

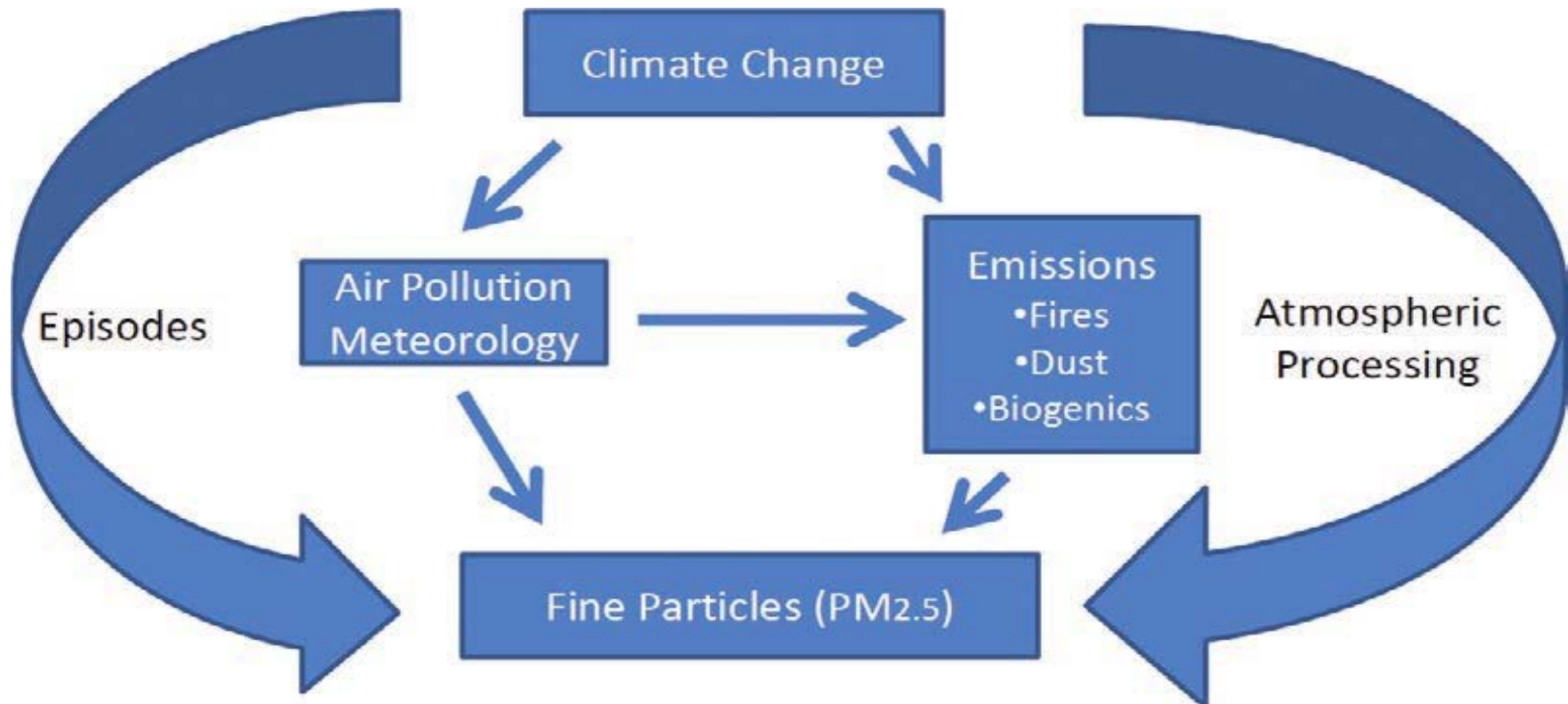
# An Increase in Aerosol Burden in a Warmer World

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16<sup>th</sup> AeroCom/5<sup>th</sup> AeroSAT Workshop

# Impacts of Climate Change on Aerosols



- **Physical** → temperature, humidity, precipitation, soil moisture, wind speed, sea-ice extent
- **Chemical** → availability of oxidants; chemical production pathways
- **Biological** → vegetation cover/properties, plankton abundance

# Summary of Prior Studies

- **Little consistency** on the magnitude or sign of the impact of climate change on sulfate (and other) aerosol:
  - Sulfate **decreases** (Racherla and Adams, 2006; Liao et al., 2006; Unger et al., 2006; Pye et al., 2009).
  - Sulfate **increases** (Rae et al., 2007; Ackerley et al., 2009).
- **ΔSea salt** ranges from **20% reduction** (Liao et al., 2006) to **sizeable increases** (Jones et al., 2007; Bellouin et al., 2011).
- **Dust increases** or **decreases** moderately (**10-20%**) (Tegen et al., 2004; Jacobson and Streets, 2009; Liao et al., 2009).
- With **low confidence**, IPCC assesses a relatively small feedback parameter (**+/- 0.2 W m<sup>-2</sup> K<sup>-1</sup>**).

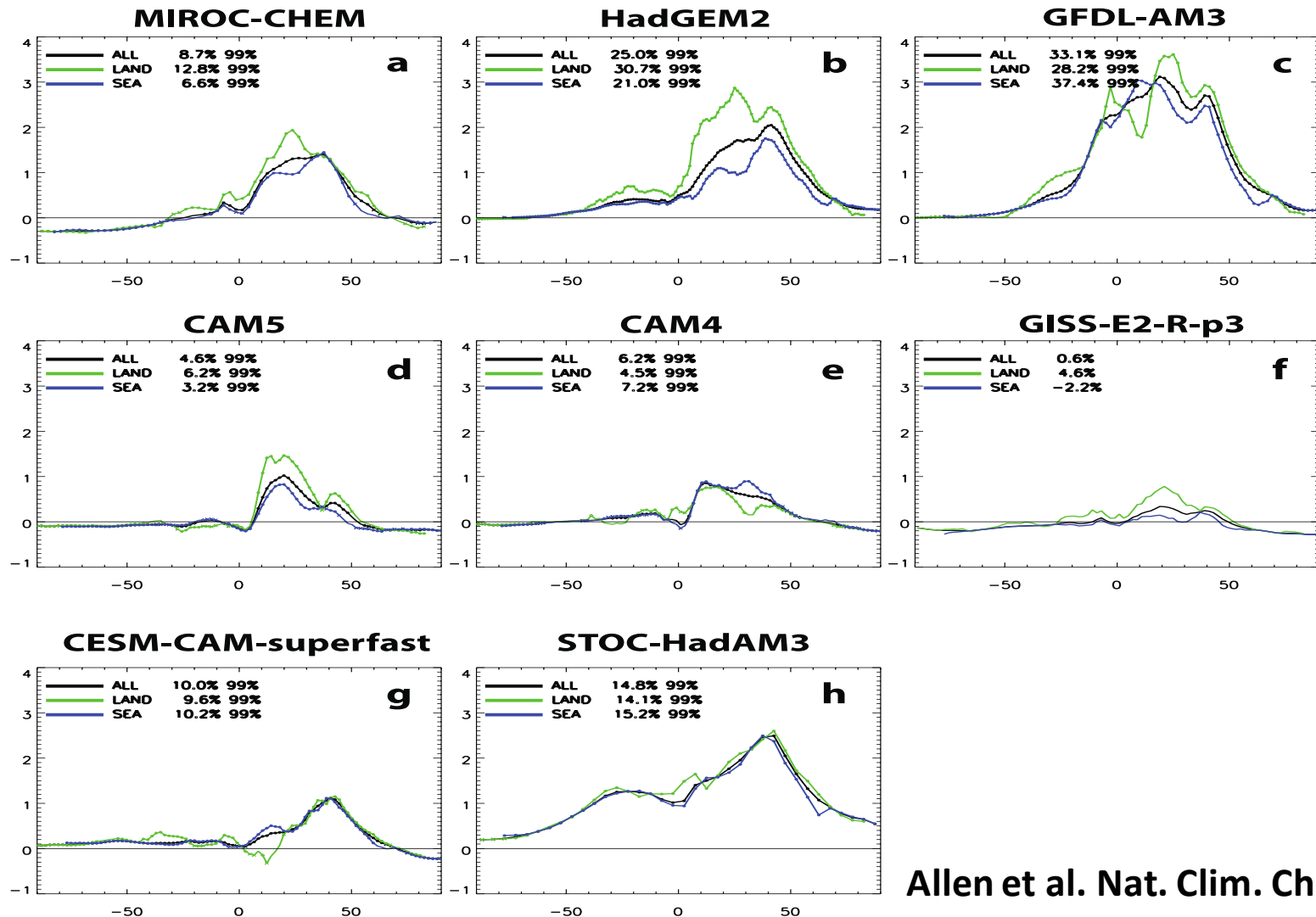


# Data/Simulations

- ACCMIP → Collection of ~16 **chemistry-climate models** targeting changes in **atmospheric composition & radiative forcing** (Lamarque et al., 2013).
- A limited subset of ACCMIP models (< 8) performed the necessary constant emission, time-slice simulations (**Em2000Cl2000** & **Em2000Cl2100**). Fewer archived the relevant diagnostics.
- Supplement with ~20 CMIP5 models where appropriate (natural aerosols).
- Perform ACCMIP-type experiments with NCAR CAM4 and CAM5 (different aerosol schemes).



# ACCMIP Sulfate Burden [mg m<sup>-2</sup>]

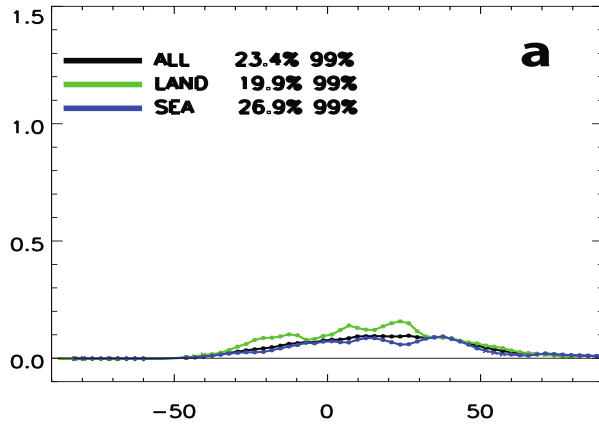


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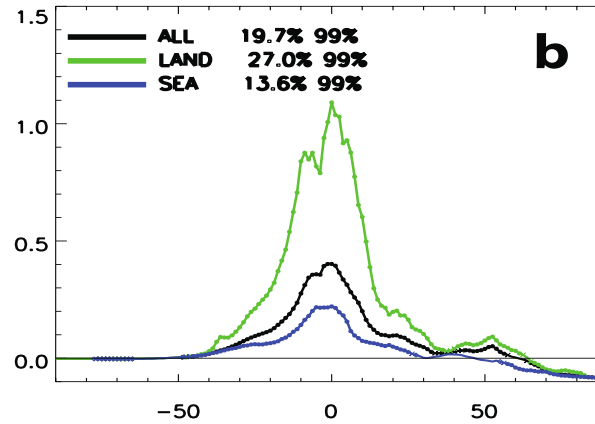
- All ACCMIP models yield a global annual mean **increase** in sulfate burden (and surface concentration) in a **warmer world** → **12.9%** with a range from **0.6 to 33%**.
- **Increase** largest in tropics and NH mid-latitudes.

# ACCMIP Black Carbon Burden [ $\text{mg m}^{-2}$ ]

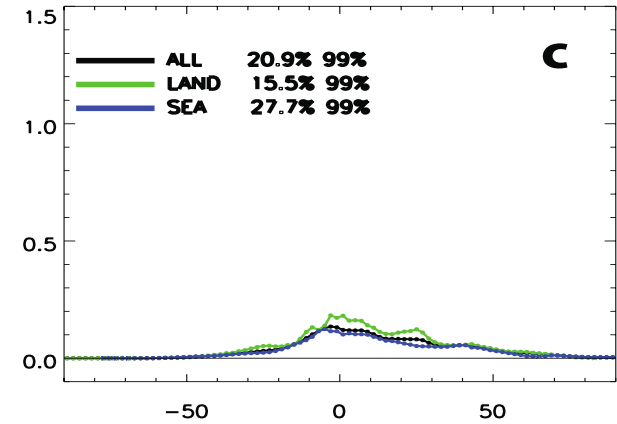
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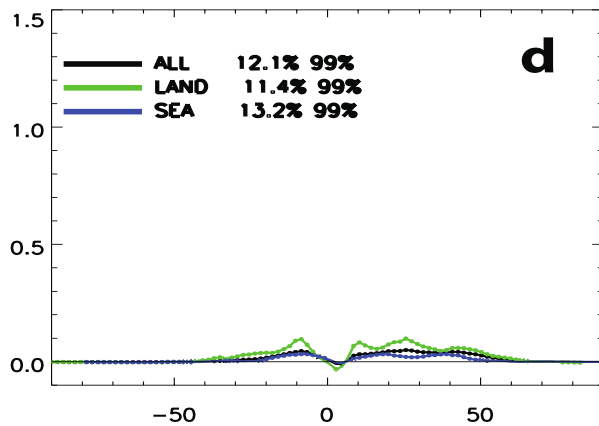
## HadGEM2



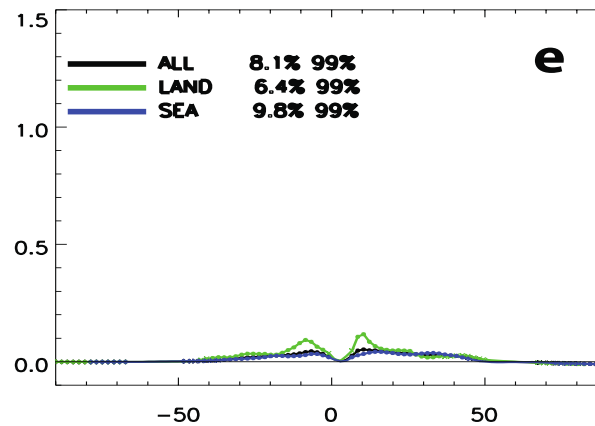
## GFDL-AM3



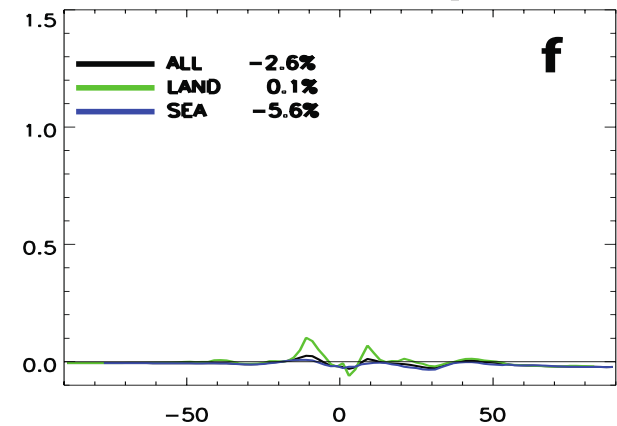
## CAM5



## CAM4



## GISS-E2-R-p3

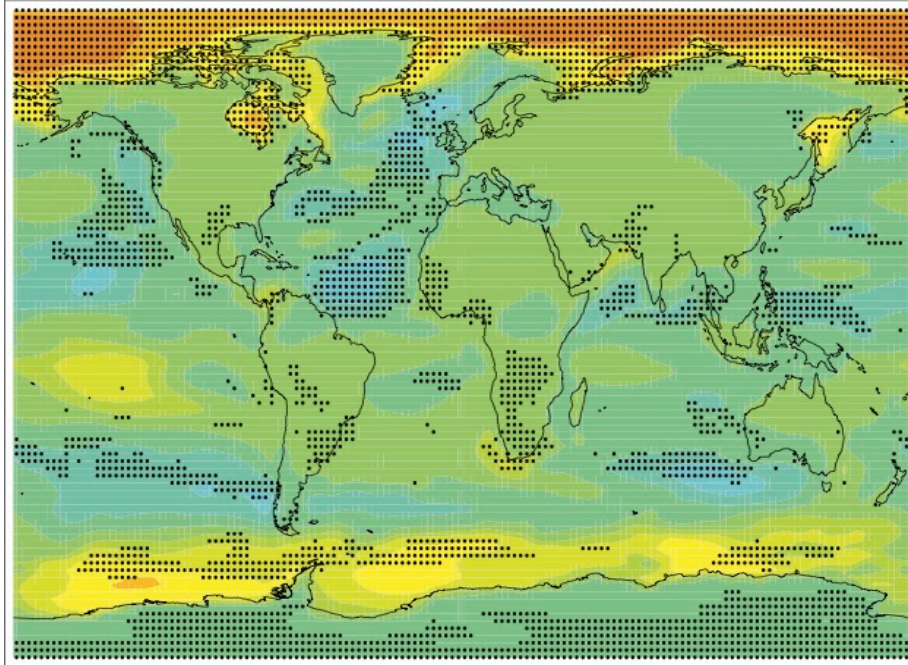


- 5 of 6 models yield **increase** in black carbon burden (and primary organic matter) → 13.6% (-2.6- 20.9%).
- All models yield an **increase** in BC & POM surface concentrations.

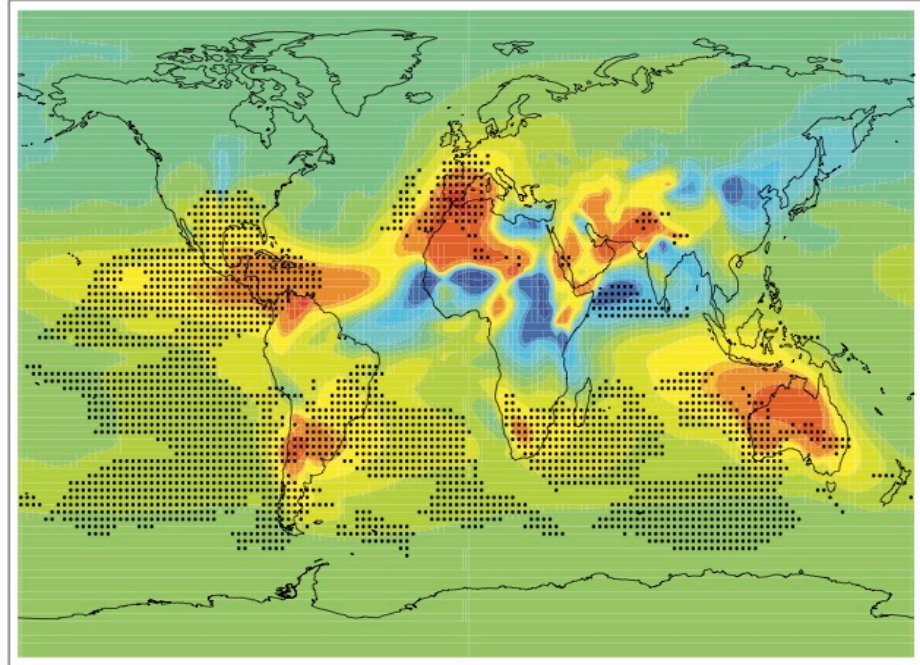
# Natural Aerosols

CMIP5 Models

Sea Salt Burden [ $\text{mg m}^{-2}$ ]



Dust Burden [ $\text{mg m}^{-2}$ ]



- **Natural aerosols** (sea salt, dust) are also generally projected to **increase**.
- Based on a larger set of models (CMIP5), **74%** (**78%**) of models yield an increase in **sea salt** (**dust**) burden.

# Global Mean Sulfate Statistics

	%	Tg/year	Gg	1/day
2000-2010	67	51	14	11
2010-2020	67	51	14	11
2020-2030	67	51	14	11
2030-2040	67	51	14	11
2040-2050	67	51	14	11
2050-2060	67	51	14	11
2060-2070	67	51	14	11
2070-2080	67	51	14	11
2080-2090	67	51	14	11
2090-2100	67	51	14	11
2100-2110	67	51	14	11
2110-2120	67	51	14	11
2120-2130	67	51	14	11
2130-2140	67	51	14	11
2140-2150	67	51	14	11
2150-2160	67	51	14	11
2160-2170	67	51	14	11
2170-2180	67	51	14	11
2180-2190	67	51	14	11
2190-2200	67	51	14	11
2200-2210	67	51	14	11
2210-2220	67	51	14	11
2220-2230	67	51	14	11
2230-2240	67	51	14	11
2240-2250	67	51	14	11
2250-2260	67	51	14	11
2260-2270	67	51	14	11
2270-2280	67	51	14	11
2280-2290	67	51	14	11
2290-2300	67	51	14	11
2300-2310	67	51	14	11
2310-2320	67	51	14	11
2320-2330	67	51	14	11
2330-2340	67	51	14	11
2340-2350	67	51	14	11
2350-2360	67	51	14	11
2360-2370	67	51	14	11
2370-2380	67	51	14	11
2380-2390	67	51	14	11
2390-2400	67	51	14	11
2400-2410	67	51	14	11
2410-2420	67	51	14	11
2420-2430	67	51	14	11
2430-2440	67	51	14	11
2440-2450	67	51	14	11
2450-2460	67	51	14	11
2460-2470	67	51	14	11
2470-2480	67	51	14	11
2480-2490	67	51	14	11
2490-2500	67	51	14	11
2500-2510	67	51	14	11
2510-2520	67	51	14	11
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2530-2540	67	51	14	11
2540-2550	67	51	14	11
2550-2560	67	51	14	11
2560-2570	67	51	14	11
2570-2580	67	51	14	11
2580-2590	67	51	14	11
2590-2600	67	51	14	11
2600-2610	67	51	14	11
2610-2620	67	51	14	11
2620-2630	67	51	14	11
2630-2640	67	51	14	11
2640-2650	67	51	14	11
2650-2660	67	51	14	11
2660-2670	67	51	14	11
2670-2680	67	51	14	11
2680-2690	67	51	14	11
2690-2700	67	51	14	11
2700-2710	67	51	14	11
2710-2720	67	51	14	11
2720-2730	67	51	14	11
2730-2740	67	51	14	11
2740-2750	67	51	14	11
2750-2760	67	51	14	11
2760-2770	67	51	14	11
2770-2780	67	51	14	11
2780-2790	67	51	14	11
2790-2800	67	51	14	11
2800-2810	67	51	14	11
2810-2820	67	51	14	11
2820-2830	67	51	14	11
2830-2840	67	51	14	11
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3880-3890	67	51	14	11
3890-3900	67	51	14	11
3900-3910	67	51	14	11
3910-3920	67	51	14	11
3920-3930	67	51	14	11
3930-3940	67	51	14	11
3940-3950	67	51	14	11
3950-3960	67	51	14	11
3960-3970	67	51	14	11
3970-3980	67	51	14	11
3980-3990	67	51	14	11
3990-4000	67	51	14	11

AP DD WD Burden k k<sub>wet</sub> k<sub>dry</sub>

- Warming → decrease (increase) in sulfate wet (dry) removal.
- Removal rate (k = deposition/burden) decreases, esp. k<sub>wet</sub>.
- Inconsistent w/ Δglobal mean precipitation (+6.4%).
- Similar results for BC, POM → Efficiency with which aerosols are removed from the atmosphere by precipitation decreases in a warmer world.

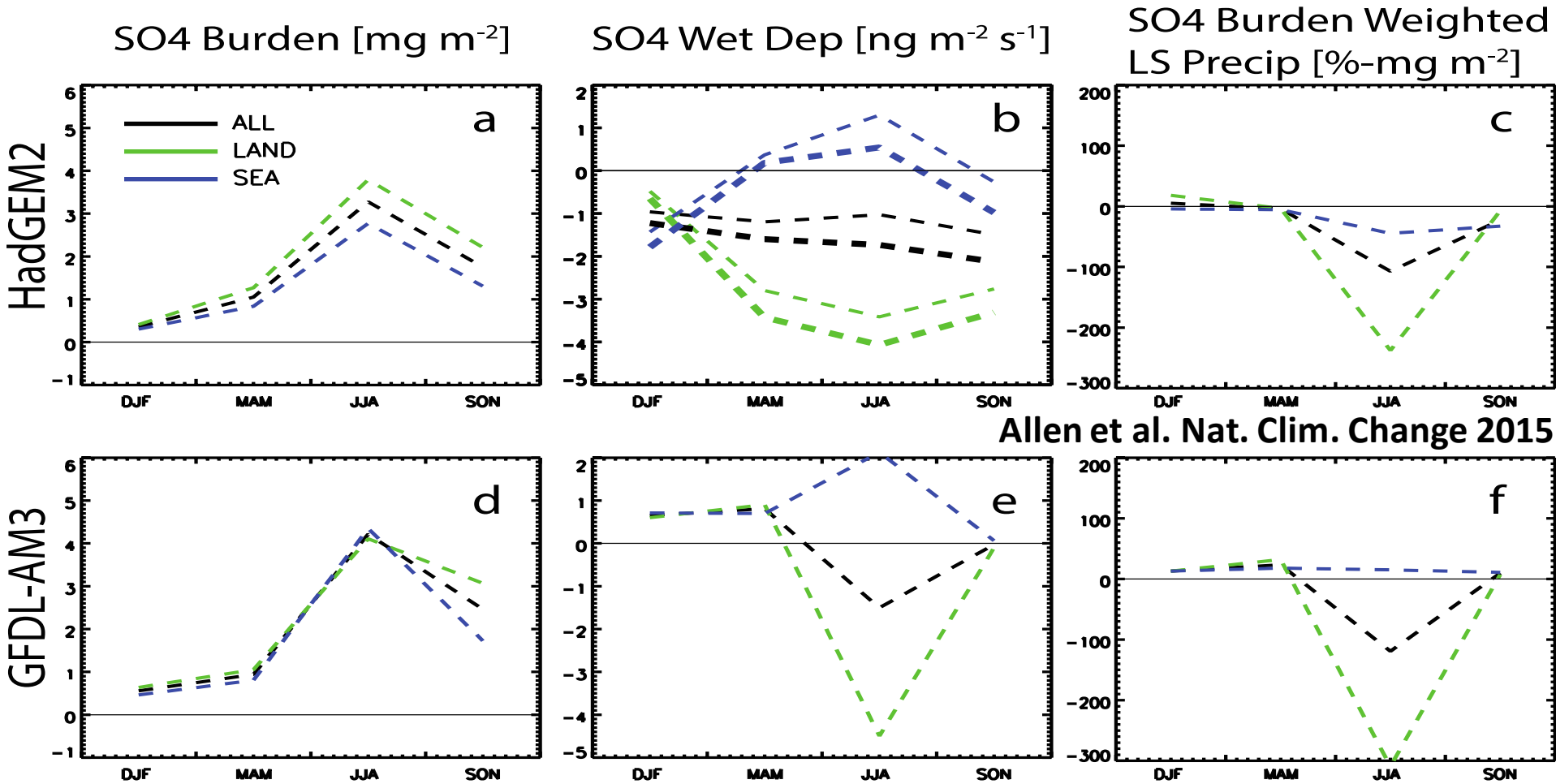
# Wet Removal: Large Scale (LS) vs Convective (CON) Precipitation

Model	SO4 LS WD		SO4 CON WD		BC LS WD		BC CON WD		POM LS WD		POM CON WD	
	2000	2100	2000	2100	2000	2100	2000	2100	2000	2100	2000	2100
CAM5	79.92	77.32	63.79	61.48	3.35	3.23	3.10	3.15	19.24	18.67	23.18	23.40
HadGEM2	115.31	110.06	30.60	35.31	2.68	2.43	3.45	3.58	28.52	26.34	18.09	19.72

- Nearly all of the **decrease** in **wet removal** is associated with **LS P** (i.e., precipitation produced by cloud/microphysics scheme).
- **Wet removal** by **CON P** generally **increases**.



# NH Mid-latitude $\Delta\text{SO}_4$ by Season



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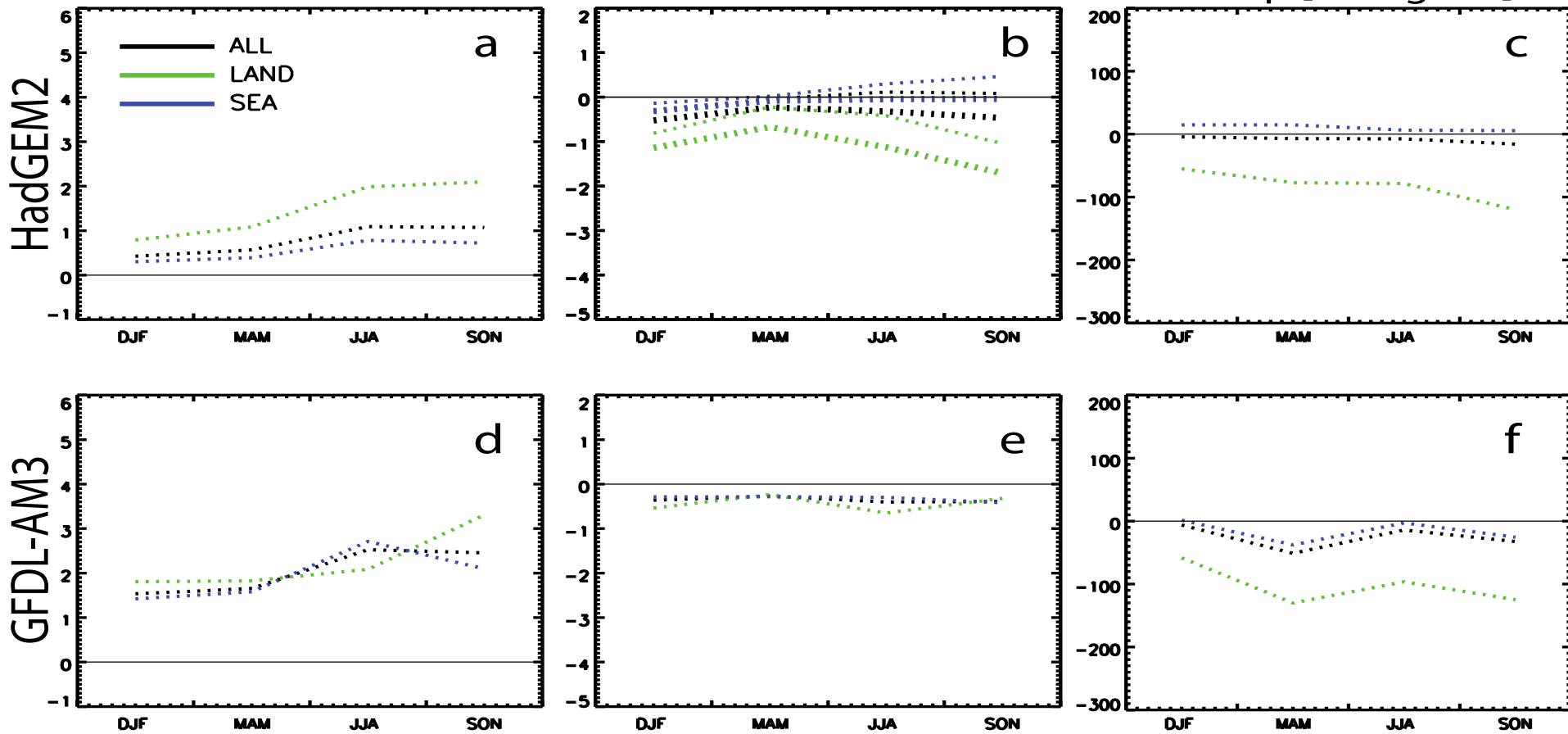
- SO4 burden **increase** largest over **NH midlatitude land** during **JJA**.
- Corresponding **maximum decrease** in wet removal (esp. due to **LS P**) & **burden-weighted LS P**.
- **Wet removal** over **ocean** tends to **increase** (esp. **JJA**).
- Similar results for BC, POM & other models.

# Tropical $\Delta\text{SO}_4$

SO4 Burden [ $\text{mg m}^{-2}$ ]

SO4 Wet Dep [ $\text{ng m}^{-2} \text{s}^{-1}$ ]

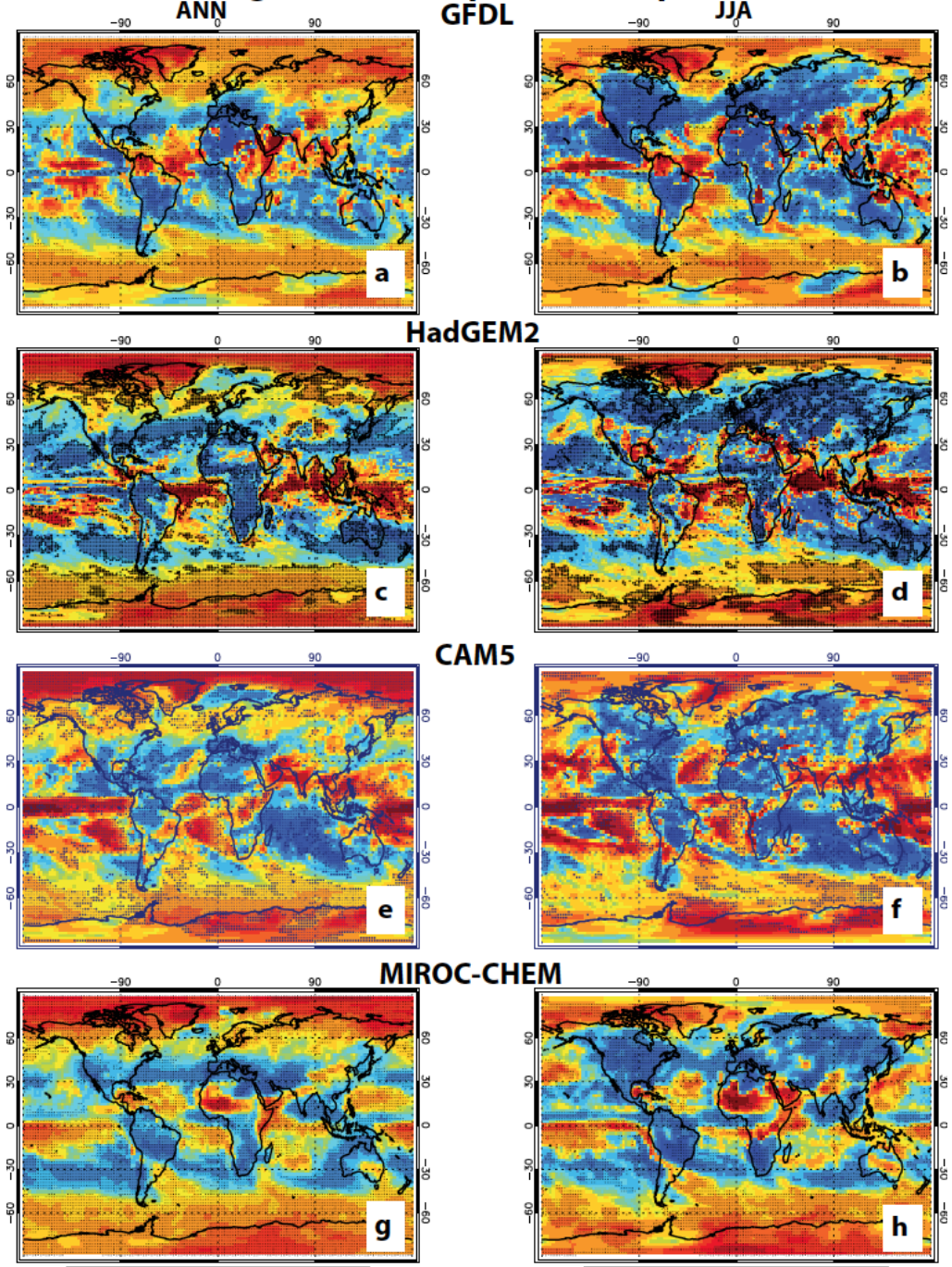
SO4 Burden Weighted  
LS Precip [ $\% \text{-mg m}^{-2}$ ]



- More seasonally uniform **increase** in the tropics.
- **Decrease** in wet deposition (esp. due to **LS P**) and burden-weighted **LS P**, esp. over **land**.
- Similar results for black carbon (and POM).

# Large-Scale Precipitation Response [%]

- Although global **increase** in **LS P** → **NH mid-latitude & tropical land LS P decreases** (esp. JJA).
- **20-40% JJA LS P decrease** over **NH mid-latitude land masses** (CMIP5 similar).
- Multi-model mean **NH spatial correlation** between  $\Delta SO_4$  **burden** and  $\Delta LS P$  is -**0.48**.

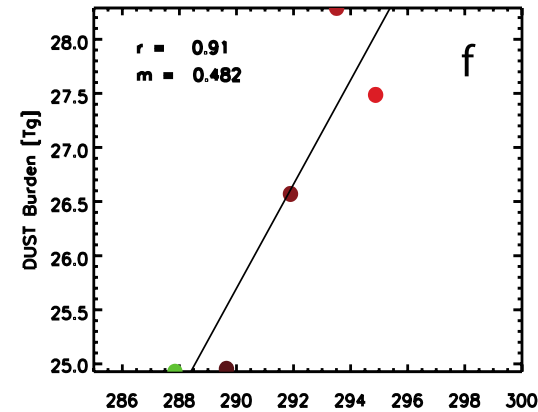
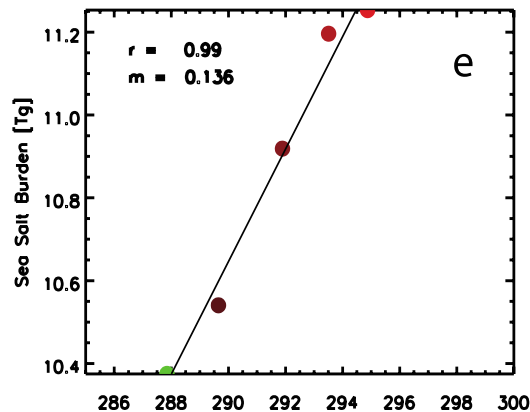
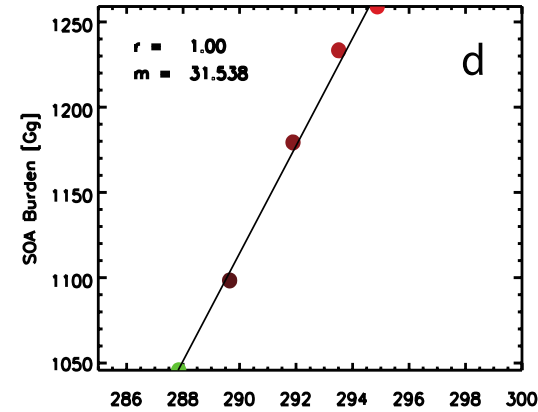
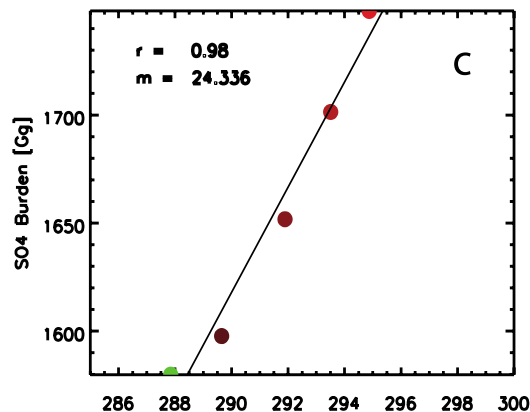
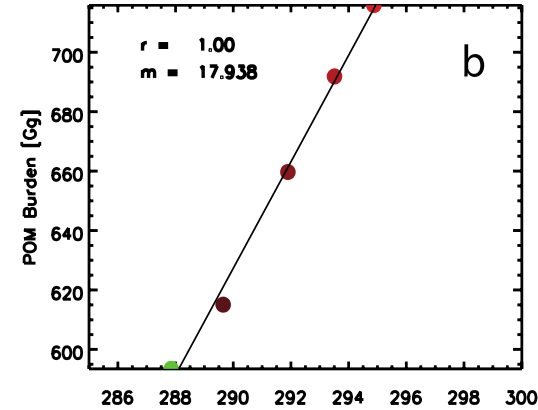
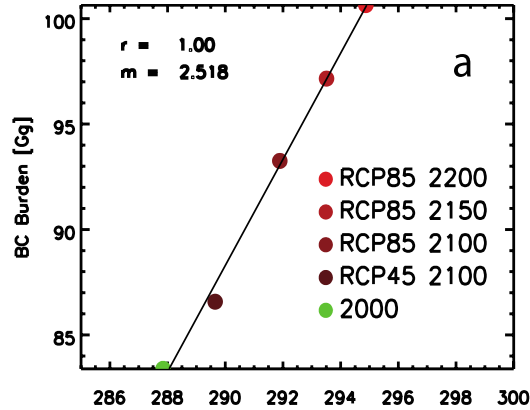


# Summary of Mechanism

- The **increase** in sulfate burden, most of which occurs during *JJA*, is associated with a **decrease** in *JJA LSP* over *NH mid-latitude* and *tropical land* areas, where burden is already relatively large.
- This drives a **decrease** in *wet removal*, and an **increase** in sulfate burden, some of which gets transported over the **ocean**.
- This leads to an **increase** in **wet removal** over the **ocean**, but this increase is not large enough to offset the enhanced transport, resulting in a net **increase** in burden over the **ocean** as well.
- Similar argument exists for other anthropogenic aerosol species (BC, POM).
- The increase in **sea salt** is primarily driven by an **increase** in **surface winds** (and a **reduction** in **sea-ice**), especially at high-latitudes.

# CAM5 Global Warming Results

- All aerosol species yield a **positive** slope w/  $T_s \rightarrow$  an **increase** in aerosol burden is a **robust response** to **warming**.
- Similar results with CAM4 (different aerosol scheme).



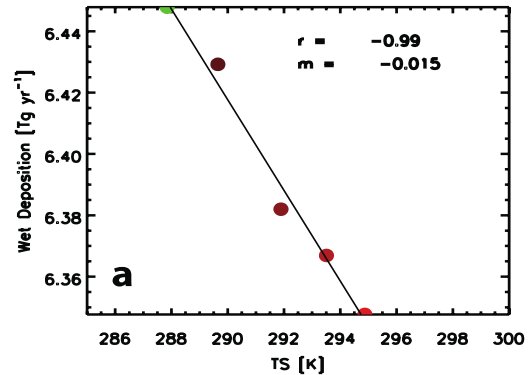


- **CAM5 wet (dry)** deposition of SO<sub>4</sub>, BC and POM linearly **decreases (increases)** as the surface warms.

- Further supports importance of a **decrease** in **wet removal** as the dominant driver of the **increase** in **aerosol burden**.

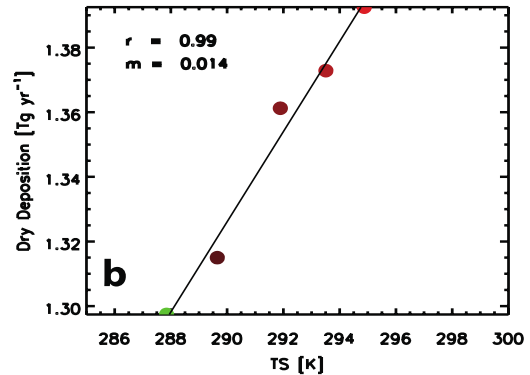
CAM5

Wet Deposition

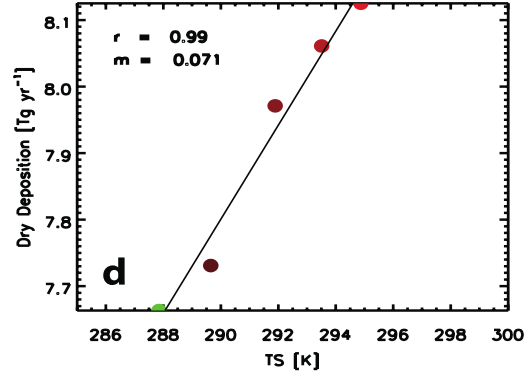
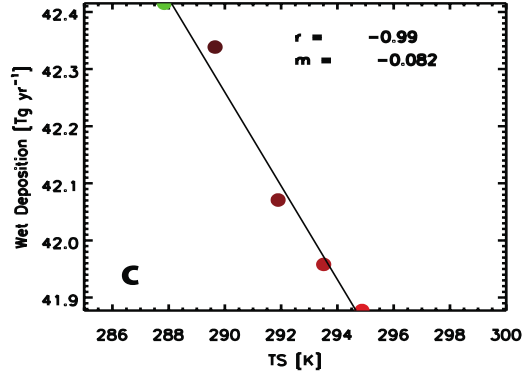


Black Carbon

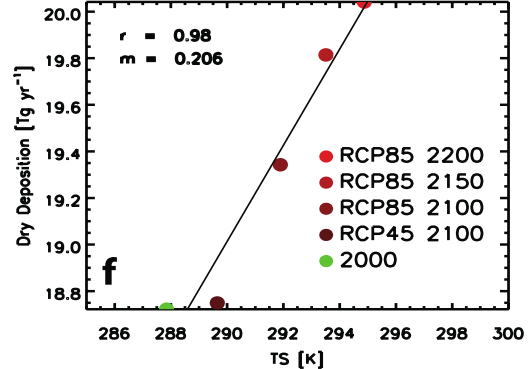
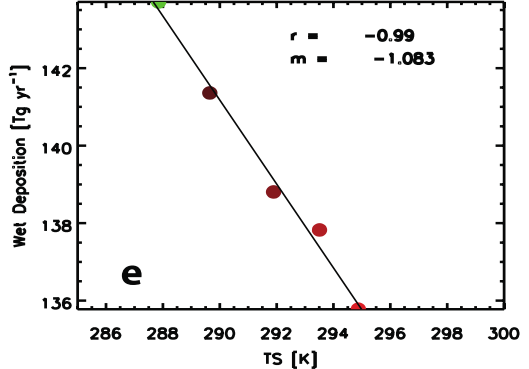
Dry Deposition



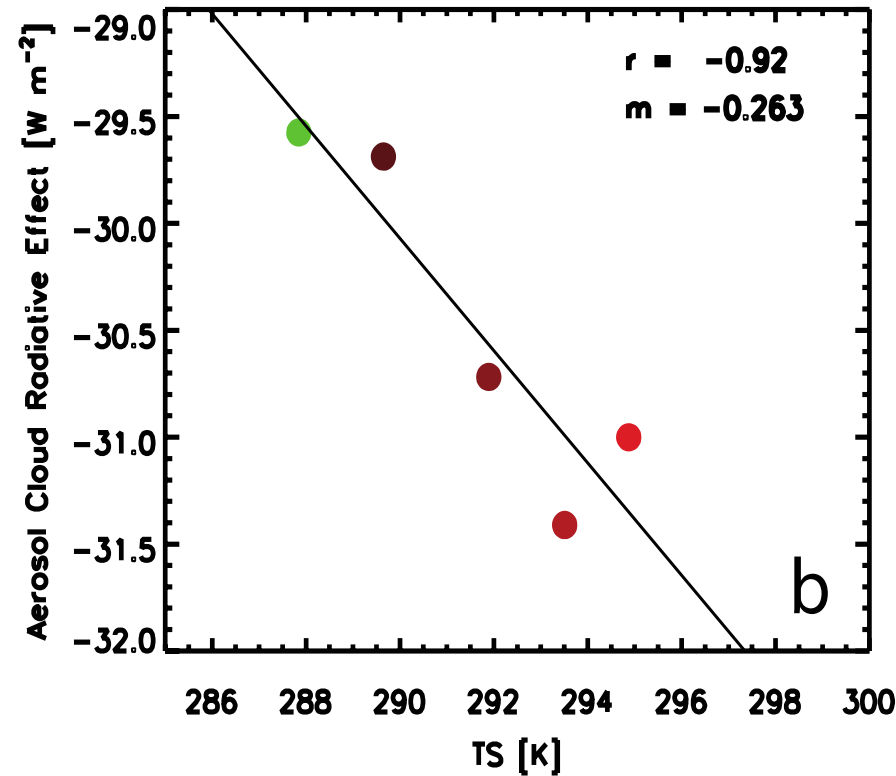
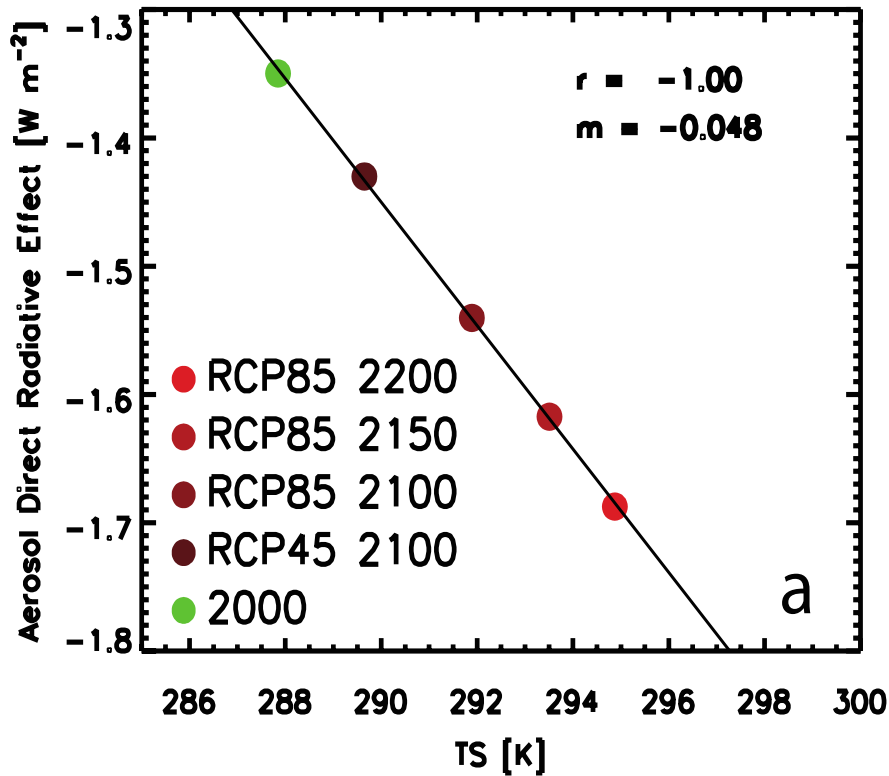
Primary Organic Matter



Sulfate



# CAM5 Aerosol Climate Feedback

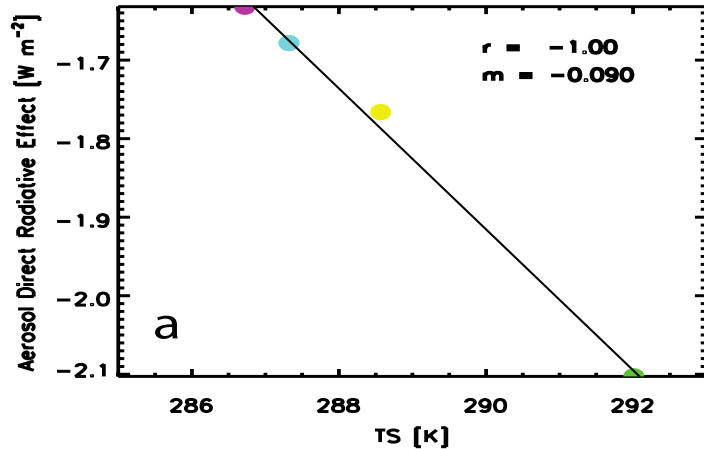


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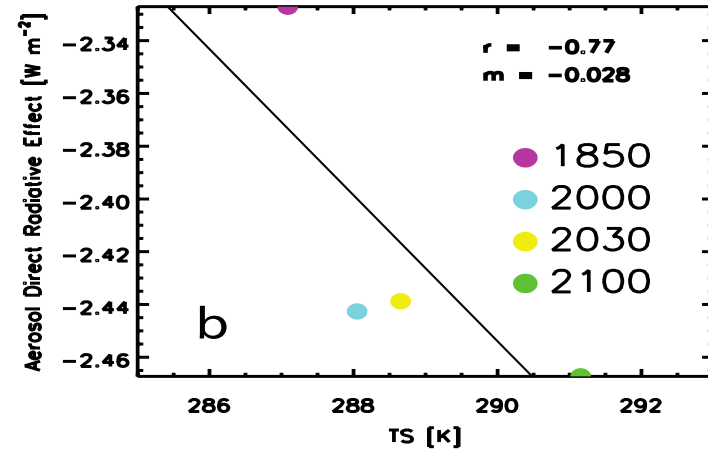
- Warming increases the (negative) **direct radiative effect** of aerosols  $\rightarrow$  **negative** feedback to imposed warming of  $-0.05 \text{ W m}^{-2} \text{ K}^{-1}$ .
- **Anthropogenic aerosols** account for **30%**; **natural aerosols** (primarily sea salt) account for **70%**.
- Much **larger cloud radiative effect feedback**  $\rightarrow -0.26 \text{ W m}^{-2} \text{ K}^{-1}$ .

# ACCMIP Aerosol Direct Radiative Effect [ $\text{W m}^{-2}$ ]

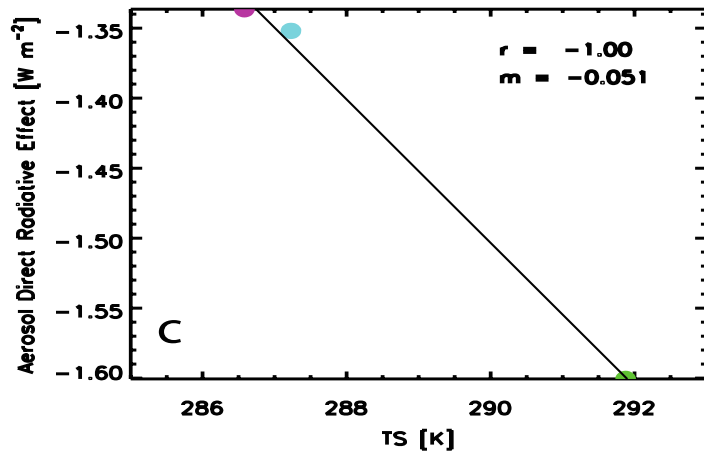
GFDL-AM3



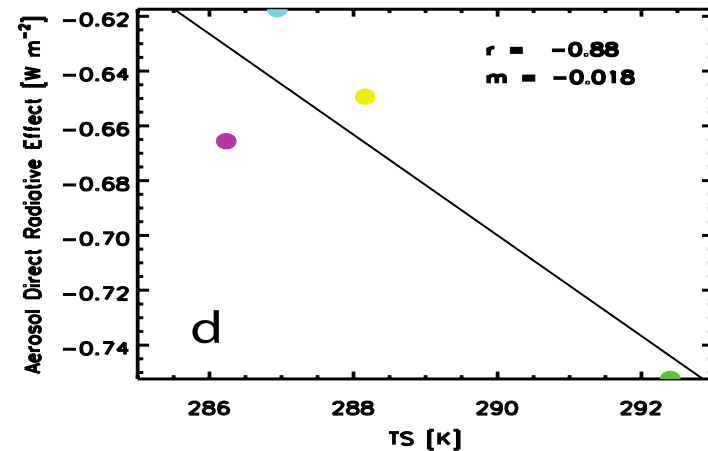
GISS-E2-R-p3



HadGEM2



MIROC-CHEM

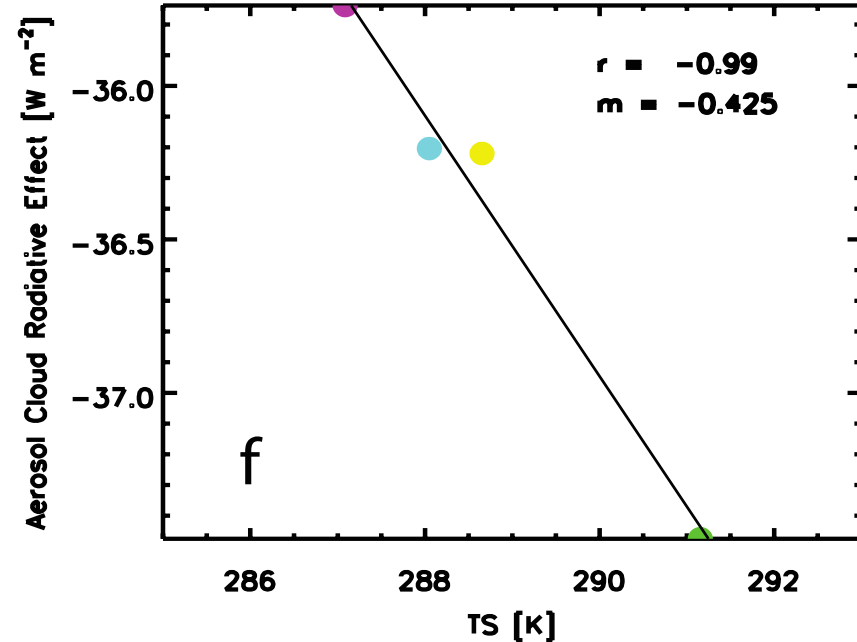
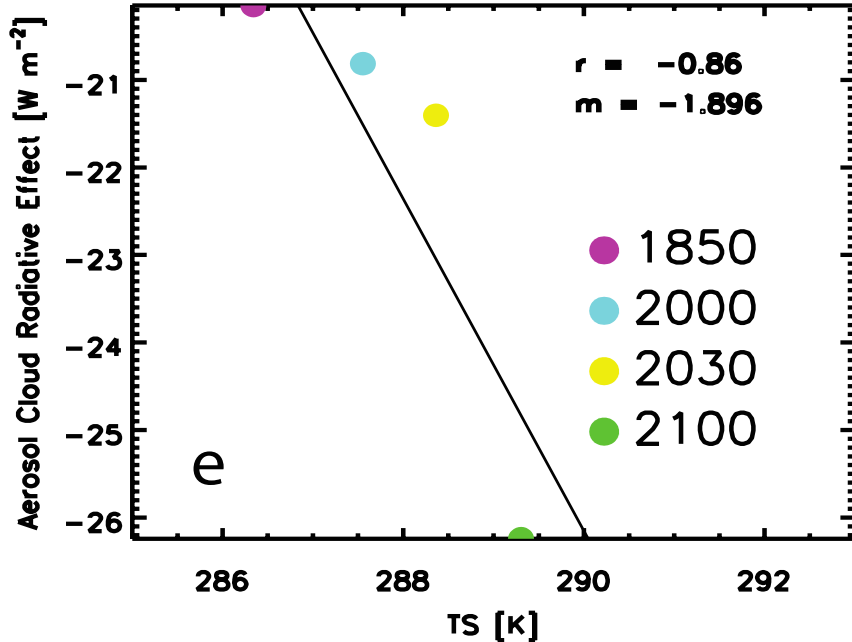


- Similar **negative DRE feedback** in ACCMIP of **-0.05 (-0.02 to -0.09)  $\text{W m}^{-2} \text{K}^{-1}$** .
- Weaker increases in sea salt  $\rightarrow$  **anthropogenic (natural)** aerosols likely a **larger (smaller)** contributor than in CAM5.

# ACCMIP Aerosol Cloud Radiative Effect [ $\text{W m}^{-2}$ ]

CESM-CAM-superfast

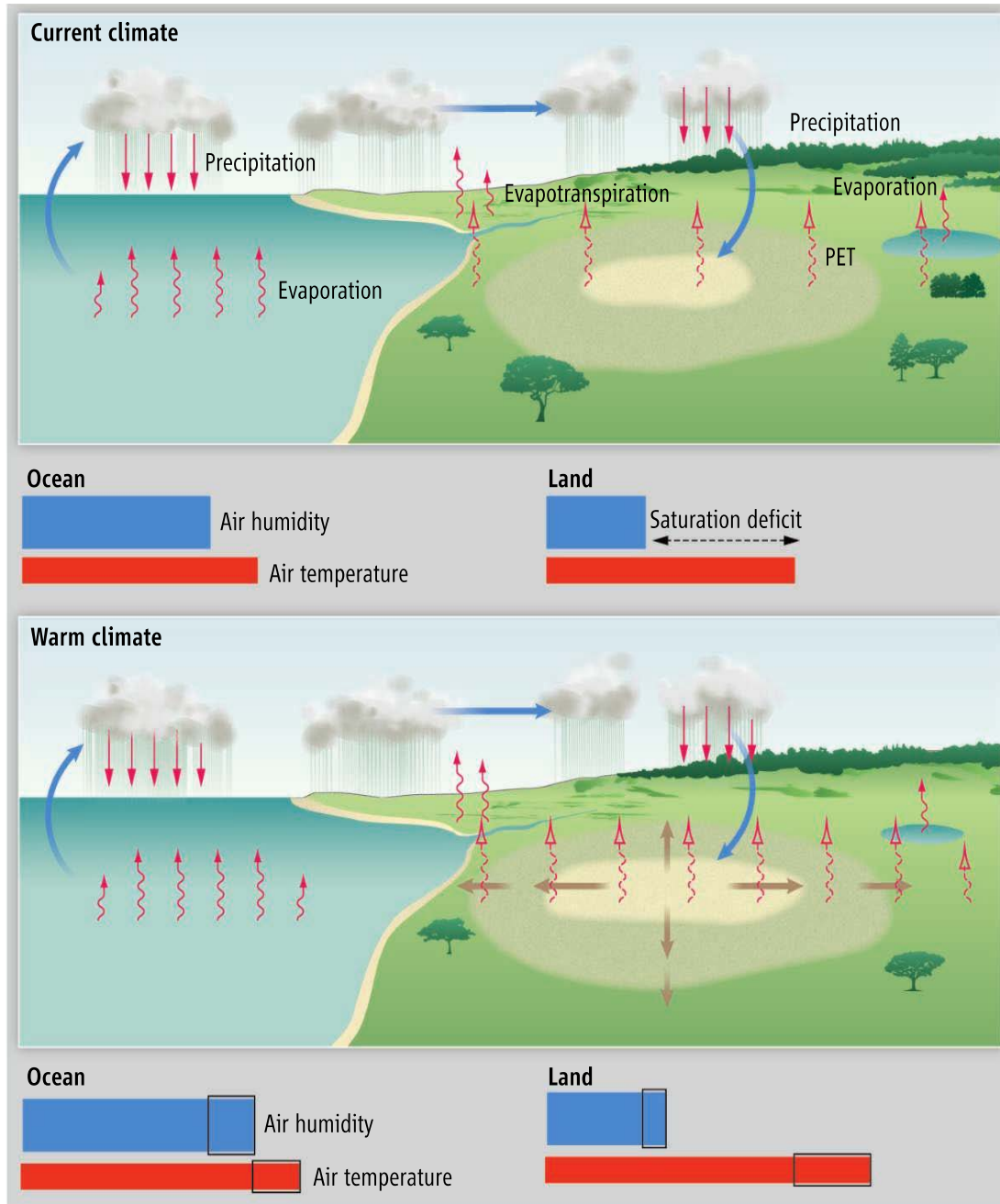
GISS-E2-R-p3



- **CRE feedback** of  $-0.43 \text{ W m}^{-2} \text{ K}^{-1}$  (GISS-E2-R) and  $-1.90 \text{ W m}^{-2} \text{ K}^{-1}$  (CESM-CAM-superfast).
- **Total aerosol feedback (DRE+CRE)** based on CAM5 and GISS-E2-R ranges from  $-0.21$  to  $-0.46 \text{ W m}^{-2} \text{ K}^{-1}$ , most of which is due to **aerosol-cloud interactions**.

# Future Work

- Due to strong increases in **TS** over land → **saturated water vapor concentration** exceeds growth in actual **water vapor concentration**.
- **Relative humidity decreases** over land.
- Is this why models simulate robust **LS P decreases**? Cause of the **aerosol increase** under warming?





# Proposed AeroCom Experiments

- To evaluate **how/why aerosol burden responds to warming** → 2 simulations with identical aerosol emissions:
  - One based on present-day climate (SSTs, sea-ice, GHGs).
  - One based on end-of-the-century climate (e.g., RCP8.5 2100). Similar to ACCMIP.
  - Important diagnostics include: aerosol concentrations, LS/CON P, wet/dry removal (LS/CON P), chemical production rates (SOA, SO<sub>4</sub>), RH, surface U, V, T, maybe others?
- To evaluate importance of **enhanced land warming/decreases in land RH and LS P**:
  - Identical end-of-the-century simulation, but near-surface land temperatures are nudged to the control (present-day) simulation.
- If interested, please see me, or email at:  
**[rjallen@ucr.edu](mailto:rjallen@ucr.edu)**

# Conclusions

- State-of-the-art chemistry-climate models simulate an **increase** in **most aerosol species** under warming.
- Bulk of response driven by **decreases** in **large-scale precipitation** over **land**, esp. the **NH mid-latitudes JJA**.
- Global warming may **exacerbate air quality** and drive a **negative aerosol-climate feedback**.
- Future work:
  - Relate this response to fundamental/robust changes over **land** (i.e., **increased aridity**).
  - Analyze new simulations (CCMI; CMIP6; AeroCom)
  - Perform experiments with new CAM and GFDL models.