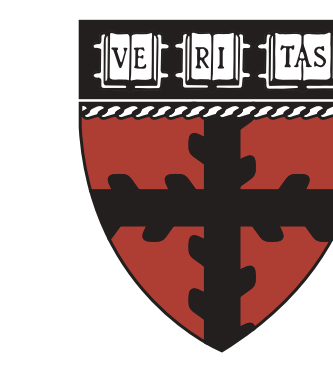


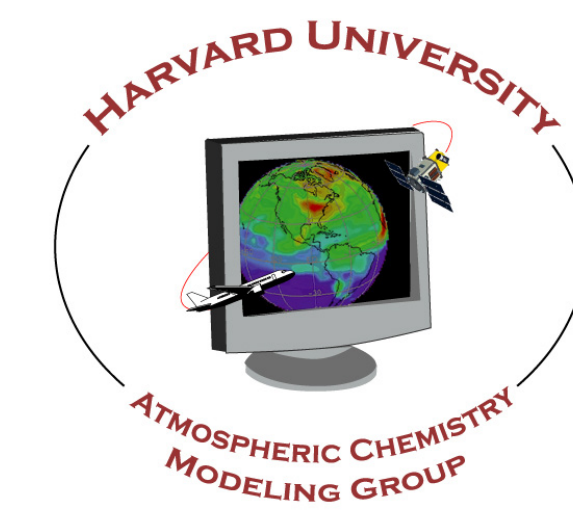
Climate Response to 1950-2050 US Aerosol Trends

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ABSTRACT
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SUMMARY

US aerosol concentrations peaked in the 1980s and have since been decreasing due to ongoing regulation of SO₂, NO_x, organic carbon, and black carbon sources. The build-up of aerosols from US sources have caused climate effects that are undone during the reduction of anthropogenic sources designed to improve air quality.

We conduct an ensemble of global climate simulations to quantify the effects of US aerosol sources over the 1950-2050 period. Multiple simulations are conducted to isolate the aerosol direct and indirect effects of US sources. Our simulations allow us to identify the role US aerosol sources have had on recent climate change and the effects of emission reductions.

We find that the aerosol direct and indirect effects of US aerosols cooled the eastern US by an average of 0.7°C

in the annual mean during 1975-1999. The cooling is largest in the summer and autumn, when it reaches more than 1.0°C. Spatially, the largest amount of cooling occurs in the central US, west of the region of highest aerosol concentrations. This cooling arises from a local hydrological feedback.

Aerosol cooling extends throughout the Northern Hemisphere, but the magnitude is largely collocated with the radiative forcing pattern. Cooling occurs beyond the US and North Atlantic, but it is generally not statistically significant above interannual variability.

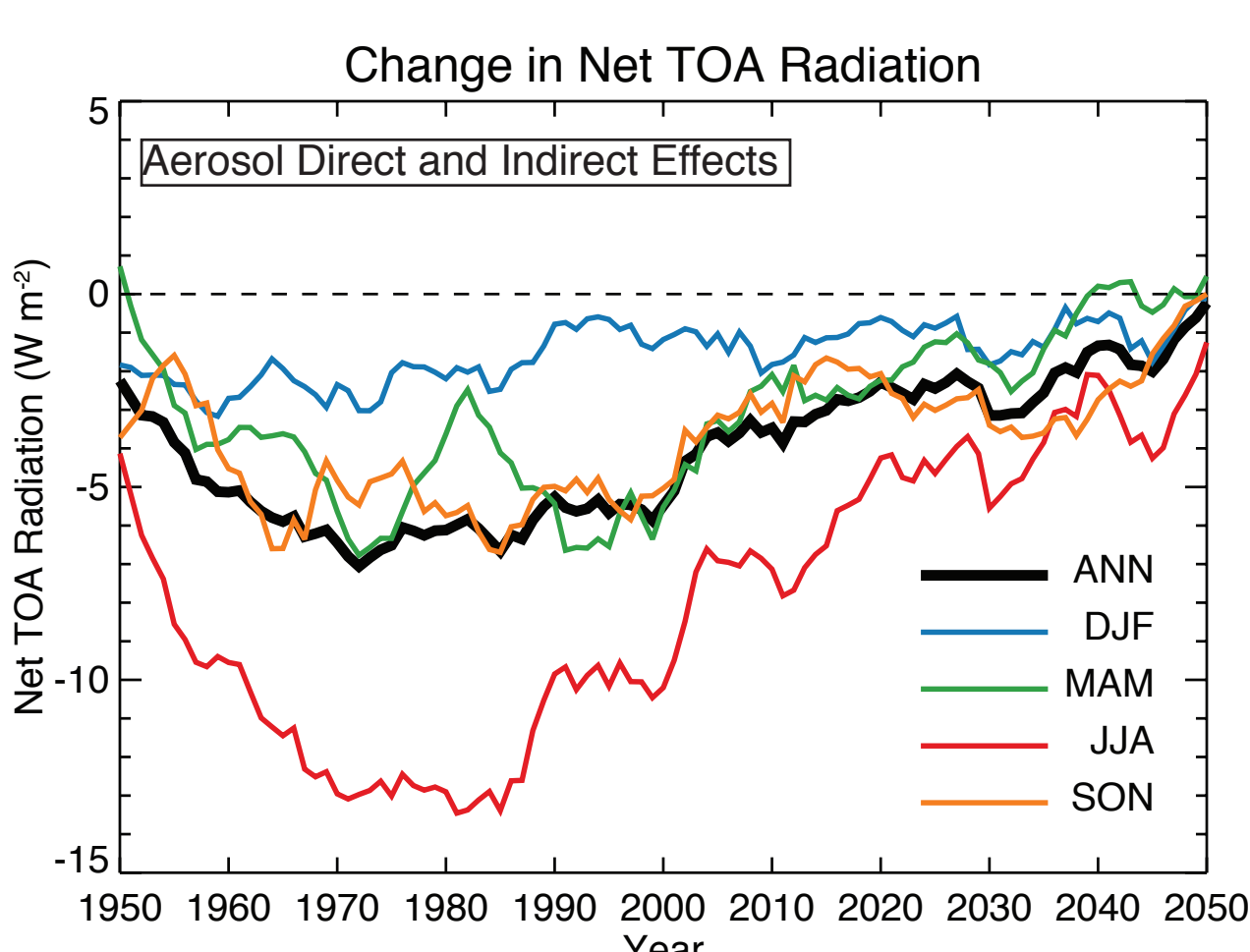
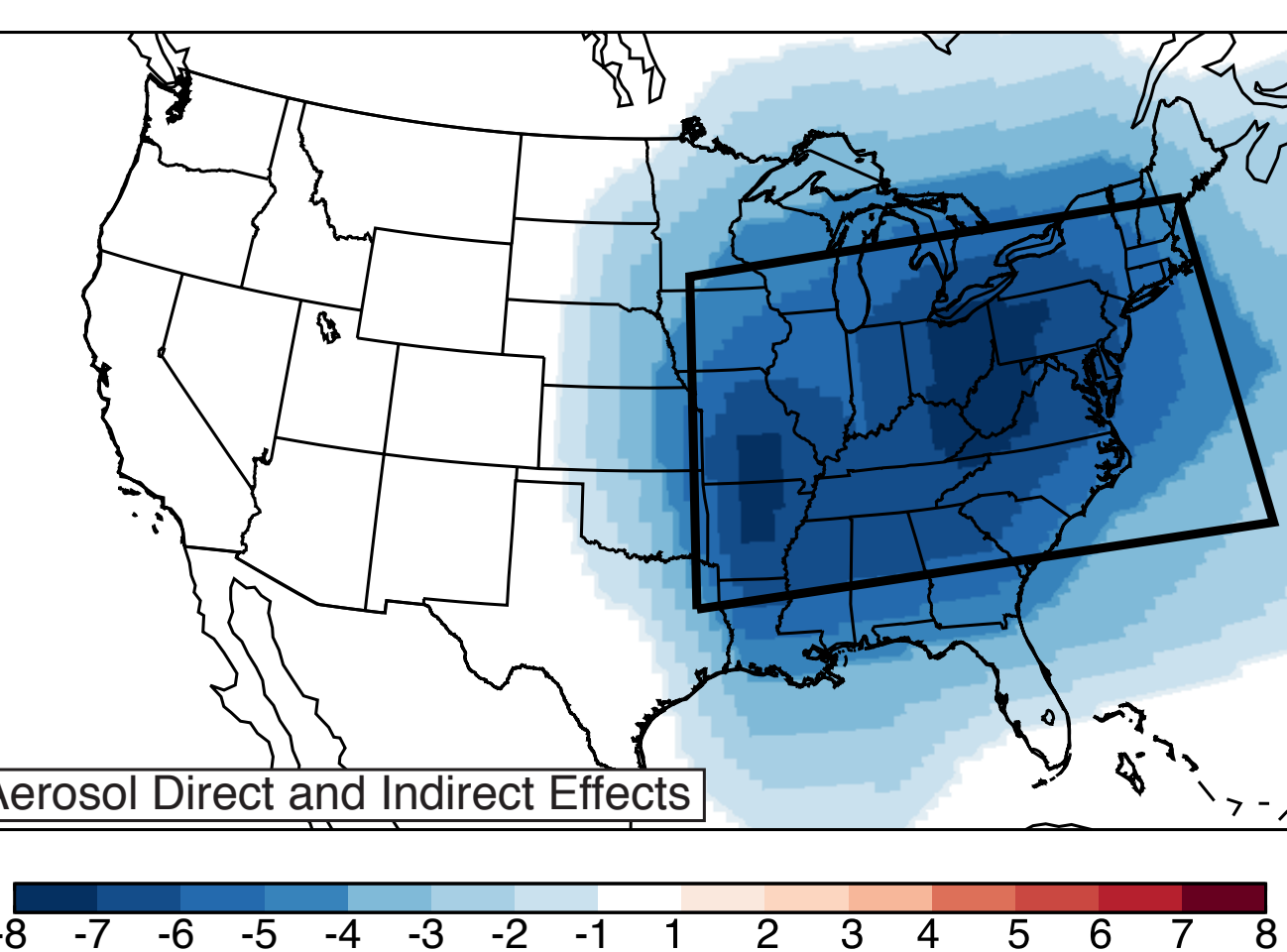
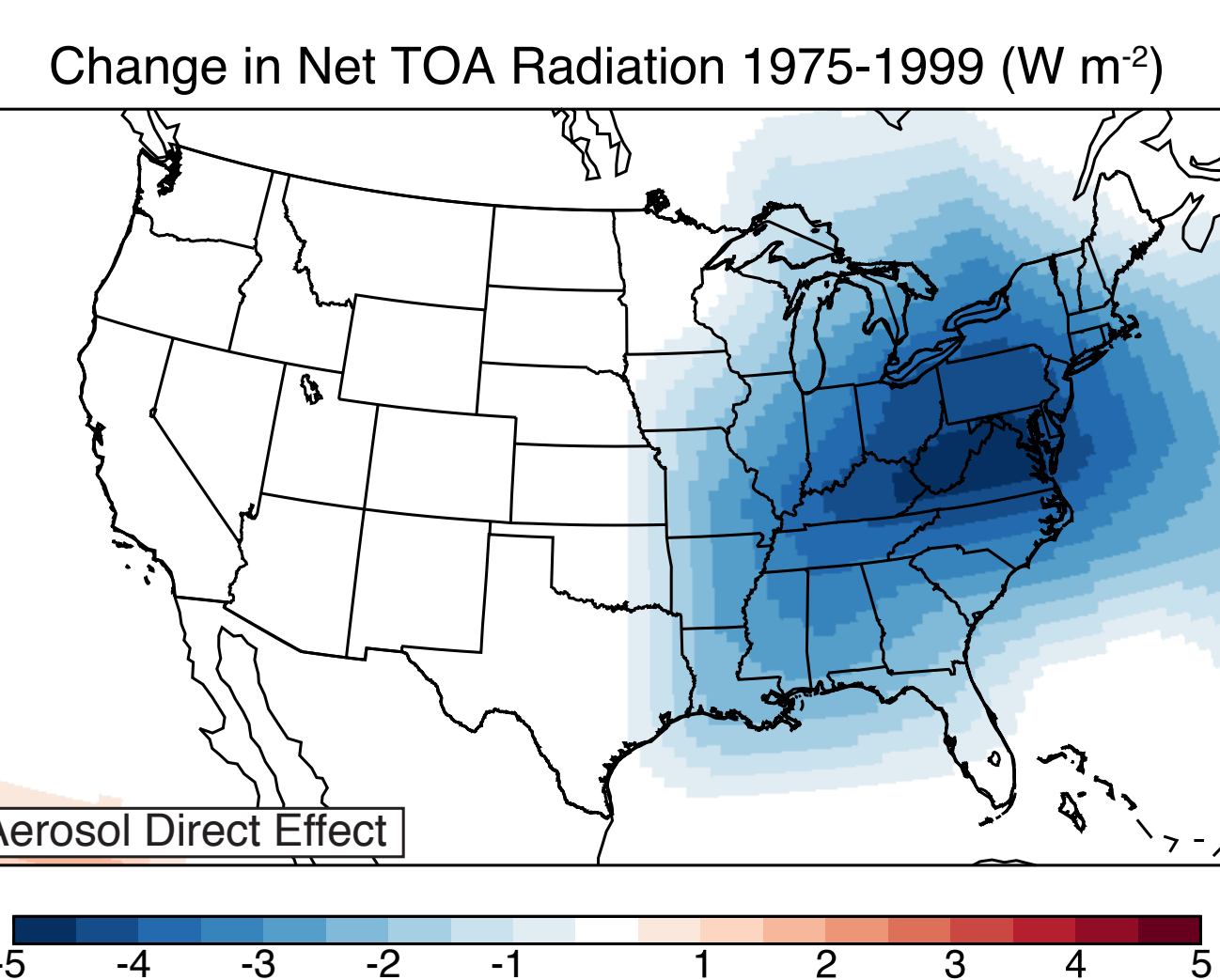
Our simulation without US aerosol sources overestimates the observed warming across the US between 1960 and 2009. The control simulation is more successful between 1960 and 1990, but overestimates the subsequent warming.

1. Radiative Forcing from US Aerosols

We evaluate the effects of US aerosol sources by conducting simulations with GEOS-Chem, a chemical transport model with coupled aerosol-gas phase chemistry, and the Goddard Institute for Space Studies General Circulation Model 3 (GISS GCM 3) [Rind et al., 2007, Chen et al., 2010].

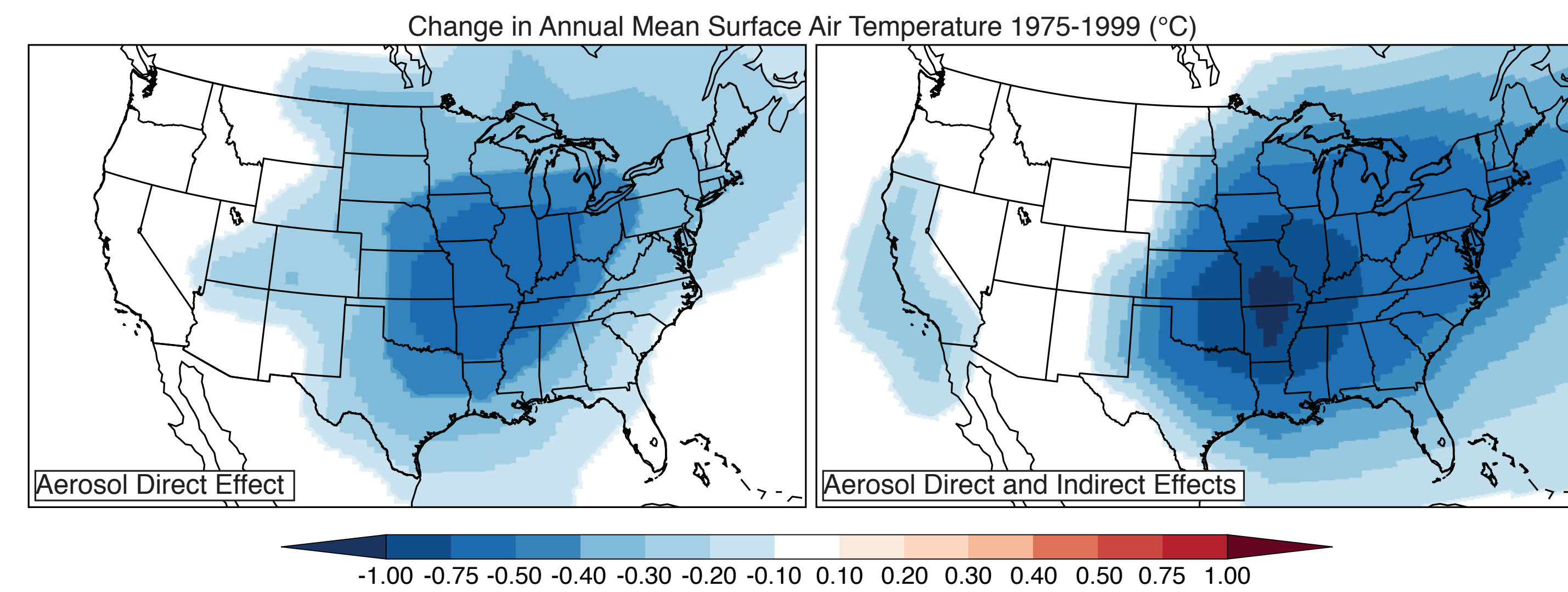
Aerosols are generated with decadal resolution by GEOS-Chem using historical and future emissions based on the IPCC SRES A1B. Aerosol and offline derived cloud droplet number concentration fields [Chen et al., 2010] with and without US anthropogenic sources are used within GISS GCM 3 to isolate the direct and indirect effects of US sources.

US aerosol sources provide radiative forcing primarily in the eastern US through the aerosol direct (right, top) and indirect effects (right, bottom).

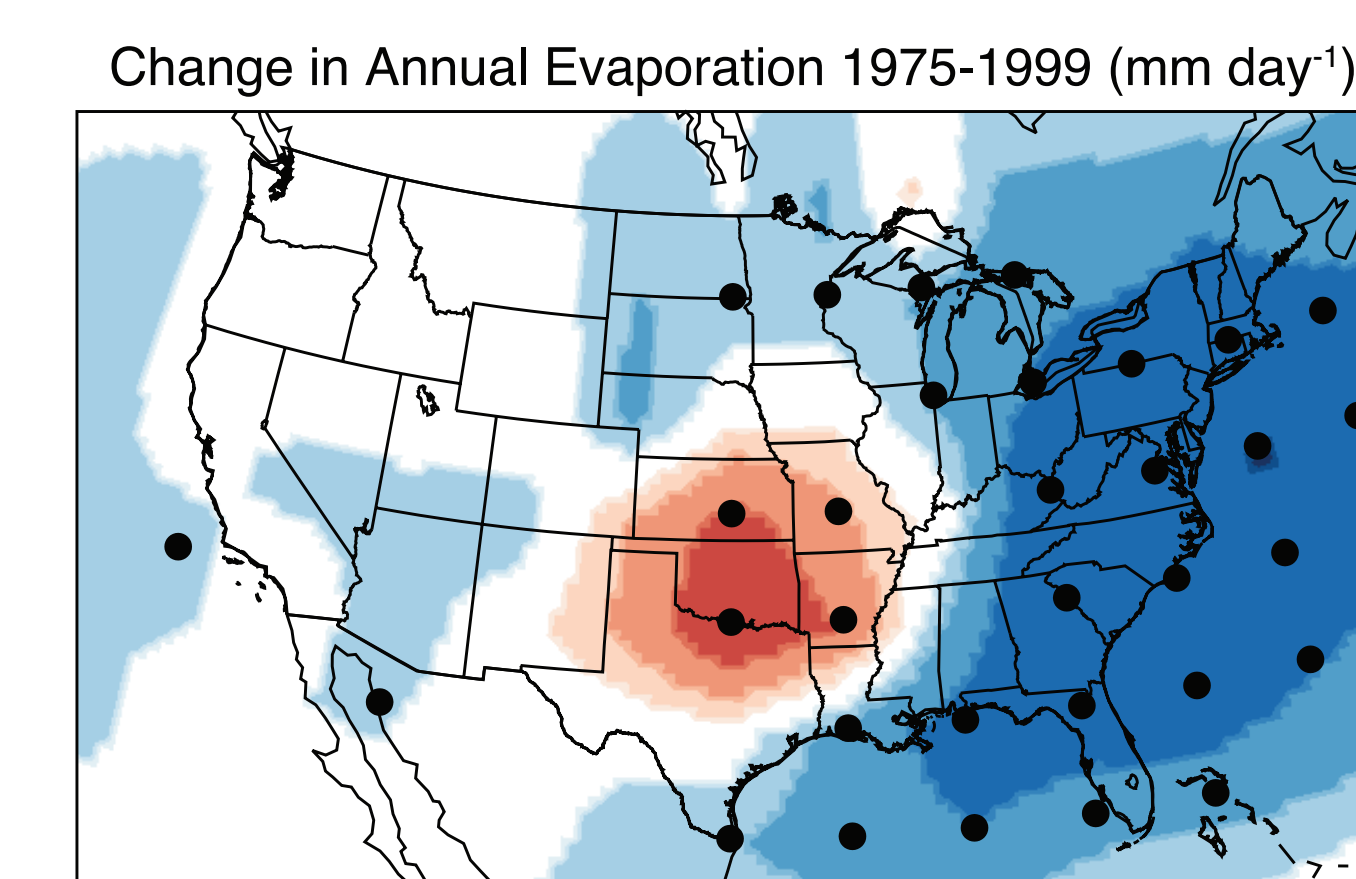


The figure to the left shows the top of the atmosphere (TOA) aerosol radiative forcing averaged over the highlighted domain above. The forcing largely follows SO₂ emissions. Radiative forcing is largest in the summer when aerosol concentrations and insolation are at their strongest.

2. Climate Response to US Aerosols

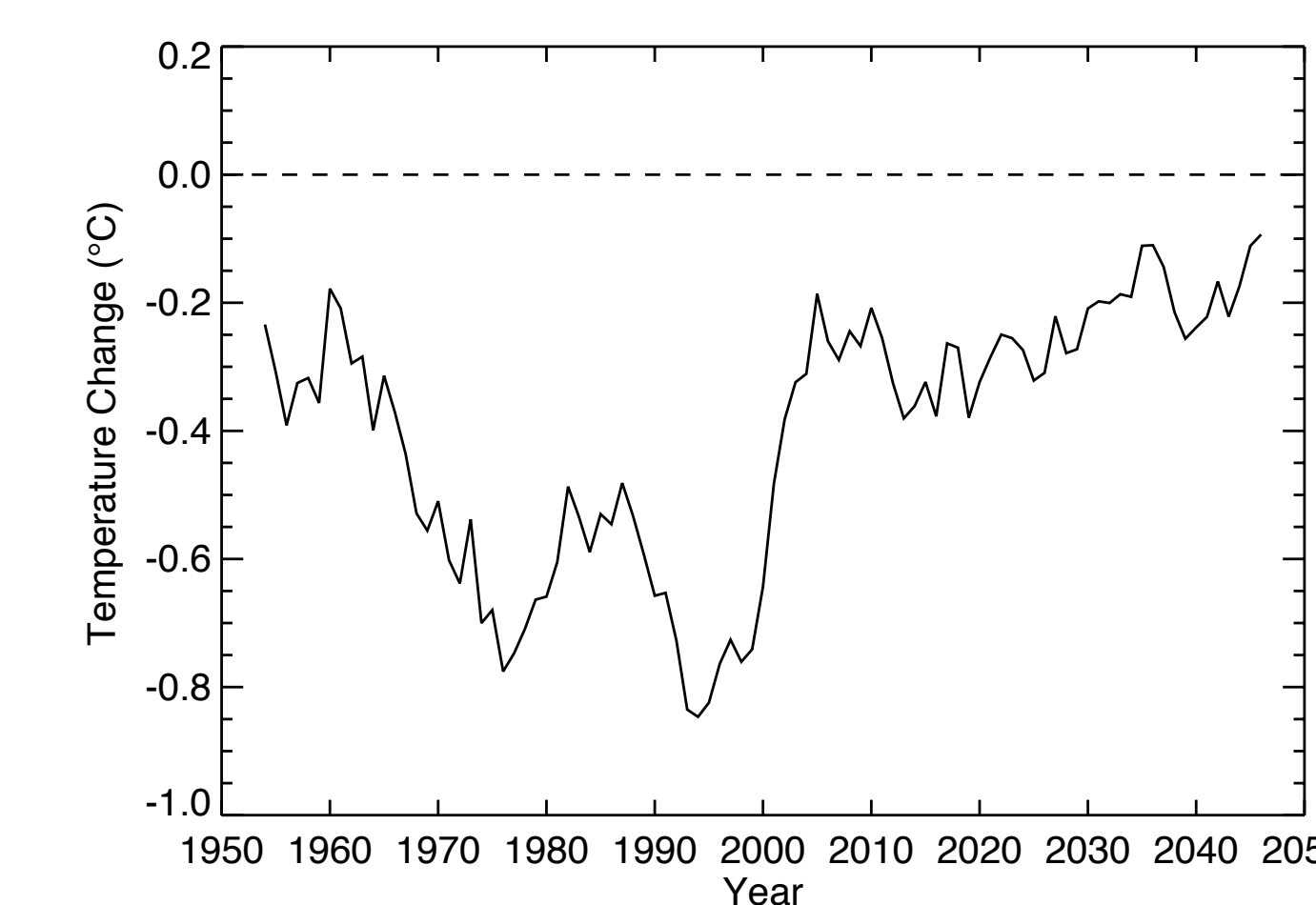


The figure above shows the change in annual mean surface air temperature due to the aerosol direct effect (left) and aerosol direct and indirect effects (right) averaged over 1975-1999, the period of peak aerosol forcing. The two have similar spatial patterns. Temperatures are lowered by more than 0.5°C along the East Coast, but cooling in the central US reaches more than 1.0°C. Cooling is strongest in summer and autumn when temperatures in the central US are lowered by up to 1.25°C.



The figure to the left shows the change in annual mean evaporation (top) and precipitation (bottom). Dots indicate differences significant at the 95th percentile. Reduced surface insolation decreases evaporation rates across much of the eastern US. A compensating decrease in precipitation occurs over the Atlantic Ocean.

Conversely, evaporation and precipitation rates increase in the central US. This results from stronger southerly flow from the Gulf of Mexico. The anomalous flow brings additional moisture to the central US, enhancing cloud cover, precipitation, soil moisture, and evaporation. The increased cloud cover and strengthened latent heat flux cause the large cooling in the central US noted above.



The figure to the right shows the evolution of the effects of US aerosols on the eastern US. Following the trend in emissions and radiative forcing, aerosol cooling increases from 1950 until the mid 1990s.

Afterwards, aerosol cooling is diminished and realized as a warming trend, which acts in addition to the warming from the well-mixed greenhouse gases. Between 1990 and 2050, an additional 0.5°C of warming can be expected due to aerosol reductions through regulation.

Acknowledgements:

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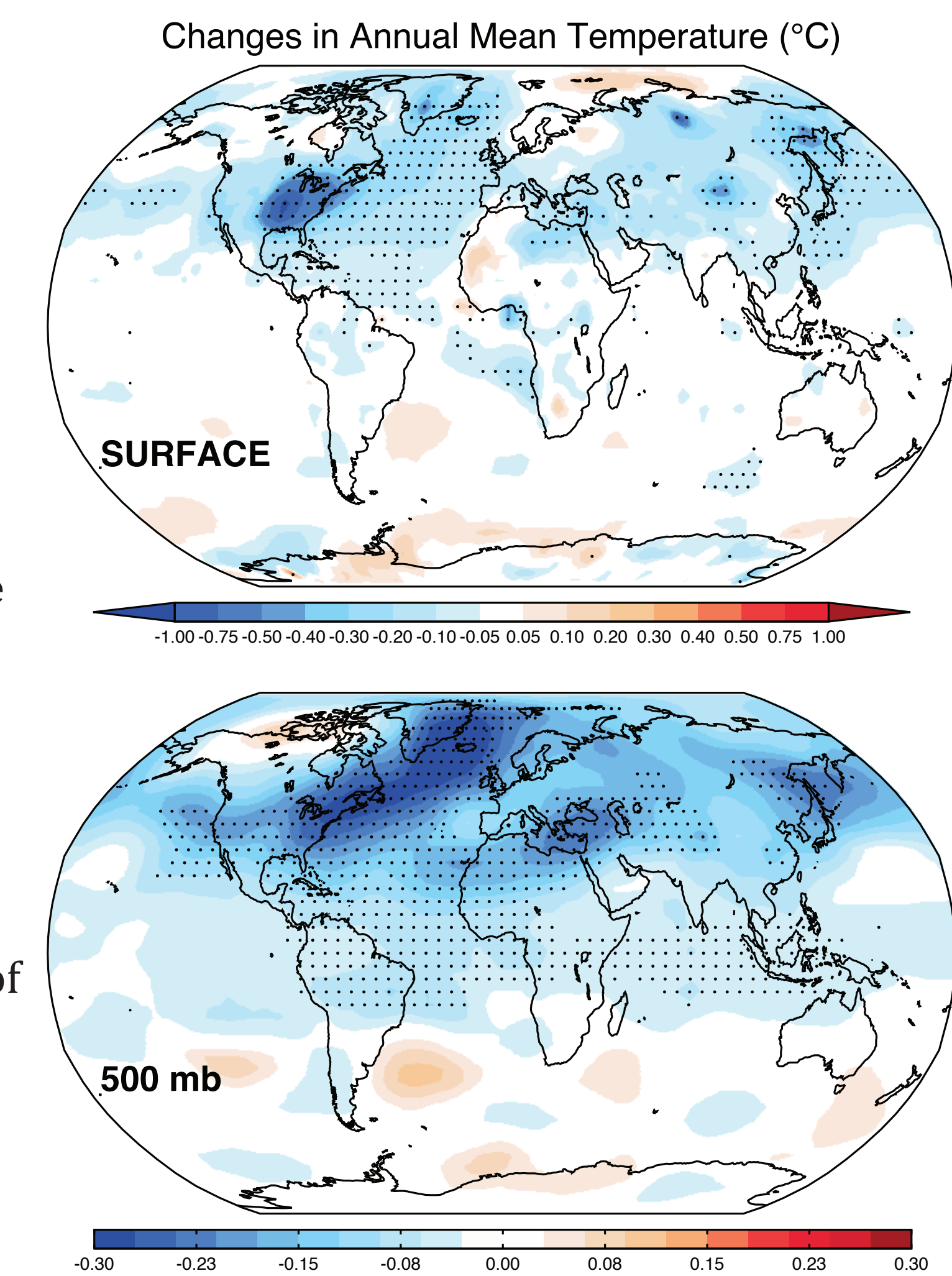
3. Effects Outside of the US

The figure to the right shows the change in annual mean temperature at the surface (top) and 500 mb (bottom). Dots indicate changes that are significant at the 95th percentile.

At the surface, cooling is widespread throughout the Northern Hemisphere, but the areas with statistically significant changes are largely within the US and North Atlantic Ocean. The temperature response is thus correlated to the forcing pattern. This result is in contrast to some previous studies, which concluded that aerosol forcing and temperature response are not correlated (CCSP, 2008; Levy et al., 2008; Shindell et al., 2008). We can reconcile the difference by realizing these studies applied changes in aerosols worldwide, which amplifies the response in remote regions. Our localized sensitivity to US aerosols, however, remains a point of contrast.

Away from the surface, at 500 mb, the cooling is more widespread and the area with statistically significant changes increases. The region of largest cooling

at this level is downwind of the US in a location sensitive to the outflow of heat and moisture from the US.



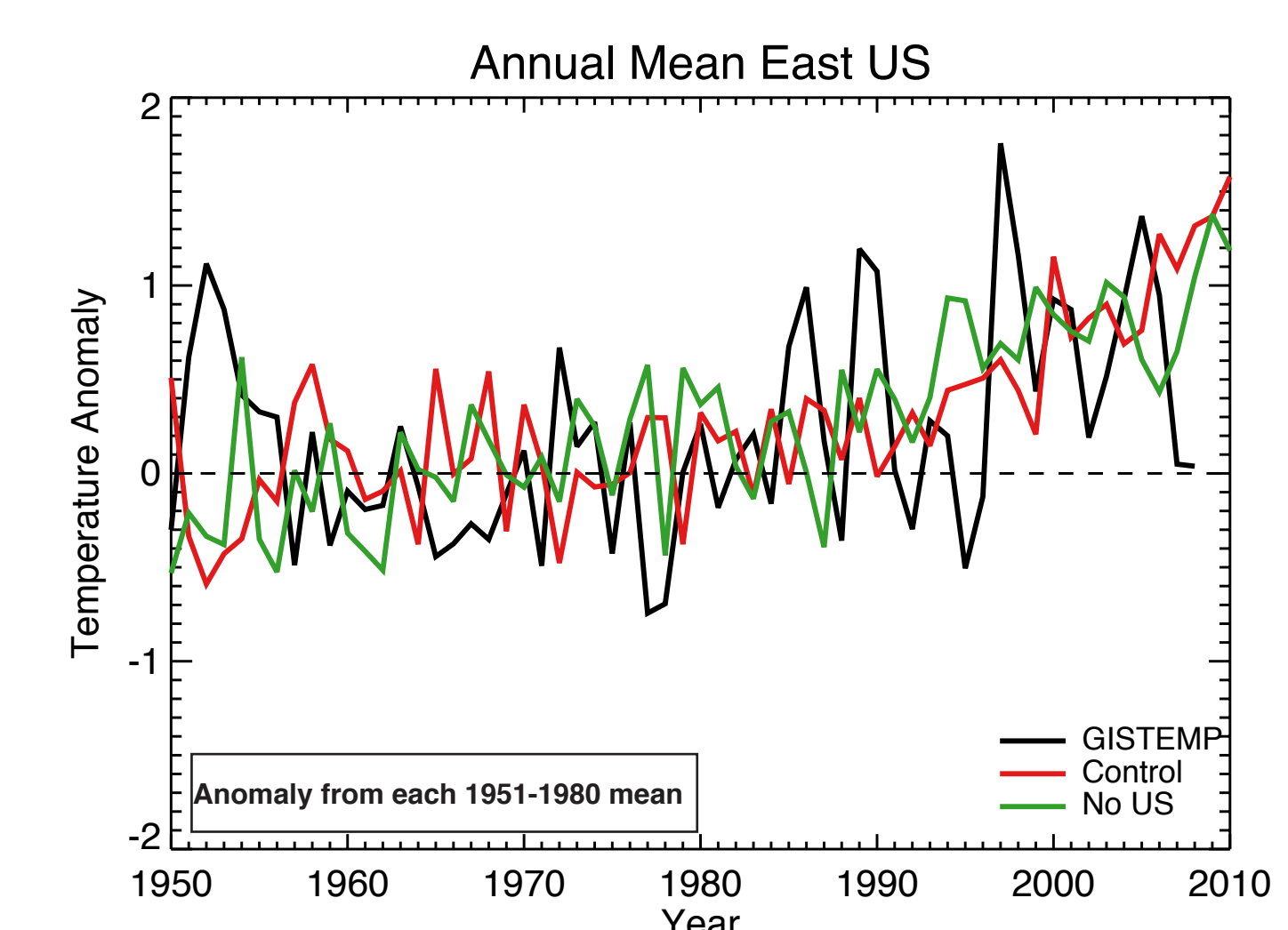
4. Comparison to Observed Trends

The figure to the right shows the observed trend in surface air temperatures averaged over the eastern US (black line; same region as in previous sections). The observations are from the NASA GISS Surface Temperature Analysis (GISTEMP).

The observations show little trend between 1960 and 1980. Our simulations without US aerosols (green line) reveal a large warming trend of +0.27°C dec⁻¹. The control simulation (red line), which includes an increasing amount of aerosol radiative forcing during this period, is able to better represent this period.

After 1980, observations indicate an increasing trend of +0.20°C dec⁻¹.

Annual Mean Temperature Trend (°C dec ⁻¹)		
	1960-1979	1980-2009
Obs. (GISTEMP)	-0.02	+0.20
Control	-0.01	+0.39
No US Aerosols	+0.27	+0.31



Both simulations produce trends that are too strong during this period, with the control simulation producing the largest trend.

Our simulations indicate that US aerosols are necessary to reproduce observed 1960-1980 temperature trends, but cause trends that are too steep following aerosol reduction.

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