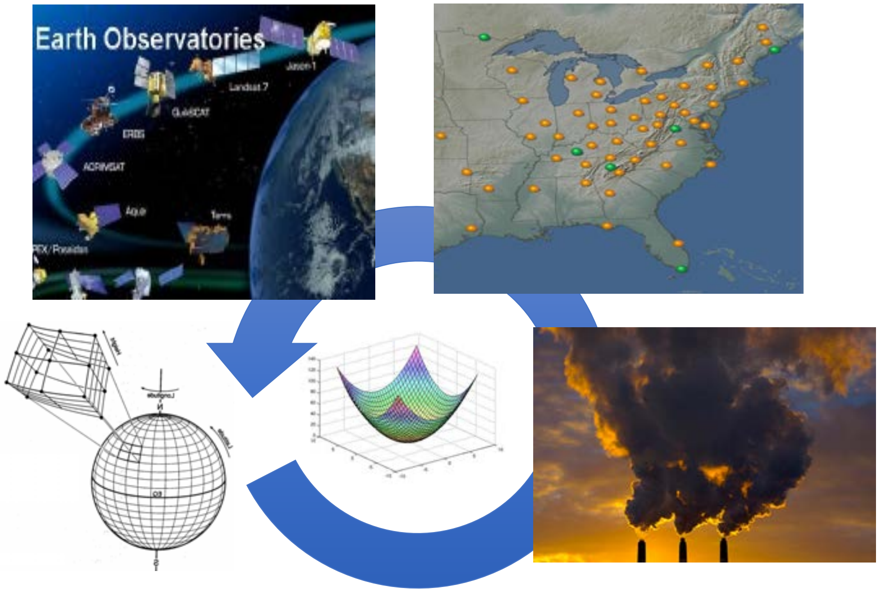
Tracking $PM_{2.5}$: How Models and Remote Sensing can be Used to Estimate Global Health Impacts of Ambient Fine Particulate Matter ($PM_{2.5}$)



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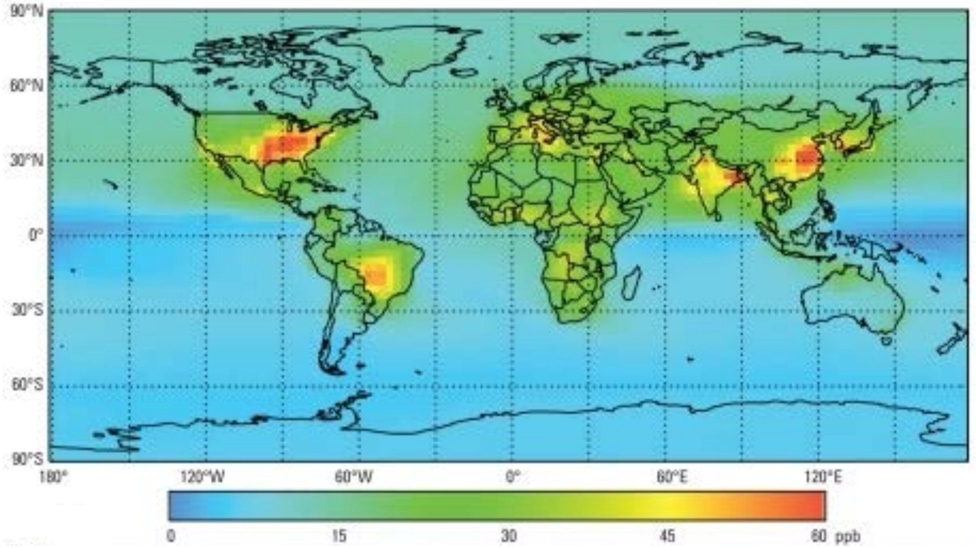
Funding: CCAC, NASA HAQAST

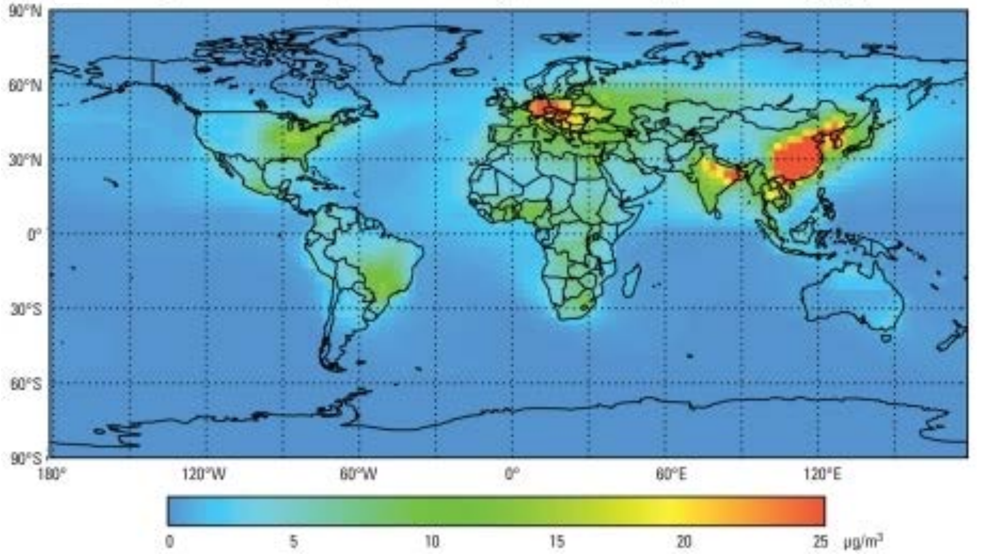
First global estimates of anthropogenic impacts on human health

Exposure estimated using model simulations alone (MOZART, 2.8° x 2.8°, Horowitz et al., 2006)

O_3



$PM_{2.5}$

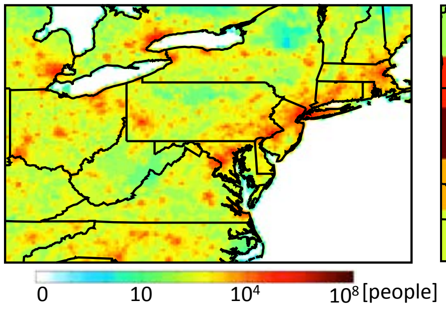


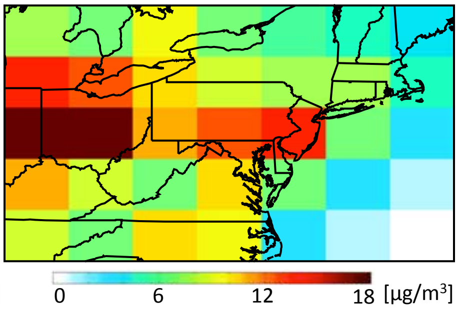
0.7 million from O_3 and 3.7 million from $PM_{2.5}$ (Anenberg et al., EHP, 2010)

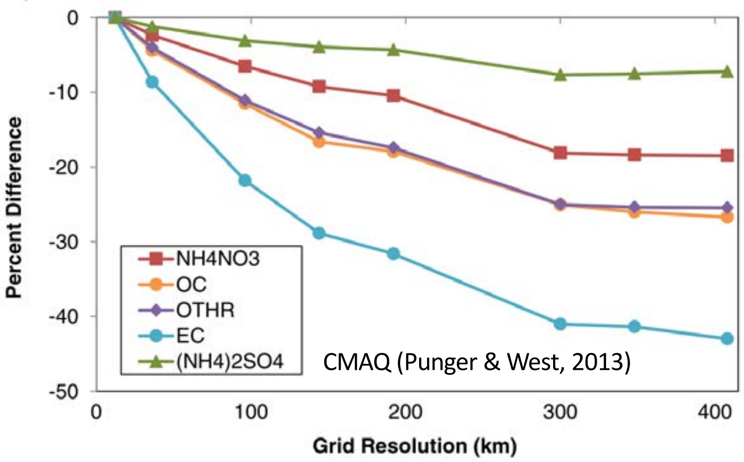
Significantly more than previous estimates of 0.8 million from Cohen et al. (2004) based on urban PM monitoring

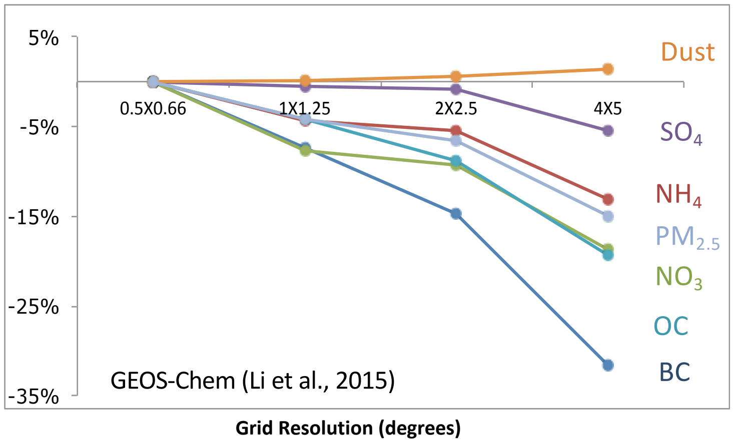
Lingering questions: is the model correct? is the resolution sufficient?

Global-scale models struggle to estimate exposure (concentration x population)


Population


2° × 2.5° modeled $PM_{2.5}$



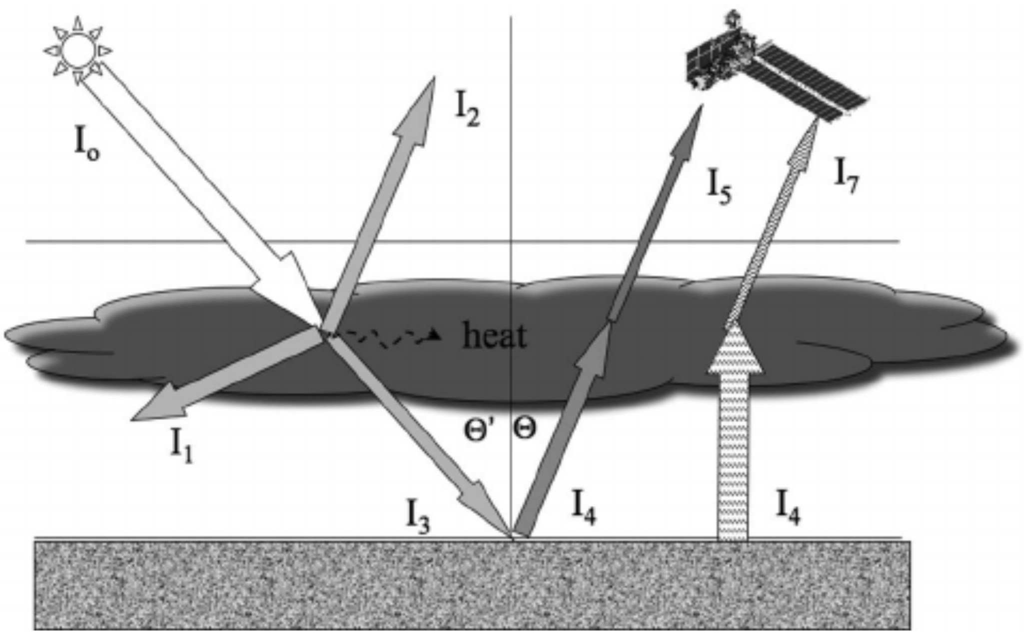


Individual components of $PM_{2.5}$ exposure underestimated by 5-40% in a 2°x2.5° simulation over the US.
Resolution error ***not*** globally heterogeneous.

Satellite-derived estimates of $PM_{2.5}$

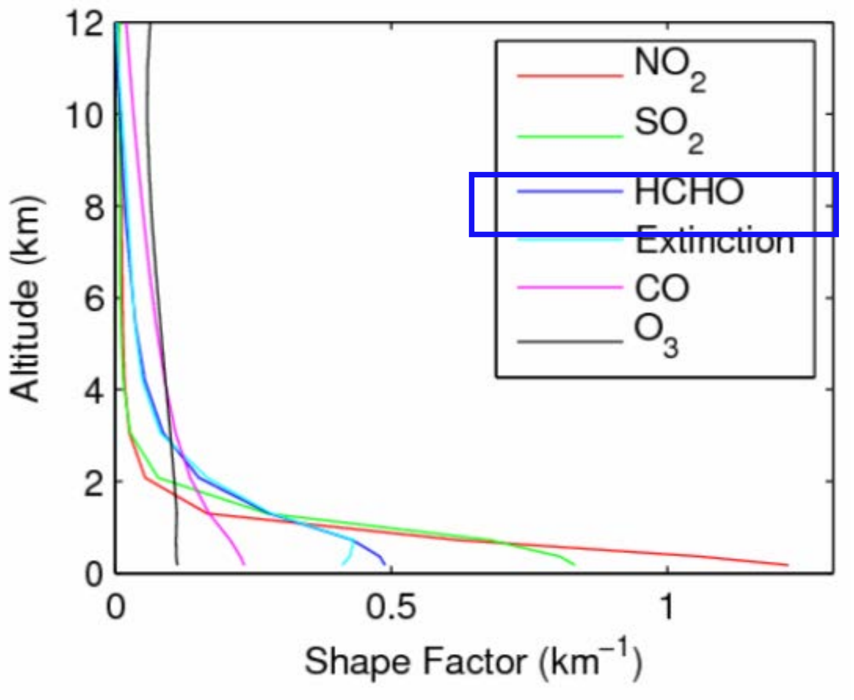
Aerosol option depth (AOD) or Aerosol Optical Thickness derived from measurements of short-wave radiation

Sources of radiation seen by a satellite:



Hoff and Christopher (2009)

Vertical distribution of AQ components

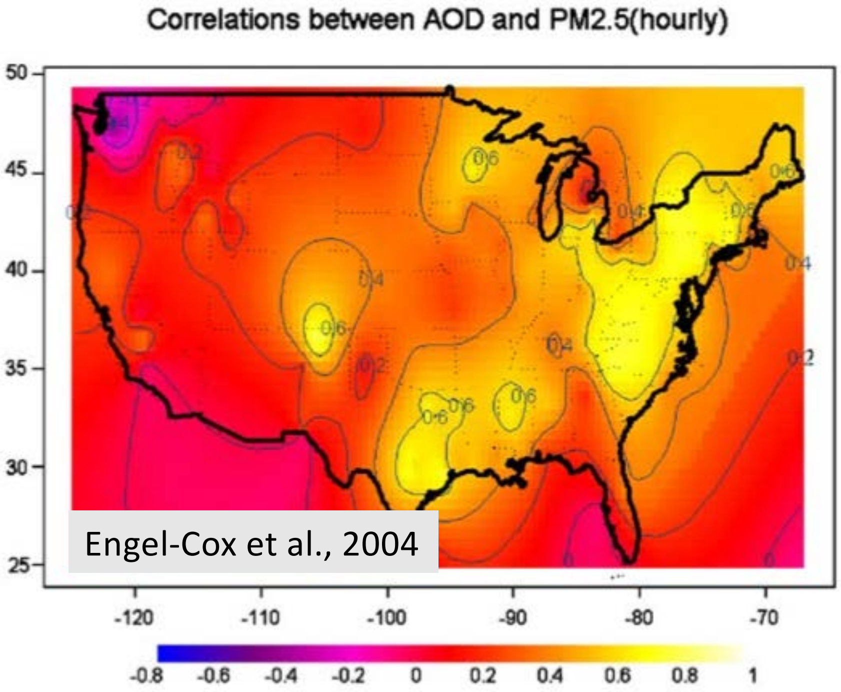


Martin (2008)

Concern: how closely linked are these to $PM_{2.5}$ concentrations at surface level?

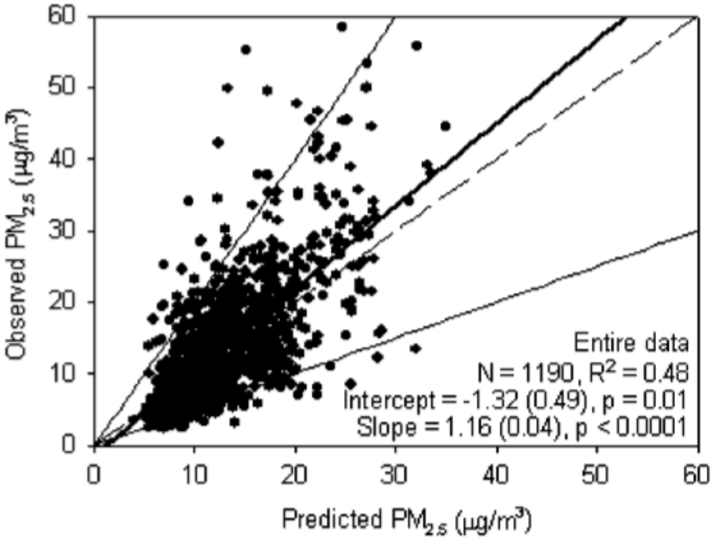
Satellite-derived estimates of $PM_{2.5}$

Statistical relationship between observed $PM_{2.5}$ and AOD



Engel-Cox et al., 2004

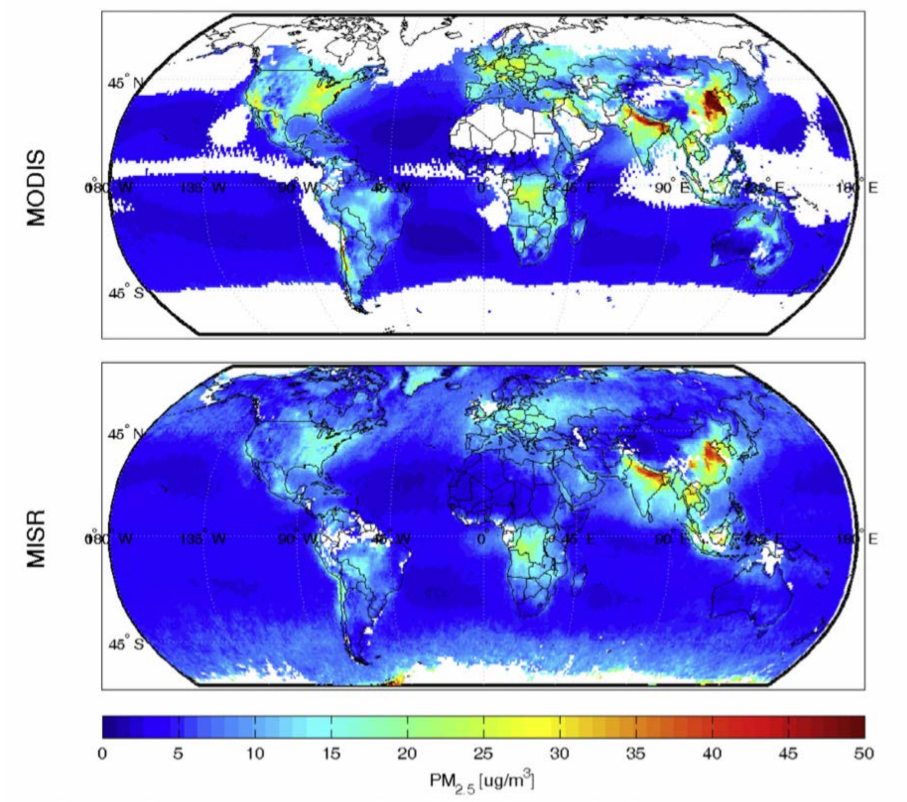
Liu et al., 2005



Can be improved by
- sorting $PM_{2.5}$ by type
- including other geophysical variables in the regression (RH, region, distance from coast,…)

Satellite-derived estimates of $PM_{2.5}$

Modeled relationship between observed $PM_{2.5}$ and AOD



van Donkelaar et al. (2006)

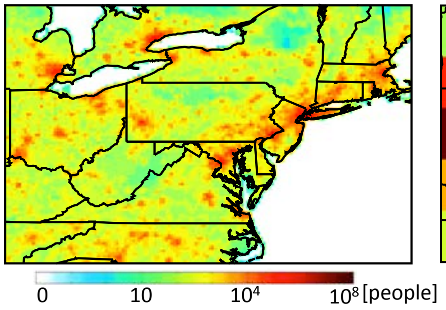
A global chemical transport model is used to relate surface $PM_{2.5}$ to AOD

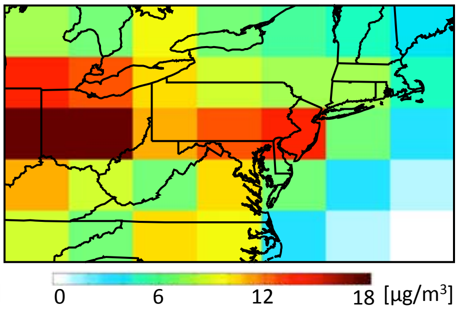
$$\text{“satellite } PM_{2.5}\text{”} = \frac{\text{model } PM_{2.5} * \text{satellite AOD}}{\text{model AOD}}$$

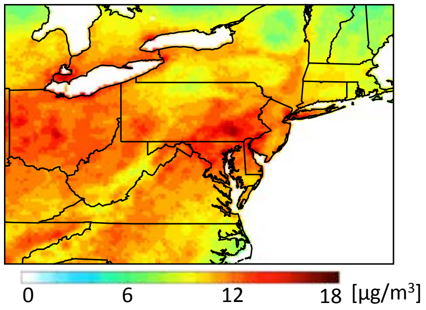
Provides a globally consistent dataset for global-health studies

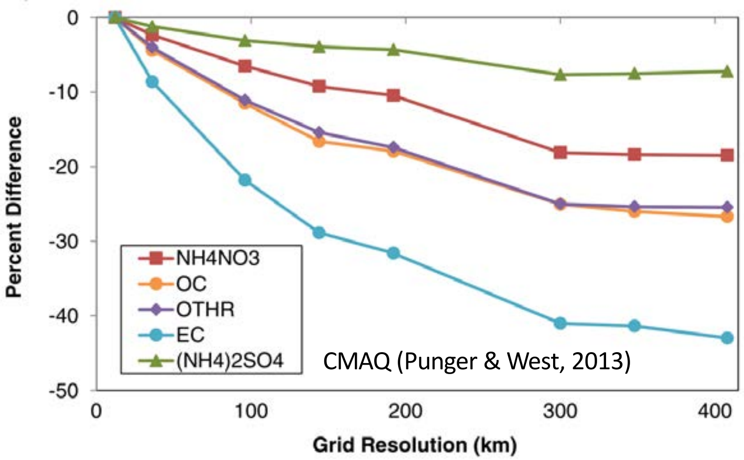
Has evolved over the years using improved modeling, more remote sensing data…

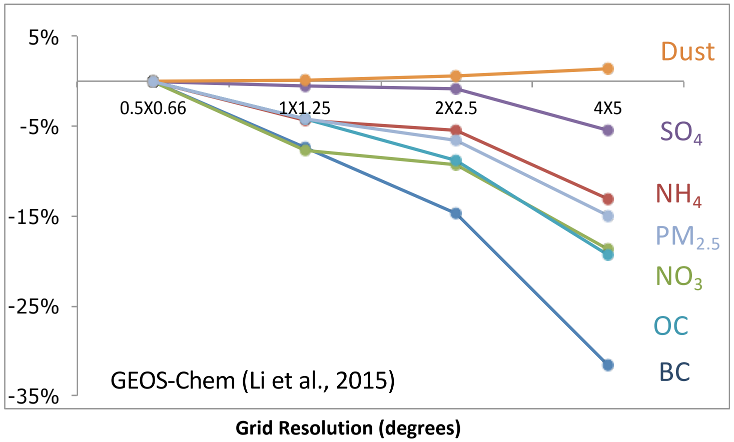
Global models struggle to estimate exposure (concentration x population)


Population


2° × 2.5° modeled $PM_{2.5}$


0.1° × 0.1° sat-derived $PM_{2.5}$ (van Donkelaar et al., 2016)


CMAQ (Punger & West, 2013)

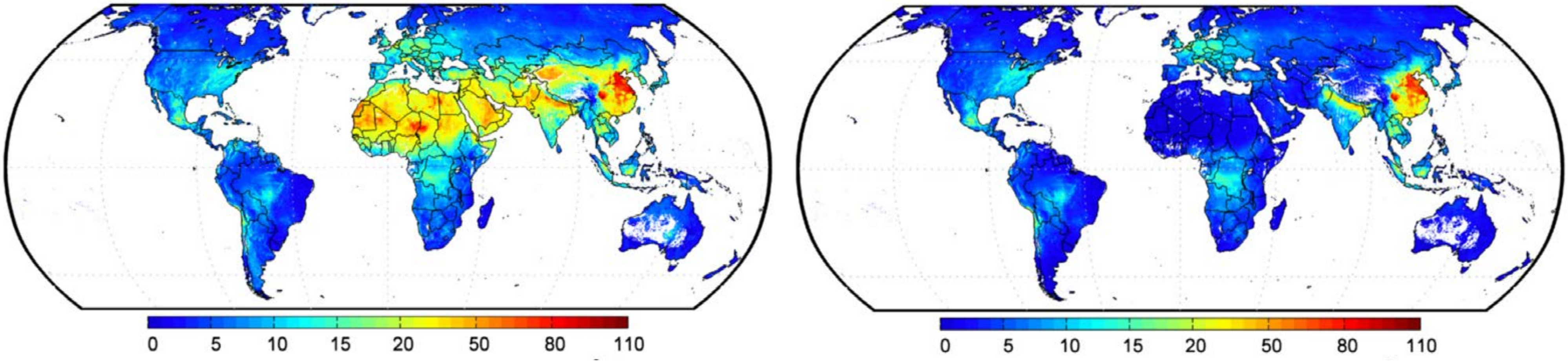

GEOS-Chem (Li et al., 2015)

Individual components of $PM_{2.5}$ exposure underestimated by 5-40% in a 2°x2.5° simulation over the US.
Resolution error ***not*** globally heterogeneous.

Global estimates of $PM_{2.5}$ health impacts from satellite-derived exposure estimate

Hoff and Christopher (JAWMA, 2009) “Remote sensing of particulate pollution from space: have we reached the promised land?” – uncertainty in AOD-derived $PM_{2.5}$ reaching ~30%.

Satellite derived $PM_{2.5}$ from van Donkelaar et al. (EHP, 2010) at 0.1° x 0.1° globally:



Total $PM_{2.5}$

$PM_{2.5}$ with dust removed

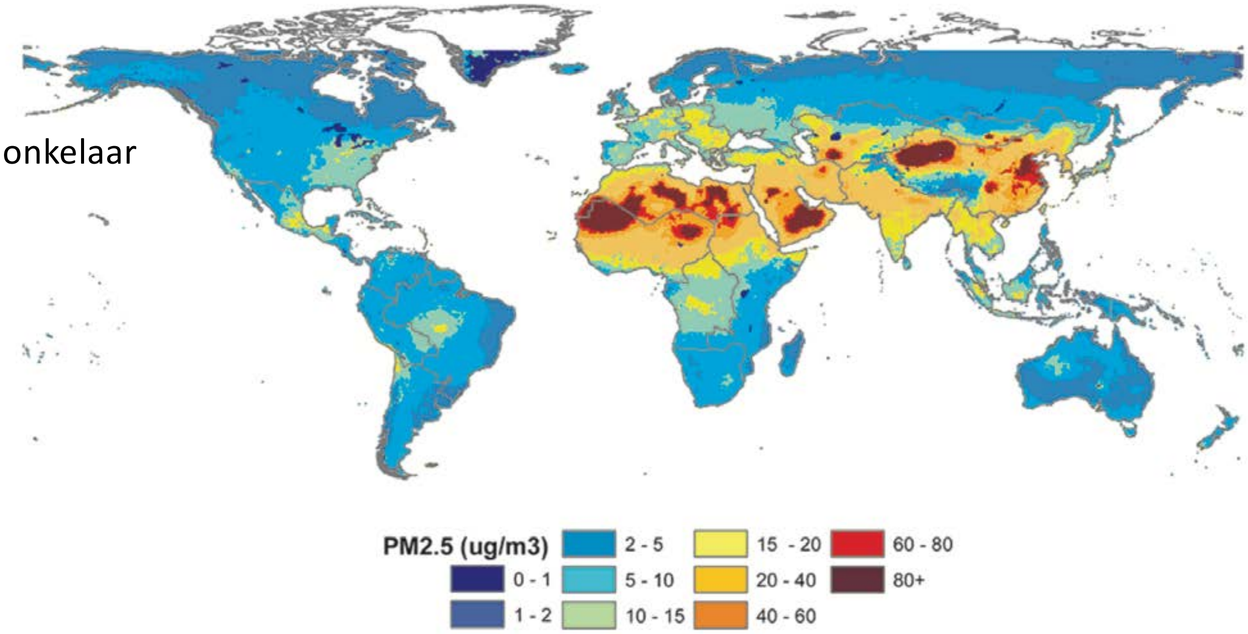
First estimates of global $PM_{2.5}$ health impacts from satellite-derived PM2.5 (van Donkelaar et al., 2010) reported in in Evans et al. (ER, 2013): 2.4 million cause-specific premature deaths in 2004

Global estimates of $PM_{2.5}$ health impacts from satellites and models

Brauer et al. (ES&T, 2011): Average of model and satellite, globally calibrated to surface observations

TM5 = model estimated $PM_{2.5}$
SAT = satellite-derived $PM_{2.5}$ from van Donkelaar et al. (2010)

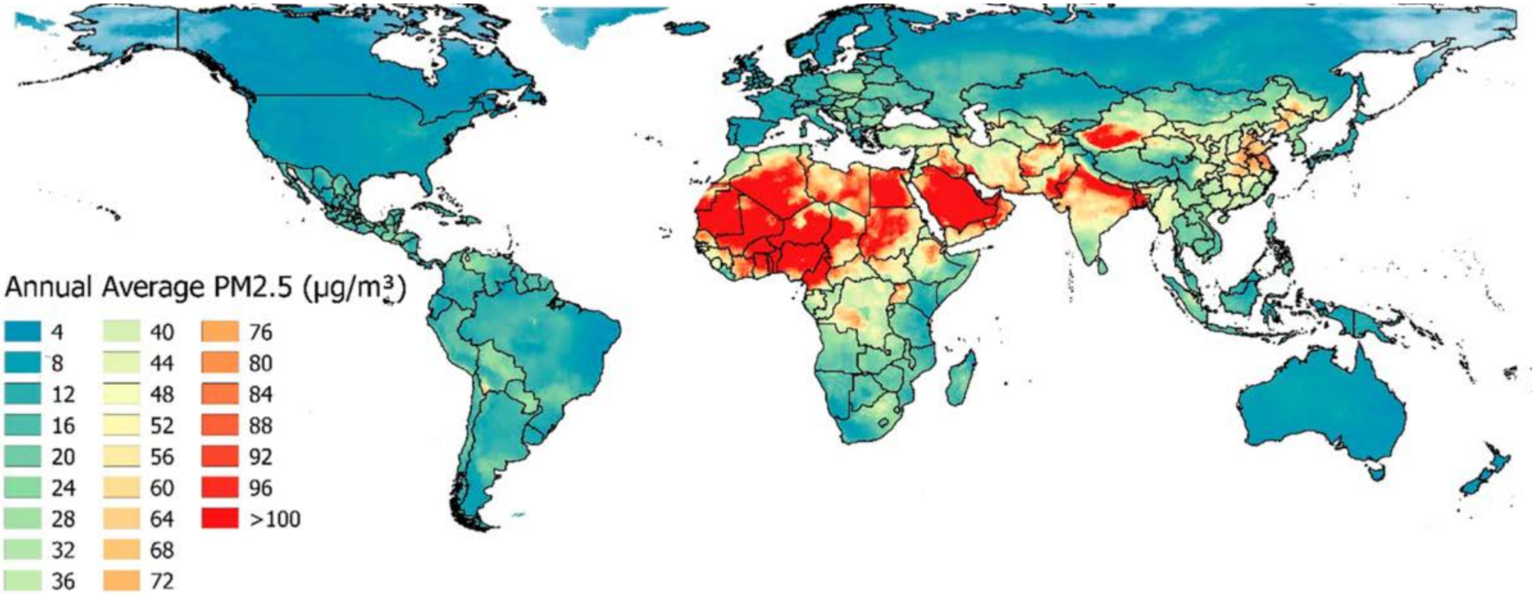
$PM_{2.5} = 1.32\,[(TM5 + SAT)/2]^{0.922}$



This provided the exposure estimate for GBD 2010 (Lim et al., Lancet, 2012): 3.2 million (2.8 – 3.6)

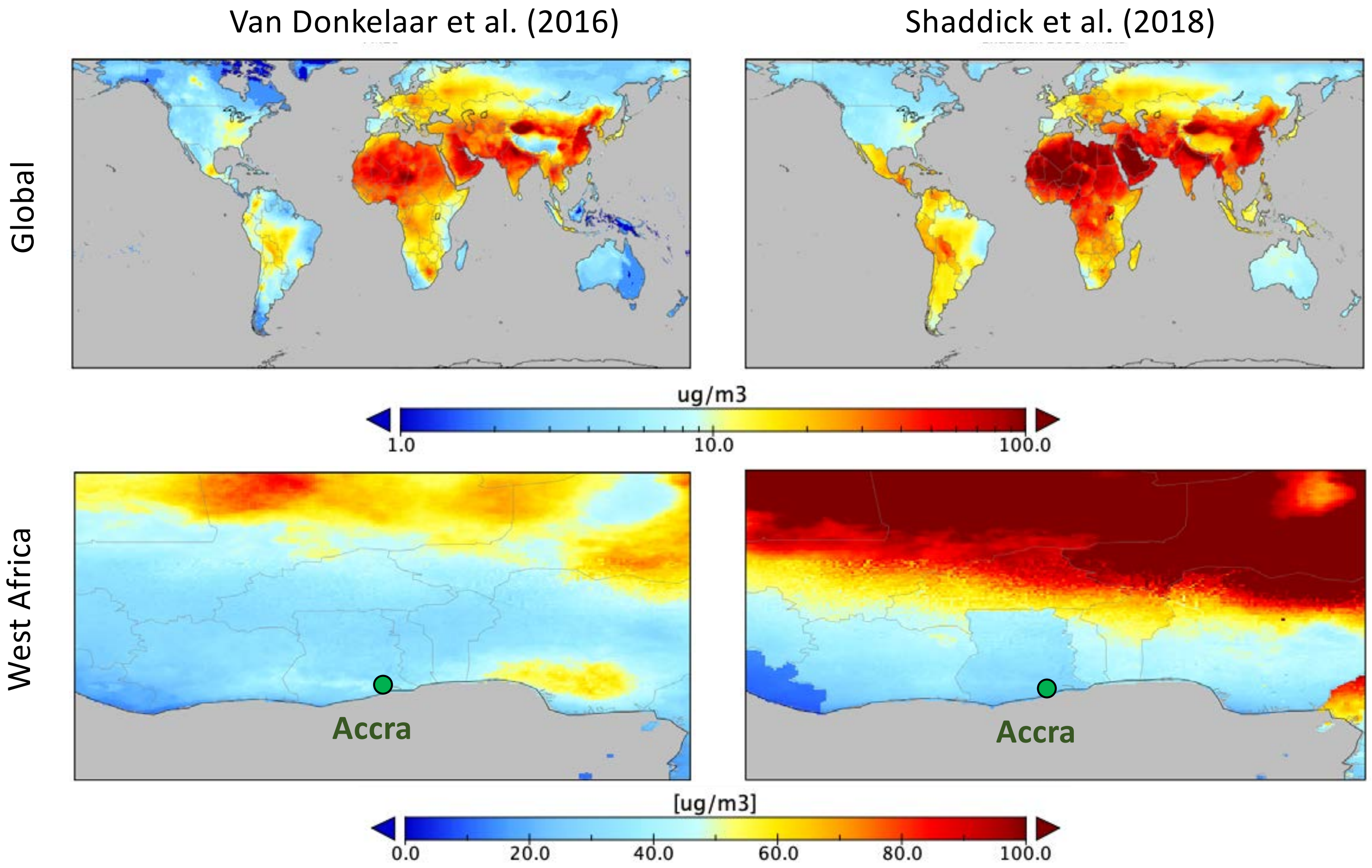
Advanced fusion of satellite and model-based $PM_{2.5}$ estimates

$PM_{2.5}$ from Shaddick et al. (2018): hierarchical Bayesian synthesis of satellite-derived products, surface observations, geostatistical information.



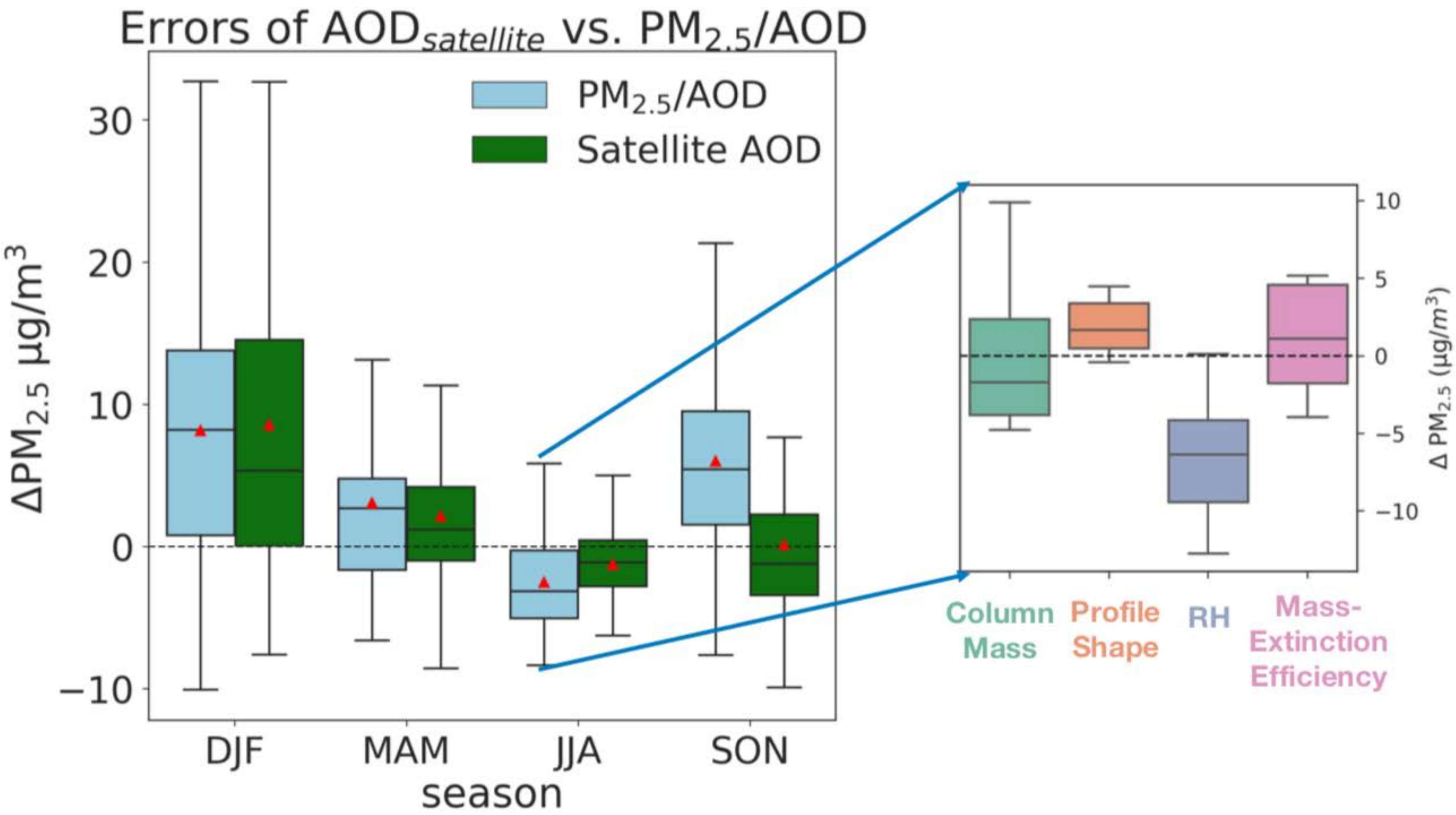
Provides exposure estimates for GBD 2015 (Cohen et al., Lancet, 2017): 4.2 (3.7 – 4.8) million premature deaths

Uncertainties in exposure estimates



- Large-scale similarities
- Considerable differences in regions with sparse $PM_{2.5}$ monitoring
- See also works such as Jin et al. (2019) looking at the NE US:
    - Different spatial patterns but similar trends from 2002 to 2012

Uncertainties in exposure estimates



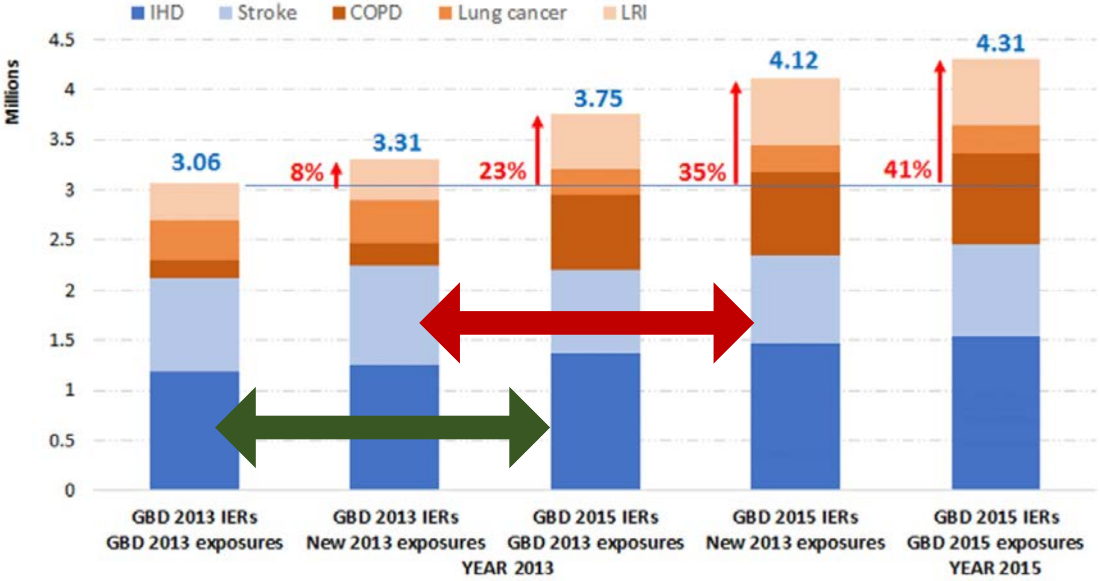
Jin et al., 2019

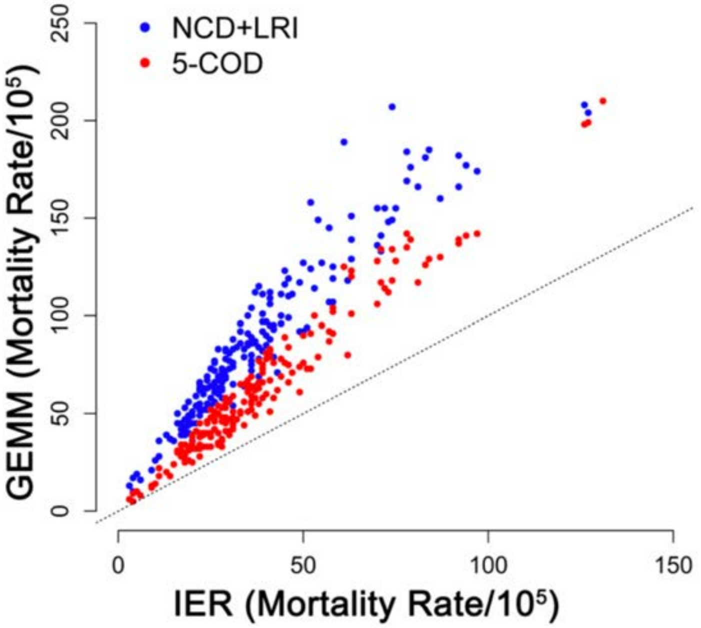
Additional factors impacting global $PM_{2.5}$ health impacts

In addition to exposure, also mortality rates, population, and concentration-response relationships

Comparison of GBD ambient AQ health impacts across the years (Ostro et al., 2018)

GEMM >> IER (Burnett et al., 2018)





Δ updating exposure: 31%

Δ updating concentration-response function (IER): 12%

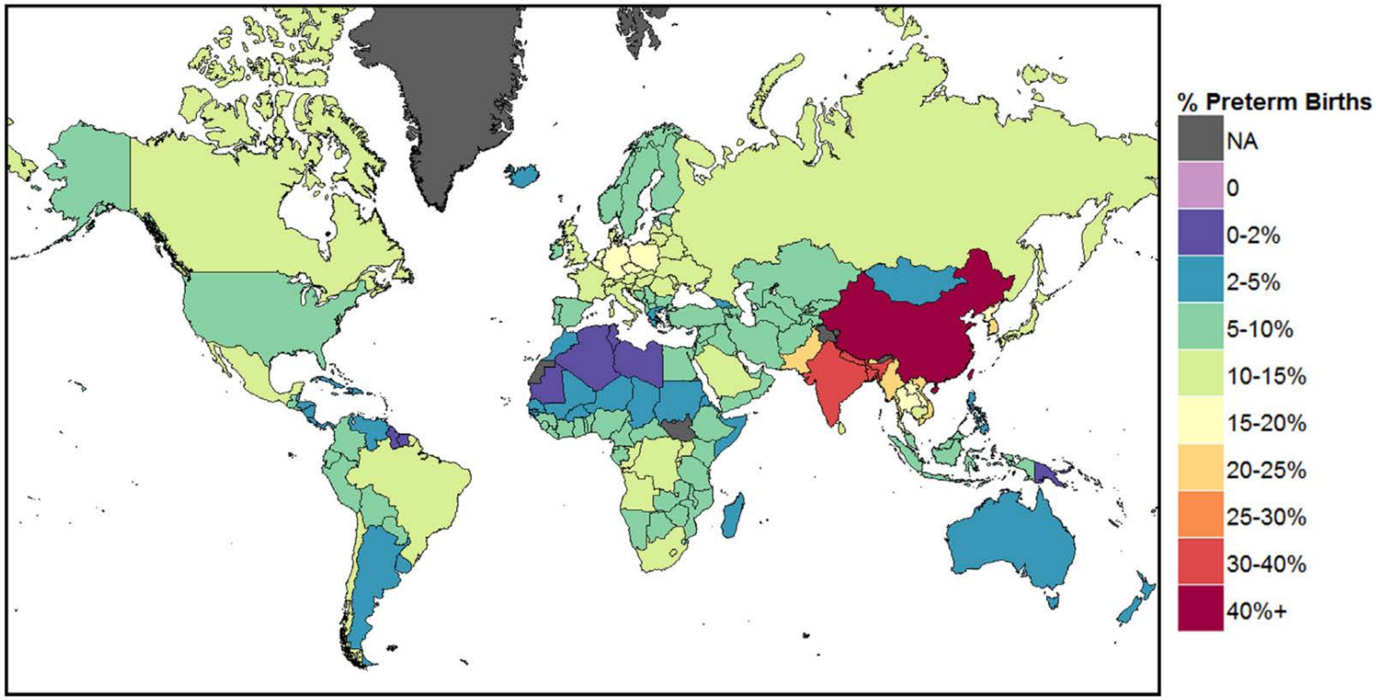
Δ concentration-response function (GEMM based on studies of exposure to high ambient concentrations): x2

Combining models and satellite-derived $PM_{2.5}$ for improving global health impacts studies

Remote-sensing based $PM_{2.5}$ estimates used for high-resolution exposure estimation (0.1° x 0.1°, van Donkelaar et al., 2016)
Model (GEOS-Chem) used to estimate anthropogenic % of $PM_{2.5}$ at coarse resolution (2° x 2.5°)

First global estimate of $PM_{2.5}$ impacts on preterm births (Malley et al., Environ. Int., 2017)

$$\mathrm{P\hat{M}}_{2.5}^{fine} = \mathrm{PM}_{2.5,sat}^{fine} \frac{\mathrm{P\hat{M}}_{2.5,mod}^{coarse}}{\mathrm{PM}_{2.5,mod}^{coarse}}$$



Of 15 million premature births, 1.8 – 3.5 million associated with exposure to anthropogenic $PM_{2.5}$.

Combining models and satellite-derived $PM_{2.5}$ for improving global health impacts studies

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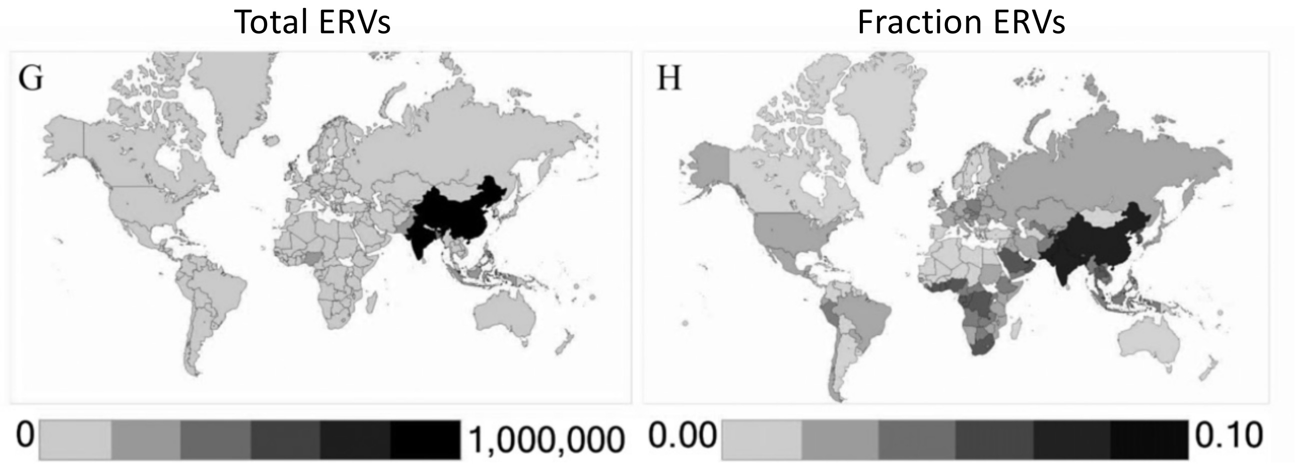
Model (GEOS-Chem) used to estimate anthropogenic % of $PM_{2.5}$ at coarse resolution (2° x 2.5°)

First global estimate of $PM_{2.5}$ impacts on asthma ERVs and incidence
(Anenberg et al., EHP, 2018)



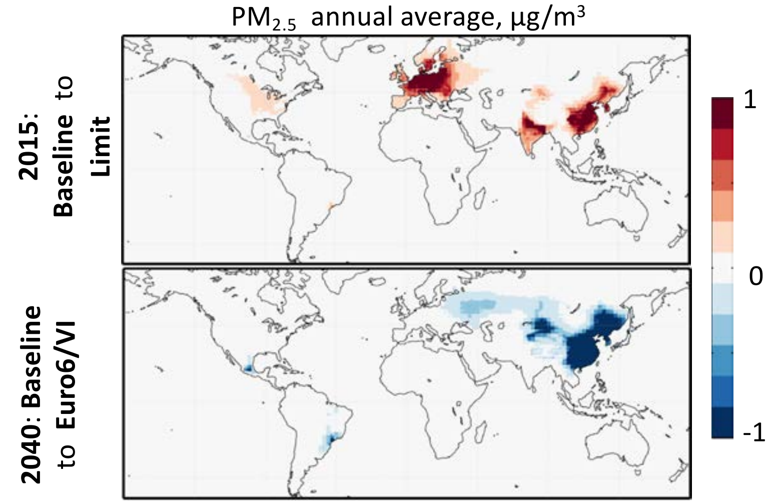
$$\hat{\mathrm{PM}}_{2.5}^{fine} = \mathrm{PM}_{2.5,sat}^{fine} \frac{\hat{\mathrm{PM}}_{2.5,mod}^{coarse}}{\mathrm{PM}_{2.5,mod}^{coarse}}$$

5-10 million annual asthma emergency room visits globally from $PM_{2.5}$, ~70% of which from anthropogenic $PM_{2.5}$

Combining models and satellite-derived $PM_{2.5}$ for improving global health impacts studies from specific sectors

Remote-sensing based $PM_{2.5}$ estimates used for high-resolution exposure estimation (0.1° x 0.1°, van Donkelaar et al., 2016)
Model (GEOS-Chem) used to estimate % of $PM_{2.5}$ at coarse resolution (2° x 2.5°) from specific sector or scenario

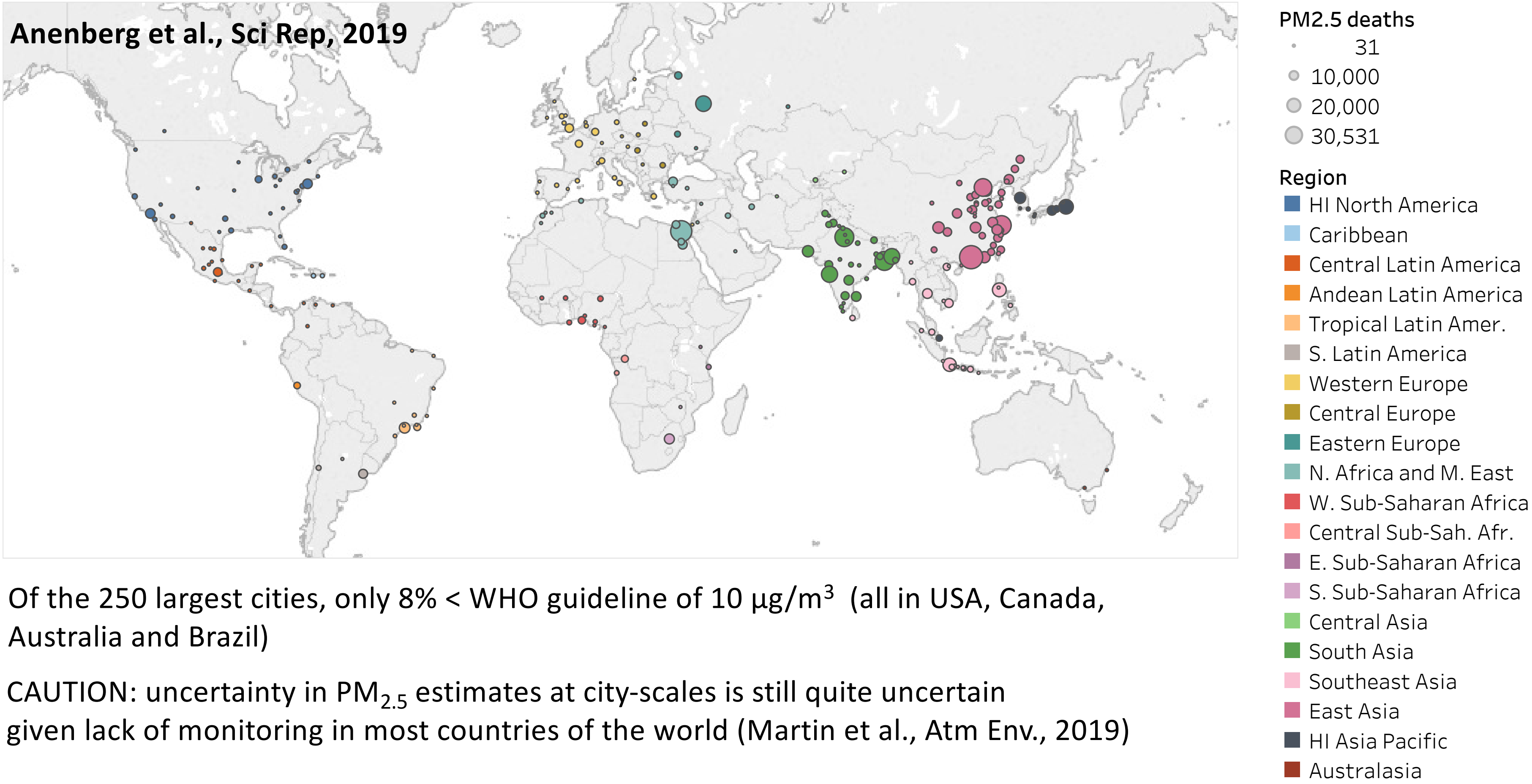
Global health impacts of transportation NOx emissions under current and future conditions (Anenberg et al., Nature, 2017)



$$\hat{PM}_{2.5}^{fine} = PM_{2.5,sat}^{fine} \frac{\hat{PM}_{2.5,mod}^{coarse}}{PM_{2.5,mod}^{coarse}}$$

Excess NOx contributed an ~38,000 additional ozone- and $PM_{2.5}$-related premature deaths globally in 2015; Strengthened diesel NOx regulations could avoid >170,000 annual $PM_{2.5}$ and ozone-related premature deaths globally in 2040

PM$_{2.5}$ associated premature deaths in cities worldwide



Of the 250 largest cities, only 8% < WHO guideline of 10 μg/m^3 (all in USA, Canada, Australia and Brazil)

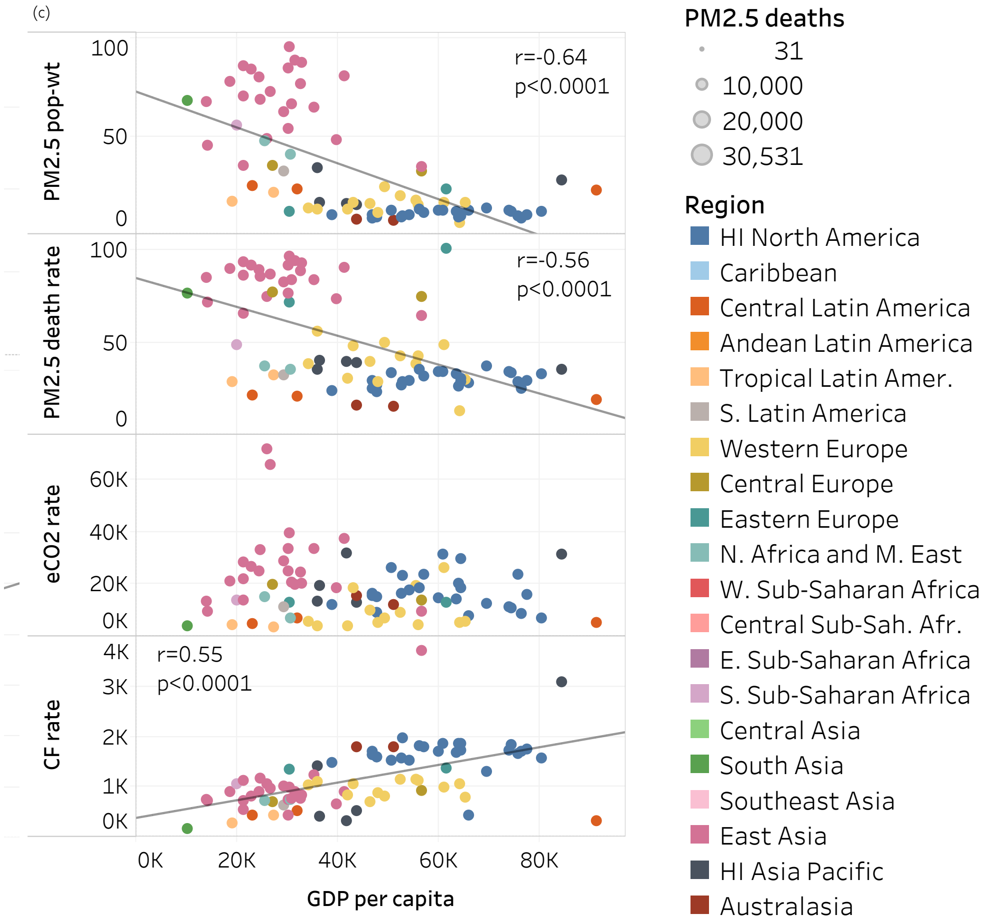
CAUTION: uncertainty in PM$_{2.5}$ estimates at city-scales is still quite uncertain given lack of monitoring in most countries of the world (Martin et al., Atm Env., 2019)

PM$_{2.5}$ associated premature deaths in cities worldwide

Anenberg et al., Sci Rep, 2019

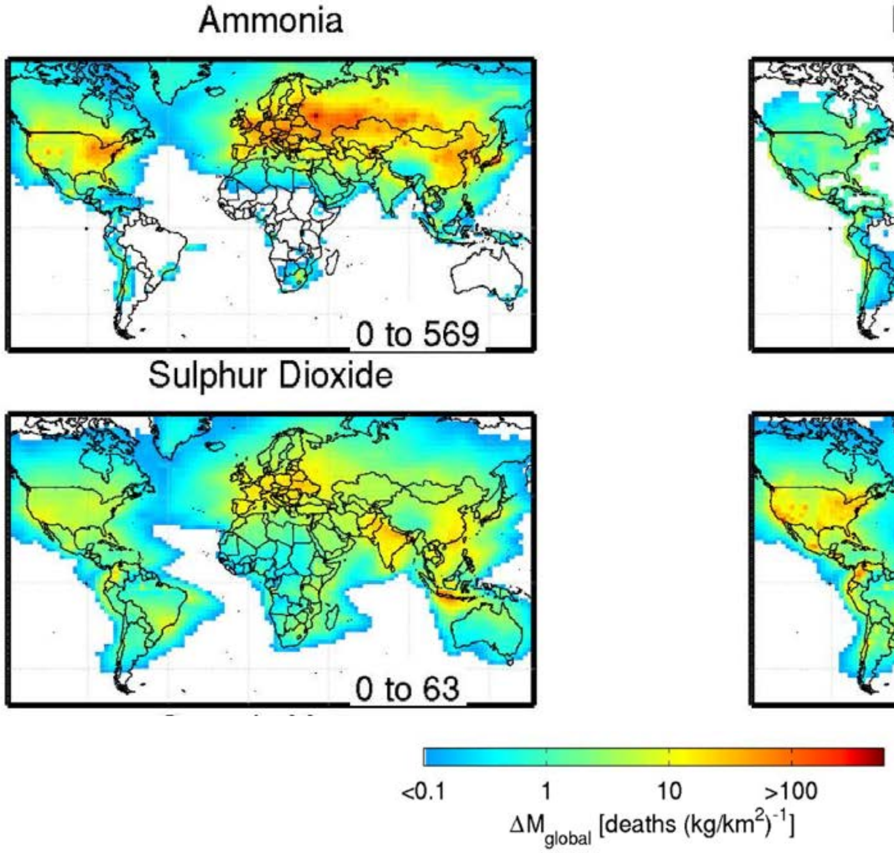
Consider trends compared to GDP per capita

- Richer countries are reducing air pollution
- Little relationship between GDP and eCO$_2$ per capita
- Richer countries still have largest carbon footprint (CF)
- “Reducing” PM$_{2.5}$ without reducing CF can mean shifting rather than reducing net AQ burden
- Within regions the trends are not as clear



Combining models and remote sensing for source apportionment of global $PM_{2.5}$ health impacts

Mortality impacts owing to addition of 1 kg/km^2 precursor emissions anywhere in the world:



Lee et al., ES&T, 2015

Contributions estimated using GEOS-Chem adjoint model (Henze et al., 2007; 2009), a numerically efficient tool for estimating sensitivities with respect to many (10^5) emissions simultaneously.

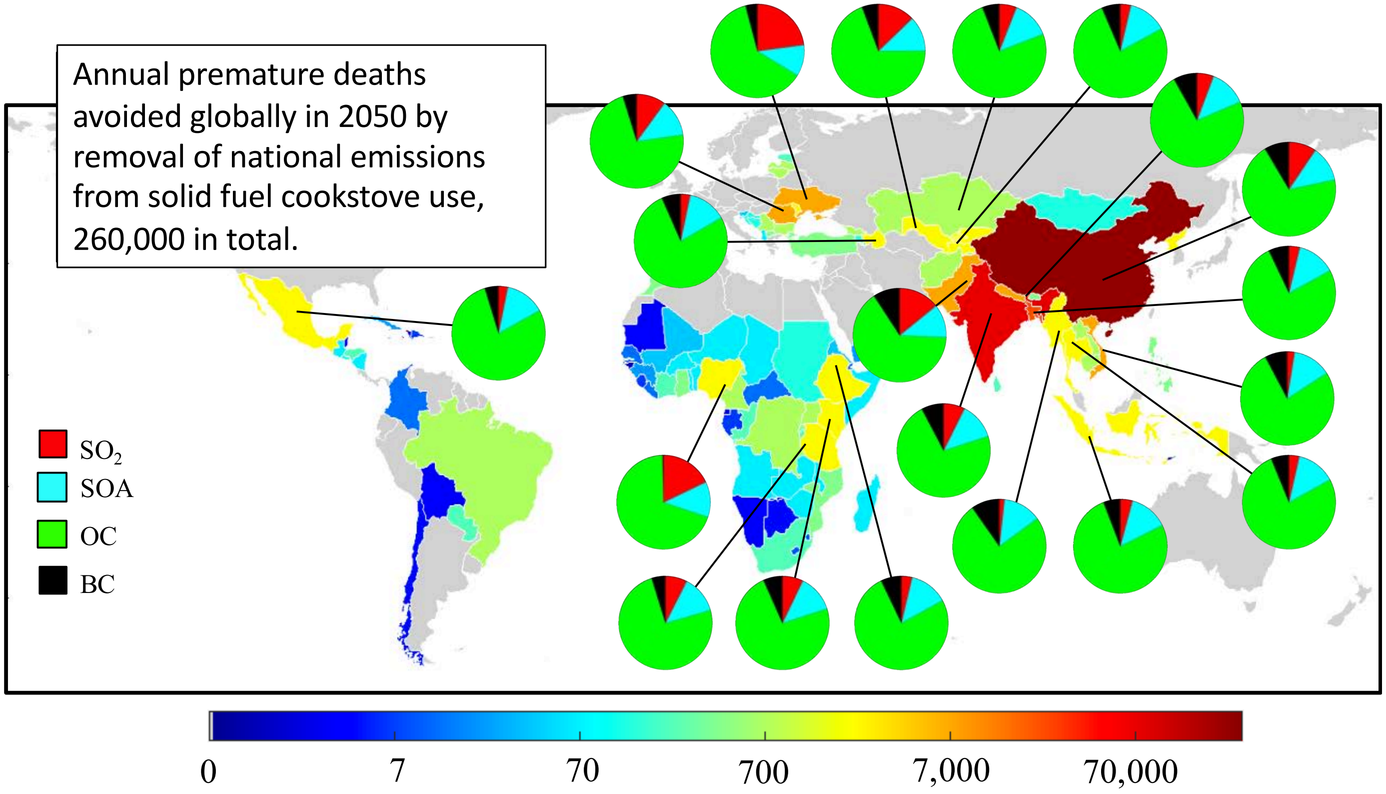
Exposure estimated using fine-scale satellite-derived $PM_{2.5}$ (van Donkelaar et al., 2010) for downscaling and rescaling.

$$x_f = M_c \left(\frac{\overline{S}_c}{M_c}\right)\left(\frac{s_f}{\overline{S}_c}\right)$$

c = coarse (2°x2.5°)
f = fine (0.1°x0.1°)
S = satellite
M = model

Health impacts in 2050 via ambient air quality from country-level phase-out (by 2020) of cookstove emissions

ΔE = Removal of residential cookstove emissions (Lacey & Henze, ERL, 2015).
Combined with ΔM/ΔE from Lee et al. (ES&T, 2015).

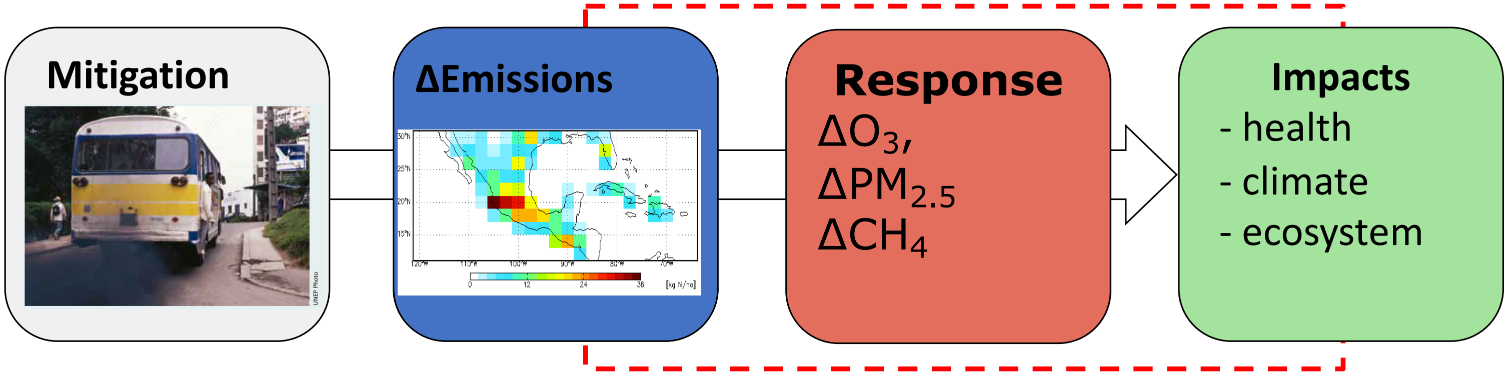


Annual premature deaths avoided globally in 2050 by removal of national emissions from solid fuel cookstove use, 260,000 in total.

Combining atmospheric models, remote sensing, and energy system models in integrated assessment tools

CCAC Short Lived Climate Pollutant (SLCP) National Action Plan (SNAP) Toolkits
http://new.ccacoalition.org/en/initiatives/snap

CCAC
CLIMATE AND CLEAN AIR COALITION
TO REDUCE SHORT-LIVED CLIMATE POLLUTANTS
www.unep.org/ccac



Mitigation

ΔEmissions

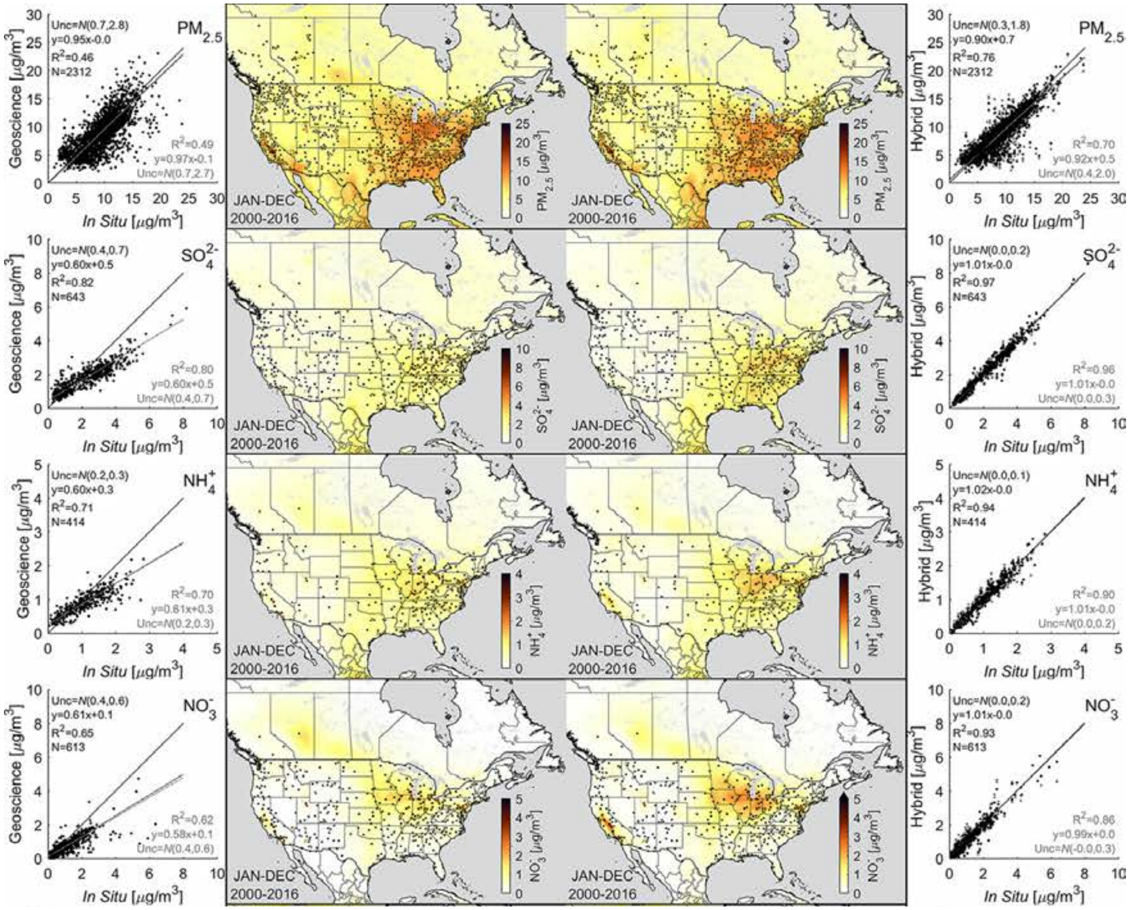
Response
ΔO_3,
$\Delta PM_{2.5}$
ΔCH_4

Impacts
- health
- climate
- ecosystem

- **GEOS-Chem (2°x2.5°) atmospheric transport and adjoint sensitivities (Henze et al., 2009)**
- **Remote sensing (0.1° x 0.1°) $PM_{2.5}$ exposure estimation (van Donkelaar et al., 2016)**
- **Health impacts following Global Burden of Disease (GBD, e.g., Cohen et al., 2017)**
- Transient climate impacts of short and long-lived species (Lacey et al., 2017)
- Cop impacts of vegetative O_3 exposure

Features built into the **LEAP-IBC** SLCP Benefits Toolkit (Kuylenstierna et al., in prep; Nakarmi et al., submitted) used by 25 CCAC member nations (Peru, Colombia, Mexico, Chile, Ghana, Bangladesh, Togo, Nigeria,…).

Future directions



AOD-based geophysical (left) and geophysical+statistical (right) estimates of PM2.5 composition (van Donkelaar et al., 2019)

New and upcoming datasets to help resolve the species-specific relationship between $PM_{2.5}$ and AOD:

- SPARTAN: network of speciated PM2.5 filter measurements placed at AERONET sites
  https://www.spartan-network.org/data

- MAIA: first remote sensing mission targeting air quality health impacts, using advanced techniques to estimate aerosol composition over select areas
  https://maia.jpl.nasa.gov

Summary

- Models are used to help derive satellite-based $PM_{2.5}$ estimates
- Satellite-based $PM_{2.5}$ estimates are used to help global modeling studies resolve exposure at fine scales
- Models are used to estimate fractions of $PM_{2.5}$ exposure owing to emissions from particular sectors, locations, or changes in response to different emissions control policies
- In conjunction with spatially explicit source apportionment modeling, remote-sensing based health impacts can be coupled to other types of models
  - Energy systems model such as LEAP-IBC
  - Models of production and trade
- Future directions include further blending of geophysical and statistical approaches, incorporation of regional modeling, calibration with in situ measurements of the AOD/ $PM_{2.5,k}$ relationship, and remote sensing observations from MAIA

Thanks!