Evaluating aerosols, clouds, and their interactions in three global climate models using satellite simulators and observations

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13th AeroCom Workshop
October 1, 2014

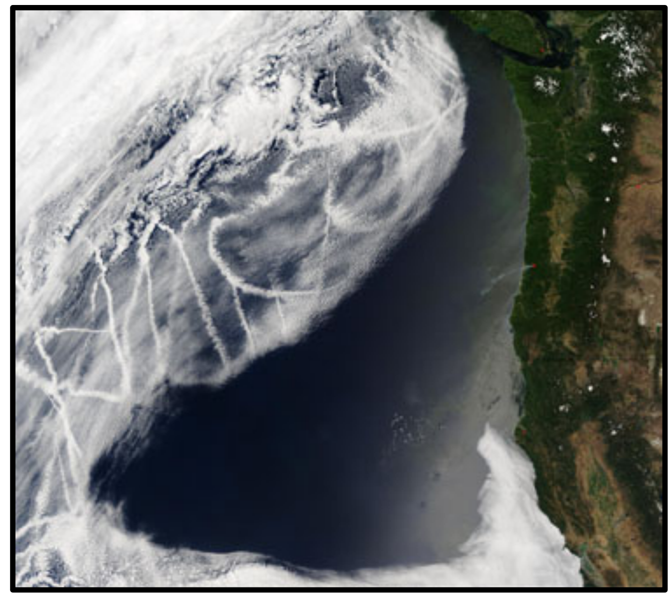
Acknowledgements

- Susanne Bauer (NASA GISS)
- Ling Jin (LBNL)
- Yi Ming (GFDL)
- Xiaohong Liu (Univ of Wyoming)
- Kai Zhang (PNNL)
- Ralf Bennartz (Vanderbilt Univ)
- Jonathan Jiang (JPL)
- Sponsor: Dept of Energy, Climate and Environmental Sciences Division, FASTER (FAst-physics System TEstbed and Research)

Aerosol impacts on climate

- Aerosols have profound impacts on climate
  - Scatter and absorb radiation
  - Alter macro- and micro-physical cloud properties

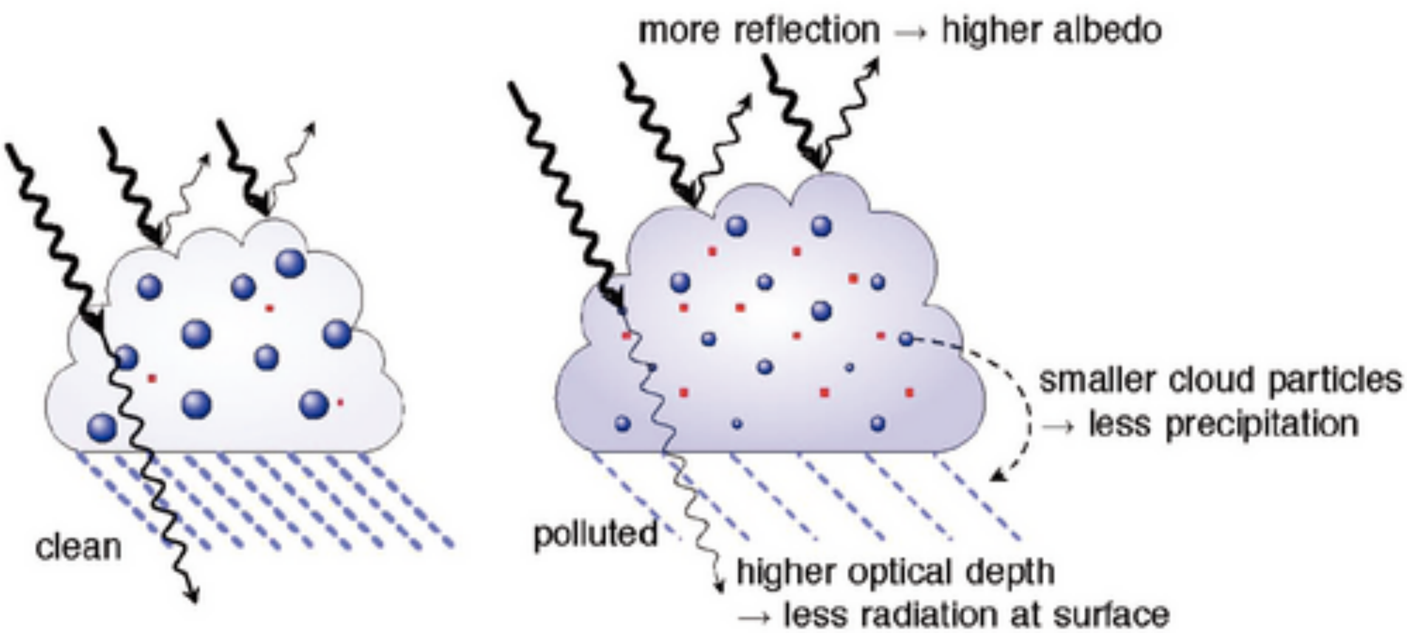
- Aerosol "indirect effects" on microphysical cloud properties are uncertain
and difficult to quantify at global scale



gfdl.noaa.gov

Aerosol "indirect effects" on warm clouds

Challenging to model these microphysical processes in a global climate model (with large grid cells)



source: IPCC AR4, WG1

Research goals

(1) Assess global distributions of aerosol and cloud properties in three global climate models and satellite observations

- Assure model vs observation comparison is as “apples to apples” as possible

(2) Compare signatures of aerosol-cloud interactions

- Focusing on regional analysis with specific cloud regimes (subtropical stratocumulus)
- Focusing on effect of aerosol on cloud droplet number conc (*N*)
- Accounting for meteorological influences

Climate models and observations

Climate models

- CAM5 (1.9°x 2.5°)
- GISS ModelE2 (2°x 2.5°)
- GFDL AM3 (2°x 2.5°)

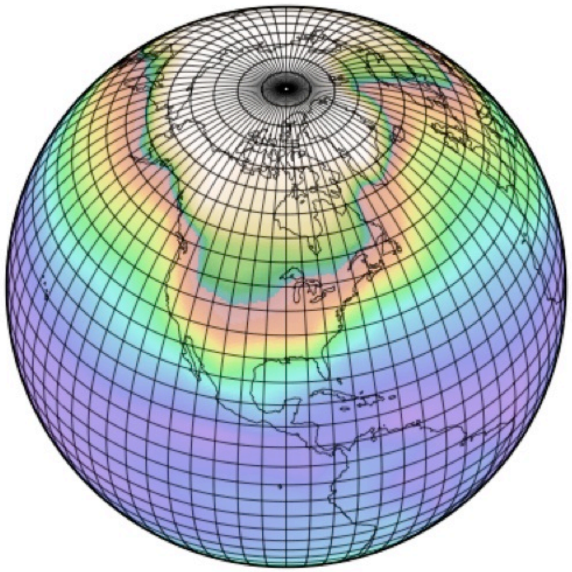
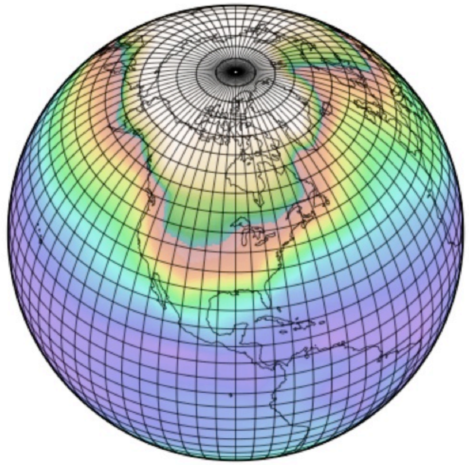


image source: serc.carleton.edu

Observations

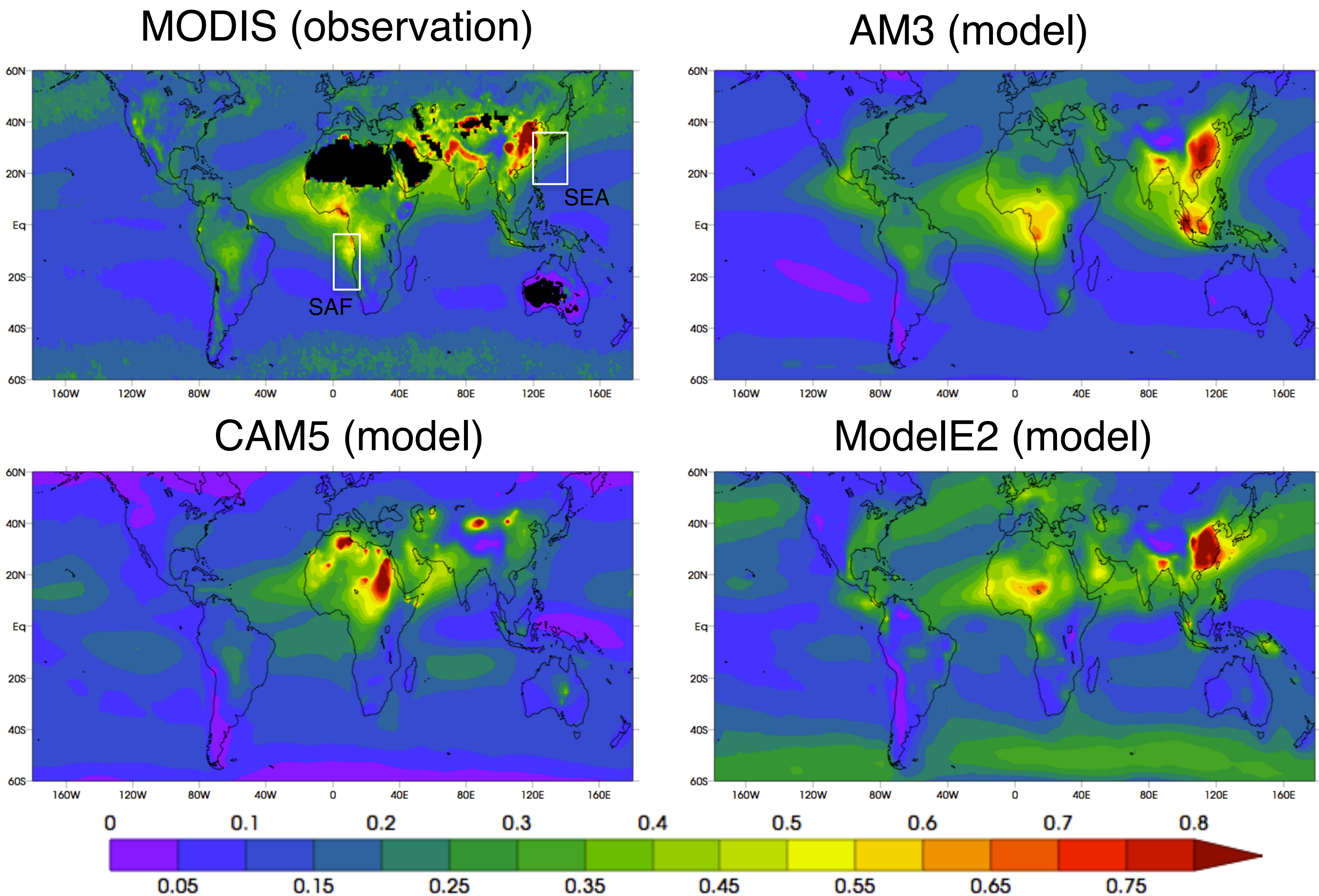
- MODIS L3C5 (1°x 1°)
- ERA-INT reanalysis (0.5°x 0.5°)

GCM simulation details



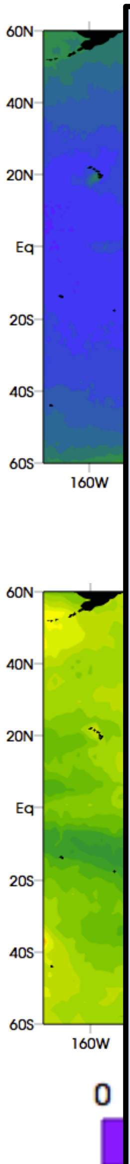
- Simulation period: Jan 1 2007- Jan 1 2009
- CMIP5 emissions
- To maximize comparability of GCM and observations:
  - Prescribed sea surface temperatures
  - Horizontal winds are nudged to reanalysis
  - High frequency (3 hourly) GCM output
  - Extract satellite overpass times
  - CFMIP Observation Simulator Package (COSP)
  - Satellite-observed and simulated cloud drop number concentration (*N*) use same algorithm

Aerosol optical depth – 2yr annual mean



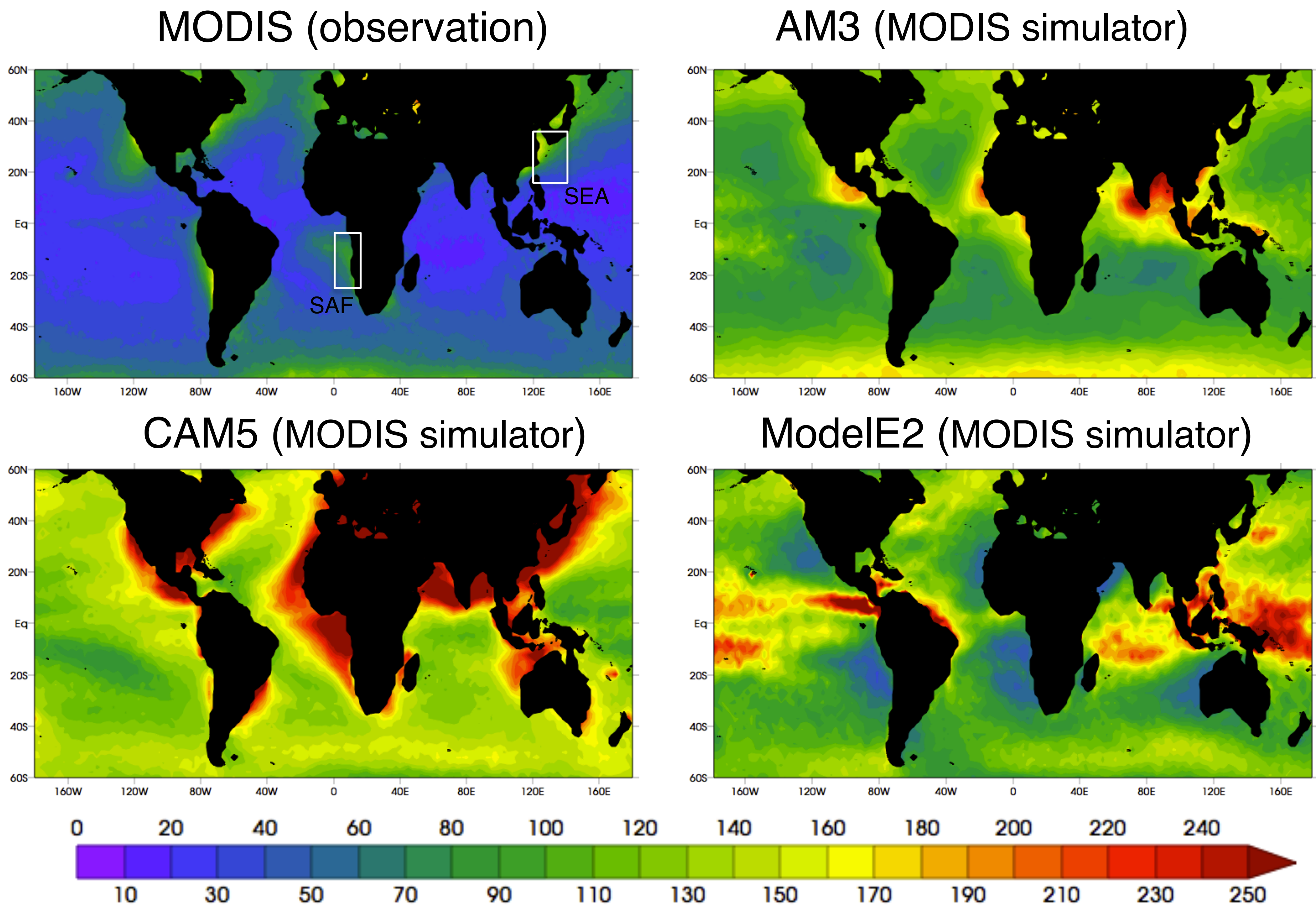
Cloud droplet number concentration (# cm^{-3})

MODIS (observation) AM3 (MODIS simulator)

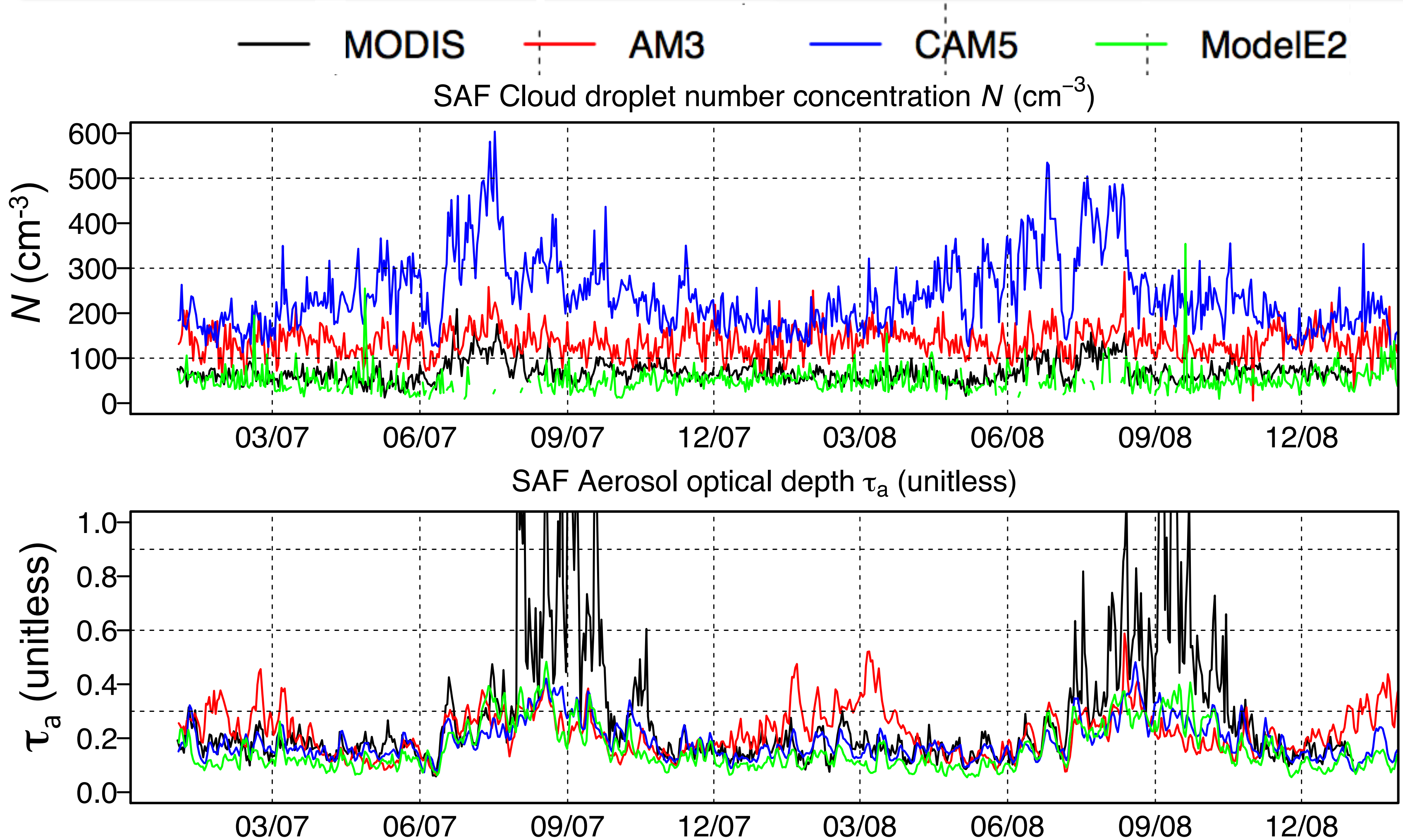


- Observed N:
  - Calculated from MODIS liquid τ_c and r_e (Bennartz 2007)
  - Assumes clouds are adiabatically stratified (LWC increases linearly and N is constant with height)
  - $N \sim \tau_c^{1/2}\, r_e^{-5/2}$
- Modeled N:
  - Computed from MODIS-simulated values using the same algorithm as MODIS observations
- Comparison:
  - Liquid clouds only
  - Pixels with liquid cloud fraction < 0.3 are screened
  - **In-cloud *N***

Cloud droplet number concentration (# cm^{-3})



Spatial-mean dailies (SAF)



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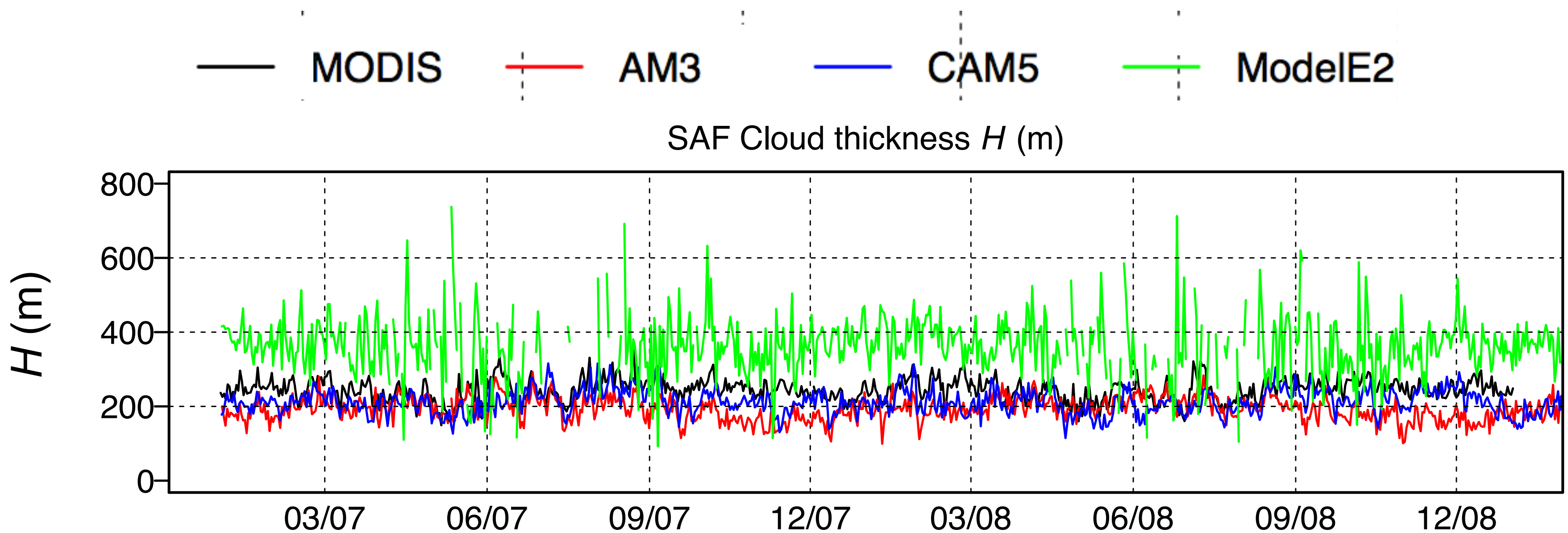
Spatial-mean dailies (SAF)

Quick aside: Interesting method for evaluating cloud thickness



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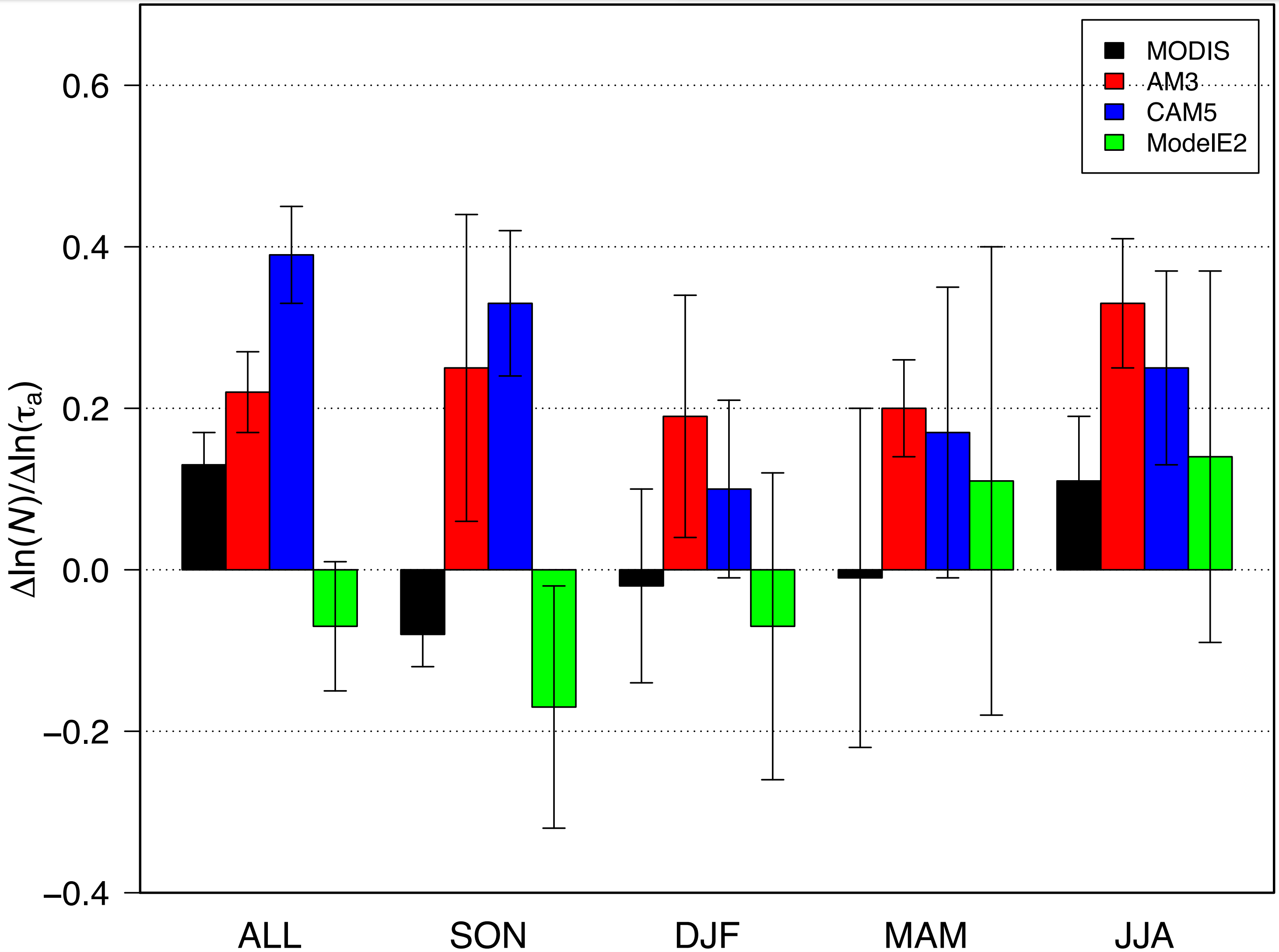
Sensitivity of N to τ_a in SAF region



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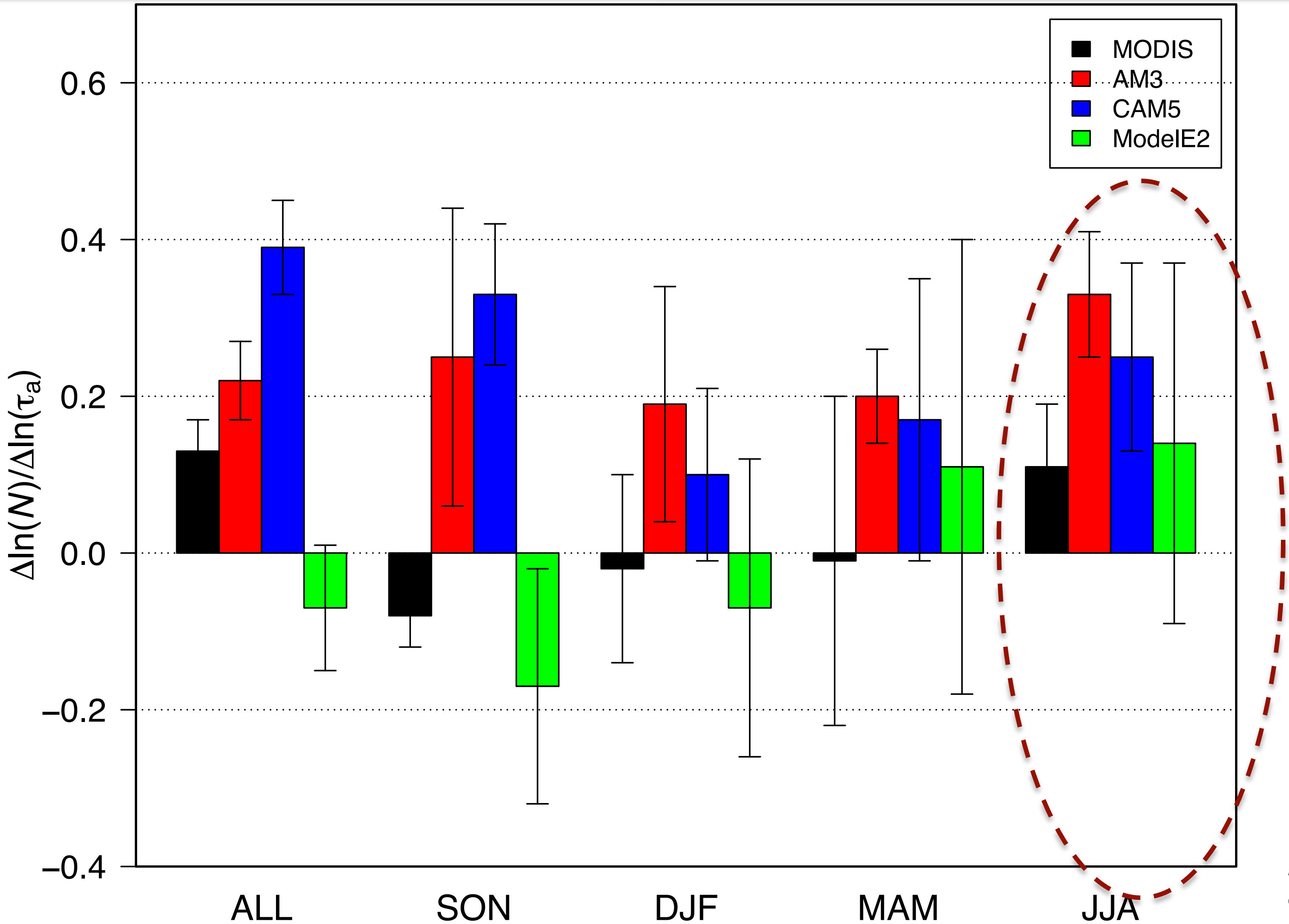

Ban-Weiss et al. (2014)

But N is also sensitive to meteorology. And meteorology and τ_a covary

$$\Delta \ln(N) = \Delta \ln(\tau_a) \left.\frac{\partial \ln(N)}{\partial \ln(\tau_a)}\right|_{\text{met}} + (\Delta met) \left.\frac{\partial \ln(N)}{\partial (met)}\right|_{\tau_a}$$

Cloud-aerosol sensitivity under constant "meteorology"

Cloud-"meteorology" sensitivity under constant aerosol

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$$\frac{\Delta \ln(N)}{\Delta \ln(\tau_a)} = \left.\frac{\partial \ln(N)}{\partial \ln(\tau_a)}\right|_{\mathrm{met}} + \frac{d(met)}{d \ln(\tau_a)} \left.\frac{\partial \ln(N)}{\partial (met)}\right|_{\tau_a}$$

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Total sensitivity — Partial sensitivity — Confounding meteorological effects

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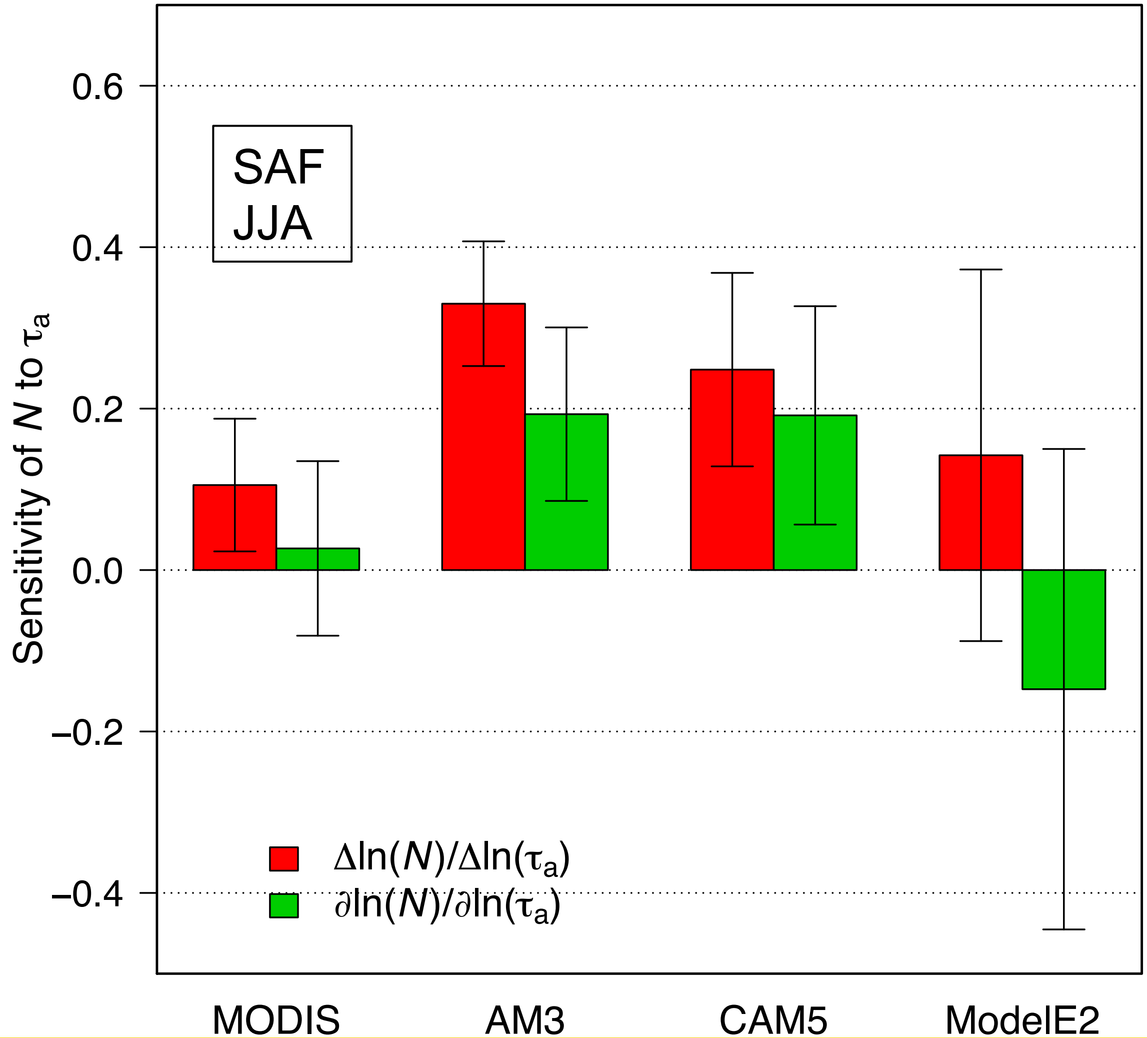
Total sensitivity — Partial sensitivity — Confounding meteorological effects

met = relative humidity @ 1000 and 700 hPa

Comparing sensitivity of N to τ_a with and without considering met (RH in two layers)



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Implications of the differences for total versus partial sensitivity

- We should expect differences between observations and models in the "total" sensitivity $\frac{\Delta \ln(N)}{\Delta \ln(\tau_a)}$ since models do not represent all confounding meteorological processes

- As aerosol-cloud parameterizations move away from empirical relationships, e.g. $N = -598 + 298 \log(N_a)$, and toward more physically realistic process descriptions, total sensitivity will change even for constant partial sensitivity $\left.\frac{\partial \ln(N)}{\partial \ln(\tau_a)}\right|_{met}$

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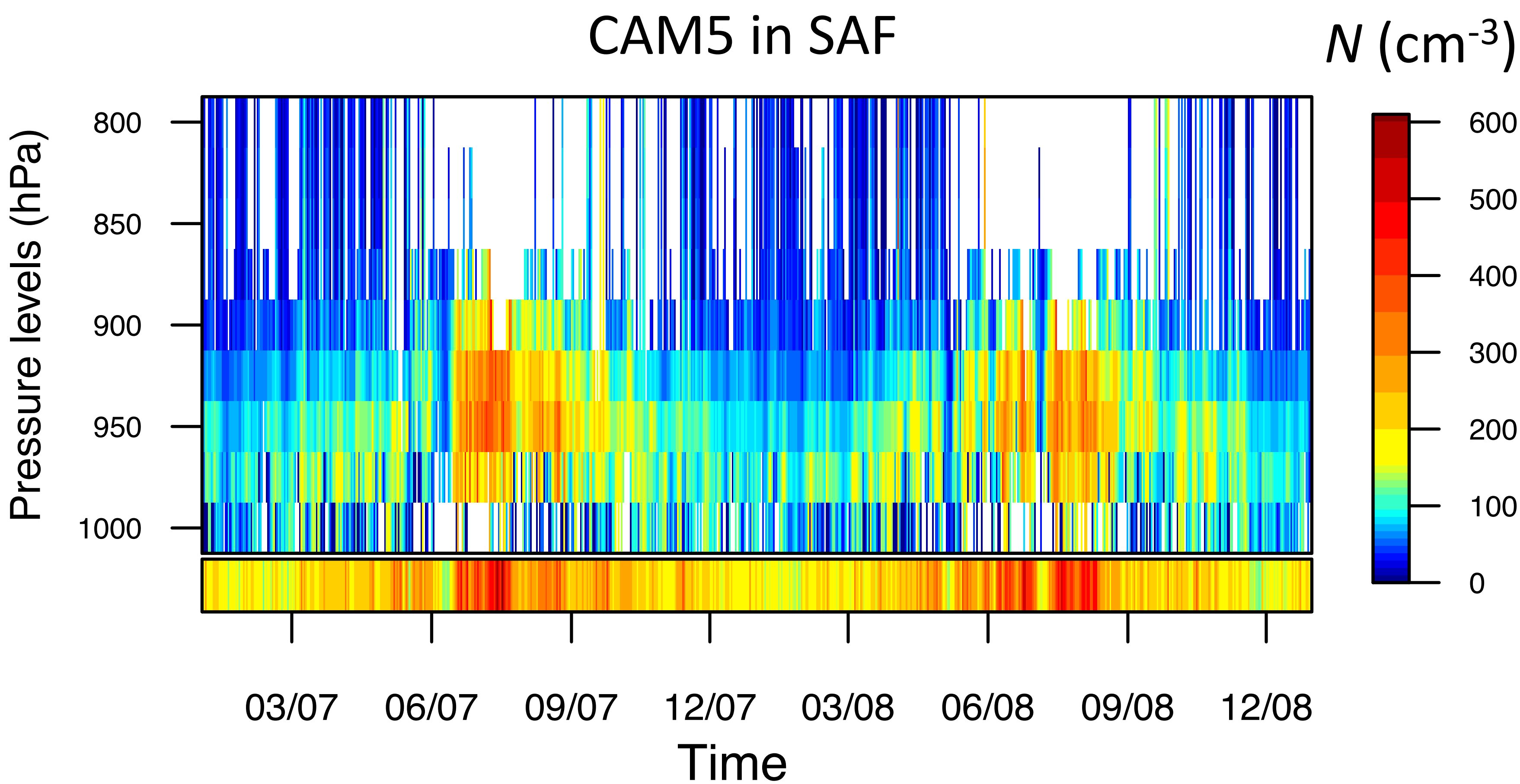
Comparing satellite-simulated model values versus standard model output



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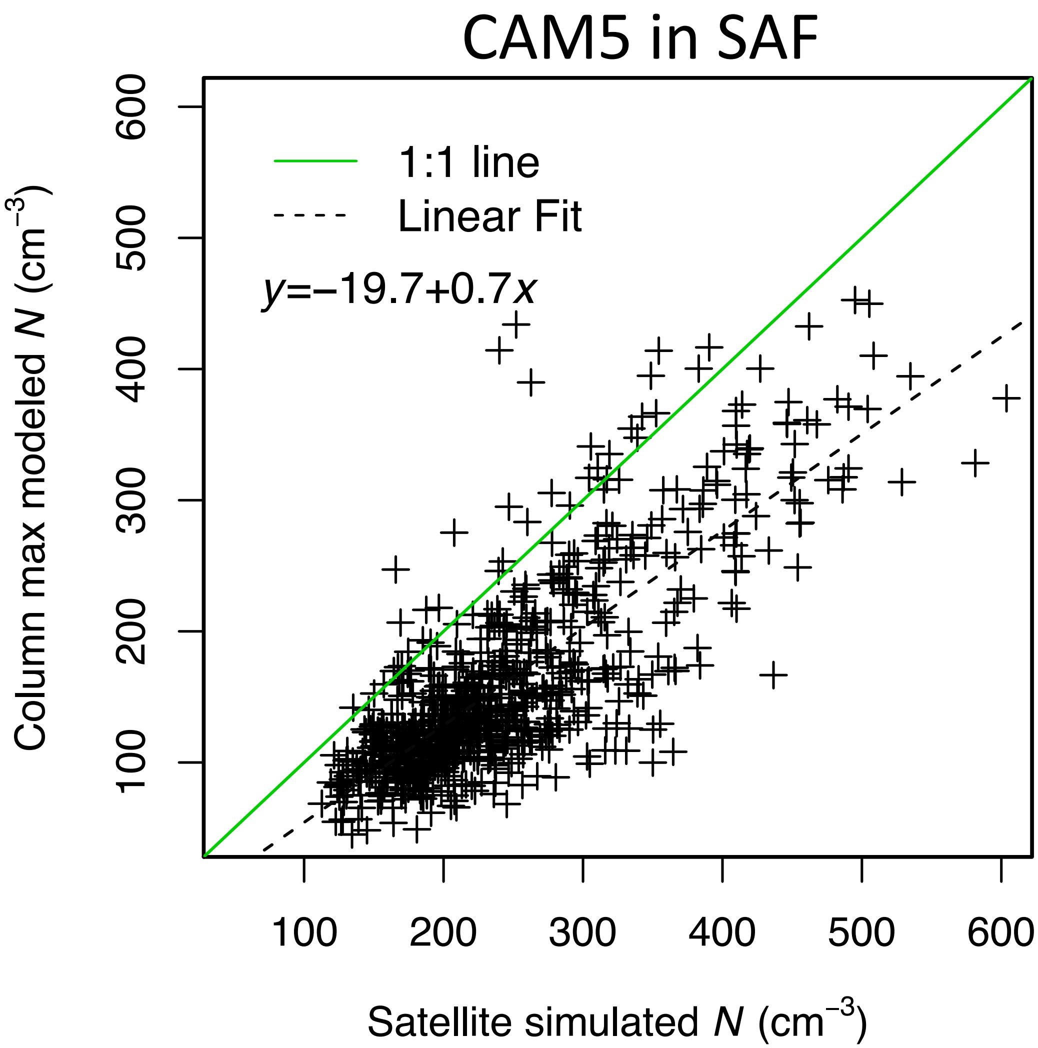
Standard model values are markedly lower than satellite-simulated values for *N*



Bias = 83 cm^{-3} **
RMS = 98 cm^{-3}

Bias ranges from 55 to 115 cm^{-3} for other models and regions

**this bias is roughly half the difference between satellite simulated and observed values

Ban-Weiss et al. (2014)

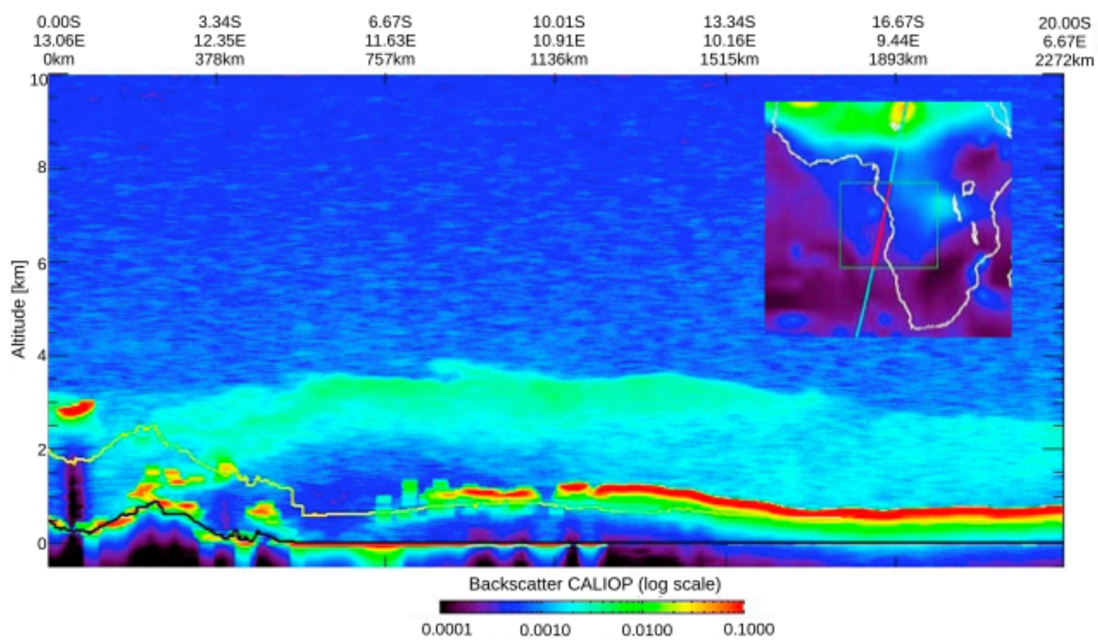
Implications: standard model values are nearer to observations than satellite-simulated values

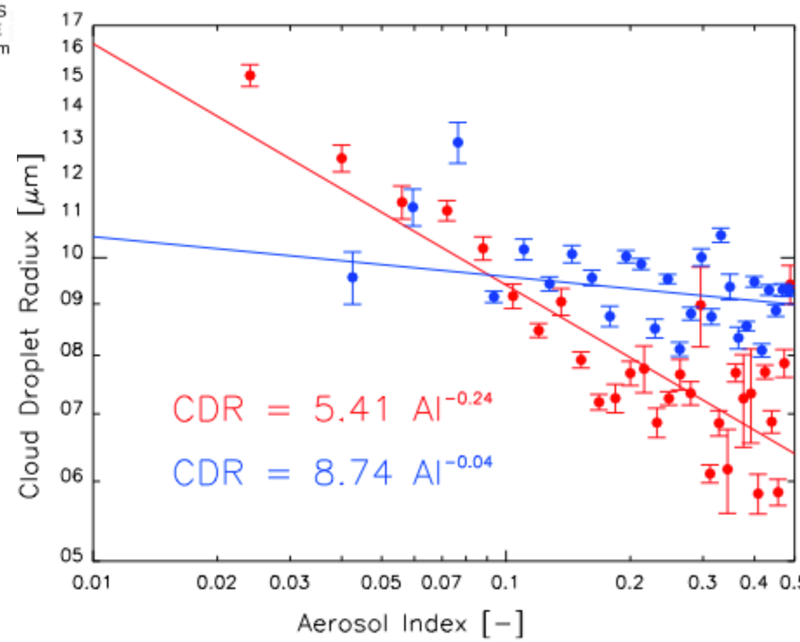
- Unclear whether difference between satellite-simulated and standard model values are driven by differences in deriving τ_c and r_e, or the algorithm for deriving *N*
- May suggest that comparing $\frac{\Delta \ln(N)}{\Delta \ln(\tau_a)}$ for observations versus standard model output is biased
- What is the right metric for comparing to observations?

Ban-Weiss et al. (2014)

Cavaets and study limitations

- Is aerosol optical depth a good proxy for cloud condensation nuclei (CCN)?
- Are aerosols and clouds vertically collocated?





Source: Costantino and Breon (2010)

See Ban-Weiss et al. (2014) JGR

- more regions and interpretations
- more detailed comparison of the differences in aerosol and cloud parameterizations between the models
- comparison to previous generations of the model

Conclusions

- Aerosol optical depth spatial pattern
  - CAM5, AM3, and ModelE2 match MODIS observed aerosol optical depth quite well
- Cloud droplet number concentration spatial pattern
  - CAM5 and AM3 capture the MODIS observed spatial pattern of *N*
  - ModelE2 pattern is reversed
- Magnitude of *N* in 'SAF':
  - AM3 and ModelE2 are near MODIS observations
  - CAM5 overpredicts *N* (because of corresponding overpredictions in liquid τ_c and underpredictions in r_e)

Conclusions

- Sensitivity of N to τ_a $\frac{\Delta \ln(N)}{\Delta \ln(\tau_a)}$ in 'SAF'
  - CAM5 and AM3 more sensitive than observations
  - ModelE2 has high uncertainty
- Covariation between N, τ_a, and meteorology confounds $\frac{\Delta \ln(N)}{\Delta \ln(\tau_a)}$
- Differences in $\frac{\Delta \ln(N)}{\Delta \ln(\tau_a)}$ between observations and models should be expected given the different degrees to which they represent these confounding factors.
- As parameterizations evolve, $\frac{\Delta \ln(N)}{\Delta \ln(\tau_a)}$ may change even for constant aerosol-cloud interactions
- Satellite-simulated model values for N are much higher than standard model values (bias = 83 cm^{-3}).