Relevance of climate change to air quality policy

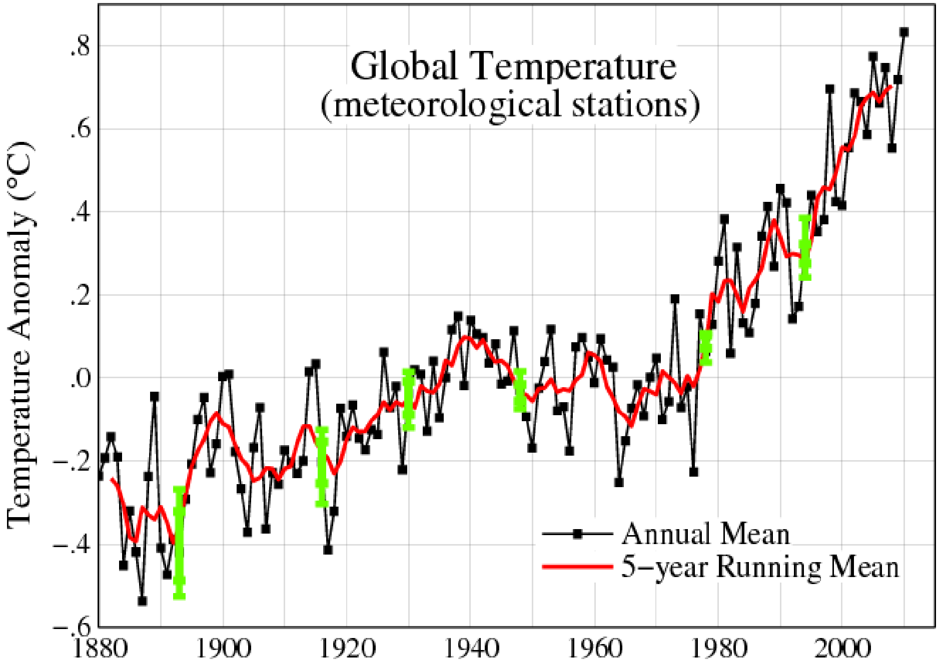
Daniel J. Jacob

with Kevin J. Wecht, Eric M. Leibensperger, Amos P.K. Tai, Loretta J. Mickley

Harvard University
Atmospheric Chemistry Modeling Group

and funding from EPRI, EPA, NASA

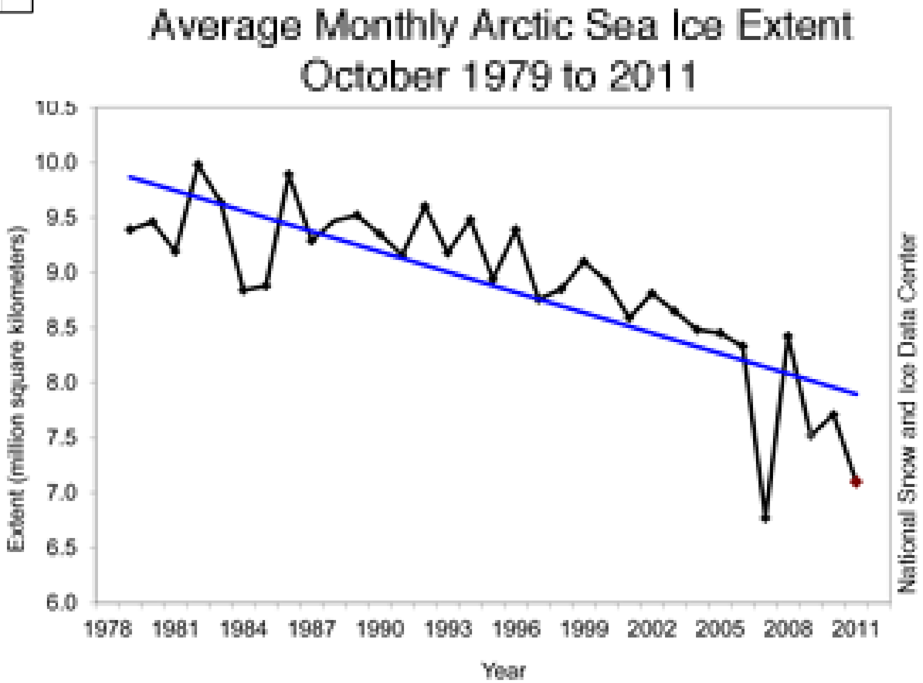
The reality of climate change



http://data.giss.nasa.gov/gistemp/

Global temperatures

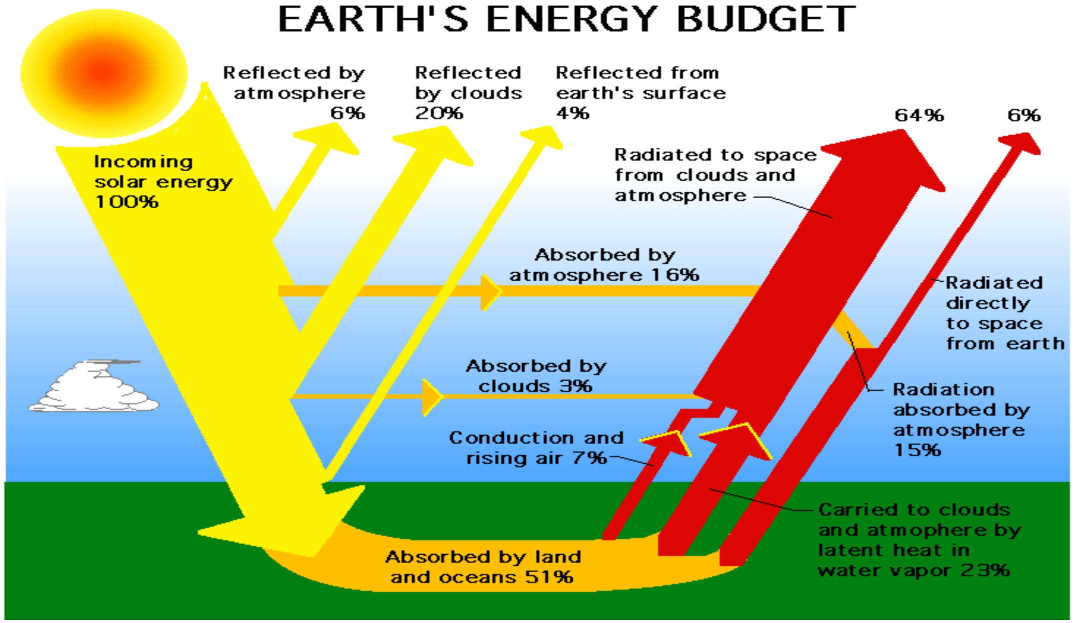
Arctic sea ice



http://nsidc.org/arcticseaicenews/

Radiative forcing: foundation of climate science and policy

Solar flux
F_{in}

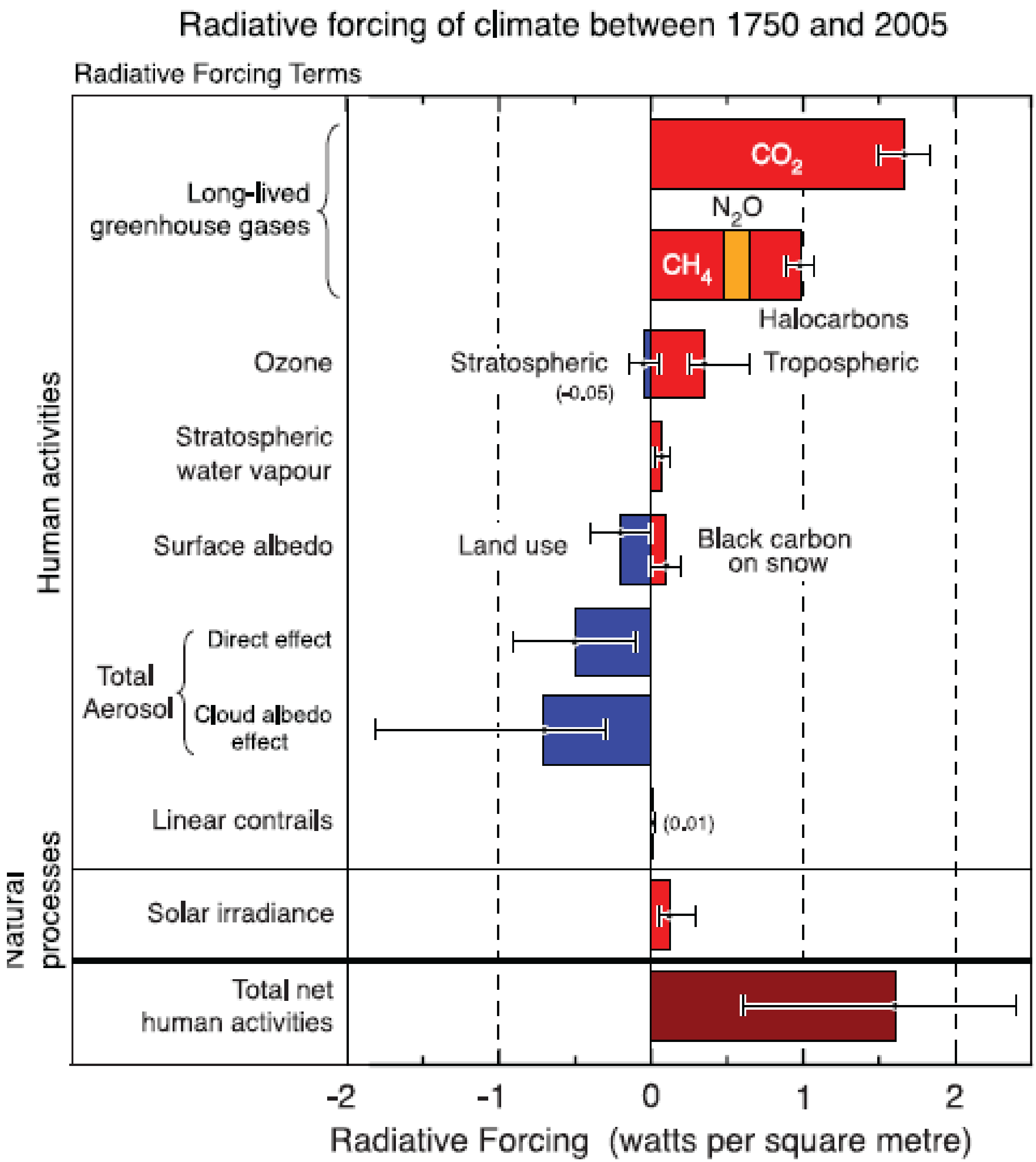


Terrestrial flux
$F_{out} \sim T^4$

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

2. Perturbation to greenhouse gases or aerosols disrupts equilibrium: $F_{in} \neq F_{out}$
   - $\Delta F = F_{in} - F_{out}$ defines 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}**

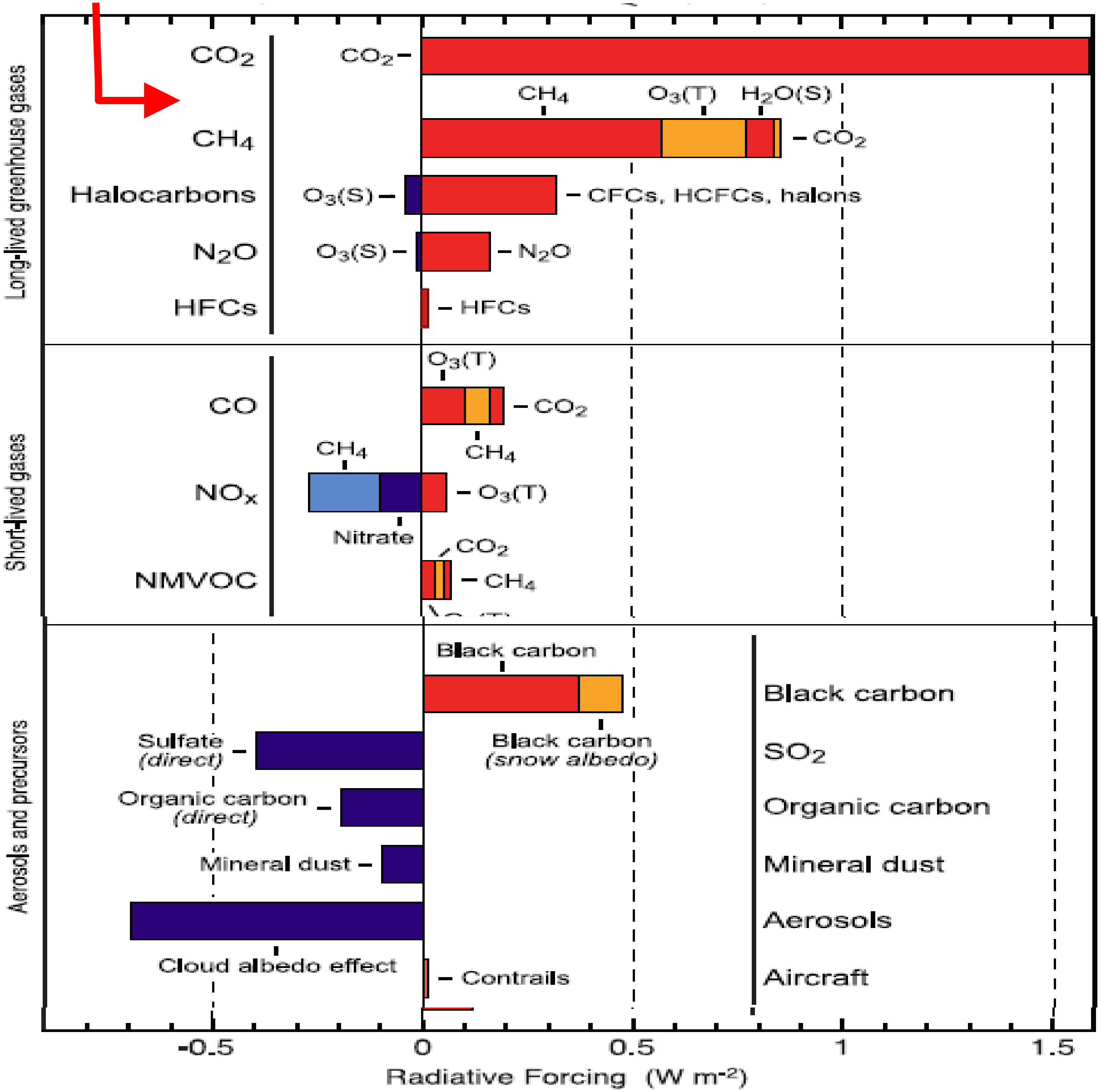
- **Tropospheric ozone forcing is +0.3-0.7 W m^{-2}; range reflects uncertainty in natural levels**

- **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, OC controls**
- **NO_x is climate-neutral within uncertainty**

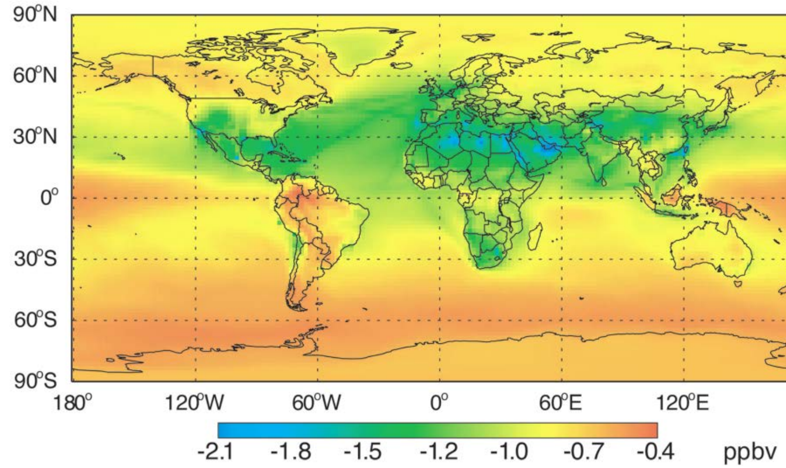
IPCC [2007]

Methane is "win-win" – 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

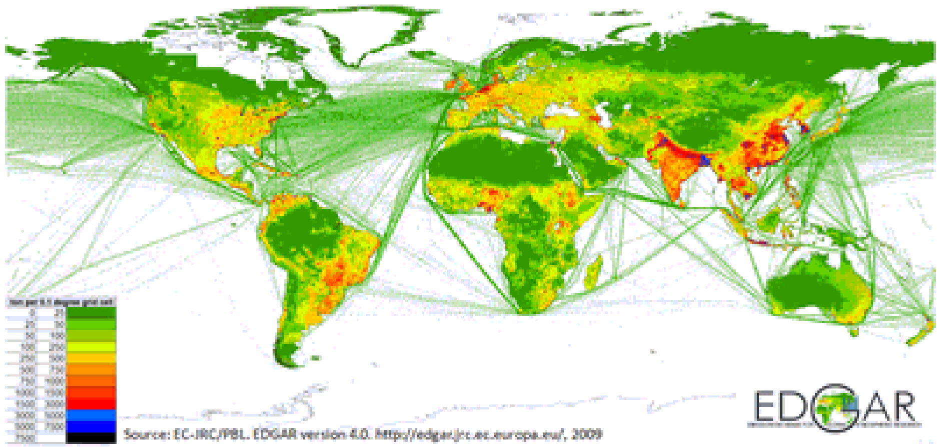
Reduction in annual MDA8 ozone from 20% global decrease in anthropogenic methane emissions

[West et al., 2006]



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

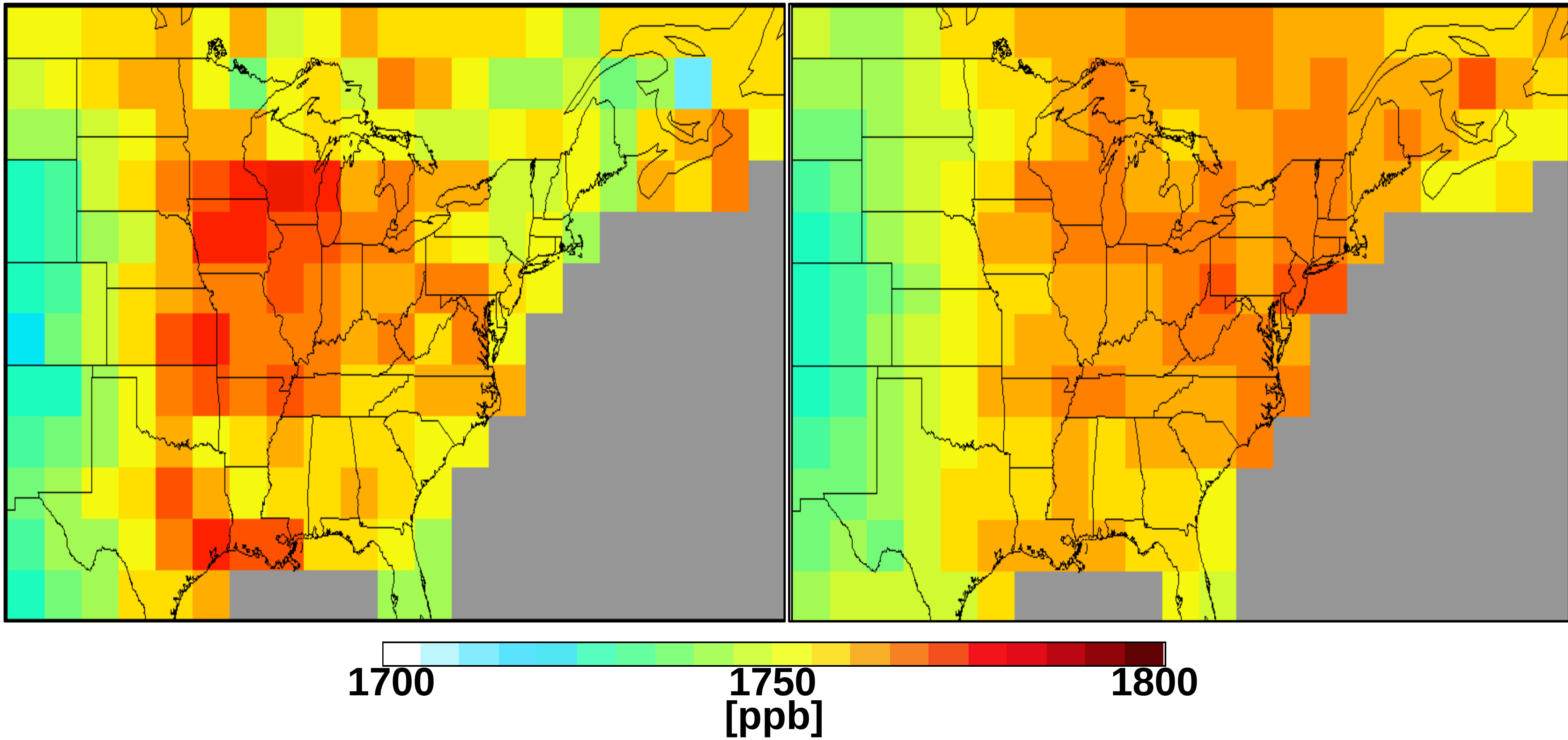
Source ($Tg\ a^{-1}$)	US [EPA, 2009]	Global
Fossil fuel	9.5	80-120
Agriculture	8.2	110-200
Landfills	7.0	40-70



SCIAMACHY satellite data indicate underestimate of EPA methane emissions from oil/gas and agriculture

SCIAMACHY column methane, 1 July - 15 August 2004

GEOS-Chem model column methane, 1 July – 15 August 2004, using EPA emission estimates



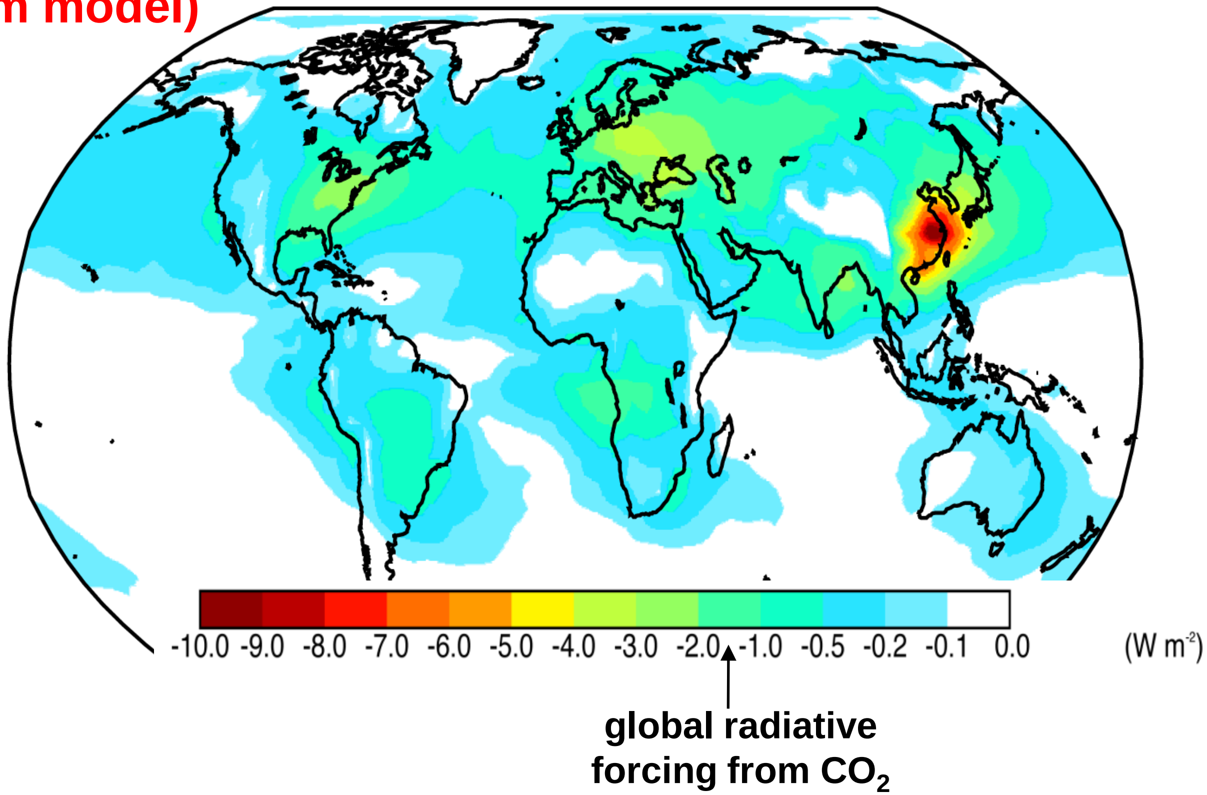
ICARTT aircraft data (summer 2004) show the same pattern of discrepancy; national emissions may be too low by ~ factor of 2

Kevin Wecht (Harvard)

Radiative forcing by aerosols is very inhomogeneous

…in contrast to the long-lived greenhouse gases

Present-day annual direct radiative forcing from anthopogenic aerosols (GEOS-Chem model)



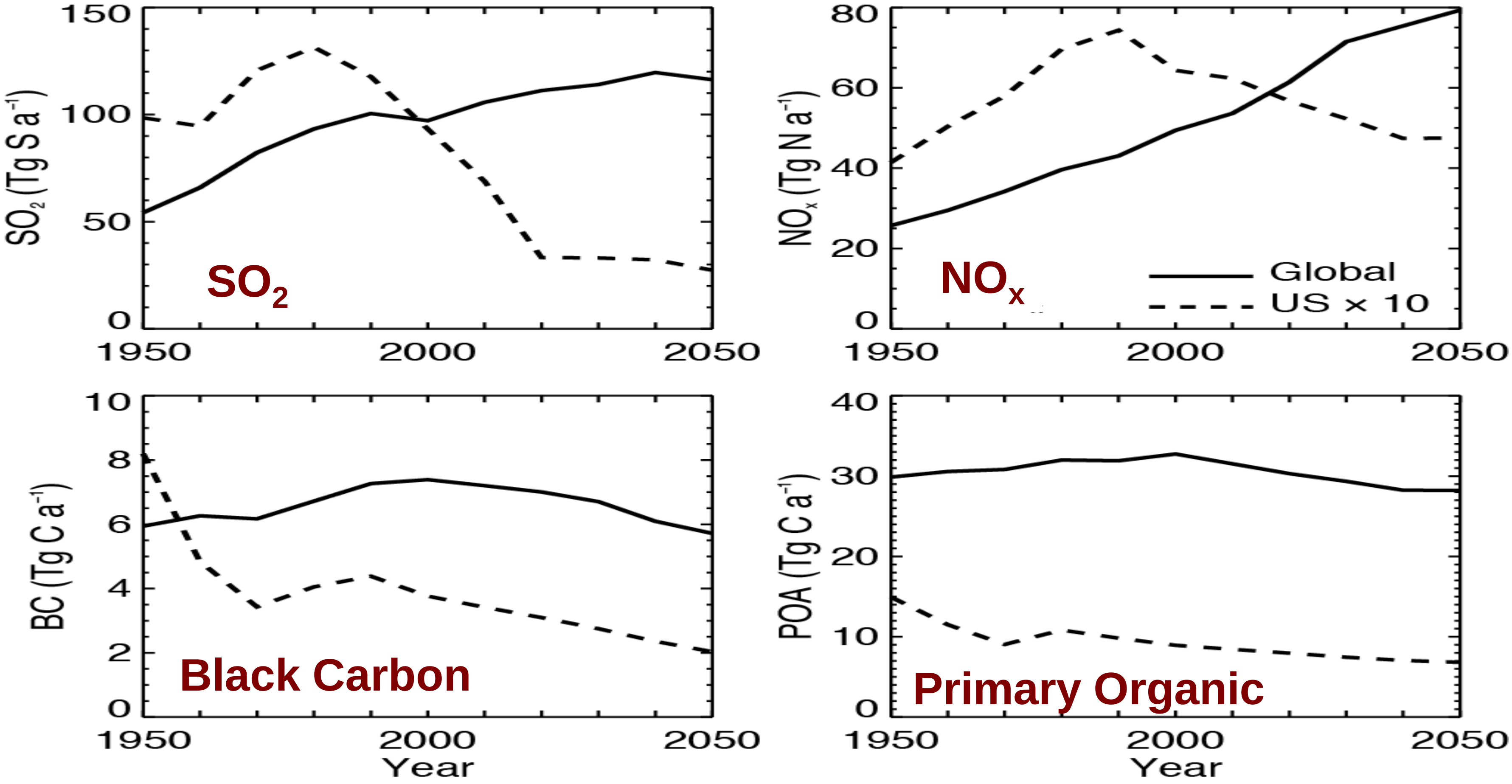
Aerosol radiative forcing more than offsets greenhouse gases over polluted continents; what is the implication for regional climate response?

Leibensperger et al. [submitted]

US aerosol sources have decreased over past decades

providing a test of regional climate response

GEOS-Chem global aerosol simulation of 1950-2050 period: emission trends from EDGAR, Bond (1950-2000), IPCC A1B (2000-2050)



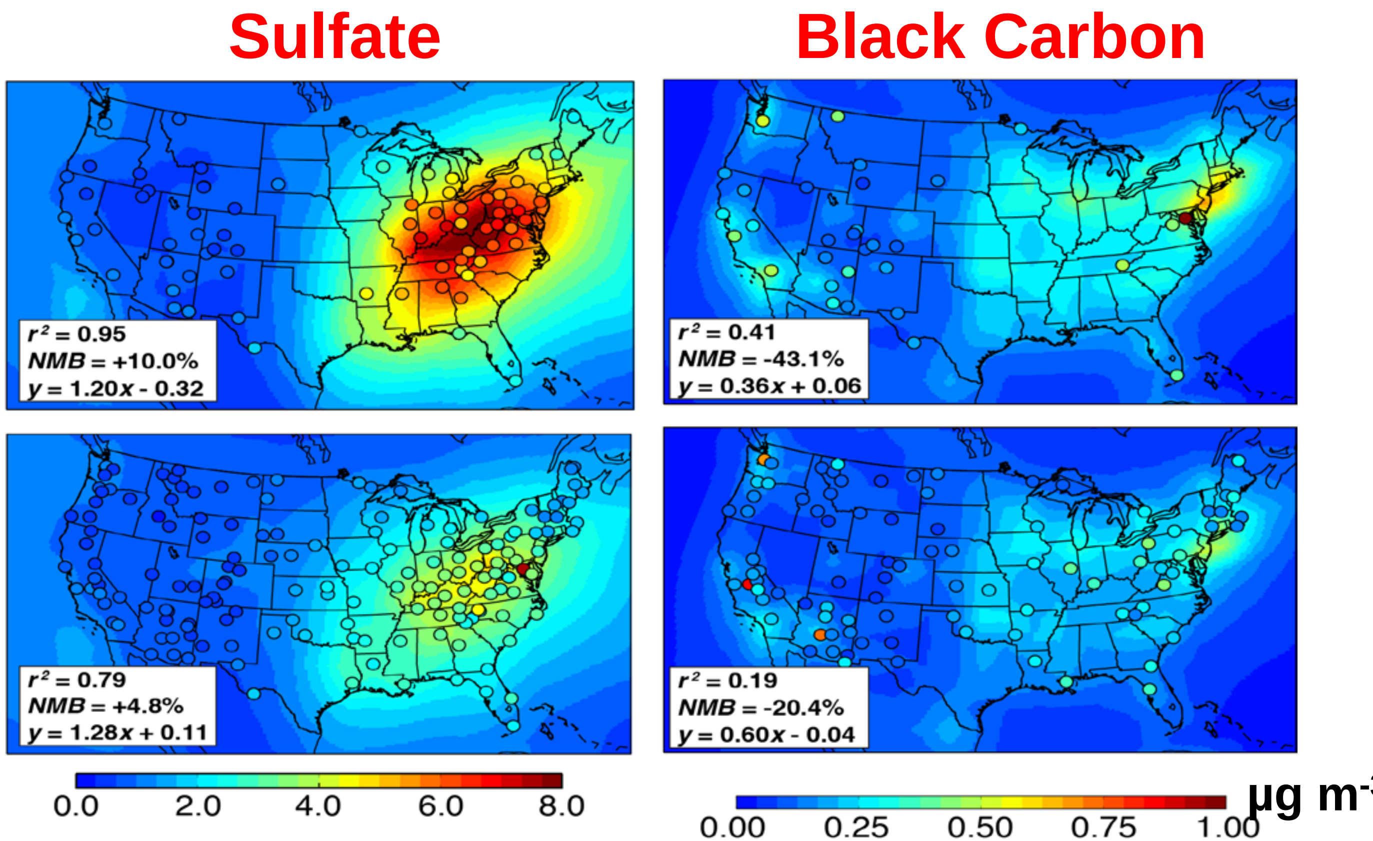
Leibensperger et al. [submitted]

Sulfate and black carbon trends, 1980-2010

Circles = observed
Background = model

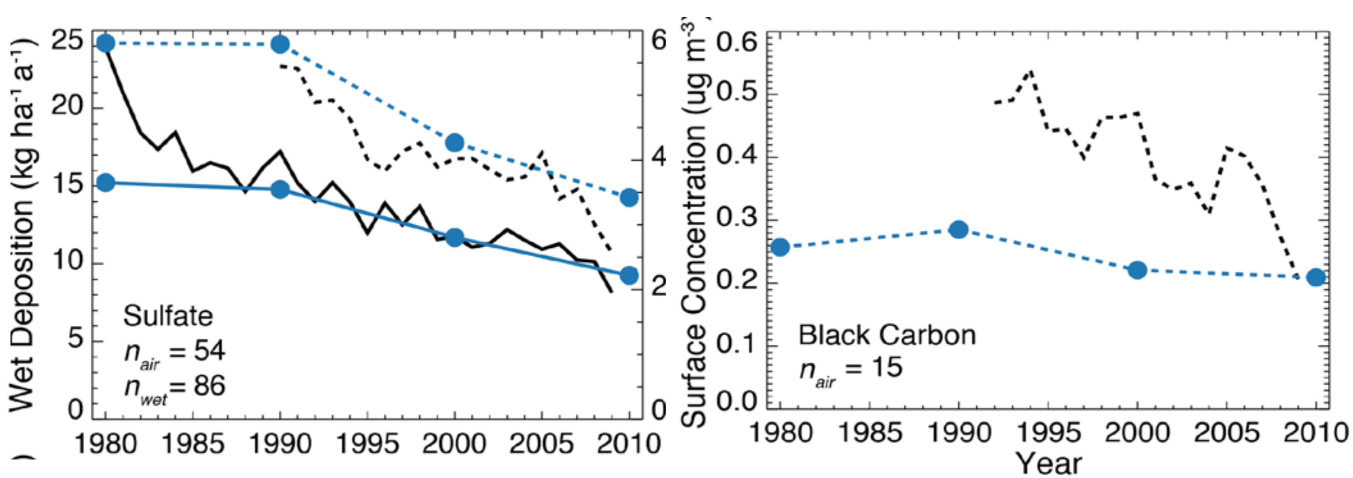
1990

2010



Observations
Surface Concentrations
Wet Deposition

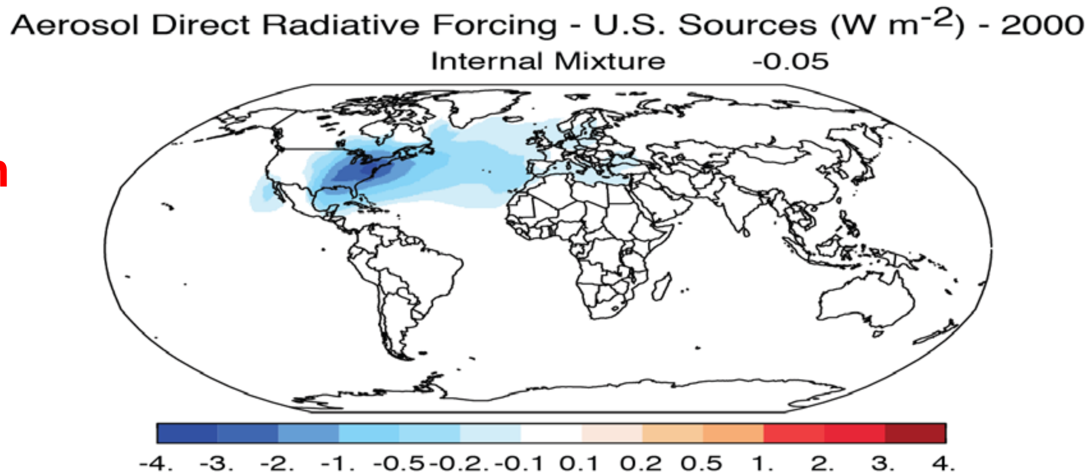
Model
Surface Concentrations
Model Wet Deposition



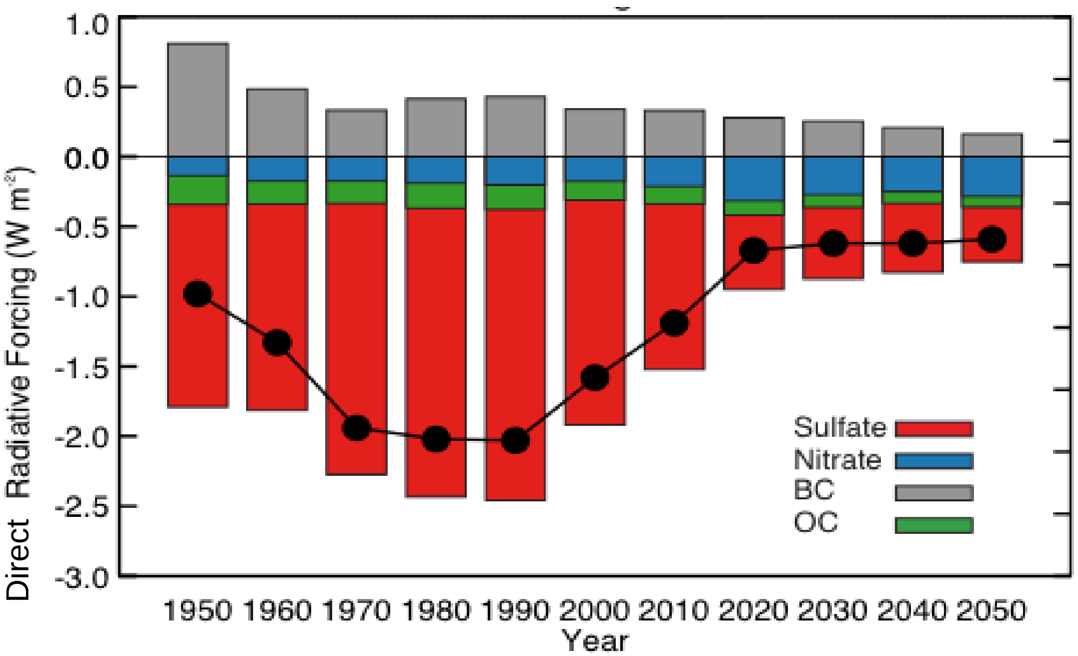
Leibensperger et al. [submitted]

Radiative forcing from US anthropogenic aerosol

Spatial pattern



1950-2050 trend over eastern US

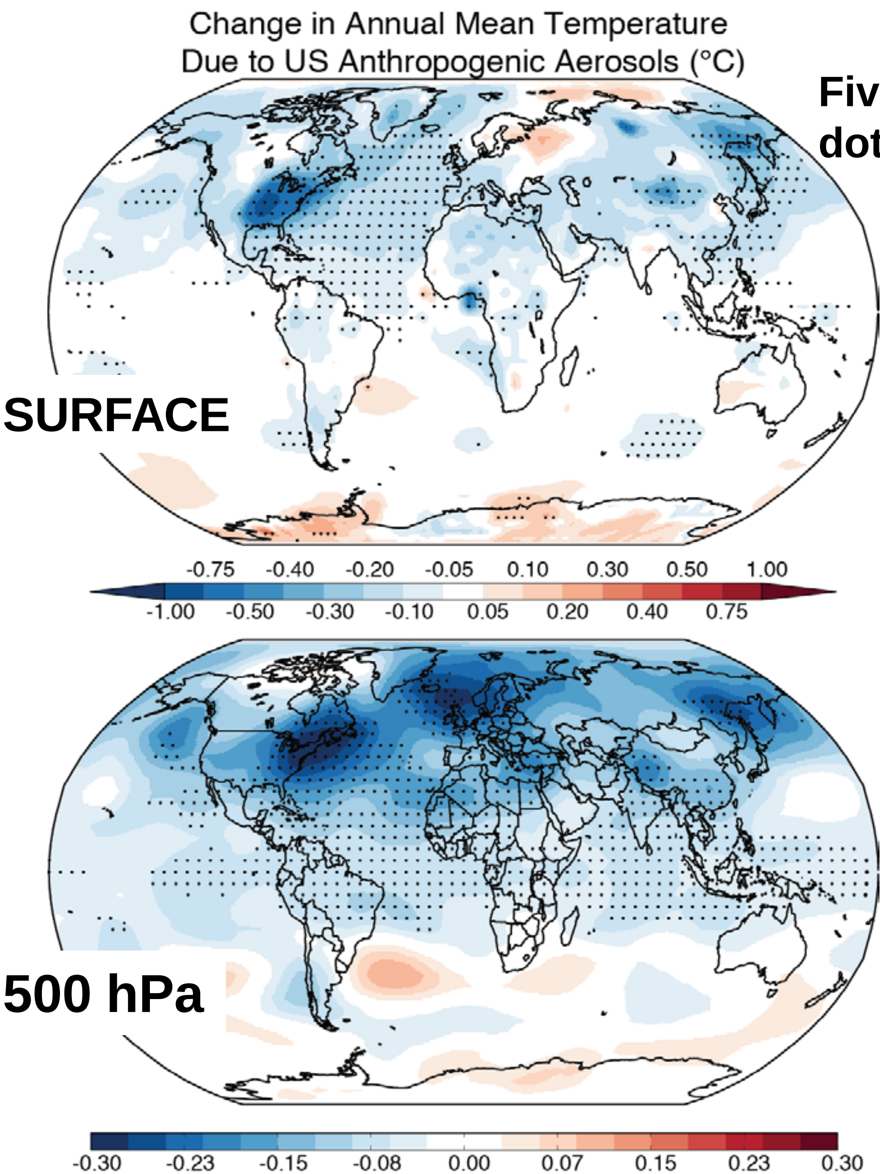


- **Forcing is mostly from sulfate, peaked in 1970-1990**
- **Little leverage to be had from BC control**
- **Indirect (cloud) forcing is of similar magnitude to direct forcing**

Leibensperger et al., [submitted]

Cooling due to US anthropogenic aerosols in 1970-1990

From difference of GISS general circulation model (GCM)simulations with vs. without US aerosol sources (GEOS-Chem), including direct and indirect effects

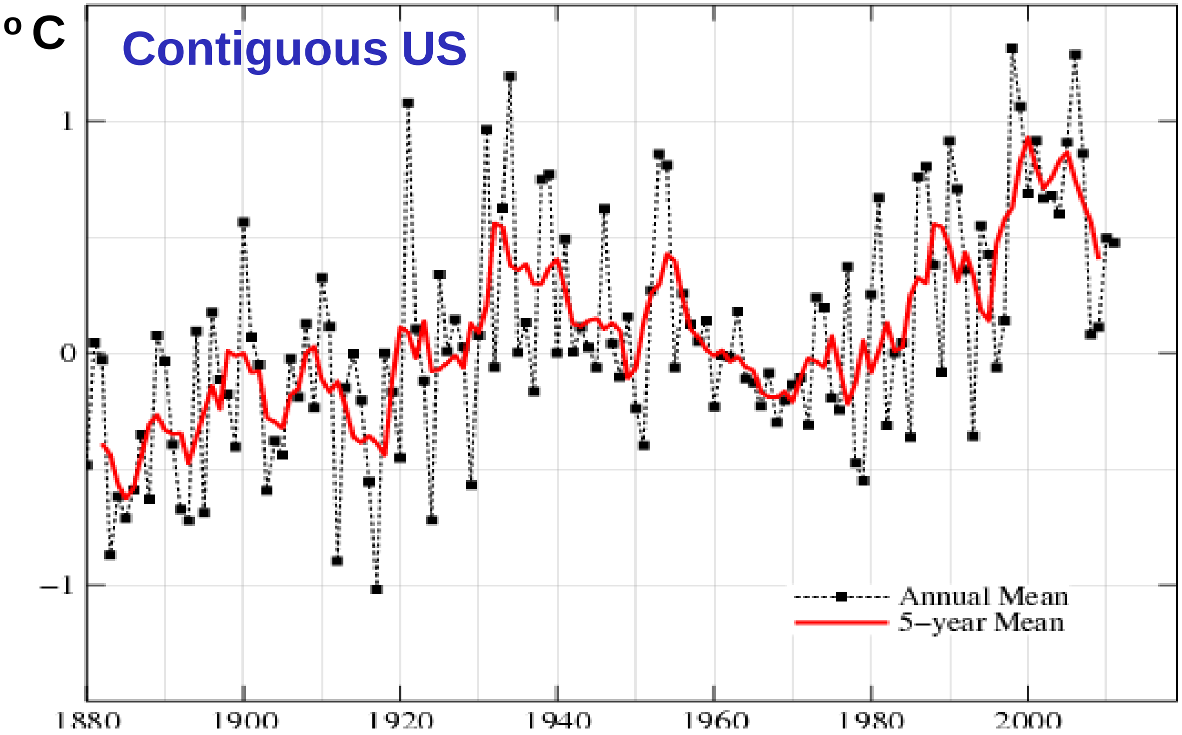


Five-member ensembles;
dots indicate statistical significance

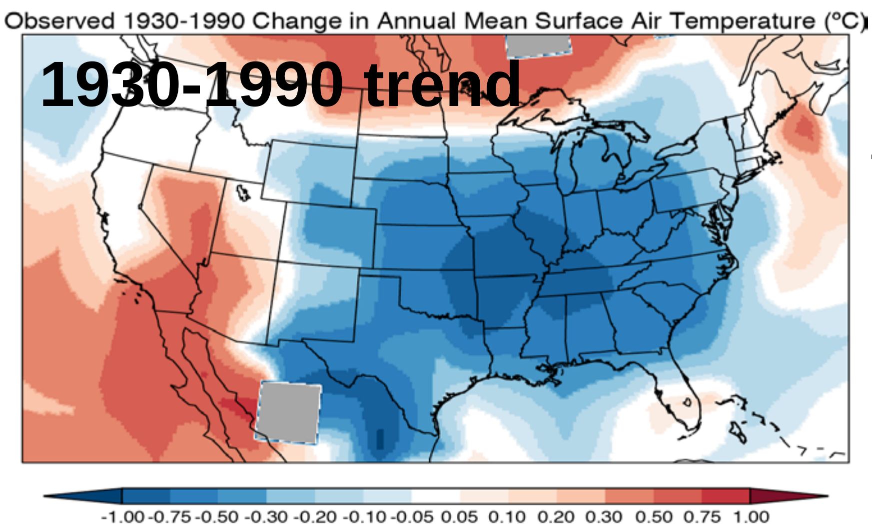
- **Surface cooling (up to 1^o C) is strongly localized over eastern US**
- **Cooling at 500 hPa (5 km) is more diffuse because of heat transport**

Leibensperger et al. [submitted]

Observed US surface temperature trend



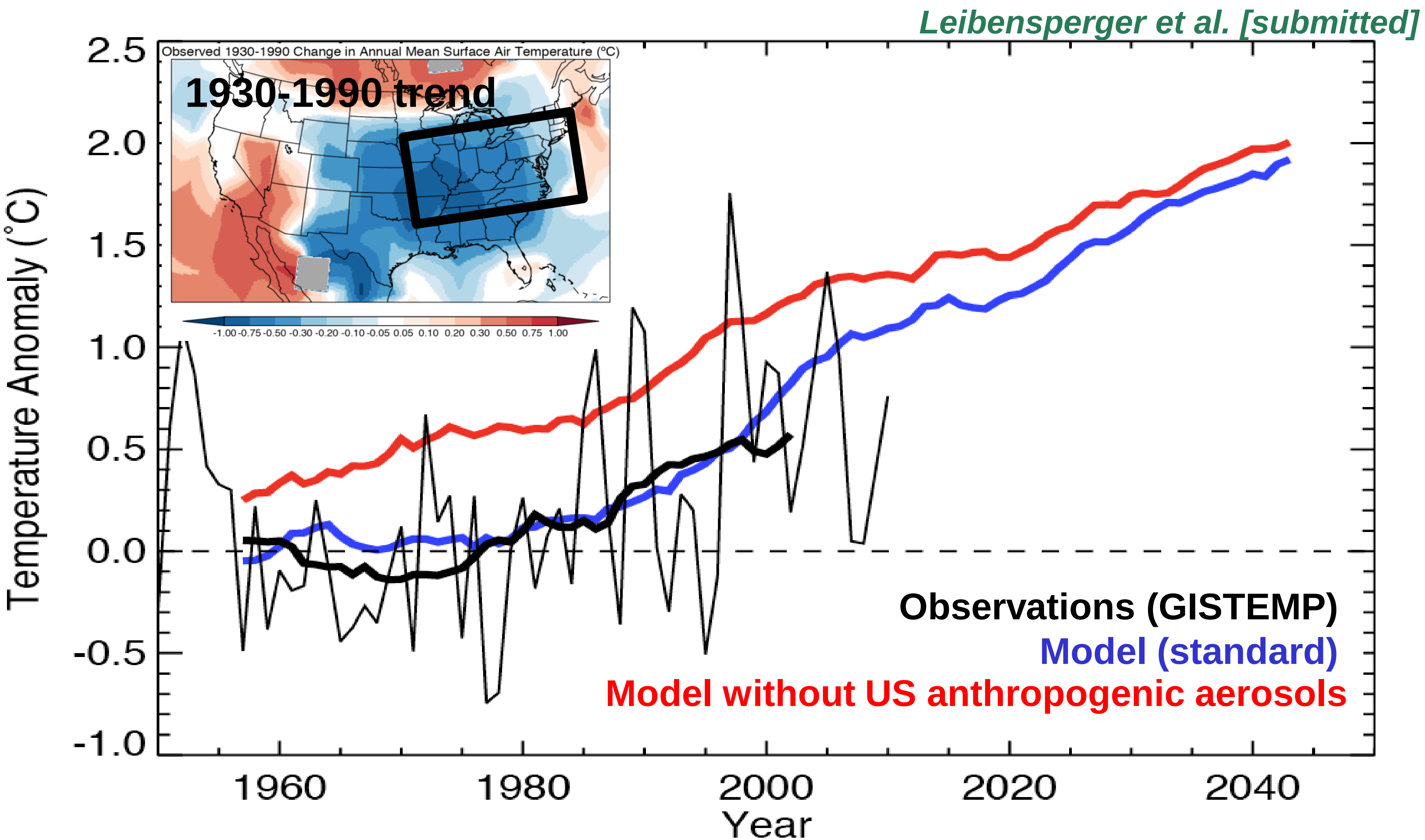
• US has warmed faster than global mean, as expected in general for mid-latitudes land
• But there has been no warming between 1930 and 1980, followed by sharp warming after 1980



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

GISTEMP [2010]

1950-2050 surface temperature trend in eastern US



- **US anthropogenic aerosol sources can explain the "warming hole"**
- **Rapid warming has taken place since 1990s that we attribute to source reduction**
- **Most of the warming from aerosol source reduction has already been realized**

Effect of climate change on air quality

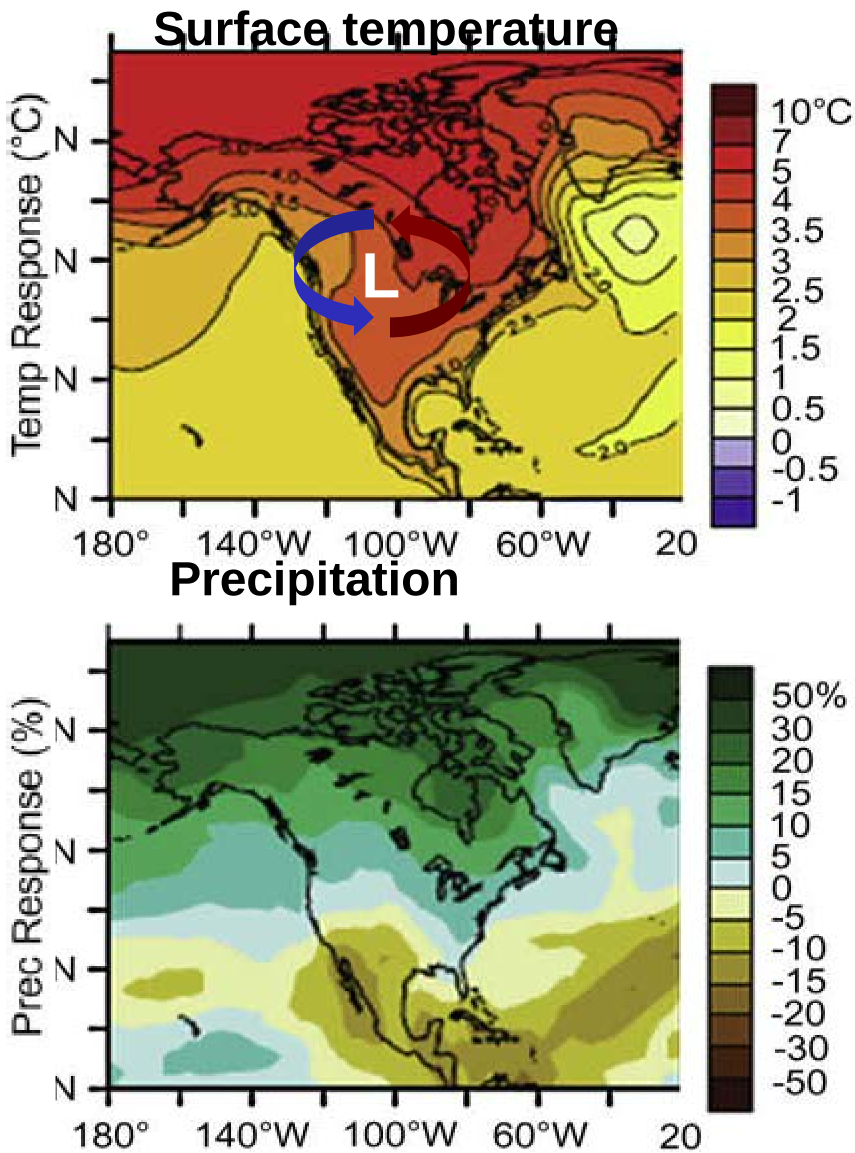
Air quality is sensitive to weather and so will be affected by climate change

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 projections of 2000-2100 climate change in N. America

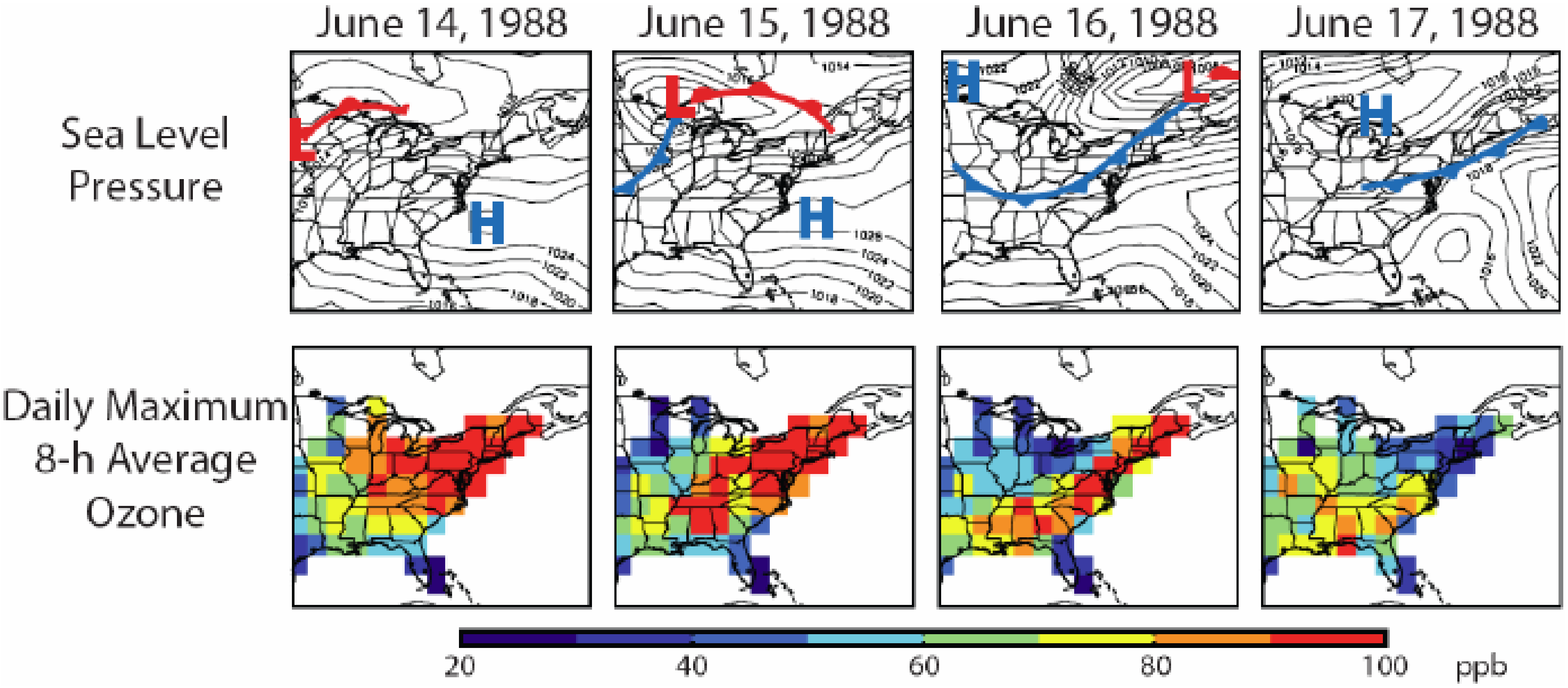


2080-2099 vs. 1980-1999 changes for ensemble of 20 models in A1B scenario

- **Increasing temperature everywhere, largest at high latitudes**
- **Frequency of heat waves expected to increase**
- **Increasing precipitation at high latitudes, decrease in subtropics but with large uncertainty**
- **Decrease in meridional temperature gradient expected to weaken winds, decrease frequency of mid-latitude cyclones**

IPCC [2007]

Importance of mid-latitudes cyclones for ventilation



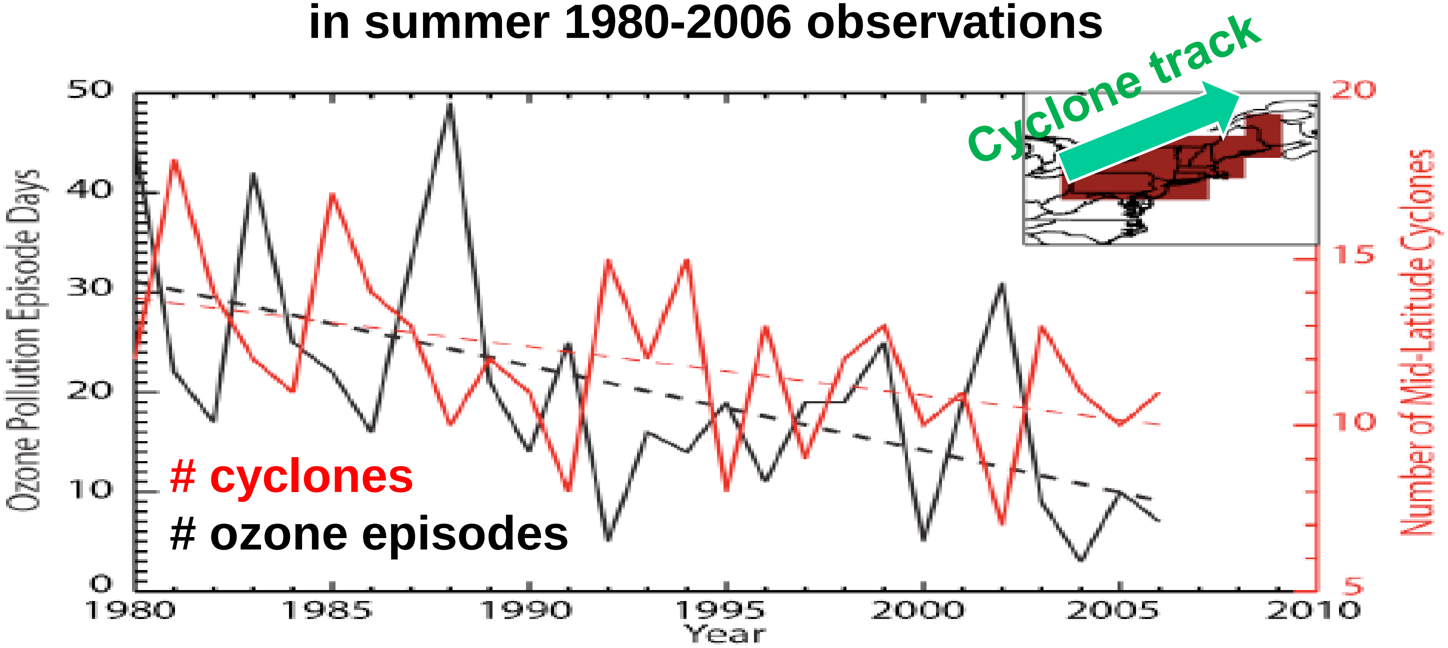
• **Cold fronts associated with cyclones tracking across southern Canada are the principal ventilation mechanism for the eastern US**

• **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

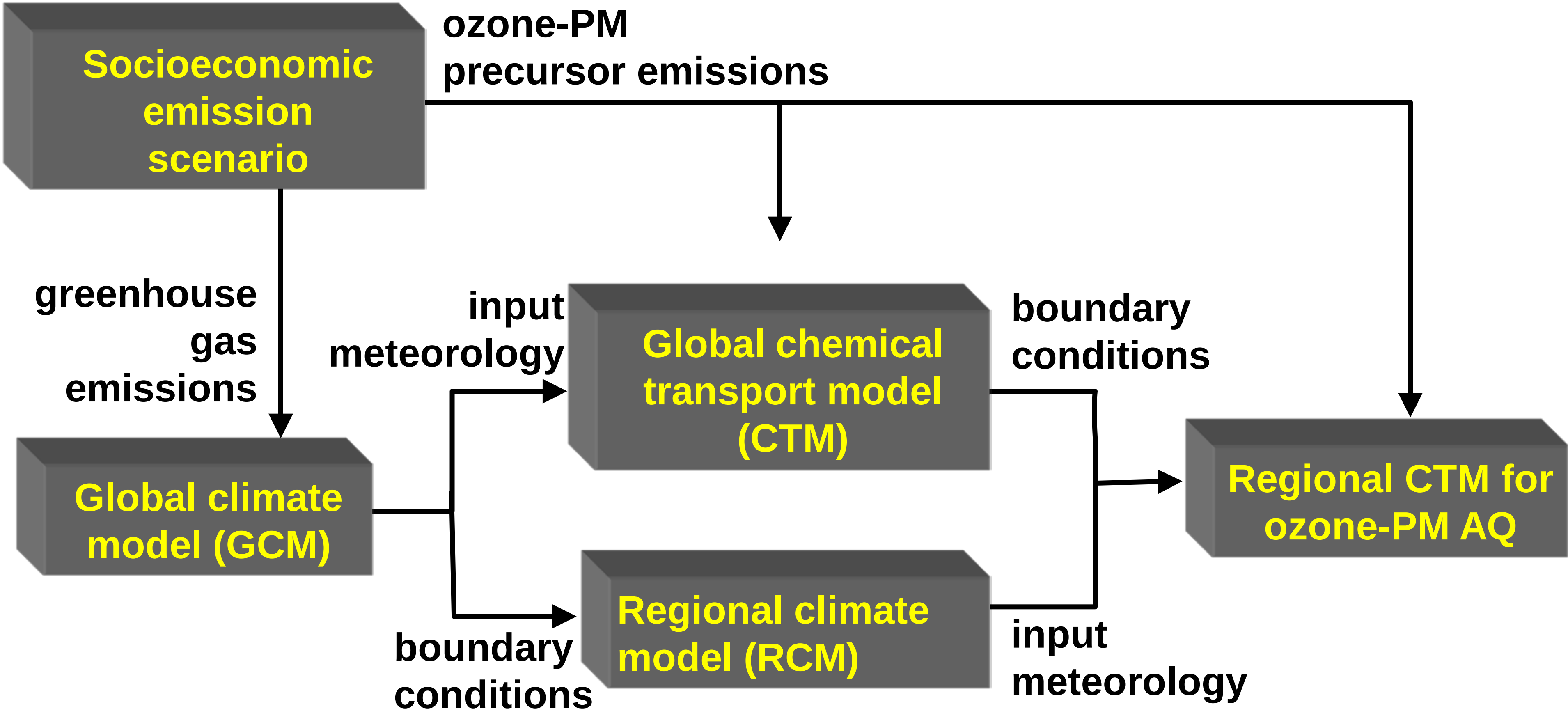
 # ozone episode days (O_3>80 ppb) and # cyclones tracking across SE Canada in summer 1980-2006 observations



- **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 in Northeast dropped from 30 in 1980 to 10 in 2006, but would have dropped to ≈ zero in absence of cyclone trend**

Leibensperger et al. [2008]

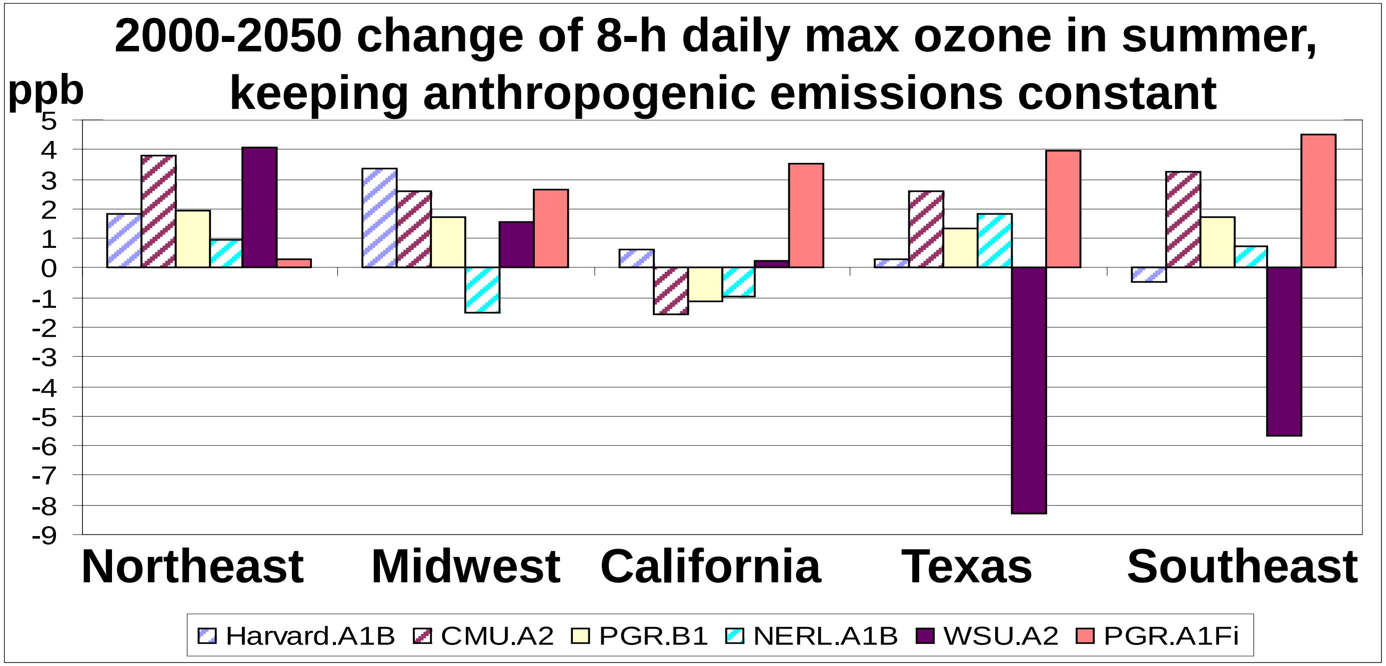
General GCM-CTM approach to quantify the effects of climate change on air quality



Jacob and Winner [2009]

Ensemble model analysis of the effect of 2000-2050 climate change on ozone air quality in the US

Results from six coupled GCM-CTM simulations

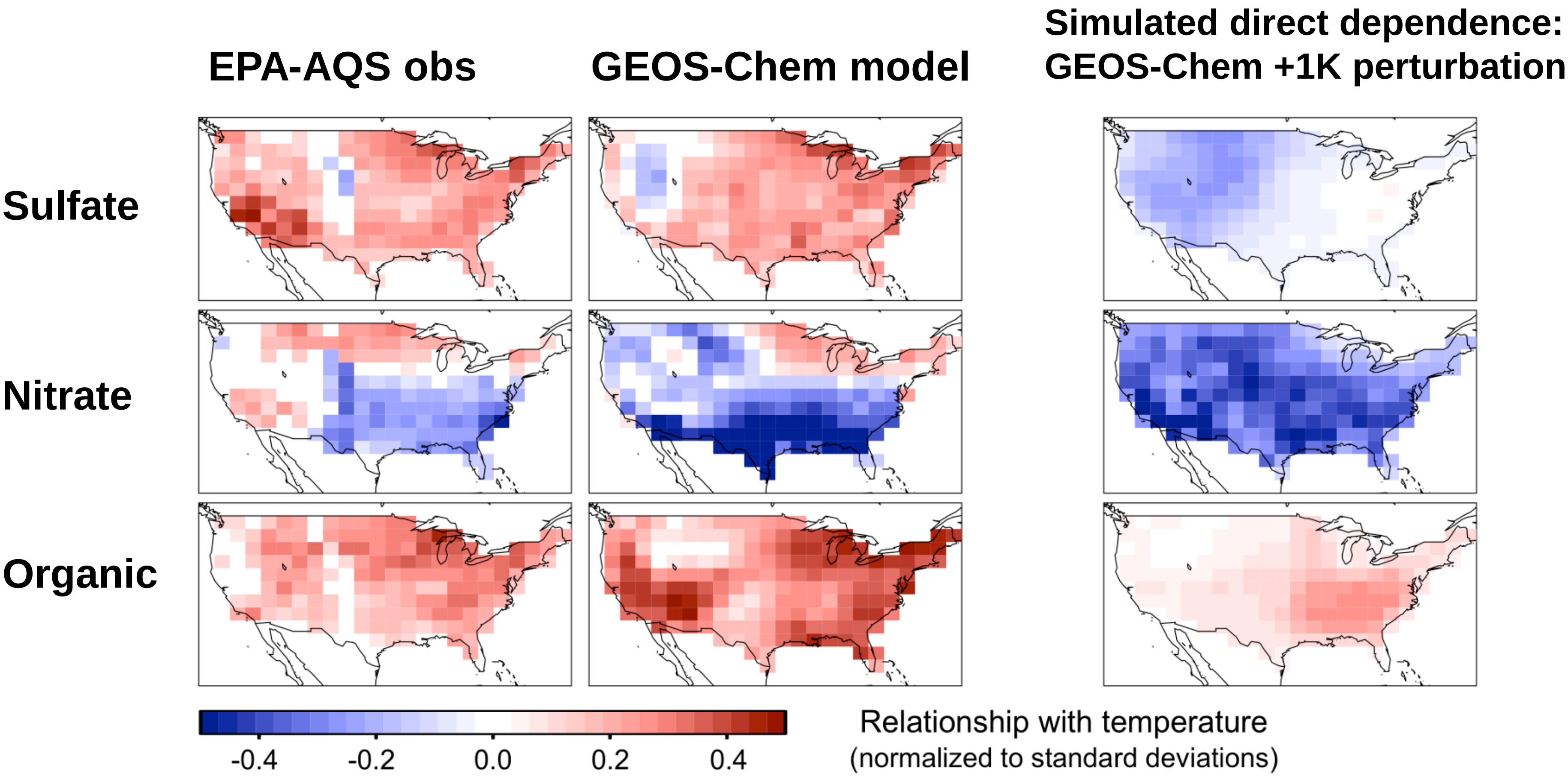


- **Models show consistent projection of ozone increase over most of US**
- **Typical mean increase is 1-4 ppb, up to 10 ppb for ozone pollution episodes**
- **No such consistency is found in model projections for PM, including in sign of effect (± 0.1-1 μg m^{-3})**

Weaver et al. [2010]

Association of $PM_{2.5}$ components with temperature

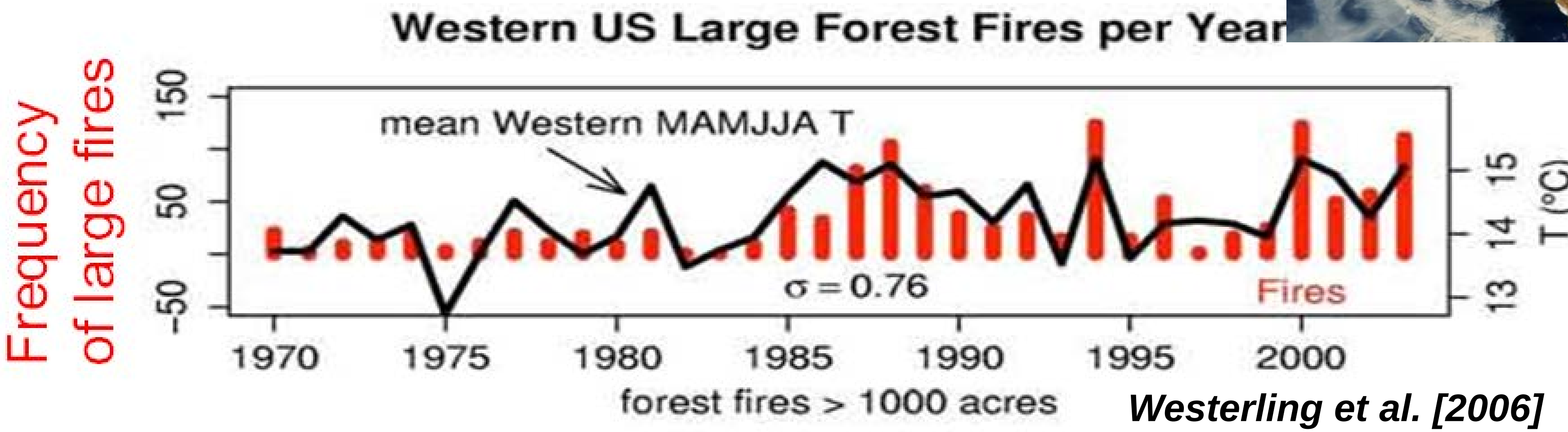
from multivariate regression of deseasonalized PM with meteorological data



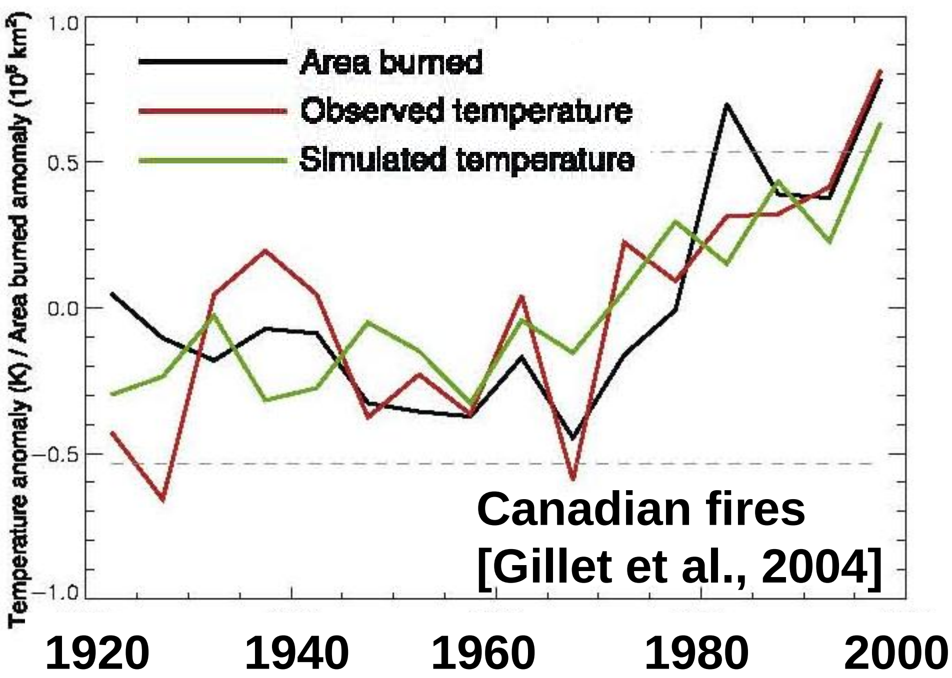
- **Correlations with *T* reflect direct dependences for nitrate (volatilization) and OC (vegetation, fires) but also covariations with other factors**
- **Correlations with meteorological modes of variability point to cyclone frequency as major factor for $PM_{2.5}$ variability in Midwest/Northeast**

Tai et al. [submitted]

Increasing wildfires could be the major effect of climate change on PM



Westerling et al. [2006]



Canadian fires [Gillet et al., 2004]

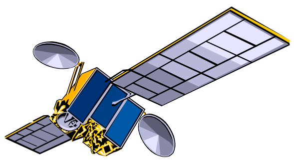
- **Temperature and drought index can explain 50-60% of interannual variability in fires**
- **Climate change is projected to increase biomass burned in US by 50% in 2050, resulting in 0.5-1 μ g m^{-3} increase in PM in West** ***[Spracklen et al., 2009]***

Air Quality Applied Sciences Team (AQAST)

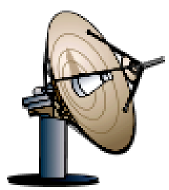
EARTH SCIENCE SERVING AIR QUALITY MANAGEMENT NEEDS

Team leader: Daniel J. Jacob

Earth science resources



satellites



suborbital platforms

models

AQAST →

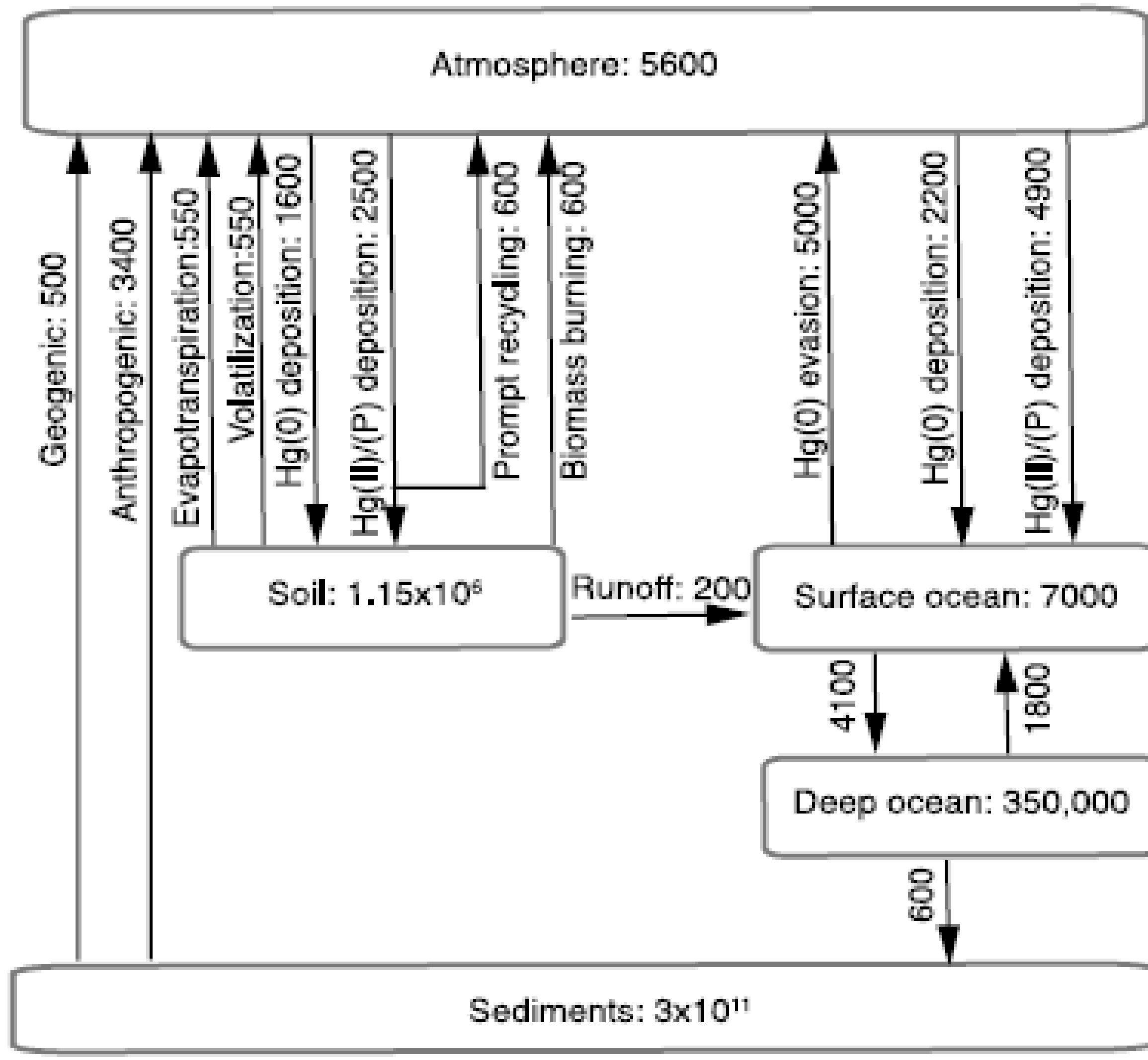
Air Quality Management Needs

- Pollution monitoring
- Exposure assessment
- AQ forecasting
- Source attribution of events
- Quantifying emissions
- Assessment of natural and international influences
- Understanding of transport, chemistry, aerosol processes
- Understanding of climate-AQ interactions

For more information on how AQAST can help you please ask me!

Effect of climate change on mercury cycling

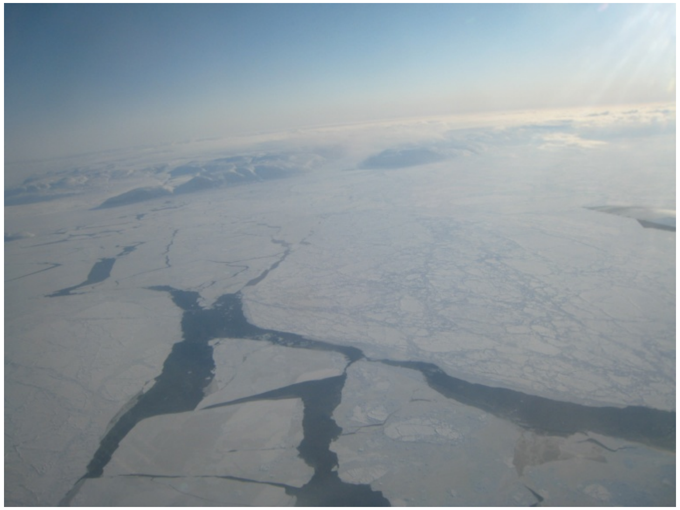
Present-day global biogeochemical cycle of mercury
[Selin et al., 2008]

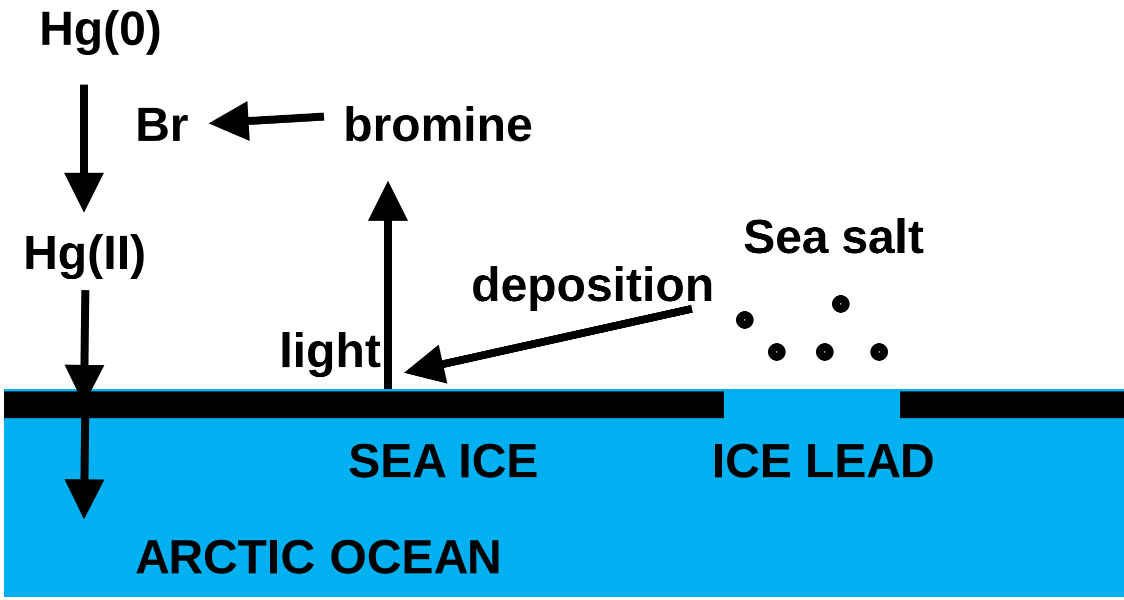


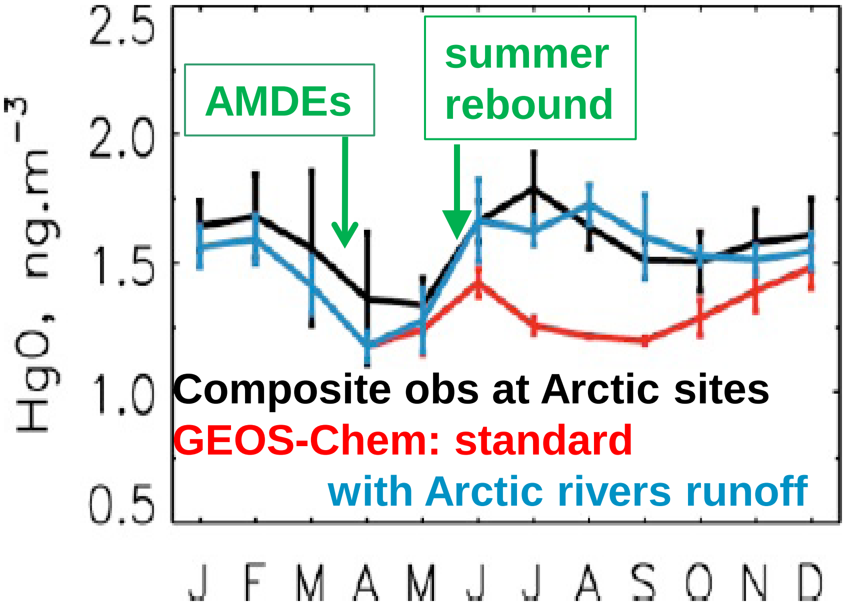
Hg has a large soil reservoir due to binding with organic carbon; as global warming causes increased soil respiration, will this Hg stockpile be released?

Effect of climate change on mercury in the Arctic Ocean

Atmospheric Hg depletion events (AMDEs) associated w/ice leads







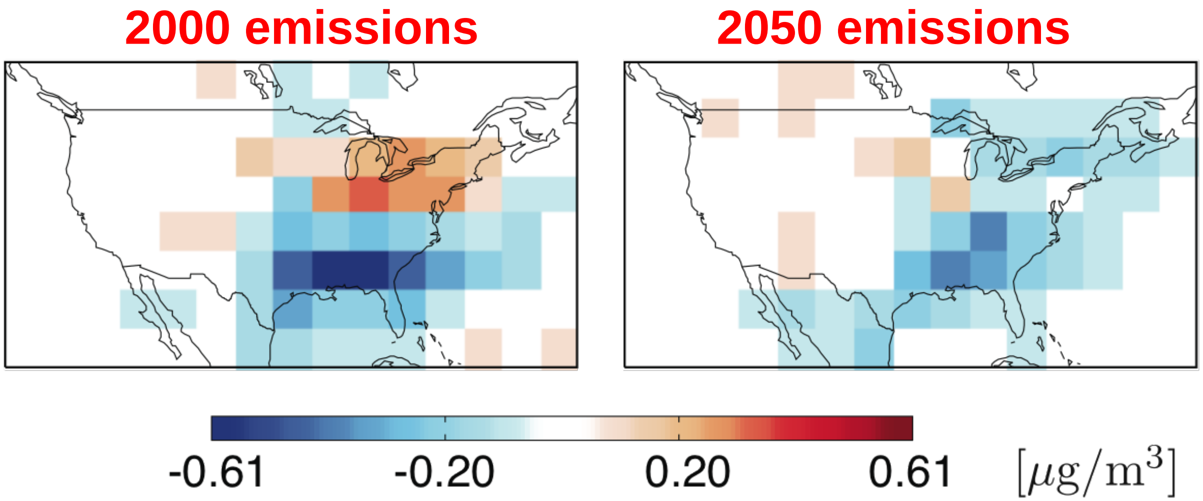
- Summer rebound in atmospheric observations cannot be explained by snow re-emission; we hypothesize a major source from Arctic rivers runoff
- Increasing river runoff in future climate could greatly affect Hg levels in Arctic Ocean

Fisher et al. [2011]

Effect of 2000-2050 climate change on annual mean $PM_{2.5}$

Different models show ± 0.1-1 μg m^{-3} effects of climate change on $PM_{2.5}$ but there is no consistency across models including in the sign of the effect

GISS GCM + GEOS-Chem CTM



CMAQ model nested in GEOS-Chem

$\Delta PM_{2.5}$ (μg m^{-3})	Midwest	Northeast	Southeast
2000 emissions	+0.5	+0.1	-0.1
2050 emissions	+0.3	-0.4	-0.7

Decrease of SO_2 emissions ameliorates effect of climate change by changing PM speciation from sulfate to nitrate

Pye et al. [2009]; Lam et al. [2010]

Correlating $PM_{2.5}$ observations to meteorological variables

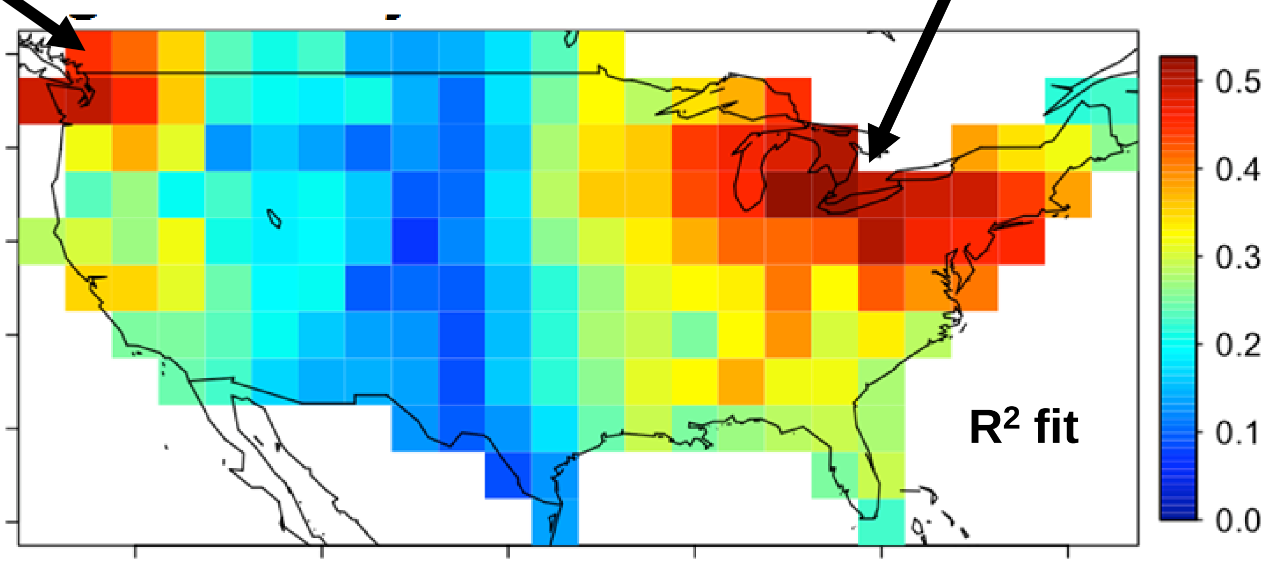
Multilinear regression model fit to 1998-2008 deseasonalized EPA/AQS data for PM2.5 (total and speciated)

$$y_i = \beta_{0,i} + \sum_{k=1}^{9} \beta_{k,i} x_{k,i} + \text{interaction terms}$$

Independent Variable	Meteorological Parameter [a]
x_1	Surface temperature (K)
x_2	Surface relative humidity (%)
x_3	Daily total precipitation (in/d)
x_4	Total cloud cover (%)
x_5	Geopotential height at 850 mb (m)
x_6	Local rate of change of sea level pressure (*dSLP/dt*) (Pa/d)
x_7	Surface wind speed (m/s), calculated from *u* and *v* wind vectors
x_8	E-W wind direction indicator ($\cos\theta$) [b]
x_9	N-S wind direction indicator ($\sin\theta$) [b]

mostly precipitation

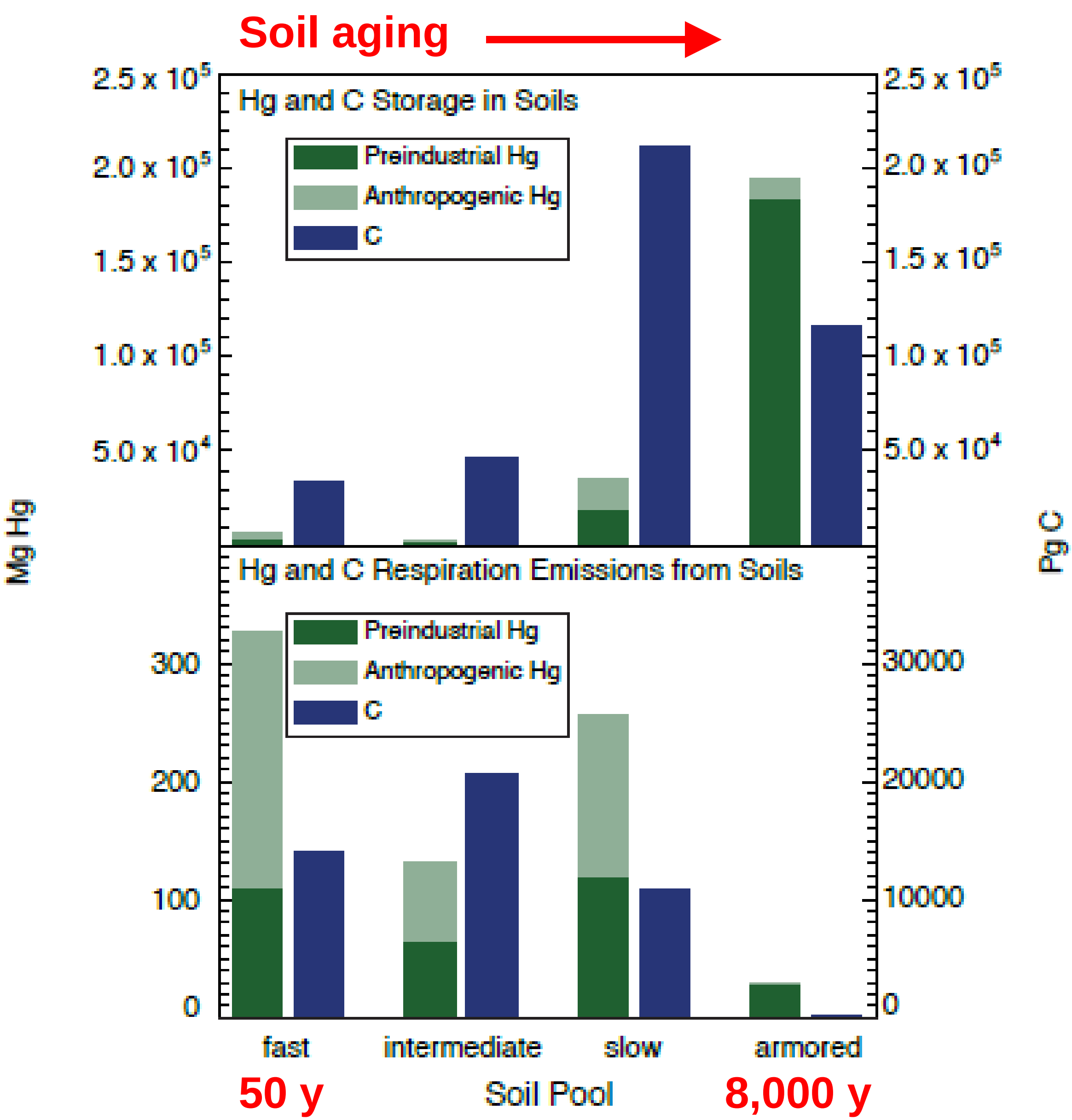
mostly temperature and stagnation



Tai et al., 2010

Climate-driven mobilization of anthropogenic Hg from soils

GEOS-Chem model simulation of soil mercury

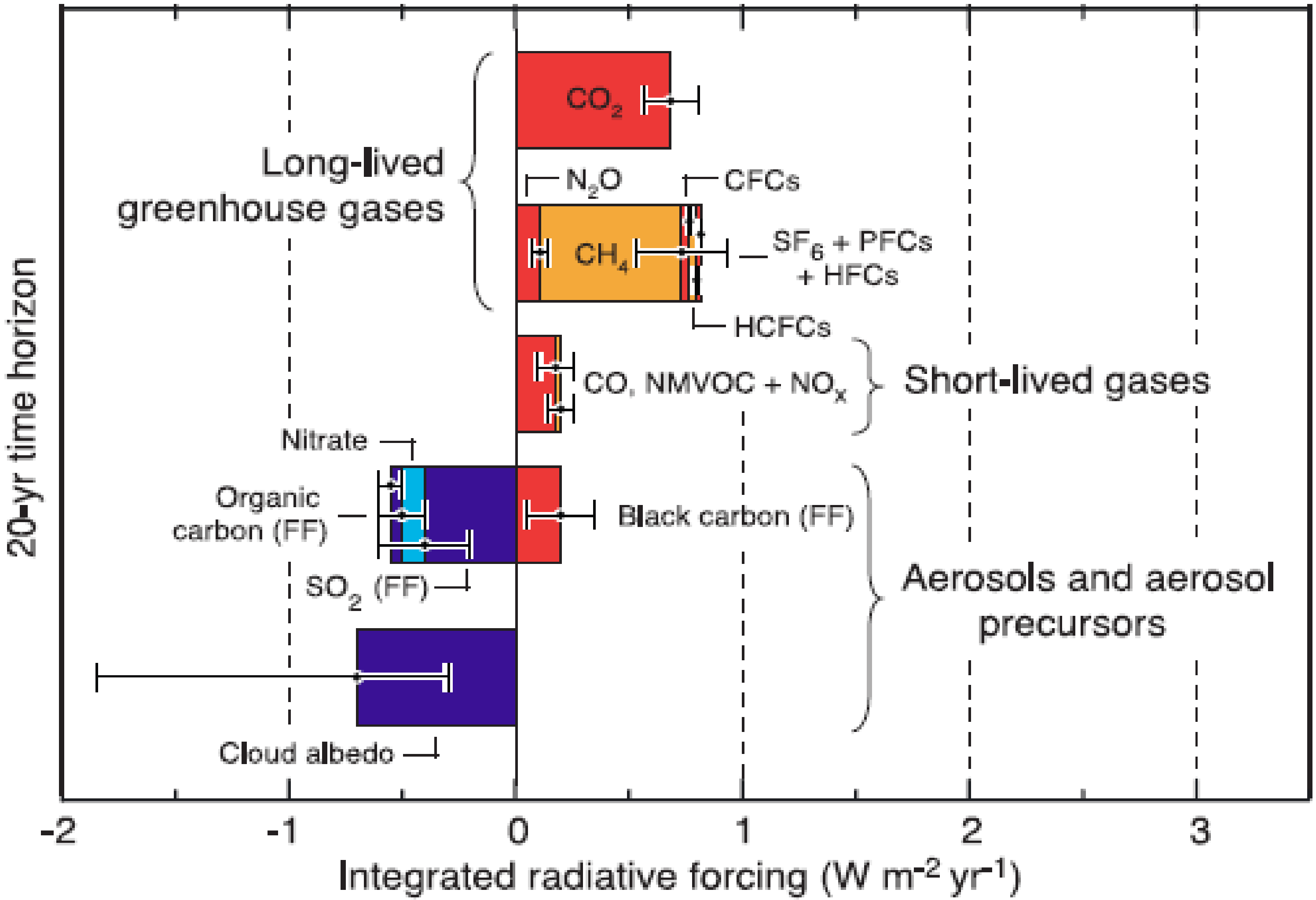


- **Mercury accumulates in soil by binding to organic carbon; part is volatilized when organic carbon is respired**
- **Mercury has a mean lifetime in soil of 600 years, but deposited anthropogenic mercury has a lifetime of only 80 years**
- **Increased soil respiration in future climate could lead to large soil mercury release**

Smith-Downey et al. [2010]

Importance of AQ-related emissions for short-term climate change

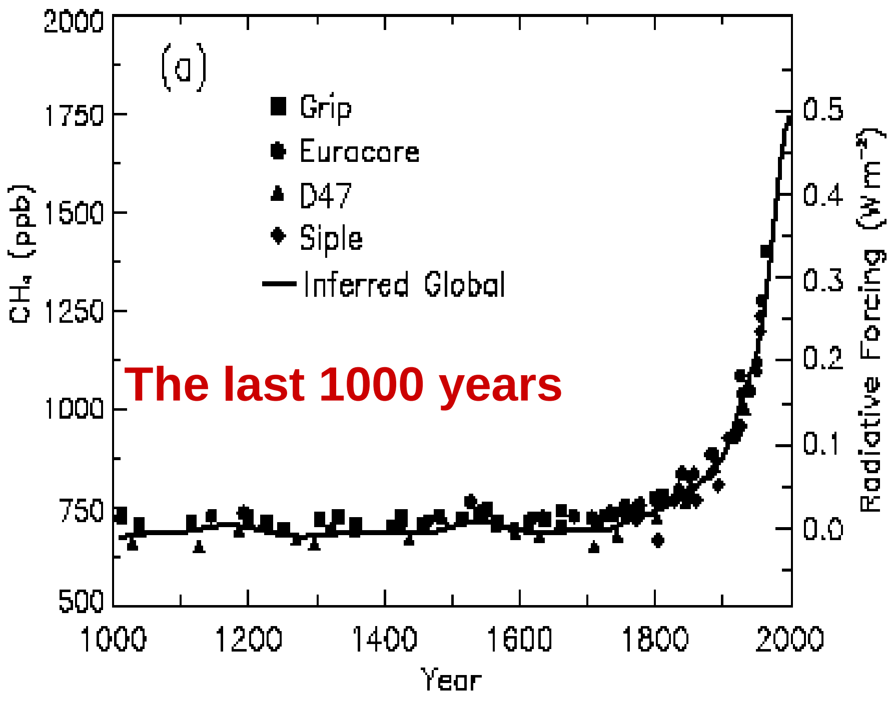
Integrated radiative forcing over 20-year time horizon from 2000 emissions

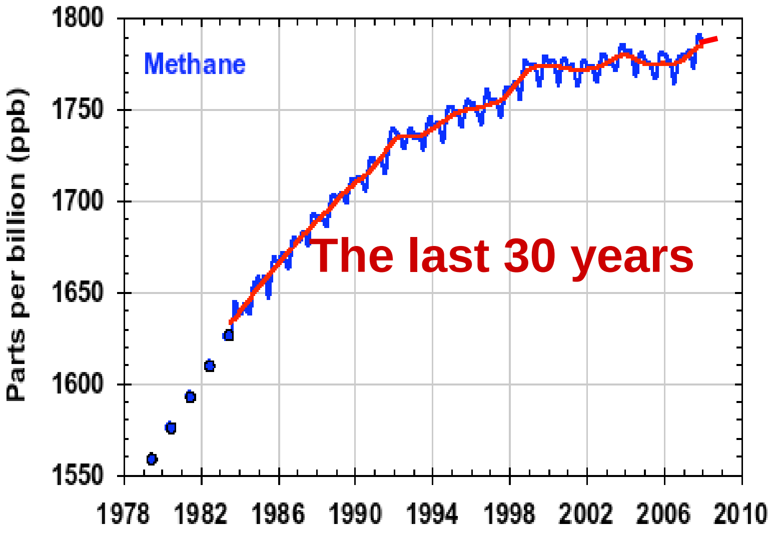


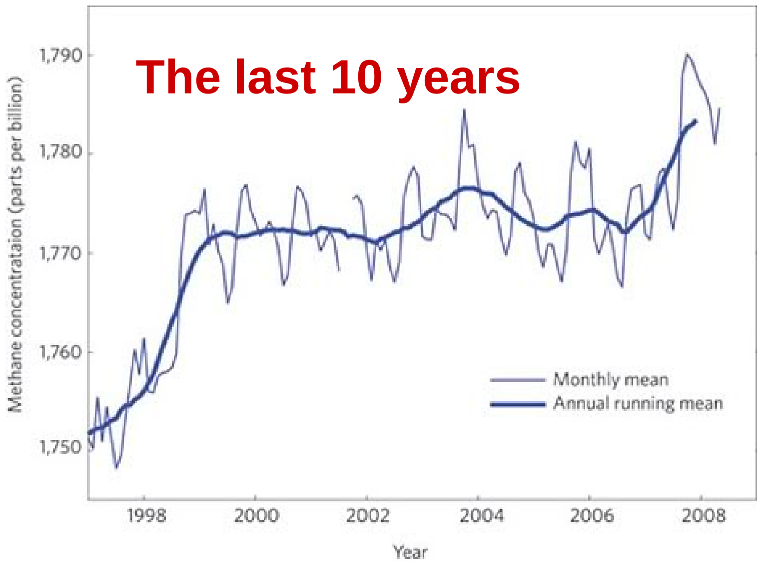
Methane and aerosol sources are as important as CO_2

IPCC [2007]

Better understanding of methane sources is needed to support emission control strategies



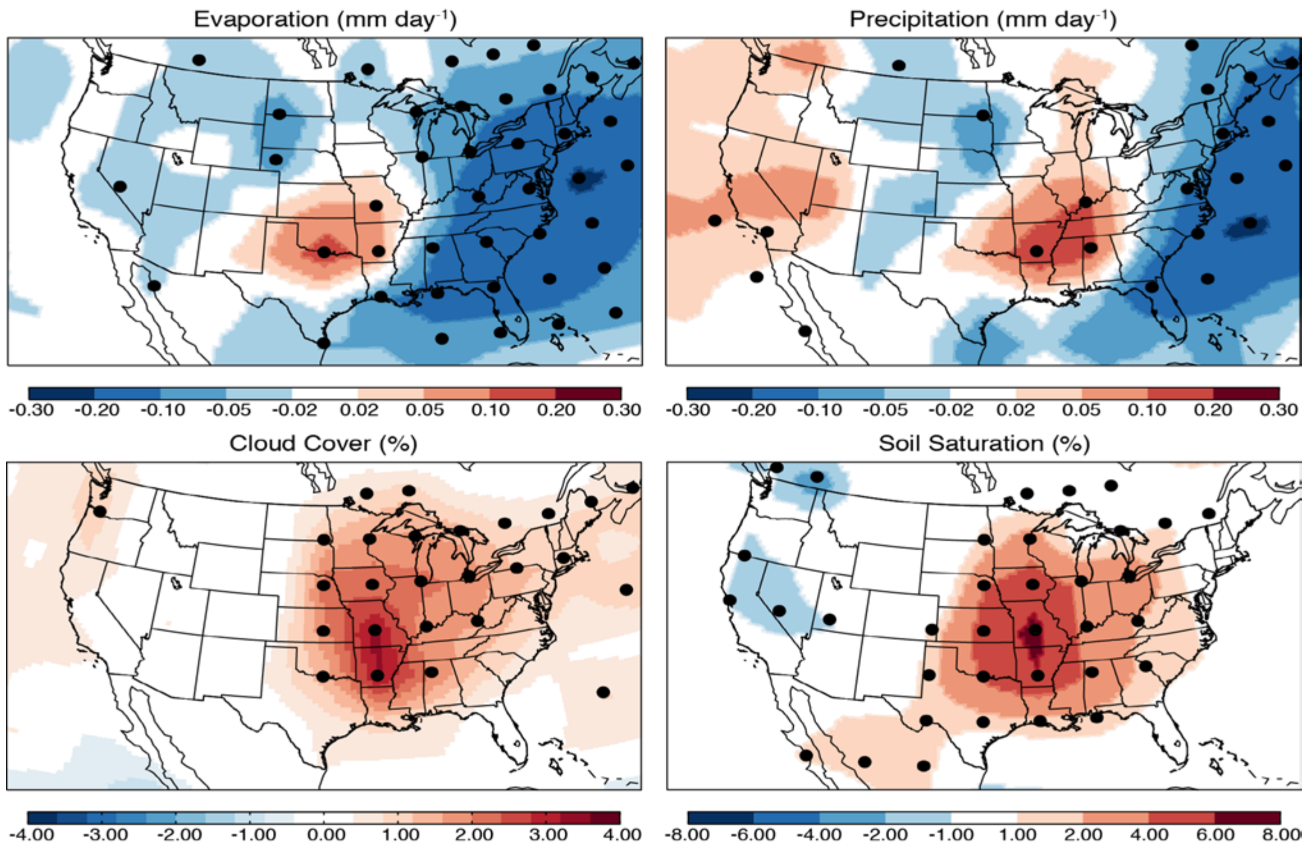




Leveling off in past decade,
uptick in past two years are not understood

Hydrological cycle perturbations due to US anthropogenic aerosols

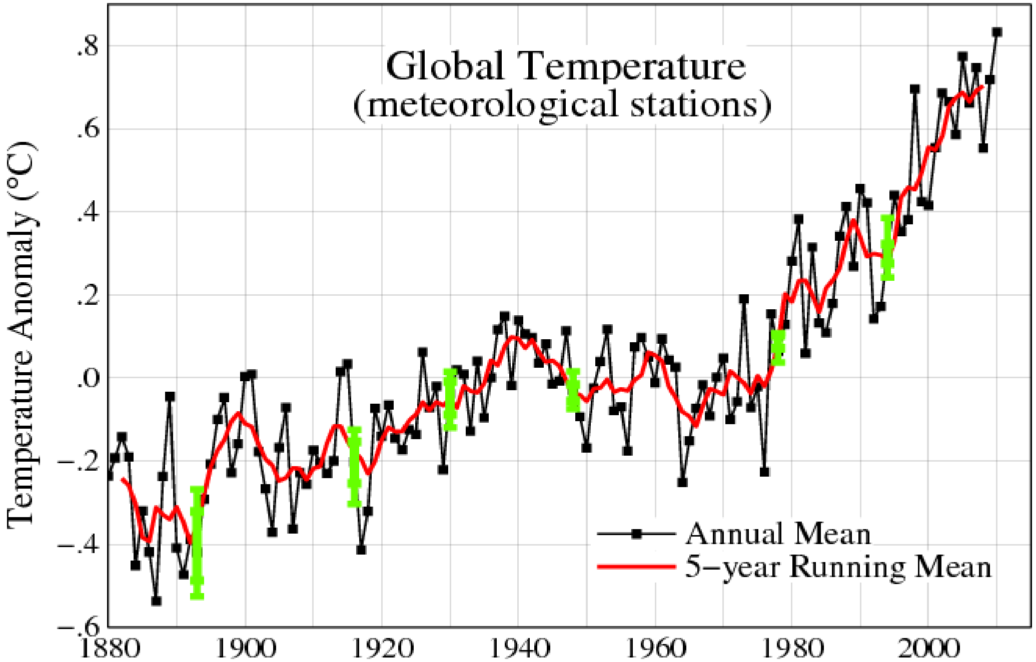
from difference of GCM simulations with vs. without US aerosol sources for 1970-1990, including aerosol direct and indirect radiative effects

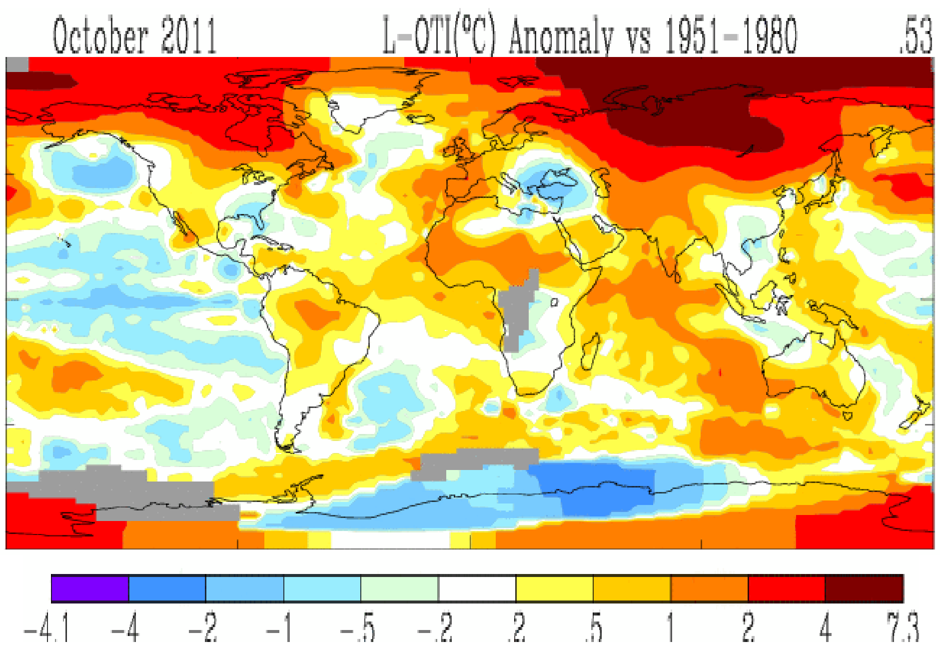


- **Cooling decreases evaporation over eastern US and hence precipitation over eastern seaboard;**
- **Increasing flow from Gulf of Mexico moistens south-central US**

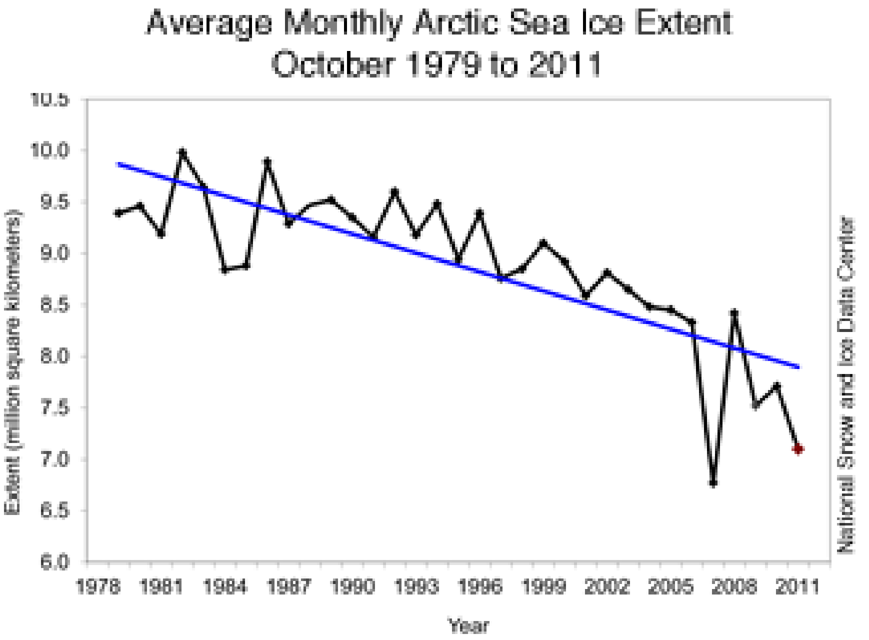
Leibensperger et al., in prep.

THE REALITY OF CLIMATE CHANGE



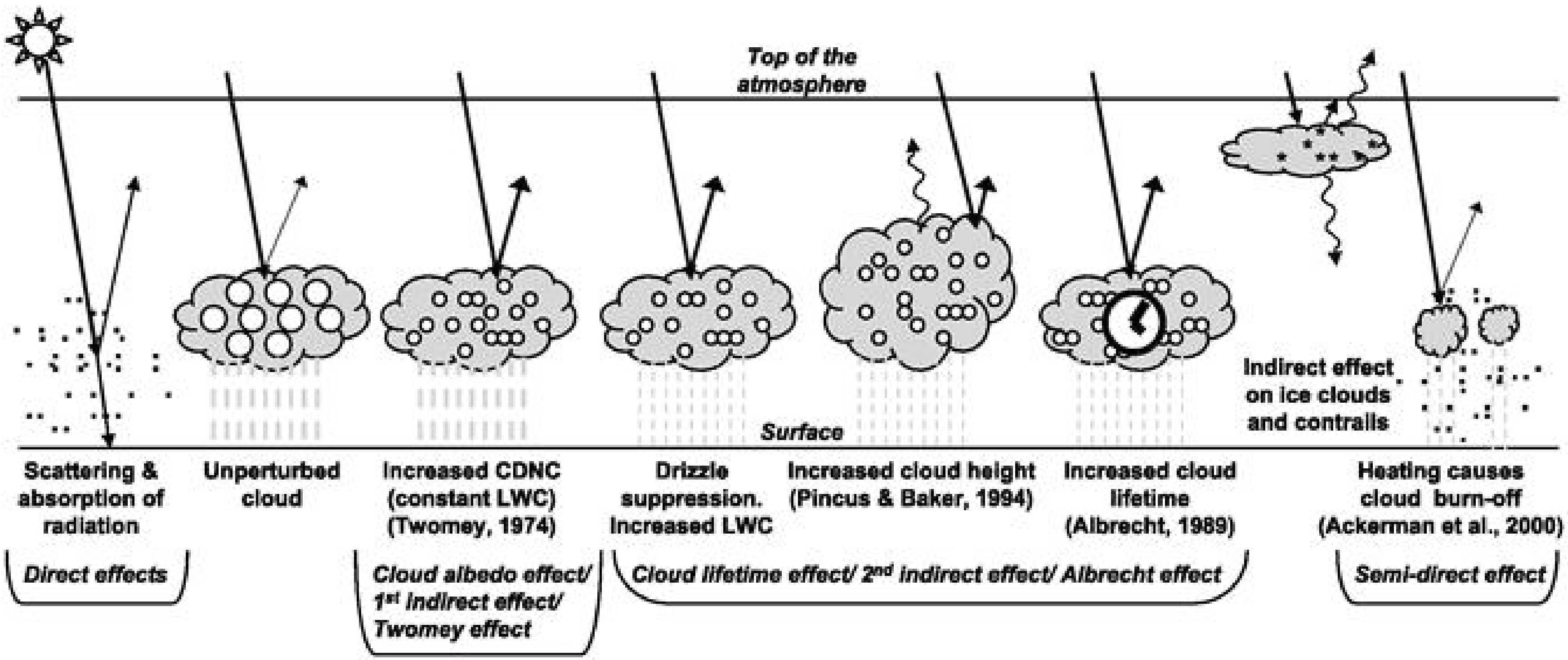


http://data.giss.nasa.gov/gistemp/



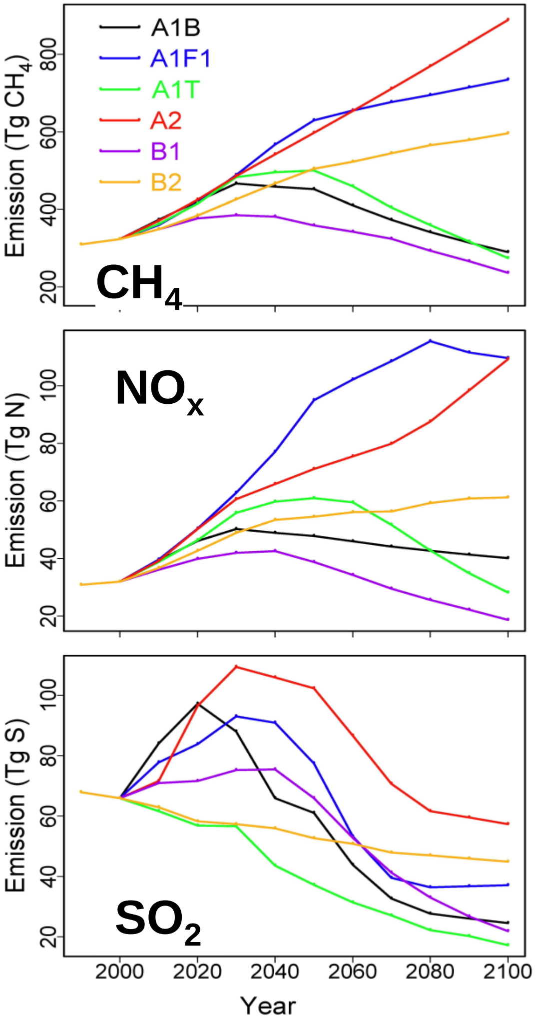
http://nsidc.org/arcticseaicenews/

Aerosol effects on climate

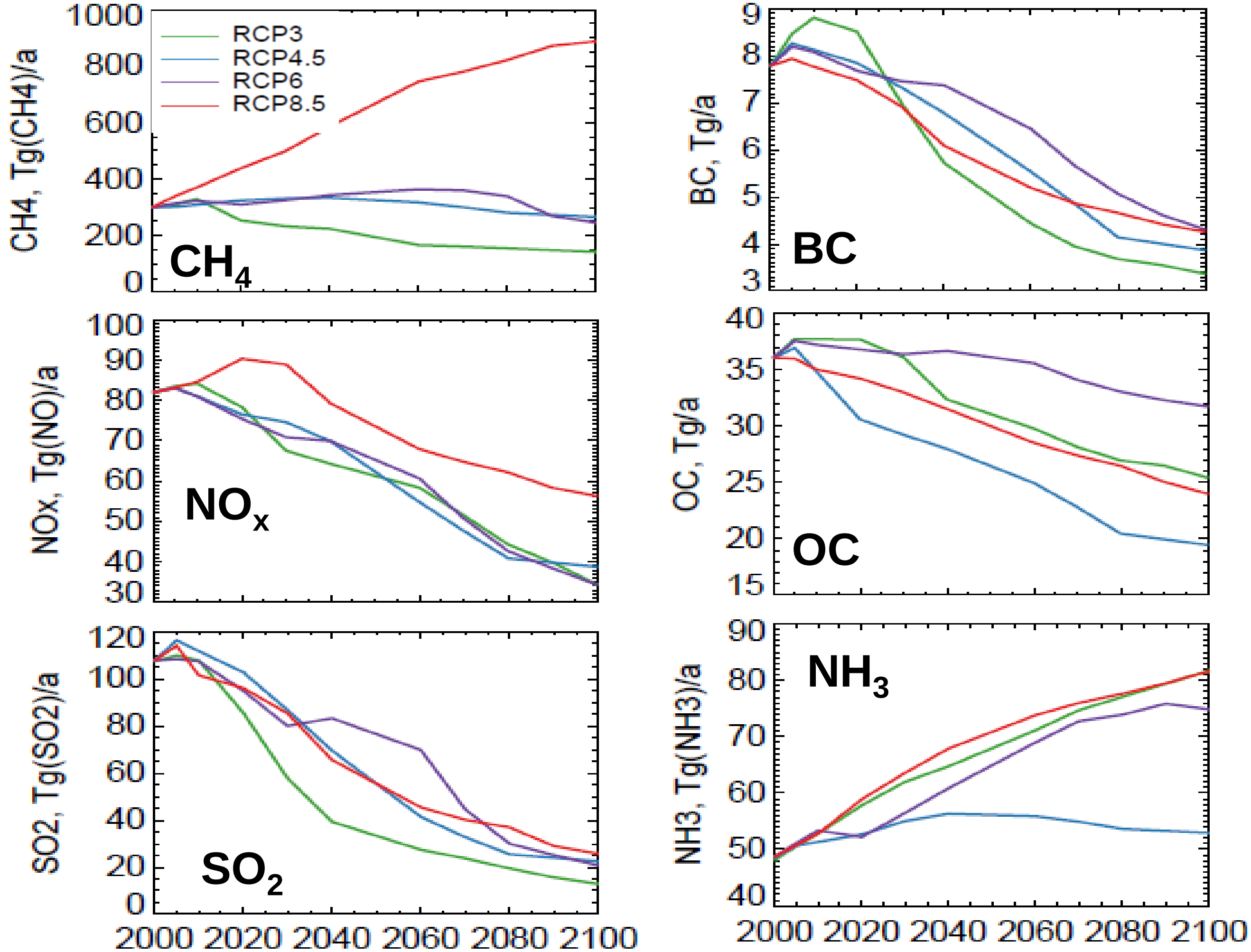


Projections of global AQ-relevant emissions in IPCC scenarios

SRES [IPCC, 2001]



RCP [IPCC, 2013]



- **Large differences in projections between SRES and RCP scenarios**
- **The RCP scenarios project large decreases for all emissions except NH_3**
- **Even China and India are projected to decrease emissions in next 2 decades except for RP8.5 (peak in 2040)**