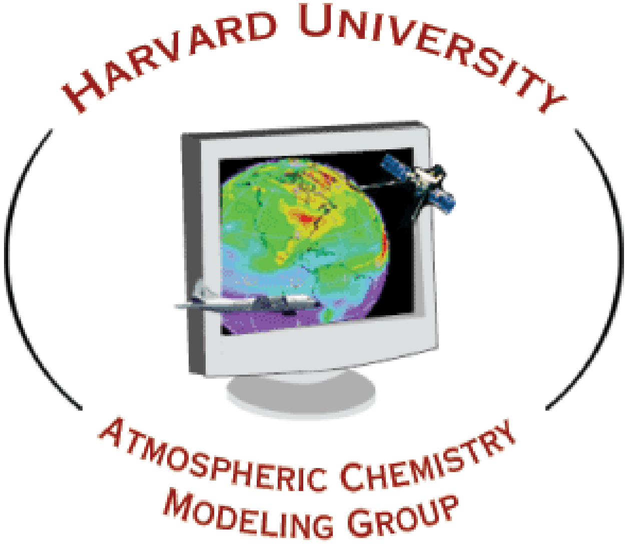
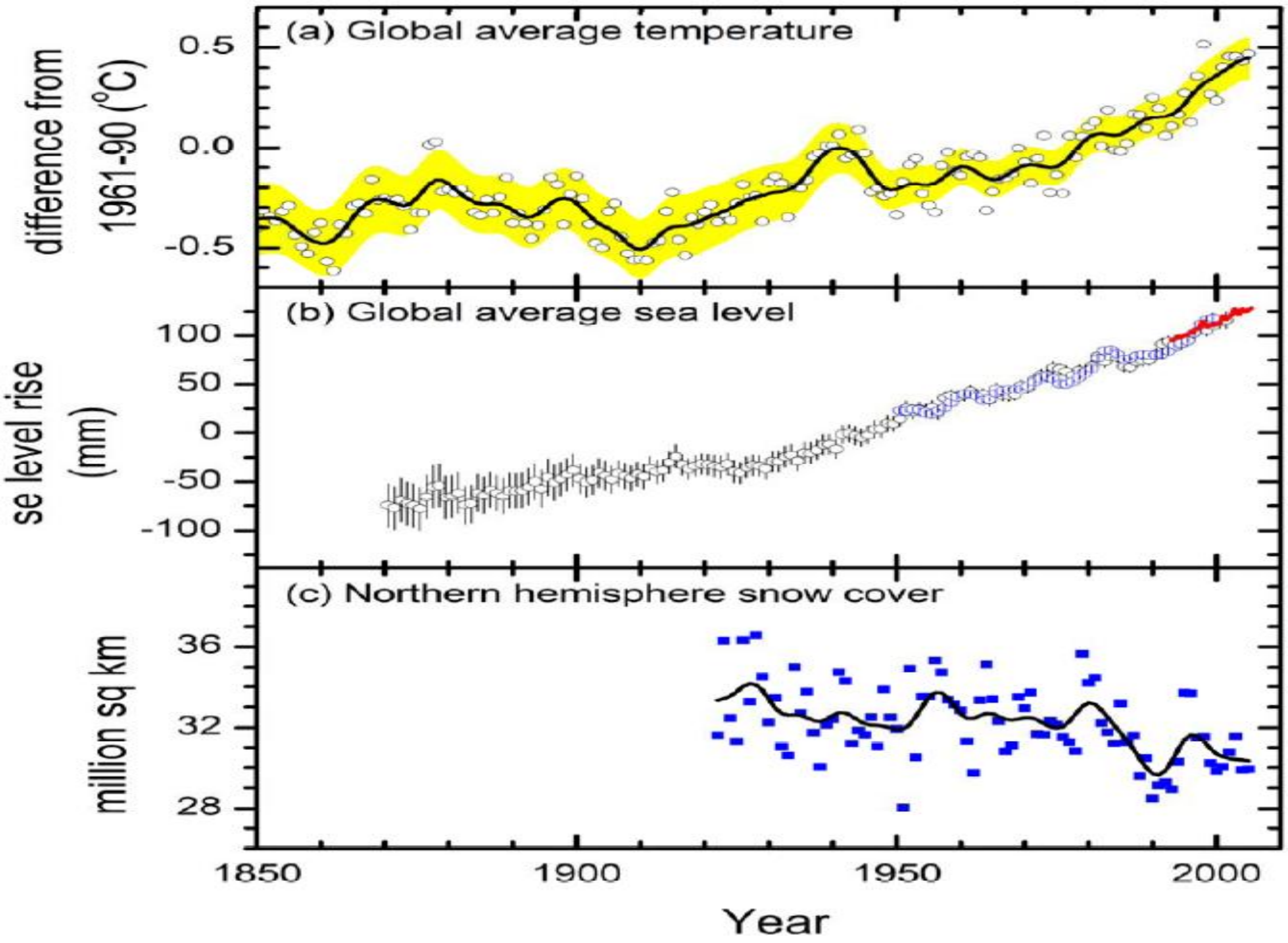
Climate Change Implications for US Air Quality

Daniel J. Jacob



Global climate change since 1850

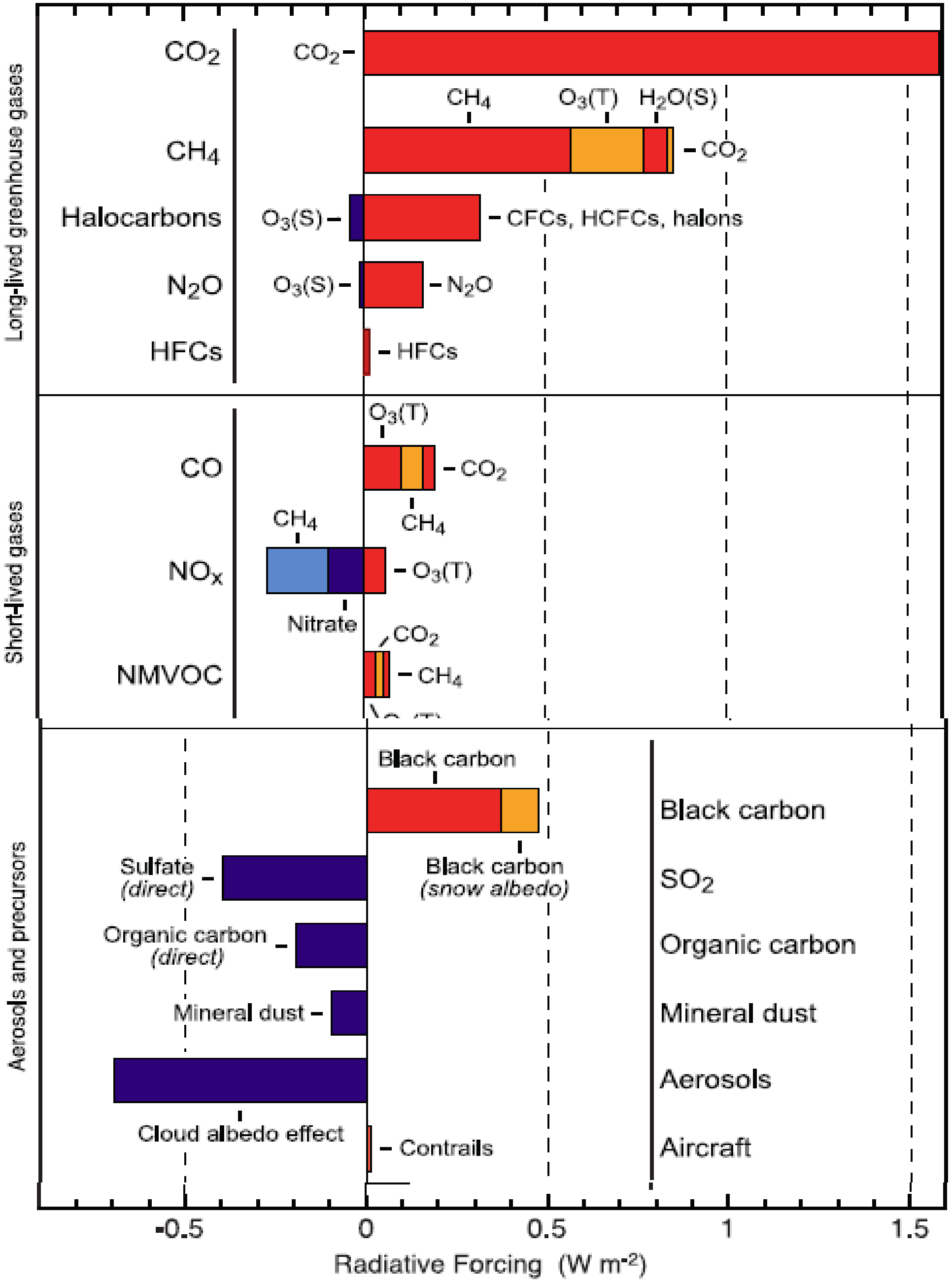


Rise in temperature and sea-level, ice retreat are well established

IPCC [2007]

Climate change is driven by radiative forcing

1750-2005 radiative forcing referenced to emissions



- ***Radiative forcing*** ΔF **is the energy imbalance at the top of the atmosphere resulting from an external perturbation to the Earth system:**

$$\Delta F = Energy\,(in) - Energy(out)$$

- **Global surface warming ΔT_o is linearly related to radiative forcing:**

$$\Delta T_o = \lambda\ \Delta F$$

- **Observed historical warming is consistent with understanding of radiative forcing by CO_2 and other agents**

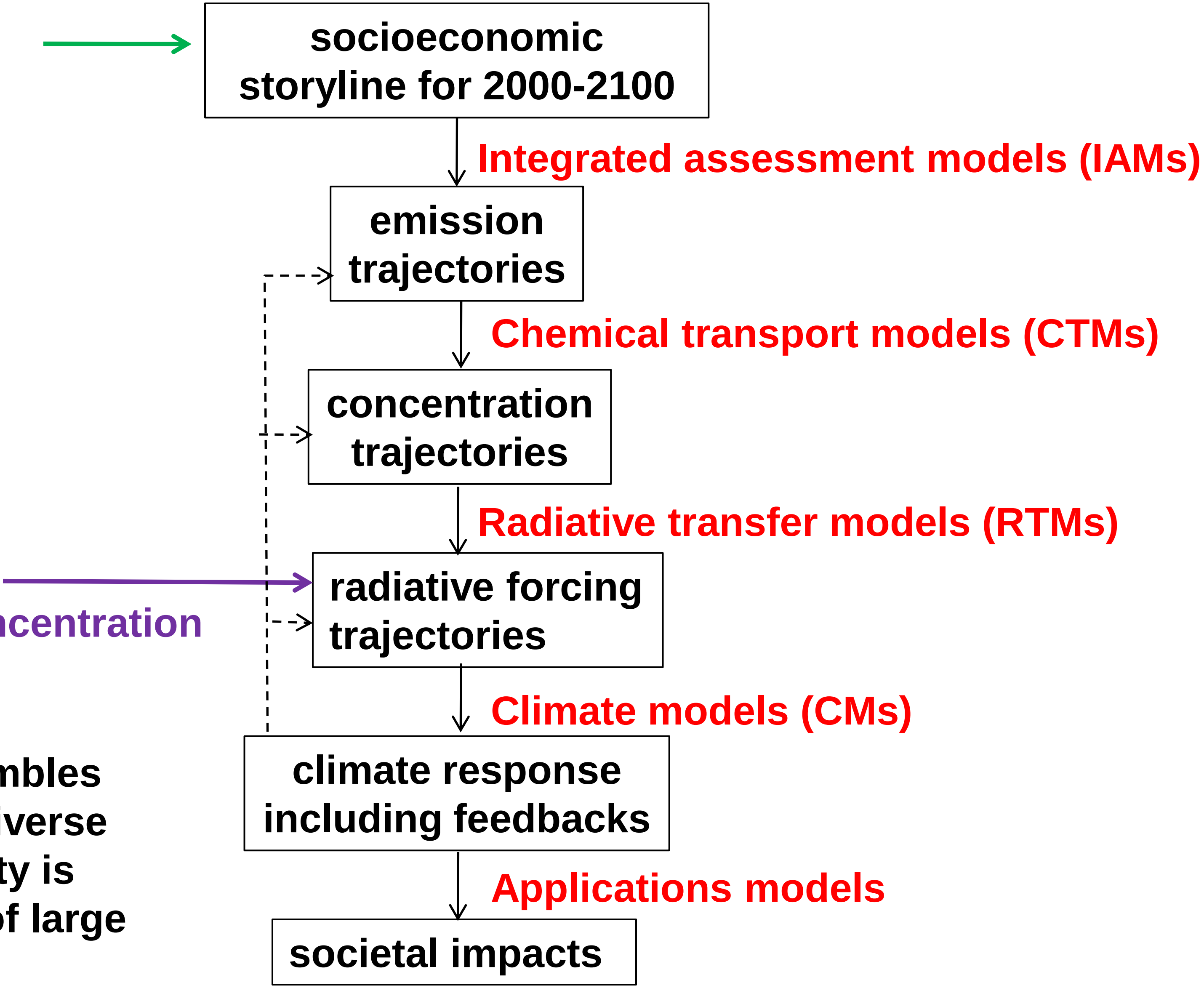
IPCC [2007]

IPCC projections of 21st century climate change

IPCC TAR and 4AR
SRES scenarios
(A1, A2, B1, B2)

IPCC 5AR (2013):
Representative Concentration
Pathways (RCPs)

Use of model ensembles drawing from the diverse scientific community is crucial in the face of large uncertainties



socioeconomic storyline for 2000-2100

Integrated assessment models (IAMs)

emission trajectories

Chemical transport models (CTMs)

concentration trajectories

Radiative transfer models (RTMs)

radiative forcing trajectories

Climate models (CMs)

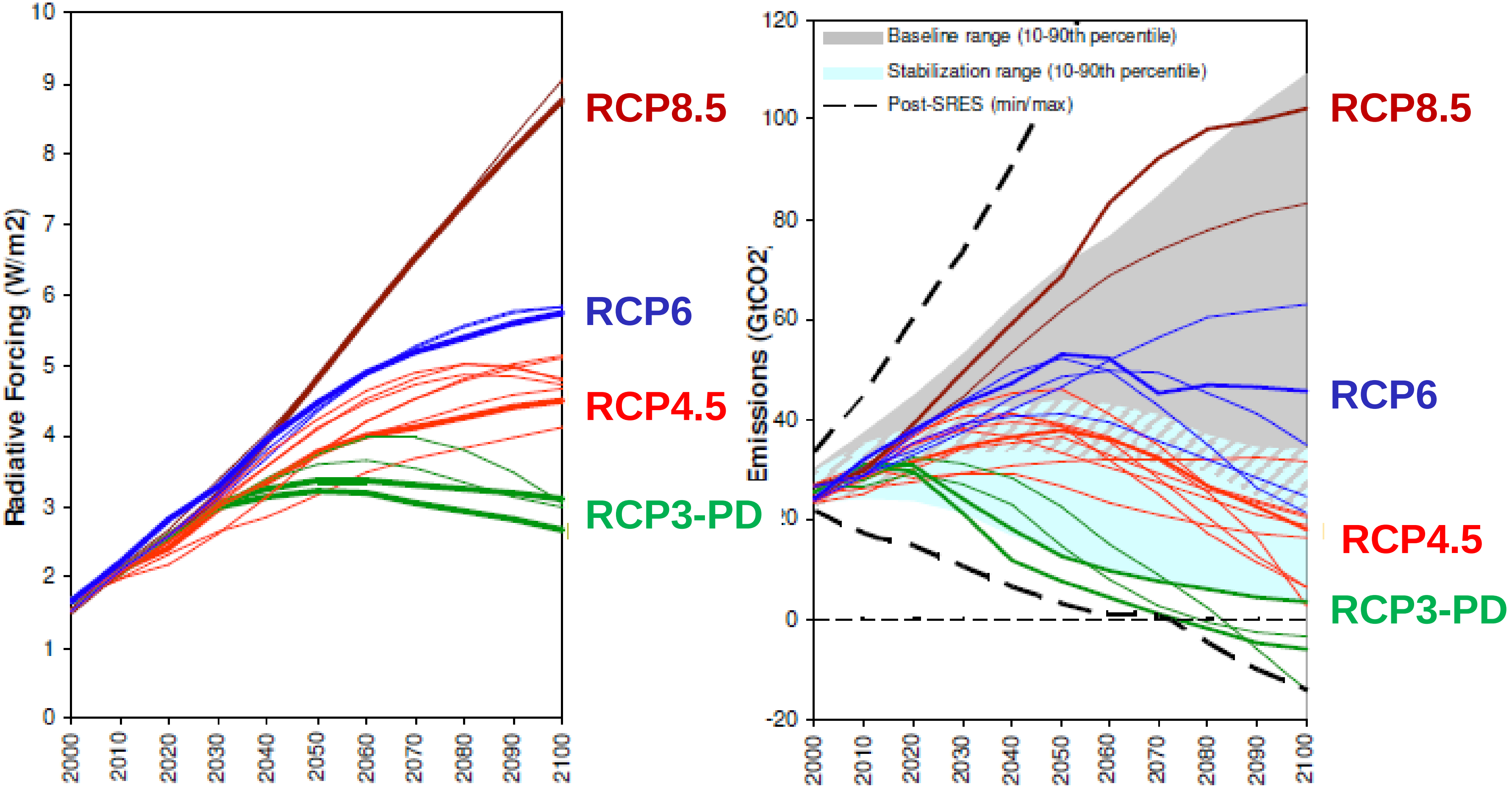
climate response including feedbacks

Applications models

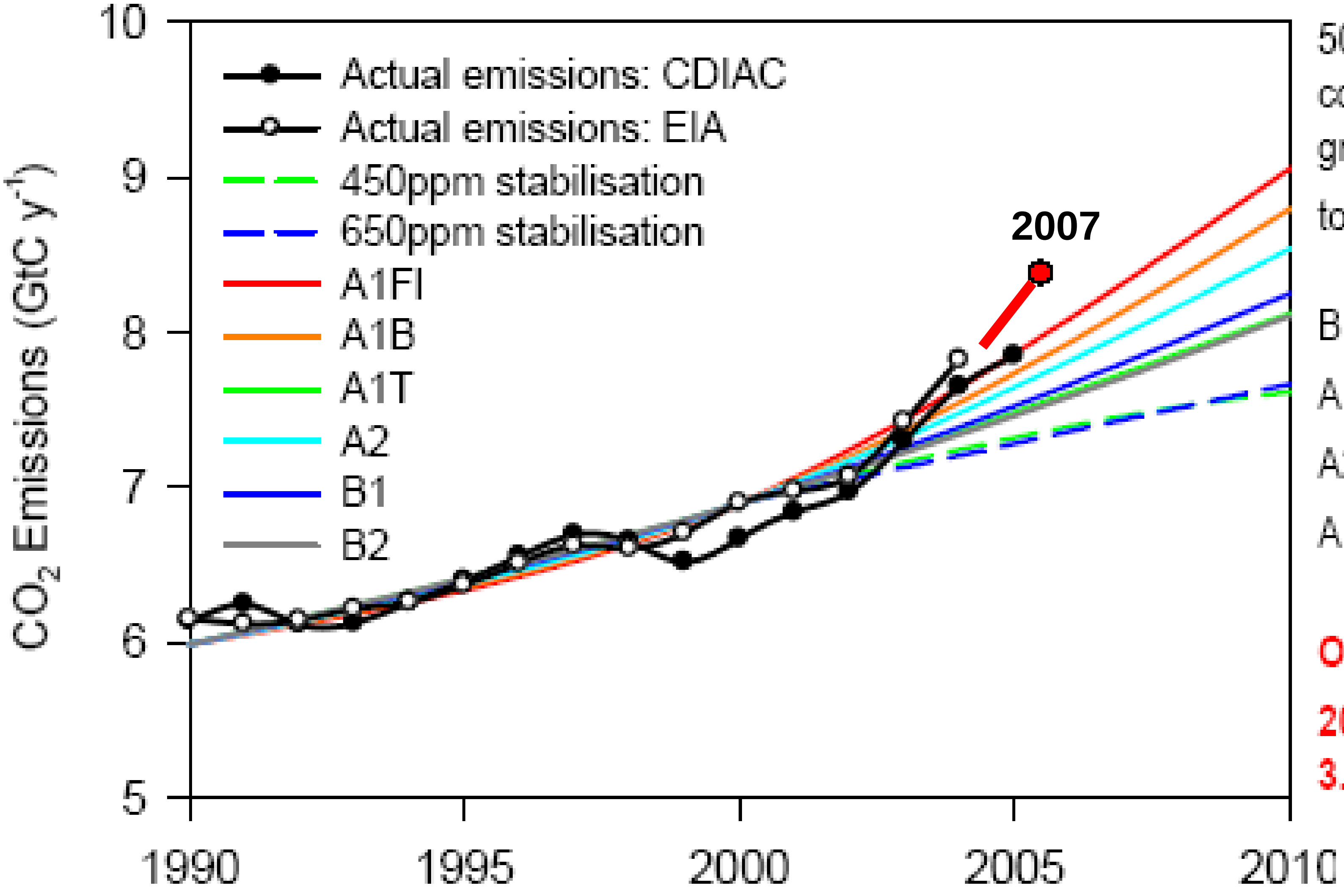
societal impacts

New IPCC AR5 Scenarios:
Representative Concentration Pathways (RCPs)

- Defined by radiative forcing trajectories rather than socioeconomic storylines
- Are representative of the Integrated Assessment Model (IAM) literature
- Provide continuity with older IPCC scenarios: RP8.5 ≈ A2, RP6 ≈ A1B, RP4.5 ≈ B1
- Introduce new “peak-and-decline” scenario – aggressive climate policy
- RCP4.5 to be used for multi-decadal high-resolution simulations



Recent CO_2 trends have followed pessimistic forecasts



50-year constant growth rates to 2050

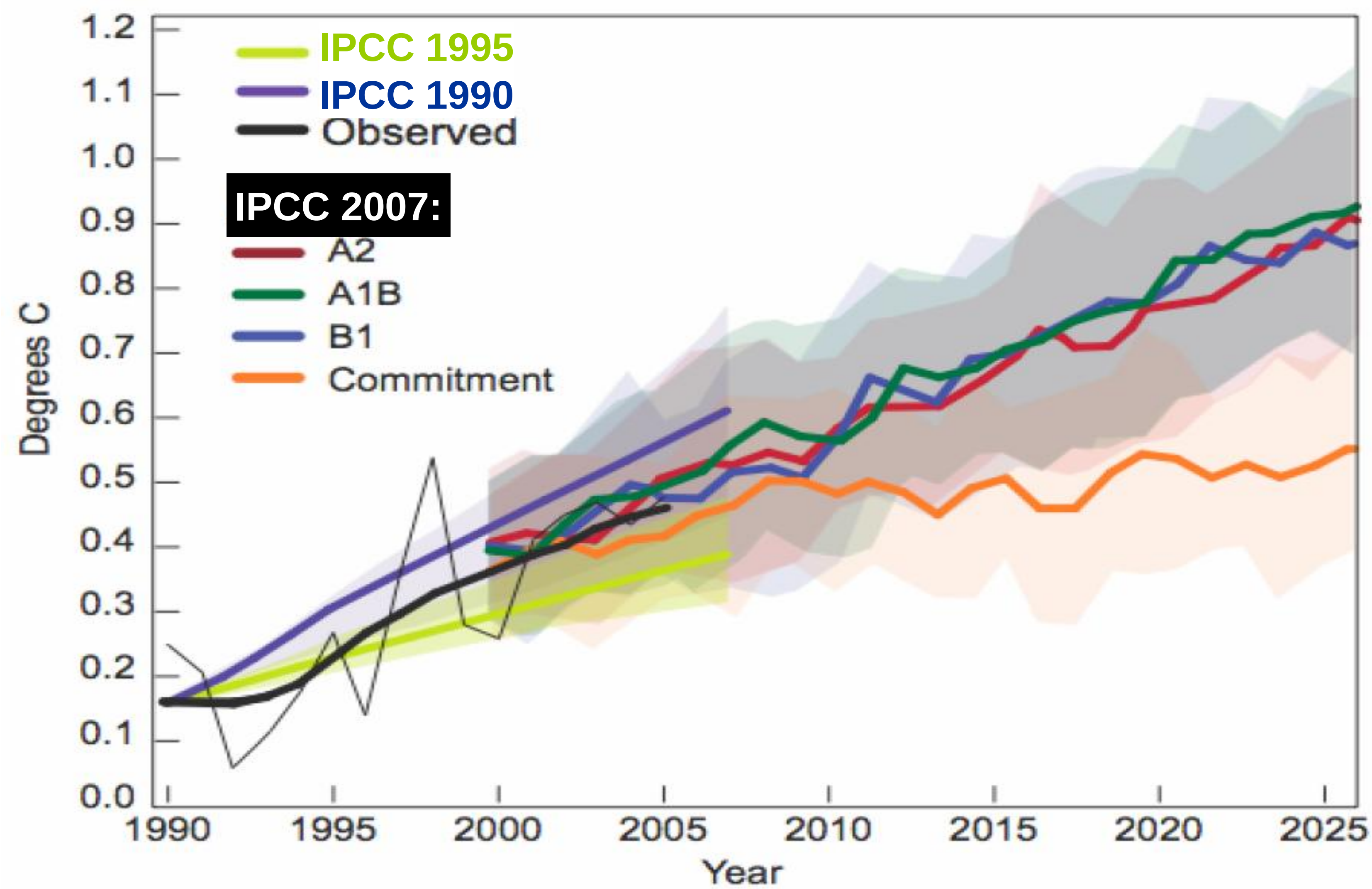
B1 1.1%,
A1B 1.7%,
A2 1.8%
A1FI 2.4%

Observed 2000-2006 3.3%

Raupach et al. 2007, PNAS; Canadell et al. 2007, PNAS

Previous and future IPCC warming projections

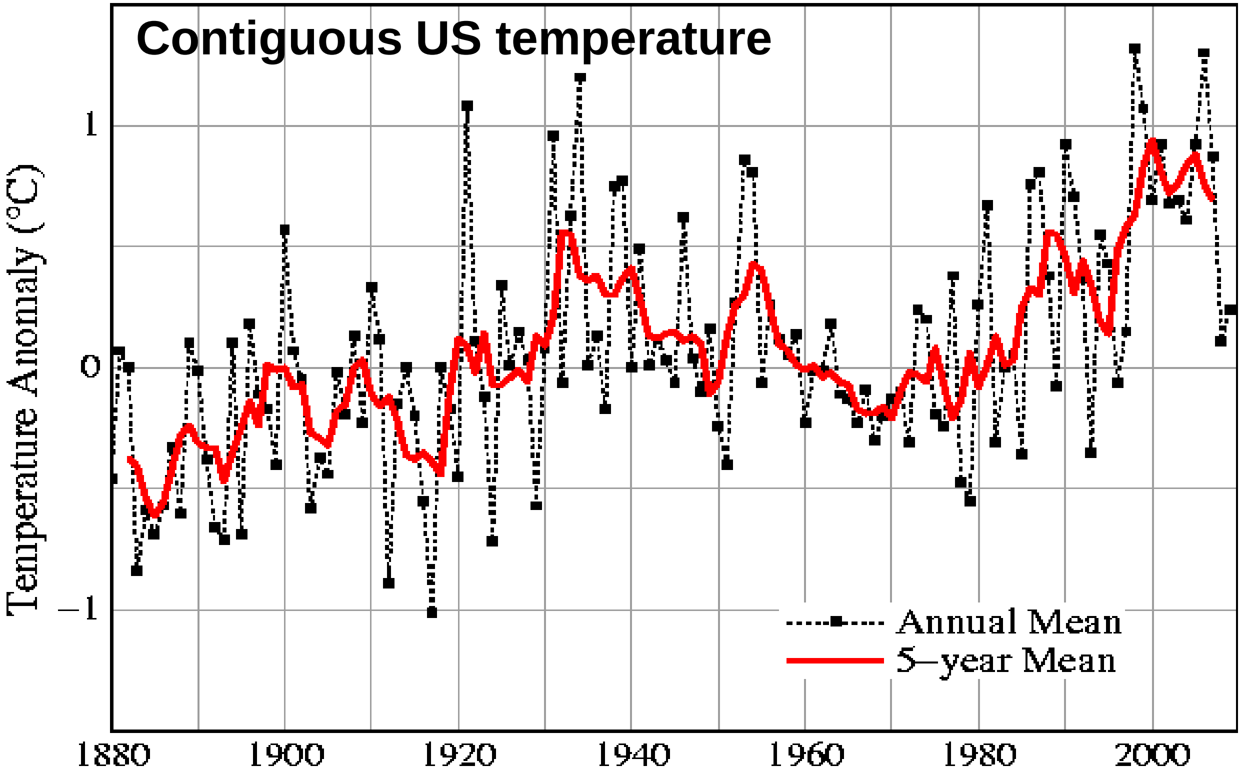
Mean results from an ensemble of GCMs using the same greenhouse scenarios



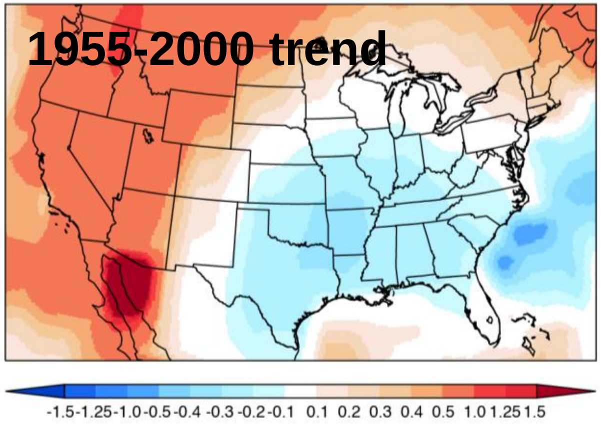
- **IPCC scenarios have successfully projected warming over past 20 years**
- **Notice small divergence between future scenarios**

IPCC [2007]

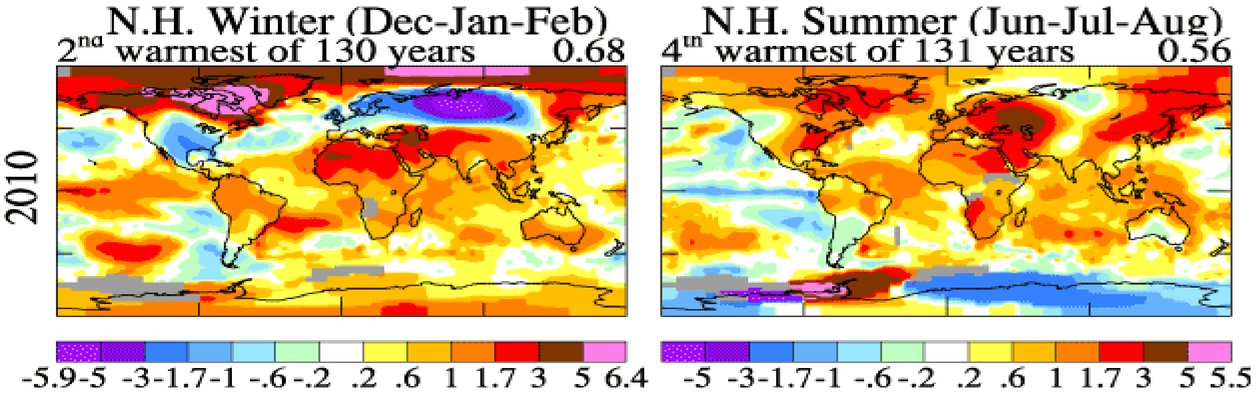
US surface temperature trend



- US has warmed faster than global mean, as expected in general for mid-latitudes land
- But no warming in East for 1955-2000



Surface Temperature Anomaly (°C): Base Period = 1951-1980

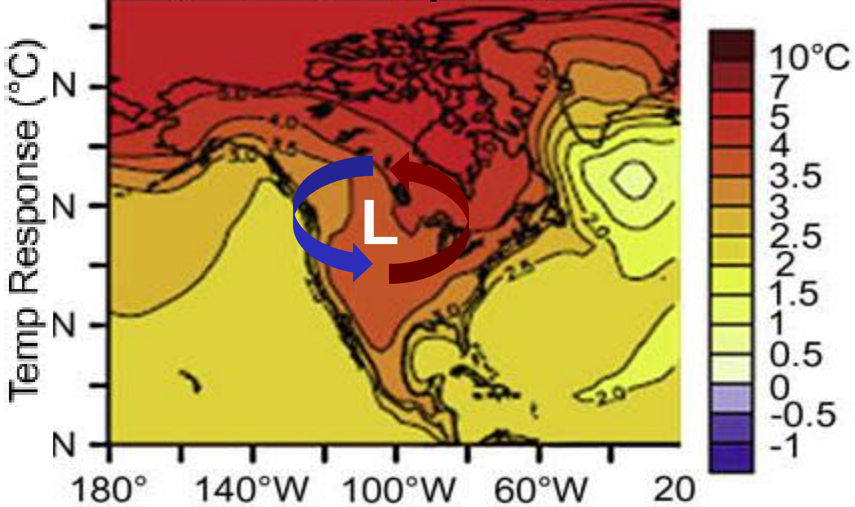


Last winter was cold in US …but warm elsewhere in world

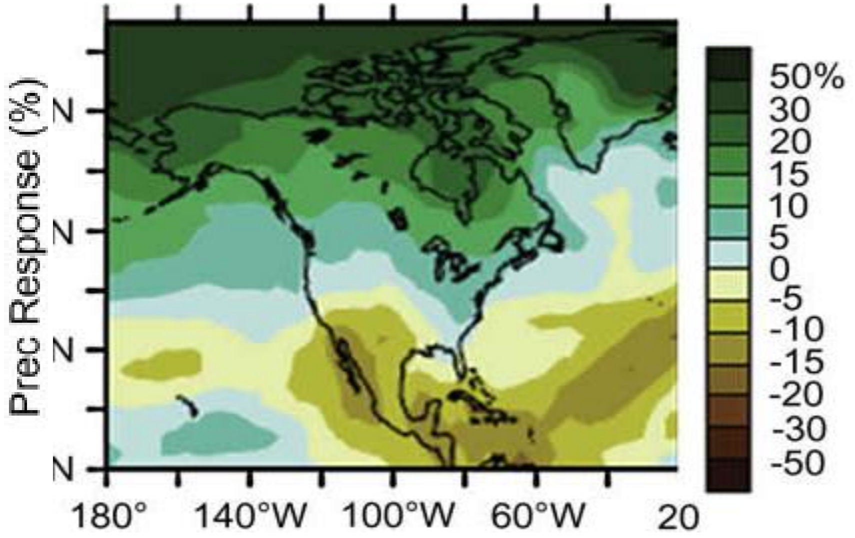
GISTEMP [2010]

IPCC projections of 2000-2100 climate change in N. America

Surface temperature



Precipitation

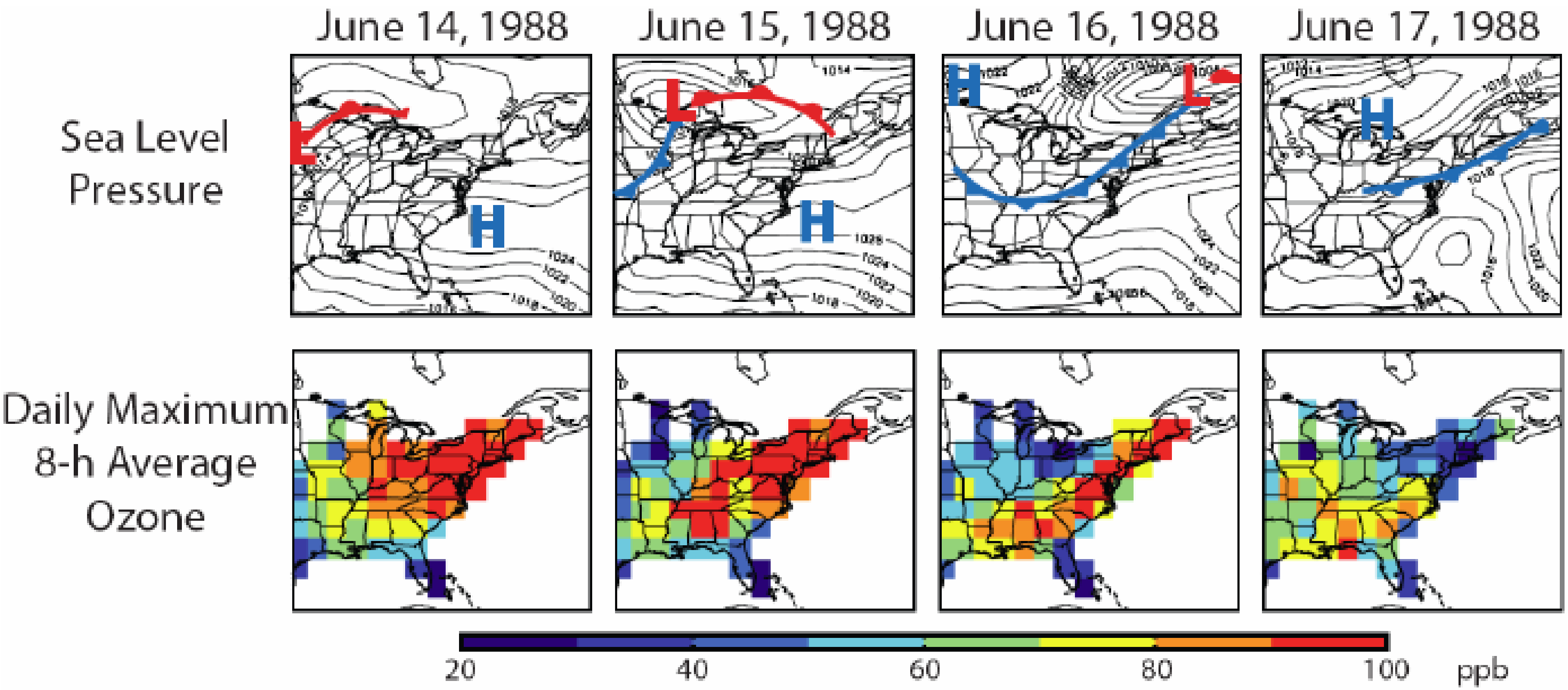


2080-2099 vs. 1980-1999 changes for ensemble of 20 models in A1B scenario

- **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; affects other components of hydrological cycle (clouds, mixing depths)**
- **Decrease in meridional temperature gradient expected to weaken winds, decrease frequency of mid-latitude cyclones**

IPCC [2007]

Importance of mid-latitudes cyclones for US ventilation

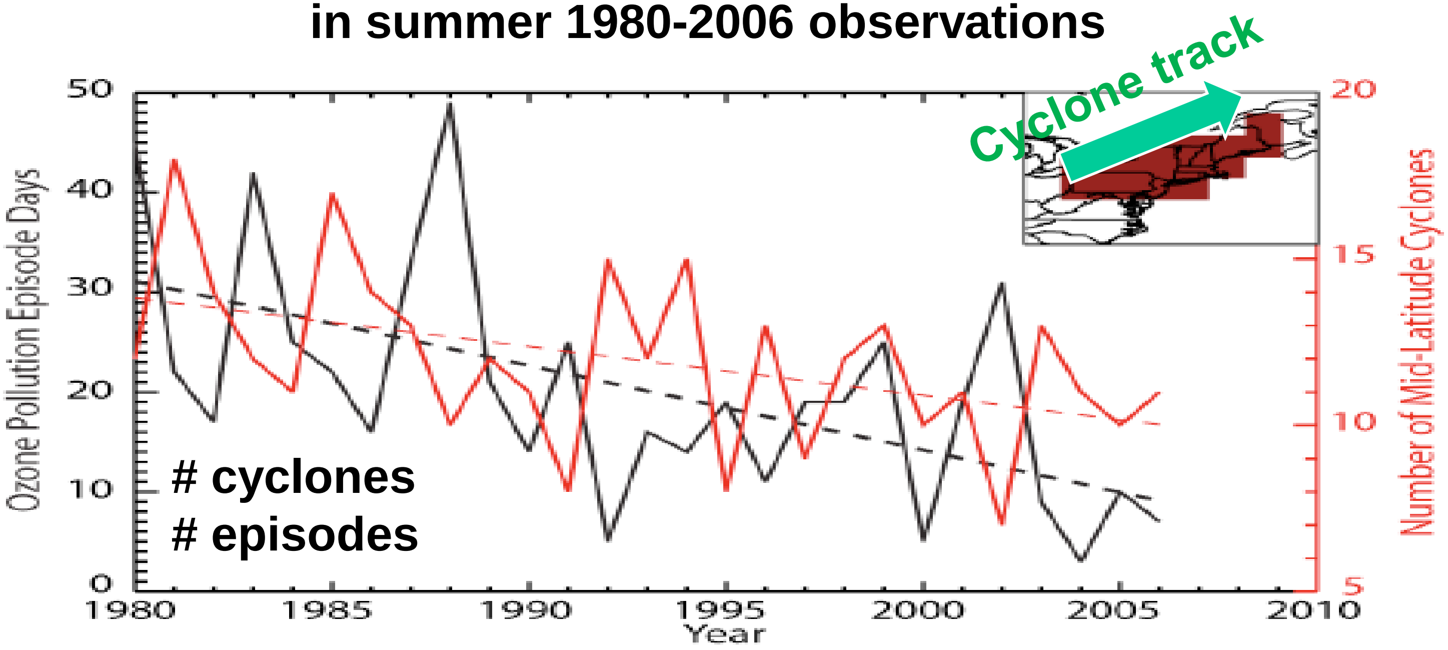


- Cold fronts associated with cyclones tracking across southern Canada are the principal ventilation mechanism for the eastern US
- The frequency of these cyclones has decreased in past 50 years, likely due to greenhouse warming

Leibensperger et al. [2008]

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



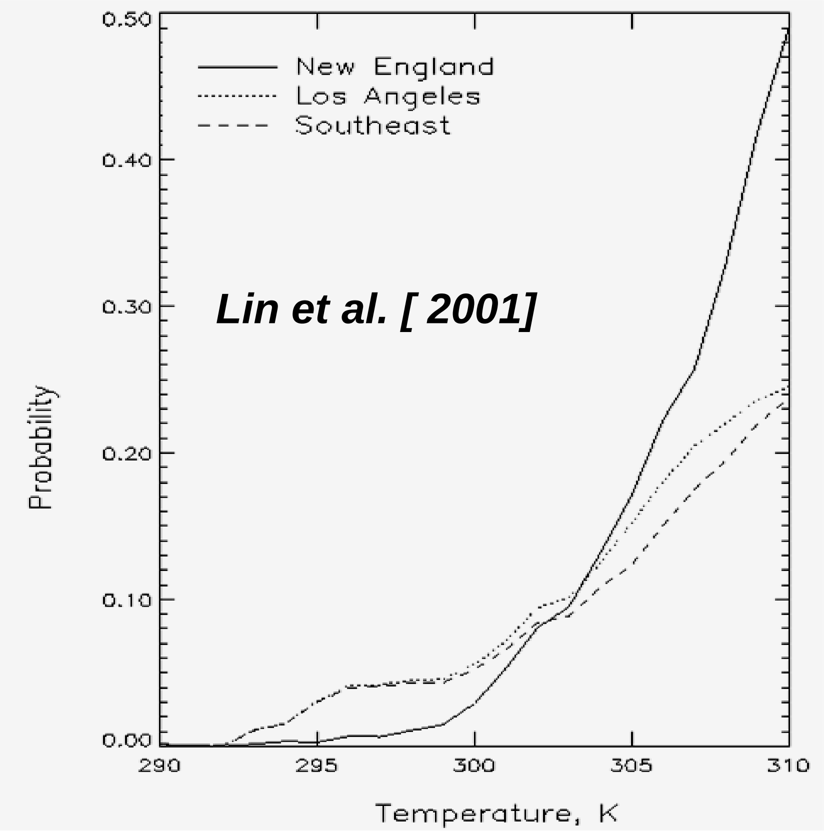
- **Strong interannual correlation; cyclone frequency is predictor of pollution episode frequency**
- **1980-2006 decrease in cyclone frequency would imply a corresponding degradation of air quality if emissions had remained constant**
- **Expected # of 80 ppb exceedance days in Northeast dropped from 30 in 1980 to 10 in 2006, but would have dropped to ≈ zero in absence of cyclone trend**

This demonstrates impact of climate change on AQ policy over decadal scale

Leibensperger et al. [2008]

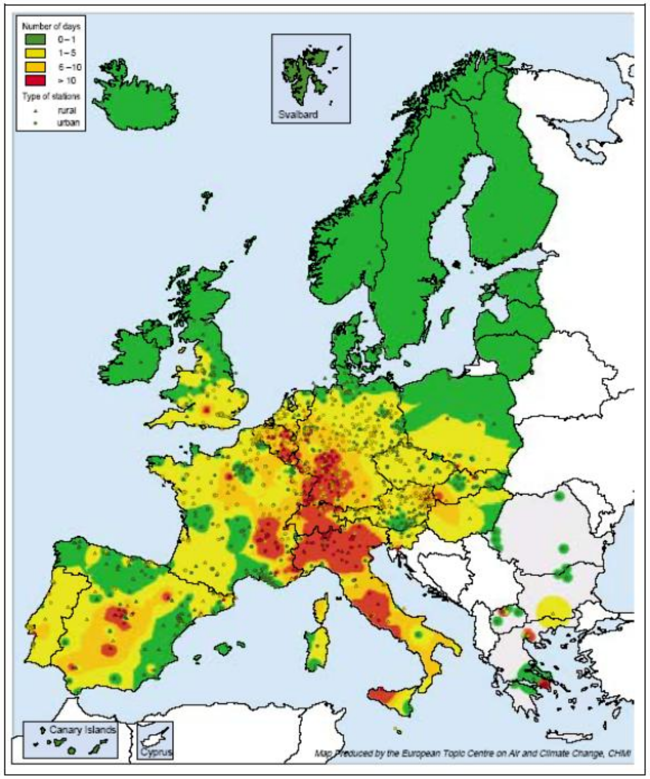
Correlation of ozone pollution with temperature

Probability of max 8-h O_3 > 84 ppbv vs. daily max. *T*



Lin et al. [2001]

Ozone exceedances of 90 ppbv, summer 2003

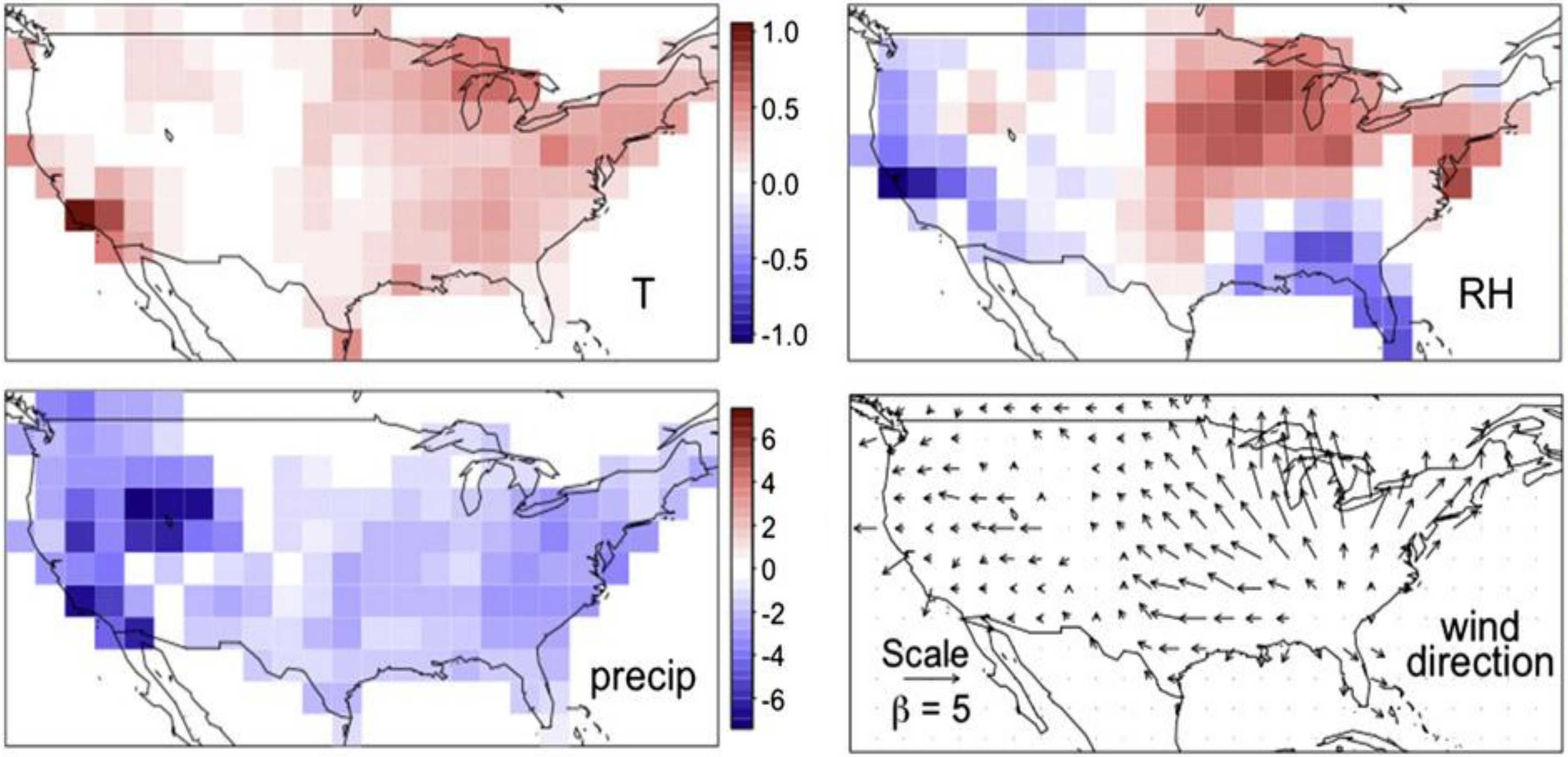


Map produced by the European Topic Centre on Air and Climate Change, CHMI

**Observed correlation of high ozone with temperature is reproduced in models;
It is driven by (1) stagnation, (2) biogenic VOCs, (3) chemistry**

Observed correlations of $PM_{2.5}$ with meteorological variables

Correlations for deseasonalized, detrended 1998-2008 data



- **Relationships are more complicated than for ozone because of PM speciation, compensating effects**
- **Air flow, precipitation, and fires are important predictors**

Tai et al. [2010]

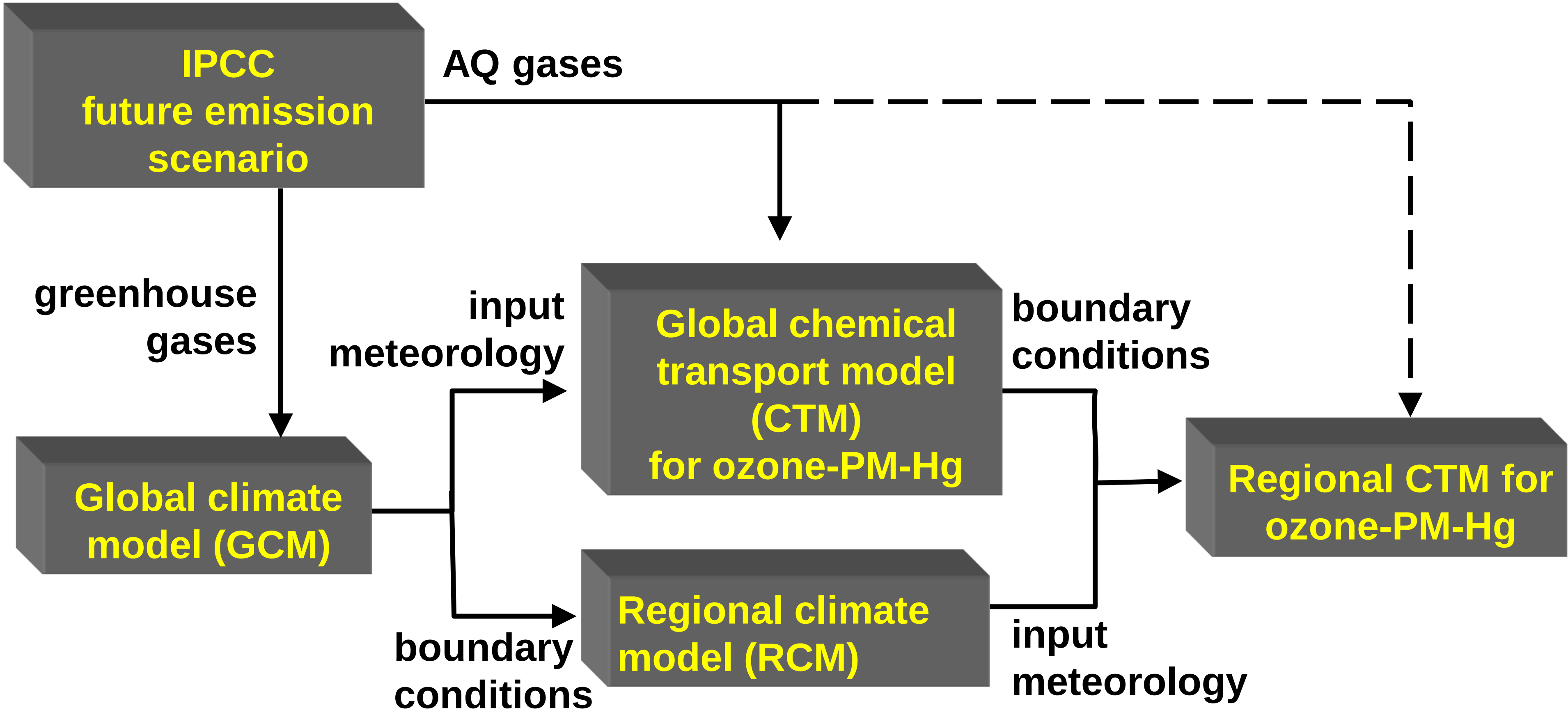
Projecting the effects of future climate change on air quality

Expected climate change		Ozone	PM
↑	**Stagnation**	↑	↑
↑	**Temperature**	↑	?
?	**Mixing depth**	=	↓
?	**Precipitation**	=	↓
?	**Cloud cover**	↓	↓
?	**Relative humidity**	=	↑

Jacob and Winner [2009]

Quantifying the effects of climate change on air quality

internal EPA project (CIRAQ) and several STAR projects



IPCC future emission scenario

AQ gases

greenhouse gases

Global climate model (GCM)

input meteorology

Global chemical transport model (CTM) for ozone-PM-Hg

boundary conditions

Regional CTM for ozone-PM-Hg

boundary conditions

Regional climate model (RCM)

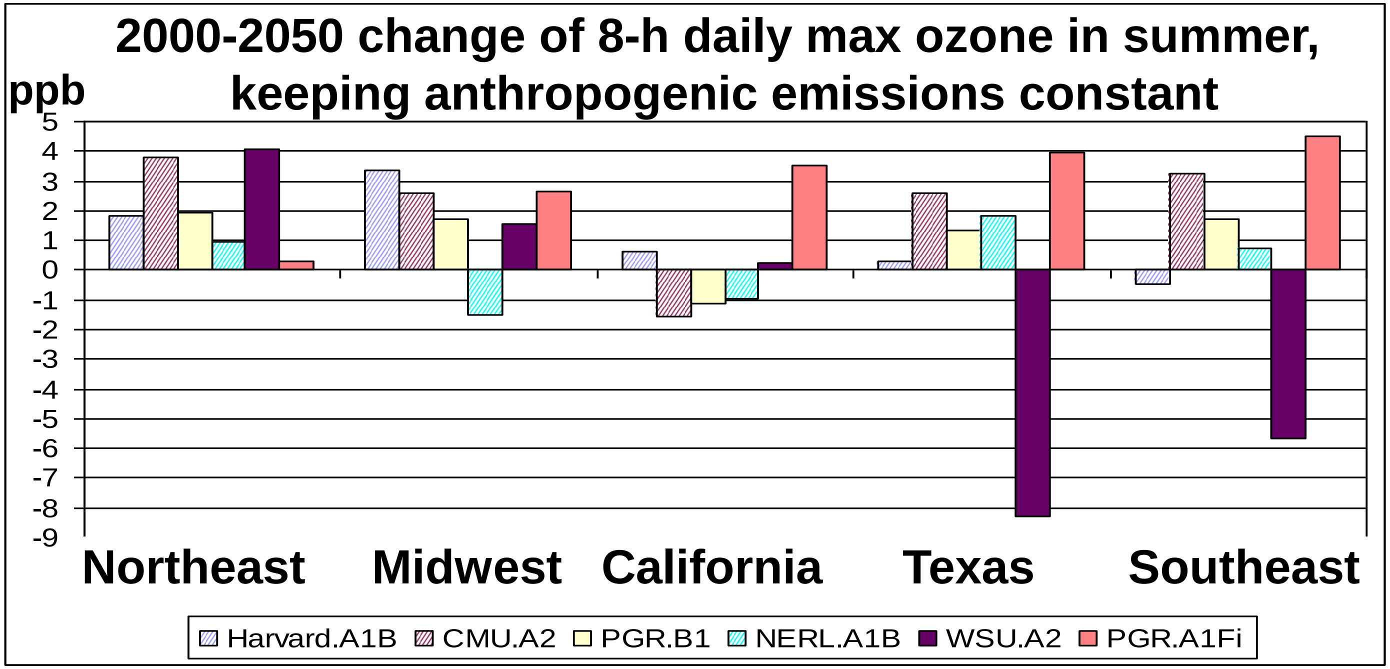
input meteorology

Computationally expensive machinery, need a number of simulation years for robust statistics

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



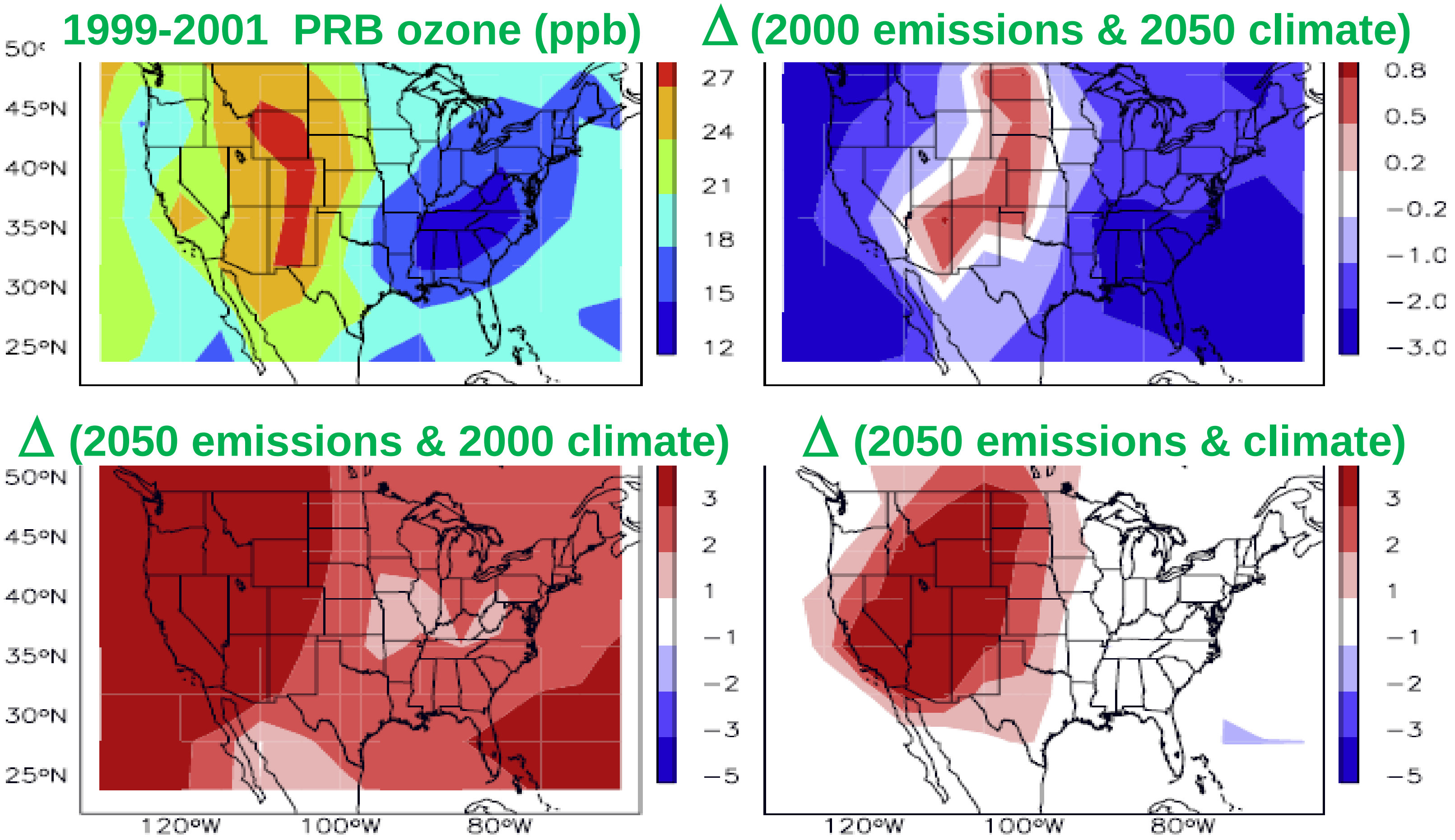
2000-2050 change of 8-h daily max ozone in summer, keeping anthropogenic emissions constant

- **Models show consistent projection of ozone increase for most of US**
- **Typical mean increase is 1-4 ppb, up to 10 ppb for ozone pollution episodes**

Weaver et al. [2010]

Effect of climate change on background ozone

Policy-relevant background (PRB): surface air concentration in absence of North American anthropogenic emissions



1999-2001 PRB ozone (ppb)

Δ (2000 emissions & 2050 climate)

Δ (2050 emissions & 2000 climate)

Δ (2050 emissions & climate)

**Jun-Aug
1-5 pm**

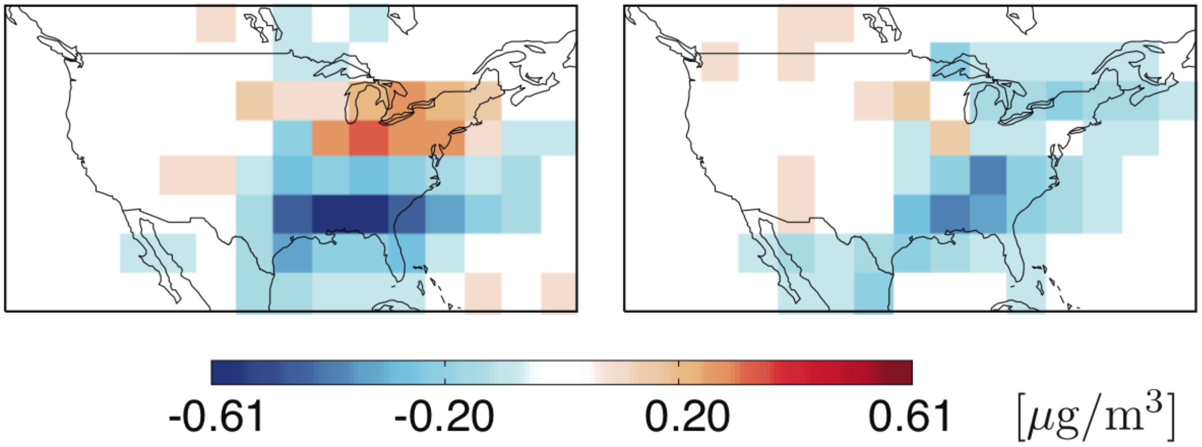
- **2050 emissions increase PRB due to rising methane, Asian sources**
- **2050 climate decreases PRB in most of US due to higher H_2O, except in the West due to subsidence and drying**
- **The two effects cancel in the East**

[Wu et al., 2008]

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

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

Global GCAP model



2000 emissions

2050 emissions

CMAQ model nested within GCAP

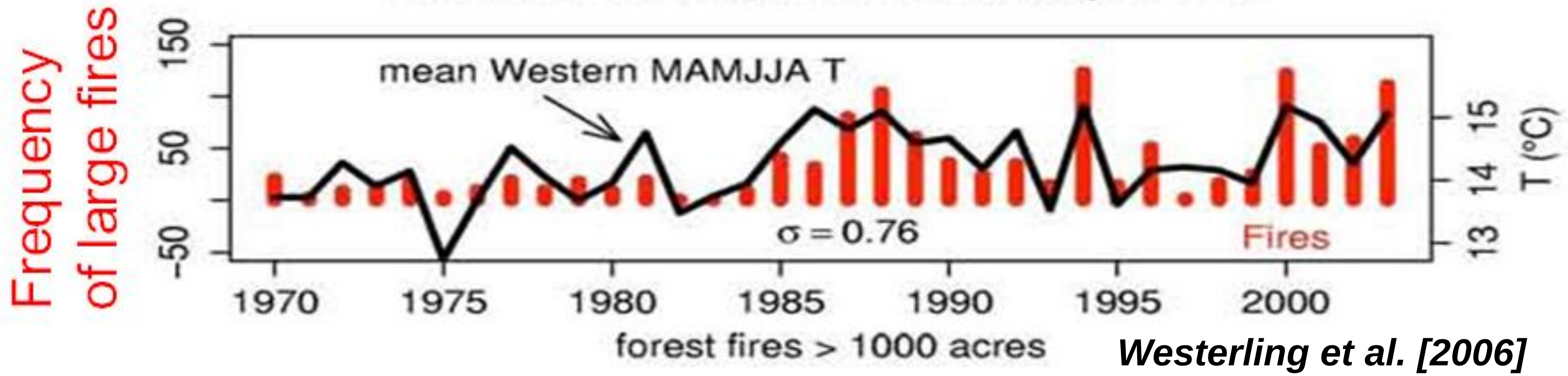
$\Delta PM_{2.5}$ (μg m^{-3})	**Midwest**	**Northeast**	**Southeast**
2000 emissions	+0.5	+0.1	-0.1
2050 emissions	+0.3	-0.4	-0.7

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

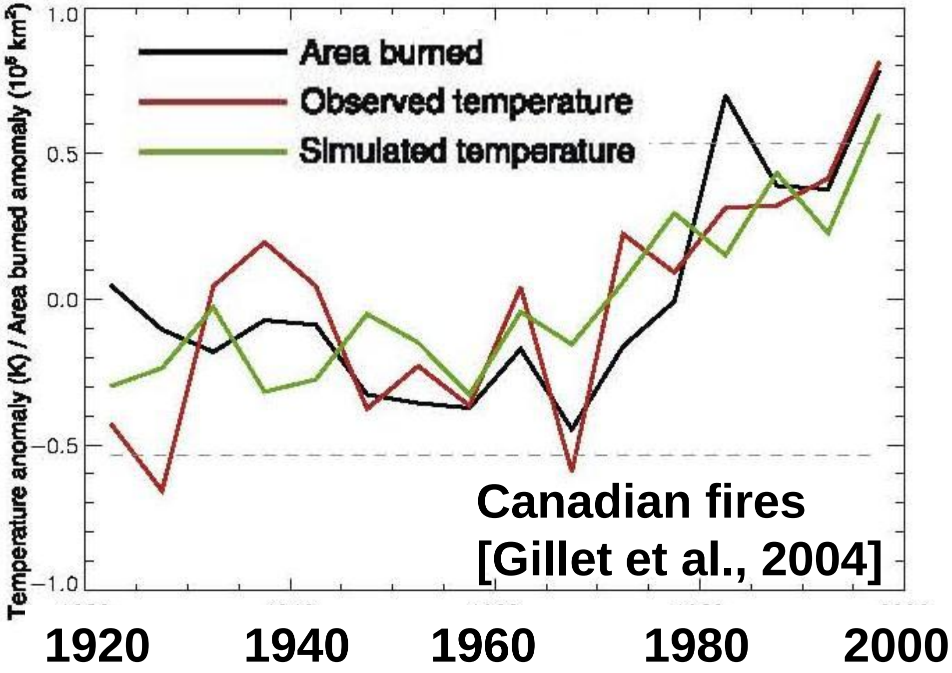
Pye et al. [2009]; Lam et al. [2010]

Increasing wildfire frequency in North America

Western US Large Forest Fires per Year



Westerling et al. [2006]



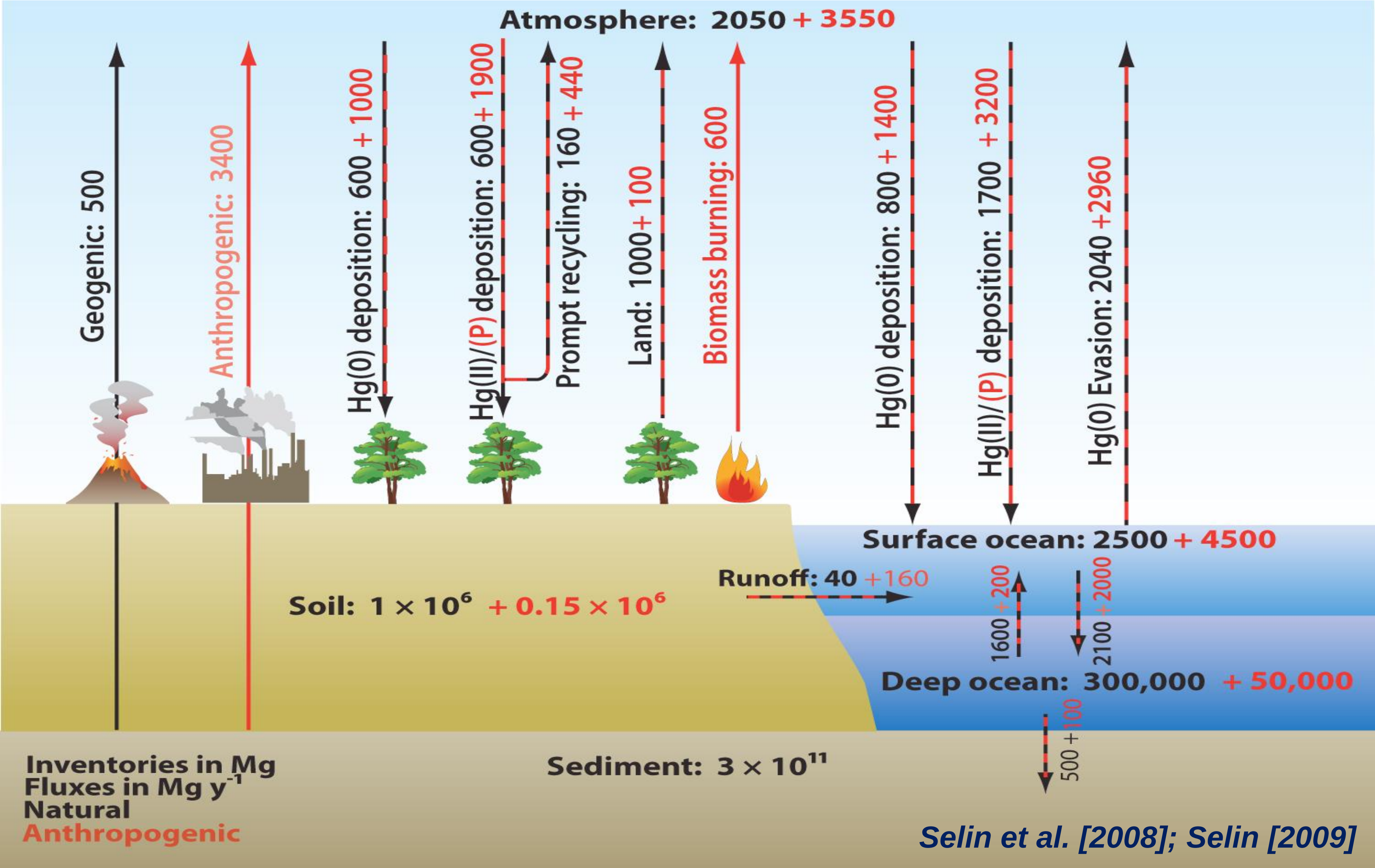
Canadian fires [Gillet et al., 2004]

- **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]***

Global biogeochemical cycle of mercury

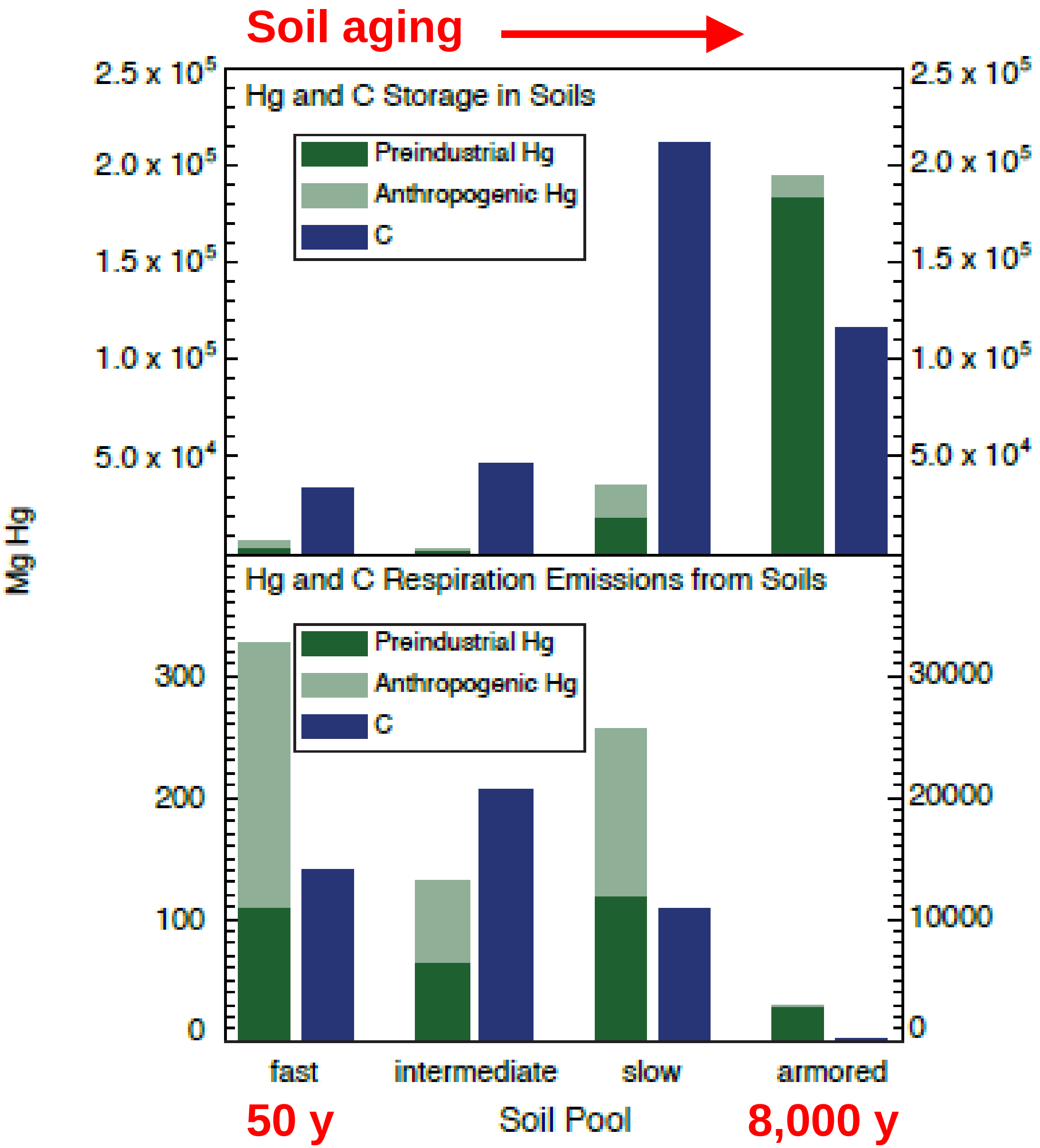
GEOS-Chem natural atmosphere + present-day human enhancement



Selin et al. [2008]; Selin [2009]

Climate-driven mobilization of anthropogenic Hg from soils

GEOS-Chem model simulation of soil mercury

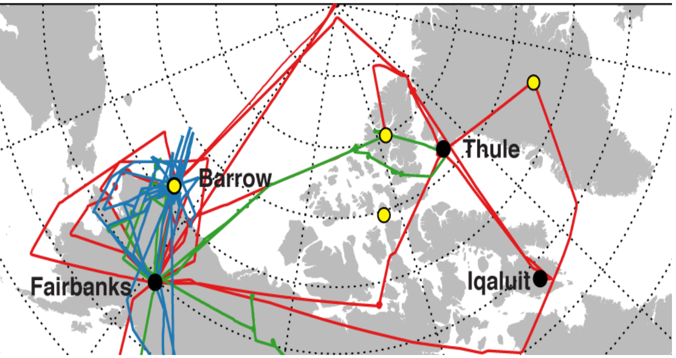


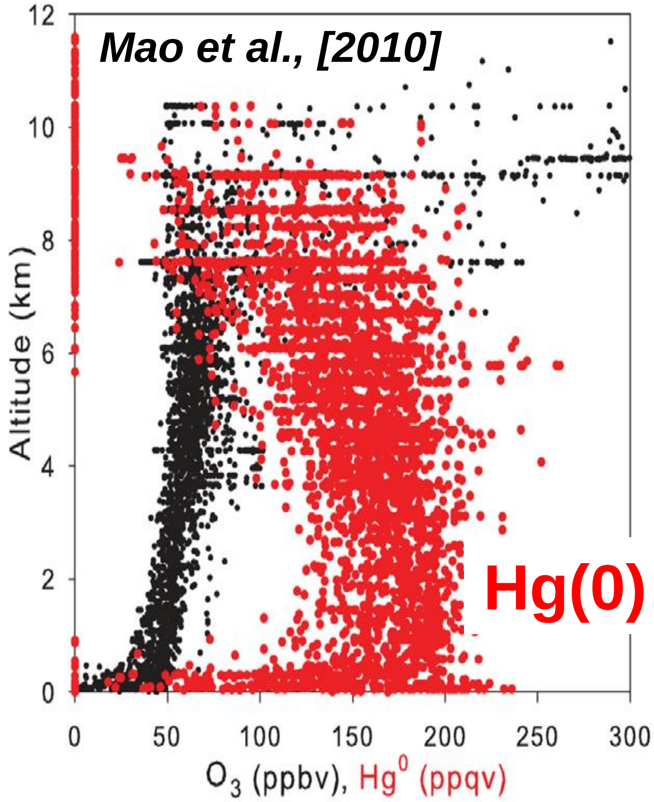
- **Mercury accumulates in soil by binding to organic carbon; part is volatilized when organic carbon is respired**
- **Mercury has a mean lifetime in soil of 600 years, but deposited anthropogenic mercury has a lifetime of only 80 years**
- **Increased soil respiration in future climate could lead to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

Smith-Downey et al. [2010]

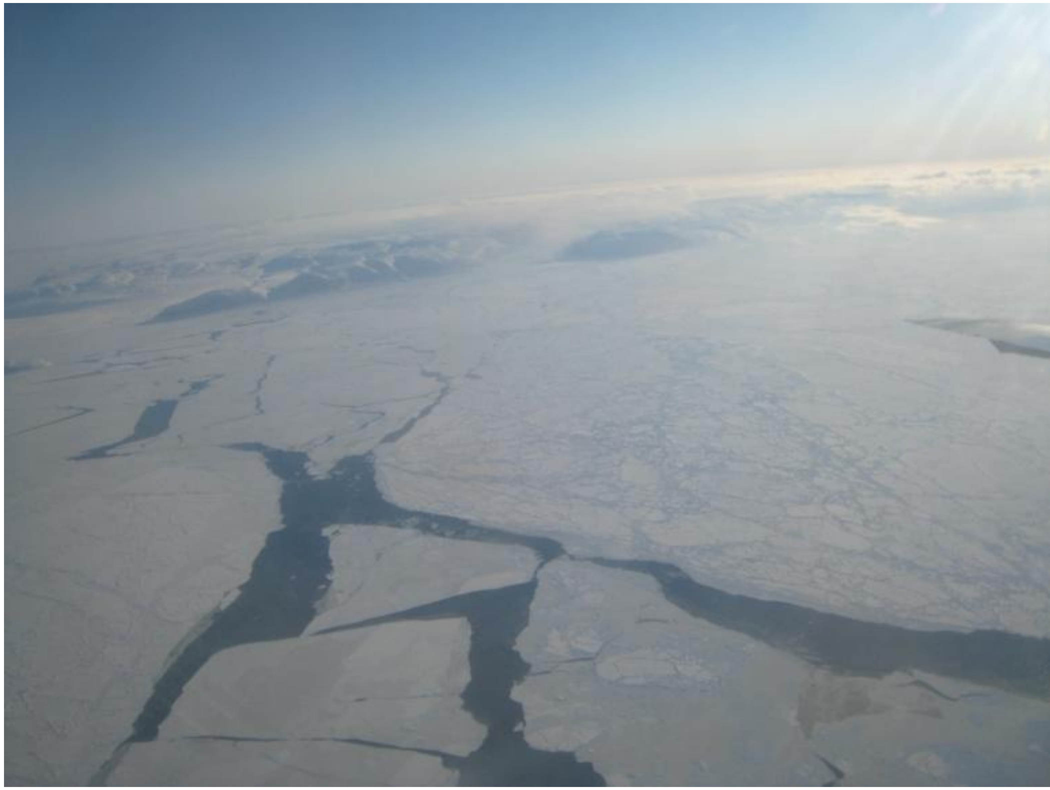
Climate-driven increase in mercury deposition to the Arctic

NASA/ARCTAS aircraft campaign
(April 2008)




Mao et al., [2010]

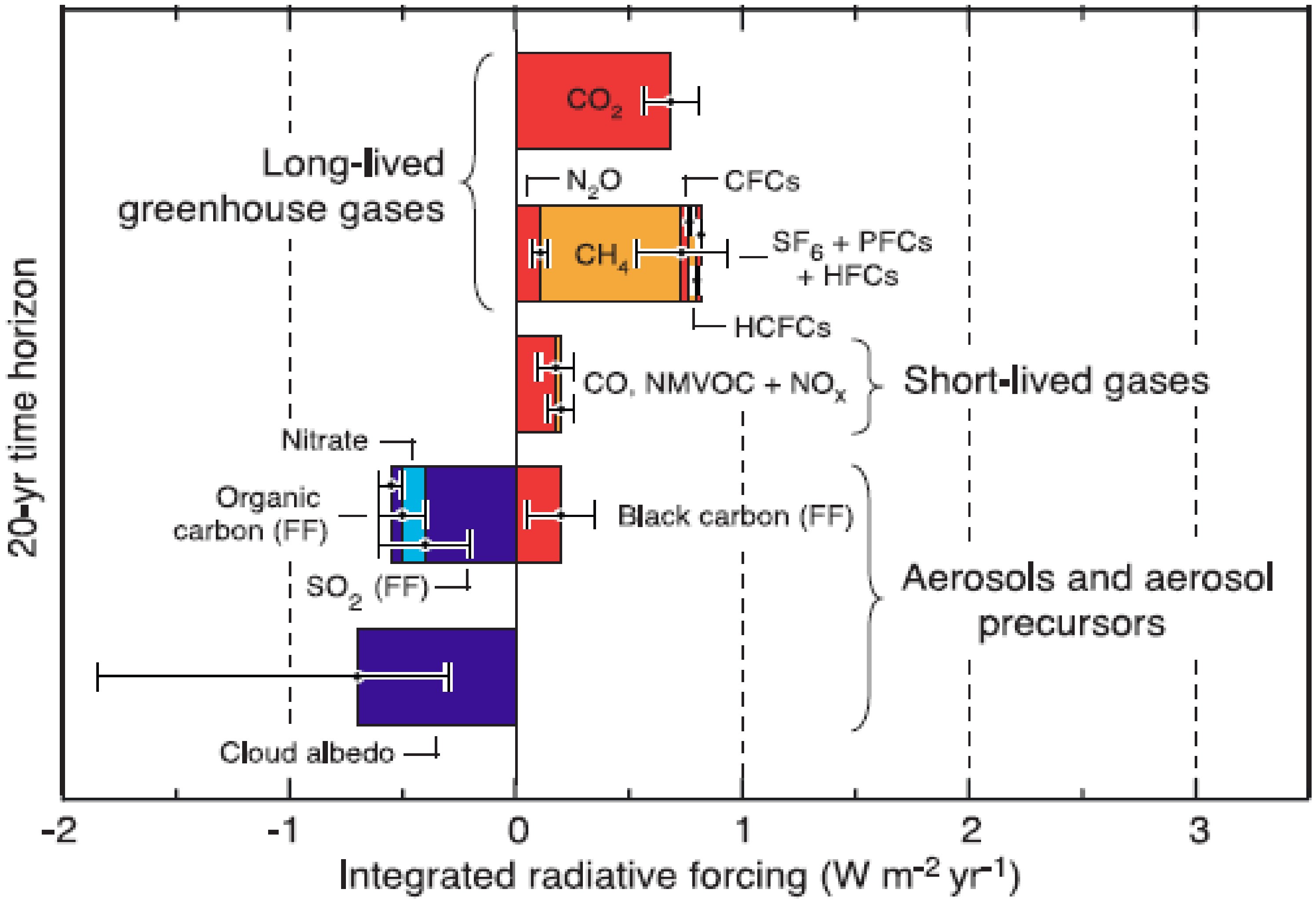
Halogen chemistry at ice leads causes fast mercury oxidation and deposition



More ice leads and open ocean in a warmer climate will increase mercury deposition to the Arctic

Importance of AQ-related emissions for climate change

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



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

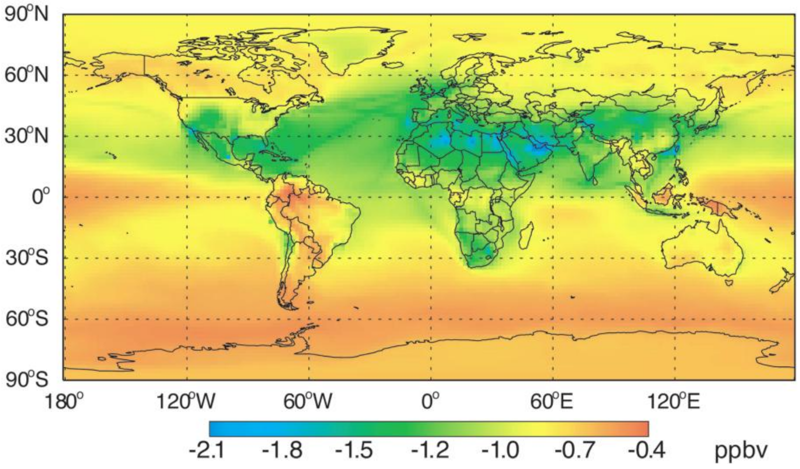
IPCC [2007]

Methane is “win-win” – but only as part of a global strategy

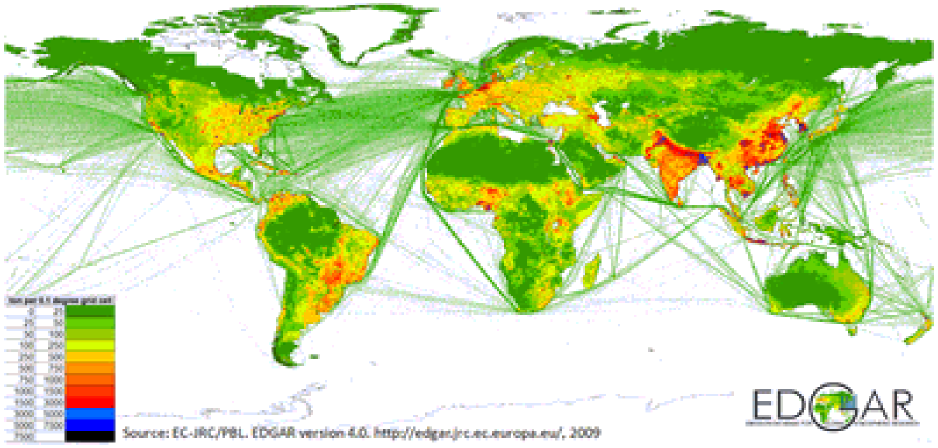
Effect on surface ozone air quality is through decrease in ozone background and does not depend on where methane emission is reduced

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

[West et al., 2006]



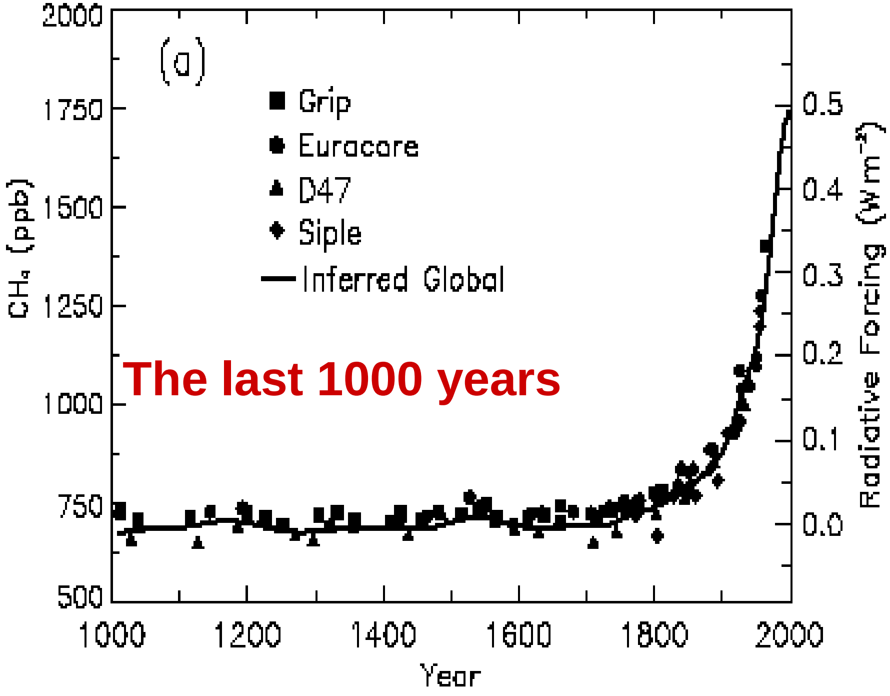
Global 2005 anthropogenic methane emissions (EDGAR inventory): US accounts for only ~10%

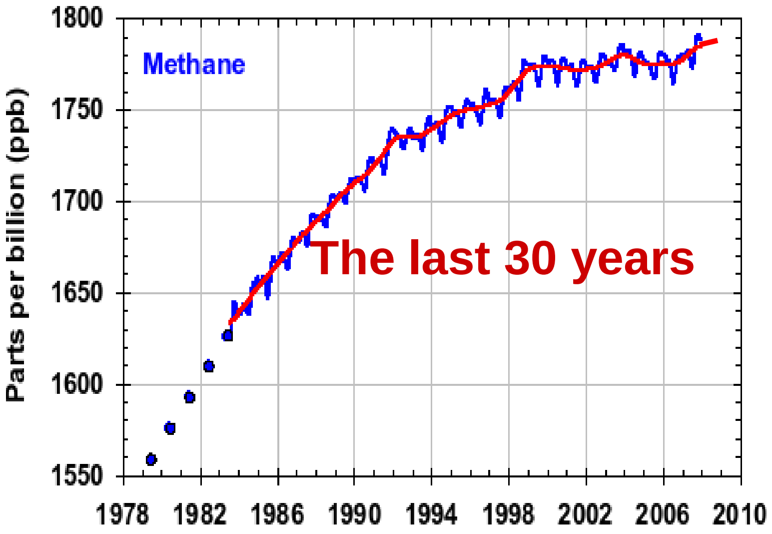


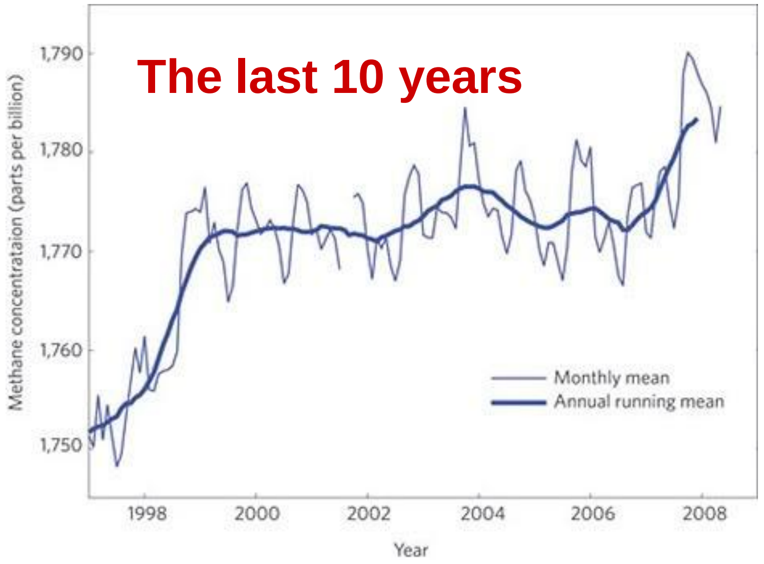
Source: EC-JRC/PBL. EDGAR version 4.0. http://edgar.jrc.ec.europa.eu/, 2009

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

Better understanding of methane trends is needed to justify an emissions control strategy


The last 1000 years


The last 30 years

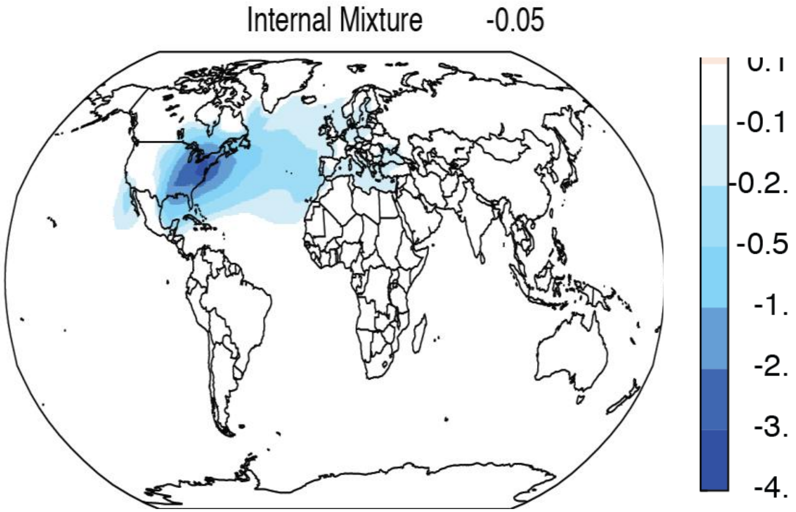

The last 10 years

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

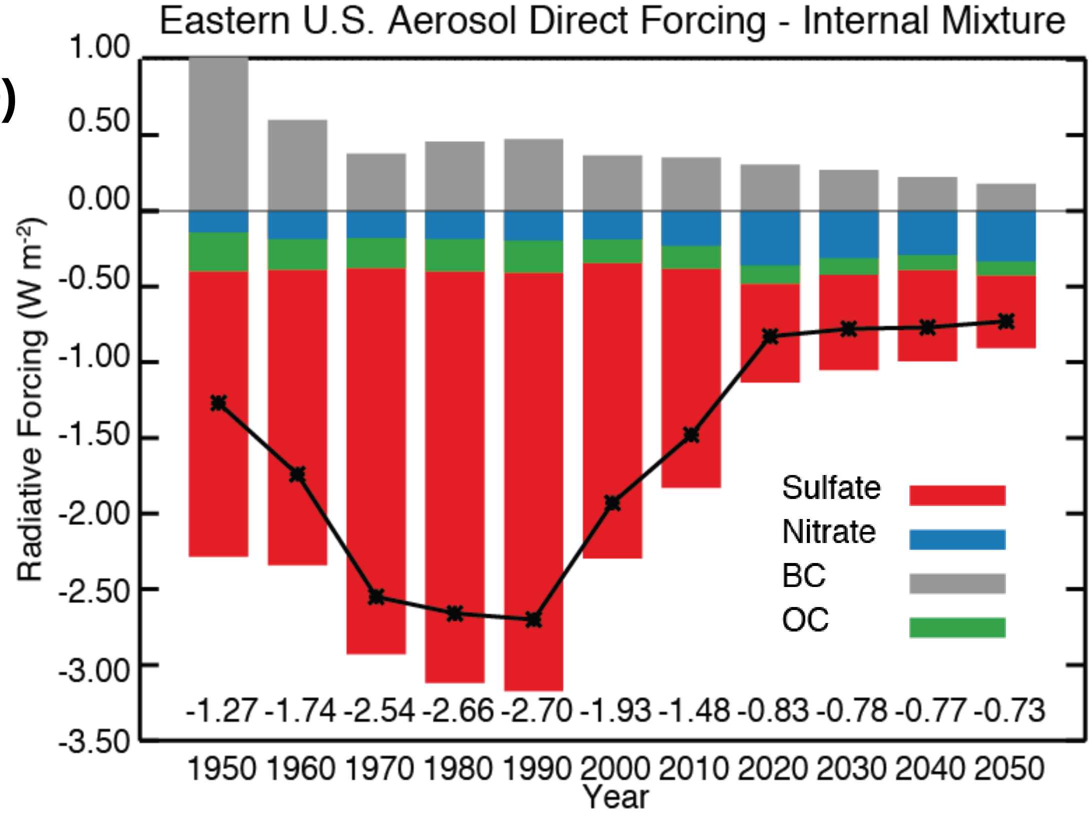
Radiative forcing from US anthropogenic PM

GISS+GEOS-Chem GCM-CTM

2000 direct radiative forcing (W m^{-2})



1950-2050 trend (A1B scenario)



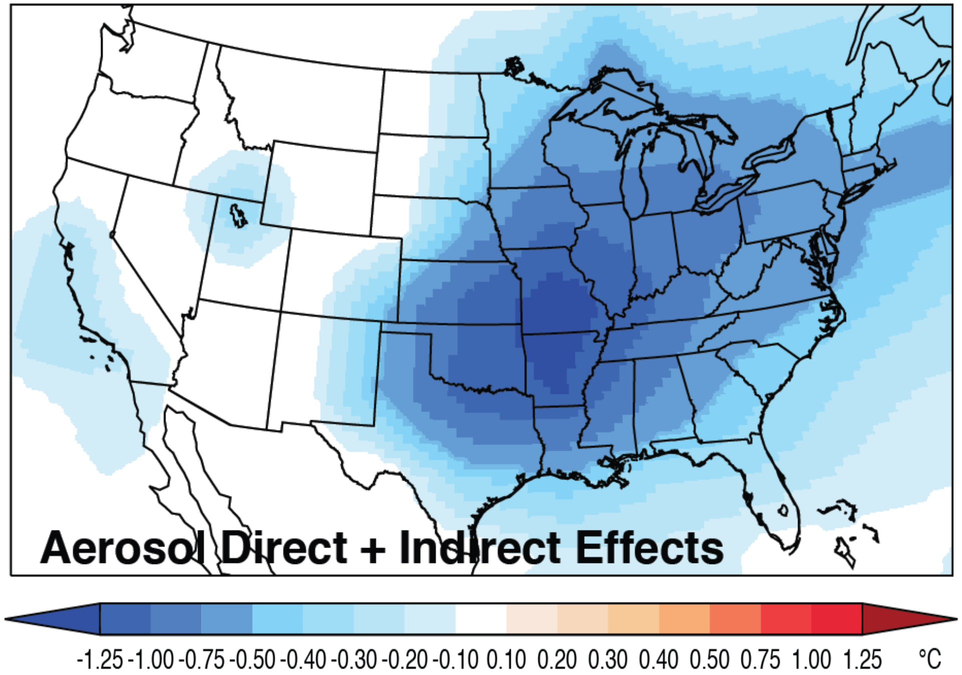
- **Maximum negative radiative forcing in 1970s-1990s driven by SO_2 emissions**
- **Little future leverage to be had from BC**
- **Role of OC is very uncertain**

Leibensperger et al. [2010]

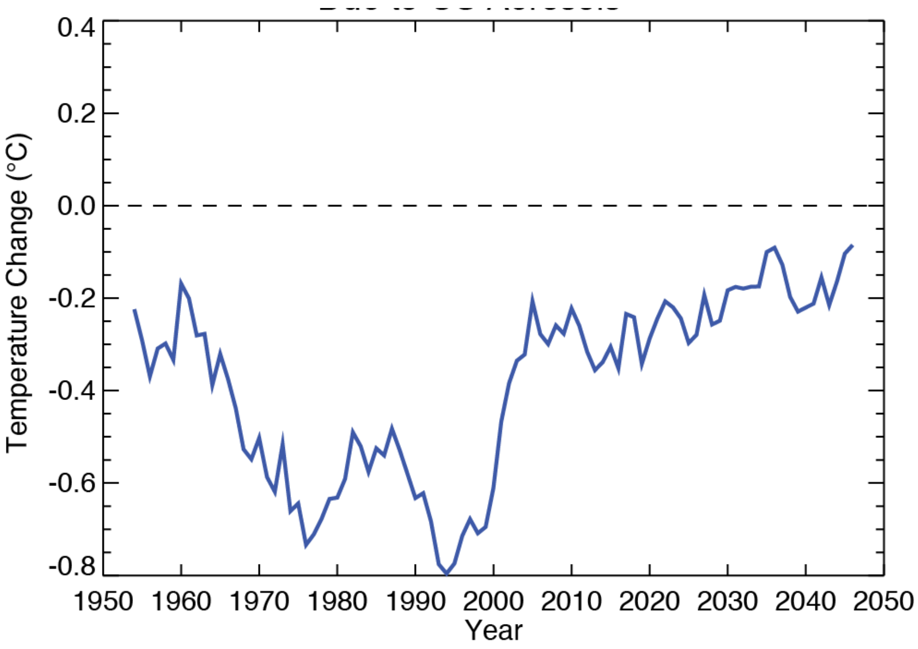
Surface cooling from US anthropogenic PM sources

Figures show cooling patterns in GISS GCM relative to climate simulation without US anthropogenic PM sources

Spatial pattern of cooling for 1975-1999



Cooling in eastern US for 1950-2050



- **During the period of maximum PM (1970s-1990s), the model estimates a 0.65^{o}C mean cooling over eastern US**
- **Emission decreases in past and coming decades are projected to remove this cooling shield**

Leibensperger et al. [2010]