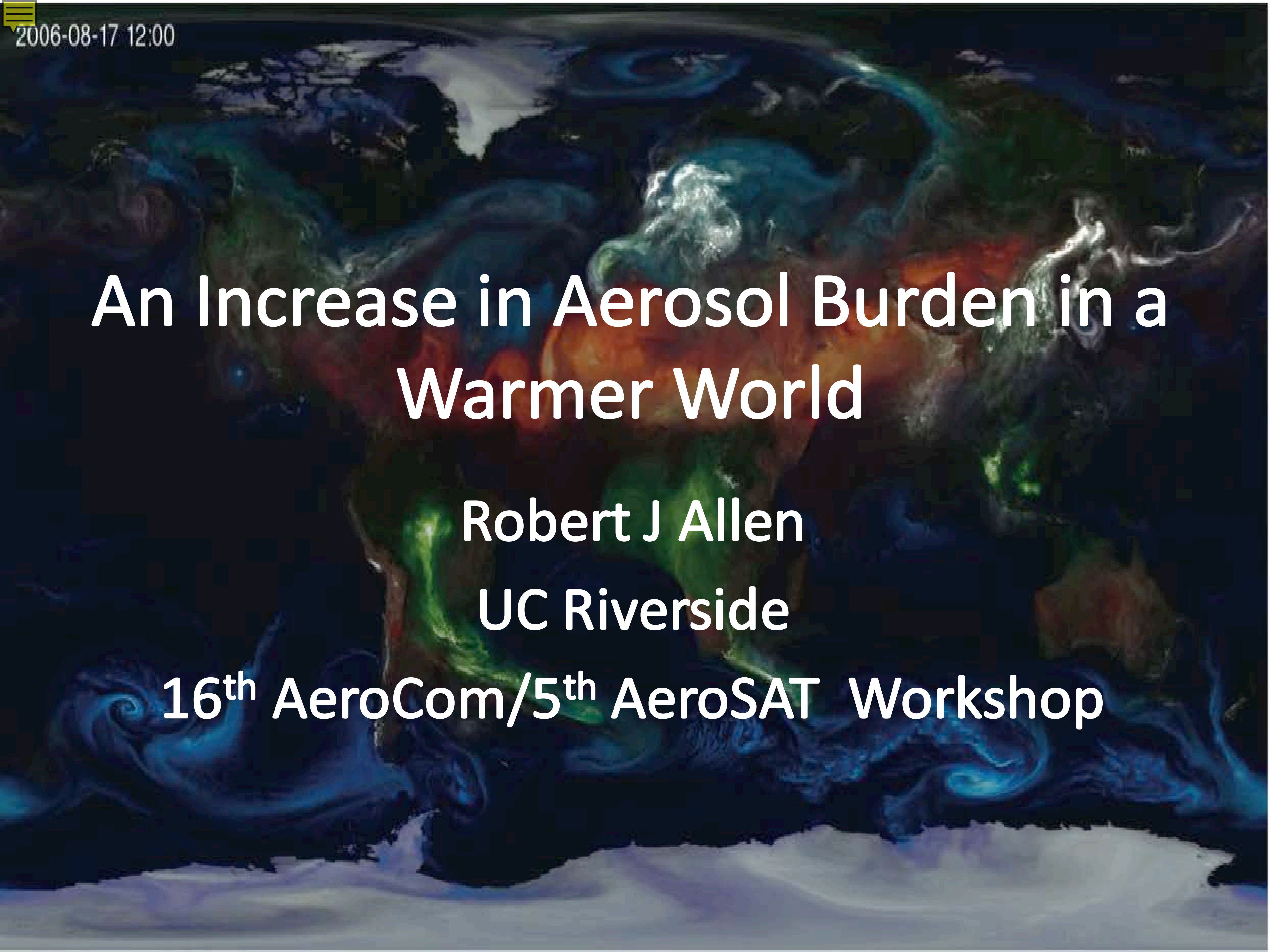

An Increase in Aerosol Burden in a Warmer World

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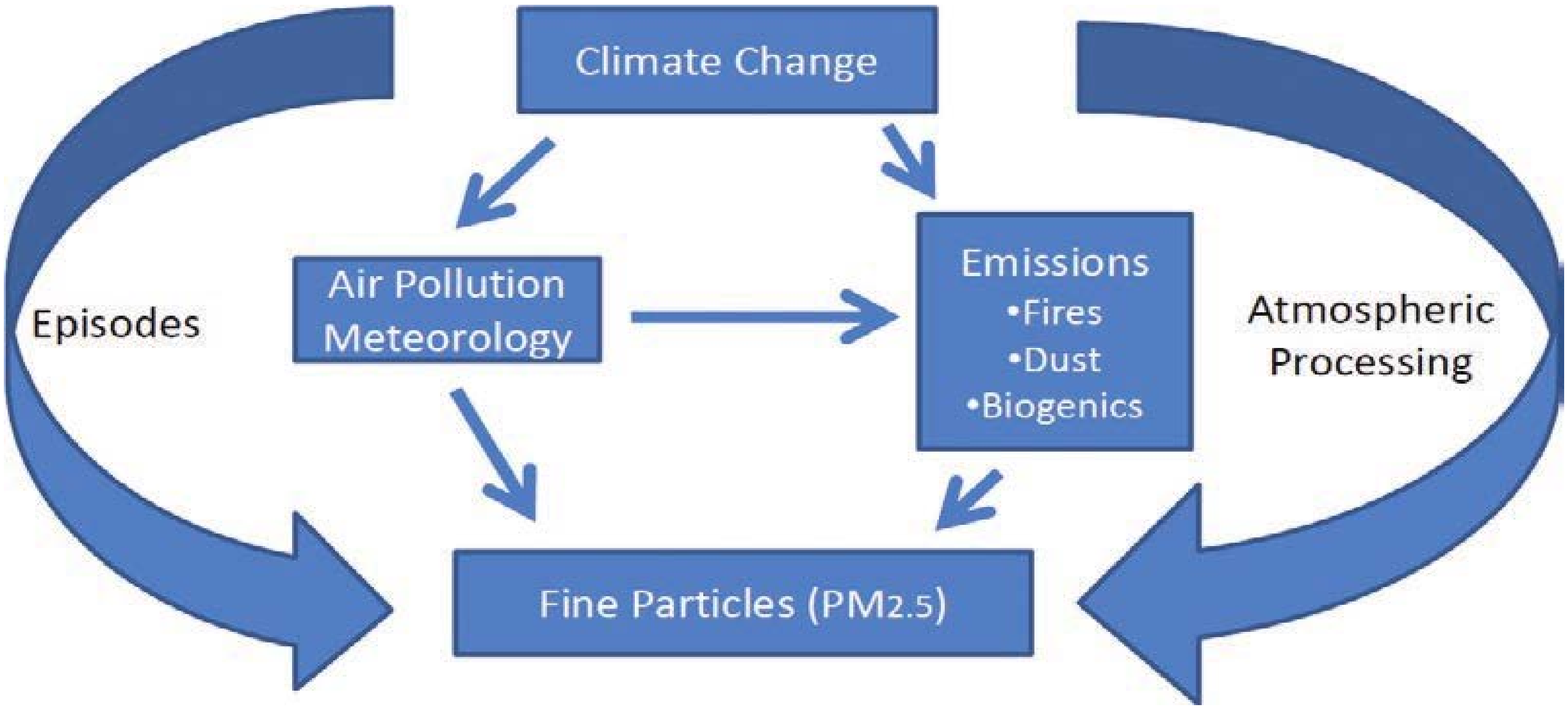
16th AeroCom/5th AeroSAT Workshop

Impacts of Climate Change on Aerosols



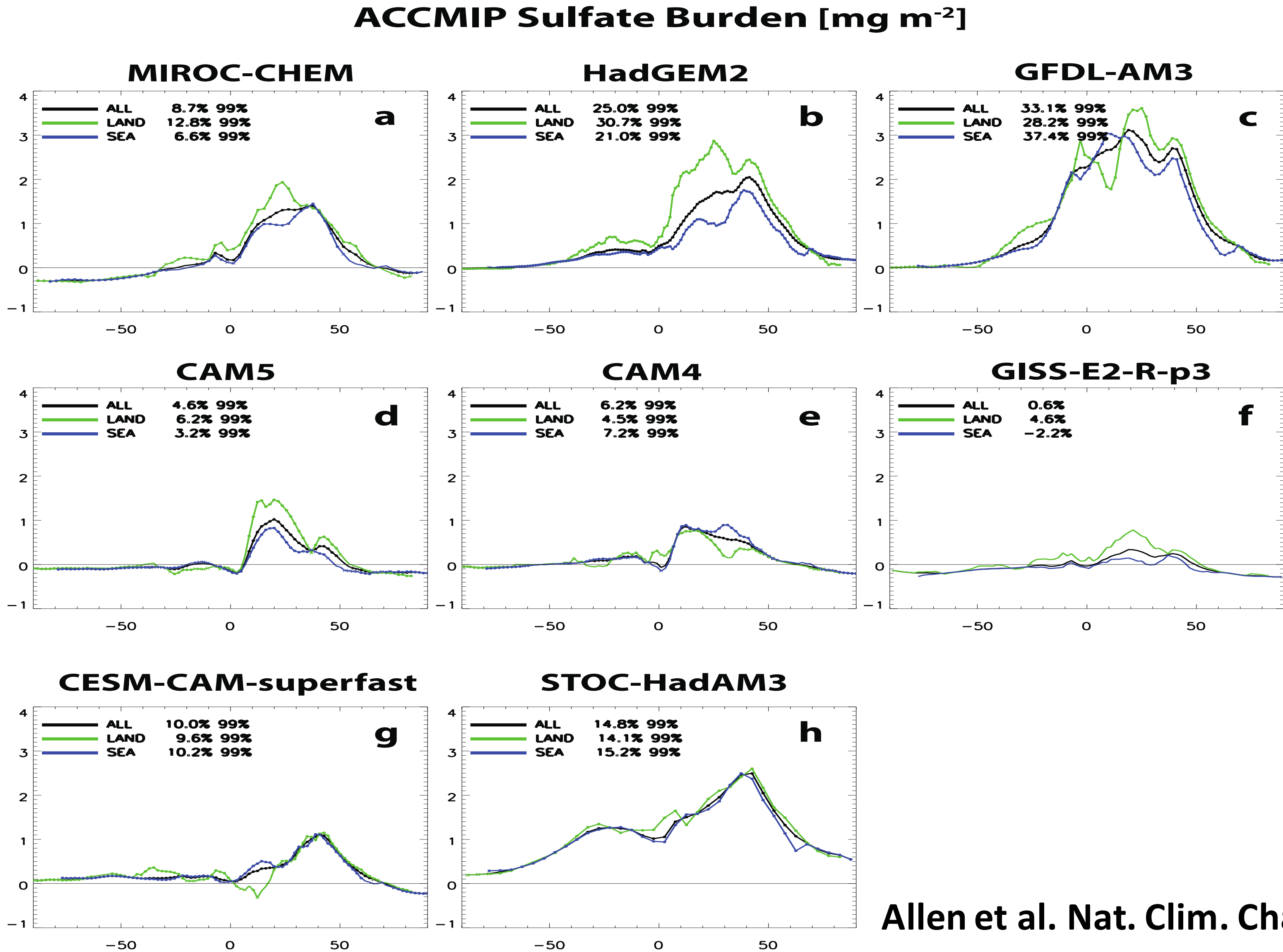
- Physical → temperature, humidity, precipitation, soil moisture, wind speed, sea-ice extent
- Chemical → availability of oxidants; chemical production pathways
- Biological → vegetation cover/properties, plankton abundance

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^{-2} K^{-1}).

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).



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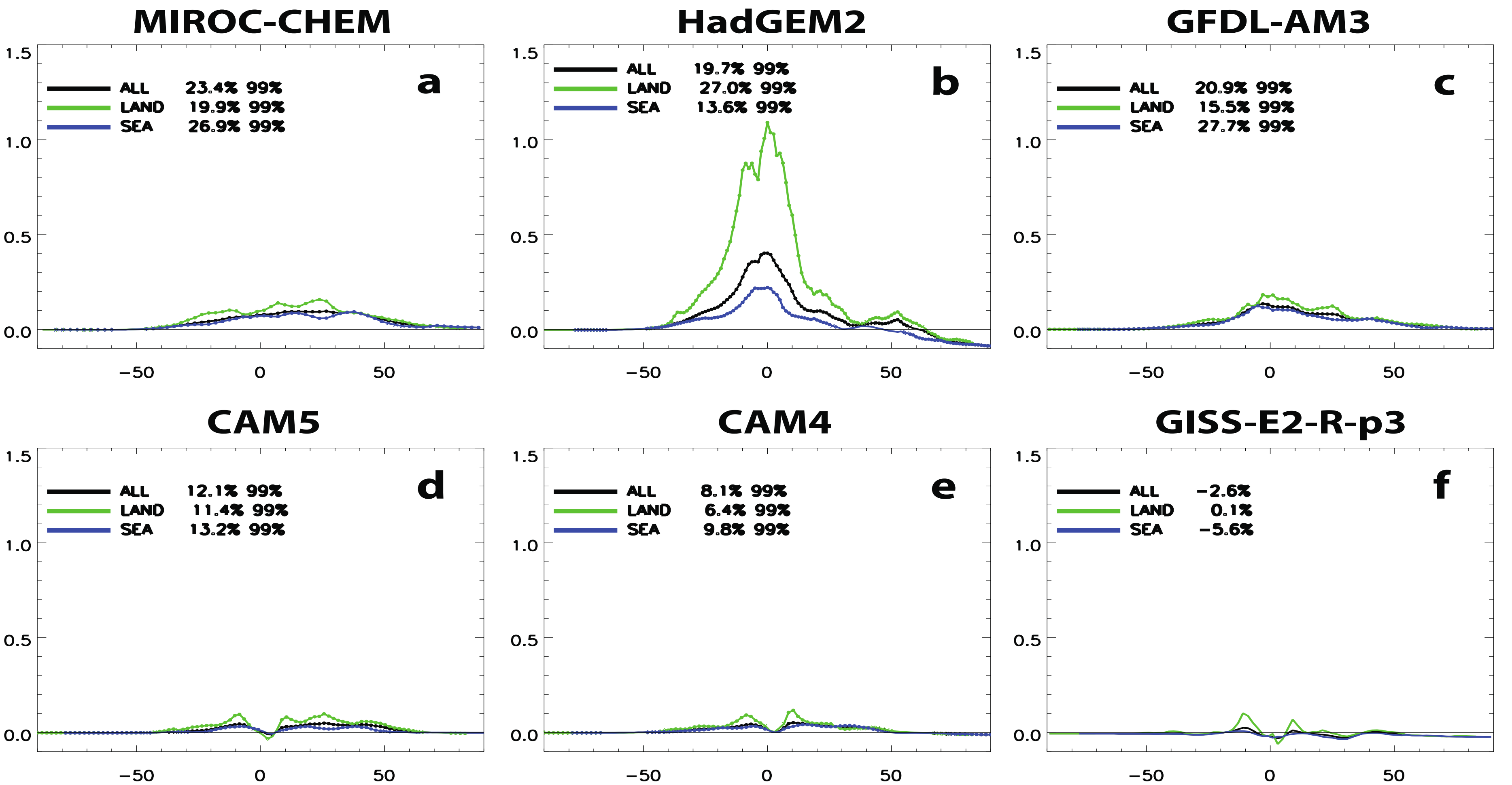
- All ACCMIP models yield a global annual mean *increase* in **sulfate burden** (and surface concentration) in a *warmer world*→ **12.9%** with a range from **0.6 to 33%.**
- Increase largest in **tropics** and **NH mid-latitudes.**

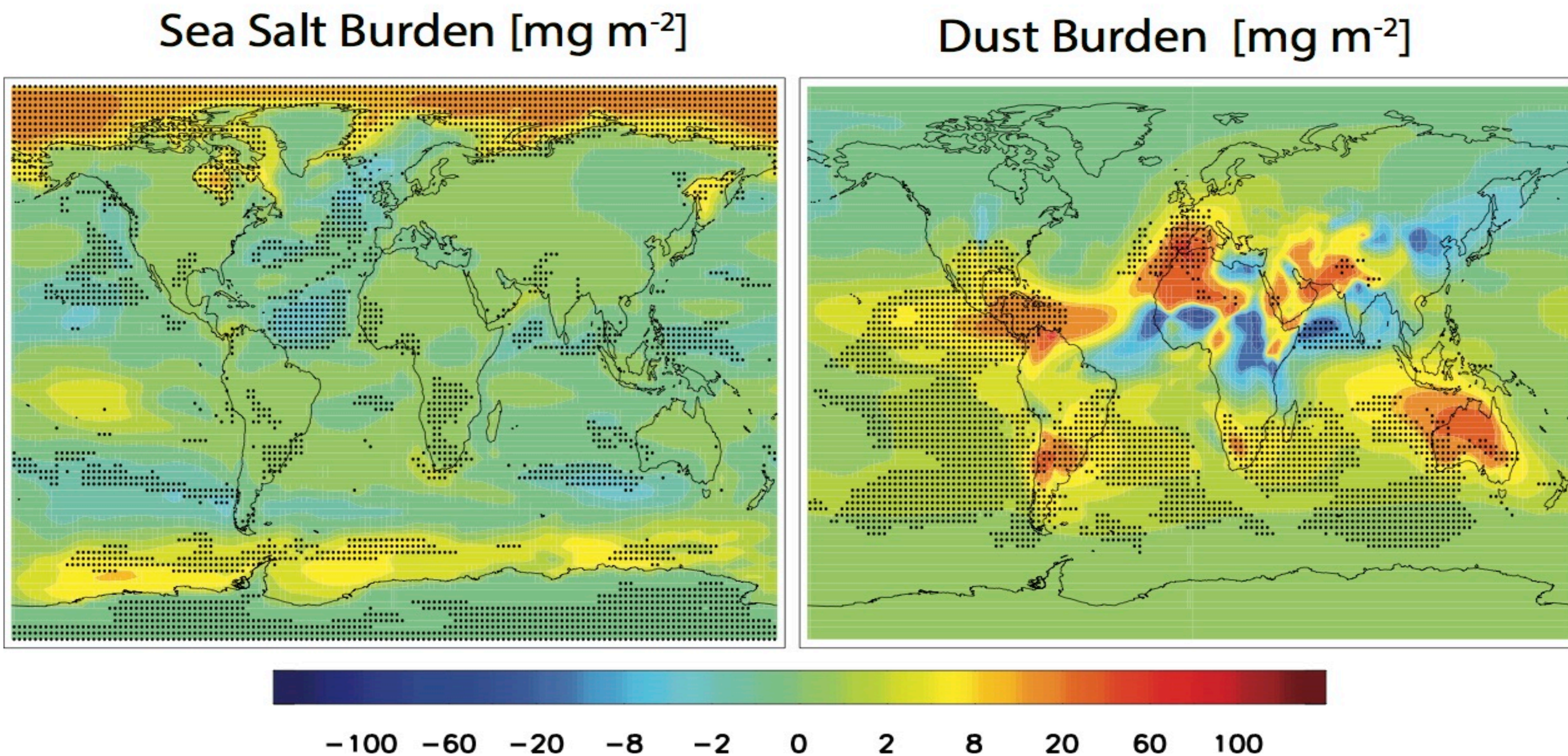
ACCMIP Black Carbon Burden [mg m⁻²]



- 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



- **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

Model	ΔP	DD 2000	DD 2100	WD 2000	WD 2100	Burden 2000	Burden 2100	k 2000	k 2100	k_{dry} 2000	k_{dry} 2100	k_{wet} 2000	k_{wet} 2100
CAM4	8.6	20.5	20.8	161.5	158.6	1919.6	2041.8	0.259	0.241	0.029	0.028	0.230	0.213
CAM5	7.0	18.7	19.3	143.7	138.8	1579.8	1651.8	0.282	0.262	0.032	0.032	0.249	0.230
CESM-CAM-superfast	1.4	15.5	15.9	118.5	119.6	1465.3	1611.9	0.250	0.230	0.029	0.027	0.222	0.203
GFDL-AM3	8.7	17.8	29.6	86.6	86.2	2255.1	3001.6	0.127	0.097	0.022	0.188	0.105	0.079
GISS-E2-R-p3	5.1	18.3	18.7	134.5	132.3	1248.3	1255.9	0.335	0.330	0.040	0.041	0.295	0.289
HadGEM2	6.7	18.9	20.1	145.9	145.4	1522.9	1903.8	0.297	0.238	0.034	0.029	0.262	0.209
MIROC-CHEM	9.8	21.1	23.9	176.1	169.5	2213.7	2406.8	0.244	0.220	0.026	0.027	0.218	0.192
STOC-HadAM3	6.5	29.1	33.3	104.4	108.8	4438.1	5095.3	0.082	0.076	0.018	0.018	0.064	0.058

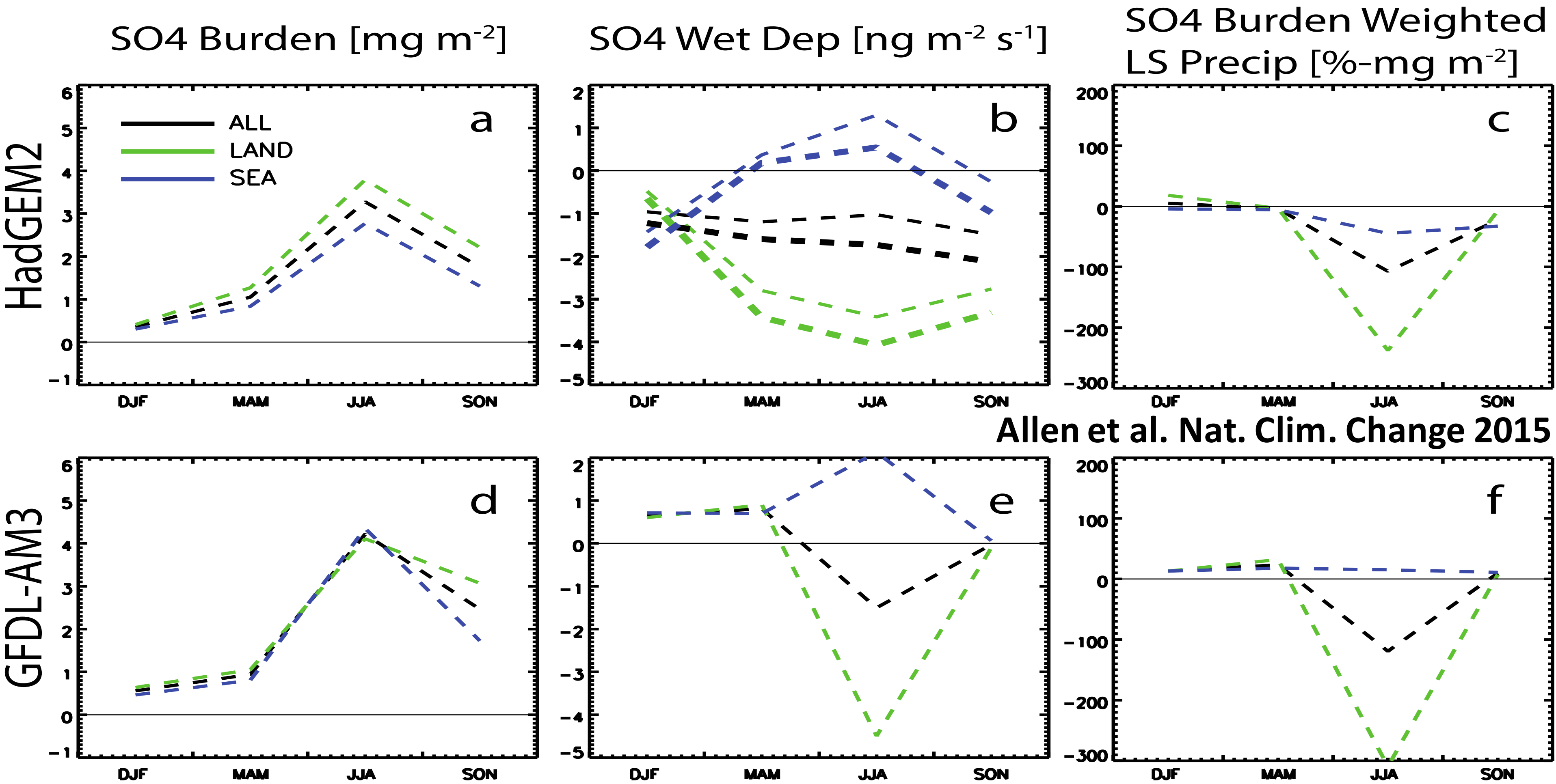
- Warming → decrease (increase) in ***sulfate wet (dry) removal***.
- **Removal rate** (k = deposition/burden) decreases, esp. k_{wet}.
- *Inconsistent* w/ Δ***global mean precipitation*** (+6.4%).
- Similar results for BC, POM →***Efficiency with which aerosols are removed from the atmosphere by precipitation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

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

	SO4 LS WD		SO4 CON WD		BC LS WD		BC CON WD		POM LS WD		POM CON WD	
Model	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

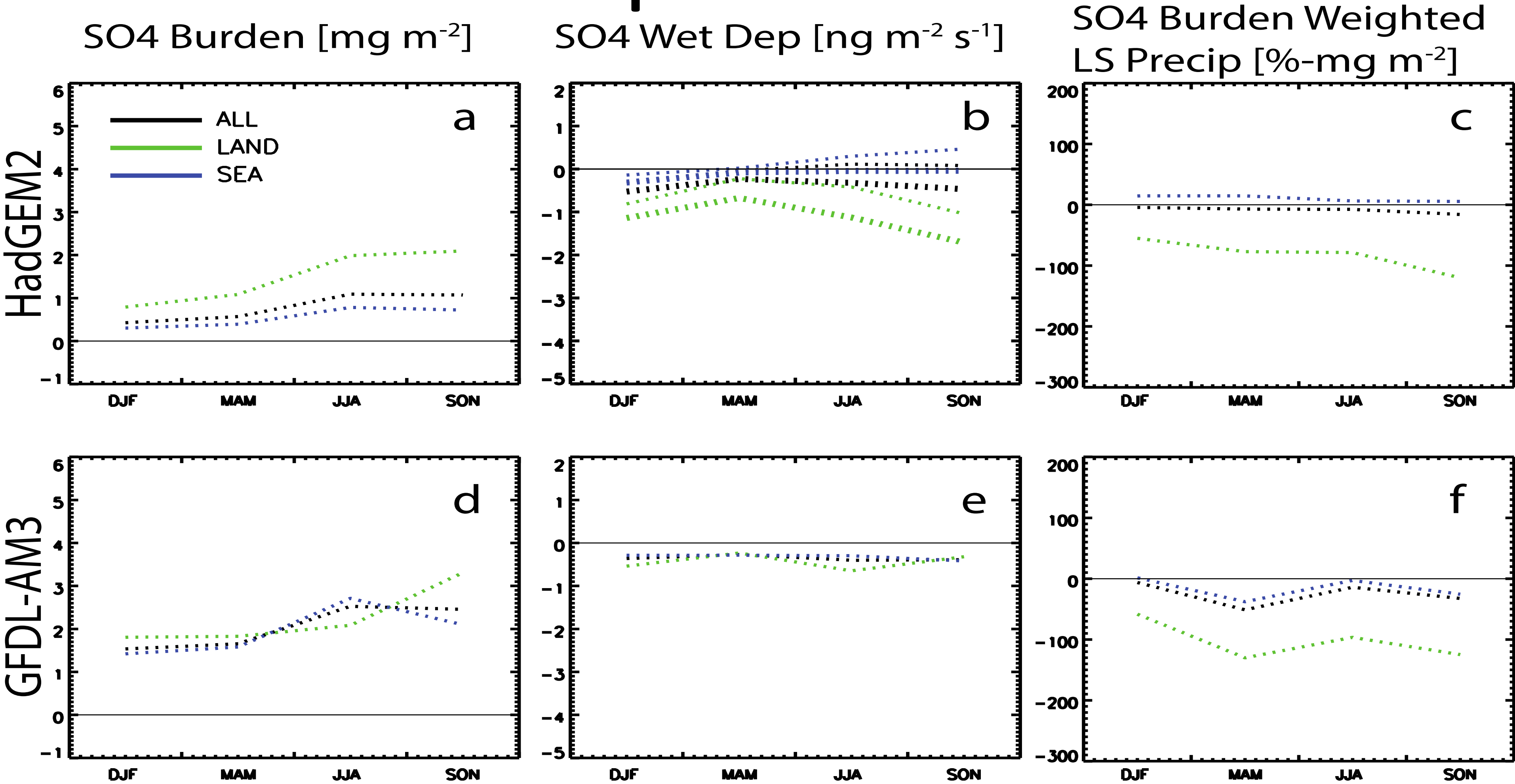
- Nearly all of the decrease in **wet removal** is associated with LS P (i.e., precipitation produced by cloud/microphysics scheme).
- **Wet removal** by CON P generally increases.

NH Mid-latitude ΔSO4 by Season



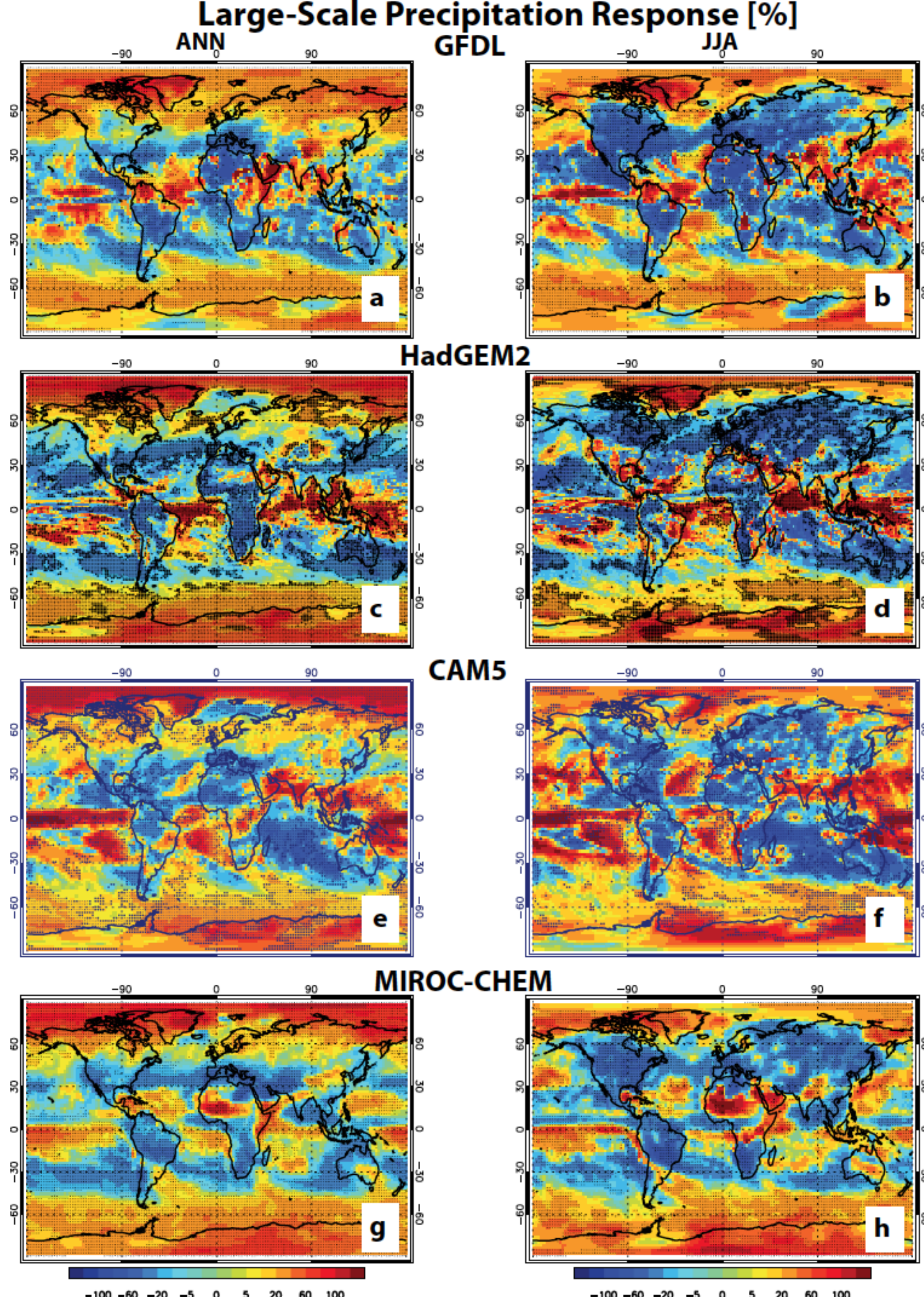
- SO4 burden *increase* **largest** over ***NH midlatitude*** *land* during ***JJA***.
- Corresponding ***maximum*** **decrease** in **wet removal** (esp. due to LS P) & **burden-weighted** LS P.
- **Wet removal** over ocean tends to increase (esp. **JJA**).
- Similar results for BC, POM & other models.

Tropical ΔSO4



- 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).

- 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 ***ΔSO4 burden*** and ***ΔLS P*** is ***-0.48.***

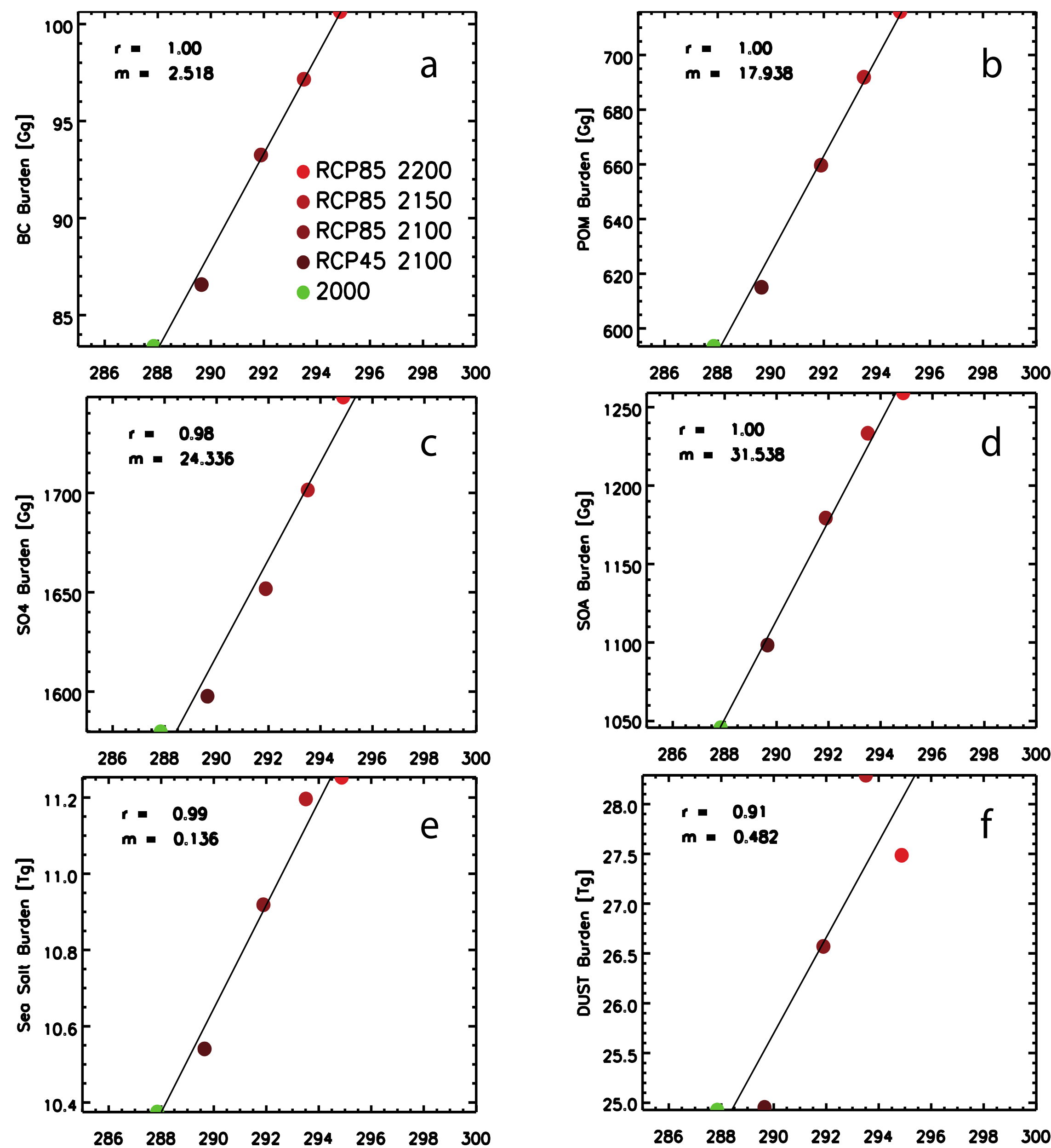


Summary of Mechanism

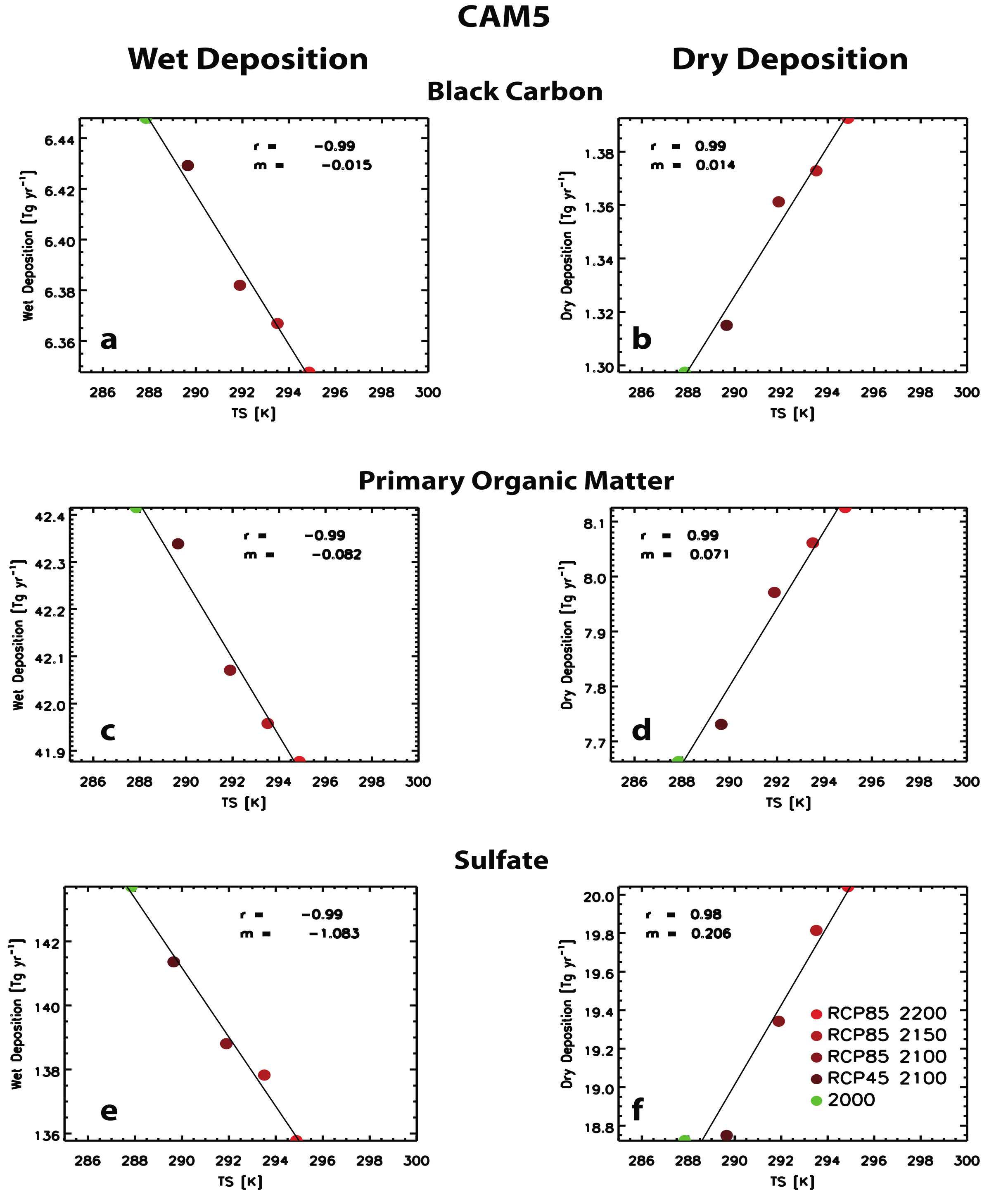
- The increase in sulfate burden, most of which occurs during ***JJA***, is associated with a decrease in ***JJA*** *LS P* over ***NH mid-latitude*** and ***tropical*** *land* areas, where burden is already relatively large.
- This drives a decrease in ***wet removal***, and an increase in sulfate burden, 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

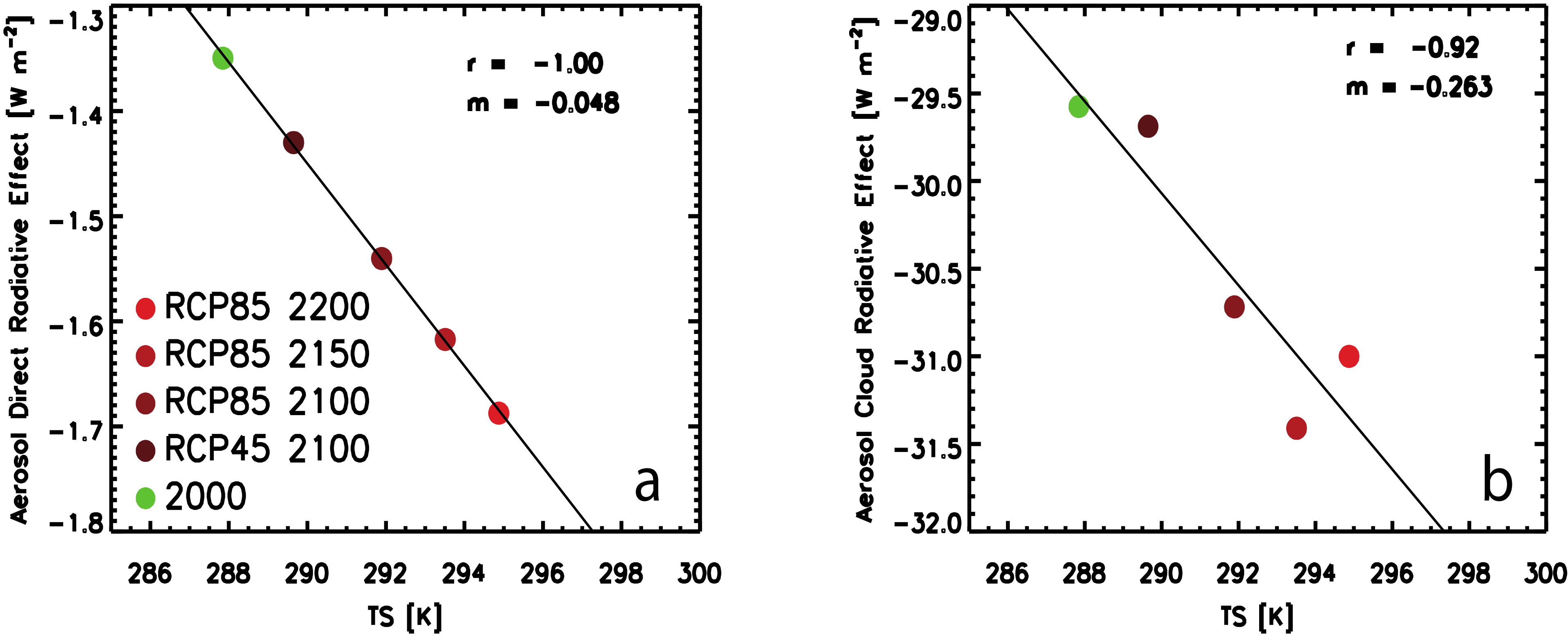
- All aerosol species yield a ***positive*** **slope** w/ $T_S \rightarrow$ an ***increase*** **in *aerosol burden*** **is a *robust response*** **to *warming***.
- Similar results with CAM4 (different aerosol scheme).



- **CAM5** wet (dry) deposition of SO4, 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 Aerosol Climate Feedback



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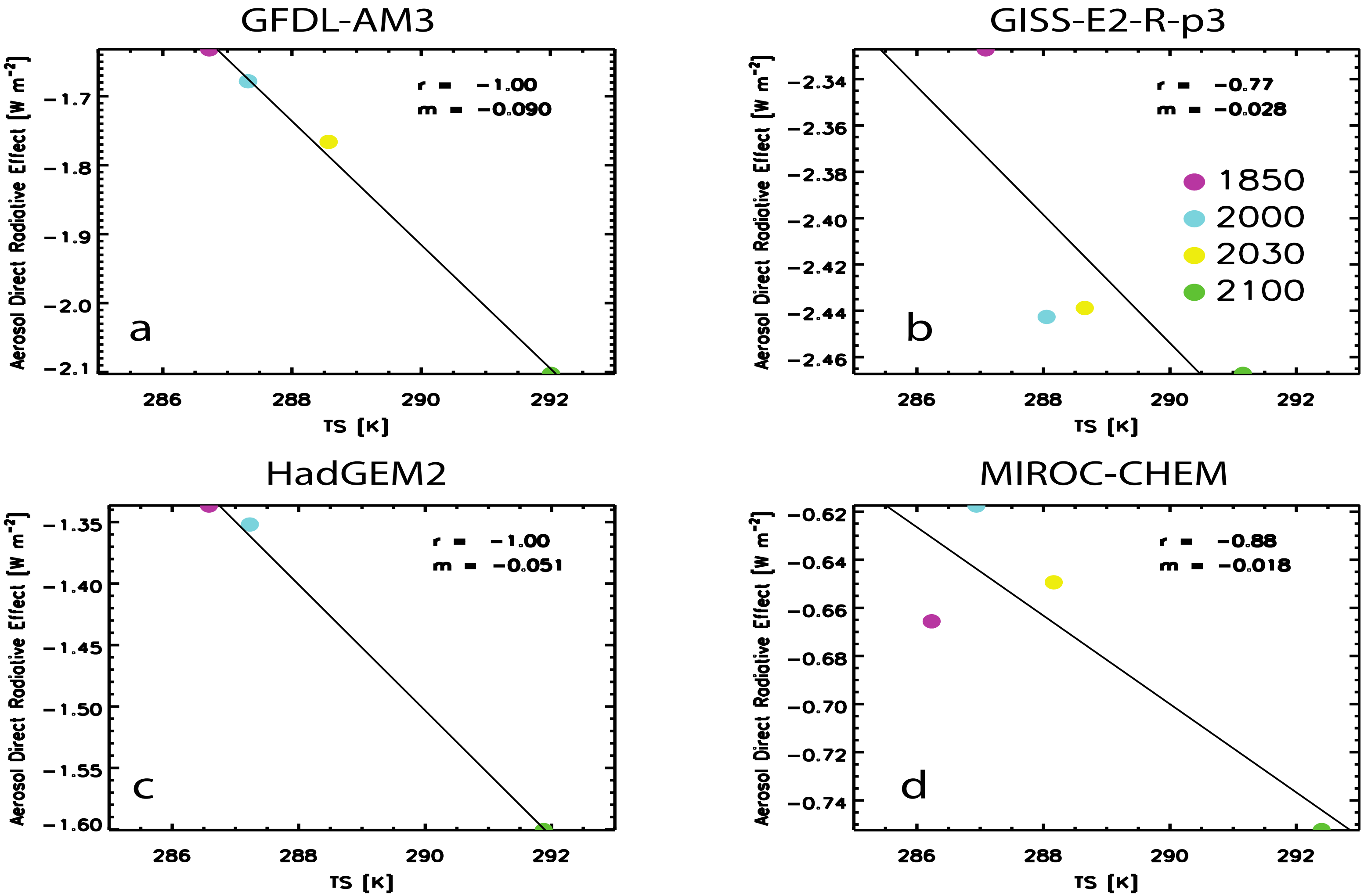
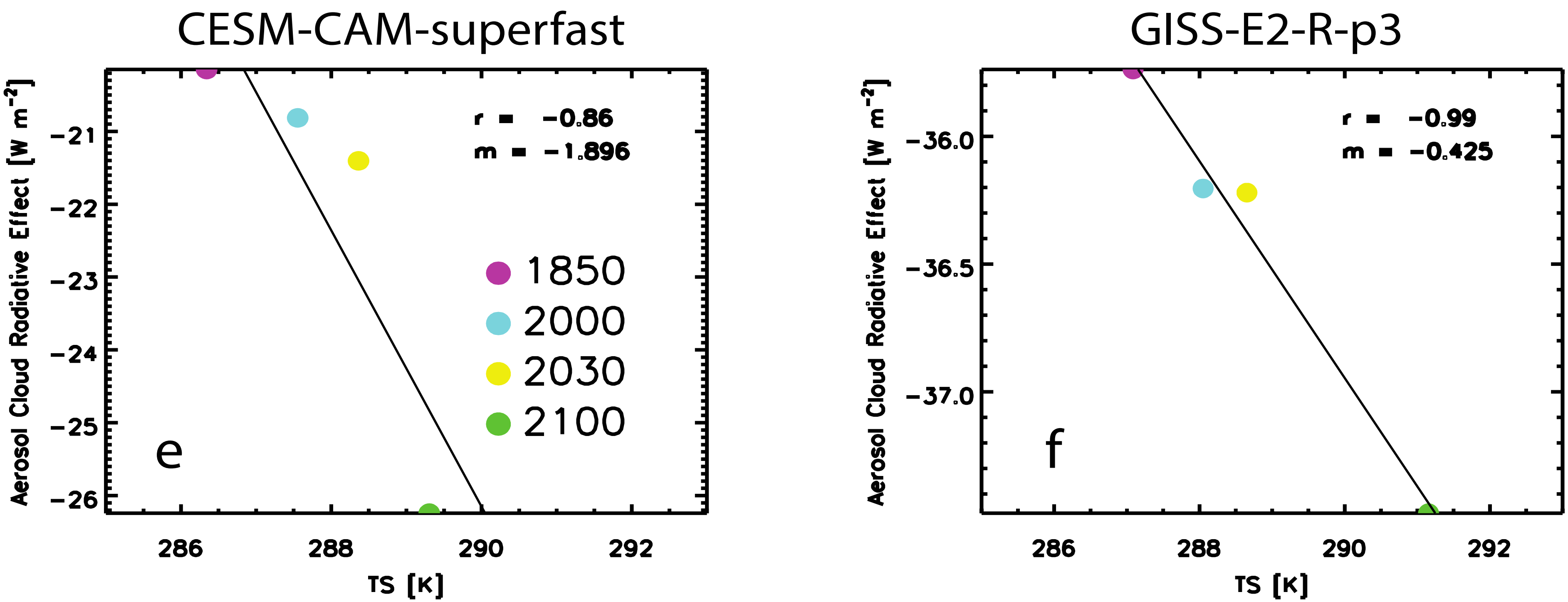
- Warming increases the (negative) direct radiative effect of aerosols → negative feedback to imposed warming of **-0.05 W m^{-2} K^{-1}.**
- **Anthropogenic aerosols** account for **30%; natural aerosols** (primarily sea salt) account for **70%.**
- Much larger cloud radiative effect feedback → **-0.26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

ACCMIP Aerosol Direct Radiative Effect [W m^{-2}]



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

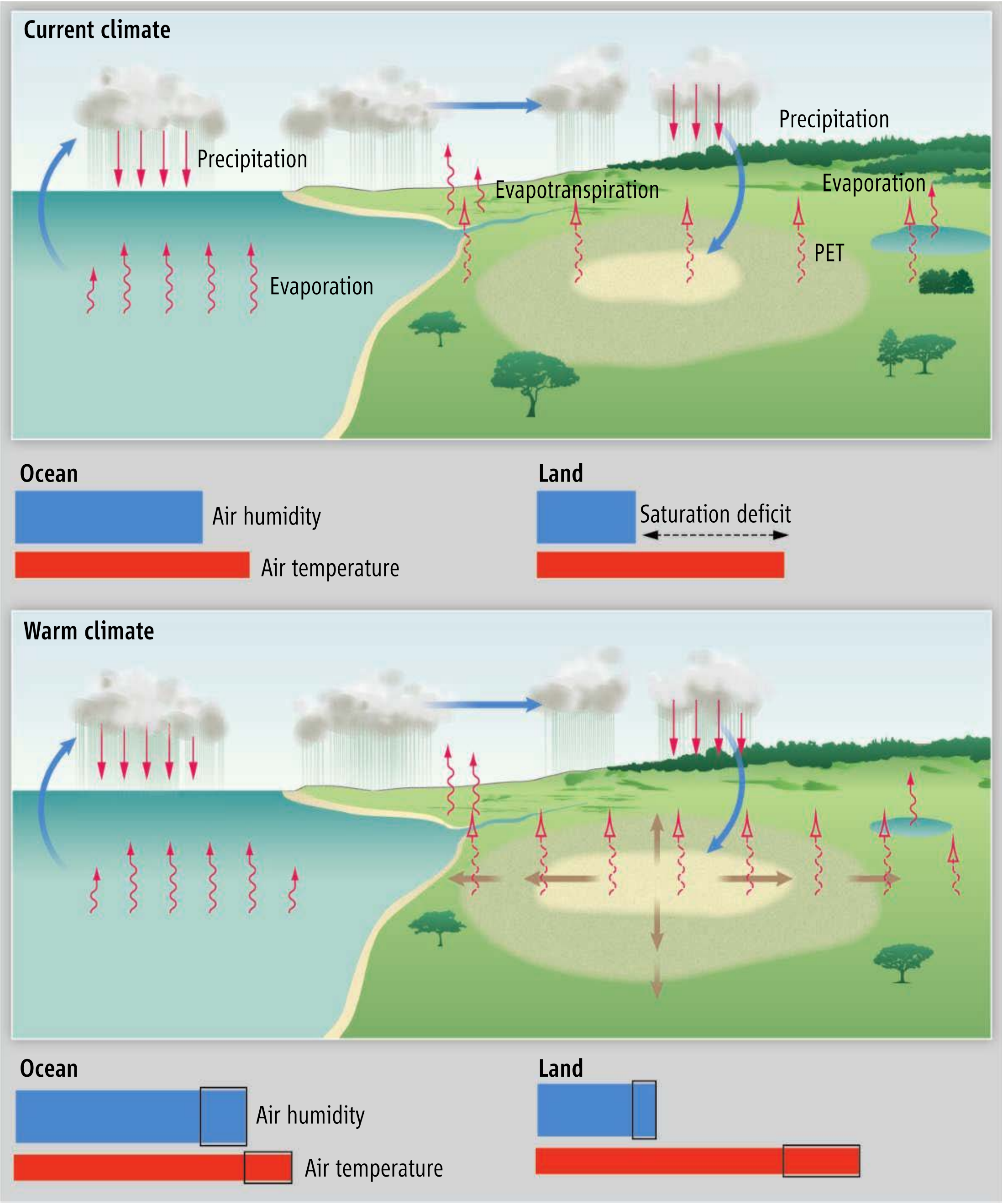
ACCMIP Aerosol Cloud Radiative Effect [W m^{-2}]



- CRE feedback of **-0.43 W m^{-2} K^{-1}** (GISS-E2-R) and **-1.90 W m^{-2} K^{-1}** (CESM-CAM-superfast).
- **Total aerosol feedback** (DRE+CRE) based on CAM5 and GISS-E2-R ranges from **-0.21** to **-0.46 W m^{-2} 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, SO4), 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

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.