Global change and air quality: climate, background ozone, nitrogen deposition, visibility, and mercury

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HARVARD UNIVERSITY
ATMOSPHERIC CHEMISTRY
MODELING GROUP

Harvard Atmospheric Chemistry Modeling Group

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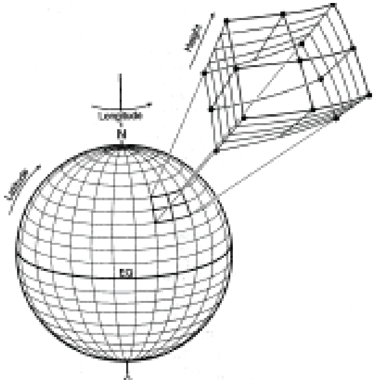
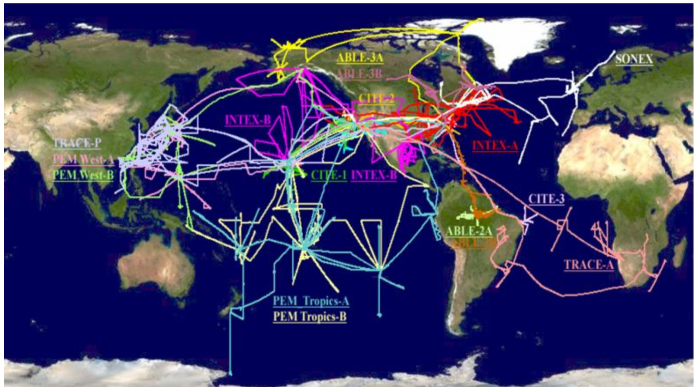
Atmospheric Chemistry Modeling Group

We work to understand the chemical composition of the atmosphere, the effect of human activity, and the implications for climate change and life on Earth

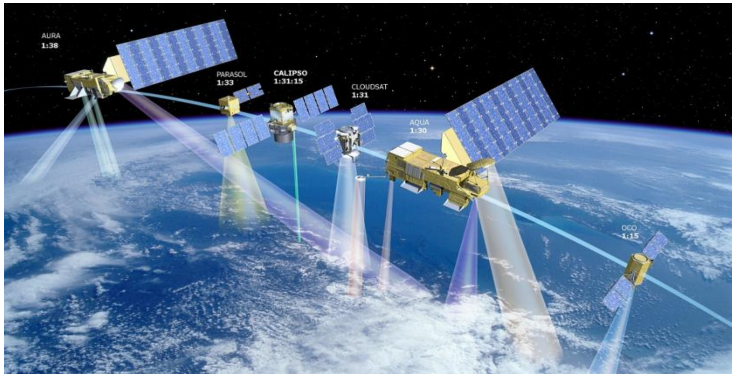
Global modeling (GEOS-Chem)



NASA aircraft missions



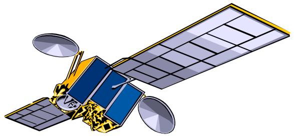
Satellite observations (NASA A-Train)



Air Quality Applied Sciences Team (AQAST)

EARTH SCIENCE SERVING AIR QUALITY MANAGEMENT NEEDS

Earth science resources



satellites

suborbital platforms

models

AQAST

Air Quality Management Needs

- **Pollution monitoring**
- **Exposure assessment**
- **AQ forecasting**
- **Source attribution of events**
- **Quantifying emissions**
- **Natural&foreign influences**
- **AQ processes**
- **Climate-AQ interactions**

19 investigators partnering with AQ managers in a large number of projects

WORK WITH US! http://acmg.seas.harvard.edu/aqast

Effect of climate change on air quality

Expected effect of 21st-century climate change		**Observed dependences on meteorological variables (polluted air)**	
		Ozone	**PM**
↑	**Stagnation**	↑	↑
↑	**Temperature**	↑	↑↓
?	**Mixing depth**	=	↓
?	**Precipitation**	=	↓
?	**Cloud cover**	↓	↓
?	**Relative humidity**	=	↑

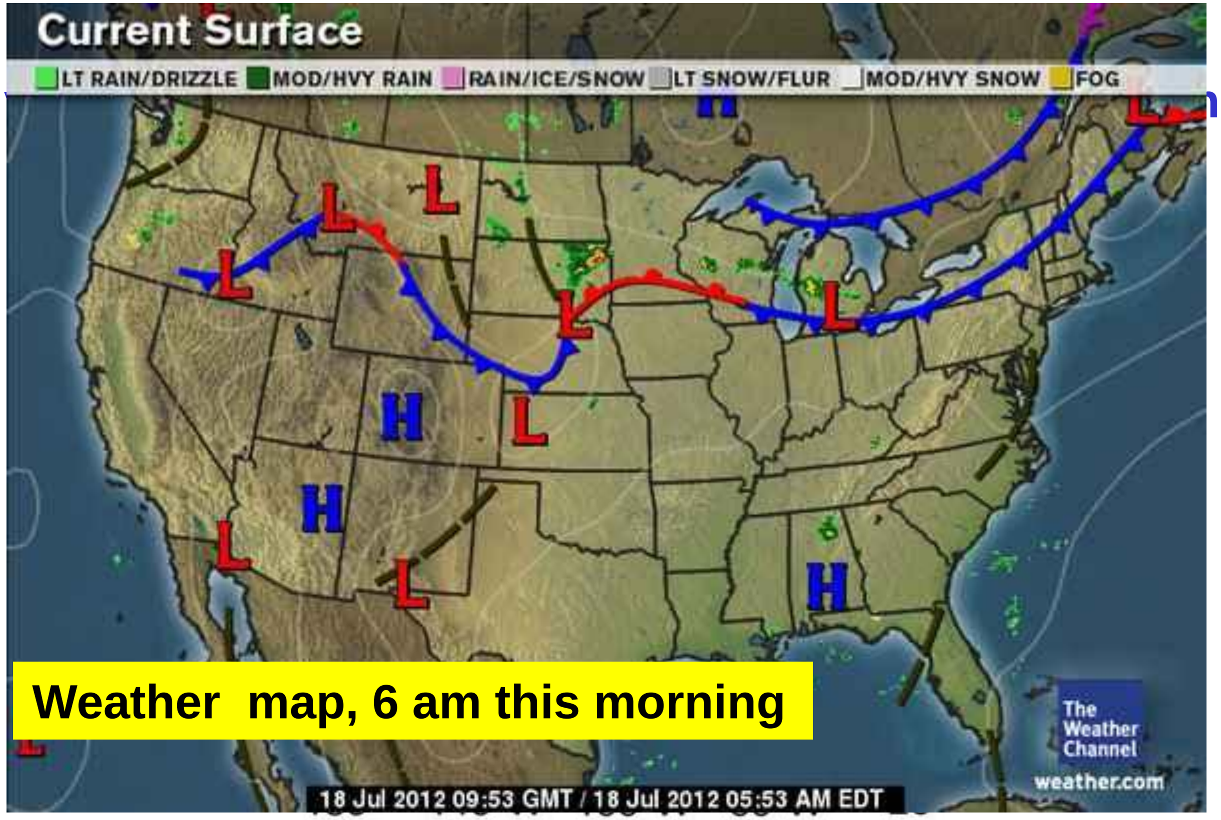
Climate change is expected to degrade ozone air quality; effect on PM uncertain

Jacob and Winner [2009]

IPCC projection of 21st-century climate change in N. America

2080-2099 v

n A1B scenario



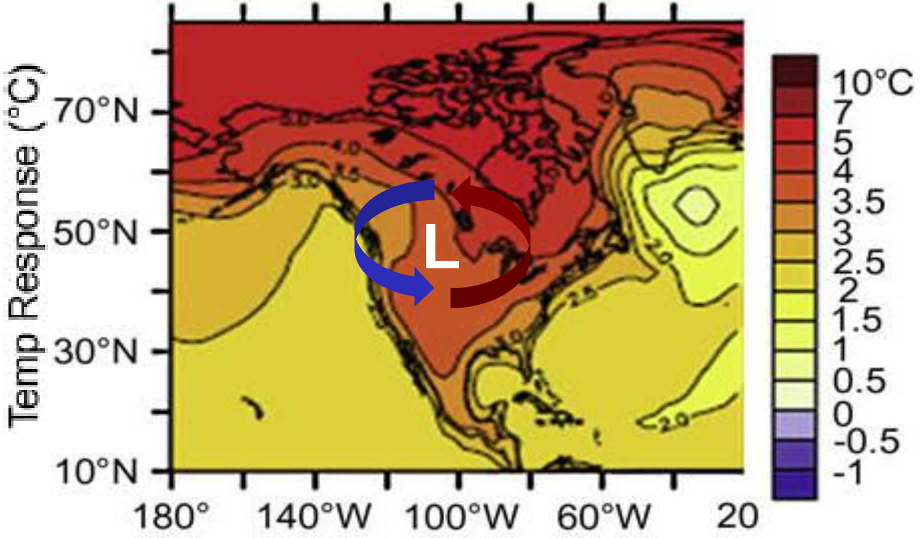
Weather map, 6 am this morning

- **Increasing temperature everywhere, largest at high latitudes**
- **Frequency of heat waves expected to increase**
- **Decrease in equator-to-pole contrast expected to weaken winds, decrease frequency of mid-latitude cyclones and associated cold fronts**

IPCC [2007]

IPCC projection of 21st-century climate change in N. America

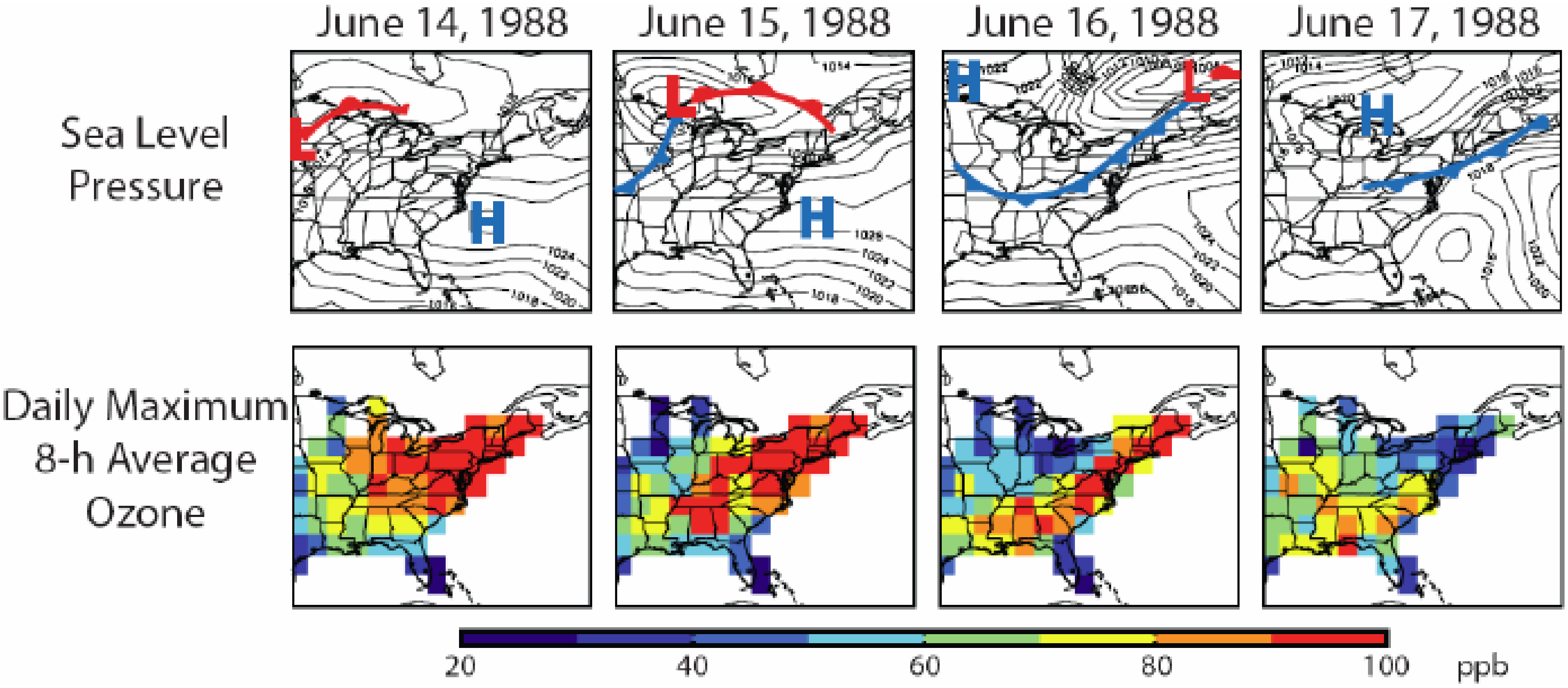
2080-2099 vs. 1980-1999 mean changes for 21 climate models in A1B scenario


Surface temperature

- **Increasing temperature everywhere, largest at high latitudes**
- **Frequency of heat waves expected to increase**
- **Decrease in equator-to-pole contrast expected to weaken winds, decrease frequency of mid-latitude cyclones and associated cold fronts**

IPCC [2007]

Importance of mid-latitudes cyclones for ventilating the eastern US

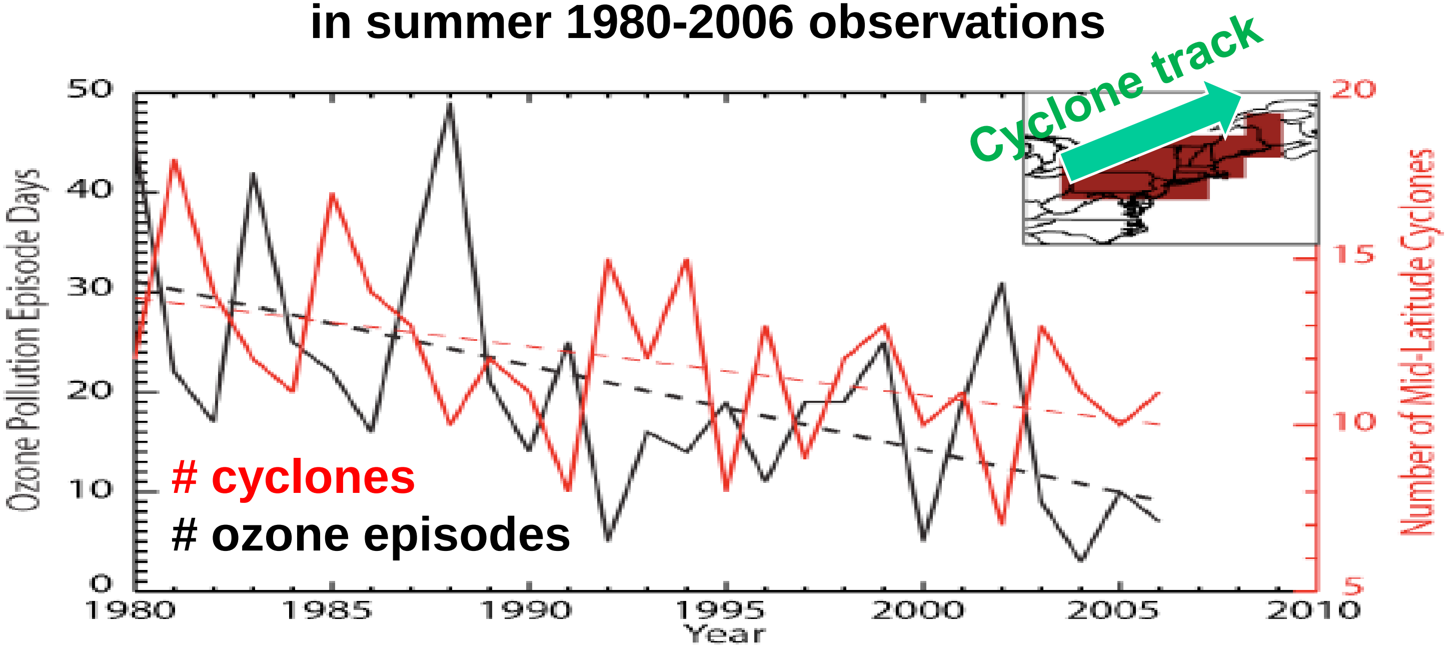


- Cold fronts associated with cyclones tracking across southern Canada are the principal ventilation mechanism for the Midwest and East
- The frequency of these cyclones has decreased in past 50 years, likely due to greenhouse warming

Leibensperger et al. [2008]

Observed trends of ozone pollution and cyclones in Northeast US

ozone episode days (O_3>80 ppb) and # cyclones tracking across SE Canada in summer 1980-2006 observations

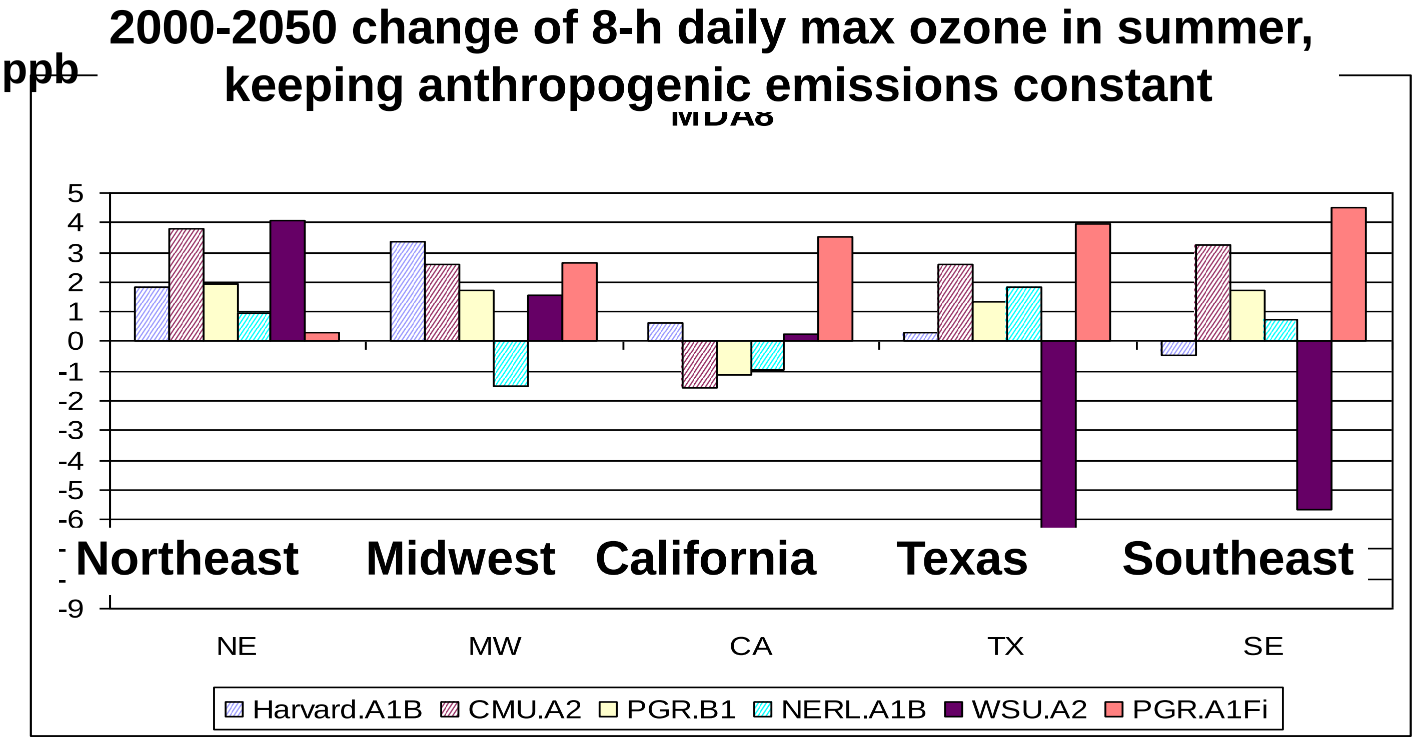


- Cyclone frequency is predictor of interannual pollution variability
- Observed 1980-2006 decrease in cyclone frequency would imply a corresponding degradation of air quality if emissions had remained constant
- Expected # of 80 ppb exceedance days for Northeast average ozone dropped from 30 in 1980 to 10 in 2006, but would have dropped to zero in absence of cyclone trend

Leibensperger et al. [2008]

Assessing the effect of 2000-2050 climate change on ozone air quality in the US

Results from six different coupled chemistry-climate models



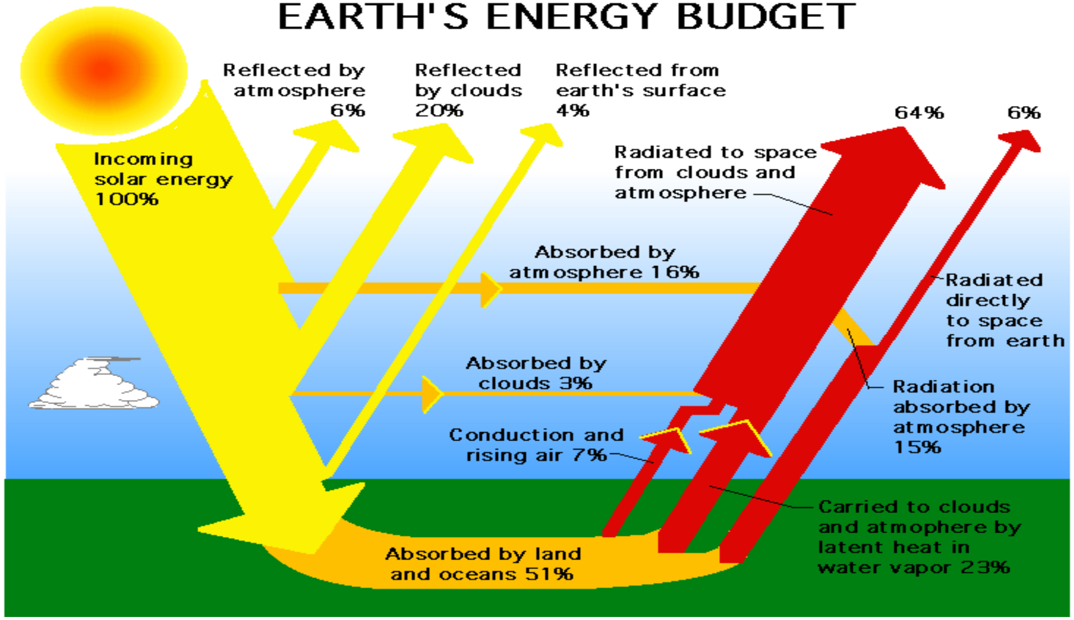
- Models show consistent projection of ozone increase over Northeast
- Typical mean increase is 1-4 ppb, up to 10 ppb for ozone pollution episodes
- Increase is largest in urban areas with high ozone

Weaver et al. [2010]

Effect of air pollutants on climate change

Radiative forcing is the fundamental metric for climate science and policy

Solar flux
F_{in}

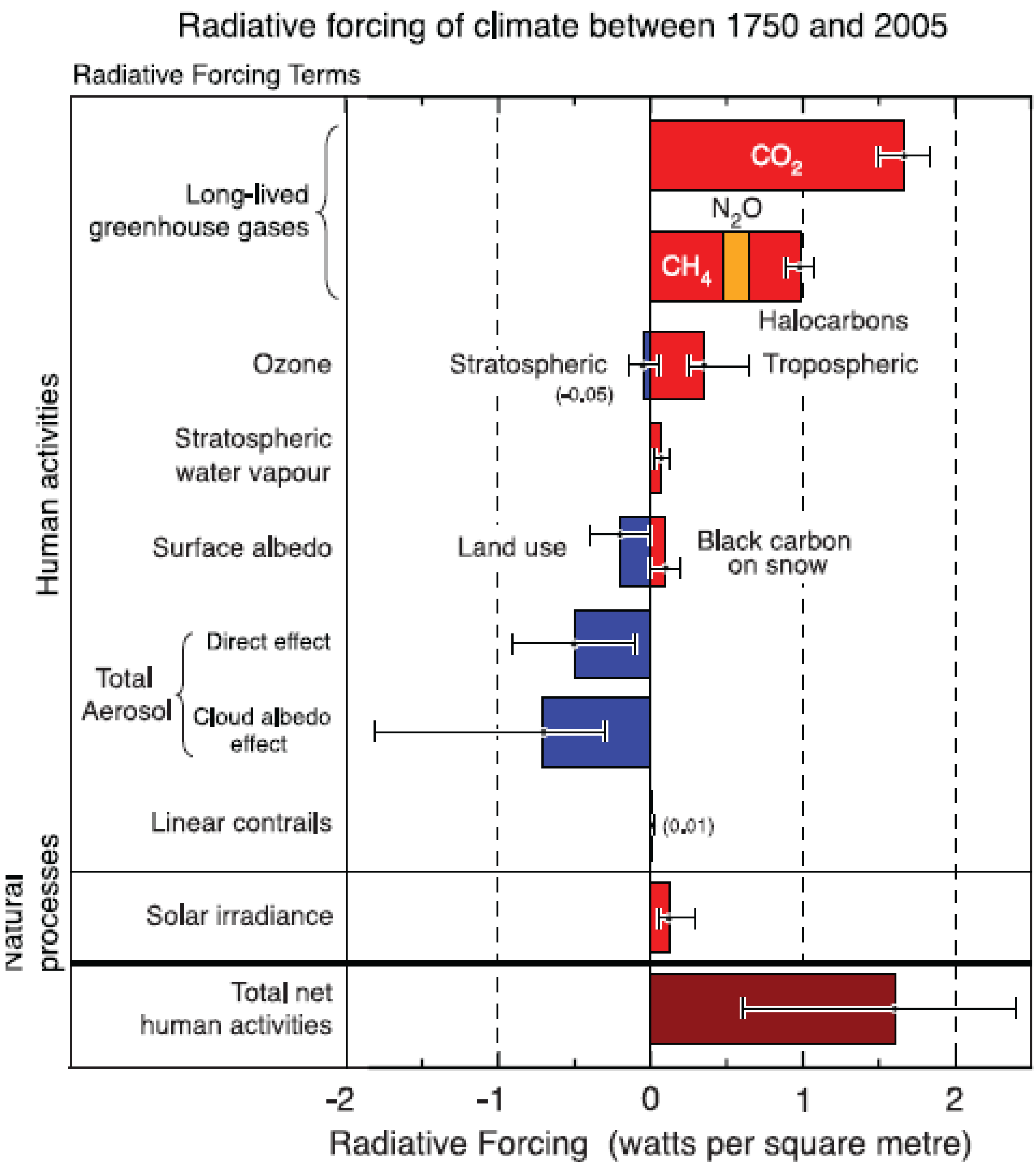


Terrestrial flux
$F_{out} \sim T^4$

1. **Global radiative equilibrium:** $F_{in} = F_{out}$

2. **Perturbation to greenhouse gases or aerosols disrupts equilibrium:** $F_{in} \neq F_{out}$
   - $\Delta F = F_{in} - F_{out}$ **is called the *radiative forcing***
   - **Global response of surface temperature is proportional to radiative forcing:** $\Delta T_{surface} \sim \Delta F$

1750-2005 radiative forcing of climate change



- CO_2 forcing is 1.6 ± 0.2 W m^{-2}

- Methane is the second most important anthropogenic greenhouse gas

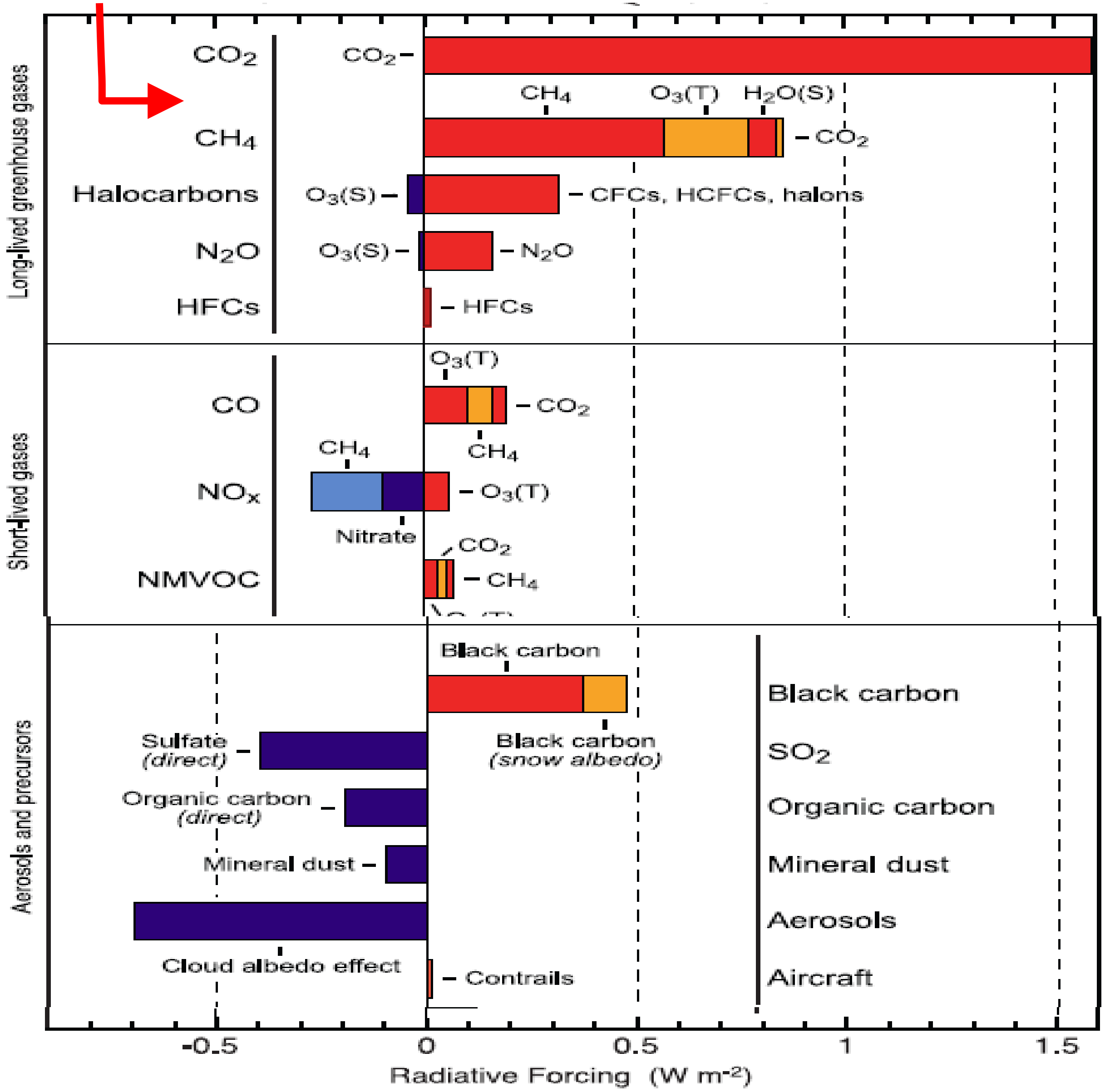
- Tropospheric ozone forcing is +0.3-0.7 W m^{-2}; range reflects uncertainty in natural levels

- Aerosol forcing could be as large as -2 W m^{-2} ; range reflects uncertainty in aerosol sources, optical properties, cloud interactions

IPCC [2007]

1750-2005 radiative forcing referenced to emissions

anthropogenic emissions



- **Beneficial impact of methane, BC, CO, NMVOC controls**
- **Detrimental impact of SO_2 and OC controls**
- **NO_x is climate-neutral within uncertainty**

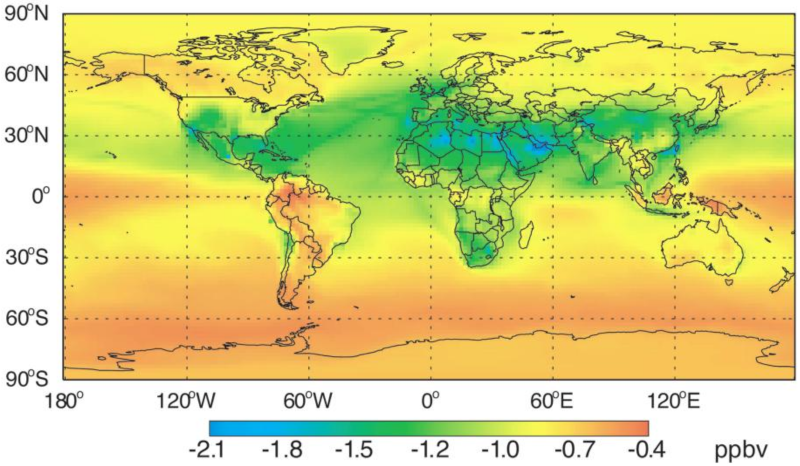
IPCC [2007]

Methane is "win-win" for climate and air quality – but only as part of a global strategy

Effect on surface ozone air quality is through decrease in ozone background and does not depend on where methane emission is reduced

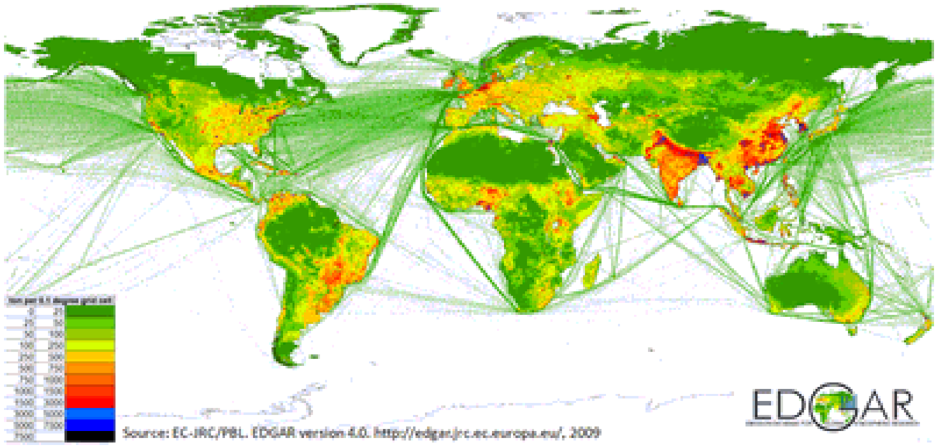
Reduction in annual MDA8 ozone from 20% global decrease in anthropogenic methane emissions

[West et al., 2006]



Global 2005 anthropogenic methane emissions (EDGAR inventory): US accounts for ~10%

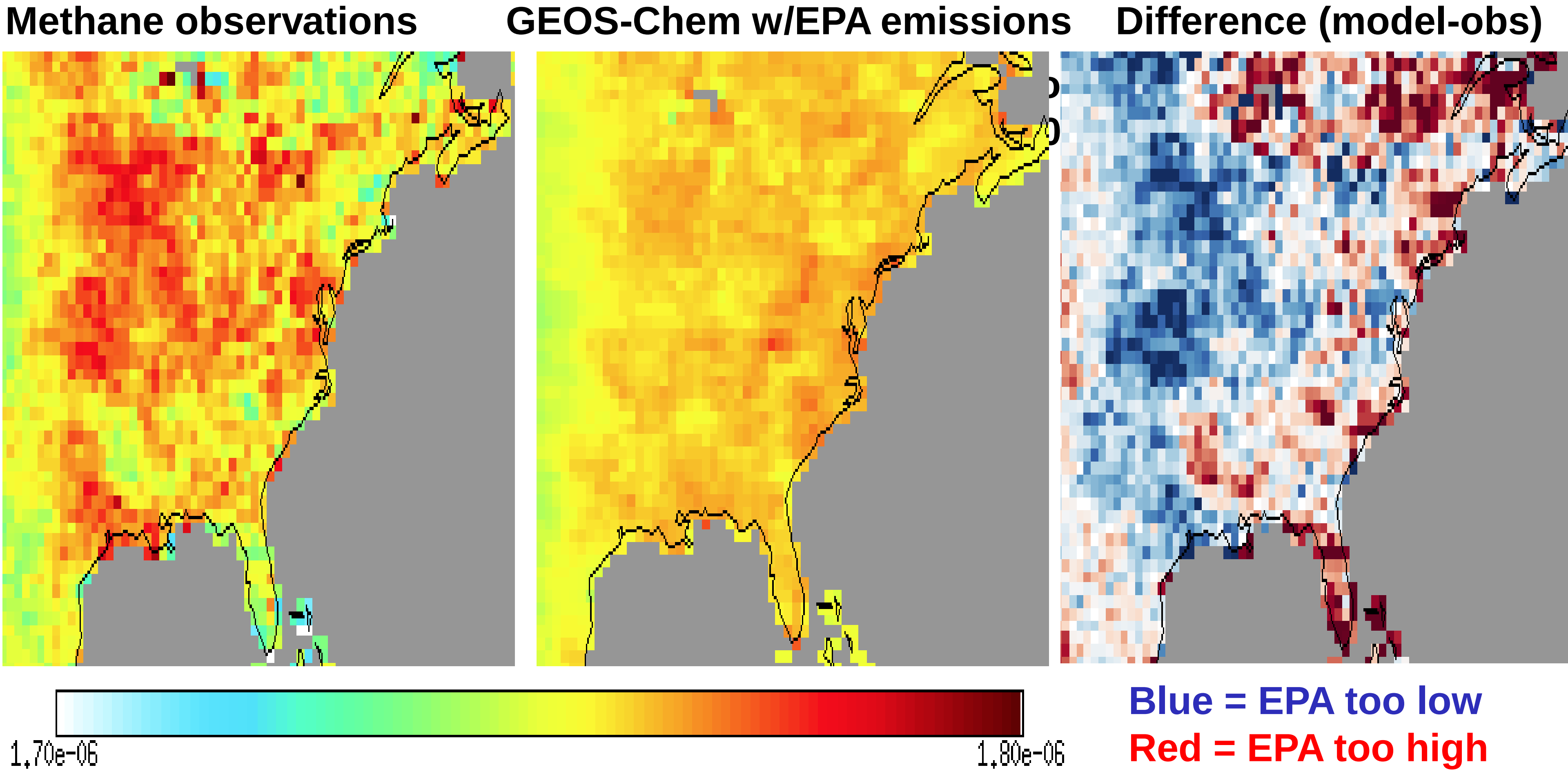
Source ($Tg\ a^{-1}$)	US [EPA, 2009]	Global
Fossil fuel	9.5	80-120
Agriculture	8.2	110-200
Landfills	7.0	40-70



Source: EC-JRC/PBL. EDGAR version 4.0. http://edgar.jrc.ec.europa.eu/, 2009

Satellite data enable monitoring of US methane emissions

SCIAMACHY column methane, June-August 2004



Methane observations **GEOS-Chem w/EPA emissions** **Difference (model-obs)**

Blue = EPA too low
Red = EPA too high

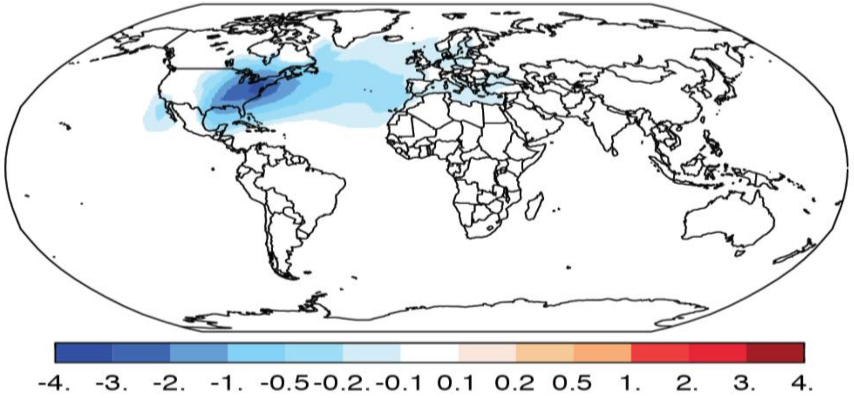
- **Inventories too low in central US: agriculture, oil/gas?**
- **Inventories too high in New England: ??**

Kevin Wecht (Harvard)

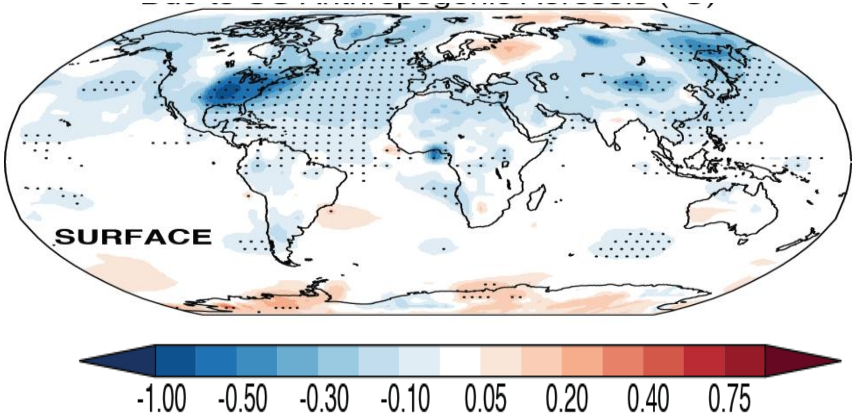
Climate effect from US anthropogenic PM

1950-2050 GEOS-Chem simulation coupled to NASA/GISS climate model

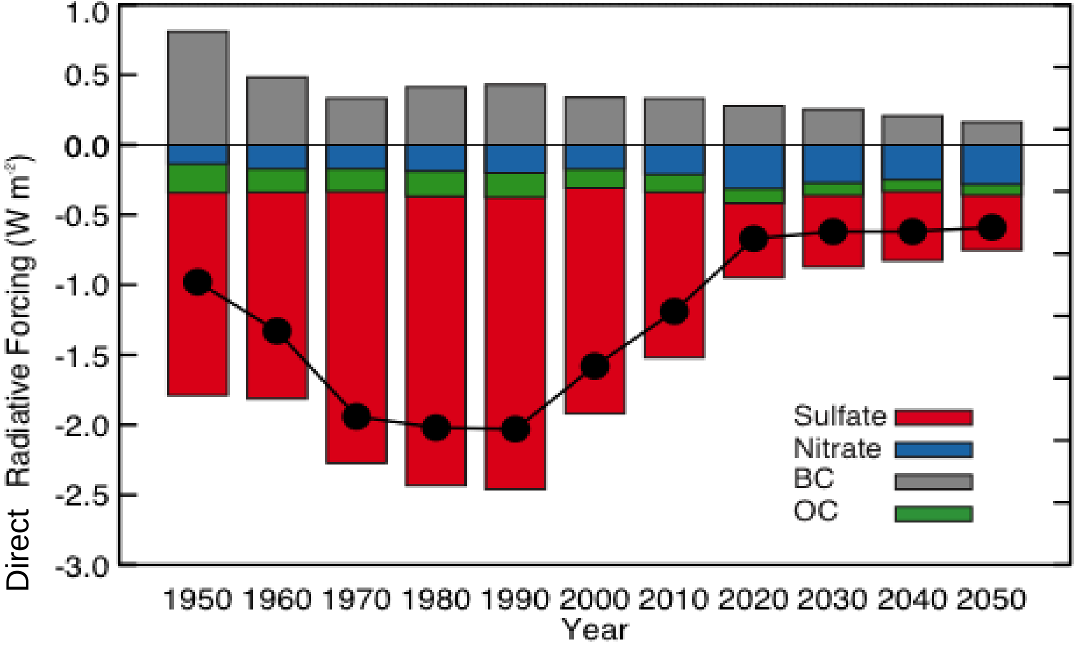
Radiative forcing from PM



Surface cooling from PM in 1980 (°C)



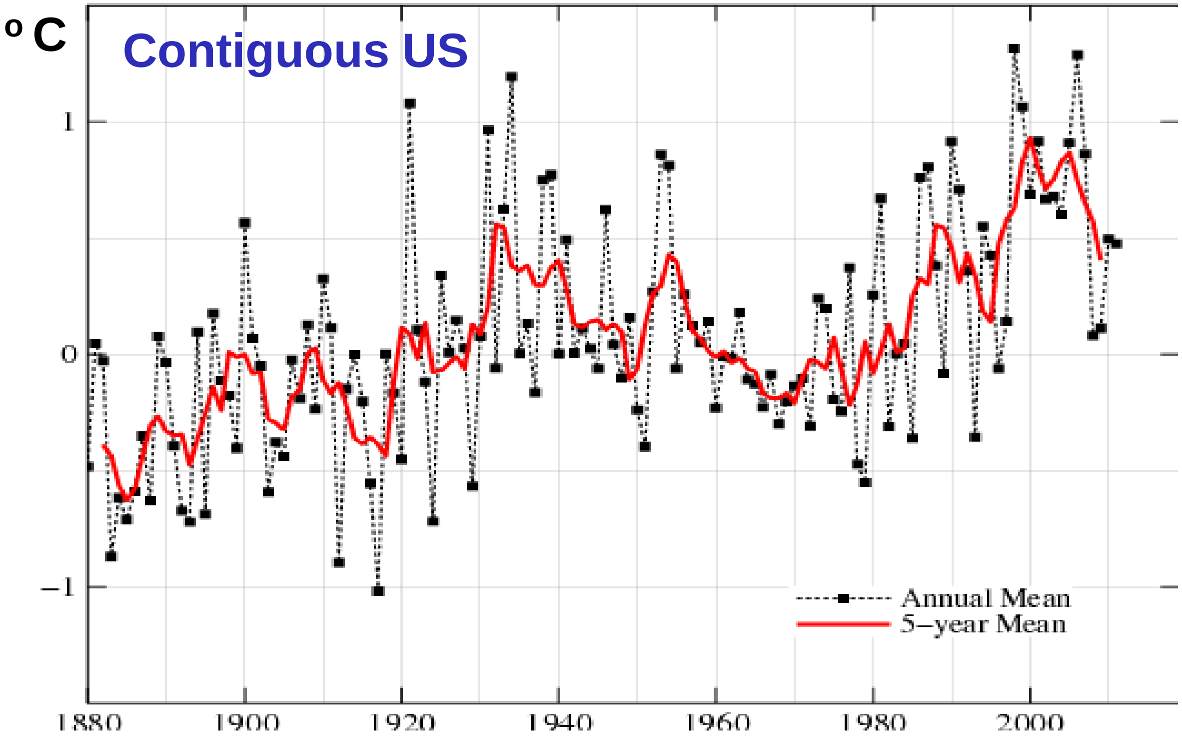
1950-2050 forcing trend over eastern US



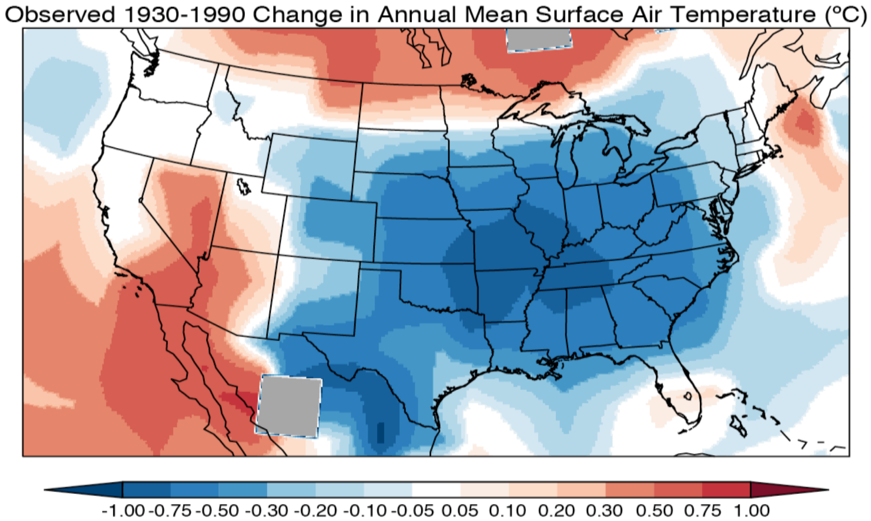
- Forcing is mostly from sulfate, peaked in 1970-1990
- Little leverage to be had from BC control
- Indirect (cloud) forcing is of similar magnitude to direct forcing

Leibensperger et al., [2012]

Observed US surface temperature trend



No warming from 1930 to 1980, sharp warming after 1980



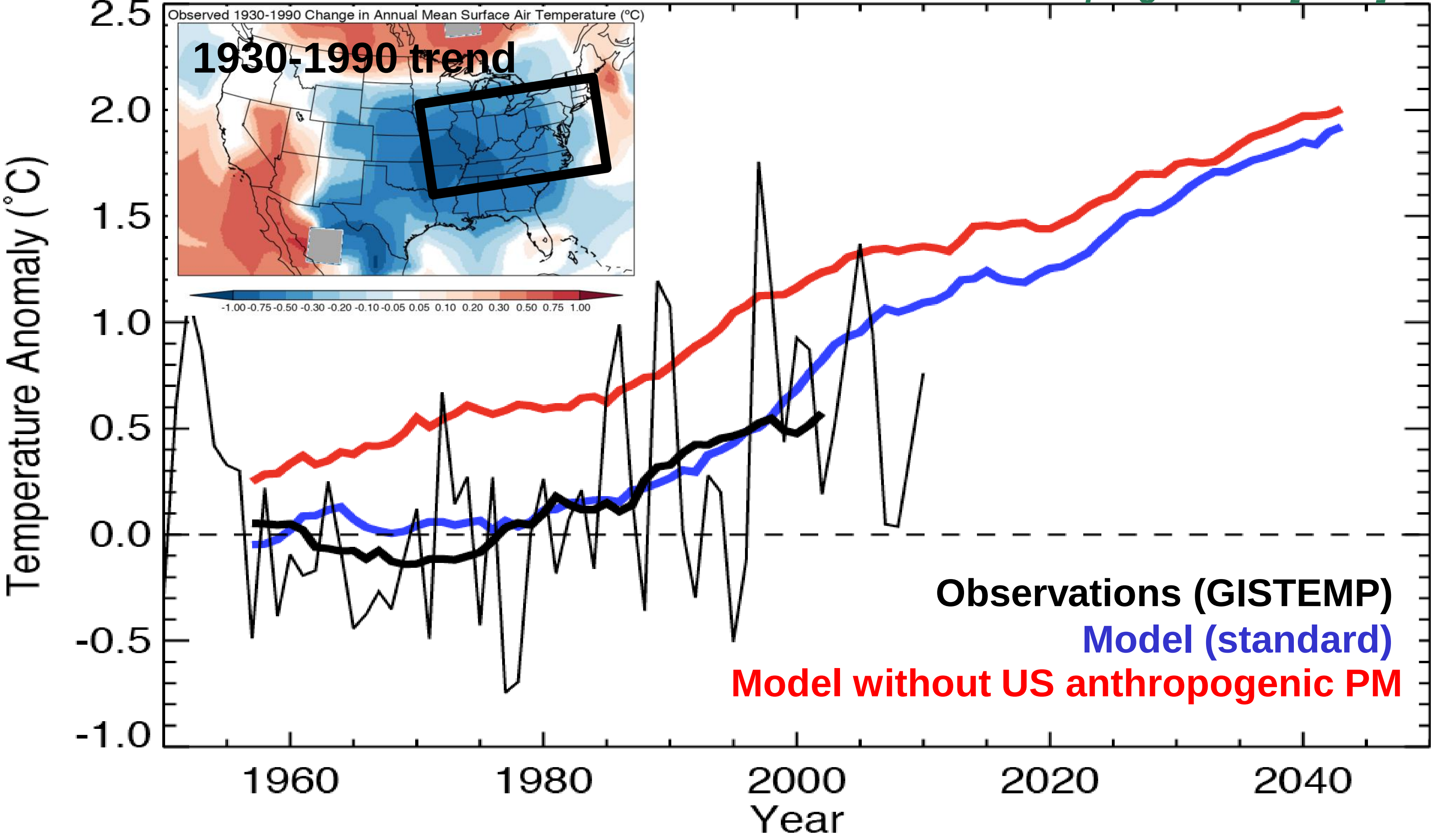
1930-1990 trend

"Warming hole" observed in eastern US from 1930 to 1990; US PM signature?

GISTEMP [2010]

1950-2050 surface temperature trend in eastern US

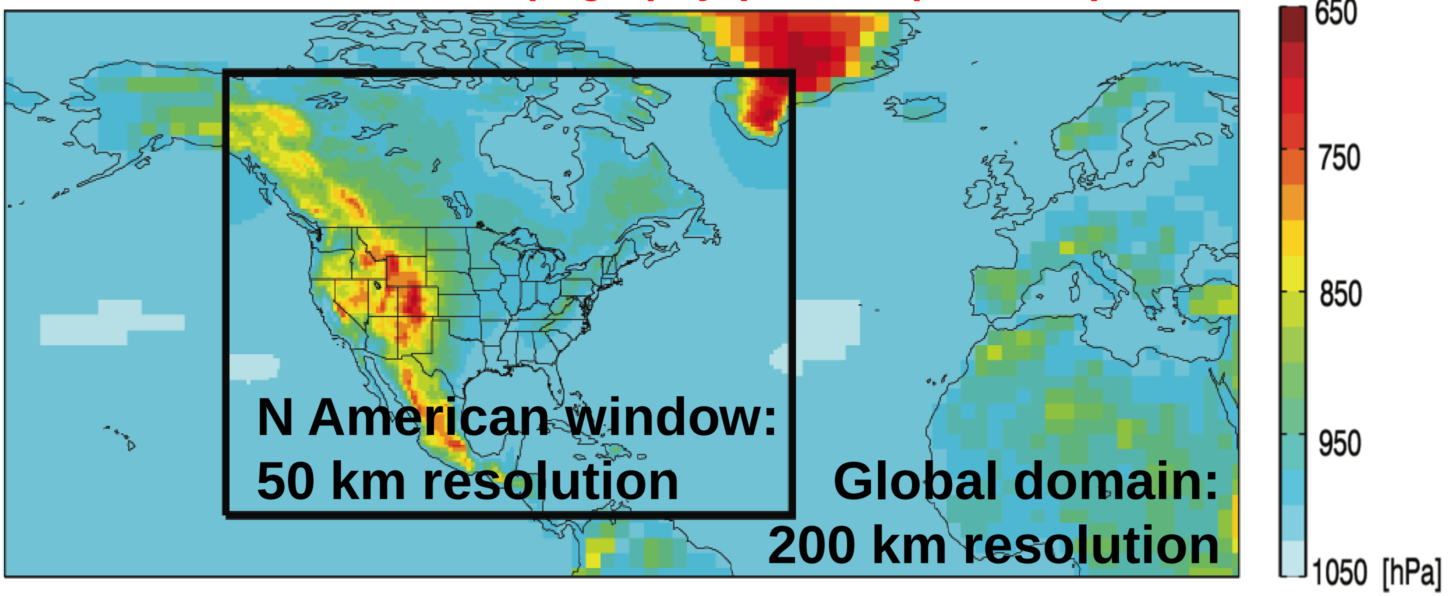
Leibensperger et al. [2012]



- **US anthropogenic PM sources can explain the “warming hole”**
- **PM removal has caused accelerated warming in eastern US since 1990s**

Application of GEOS-Chem continental-scale model simulations to regional/transboundary/intercontinental air quality issues

Color scale Indicates topography (surface pressure)



Continental-scale simulation nested within global domain

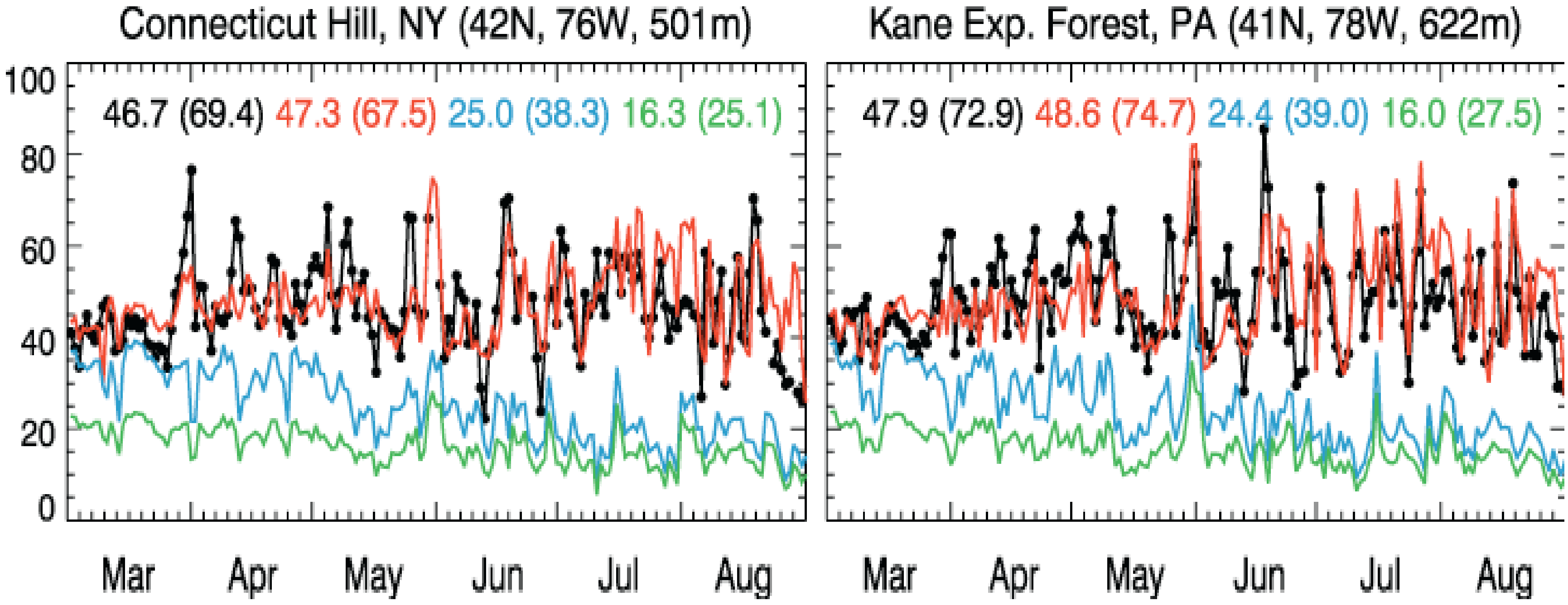
Ozone background used in EPA Integrated Science Assessment

Observations

four GEOS-Chem simulations

- **Standard – as described above**
- **US background – no US anthro emissions**
- **NA background - no N.American anthro emissions**
- **Natural – no anthro emissions worldwide**

2006 MDA8 ozone at Northeast CASTNet sites- with mean (4th highest) inset

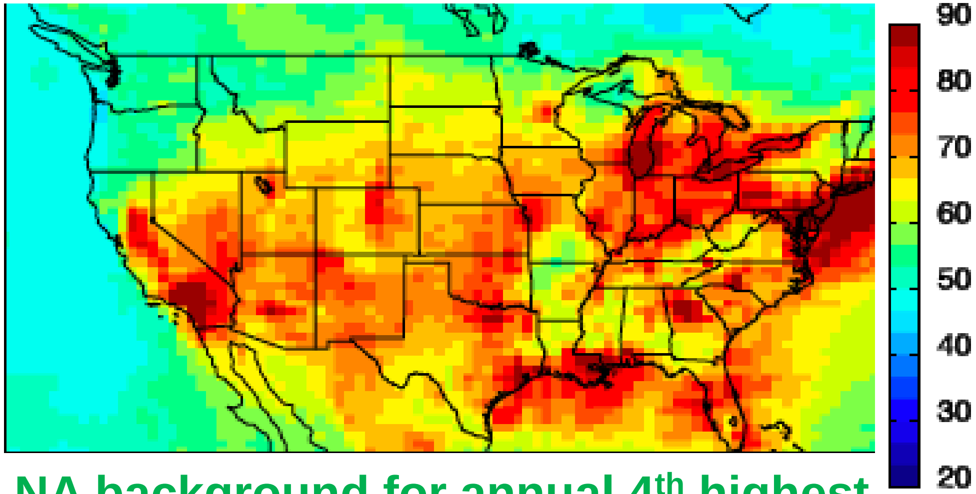


- **Mean NA background over Northeast is 29 ppb (spring), 20 ppb (summer)**
- **Peak background events of 50 ppb (lightning) can lead to total ozone > 80 ppb**

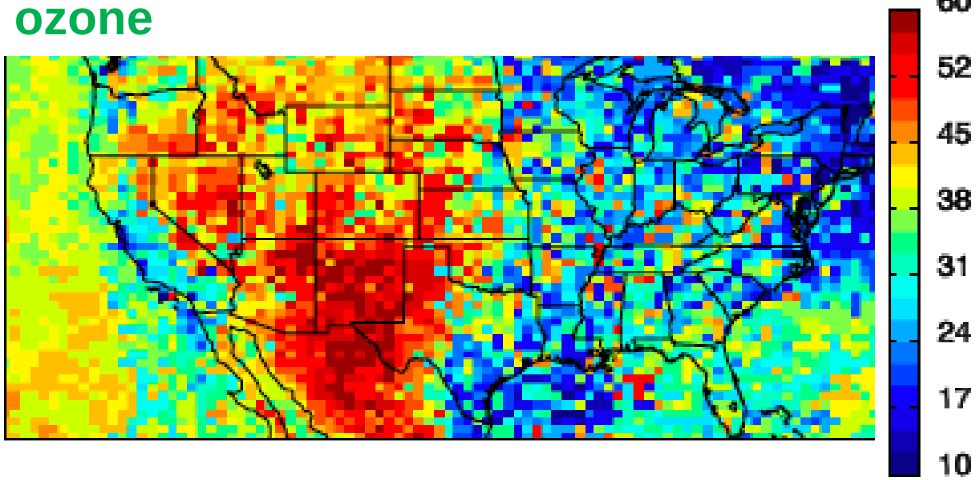
Zhang et al. [2011]

Model “4th highest” MDA8 ozone in 2006

Annual 4th highest ozone

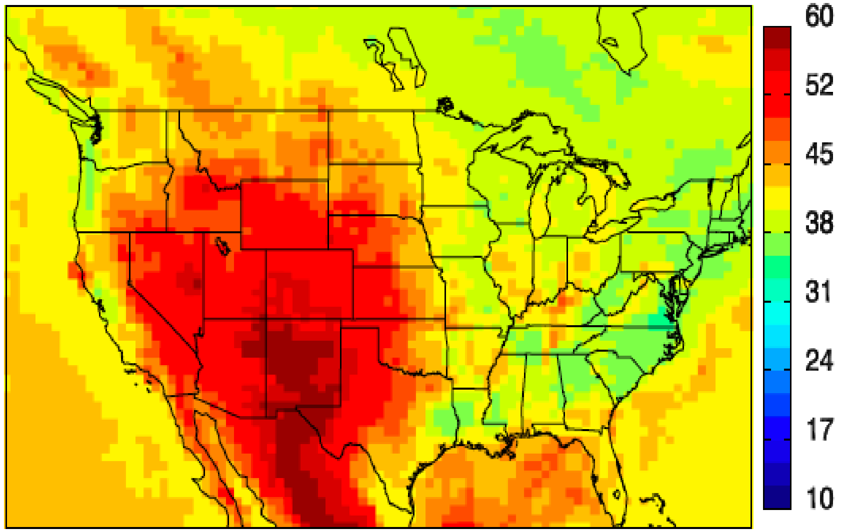


NA background for annual 4th highest ozone



- **Ozone episodes in Northeast usually (not always) associated with low background**
- **Background will become an important issue as US sources decrease and the NAAQS tightens**

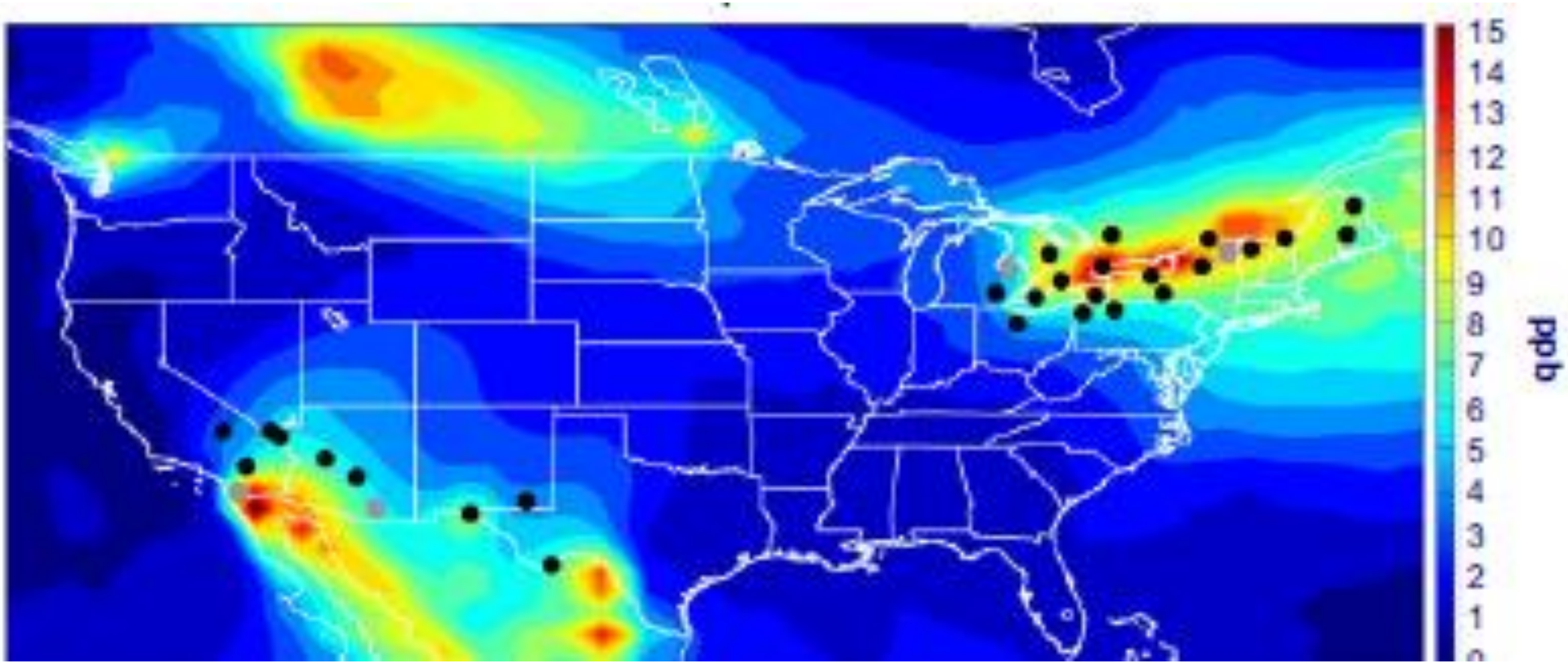
4th highest NA background value



Zhang et al. [2011]

Canadian pollution influence on ozone in Northeast US

Mean Canadian/Mexican pollution influences on MDA8 ozone (Jun-Aug 2001)
as determined by a GEOS-Chem simulation with those sources shut off

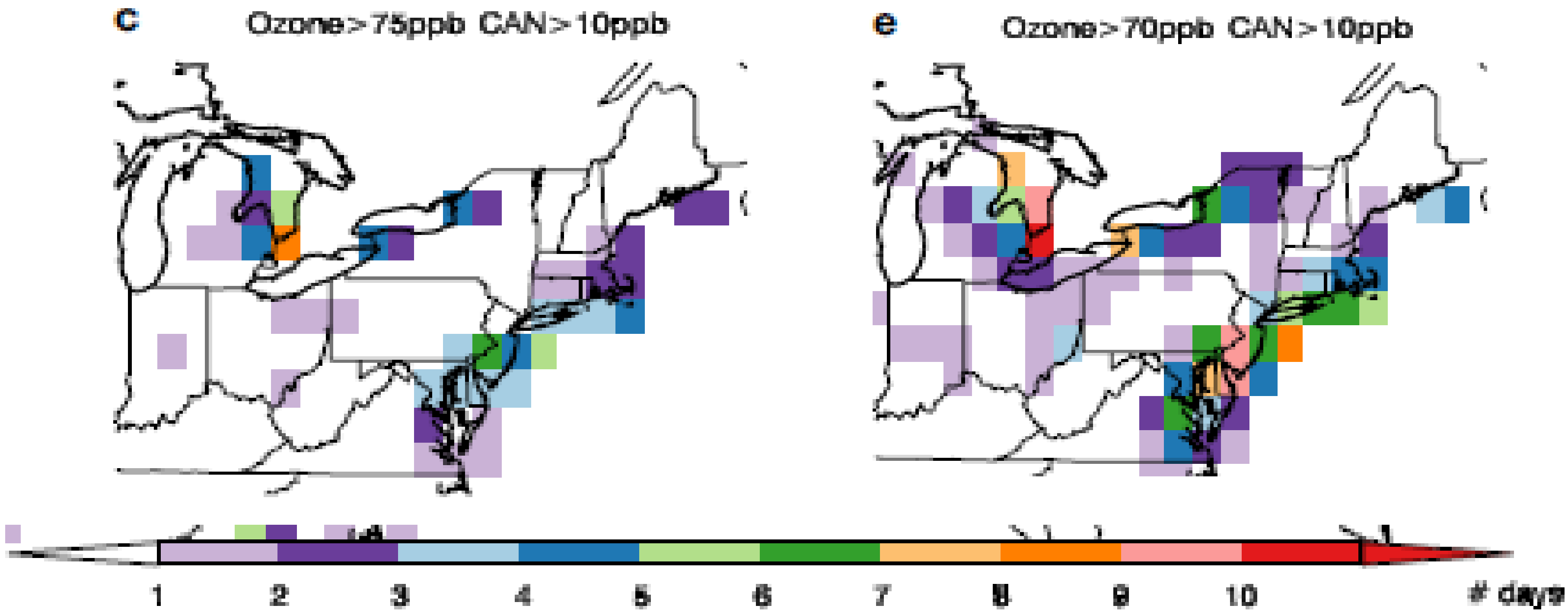


Mean national influence over US is small (3 ppb) but regional influence can be large

Wang et al. [2009]

Relevance of Canadian pollution for US air quality policy

Number of days per year when MDA8 ozone exceeds 75 or 70 ppb and Canadian pollution influence exceeds 10 ppb

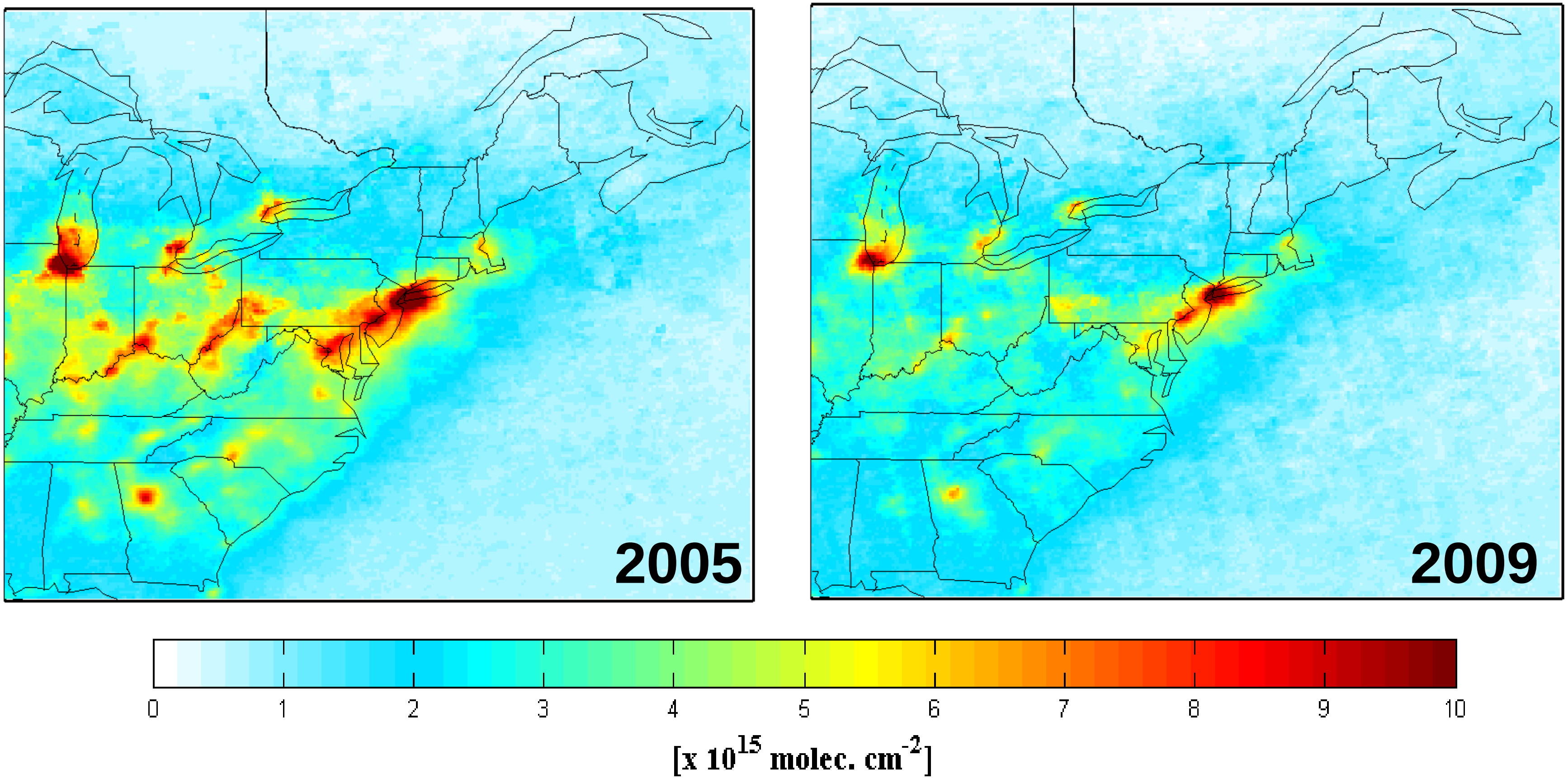


Canadian sources need to be considered in ozone mitigation plans for Northeast

Wang et al. [2009]

Decrease of North American NO_x emisssions, 2005-2009

as seen with annual mean NO_2 columns from the OMI satellite instrument



Decreases in both the eastern US and eastern Canada

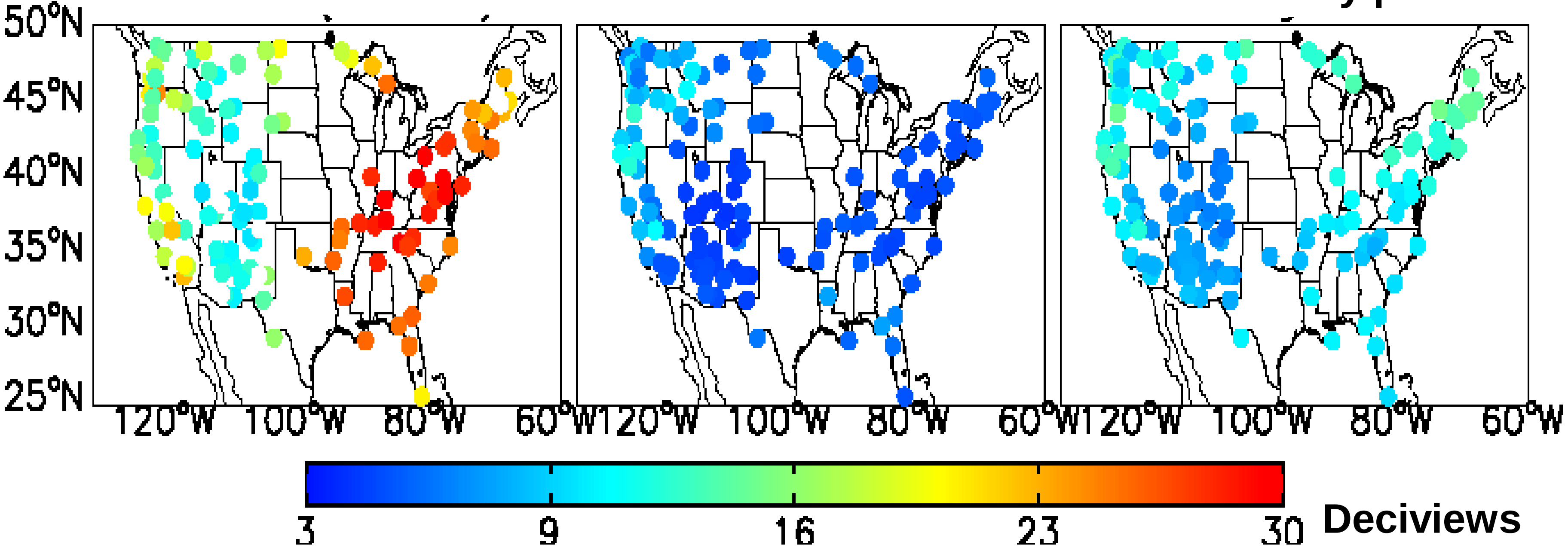
Shailesh Kharol (Dalhousie)

Visibility in US wilderness areas

EPA Regional Haze Rule aims for natural visibility to be achieved in all US Federal Class 1 areas by 2064; Phase 1 implementation for 2004-2018

GEOS-Chem simulations

2001 observations | **Natural** | **Background; includes transboundary pollution**

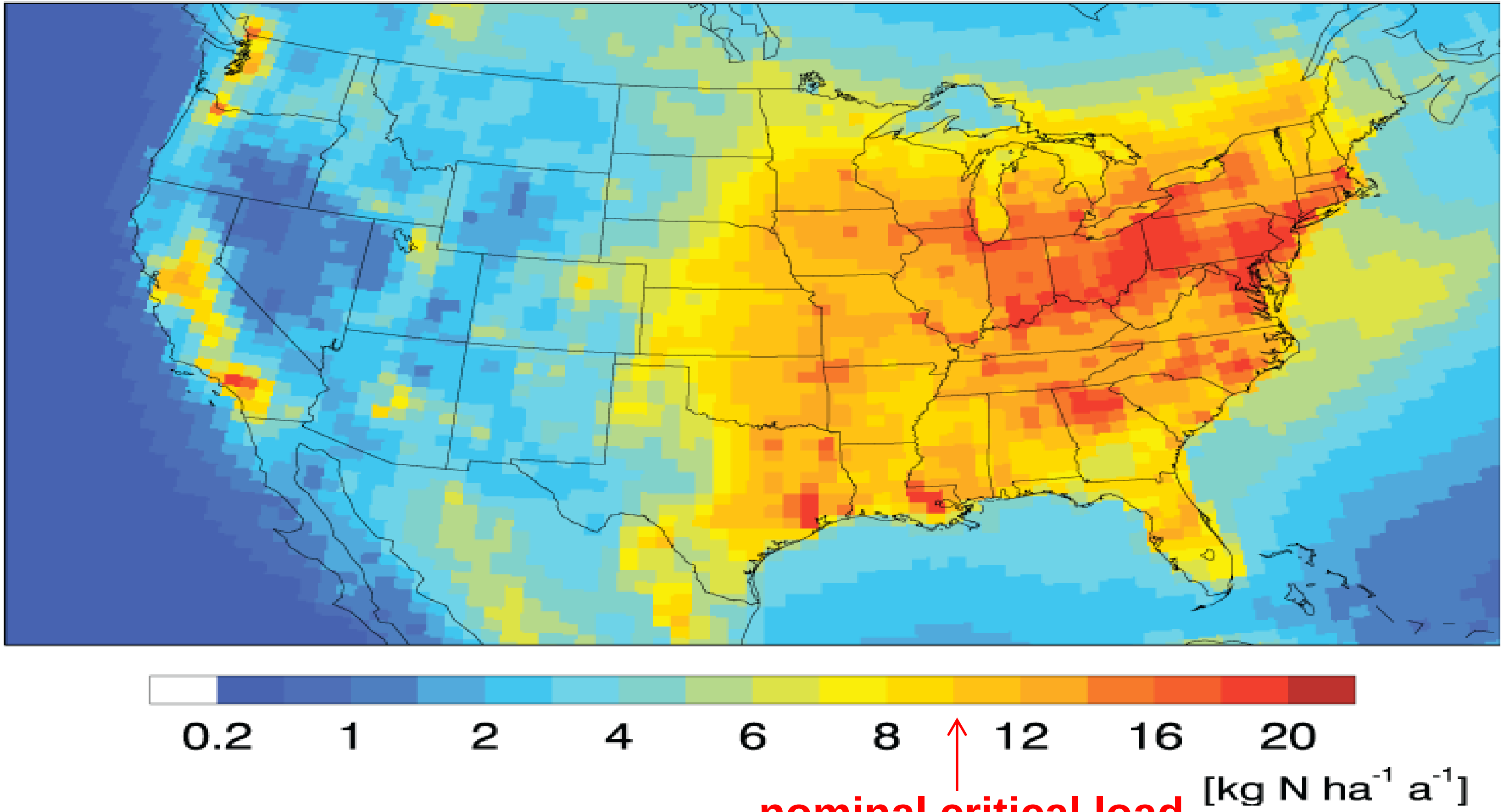


Canadian emissions would prevent attainment of natural visibility in Northeast even with zeroed US emissions; choice of endpoint affects Phase 1 implementation

Park et al. [2006]

Nitrogen deposition in the US

GEOS-Chem simulation for 2006-2008, reproduces well NADP data



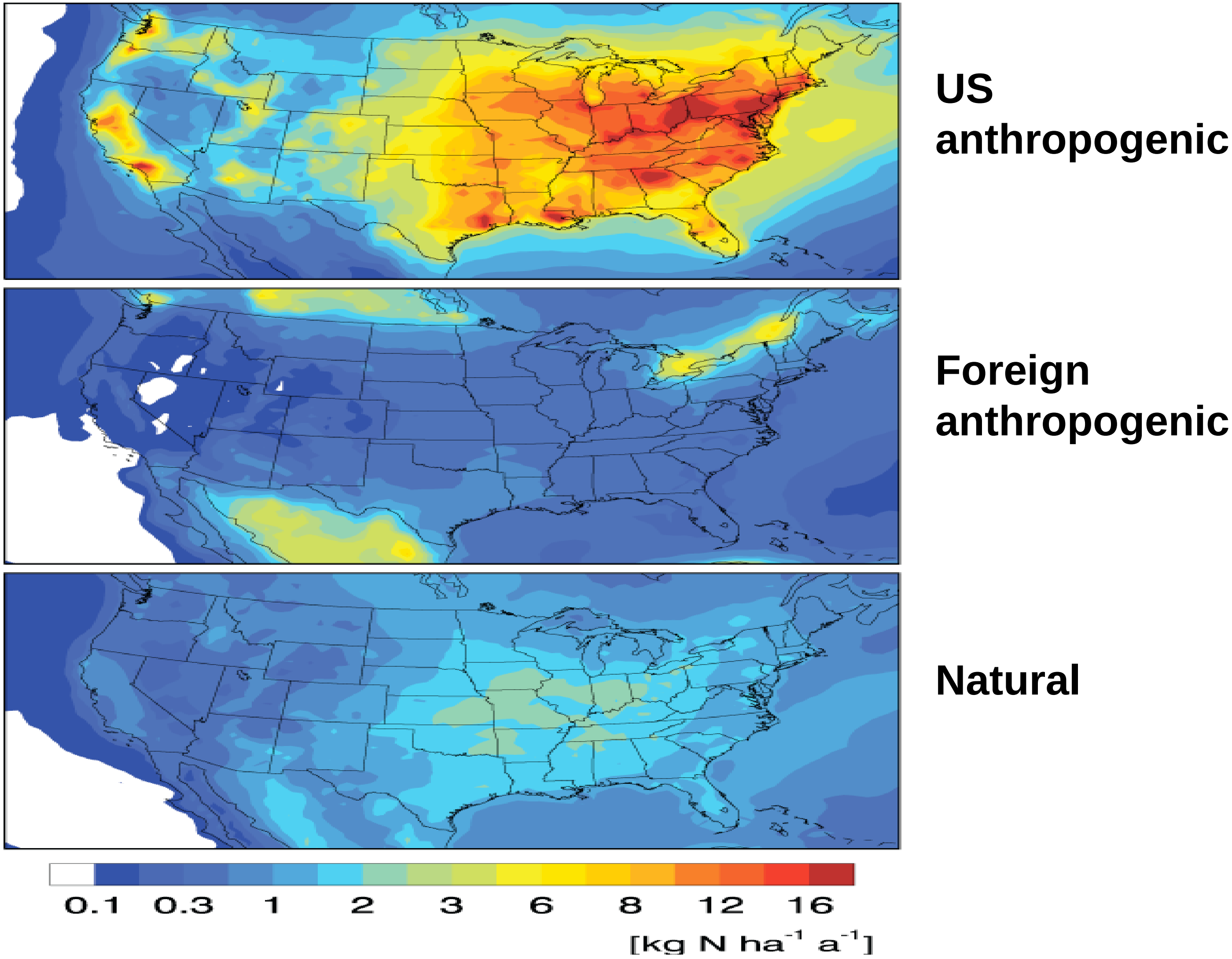
nominal critical load
for ecosystems

- Nitrogen deposition in the Notheast exceeds critical loads
- Most of that deposition is as nitric acid originating from NO_x emissions

Zhang et al. [2012]

Source contributions to nitrogen deposition

as computed from GEOS-Chem sensitivity simulations

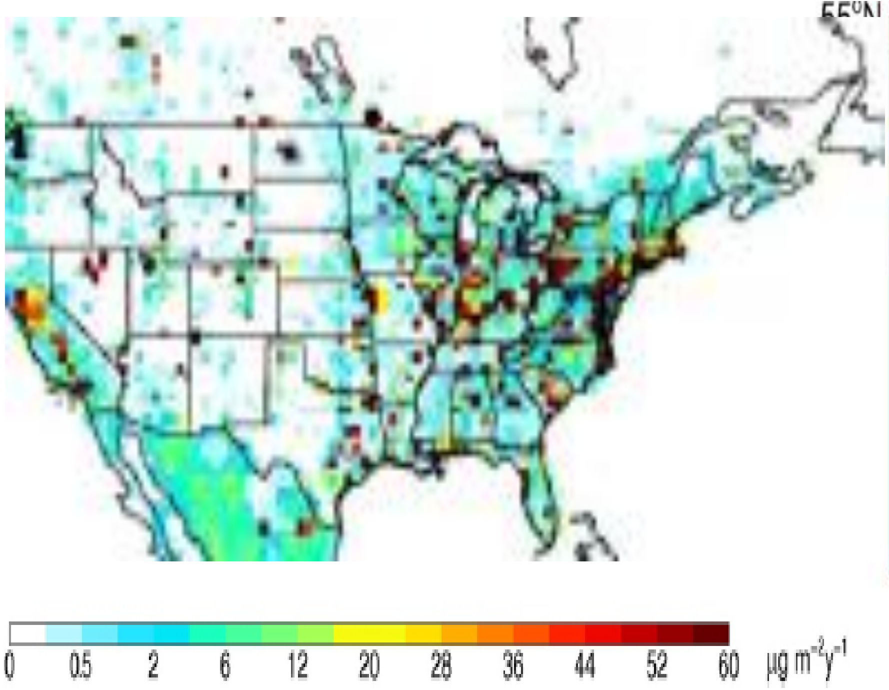


Nitrogen deposition in Northeast is 10-fold higher than natural and mainly from domestic sources

Zhang et al. [2012]

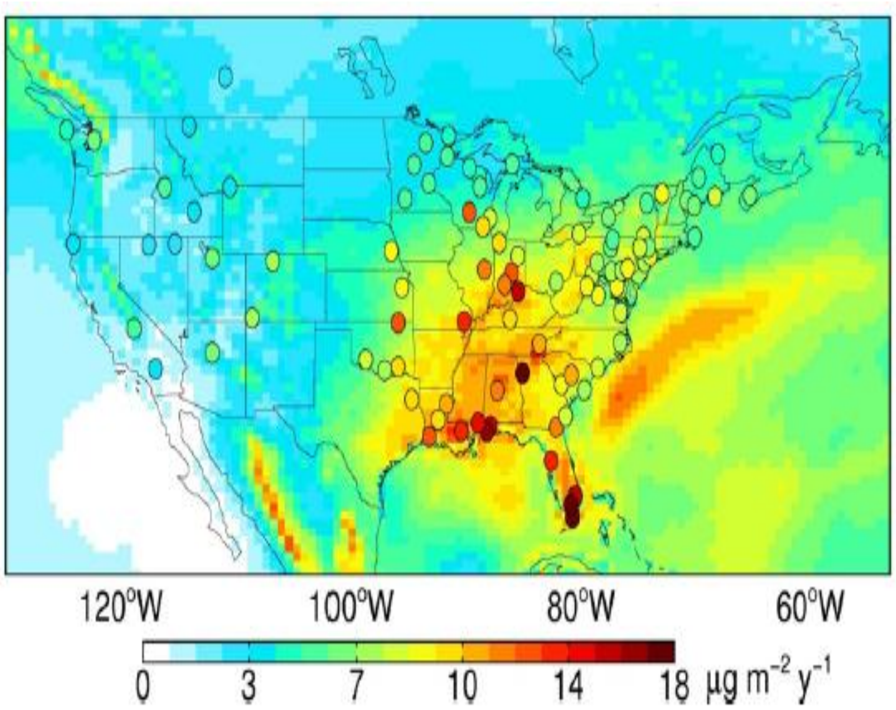
Mercury (Hg) emissions and deposition in US

Mercury emissions (EPA)



Mercury deposition(2008-2009)

Circles: observed   Background: GEOS-Chem

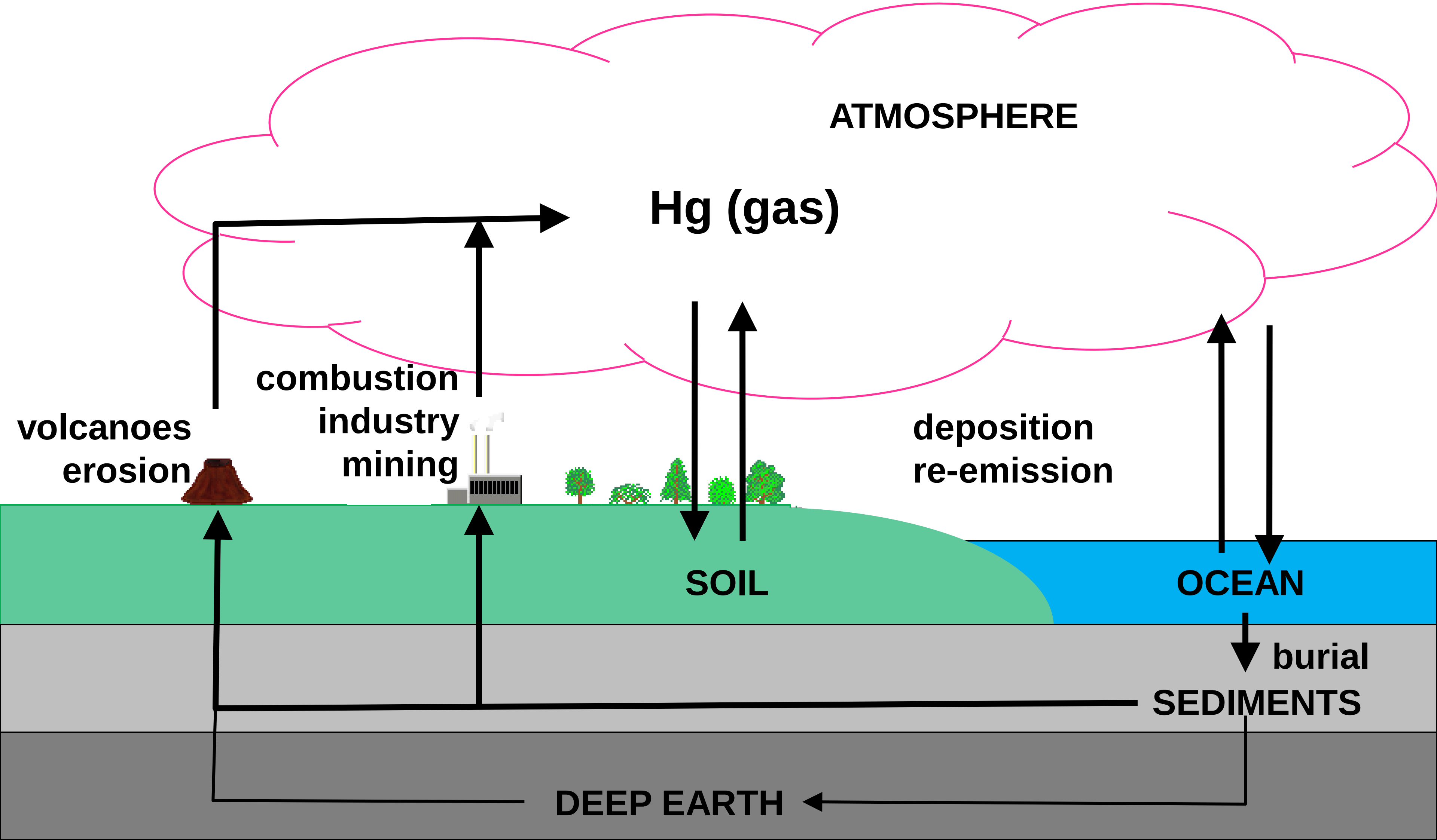


- Emission is both as Hg(0) (transported globally) and Hg(II) (deposits locally)
- There is evidence for rapid conversion of Hg(II) to Hg(0) in combustion plumes
- Only 10-20% of mercury deposited in US is of direct US anthropogenic origin

Y. Zhang et al. [2012]

BIOGEOCHEMICAL CYCLING OF MERCURY

very much the same story as carbon


ATMOSPHERE

Hg (gas)

combustion
industry
mining

volcanoes
erosion

deposition
re-emission

SOIL

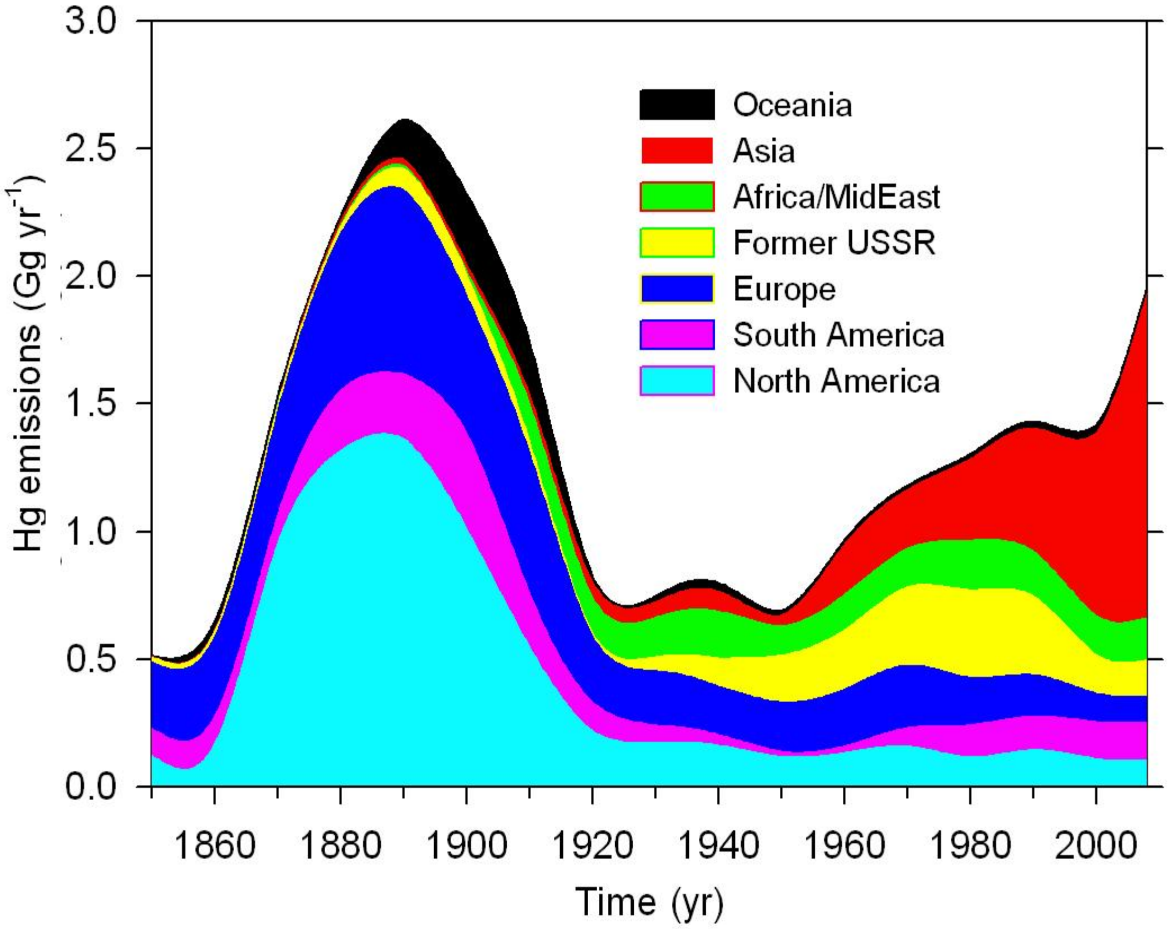
OCEAN

burial

SEDIMENTS

DEEP EARTH

Historical inventory of global anthropogenic Hg emissions

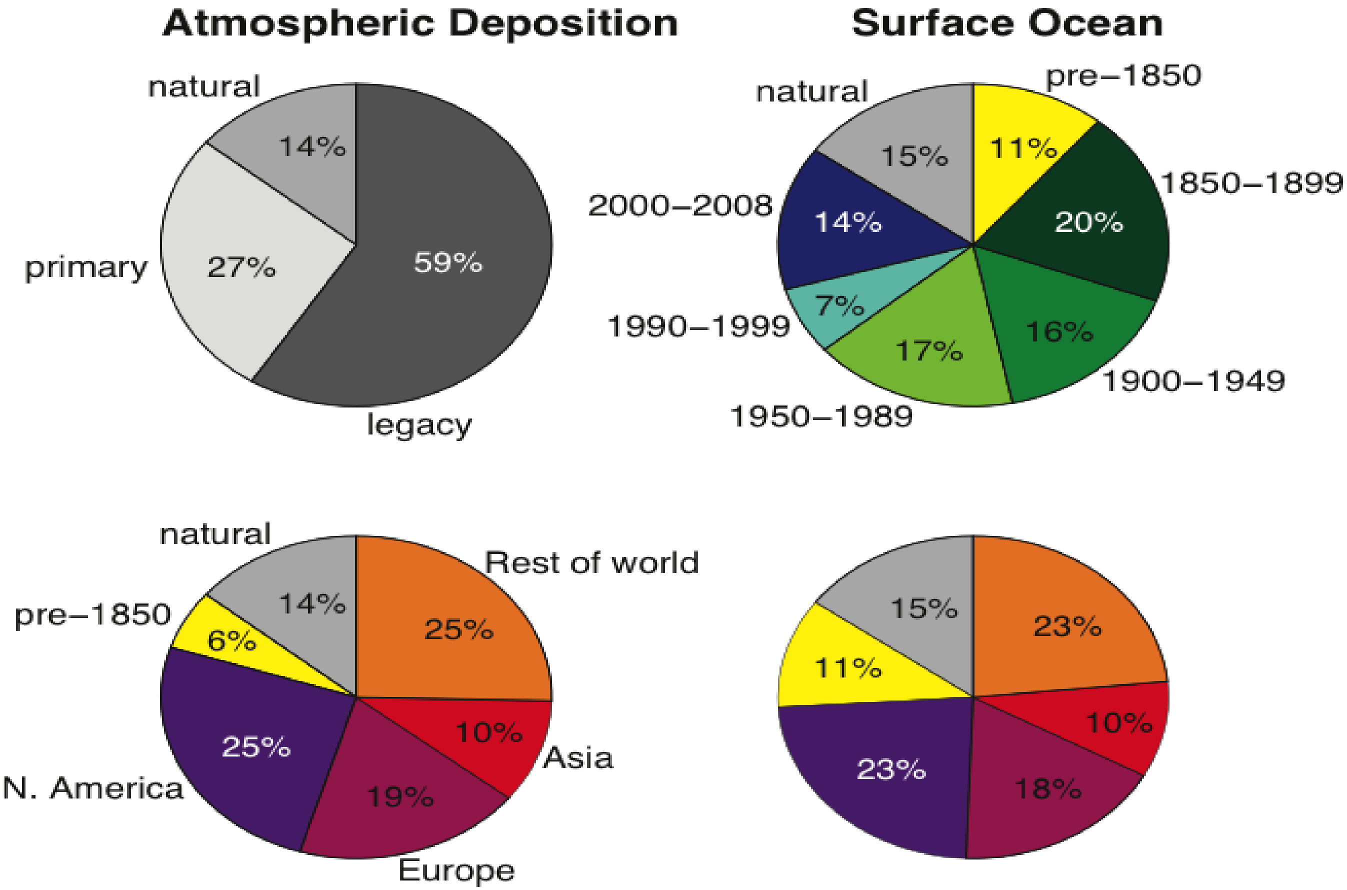


Large legacy contribution from N. American and European emissions; Asian dominance is a recent phenomenon

Streets et al. , 2012

Contribution of old anthropogenic (legacy) mercury to global atmospheric deposition and surface ocean

GEOS-Chem based global biogeochemical model of mercury cycling



Mercury pollution is mainly a legacy problem that will take centuries to fix; all we can do in short term is prevent it from getting worse

Helen Amos, Harvard