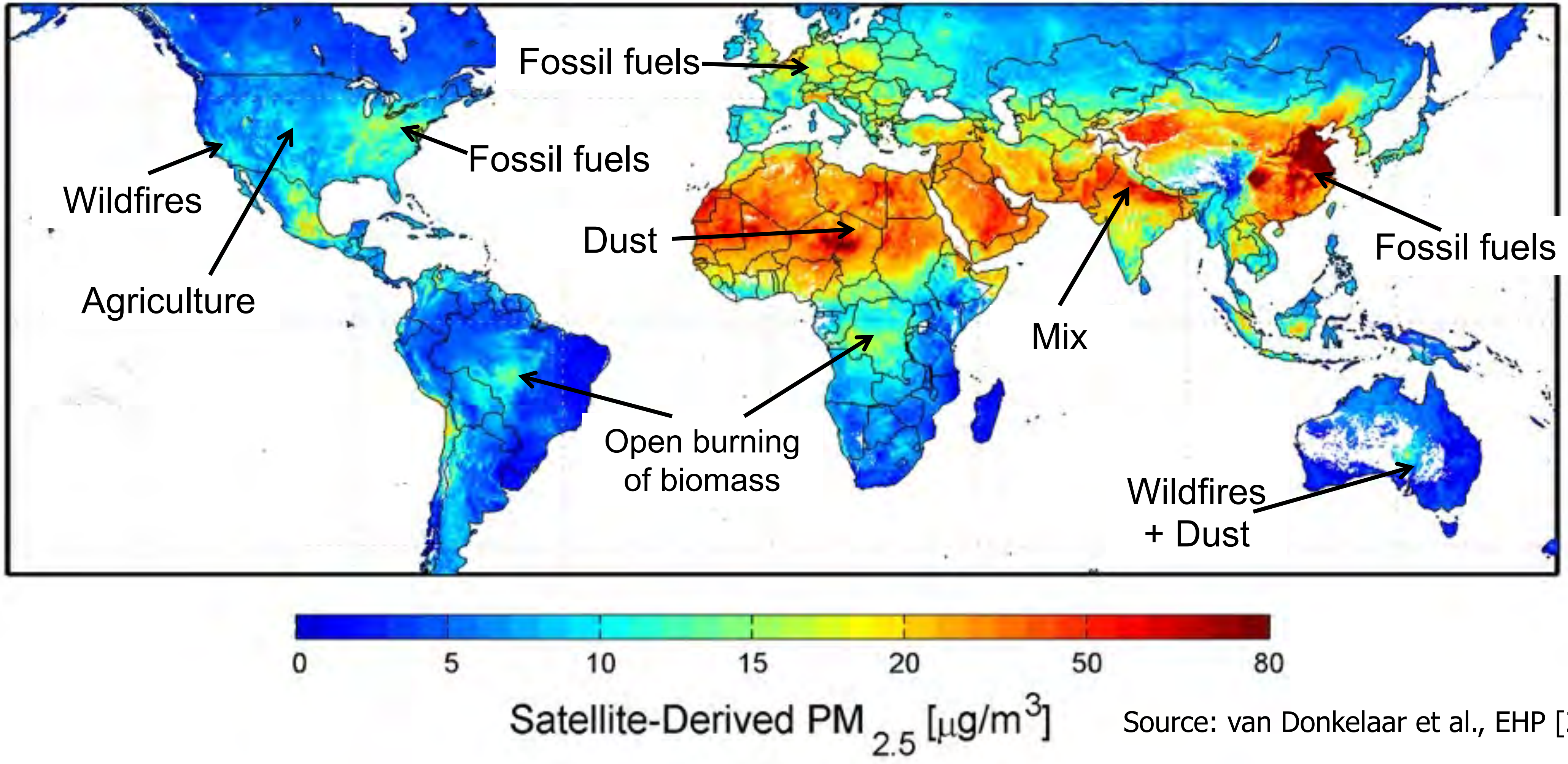
Chemistry
Transport
Dry/wet deposition

3D global/regional atmospheric concentrations

GEOS-Chem website home page: https://geos-chem.seas.harvard.edu/

Global Distribution of Fine Particles ($PM_{2.5}$)

$PM_{2.5}$ derived with satellite and surface observations and a model

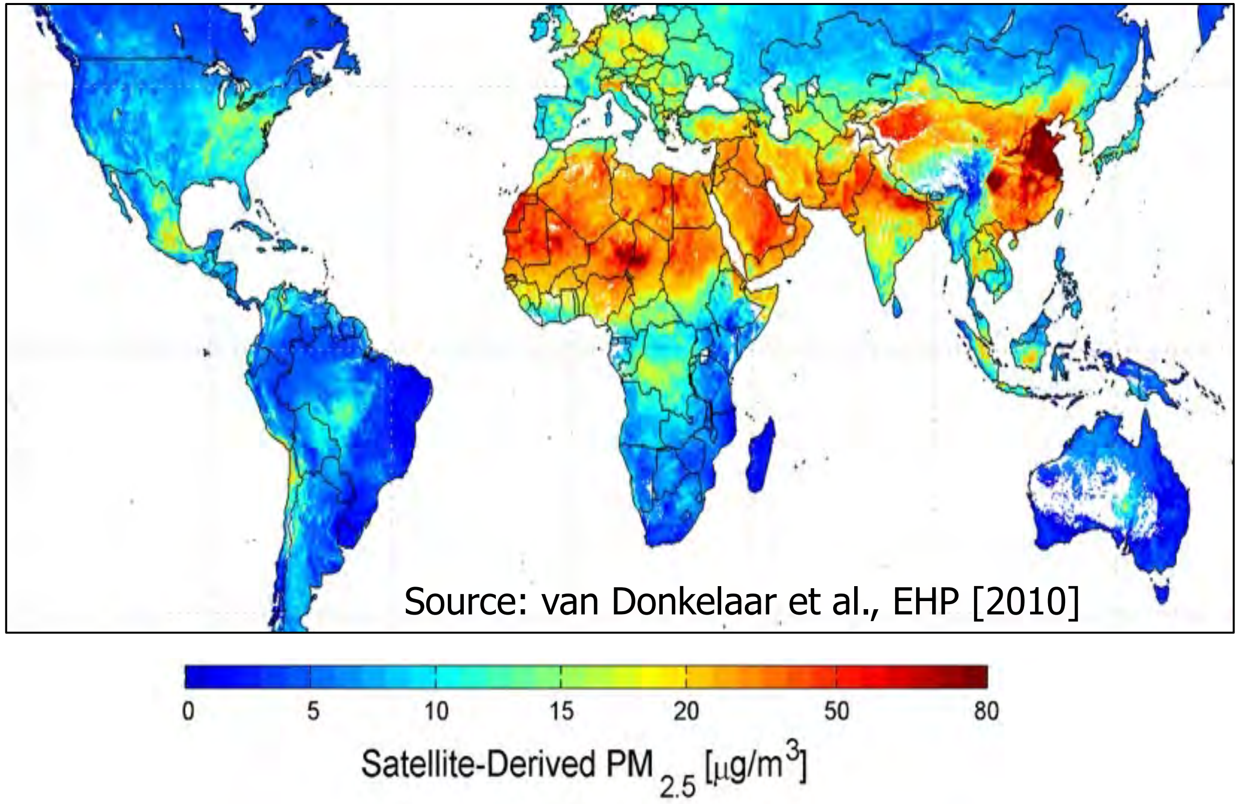


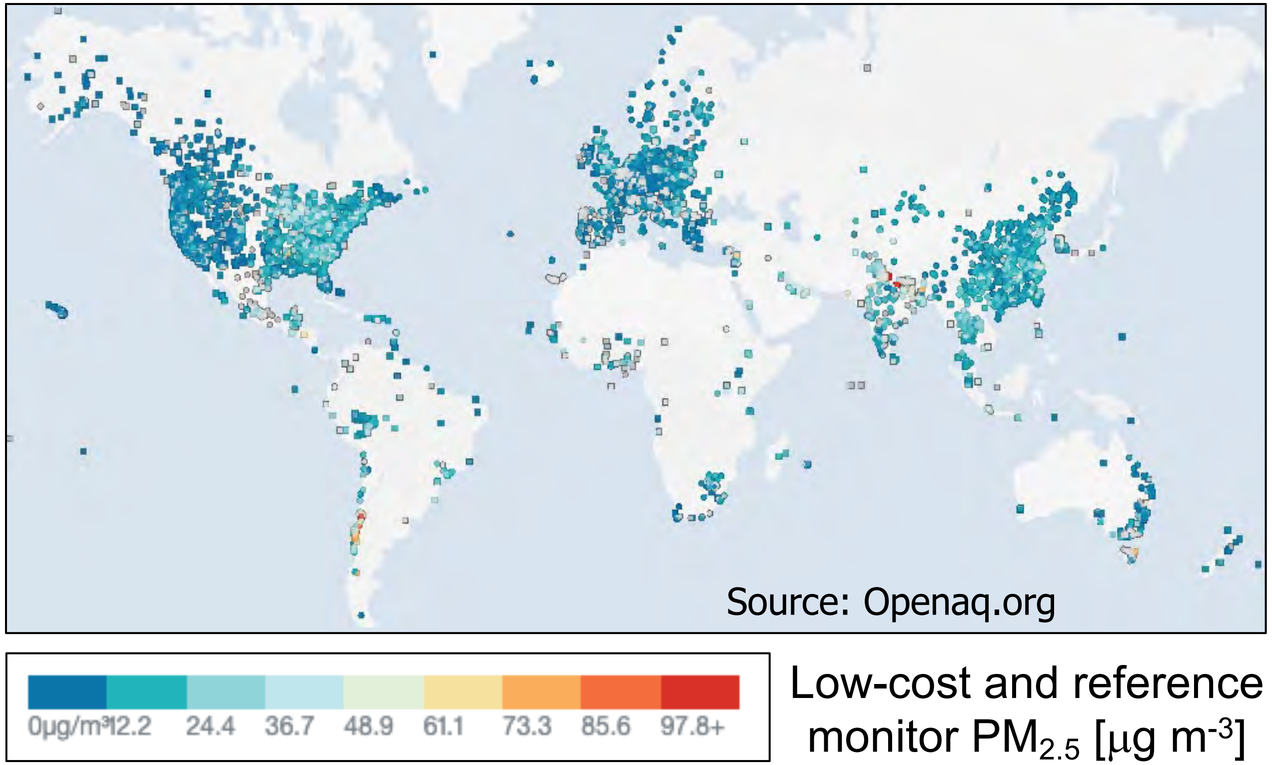
Source: van Donkelaar et al., EHP [2010]

Dominant sources include a range of natural and anthropogenic sources that vary spatially and seasonally

Challenging to isolate sources using observations

Satellite products (left) and surface measurements (right) provide total $PM_{2.5}$





Low-cost and reference monitor $PM_{2.5}$ [$\mu g\ m^{-3}$]

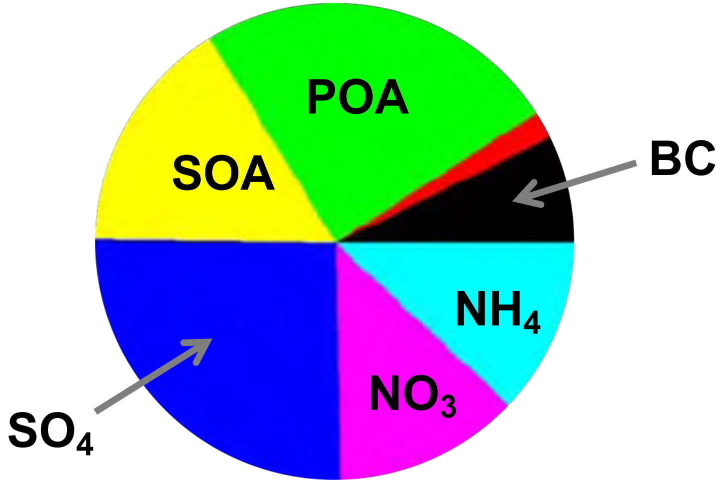
Even with measurements of individual $PM_{2.5}$ components, it is challenging to tease out the contribution from fossil fuels, **so we use a model**.

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

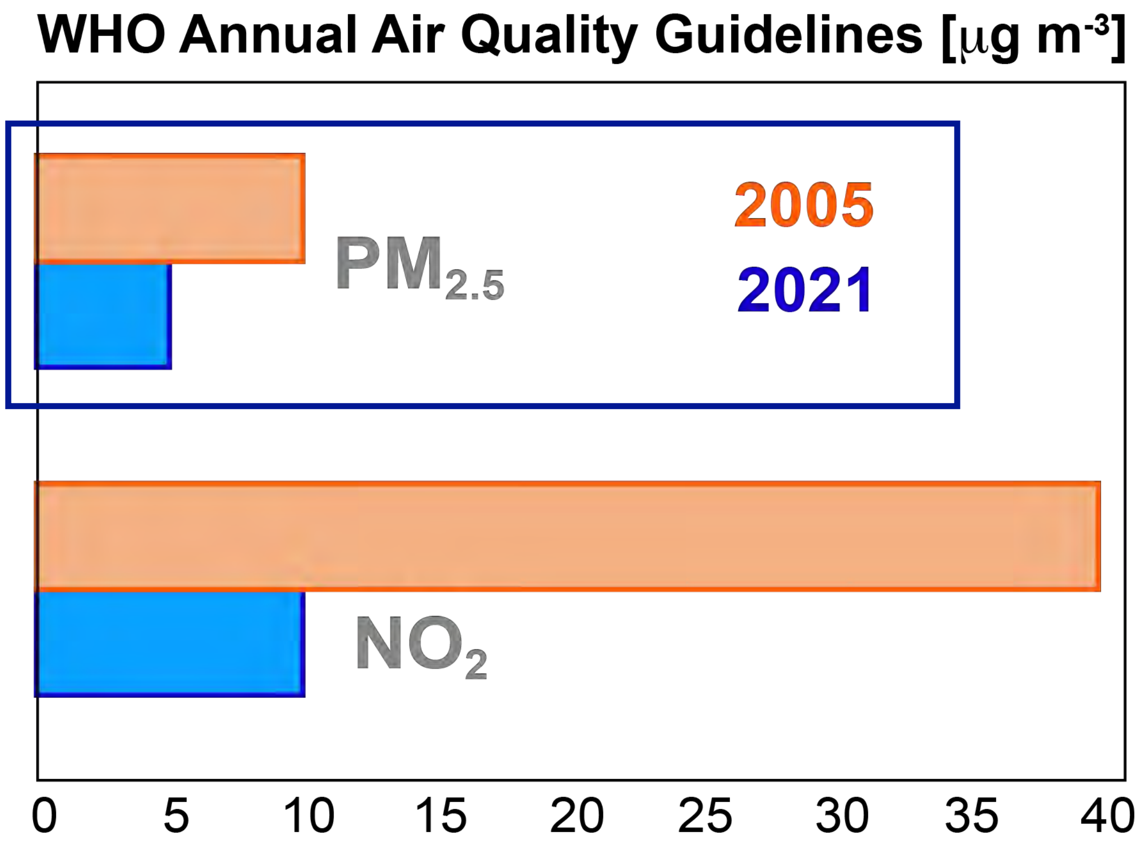
Other inorganics

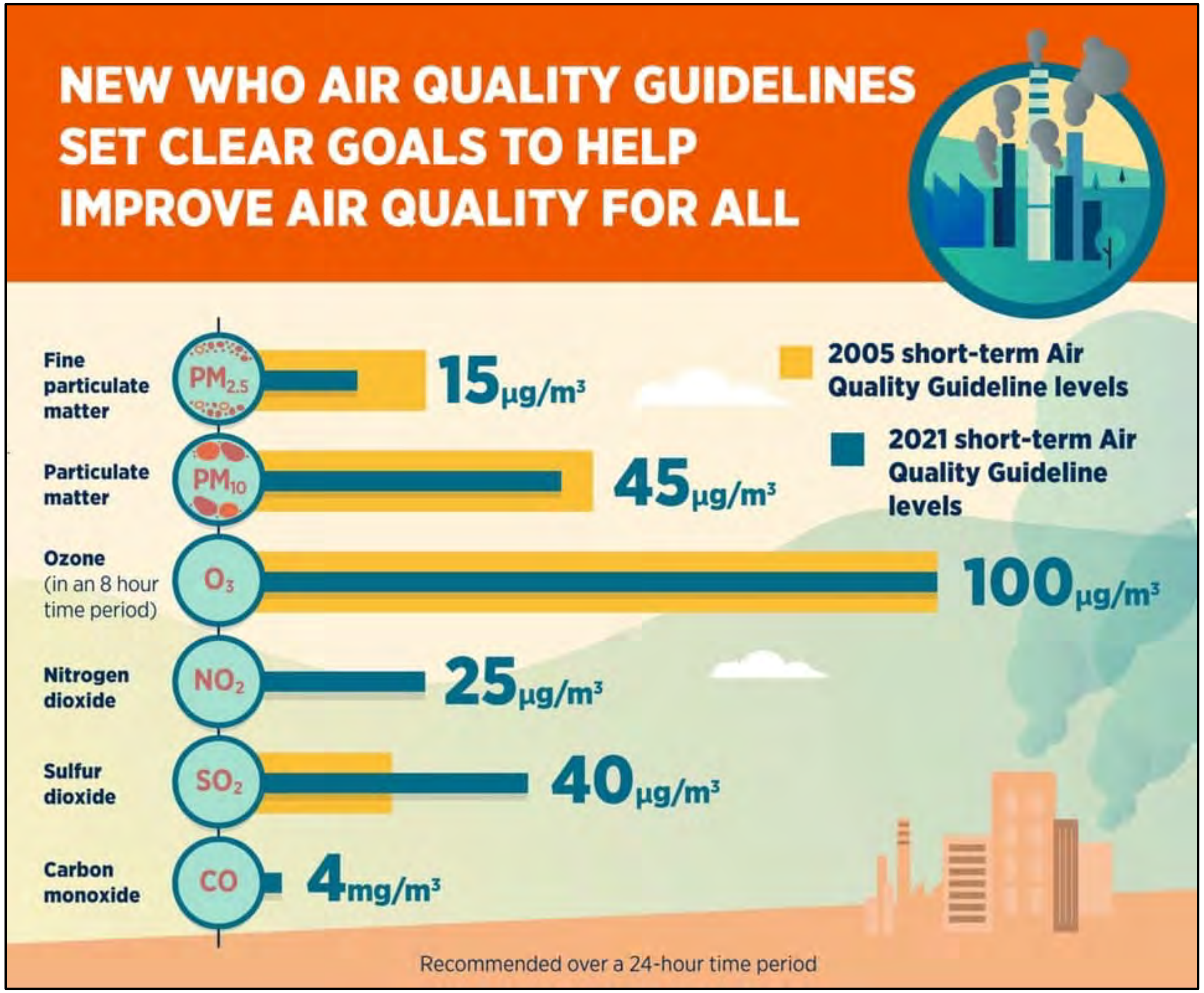
Organic aerosols primary+secondary

$PM_{2.5}$ includes local and distant sources (long atmospheric lifetime)

Stricter World Health Organization (WHO) Guideline

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





Source: WHO Facebook page

Sources of Fine Particles ($PM_{2.5}$) in UK Cities

Jamie Kelly
(postdoc)

UCL
Eloise A. Marais
Jamie M. Kelly

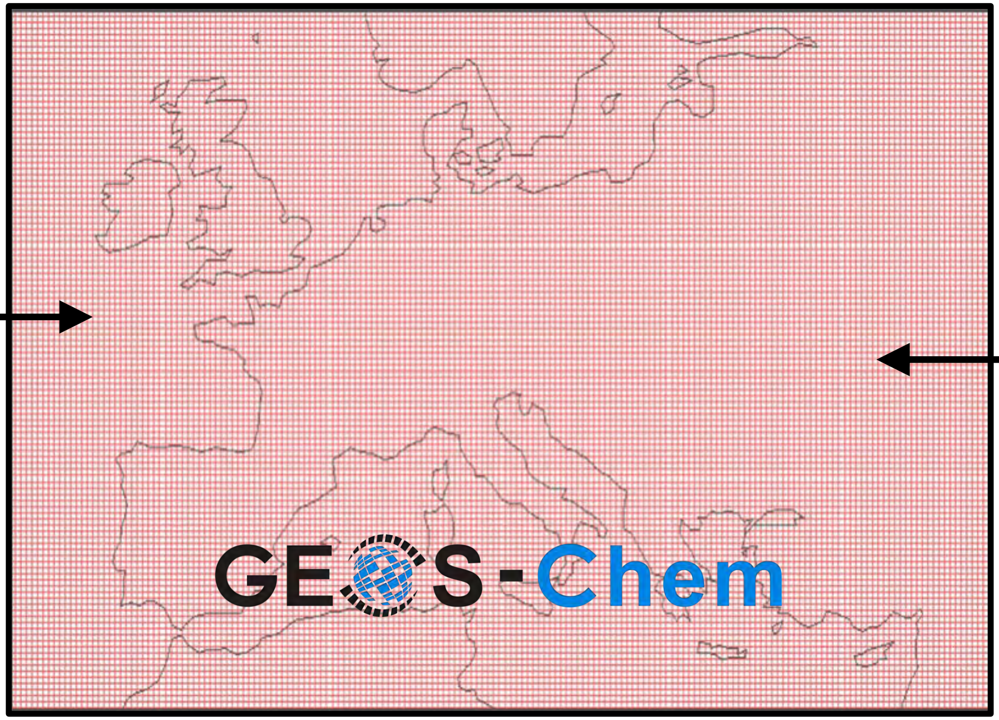
EARTH SENSE
Jordan White
Roland J. Leigh

Leicester City Council
Jolanta Obszynska
Matthew Mace

Simulate $PM_{2.5}$ and Sources with GEOS-Chem

Comprehensive emissions

3D Atmospheric Chemistry Transport Model



Chemistry, transport, loss processes

NASA Meteorology

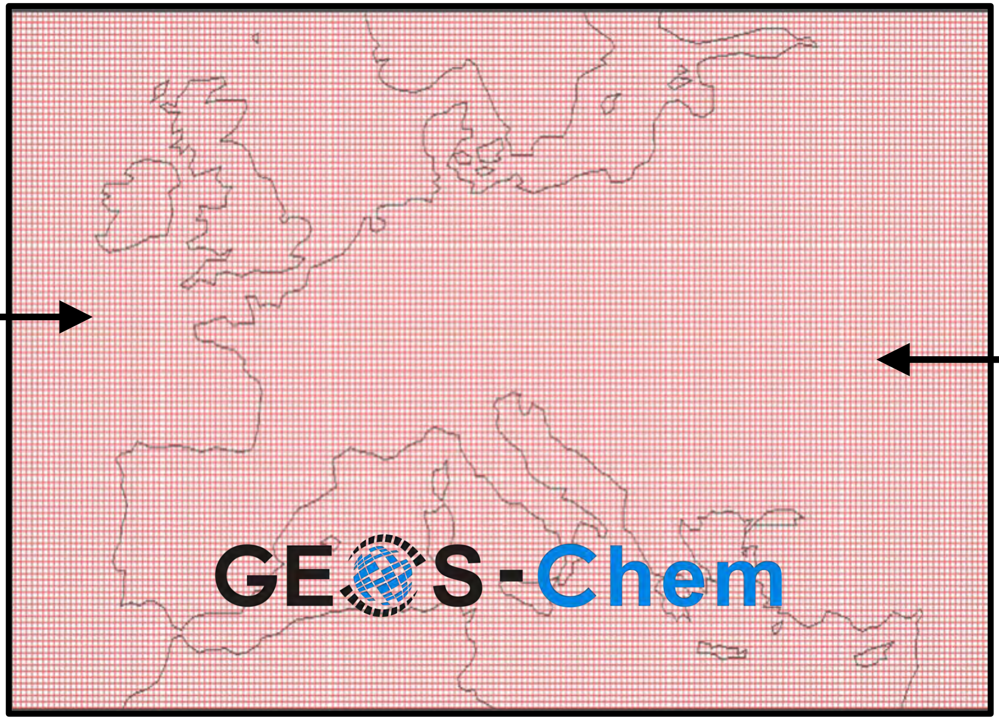
$PM_{2.5}$ from all but one source

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

Simulate $PM_{2.5}$ and Sources with GEOS-Chem

3D Atmospheric Chemistry Transport Model

Comprehensive emissions



Chemistry, transport, loss processes

NASA Meteorology

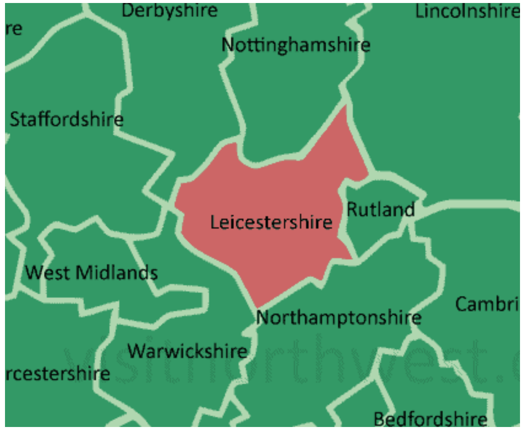
$PM_{2.5}$ from all but one location

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

Test Contribution of Potentially Influential Sources

Local

City



County

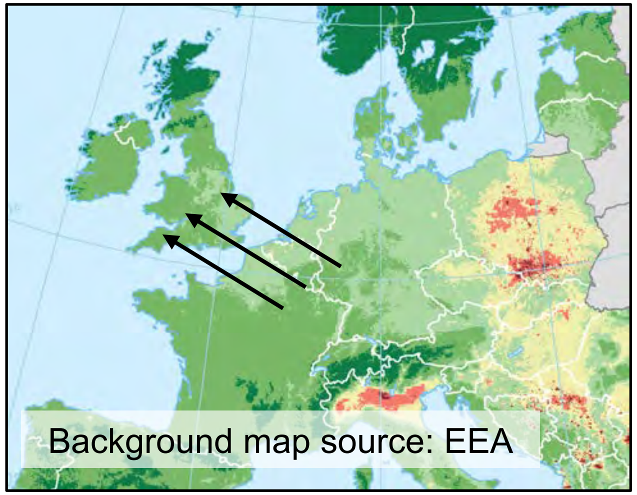
National

Nearby large cities

Transport

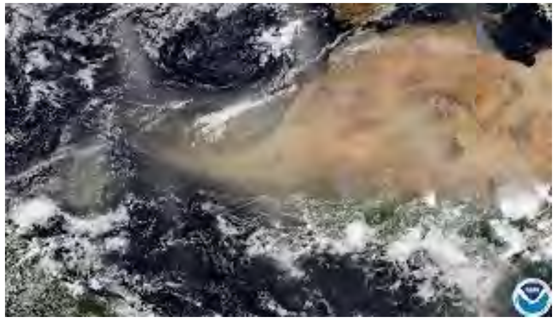
Agriculture

Regional



Mainland Europe

Global

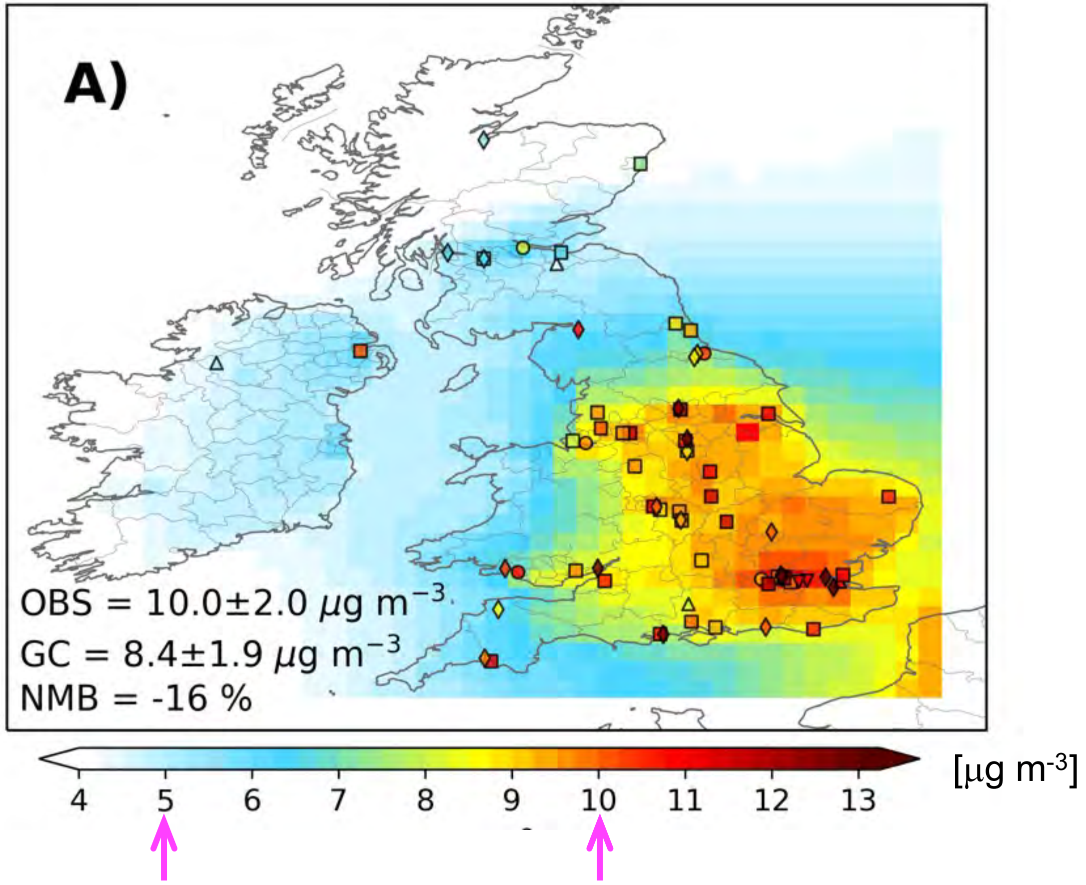


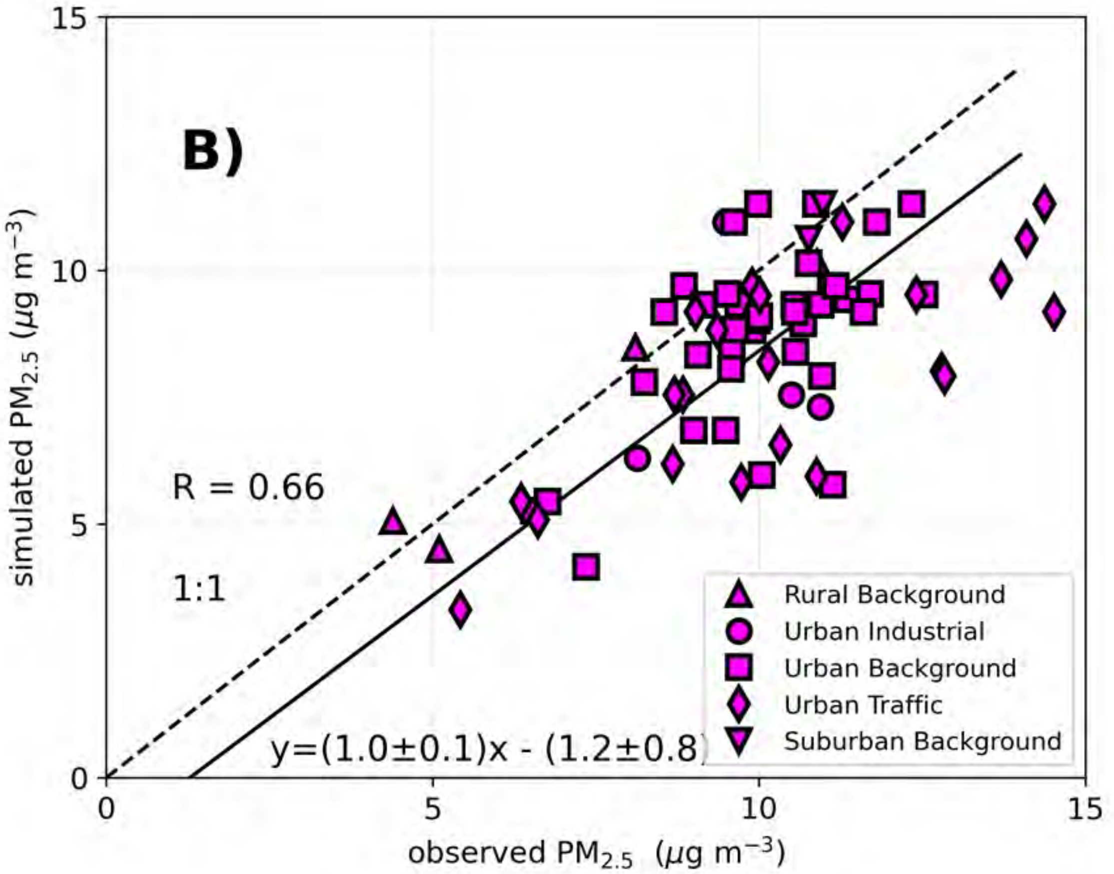
Desert Dust

Assess Model using Reference Monitors

Observations of total $PM_{2.5}$ from the Automatic Urban and Rural Network (AURN)

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



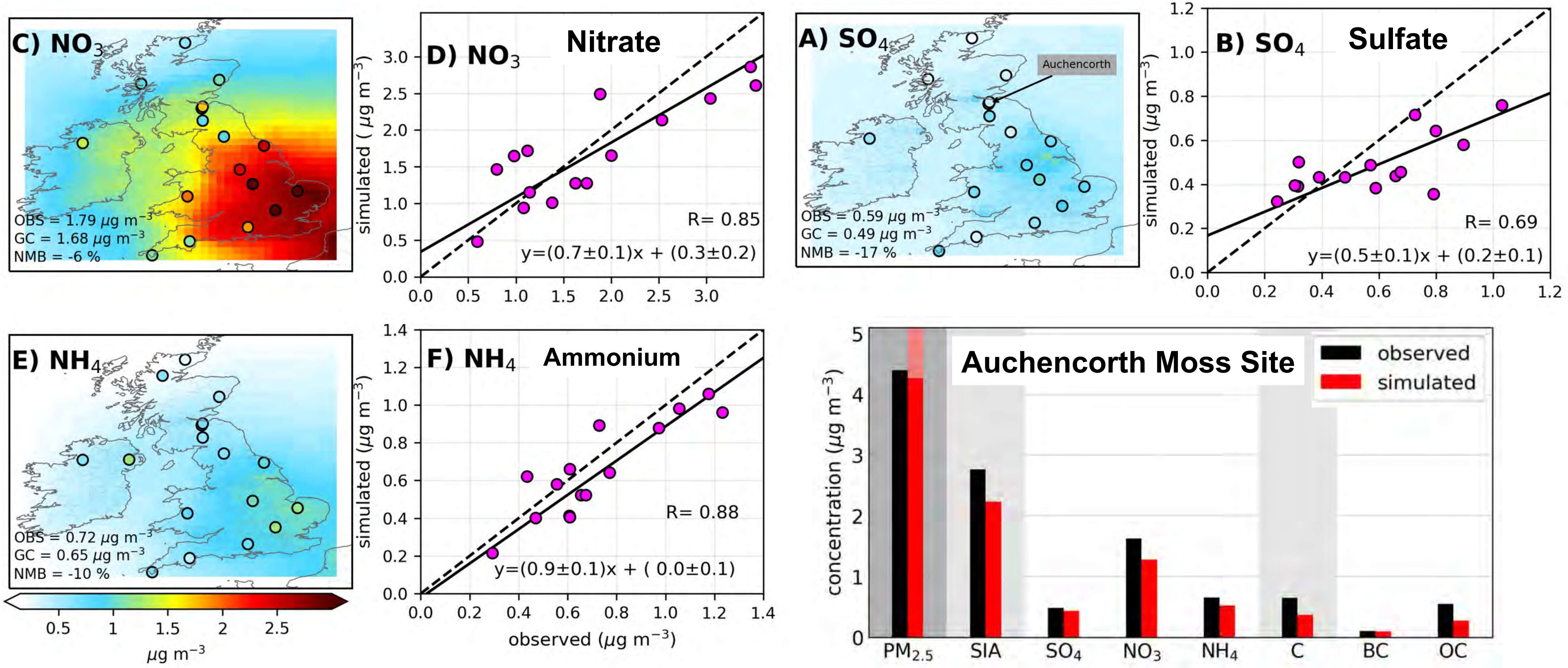


75% of UK exceeds updated WHO guideline

Consistent spatial pattern (**R = 0.66**) and variance (**slope = 1.0**). Model **16% less** than observations

Assess Validity of Model using Reference Monitors

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

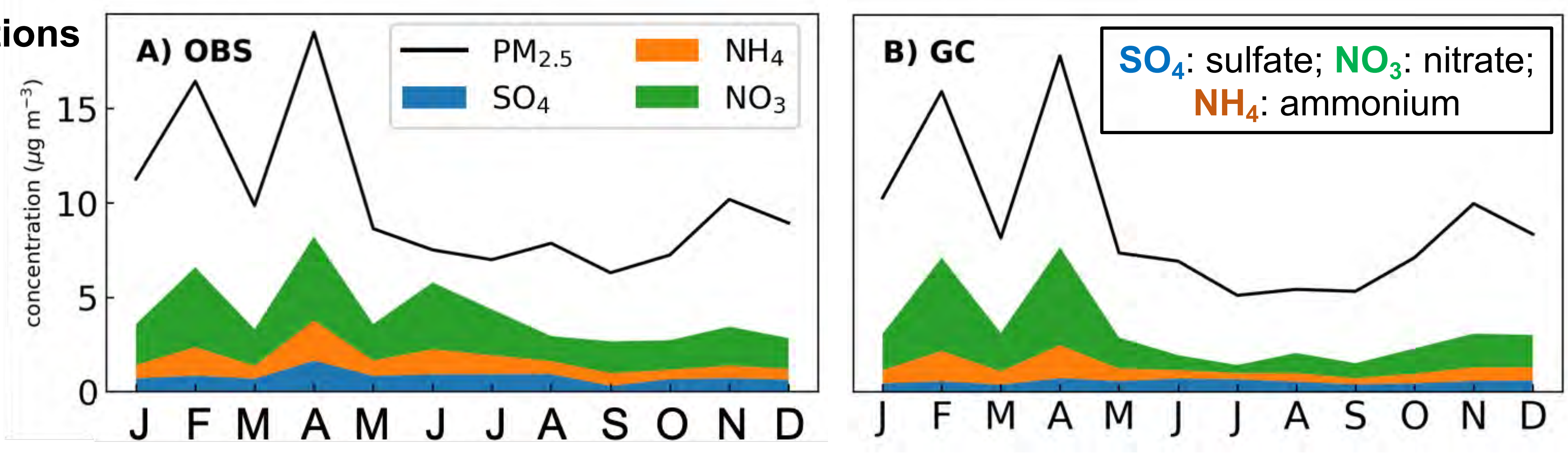


Model underpredicts observed (sulfate, nitrate, ammonium) and possibly overpredicts unobserved (dust) components. Model captures variance of components from NO_x (nitrate) and ammonia (ammonium)

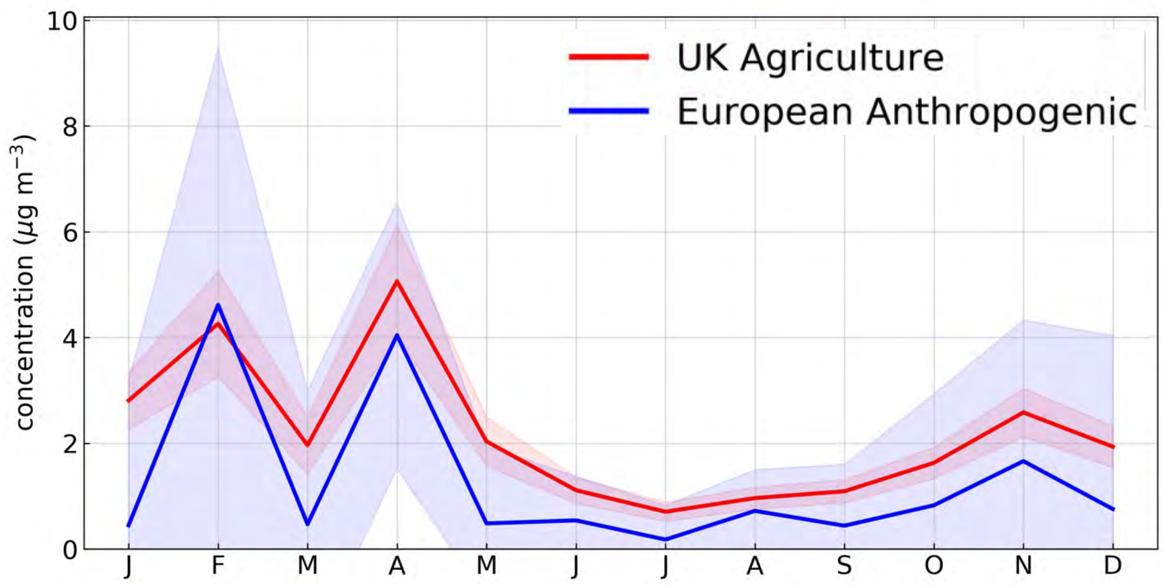
Assess Validity of Model using Reference Monitors

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

Observations



GEOS-Chem

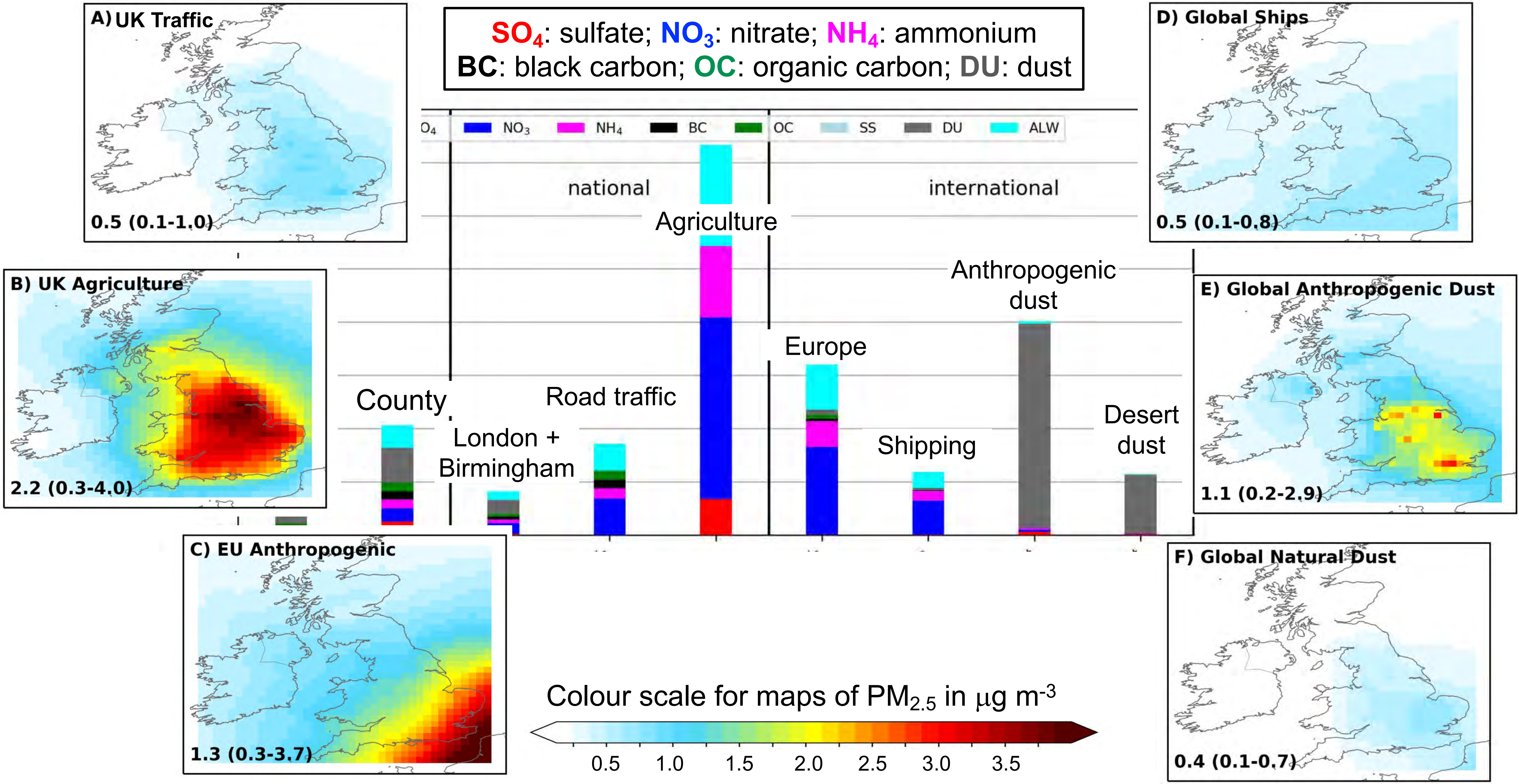


Interpret results with GEOS-Chem:

Cold season enhancements due to combined effect of pollution transport from Europe and agricultural emissions of ammonia

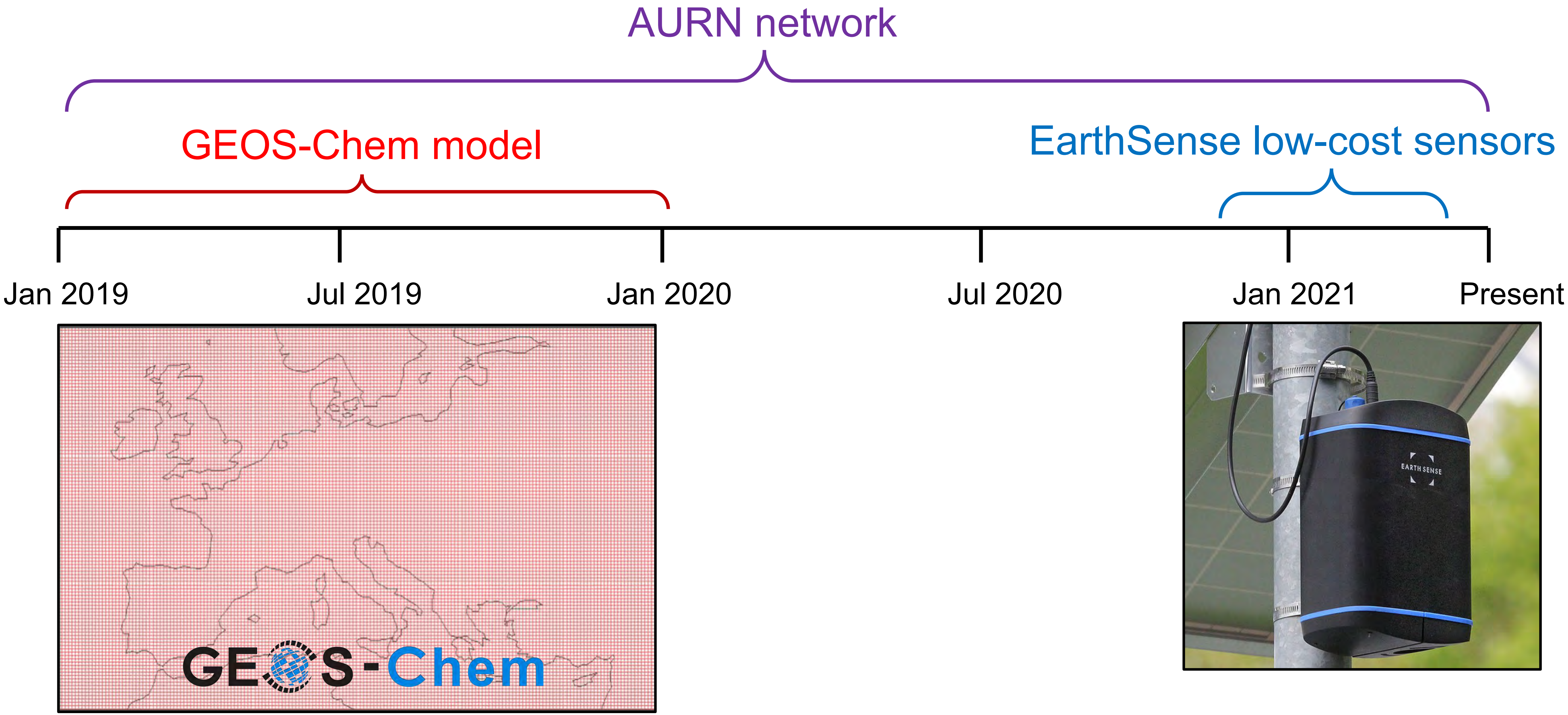
Contribution of Sources to annual $PM_{2.5}$ in Leicester

SO_4: sulfate; NO_3: nitrate; NH_4: ammonium
BC: black carbon; OC: organic carbon; DU: dust



Corroborating Evidence from Low-Cost Sensors

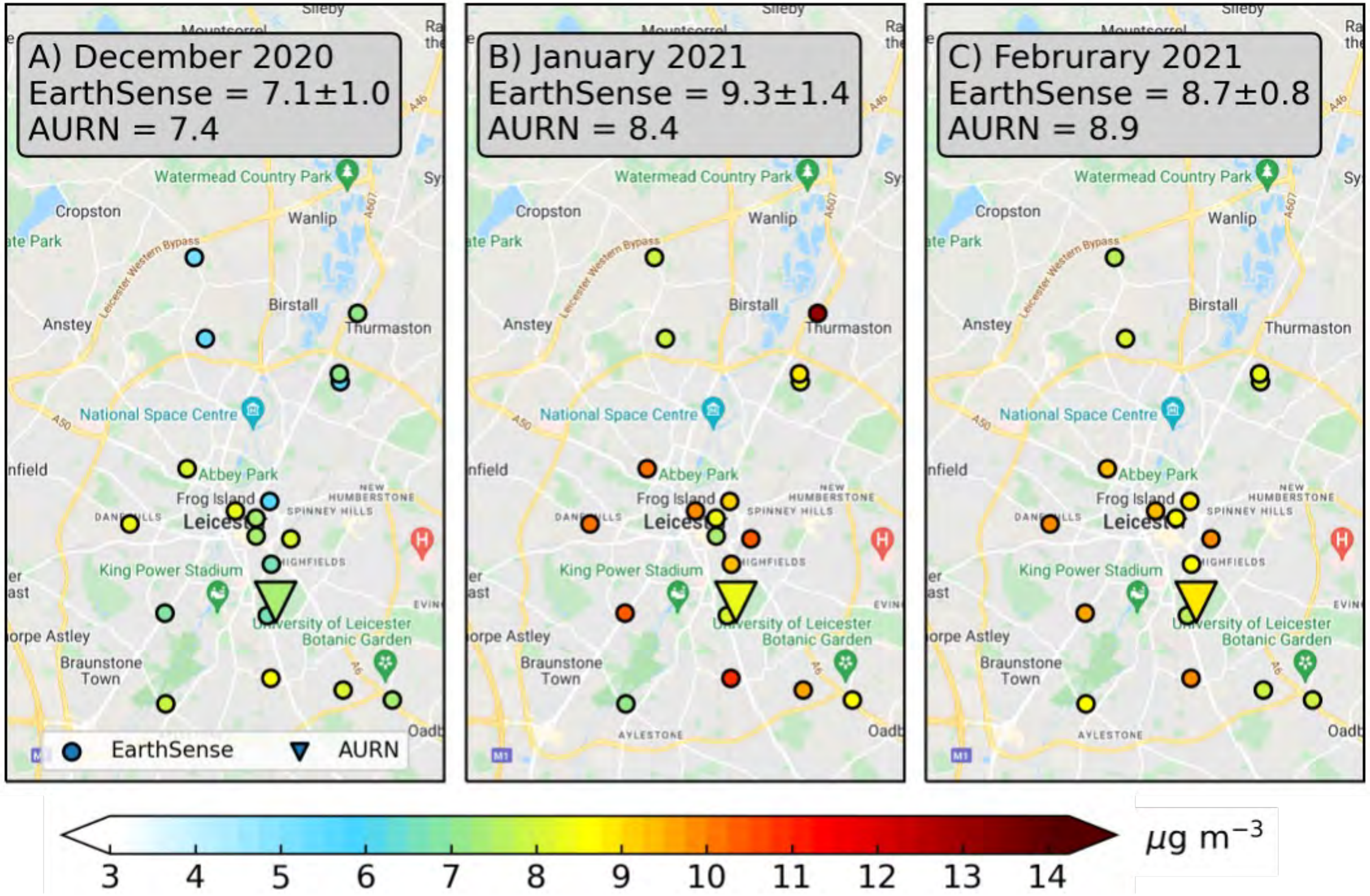
Low-cost network of sensors distributed throughout Leicester from Dec 2020 to Feb 2021



Corroborating Evidence from Low-Cost Sensors

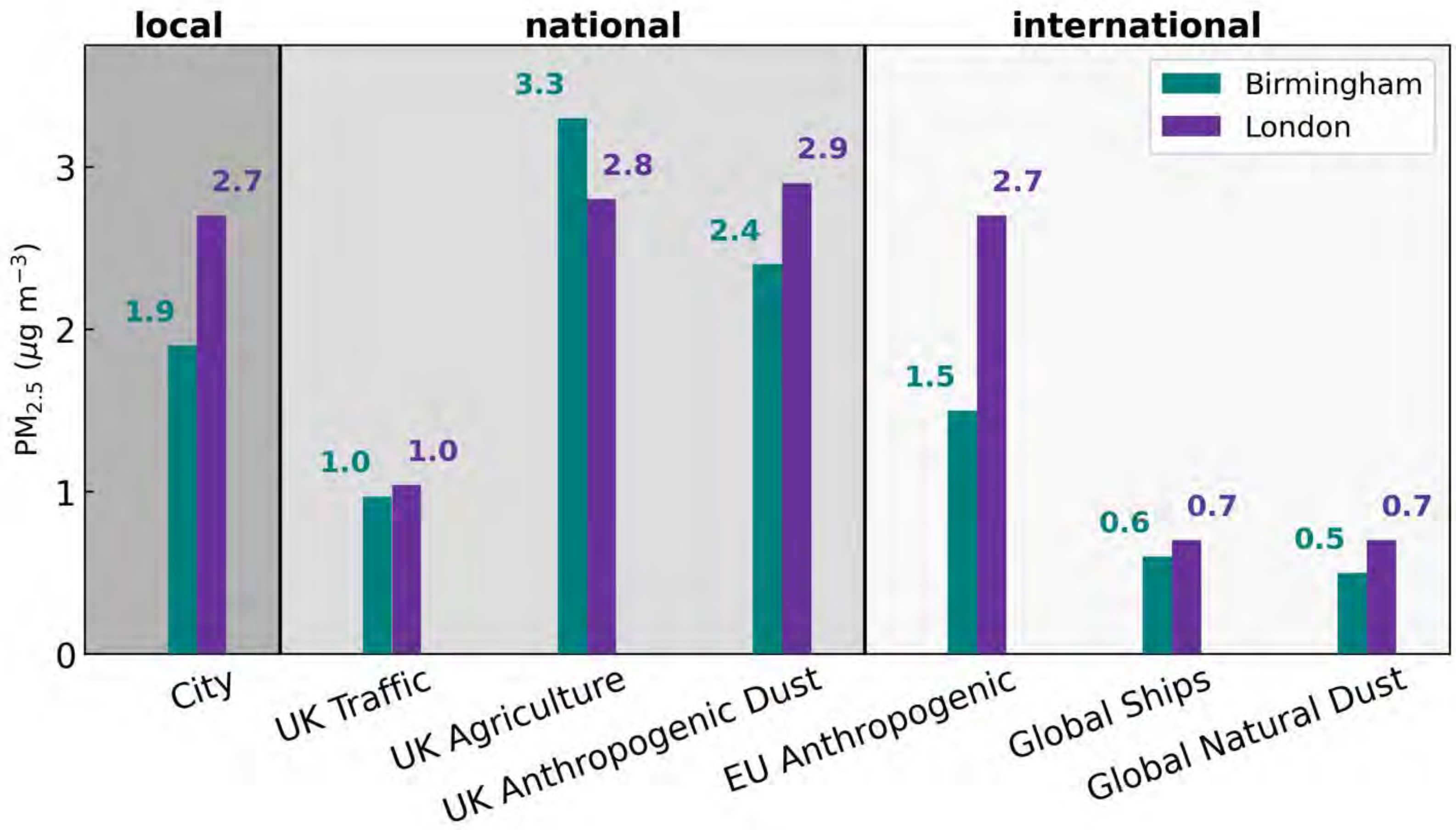
Mean ± std dev:

Low-cost sensors
Reference monitor



According to low-cost sensors, local sources contribute **7%**. Model similarly low (**2%**)

Results for Large Cities like London and Birmingham



London: 1,600 km^2

Birmingham: 270 km^2

Leicester: 70 km^2

Local sources compete with rural agriculture in anomalously large London

Generalizable expression for estimating $PM_{2.5}$ from local sources and agriculture:

$$PM_{2.5,\mathbf{local}} = +0.8 \times \mathit{ln}(\text{Area}) - 2.6 \quad (R^2 = 0.89)$$

$$PM_{2.5,\mathbf{agriculture}} = -0.3 \times \mathit{ln}(\text{Area}) + 4.9; \quad (R^2 \sim 1)$$

Conclusions and Acknowledgements

- Under-regulated agricultural sector dominates $PM_{2.5}$ year-round
- Mainland Europe makes large cold-season contribution to $PM_{2.5}$
- Policies targeting local sources only likely to have an effect in large cities
- Results reinforce the need for continued and strengthened international agreements and measures to control ammonia emissions from agriculture
- Agriculture also a prominent source of greenhouse gases (methane, nitrous oxide), so potential for climate and air quality co-benefits

Support provided by Leicester City Council from a Defra-funded Air Quality Grant

Department
for Environment
Food & Rural Affairs

Global premature mortality due to exposure to air pollution from fossil fuels

K. Vohra, A. Vodonos, J. Schwartz, E. A. Marais, M. P. Sulprizio, L. J. Mickley, https://doi.org/10.1016/j.envres.2021.110754

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UCL | HARVARD | UNIVERSITY OF BIRMINGHAM | WALLACE GLOBAL FUND

$PM_{2.5}$ from Burning Fossil Fuels

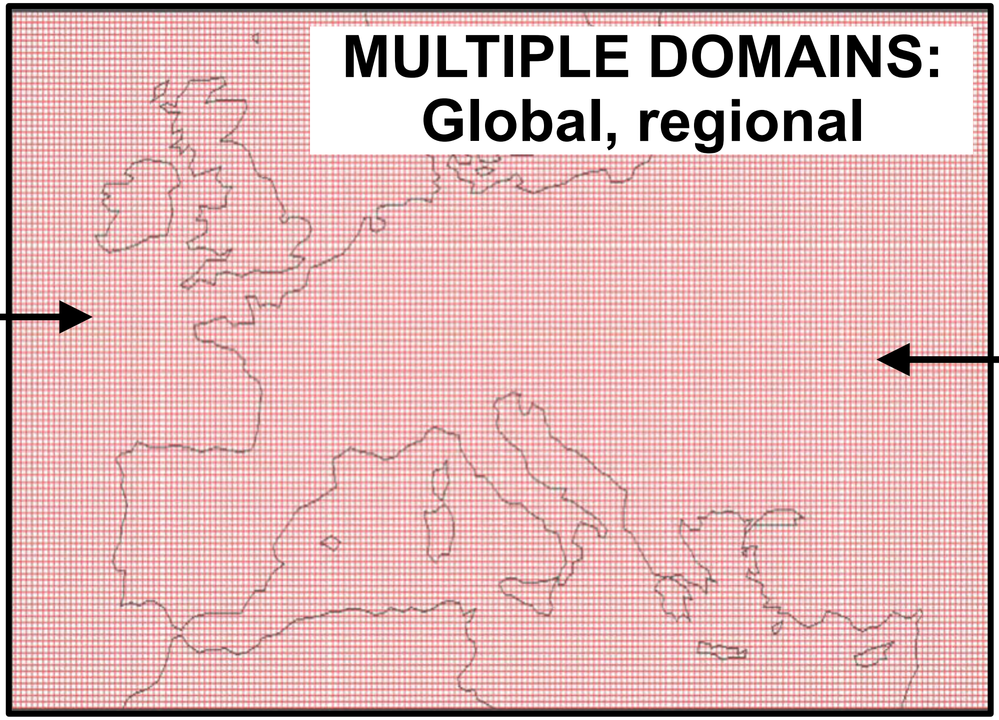
$PM_{2.5}$ precursors emitted from a range of activities that combust fossil fuels

Combustion for transport, industry, energy generation, and domestic heating, lighting and cooking

Simulate Surface $PM_{2.5}$ with GEOS-Chem

Comprehensive emissions sources

3D Atmospheric Chemistry Transport Model



Chemistry, transport loss, processes

NASA Meteorology

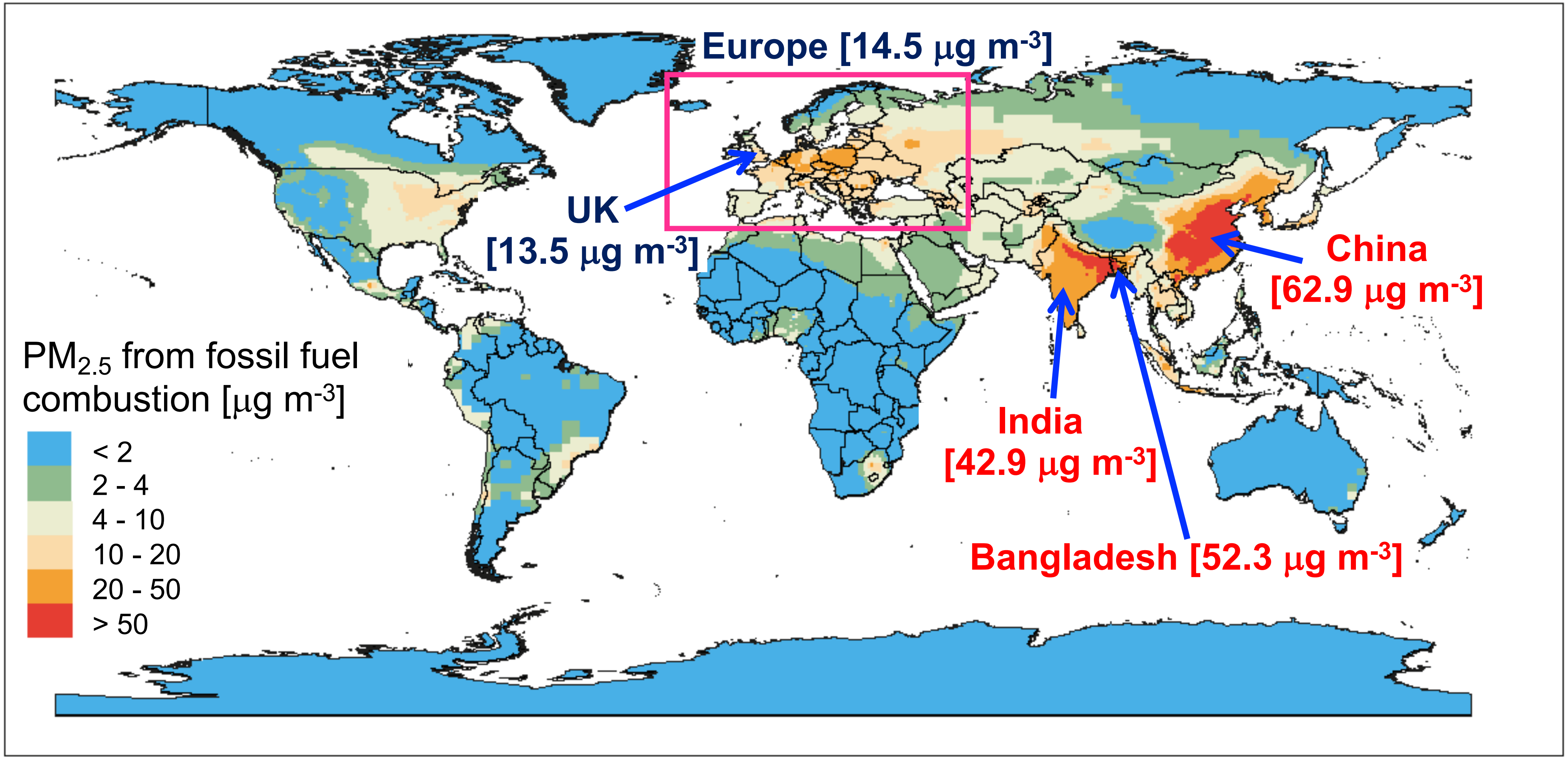
$PM_{2.5}$ from non-fossil-fuel sources

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

GEOS-Chem

GEOS-Chem Estimate of Fossil Fuel $PM_{2.5}$

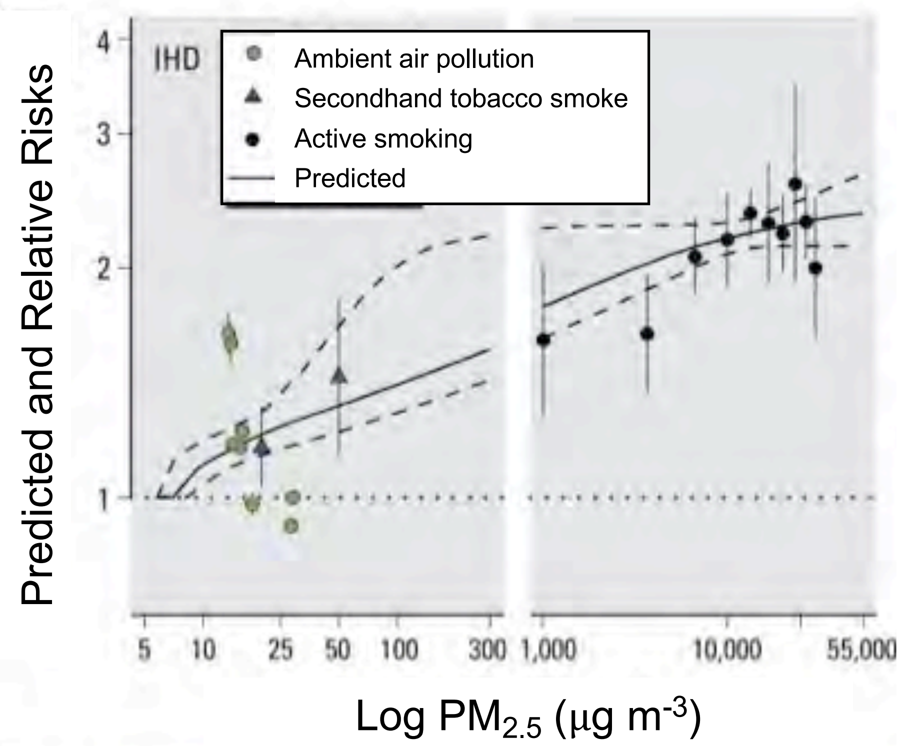
Difference between model simulations with and without fossil fuel $PM_{2.5}$



Hotspots are in China, Bangladesh, India, and central Europe

Standard and Widely used Risk Assessment Models

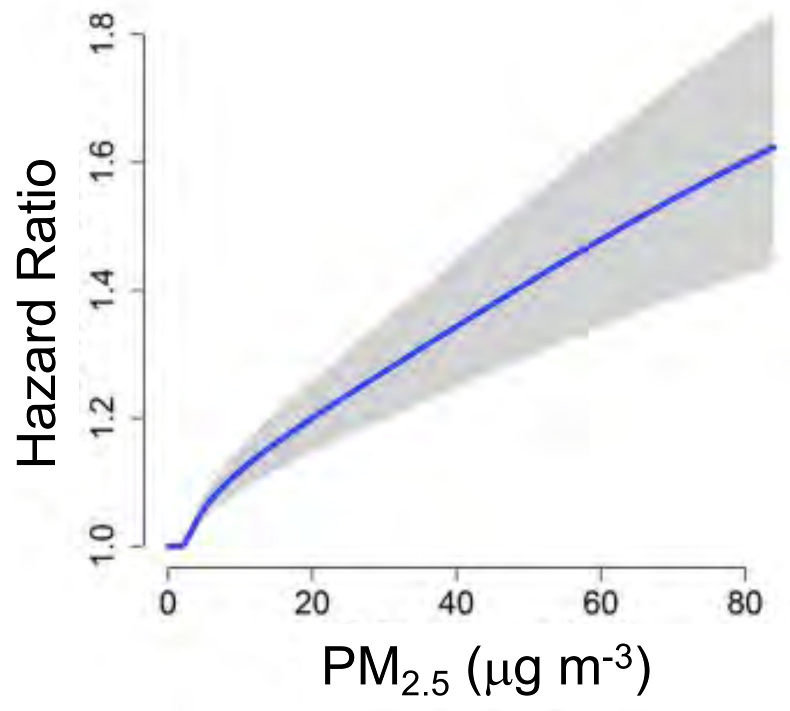
Integrated Exposure-Response (IER)



[Burnett et al., 2014]

Data includes active and passive smoking to address outdoor $PM_{2.5}$ > 40 $\mu g\ m^{-3}$

Global Exposure Mortality Model (GEMM)

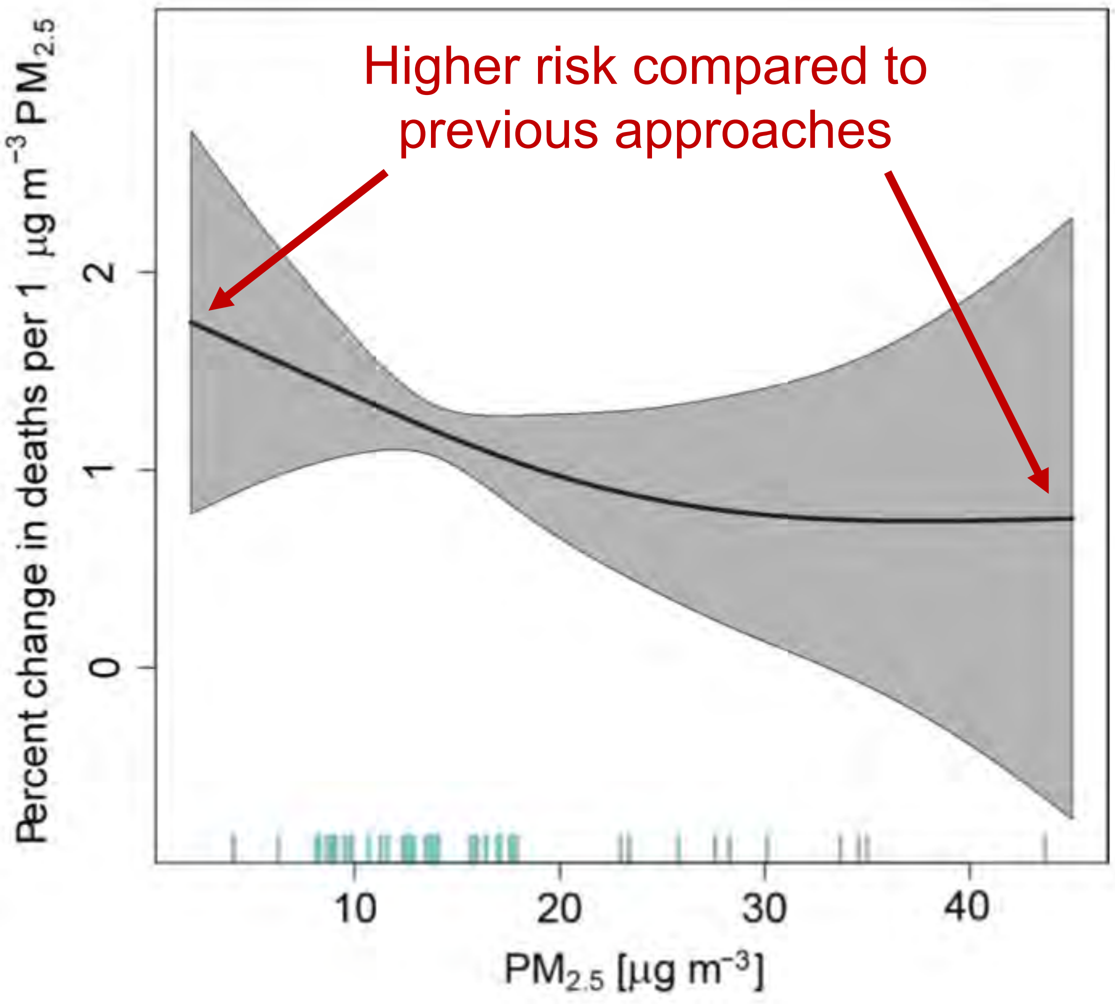


[Burnett et al., 2018]

41 cohort studies and model constrained using 4 parameters

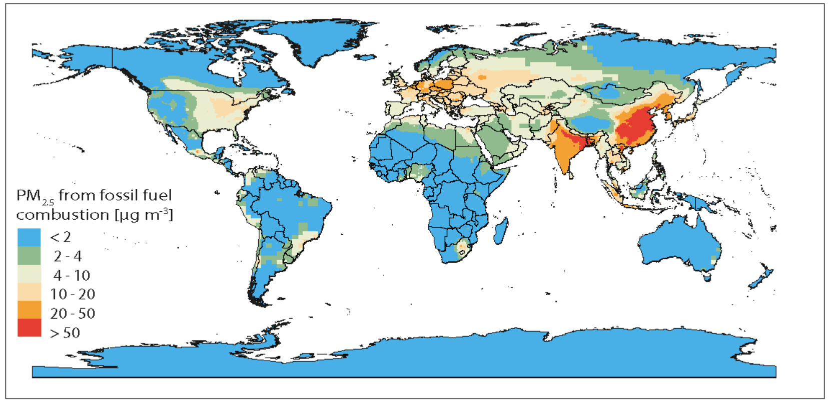
Updated Risk Assessment Model used in our Study

- Flexible shape of concentration-response function
- More cohort studies, and wider concentration and age range than previous approaches
- Includes death from all-causes

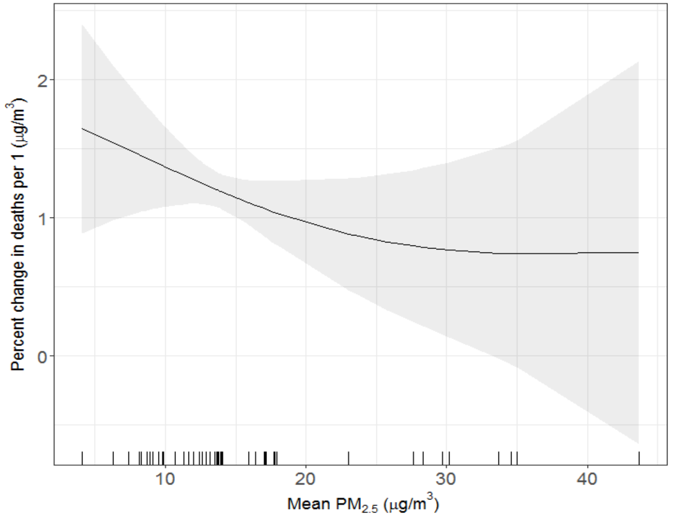


[Vodonos et al., 2018]

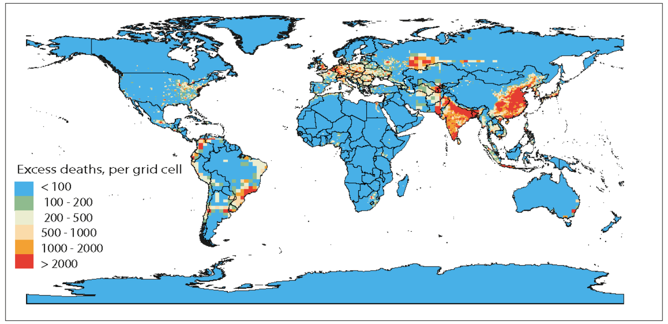
Approach used to Calculate Health Impact



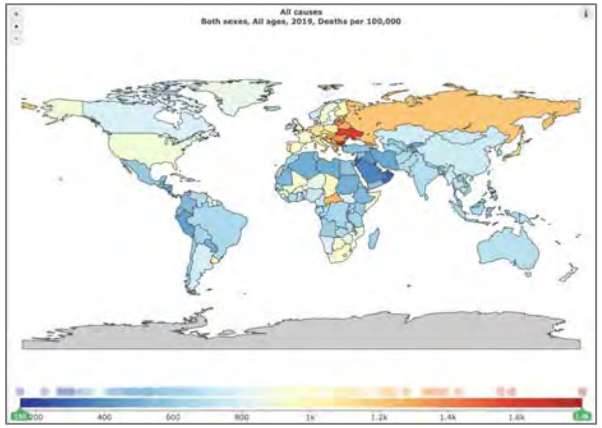
Fossil-fuel $PM_{2.5}$ from GEOS-Chem



Meta-analysis concentration-response function from cohort studies



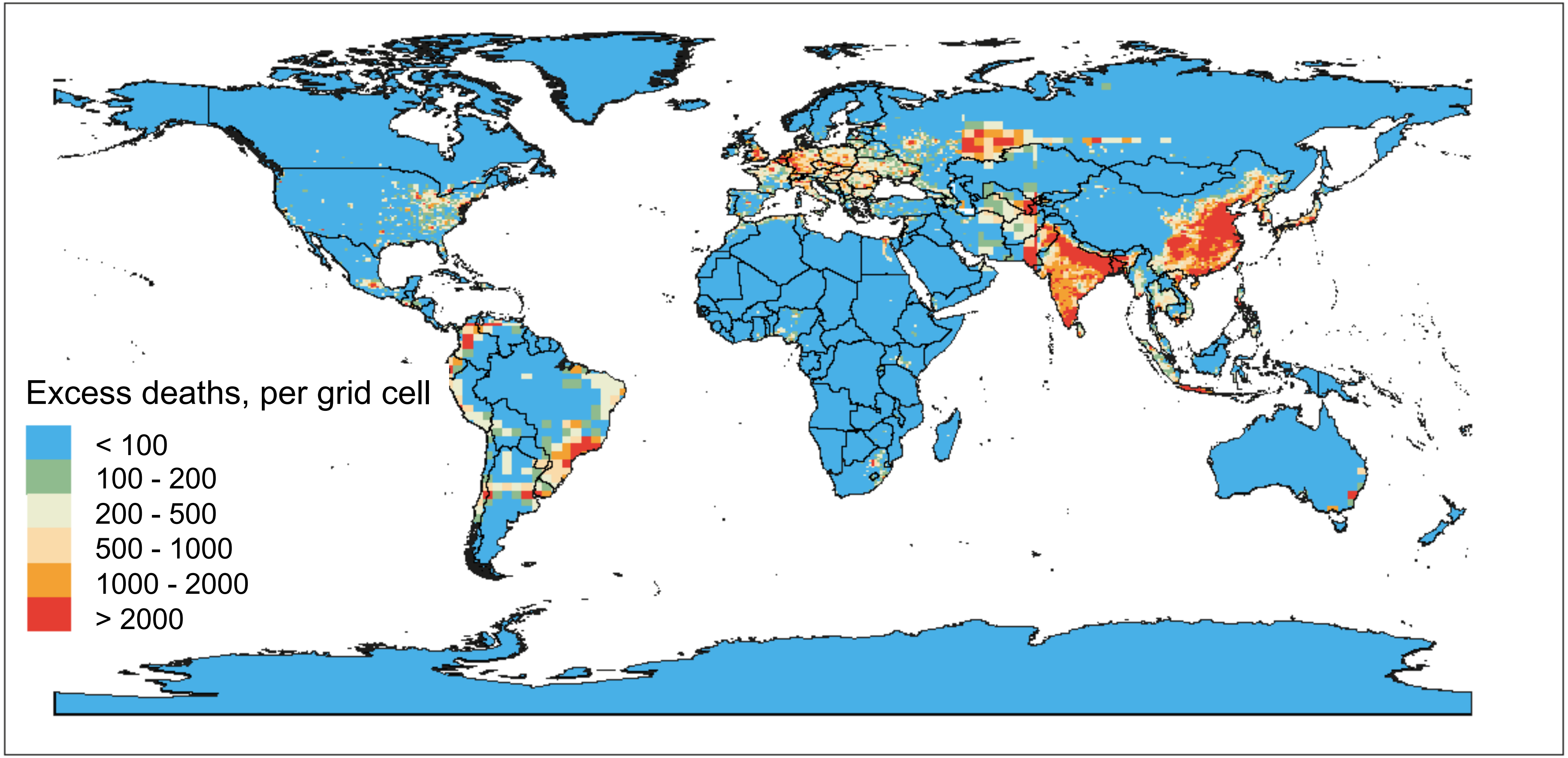
Global premature mortality



Baseline mortality from Global Burden of Disease

We use the derived fossil-fuel $PM_{2.5}$ with baseline mortality in the meta-analysis concentration-response function to estimate global premature mortality

Global Premature Mortality from Fossil Fuel combustion

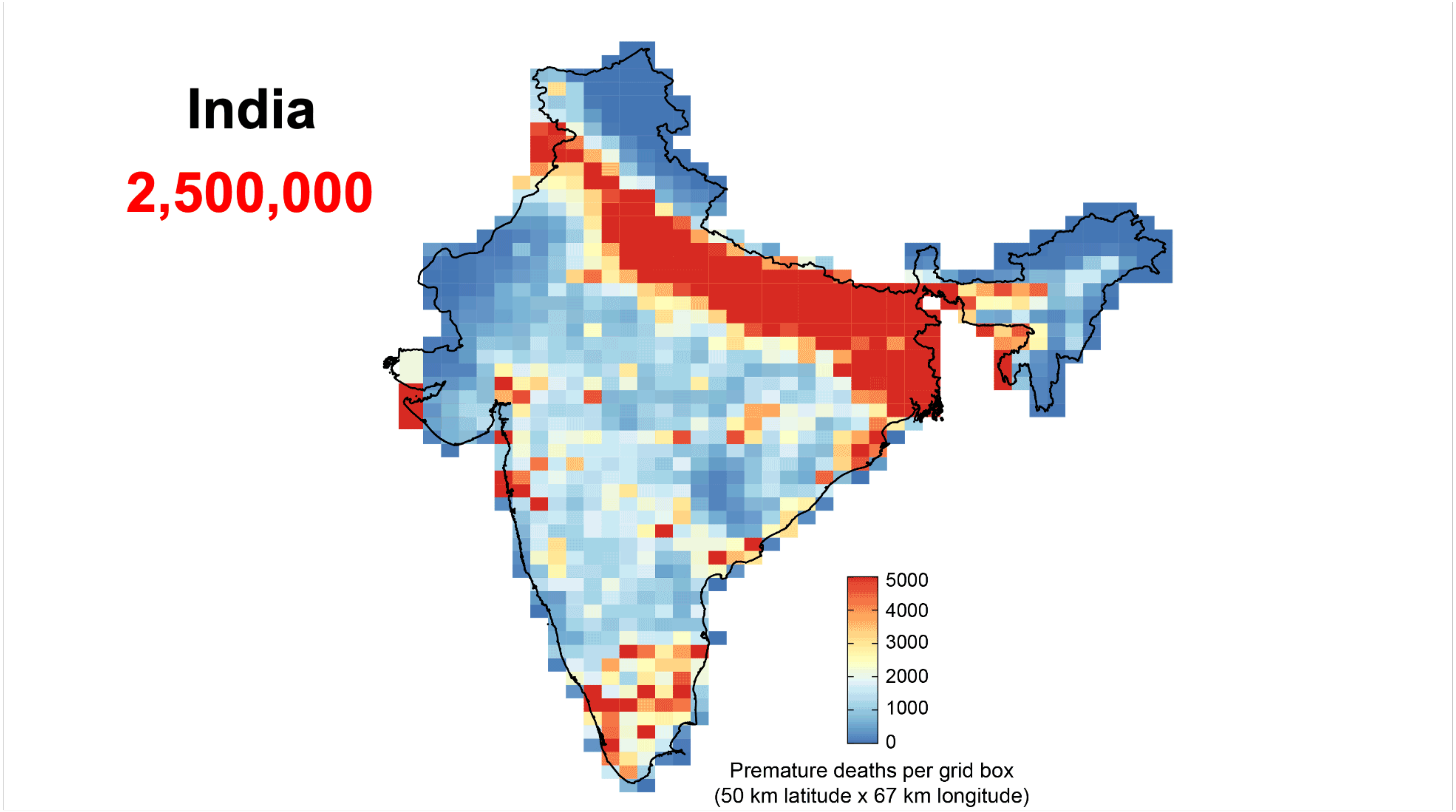


10.2 million premature deaths attributed to fossil-fuel $PM_{2.5}$ in 2012

[-47 million, 17 million]

[Vohra et al., 2021]

Regional Premature Mortality from Fossil Fuel Combustion

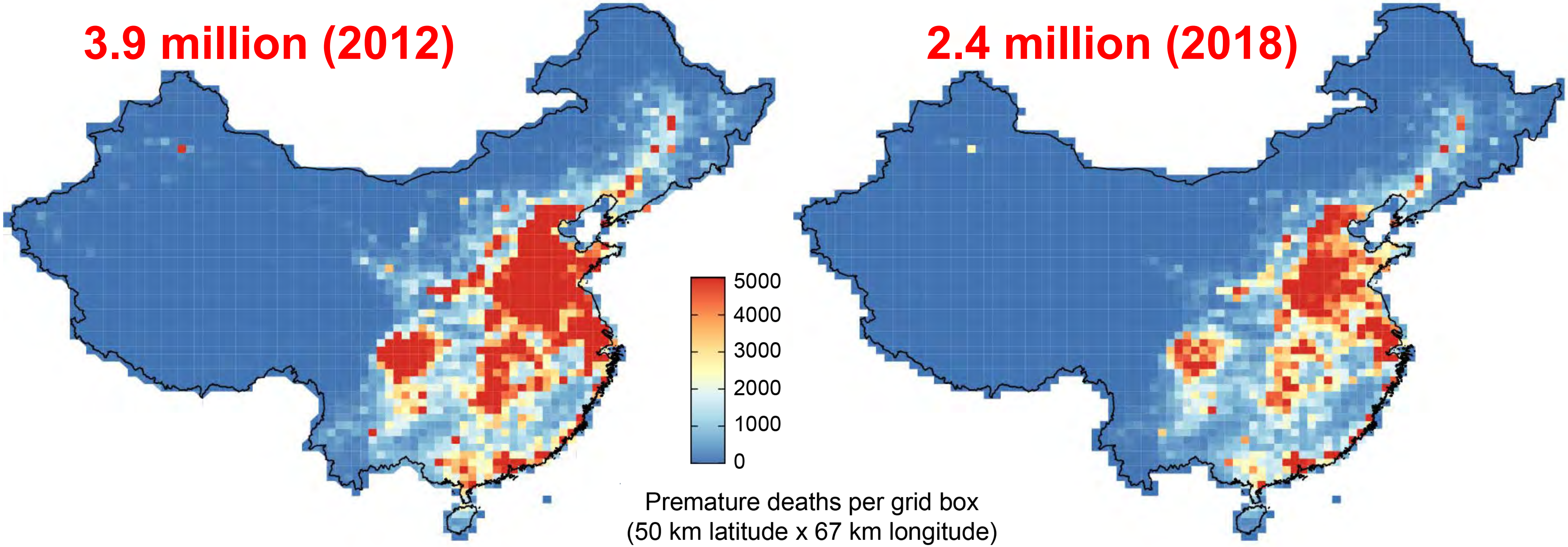


Policies Help Mitigate Premature Deaths

China

3.9 million (2012)

2.4 million (2018)



1.5 million fewer deaths in 2018 than 2012 due to policy-driven decline in $PM_{2.5}$ pollution in China

Response to Findings

We calculate global premature mortality that is much greater than previous estimates (updated risk assessment model, higher spatial resolution $PM_{2.5}$)

Swell of media attention from leading news agencies and advocacy groups

Translated into **many languages** for audiences in France, Spain, India, Canada, China, Central and South America

https://www.theguardian.com/environment/2021/feb/09/fossil-fuels-pollution-deaths-research

General Comments and Conclusions

Central to success of using models is ability validate with reliable and representative observations.

Persistent uncertainties in relative risk at extreme low and high concentrations of $PM_{2.5}$.

Controls on agriculture would be most effective at addressing $PM_{2.5}$ pollution in the UK, Europe and likely also other parts of the world that have already implemented successful measures targeting point sources.

Enhanced success of our projects resulted from working directly with policy- and decision-makers at local and national scales.

Greater synergies needed between air quality and climate agencies, due to co-benefits of targeting sources that emit air pollutants and precursors and greenhouse gases.

Additional Resources

The Conversation pieces on health and air quality:

https://theconversation.com/ditching-fossil-fuels-will-have-immediate-health-benefits-for-millions-world-leaders-must-seize-the-chance-171015

https://theconversation.com/air-pollution-in-fast-growing-african-cities-presents-a-risk-of-premature-death-183944

Datasets derived using GEOS-Chem:

Global premature mortality from fossil fuel air pollution: https://doi.org/10.5522/04/14595714

Visualization of results on Tableau dashboard:

https://public.tableau.com/app/profile/karn.vohra/viz/Globalmortalitylinkedtoairpollutionfromfossilfuelcombustion/Global_mortality_fossil-fuelPM2_5

https://public.tableau.com/app/profile/karn.vohra/viz/Trendsinairqualityinfast-growingtropicalcities/Dashboard1

Research group website:

https://maraisresearchgroup.co.uk/