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GFDL

Connecting regional aerosol emissions reductions to local and remote temperature and precipitation responses

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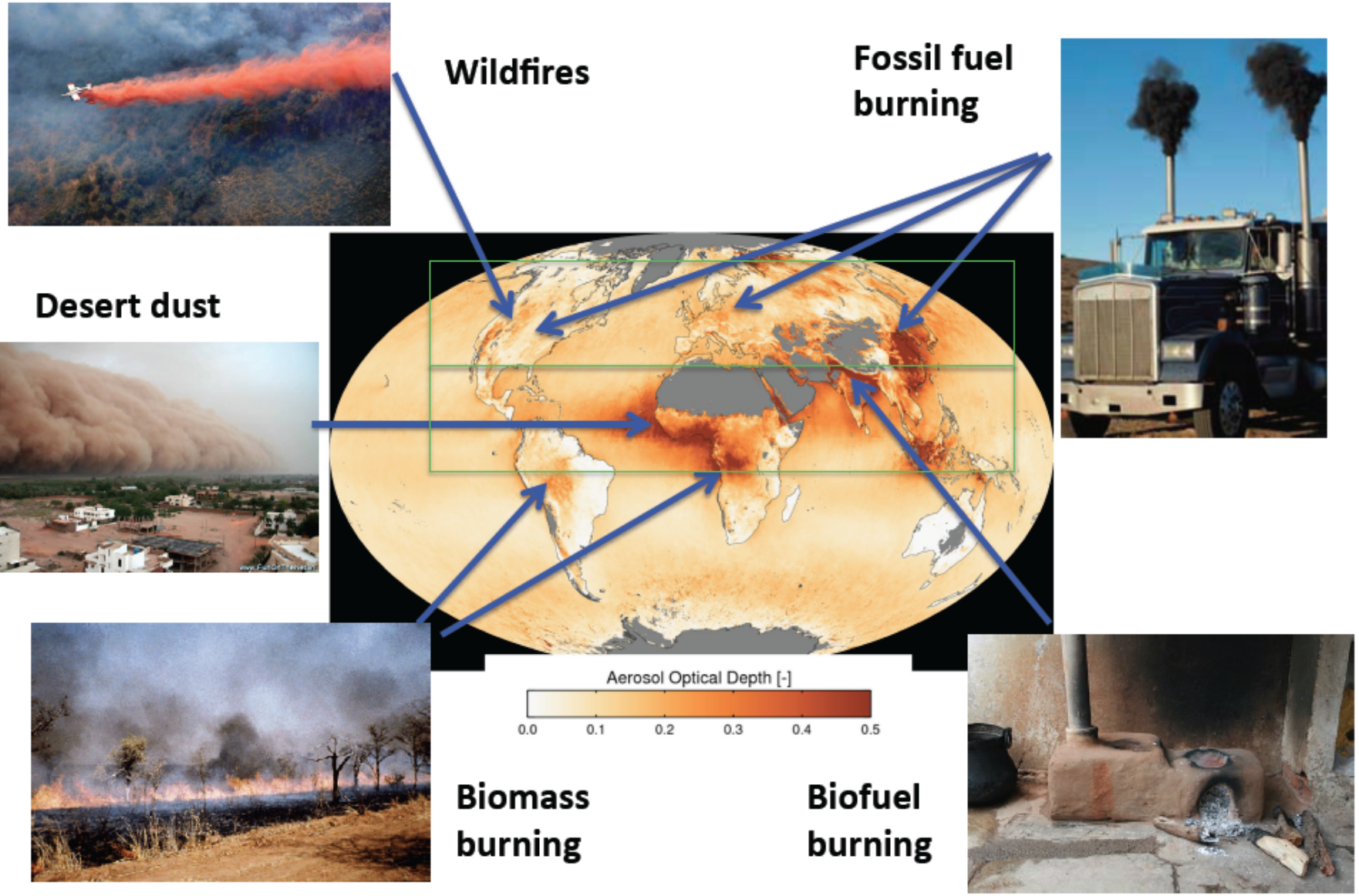
NCAR
NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

NASA

GISS lunchtime seminar
17 Oct 2018

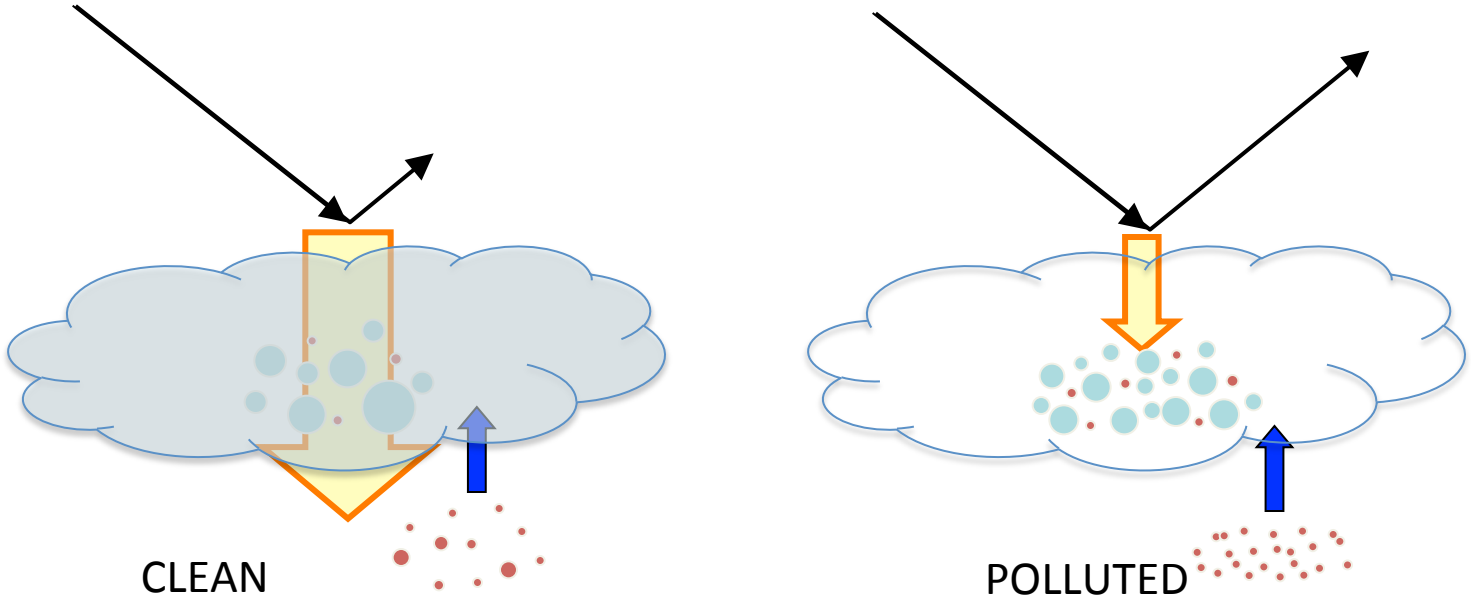
Aerosols are both emitted directly and produced from precursor gases, from natural and anthropogenic sources



Yi Ming (NOAA GFDL)

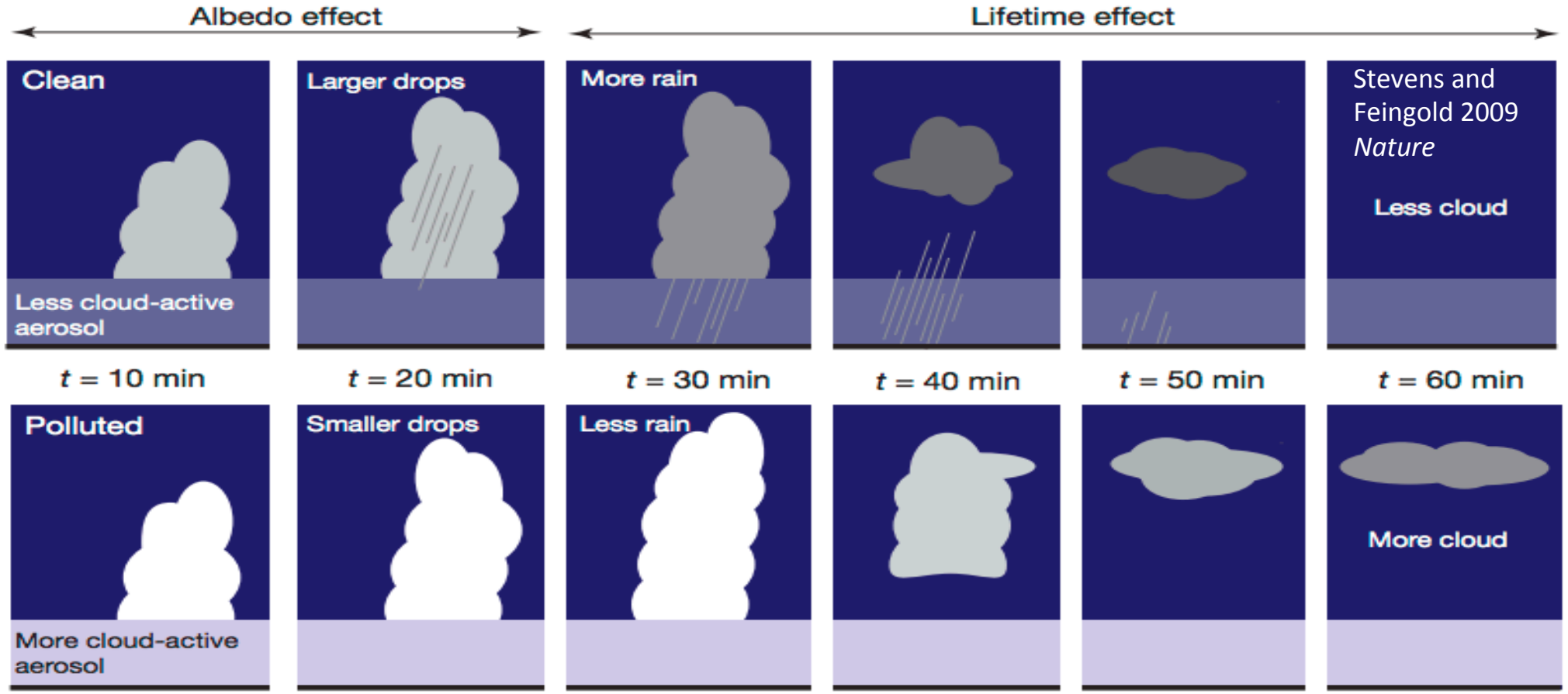
Aerosols impact climate in a variety of complex ways

- Direct effects – interaction with incoming solar radiation
- Indirect effects – modulation of cloud properties



Higher cloud droplet number concentration
Smaller cloud droplet size (effective radius)
Higher cloud albedo
Decreased precipitation/longer cloud lifetime?

Aerosols and precipitation – microphysical view



Stevens and Feingold 2009 *Nature*

Decrease in autoconversion rate
Delay of precipitation formation
Increase in cloud liquid water path (LWP) and lifetime

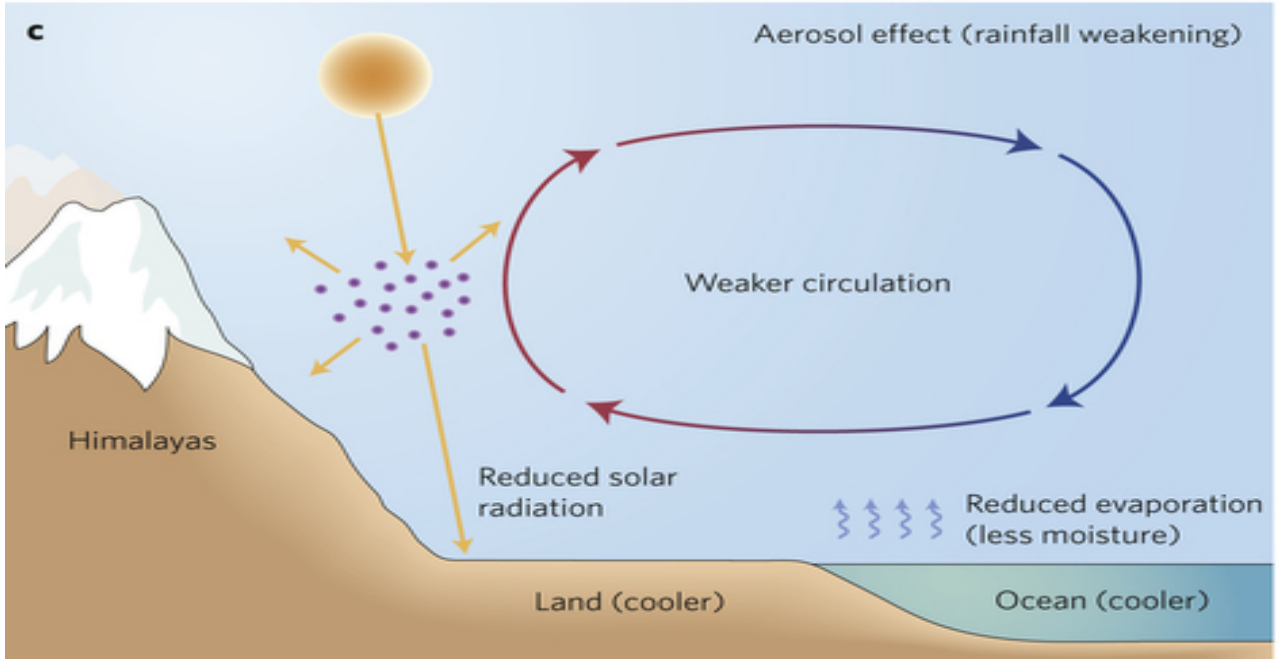
Decrease of precip with increasing aerosols

Enhanced entrainment of dry air, reducing LWP?
Invigoration of deep convection, increasing precip?

Increase of precip with increasing aerosols

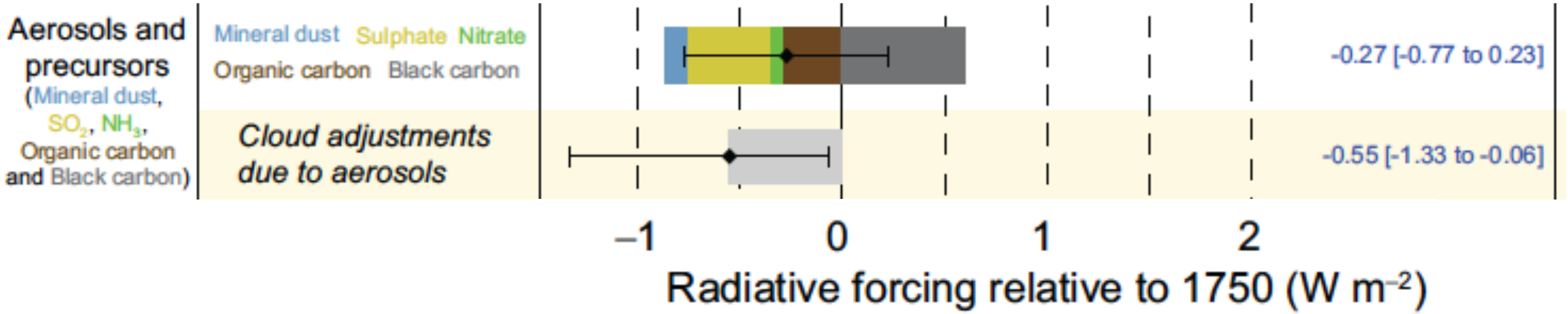
Aerosols and precipitation – large-scale dynamical view

- Aerosol extinction results in reduced surface solar radiation, thereby hindering evaporation and convection
- Results in weakened rainfall
  - Example: Asian monsoon



Singh 2015 *Nature Climate Change*

Aerosol direct and indirect radiative forcing

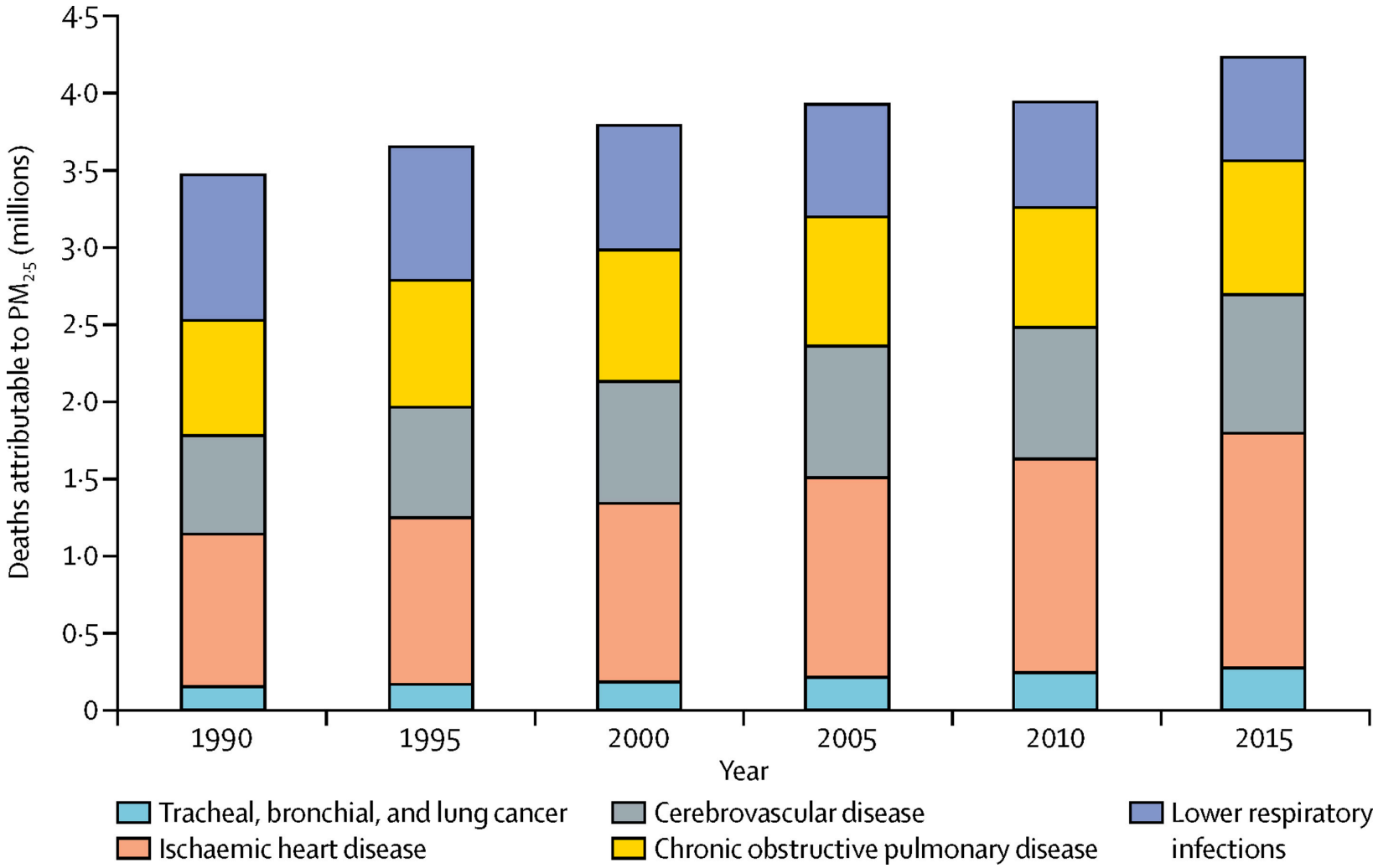


Radiative forcing = difference in energy flux absorbed by Earth and flux radiated back to space

- Aerosols most likely exert a cooling influence on present-day climate (negative radiative forcing)
- Dependence on composition: black carbon is a warming agent
- Aerosol-cloud-precipitation interactions are highly uncertain

~4 million premature deaths in 2015 globally from ambient $PM_{2.5}$

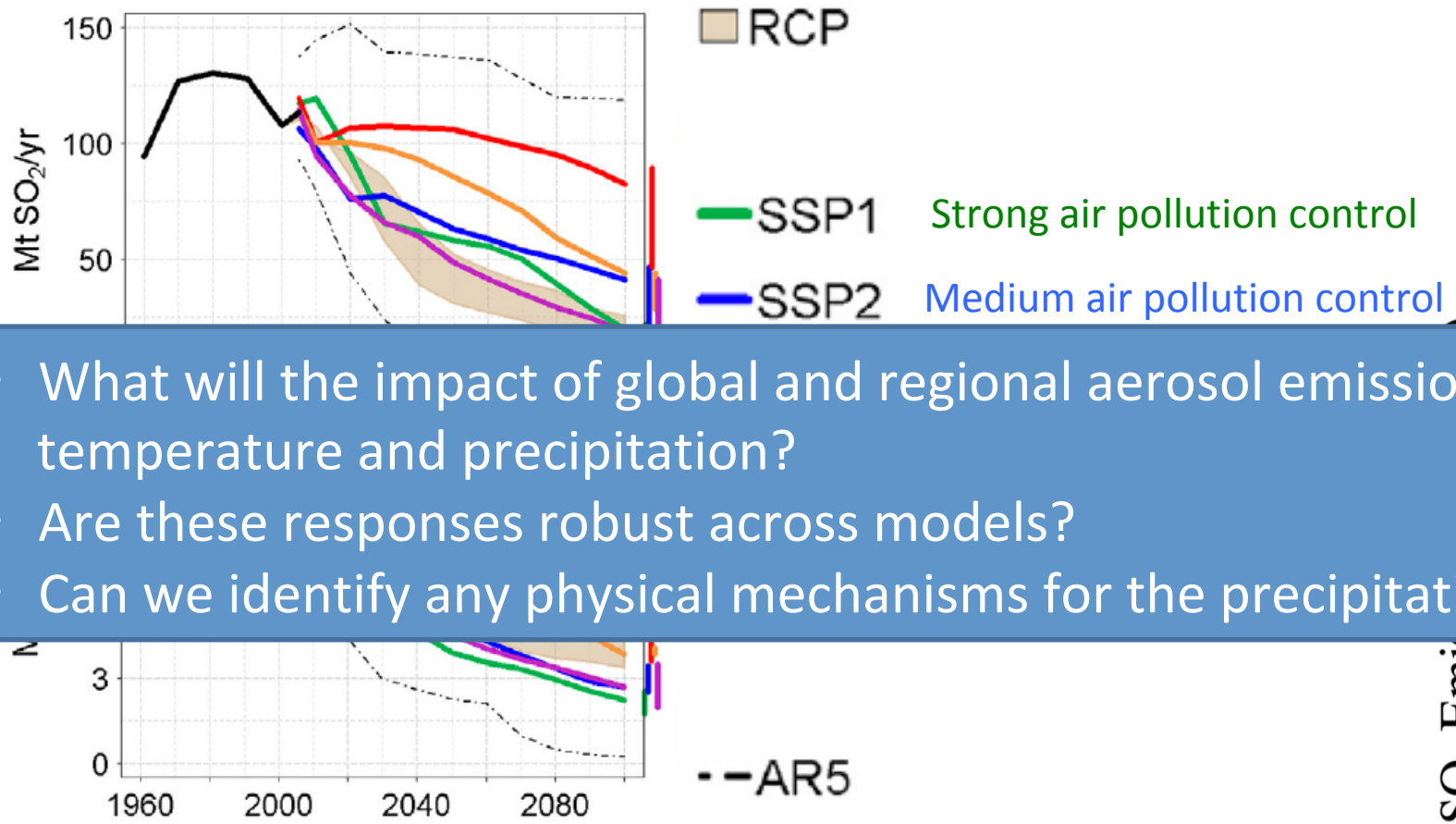
$PM_{2.5}$ – mass concentration of aerosol with diameters less than 2.5 µm



Cohen et al. 2017, *The Lancet*

Models and observations show that emissions of aerosols and their precursors are decreasing

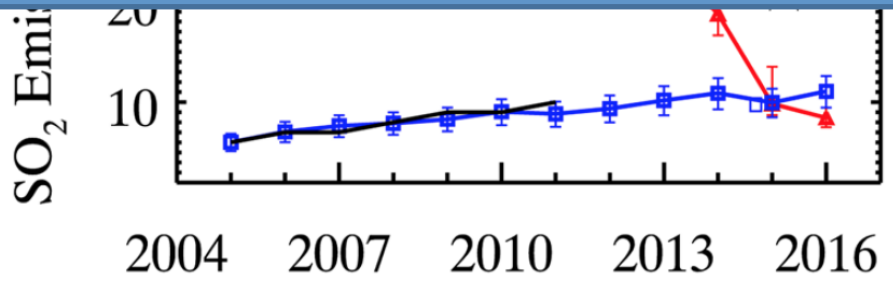
Global SO_2 and BC emissions, 1960-2100 in the SSP scenarios



Rao et al. (2017), *GEC*

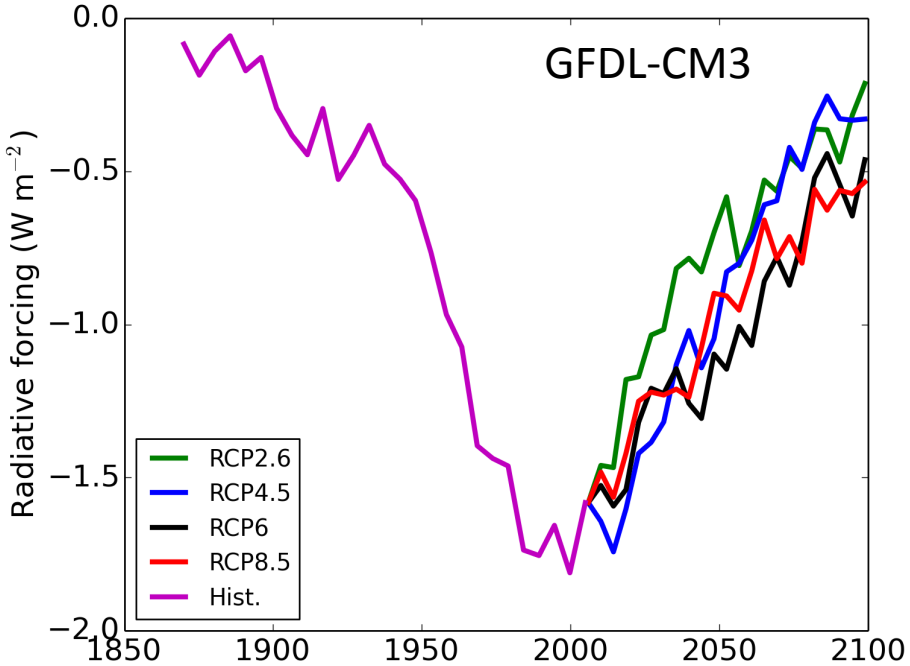
- Satellite retrievals (OMI) show that SO_2 emissions decreases are occurring in nearly all world regions including China (exception: India)

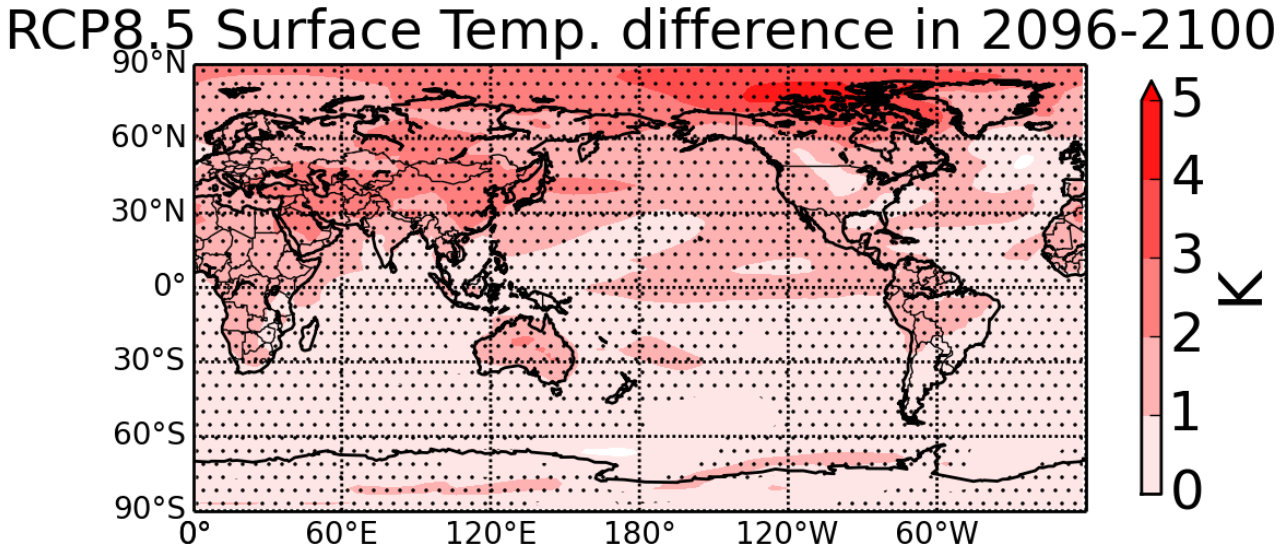
- What will the impact of global and regional aerosol emissions reductions be on future temperature and precipitation?
- Are these responses robust across models?
- Can we identify any physical mechanisms for the precipitation response?



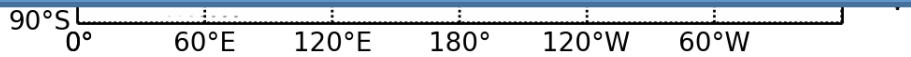
Li et al. (2017), *Sci Reports*

End of 21st century climate response to global aerosol emissions reduction is warming and precipitation increase





RCP8.5 Precip. Rate Difference in 2096-2100



Response = RCP8.5 2005AER – RCP8.5

- (Anthropogenic and biomass burning emissions

- Warming of up to 1 ºC due to aerosol emission reduction alone by 2100
- Next steps: How does the climate respond to different **regional** emissions changes? To different aerosol species?
- Physical mechanisms, robustness across multiple models?

Westervelt et al. (2015) *Atmos Chem Phys*

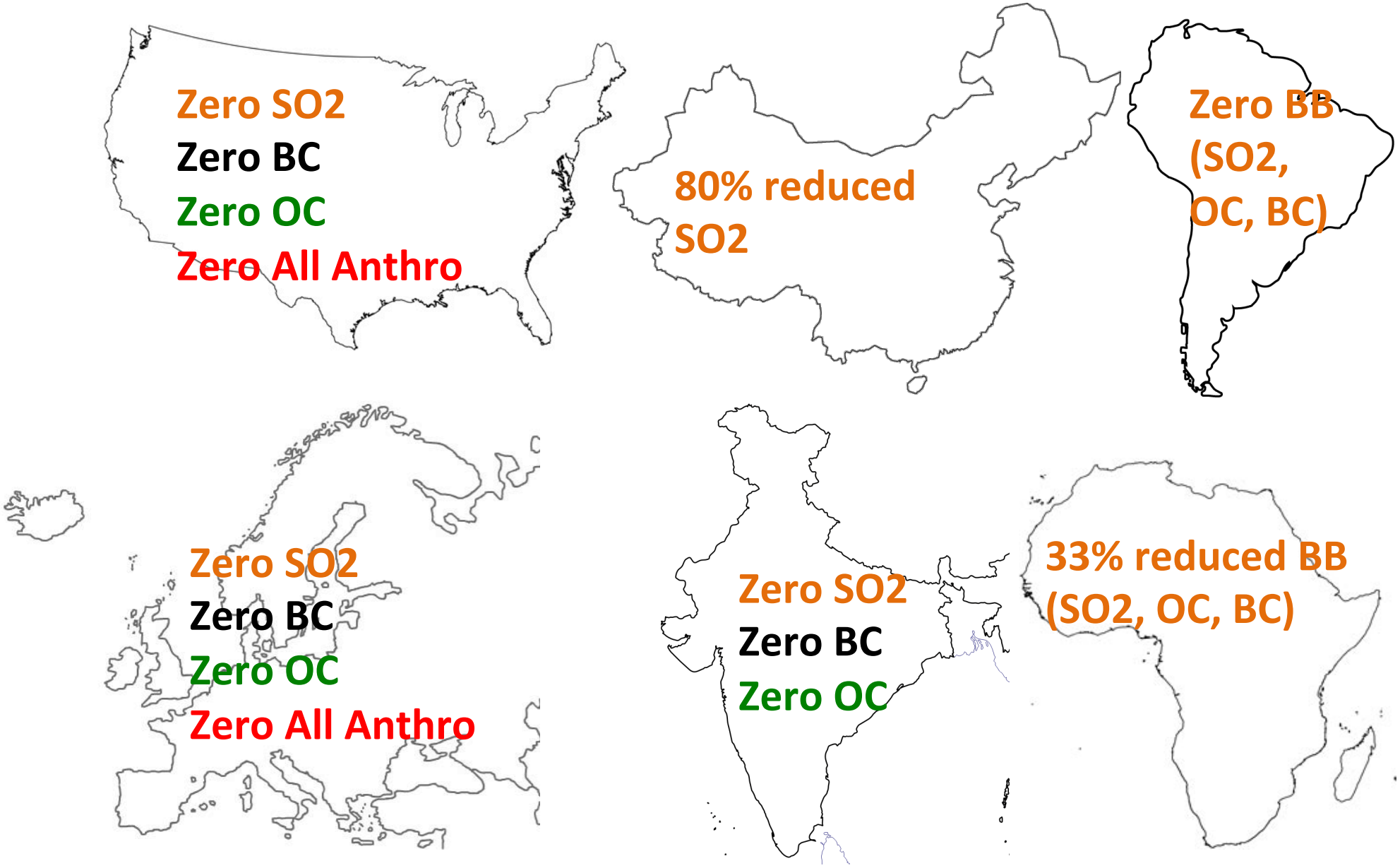
Multi- chemistry-climate model framework for assessment of robustness

- Three fully coupled chemistry-climate models (atmosphere-ocean-land-sea ice) in their CMIP5 configuration

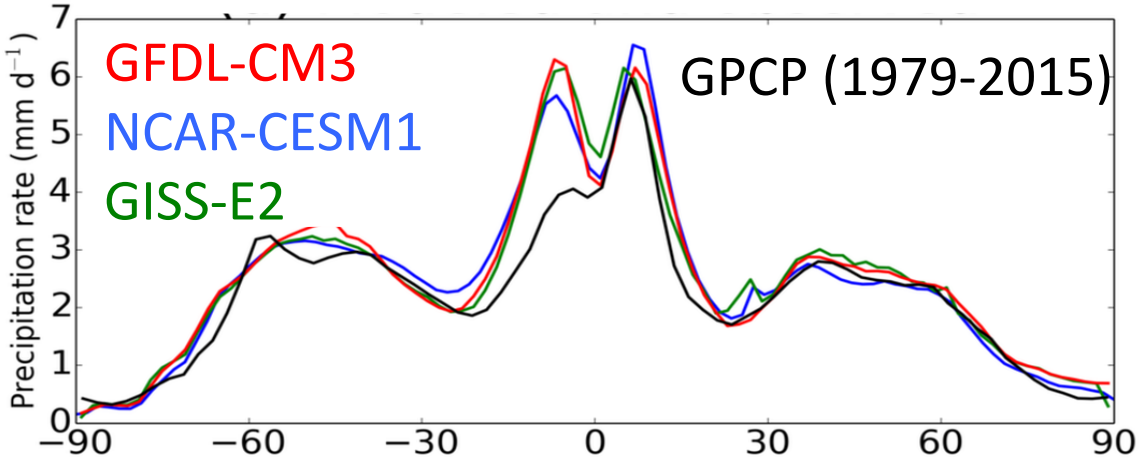
GFDL-CM3 **NCAR-CESM1** **GISS-E2-R**

- Direct and indirect effect (both) of aerosols. Exception: no cloud lifetime in GISS-E2
- Long “control” with year 2000 (2005 for CESM1) conditions
- ~200+ year “perturbation” with anthropogenic aerosol type/region set to zero (e.g. US SO_2, India BC, etc.)
- Additional “Fixed SST” simulations to quantify effective radiative forcing

A total of 34 “perturbation simulations” among all three models

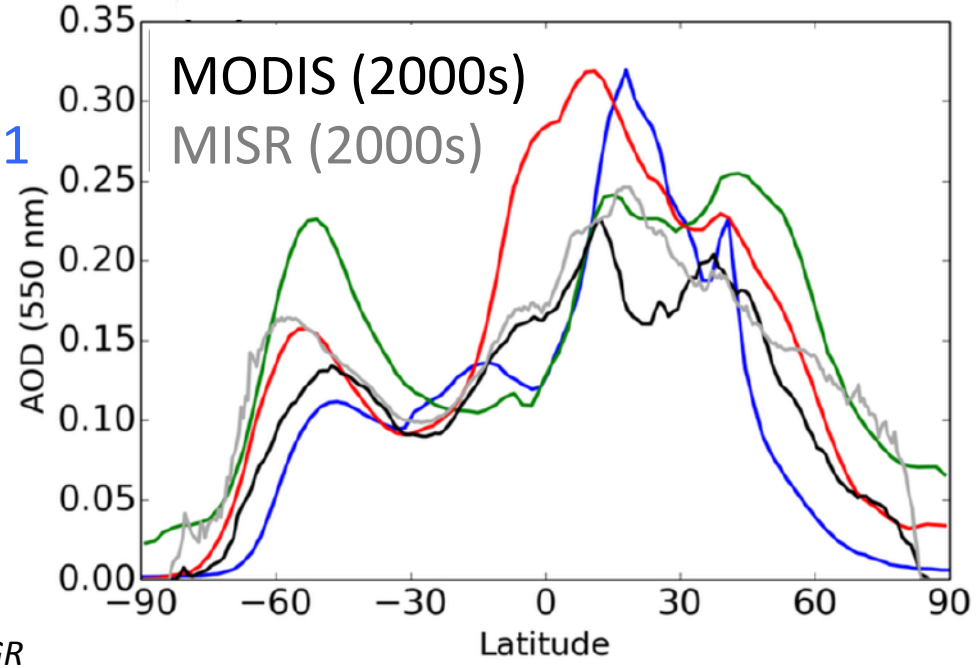


Modeled and observed observed zonal mean AOD and precipitation rate patterns (annual)



Model biases are <5% globally, except for the "double ITCZ" problem

GFDL-CM3
NCAR-CESM1
GISS-E2



Model high bias:

- 2000 vs 2001-2012 average
- Deficiencies in modeled dust and sea salt parameterizations

Westervelt et al. 2017. *JGR*

Overview of our climate response to aerosol emissions work

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Multimodel precipitation responses to removal of U.S. sulfur dioxide emissions

D. M. Westervelt, A. J. Conley, A. M. Fiore, J.-F. Lamarque, D. Shindell, M. Previdi, G. Faluvegi, G. Correa, L. W. Horowitz

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First published: 01 March 2018 | https://doi.org/10.1002/2017JD027411

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Atmospheric Chemistry and Physics
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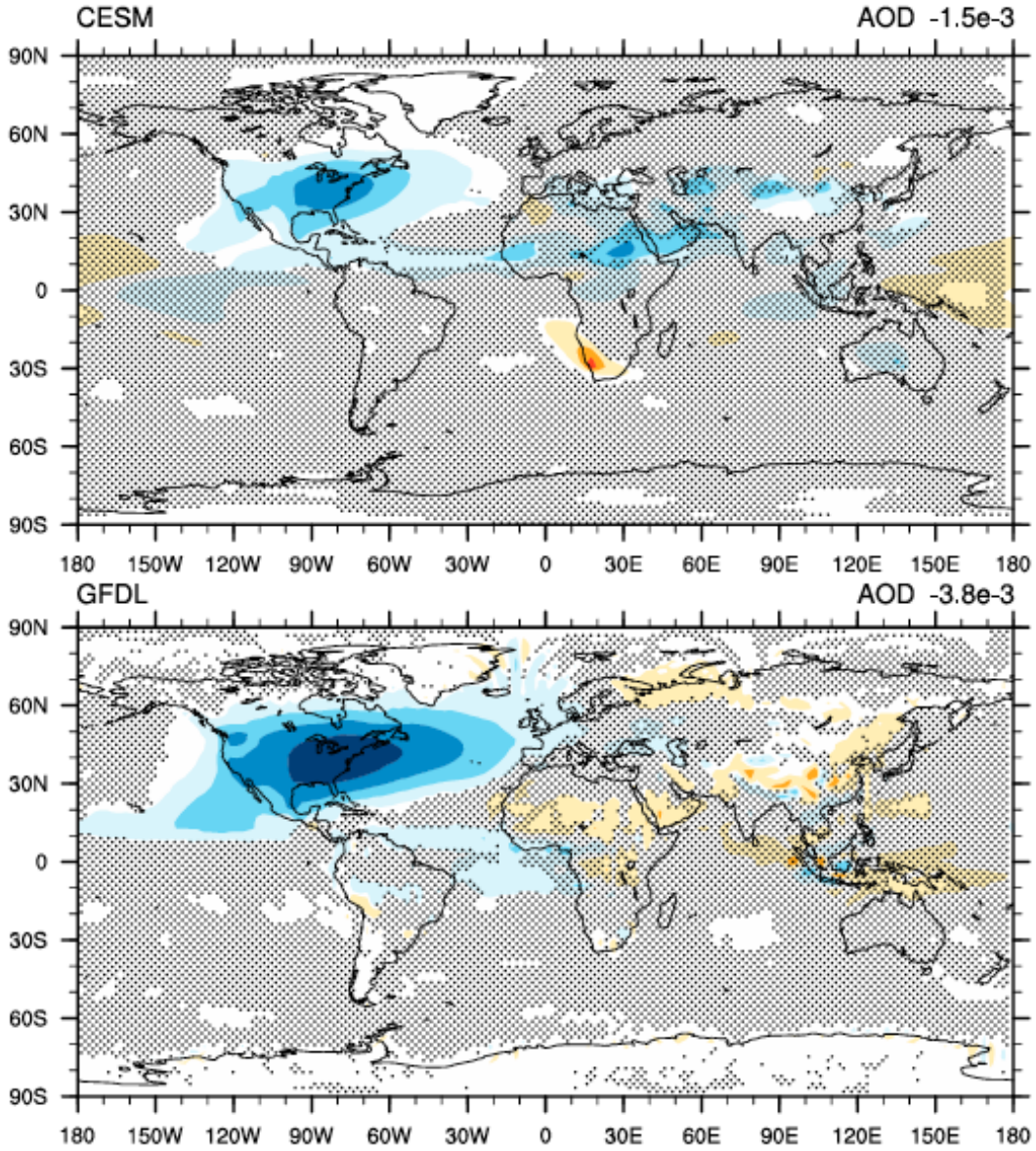
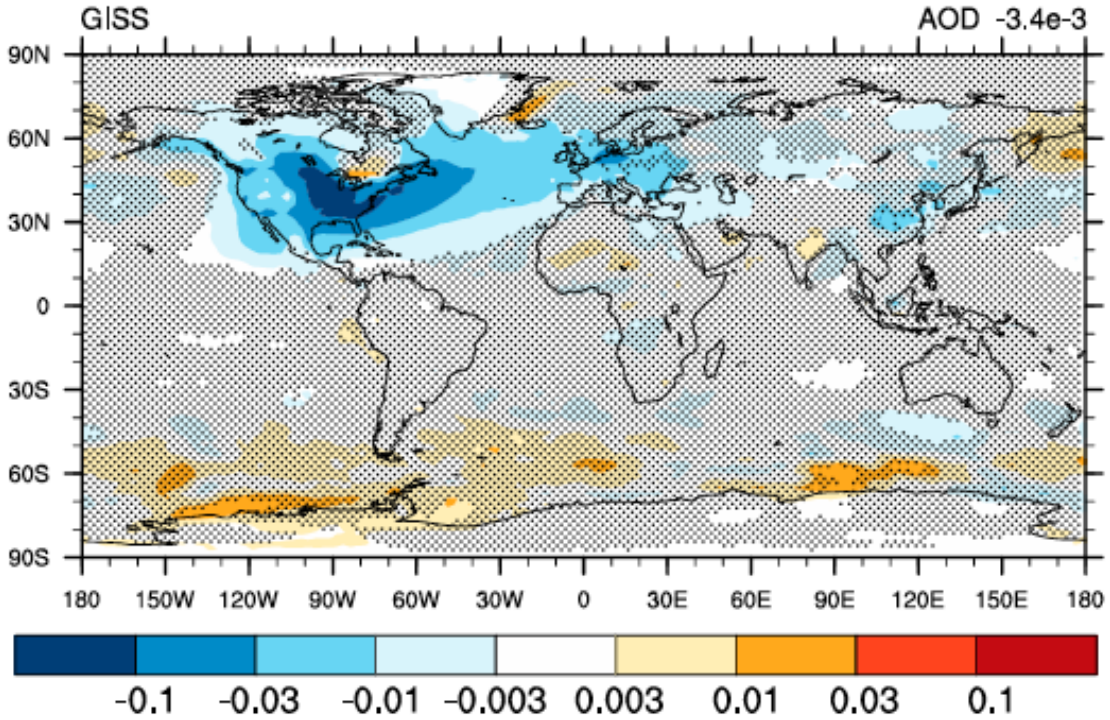
Connecting regional aerosol emissions reductions to local and remote precipitation responses

Daniel M. Westervelt[1,2], Andrew J. Conley[3], Arlene M. Fiore[1,4], Jean-François Lamarque[3], Drew T. Shindell[5], Michael Previdi[1], Nora R. Mascioli[1,4], Greg Faluvegi[2,6], Gustavo Correa[1], and Larry W. Horowitz[7]

Global annual AOD due to US SO_2 removal:
Response = Perturbation – Control

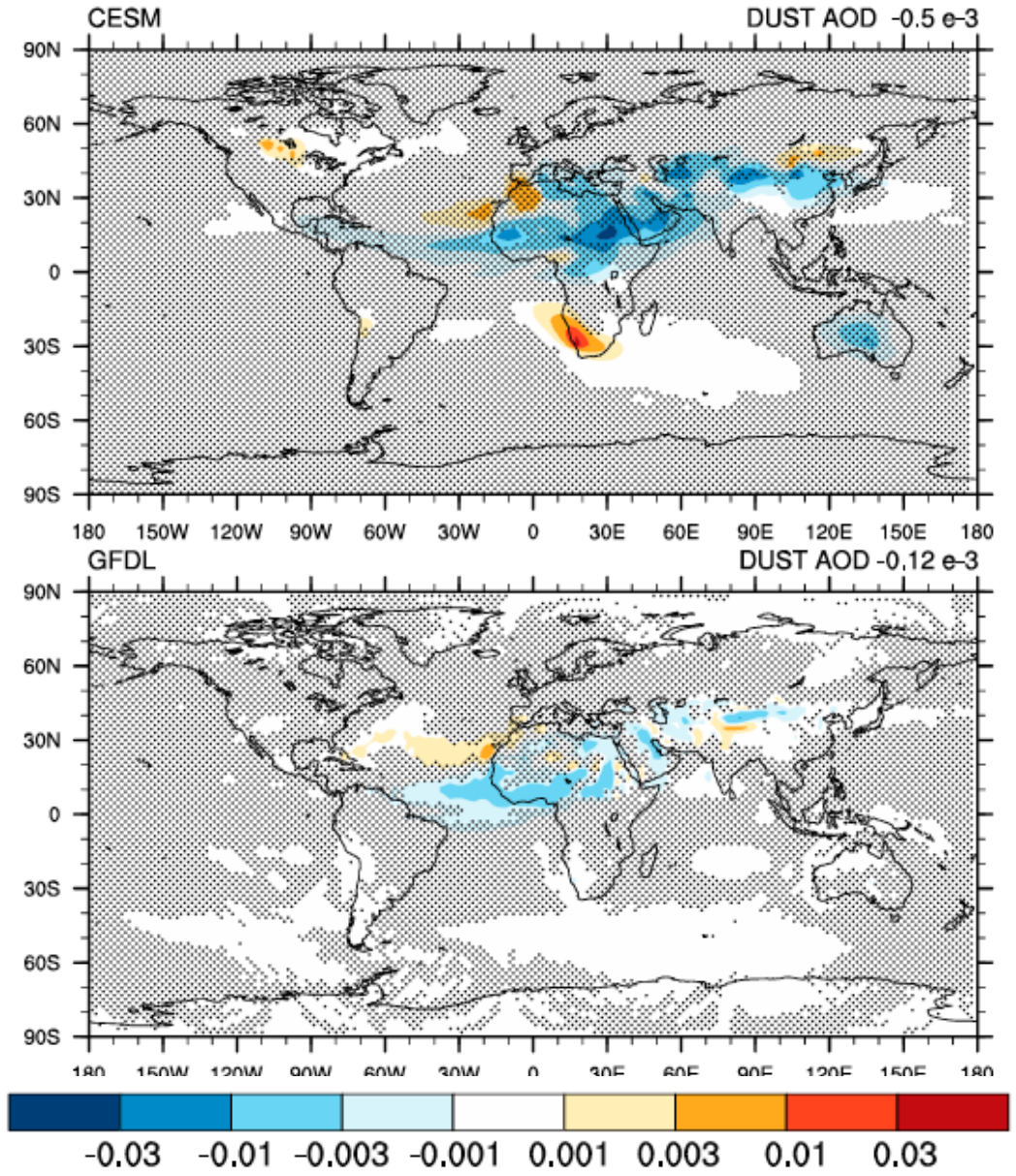




- AOD decreases by 0.0015 to 0.0038 across the three models
- Diversity in AOD change due to different model treatment, assumptions, etc
- (Grey = not statistically significant)

Conley, Westervelt et al. 2018, JGR

Global annual dust AOD due to US SO_2 removal:
Response = Perturbation – Control

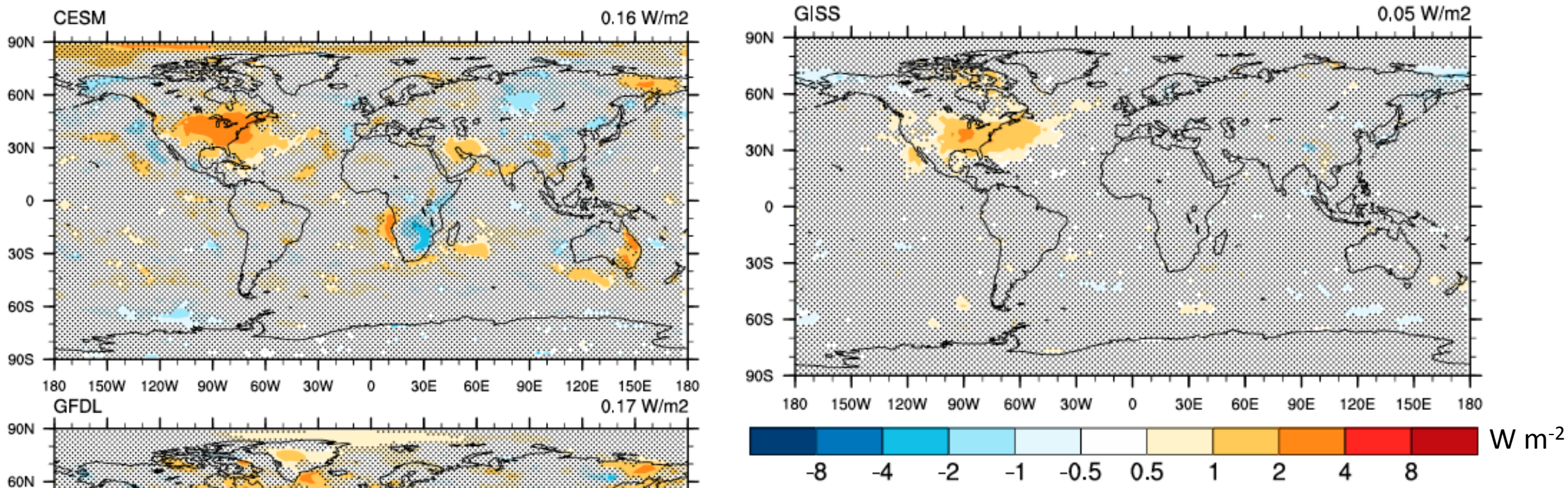


- Removal of US SO2 emissions results in significant decrease in Dust AOD in all three models
  - CESM1 Dust AOD: 0.5 x 10^{-3} or 33% of total AOD response (1.5 x 10^{-3})
  - GFDL-CM3 Dust AOD: 0.12 x 10^{-3} (3% of total)
  - GISS-E2 Dust AOD: 0.05 x 10^{-3} (<1% of total)

- Feedback of climate system (precipitation increases in Africa) on dust aerosol

Conley, Westervelt et al. 2018, JGR

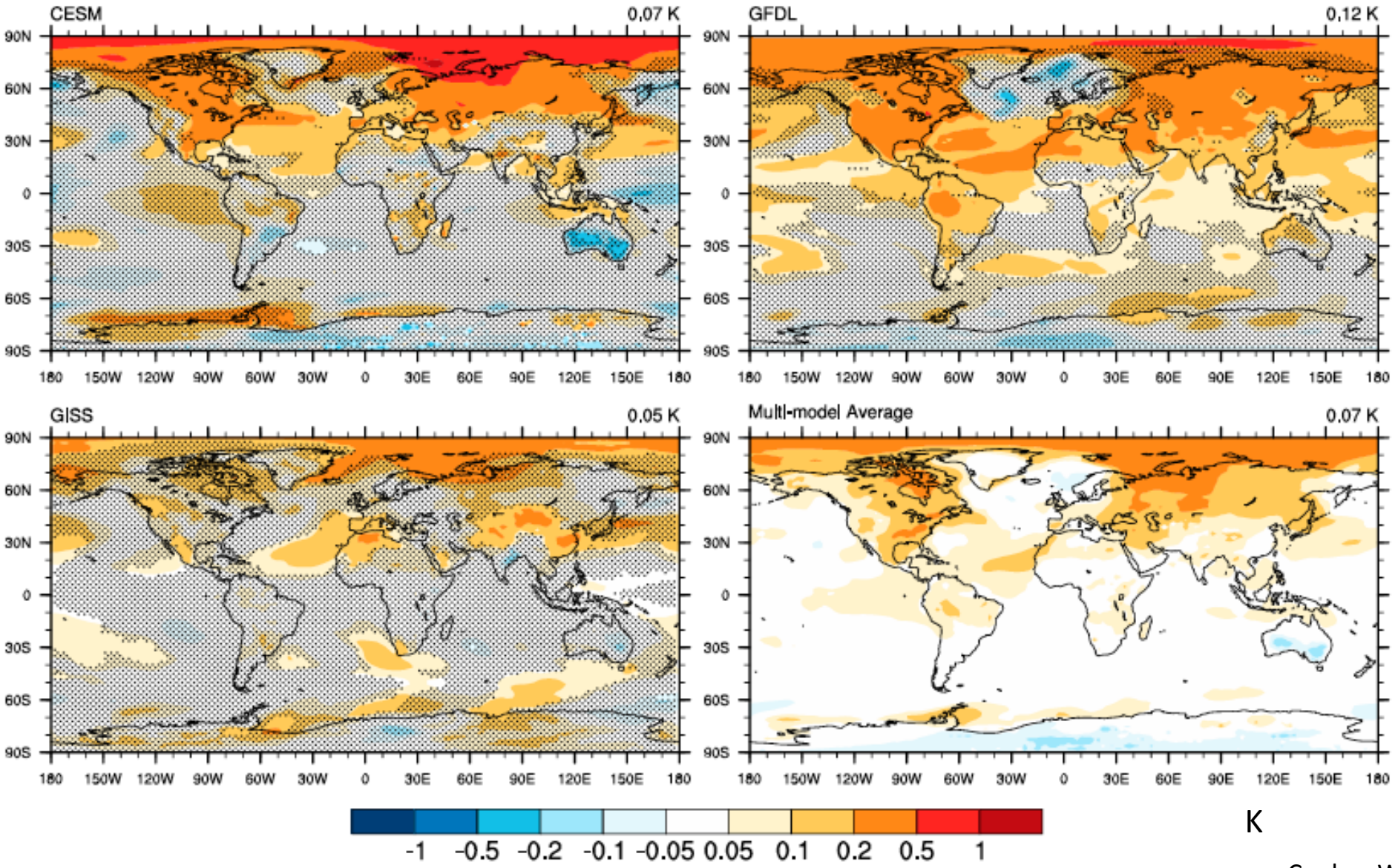
Global annual Effective Radiative Forcing (ERF) due to US SO_2 removal:
Response = Perturbation – Control



- Global mean ERF nearly identical in GFDL-CM3 and CESM1, factor of 3 smaller in GISS-E2
  - Cloud lifetime effects are not included in this version of GISS-E2, so ERF from sulfate aerosol is smaller

Conley, Westervelt et al. 2018, JGR

Global annual surface temperature due to US SO_2 removal:
Response = Perturbation – Control



Equilibrium Sensitivity of T response:

<u>CESM1</u>
0.44 K per W m^{-2}

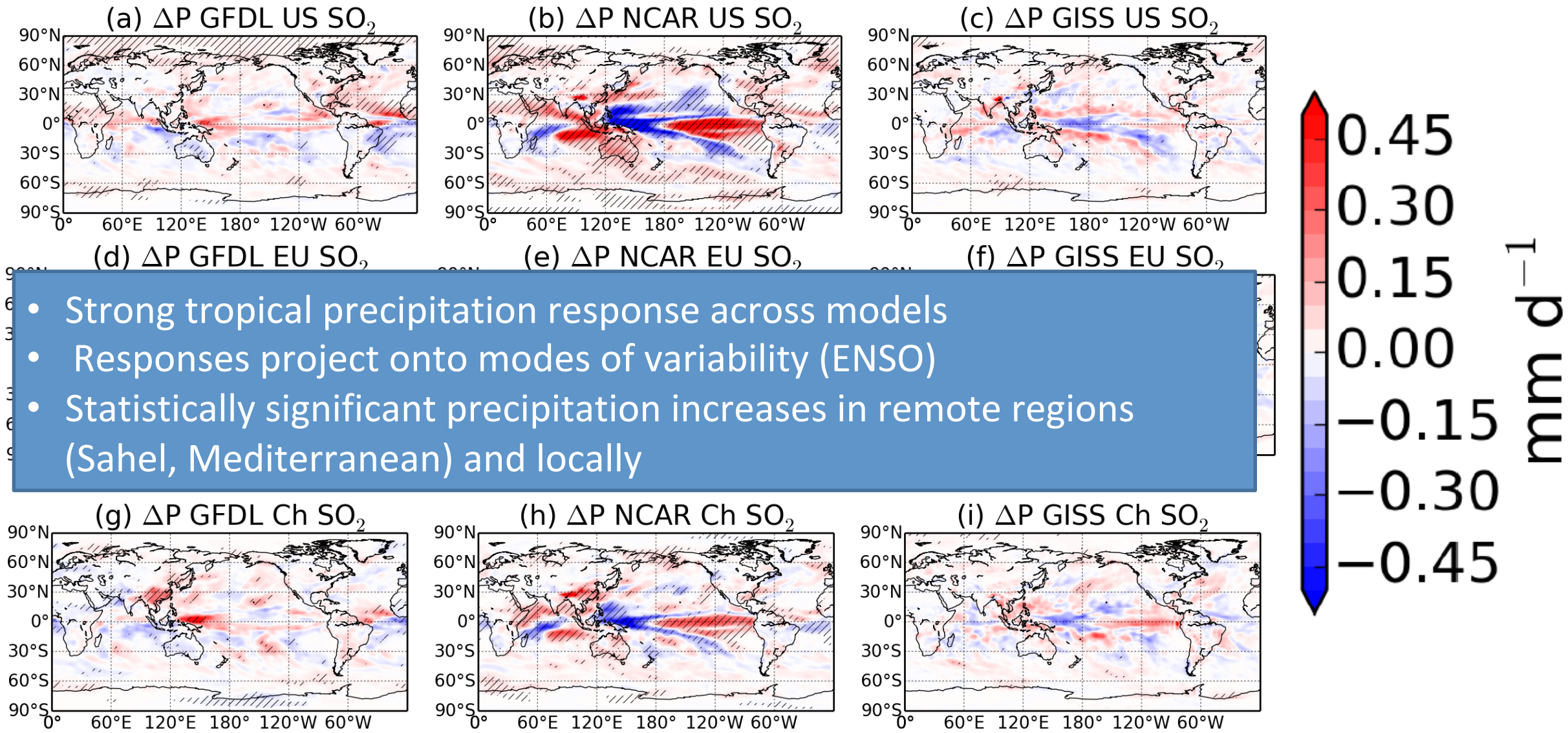
<u>GFDL-CM3</u>
0.68 K per W m^{-2}

<u>GISS-E2</u>
0.98 K per W m^{-2}

Conley, Westervelt et al. 2018, JGR

Global annual precipitation due to aerosol removal:

Response = Perturbation – Control

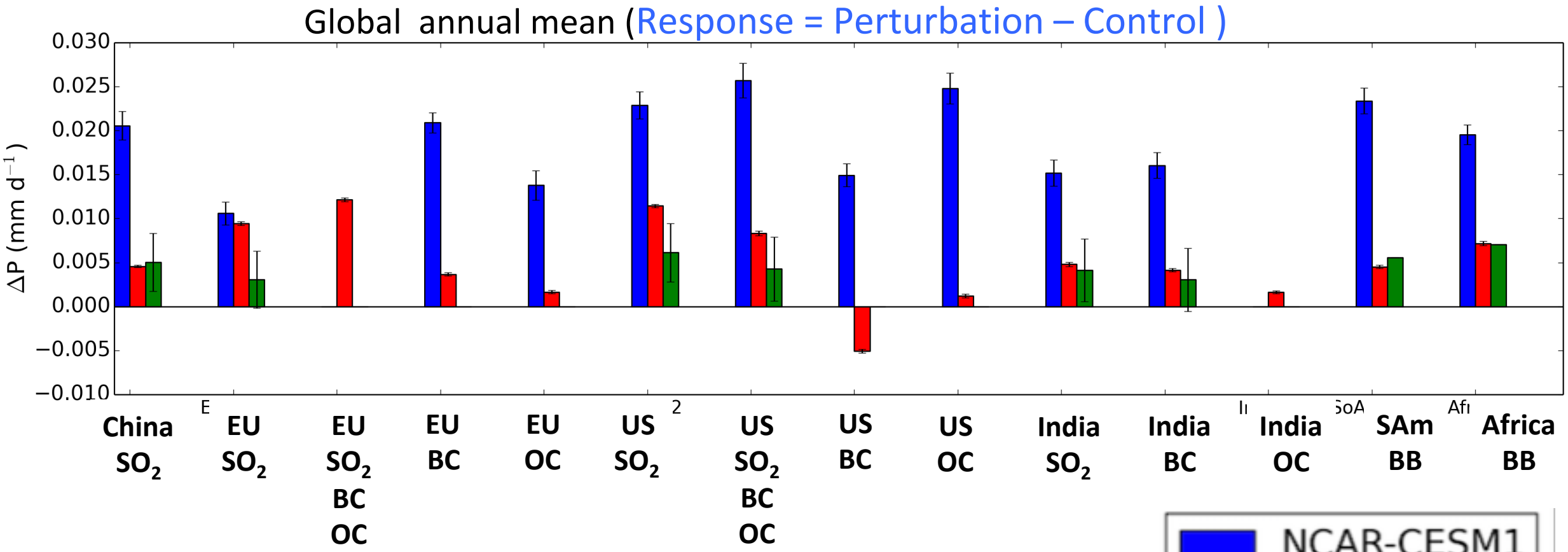


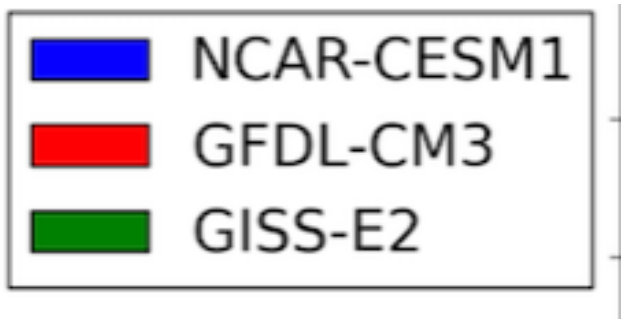
- Strong tropical precipitation response across models
- Responses project onto modes of variability (ENSO)
- Statistically significant precipitation increases in remote regions (Sahel, Mediterranean) and locally

Westervelt et al. 2018, ACP

Hatching: statistically significant

33 of 34 aerosol removal simulations result in global annual precipitation increases

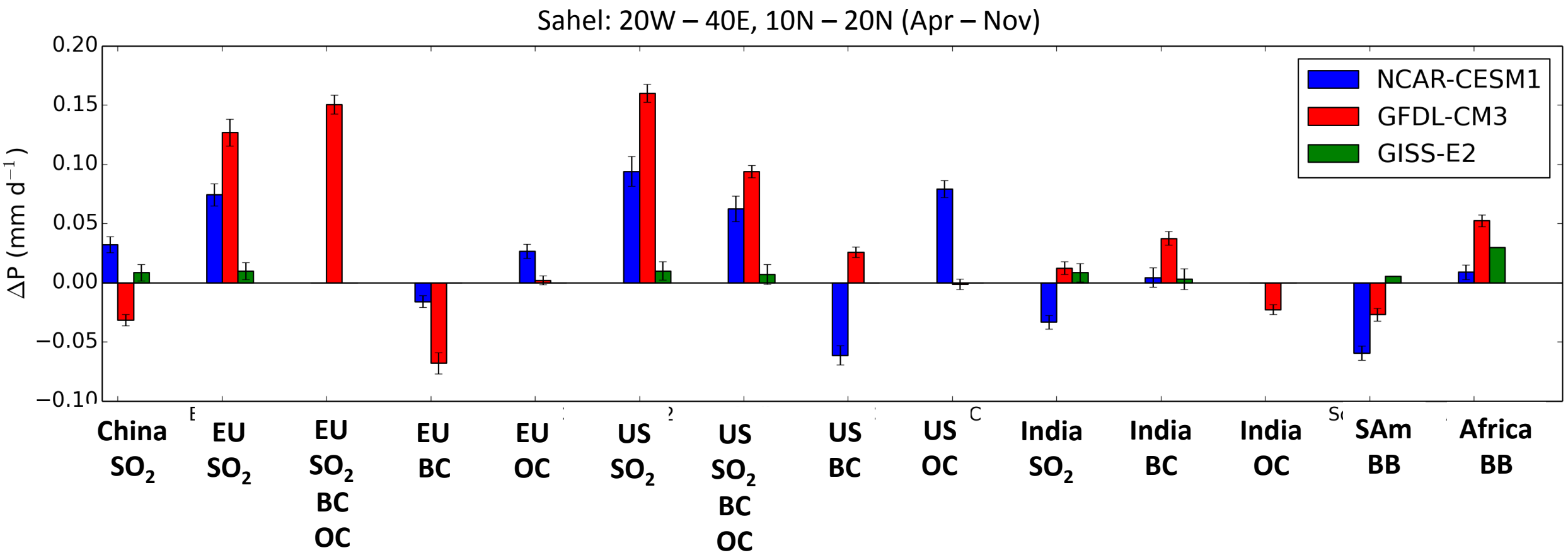




- Largest increases in CESM1, up to 0.02 mm d^{-1} or 1% of the global mean control

Westervelt et al. 2018, ACP

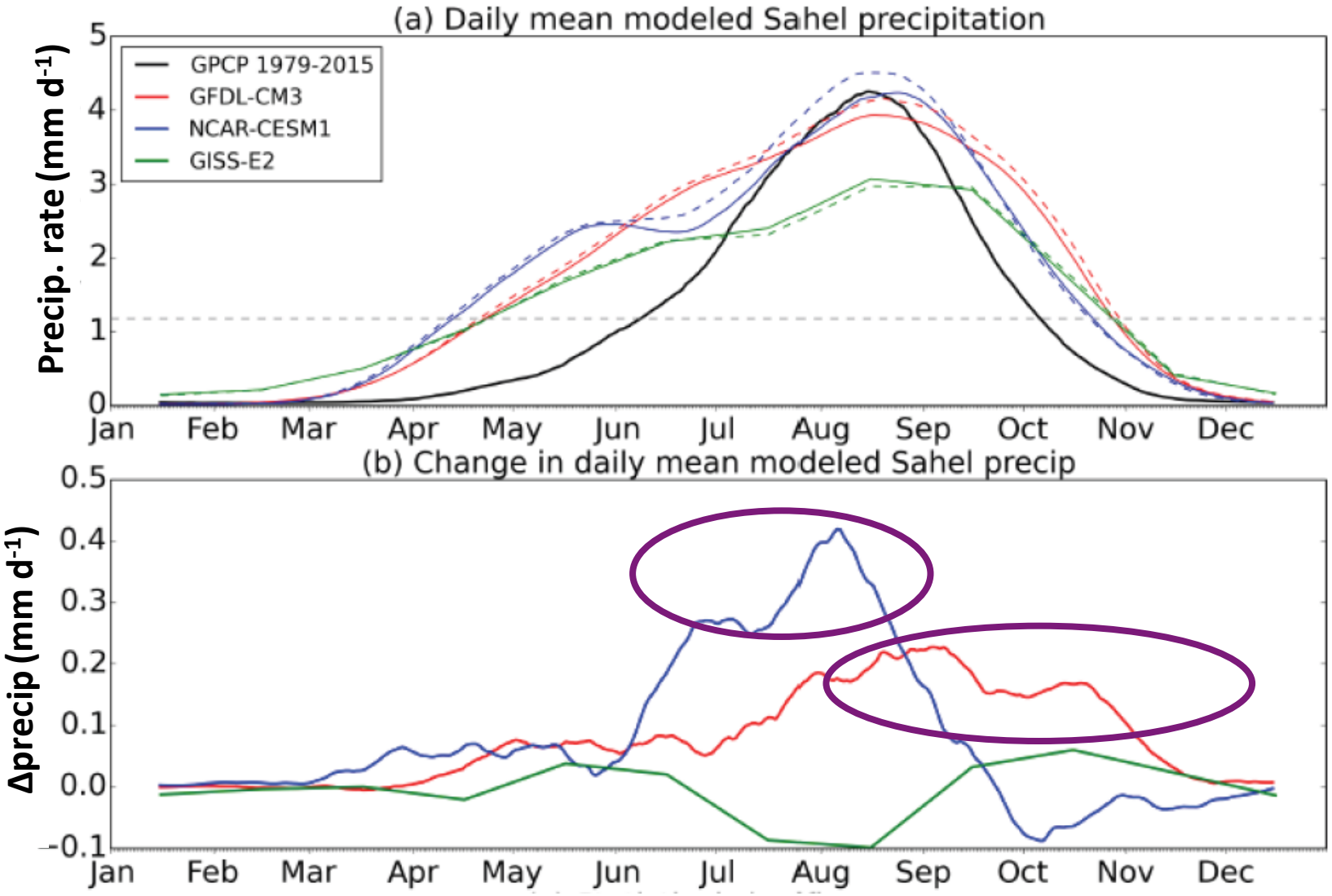
Wet season Sahel rainfall increases up to 10% compared to control



- Statistically significant wet season rainfall increases in 26 of 34 simulations, especially EU_SO2, EU_ALL, US_SO2, US_ALL
- Caused by anomalous interhemispheric temperature gradient and northward Intertropical Convergence Zone (ITCZ) shift

Westervelt et al. 2018, ACP

Precipitation over the Sahel increases (up to 10%) when US SO_2 emissions are set to zero

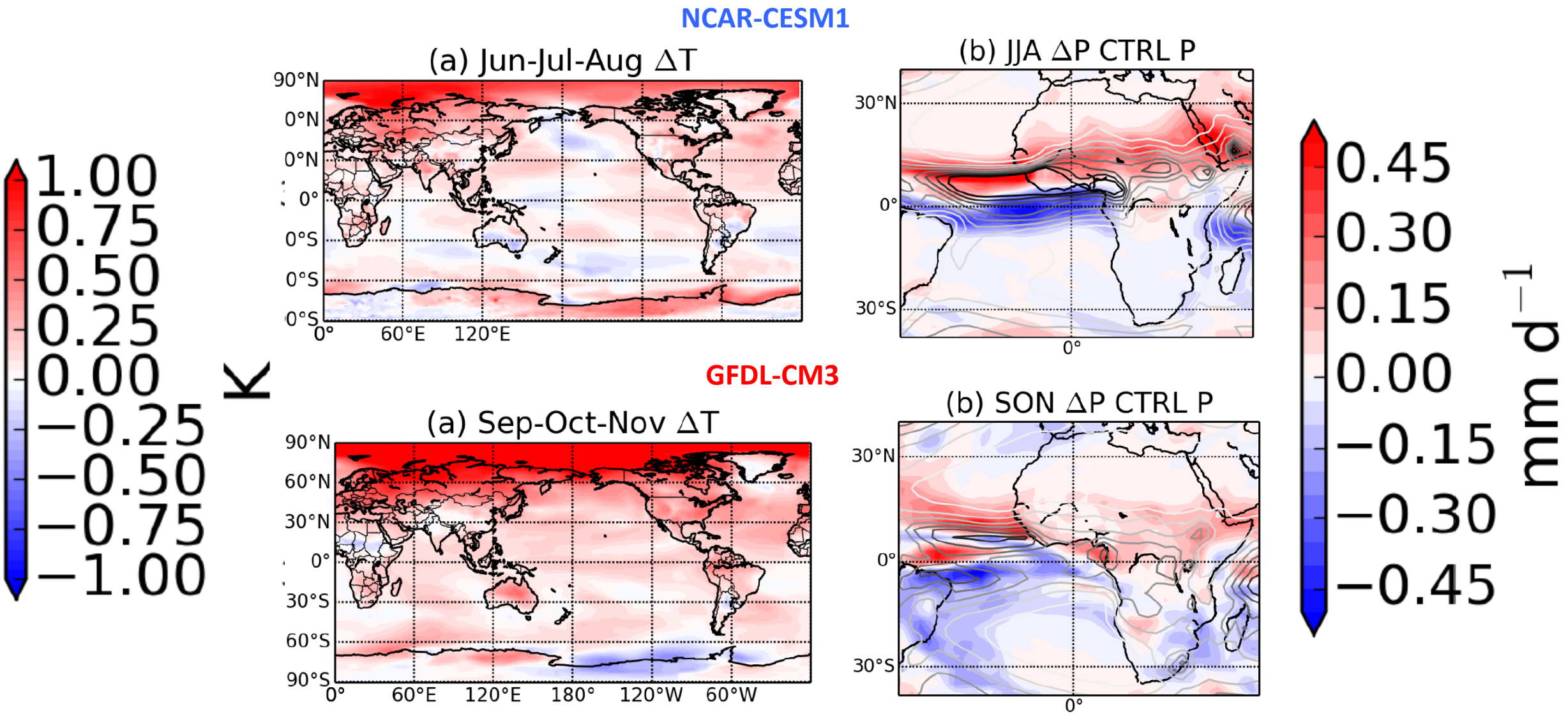


Dashed lines = perturbation
Solid lines = control

Statistically significant at the 95% confidence level

Westervelt et al., JGR 2017

US SO_2 emissions decline → NH warms more → northward ITCZ shift (+ Sahel rainfall)

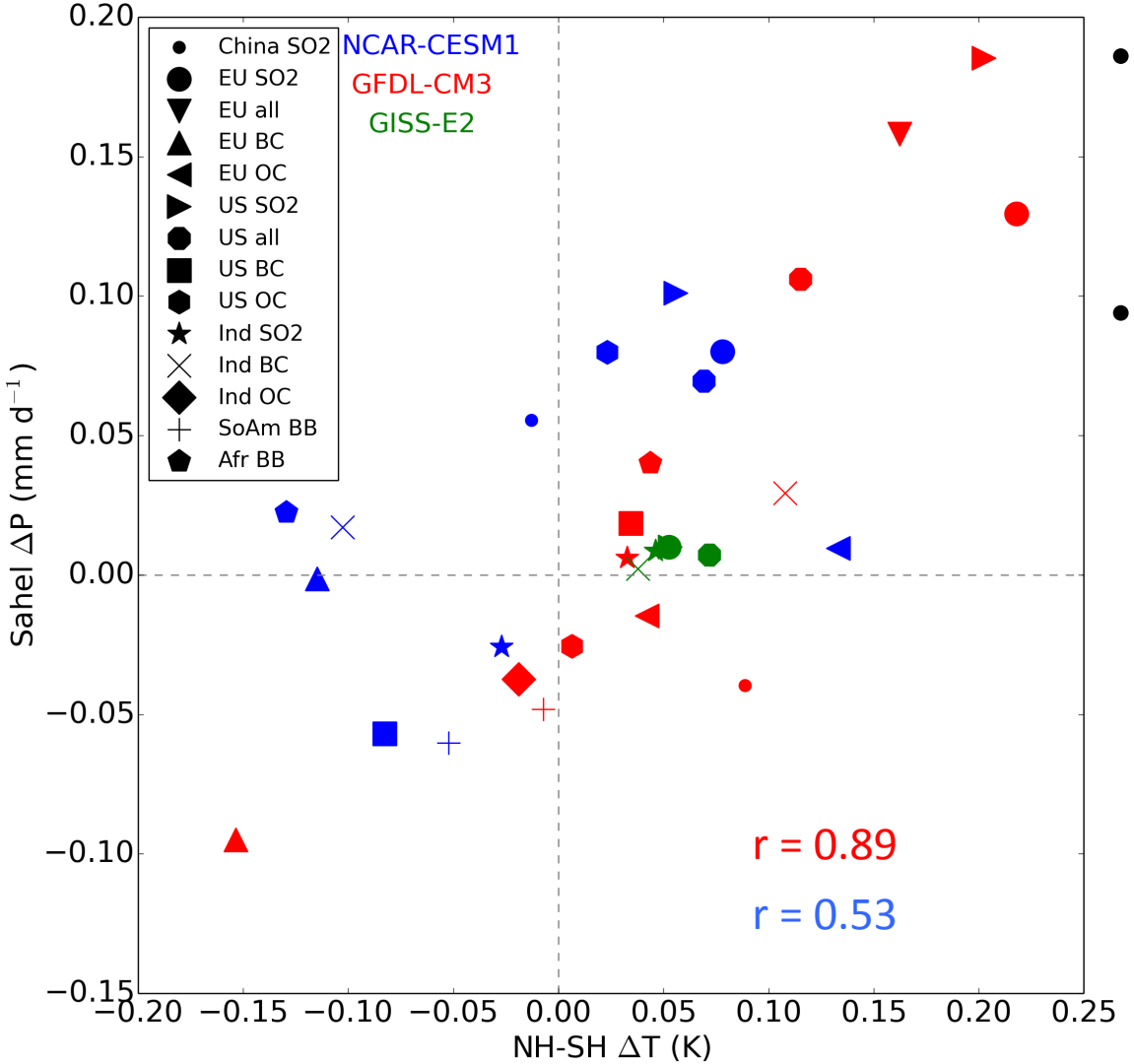


Greyscale contours represent 200-year control mean

Westervelt et al. 2017. *JGR*

Precipitation response mechanism consistent across multiple models and perturbation simulations

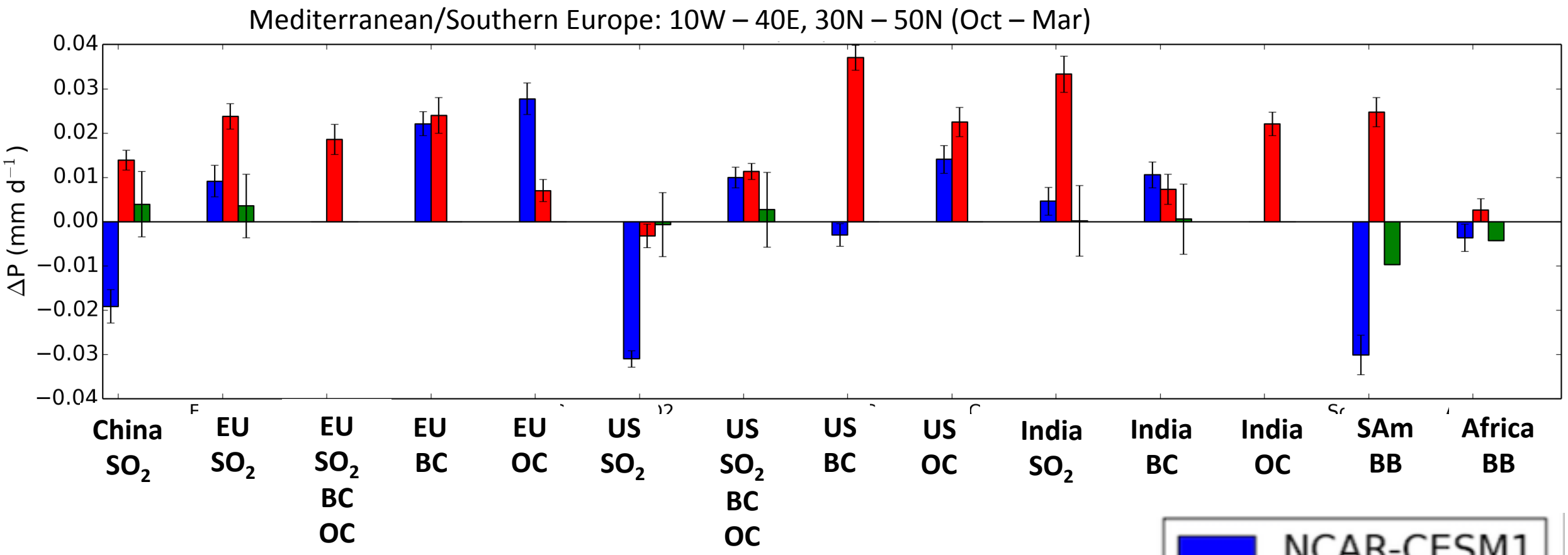
Wet season Sahel precipitation increase vs interhemispheric temperature gradient change

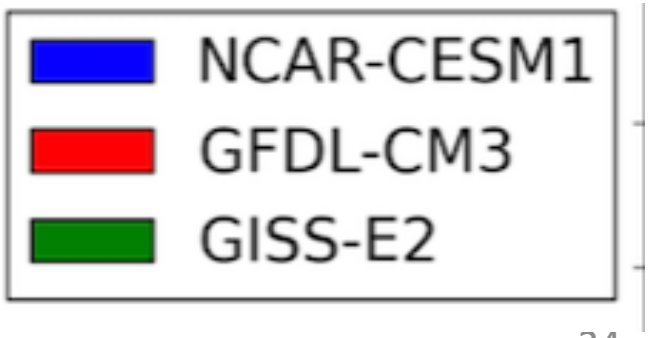


- Strong to moderate linear correlation
- Removal of aerosol cooling, especially in EU and US perturbations, brings additional rainfall to Sahel

Westervelt et al. 2018, ACP

Wet season Mediterranean rainfall increases up to 3% compared to control

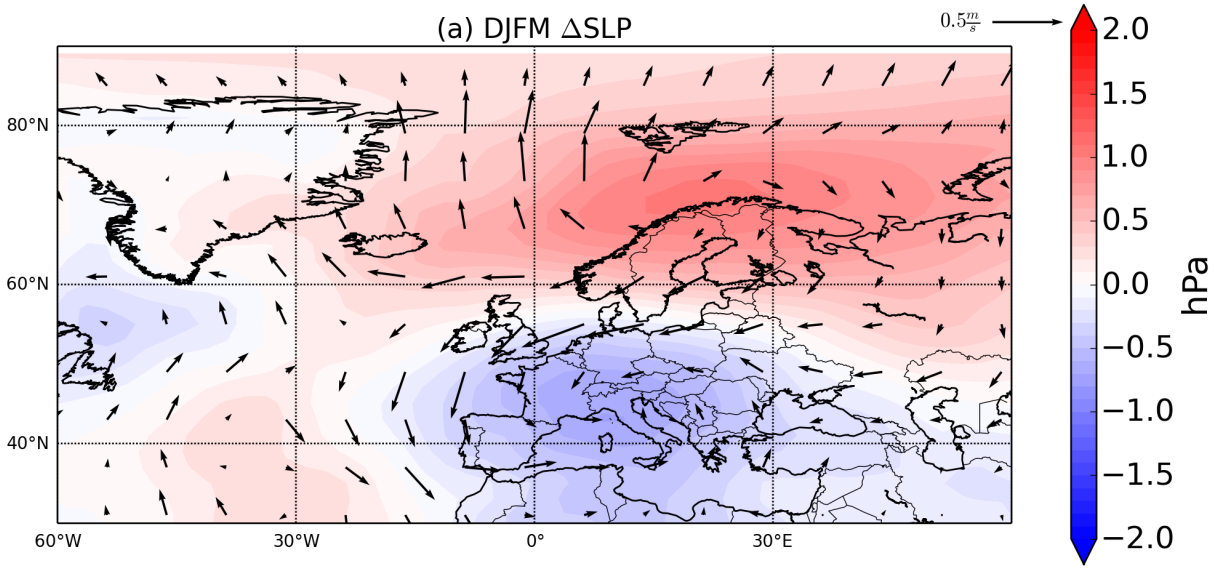




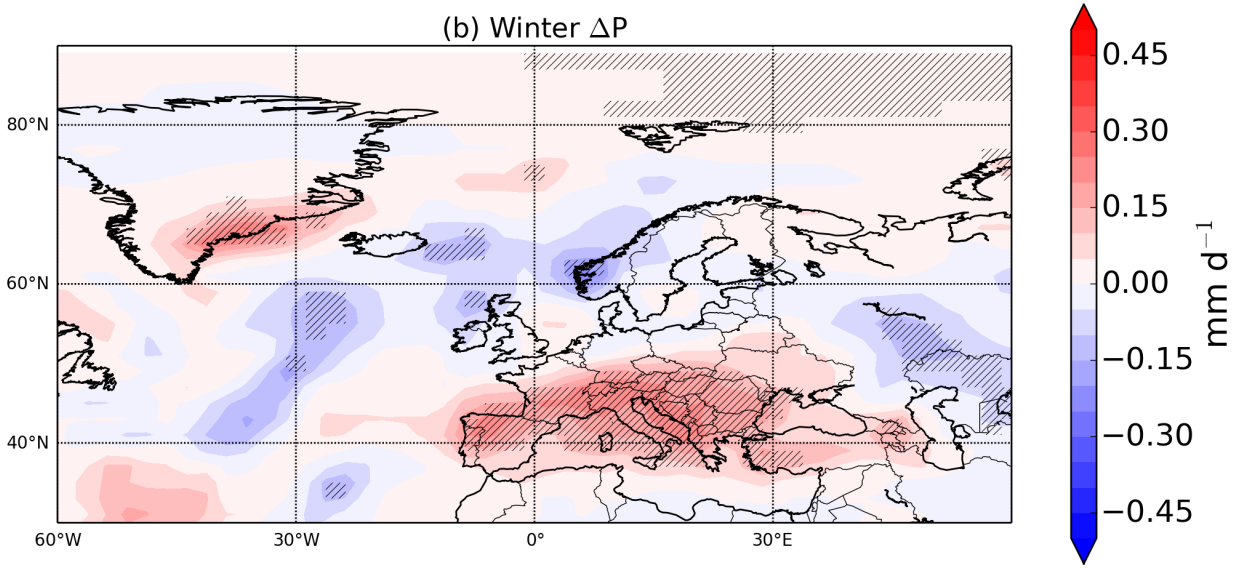
- Increases in 25 of 34 pertubation experiments
- Possible connection to NAO and southward shift of storm track over the North Atlantic

Westervelt et al. 2018, ACP

Aerosol impacts on winter European precipitation in GFDL-CM3



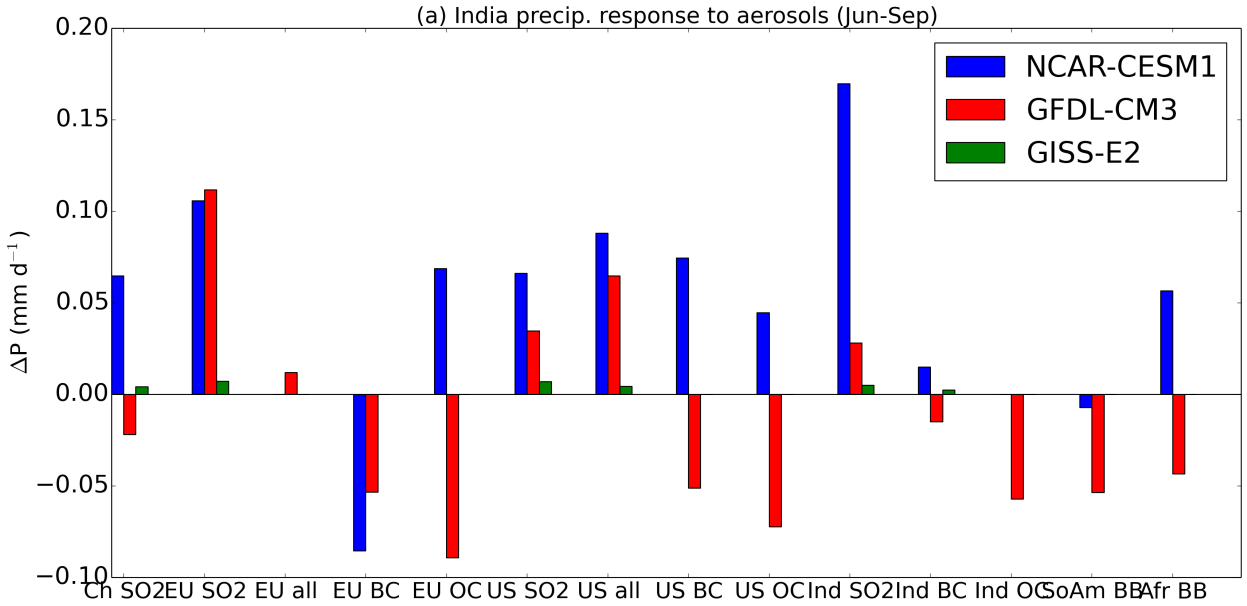
Response = Perturbation (zero EU SO2) minus Control

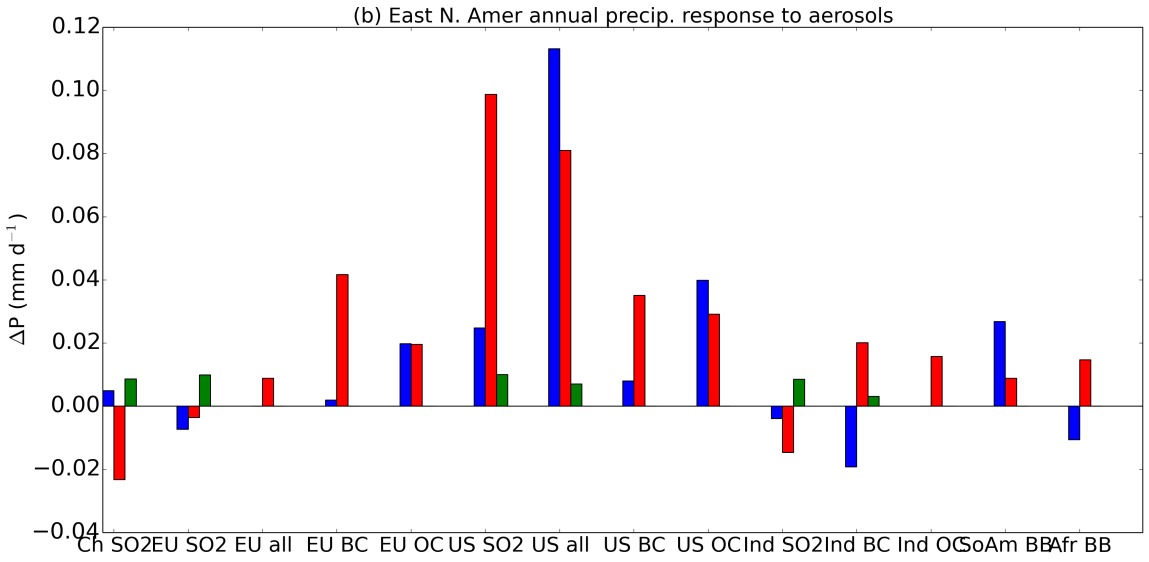


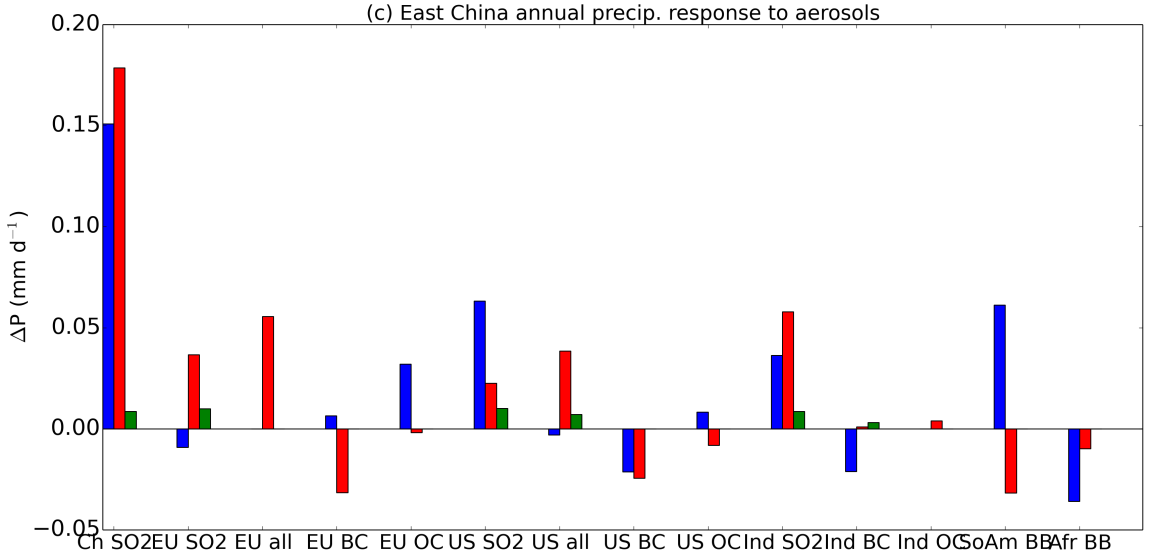
- European aerosol reductions → north-south SLP dipole that resembles NAO
- Weakened westerlies, southward shifted storm track
- Increase in S. Europe precipitation

Westervelt et al. 2018 ACP

Wet season (or annual) rainfall increases in response to regional aerosol emissions in other impact regions



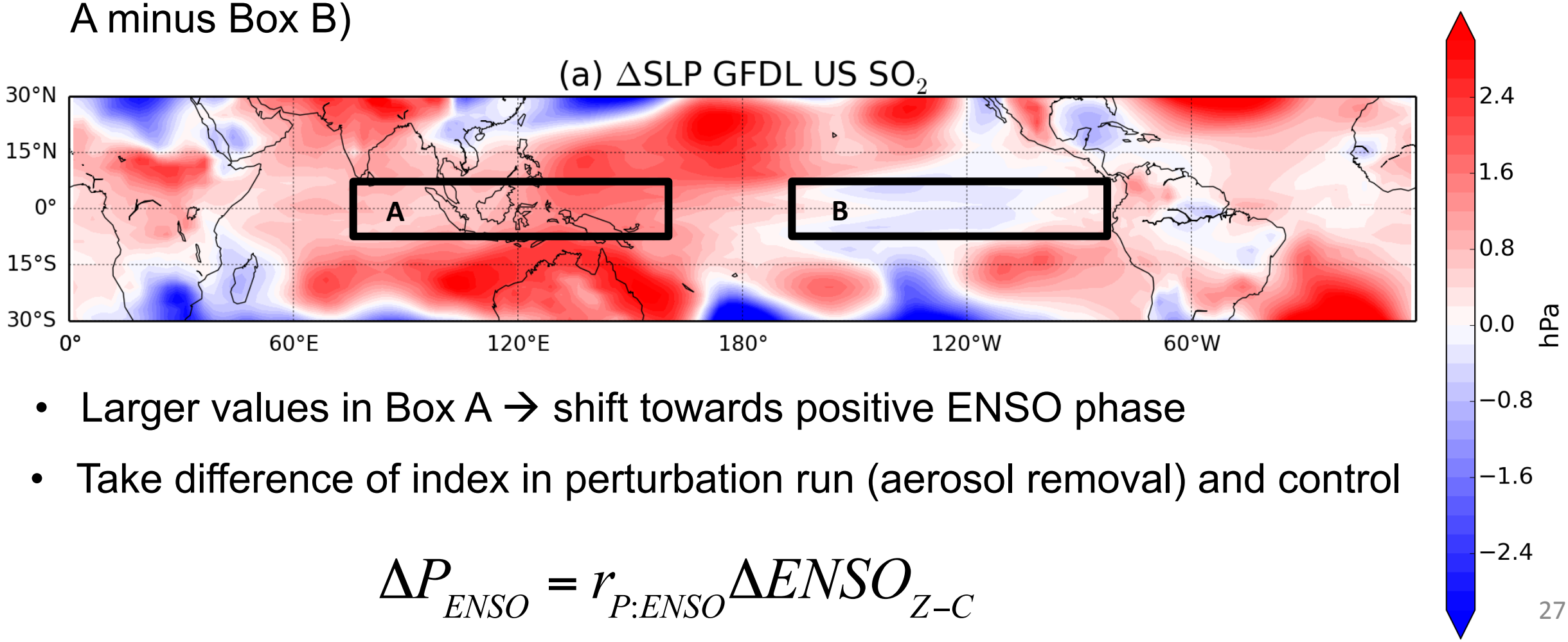




- Substantial influence of remote aerosols on Indian monsoon
  - Not much consistency between models
- Local emissions changes have the largest impact in China and USA

Is the regional aerosol impact on regional precipitation modulated through ENSO?

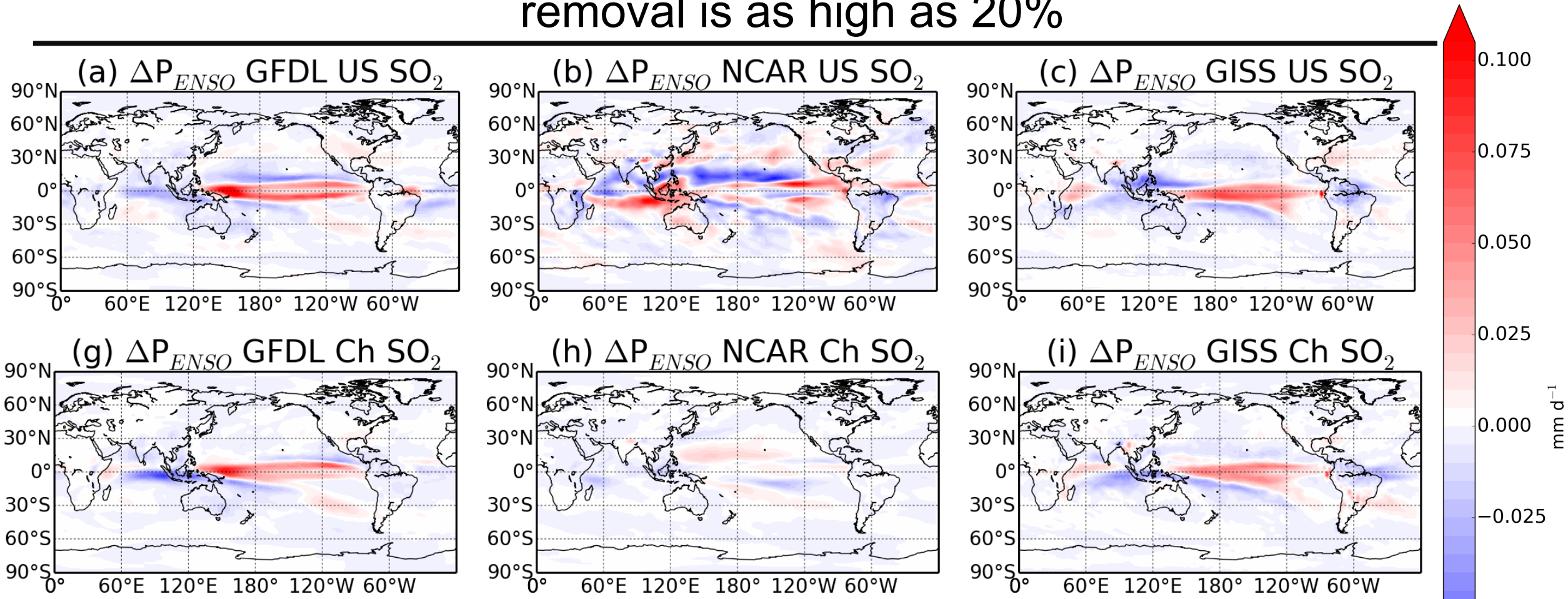
- Linear regression of large-scale Southern Oscillation index (representing Walker circulation) onto precipitation patterns (slope, $r_{P:ENSO}$)
- Index: based on a large-scale Indo-Pacific zonal sea level pressure gradient (Box A minus Box B)



- Larger values in Box A → shift towards positive ENSO phase
- Take difference of index in perturbation run (aerosol removal) and control

$$\Delta P_{ENSO} = r_{P:ENSO} \Delta ENSO_{Z-C}$$

ENSO component of precipitation response to aerosol emissions removal is as high as 20%

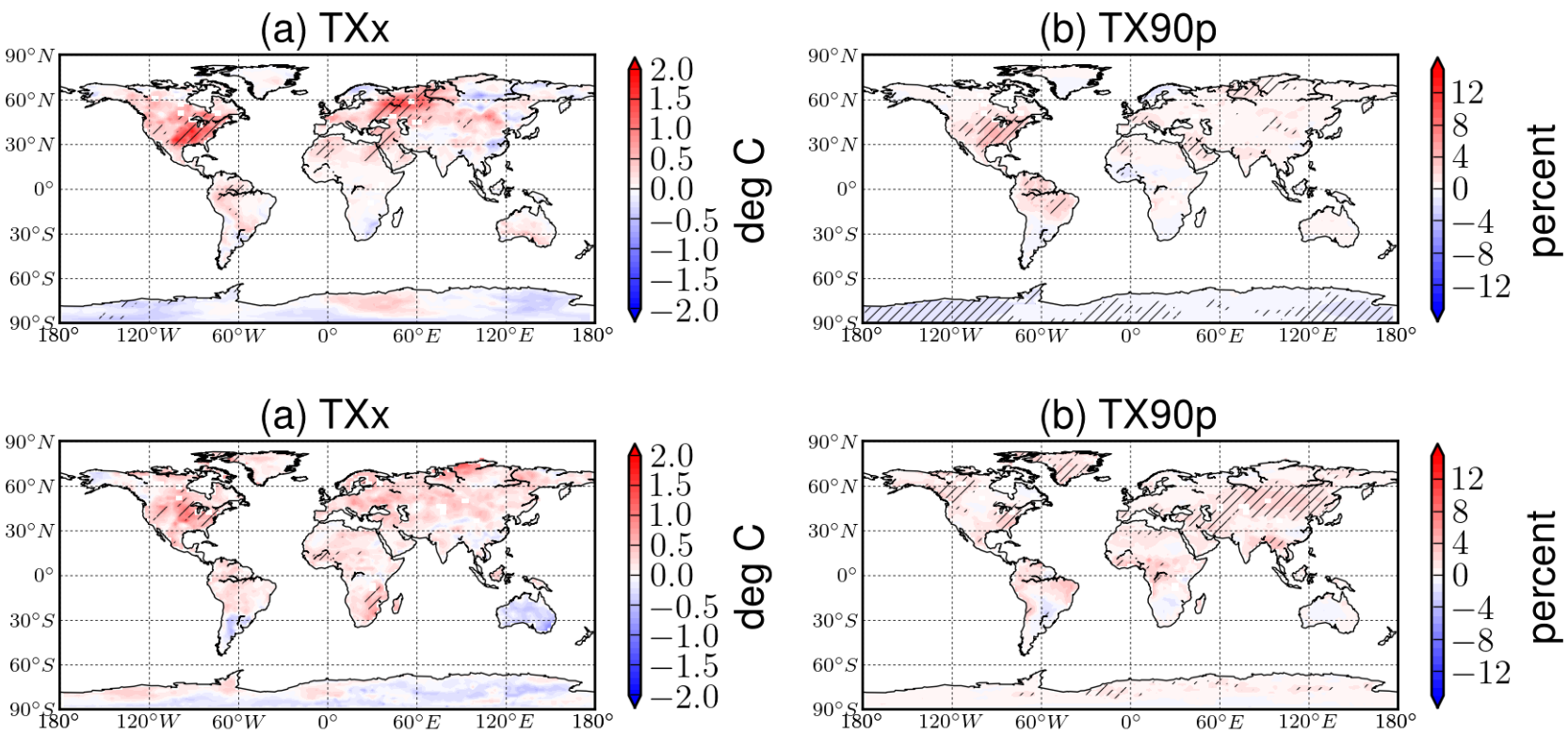


- Tend to shift toward the positive phase of ENSO (El Niño)
- Largest changes in the tropical Pacific, but also some teleconnections (i.e. US, Asian monsoon, Amazon)
- Modest agreement between models
- Changes in precipitation are as high as 0.1 mm d^{-1}, or 20% of the total precipitation response to aerosols

Westervelt et al. 2018, ACP

Global annual extreme temperature response due to US SO_2 removal:

Response = Perturbation – Control



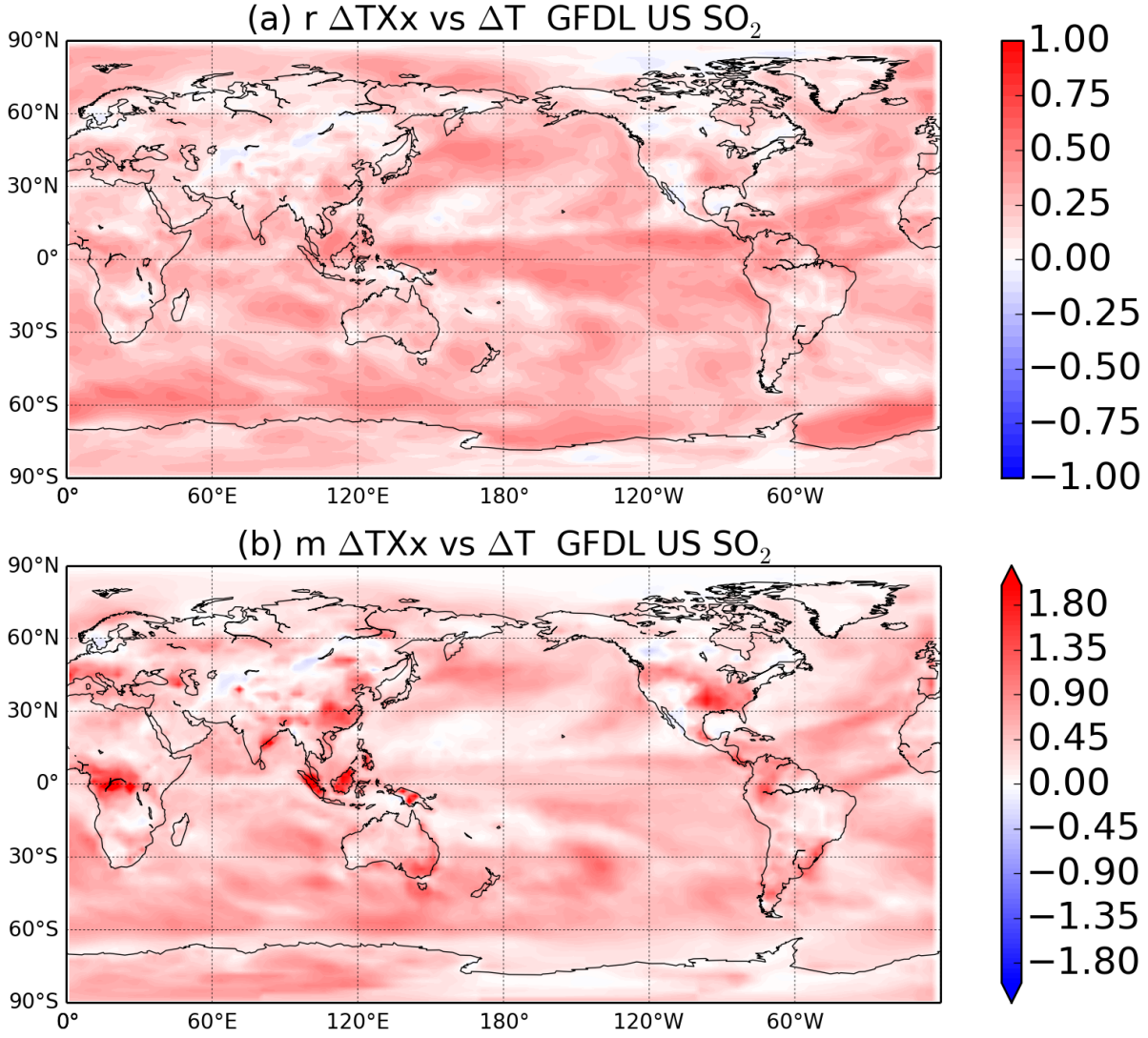
GFDL-CM3

CESM1

- TXx = maximum of daily maximum temperatures
- TX90p = percentage of warm days (above 90th percentile)

Functional relationship between extreme and mean responses?

(a) Correlation coefficient, (b) linear regression slope



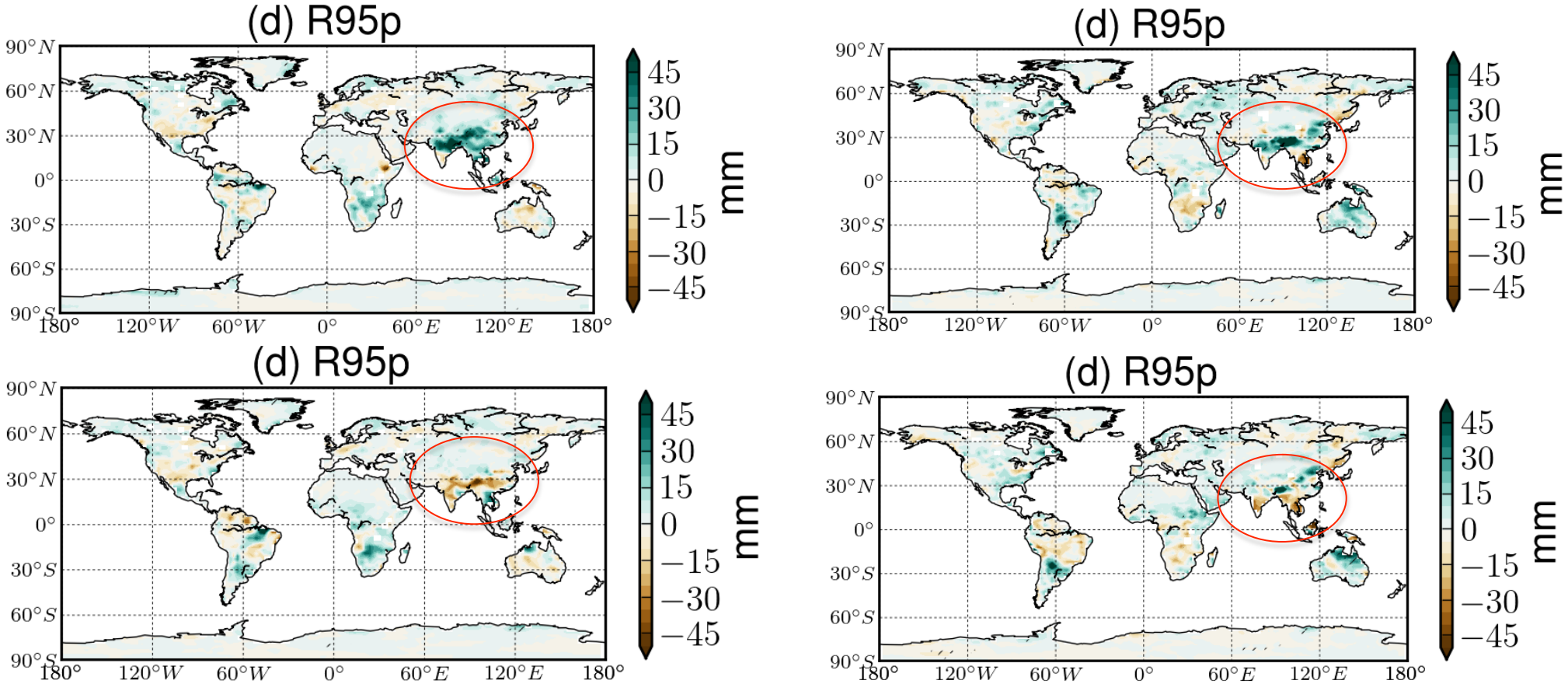
- For every 1 K of mean temperature increase, up to 2 K in extreme temperature increase (TXx) in several key locations
- Do these differ for other aerosol and greenhouse gas perturbations?

Global annual extreme precipitation response due to aerosol removal:
Response = Perturbation – Control

- Wetting associated with SO_2 removal, Drying with BC removal (both models)
- R95p = very wet days

GFDL-CM3

CESM1



India SO2 removal

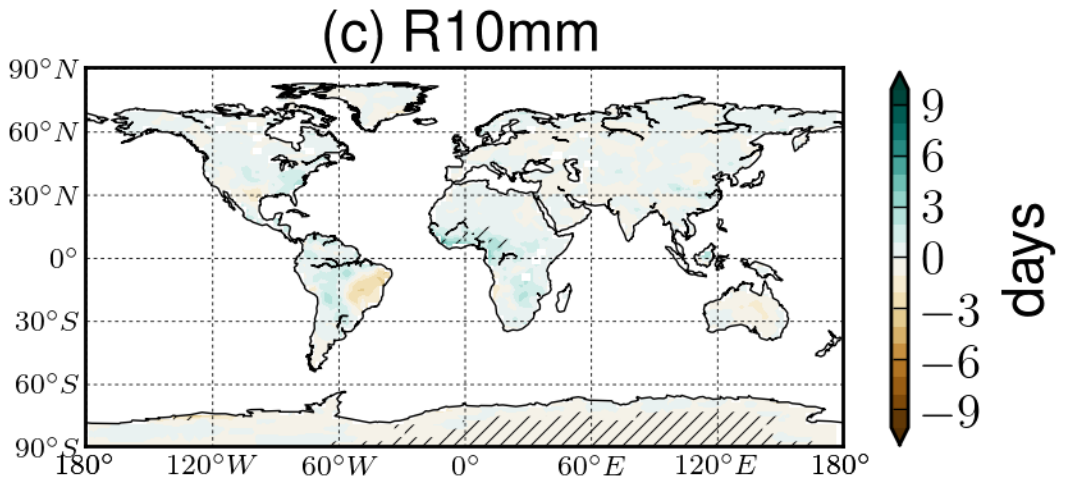
India BC removal

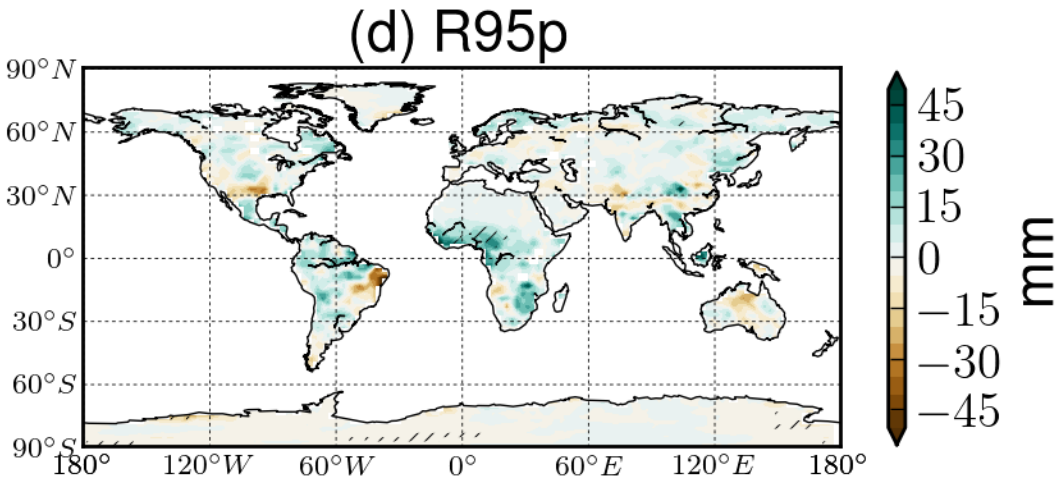
Global annual extreme precipitation response due to US SO_2 removal:

Response = Perturbation – Control

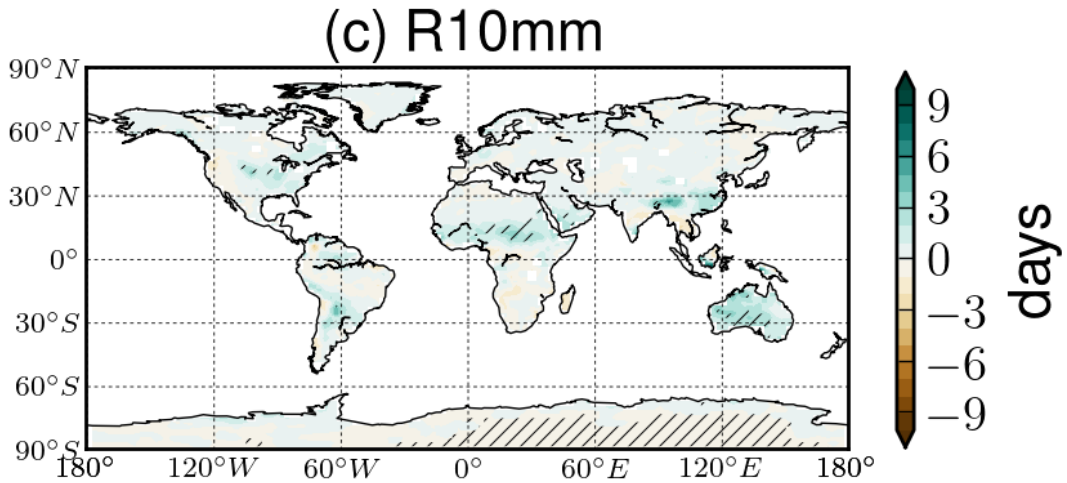
Extreme precipitation increases in Sahel due to removal of US anthropogenic SO2 emissions. Possible disbenefits?

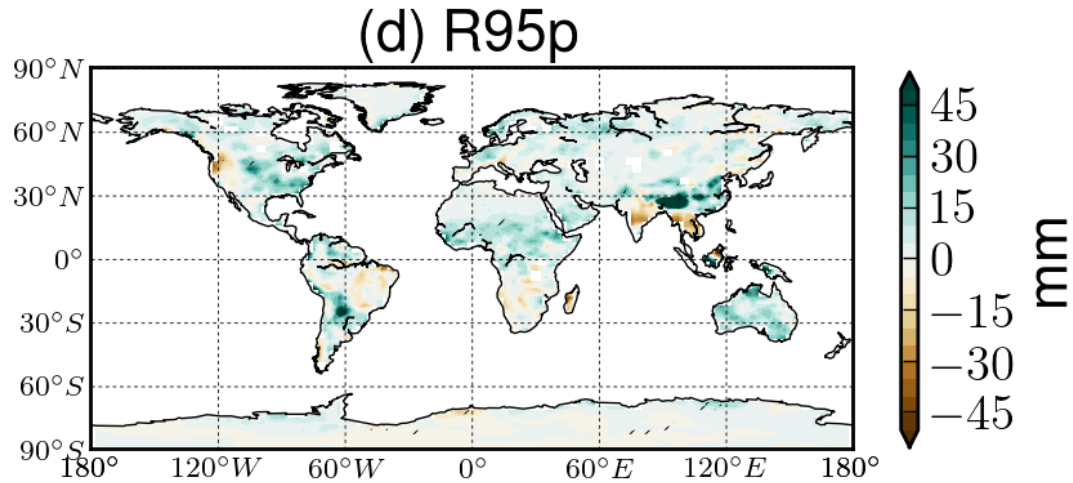
GFDL-CM3





CESM1





Summary

- Possible increase in GMST up to 1 ºC by 2100 due to health-driven aerosol reductions
- Air pollution emissions reduction policies in regions such as the US and Europe have far-reaching impacts
  - Sahel increase in rainfall in GFDL-CM3 and NCAR-CESM1 up to 10%
- Global precipitation rates increase in 33 of 34 regional aerosol emissions reduction simulations
- Precipitation responses project onto modes of variability (ENSO, NAO)
  - ENSO component of precipitation response to regional aerosol emissions removal is as high as 20%, causes shift towards positive phase
- Extreme temperature response to aerosol reductions is larger than mean response
  - These might be functionally related