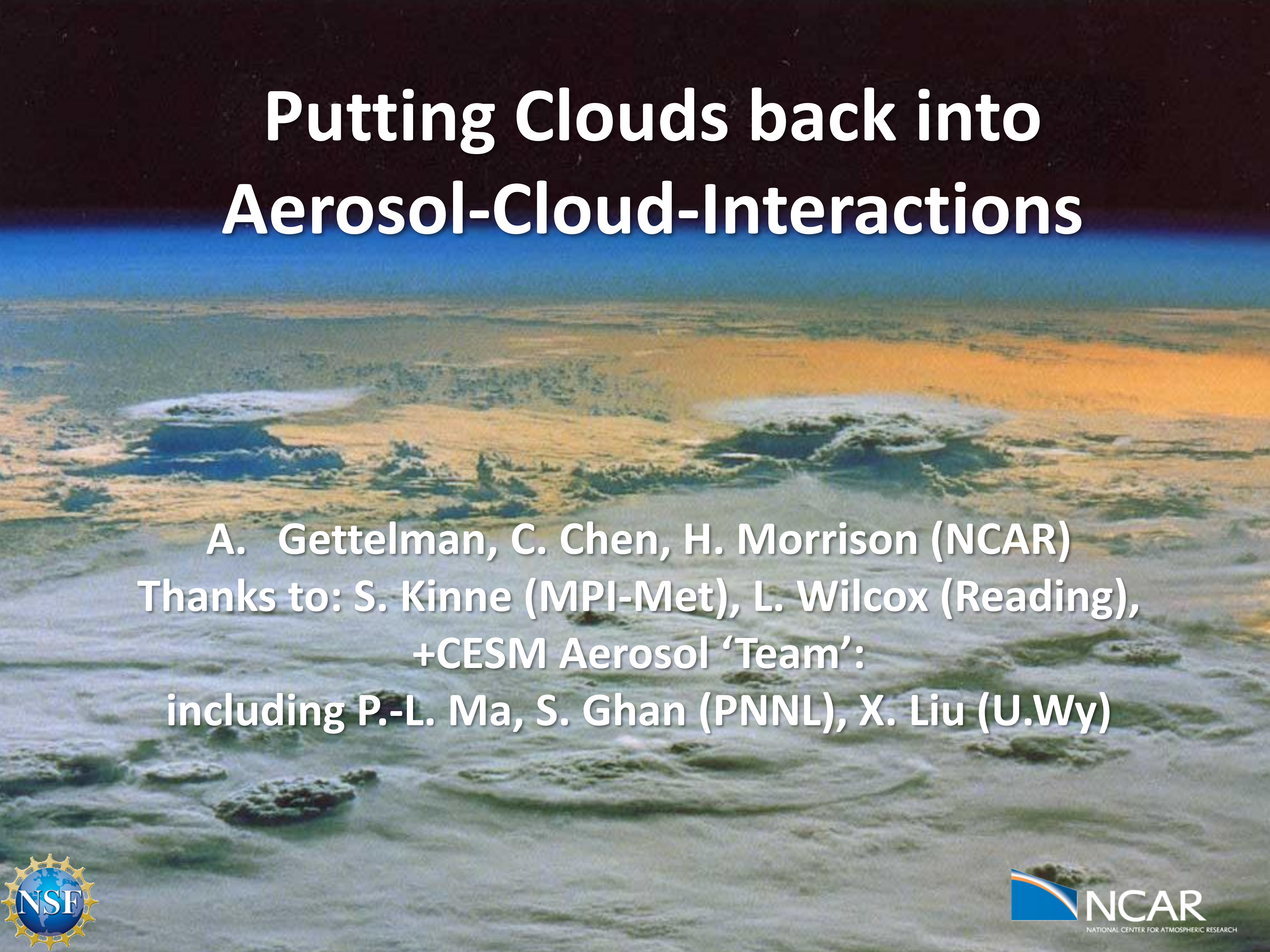
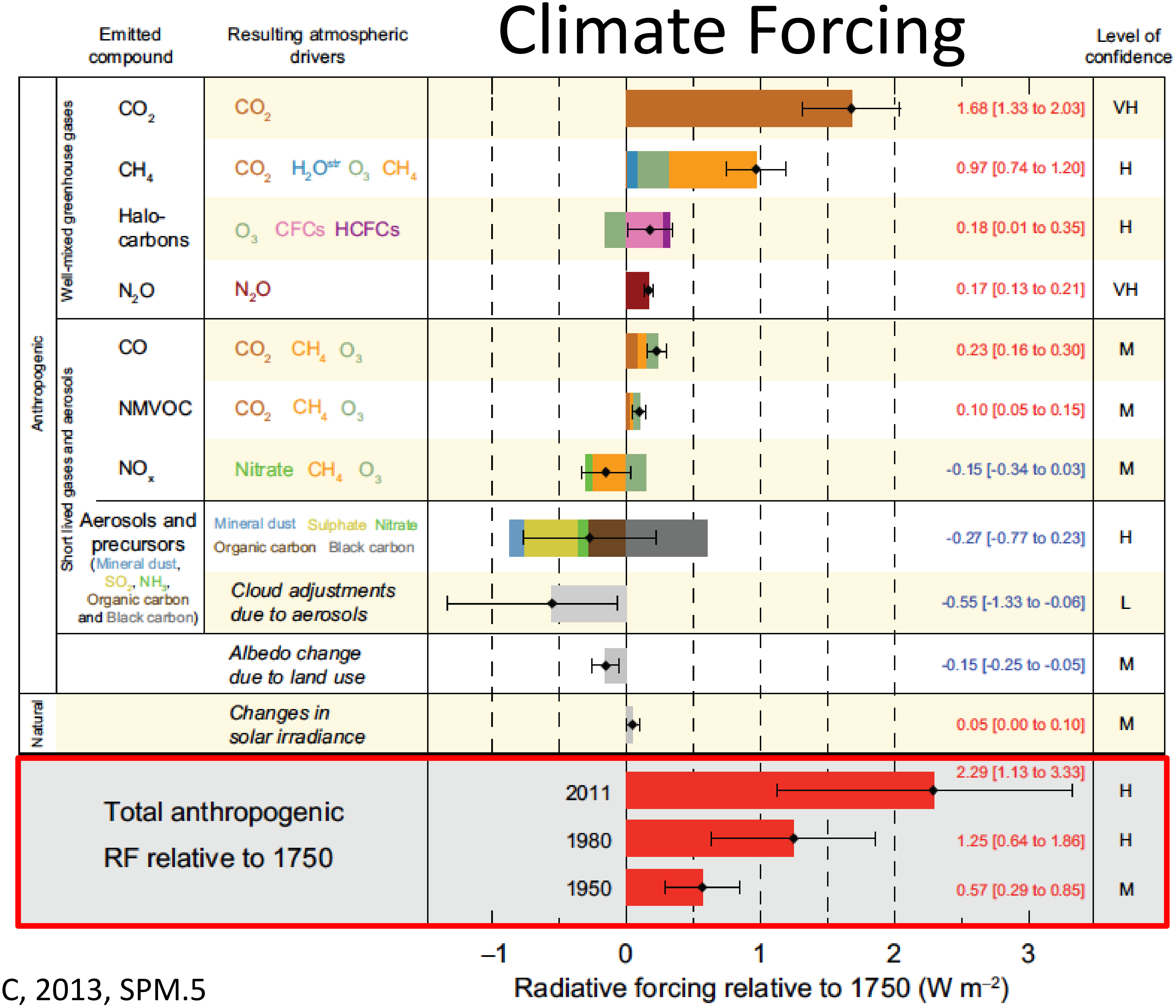


Putting Clouds back into Aerosol-Cloud-Interactions

A. Gettelman, C. Chen, H. Morrison (NCAR)
Thanks to: S. Kinne (MPI-Met), L. Wilcox (Reading),
+CESM Aerosol ‘Team’:
including P.-L. Ma, S. Ghan (PNNL), X. Liu (U.Wy)

Climate Forcing



IPCC, 2013, SPM.5

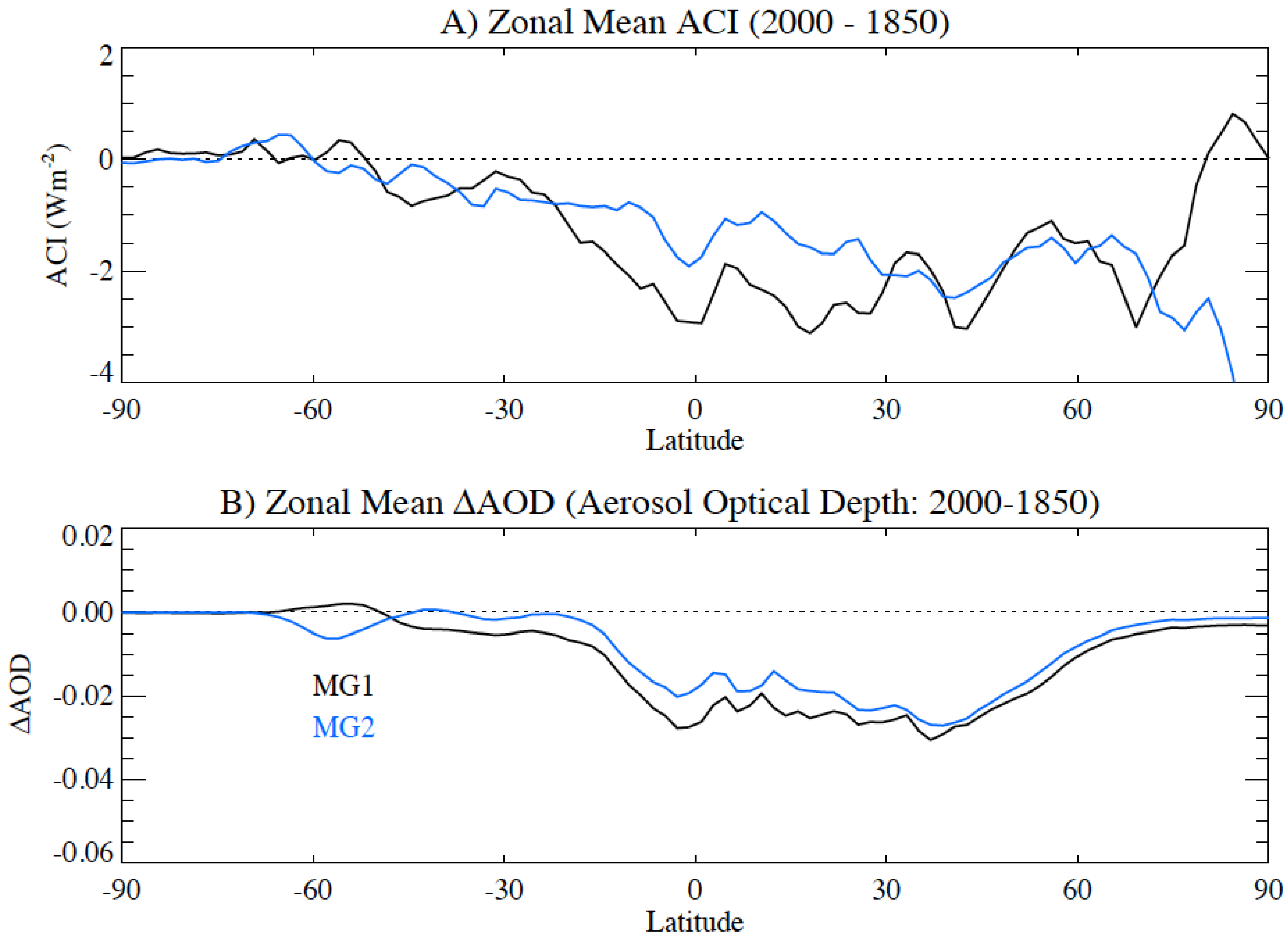
Outstanding Questions

- How do changes in cloud processes affect Aerosol-Cloud Interactions (ACI)?
- How can we constrain relationships between clouds and aerosols?
- How does cloud state interact with aerosols: and can this affect climate feedbacks?
- Can we use models to help target processes and observations?

Simulations

- NCAR Community Earth System Model (CESM)
  - GCM with 2-moment cloud microphysics
  - 3 Mode Aerosol Model
- Forcing: Stand alone atmosphere, fixed SSTs, 2000 – 1850 aerosol emissions
- Feedbacks: Mixed Layer Ocean: 360, 720ppm CO_2
- Concept: Change CLOUD properties (same aerosol emissions and processes) and see the impact on ACI
- Experiment: new microphysics version (MG1→MG2) with prognostic precipitation
  - Keep aerosols the same

Changing ACI with microphysics



A) Zonal Mean ACI (2000 - 1850)

B) Zonal Mean ΔAOD (Aerosol Optical Depth: 2000-1850)

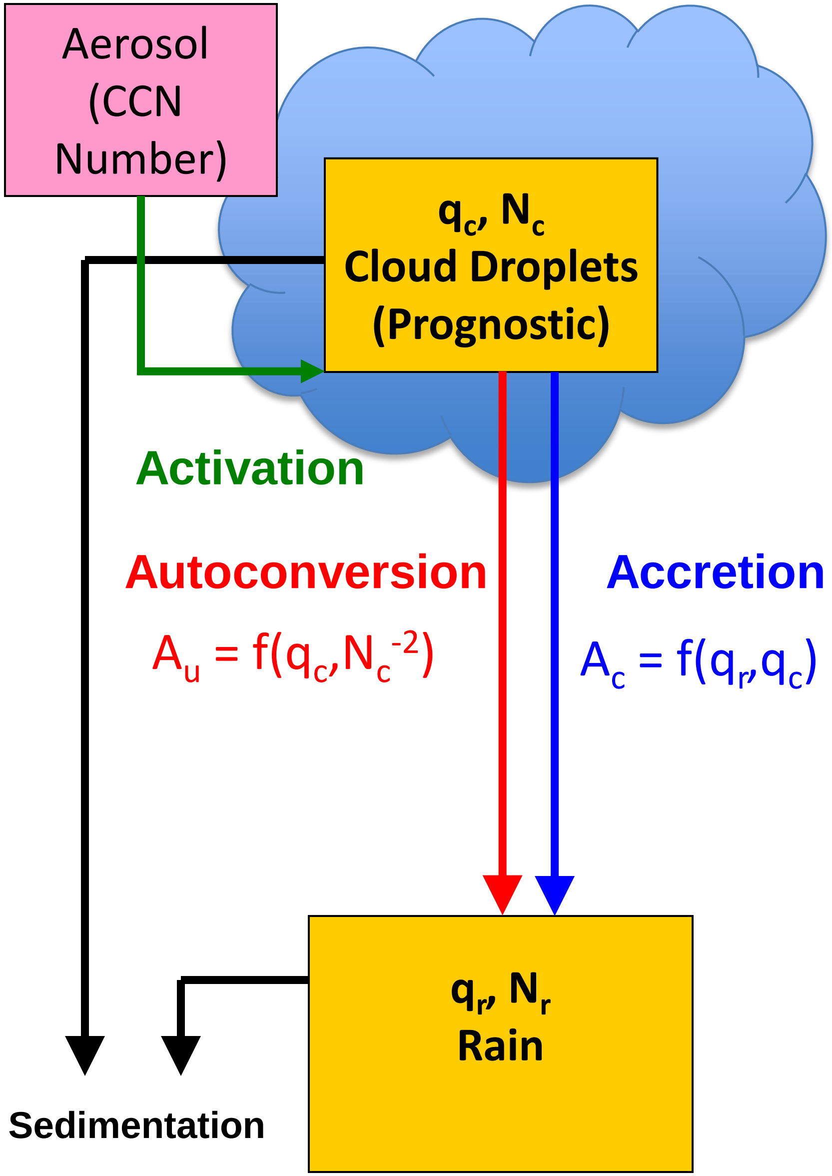
-1.25 Wm^{-2} Base

-0.76 Wm^{-2} New Micro

MG2 = 40% reduction in ACI

AOD changes similar

Process rates: Essence



1. Activation (CCN) = f(RH,w)
   W at cloud scale is critical
2. Autoconversion (loss process) is a function of N_c^{-2} (=ACI)
3. Accretion depends on q_r

With Prognostic rain:

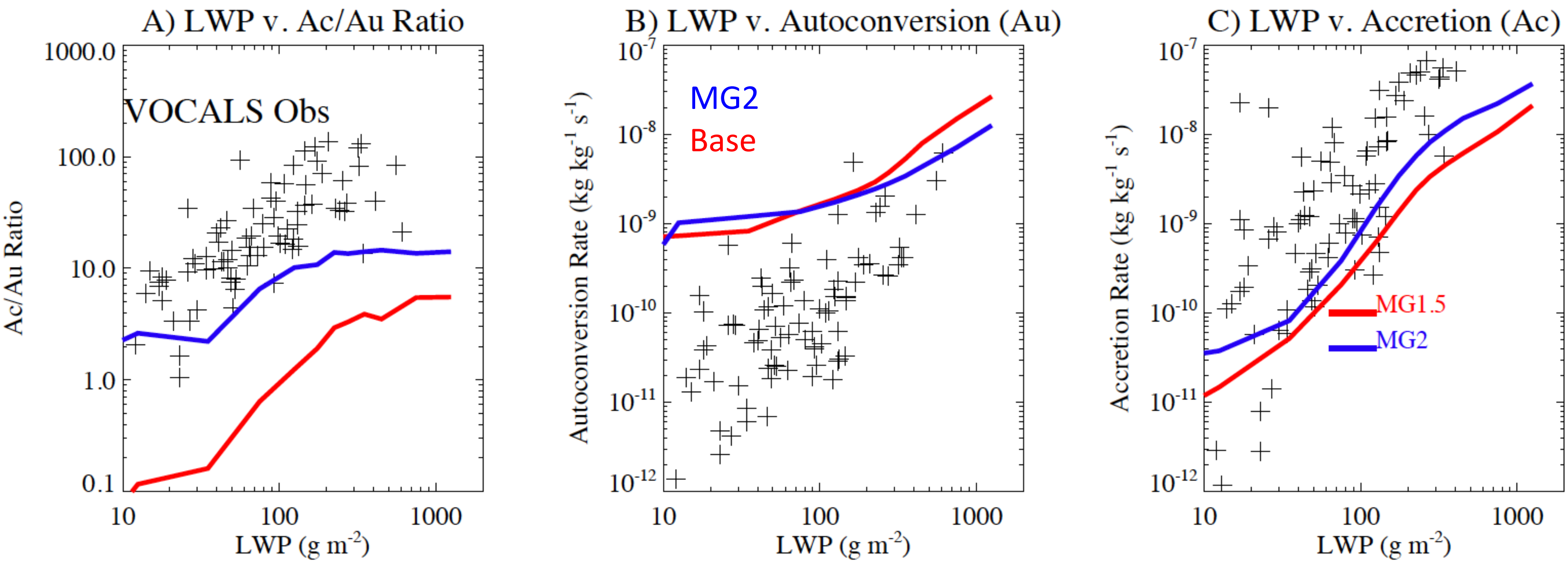
A. Better representation of q_r

B. Increase in A_c / A_u

C. Reduced ACI (reduced N_c effect)

ACI and process rates

Prognostic precipitation (MG2) v. base (MG1)



Prognostic precipitation (q_r) increases accretion (Ac)

“VOCALS Obs” are actually a detailed model using observations as input

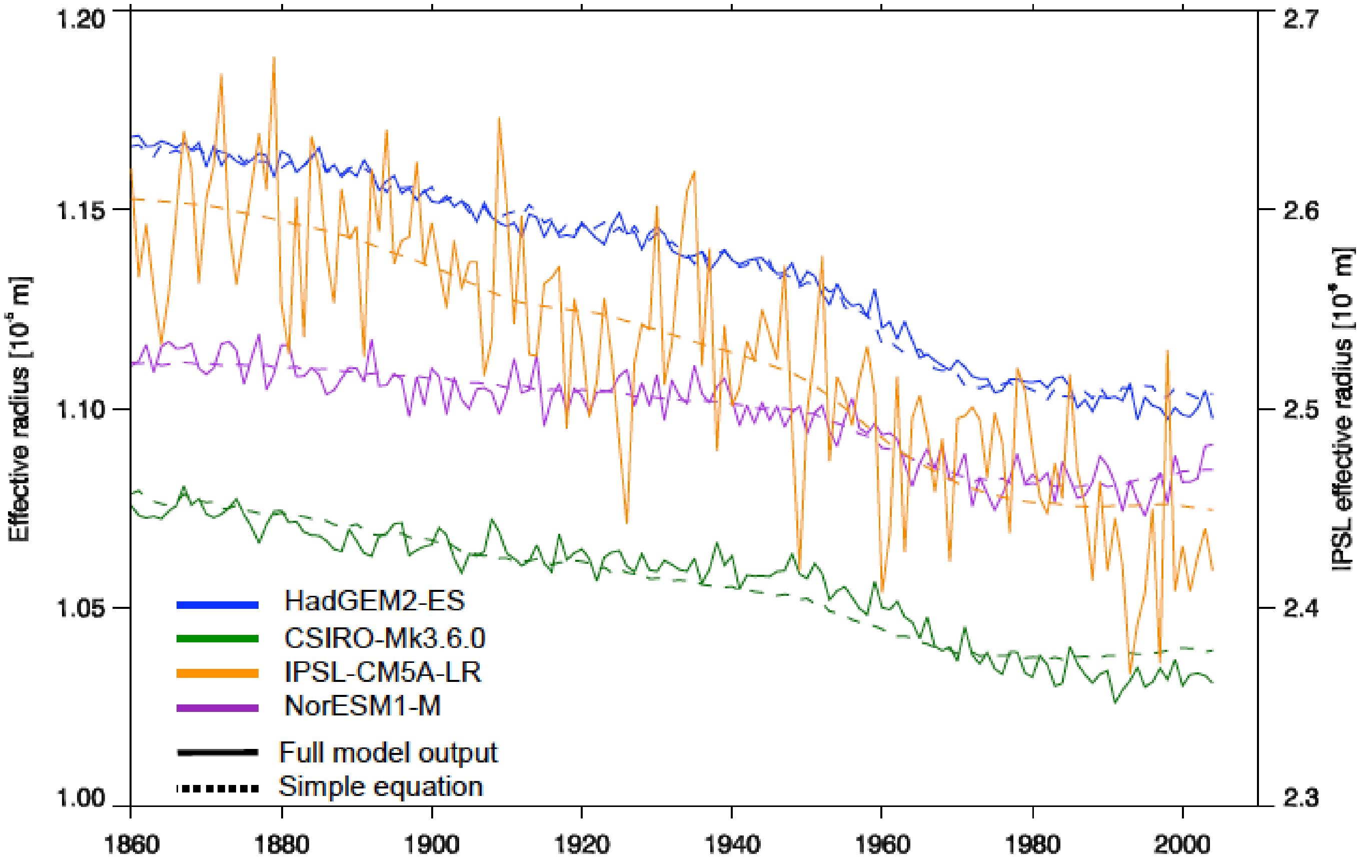
Constraining ACI

- So how do we better constrain ACI?
- This example: MG1 v. MG2
- Process rates are one way
  - Argue that prognostic precipitation is ‘better’
- Let’s look at some microphysical relationships
- Things we can compare to observations
  - Comparisons at the large scale
  - Comparisons with observations of clouds
  - In the spirit of other work (e.g. Quaas et al 2009, Gryspeerdt and Stier 2012)
- But: AOD (τ_a) may not be the right metric…

Motivation: A simple model

Wilcox (Highwood & Booth) take SO_4 burden v. Re, and fit a simple model. This works for Re

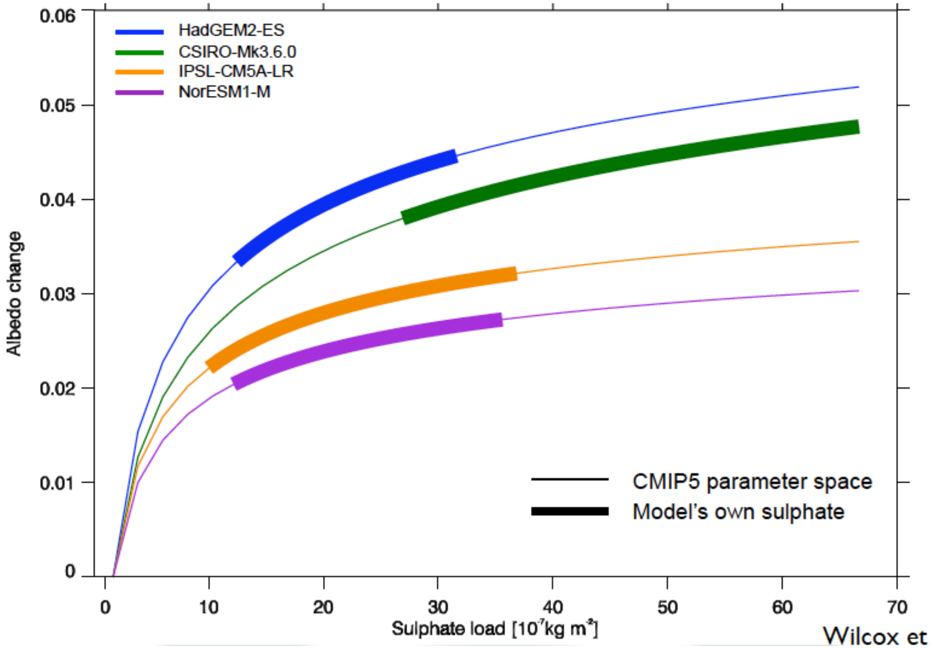
Wilcox et al. 2014 use climate models with empirical relationships for CCN or drop number



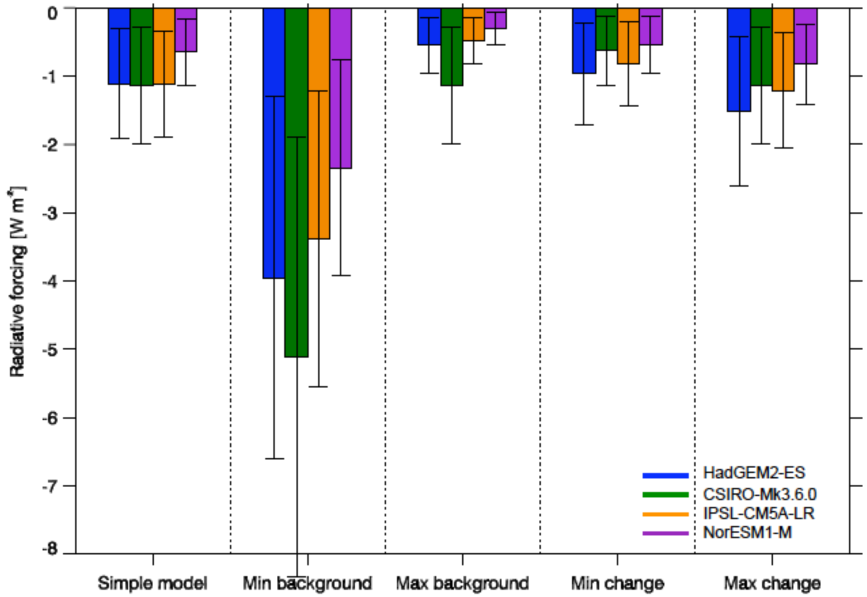
Wilcox et al, in Prep (thanks to L. Wilcox for unpublished figures)

Motivation: A simple model

Then, they turn Re→ Albedo change



Wilcox et al.



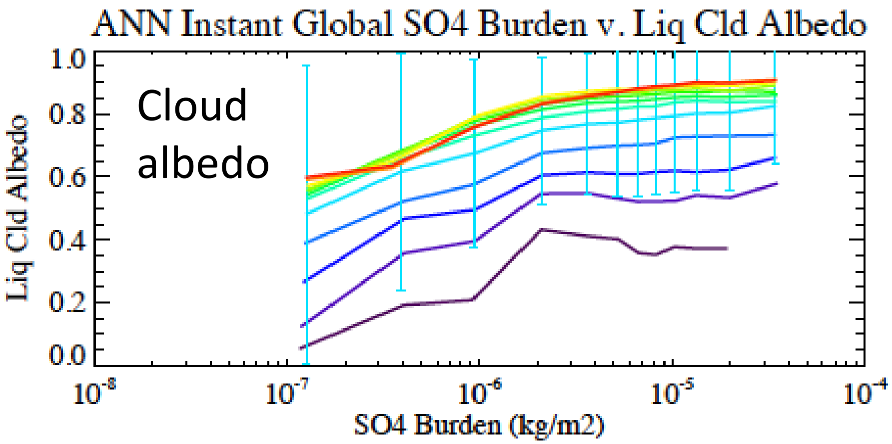
Wilcox et al. (2014a), in prep.

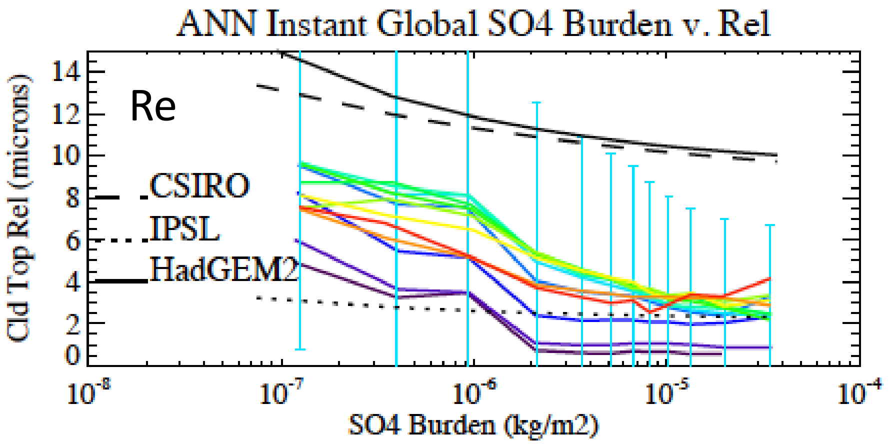
And using the curves above, go from albedo to RF given different factors.

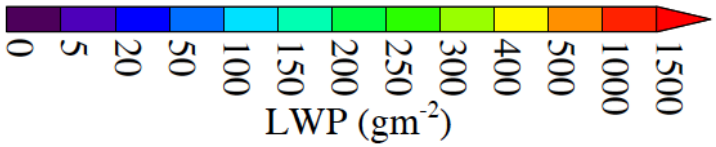
Picking the smallest background load gives the biggest effect

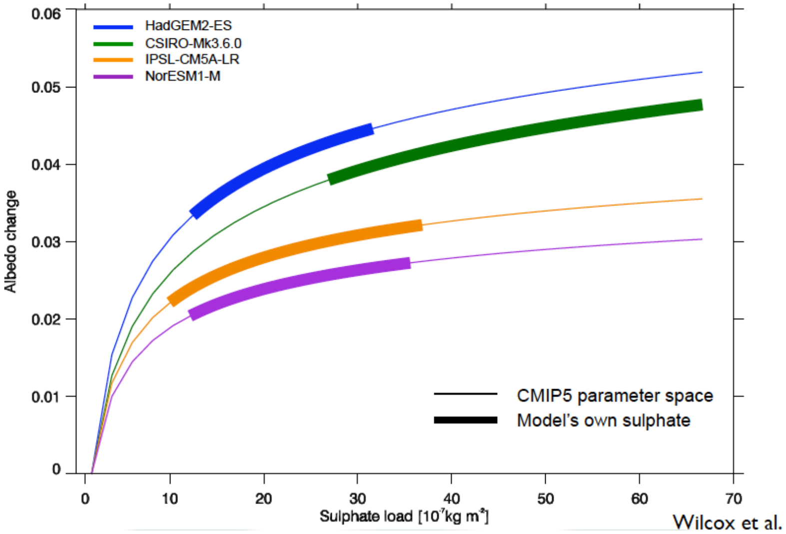
So does this work if you follow it through a comprehensive model?

CESM: Cloud Albedo & Re v. SO_4









Wilcox et al.

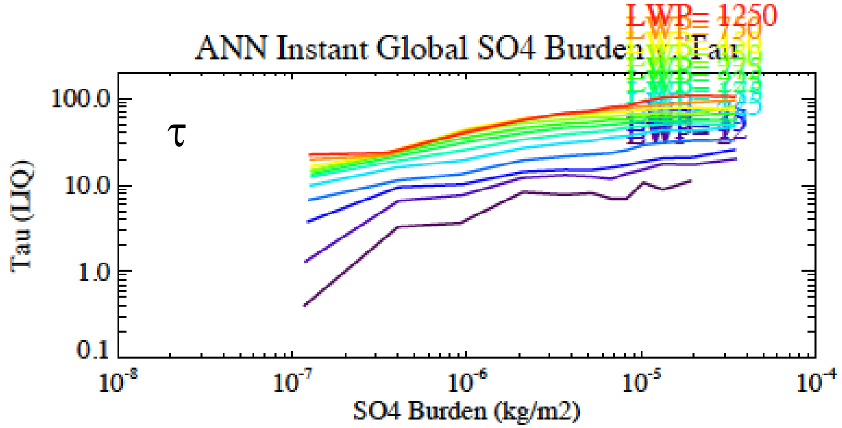
Does this work? It does for Re, and it does for albedo.

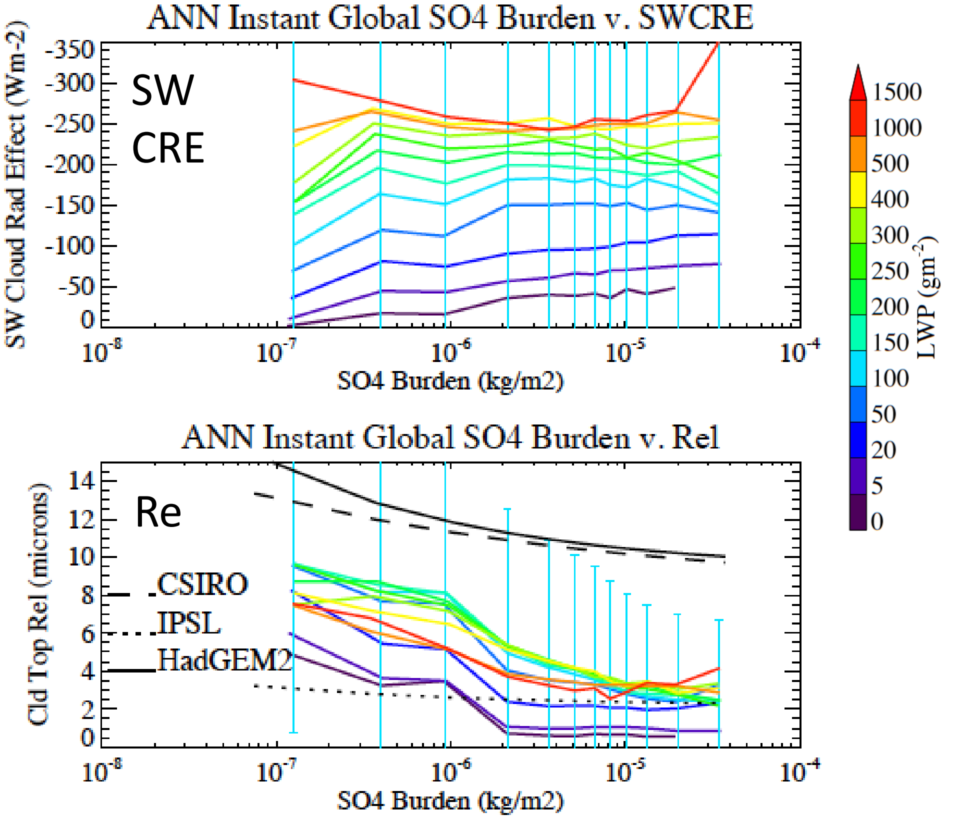
But: slope is LWP dependent: means that it is going to be a bit more complicated….

Methodology

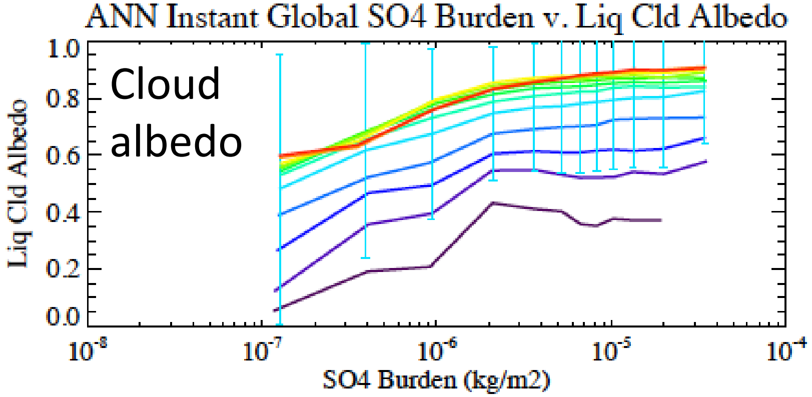
- Scatterplots/Joint PDFs
- X axis: aerosol or cloud ‘micro’ properties
  - SO_4, Dust or Sea Salt burden, AOD, CDNC
- Y axis: ‘radiative’ cloud properties
  - Cld Optical Depth (τ), Cld Albedo, SWCRE, CDNC
- Sort by LWP or CDNC
- Wilcox et al: SO_4 Burden v. Re → albedo

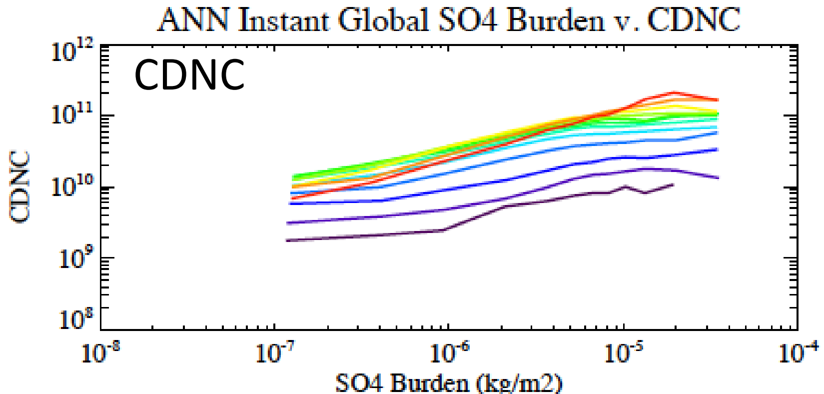
SO4 v Cloud Albedo, Re and CDNC


ANN Instant Global SO4 Burden v. Tau


ANN Instant Global SO4 Burden v. SWCRE

ANN Instant Global SO4 Burden v. Rel

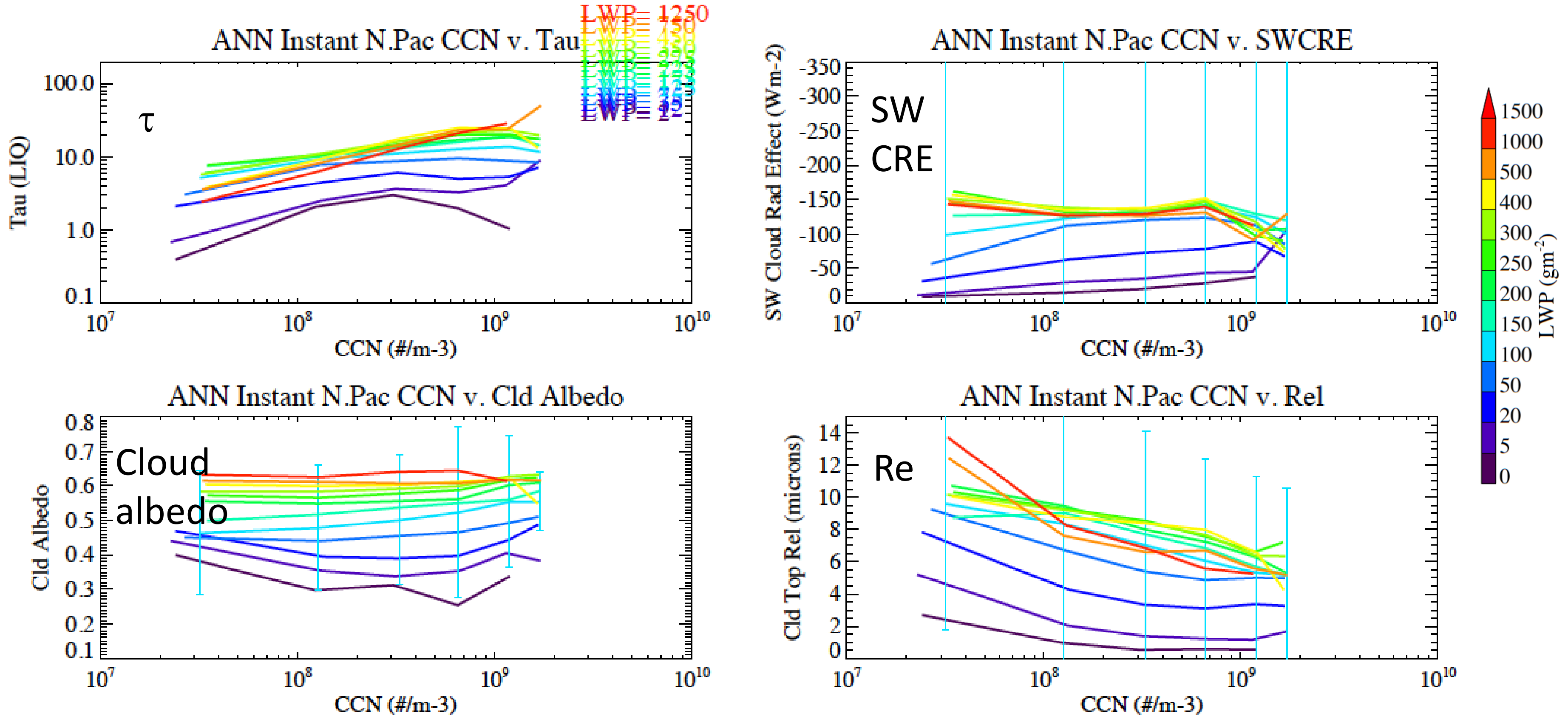

ANN Instant Global SO4 Burden v. Liq Cld Albedo


ANN Instant Global SO4 Burden v. CDNC

Clear relationships with CDNC & Re, but translation to CREs not direct: SWCRE change only in some LWP ranges.

Why: Looks like different regimes.

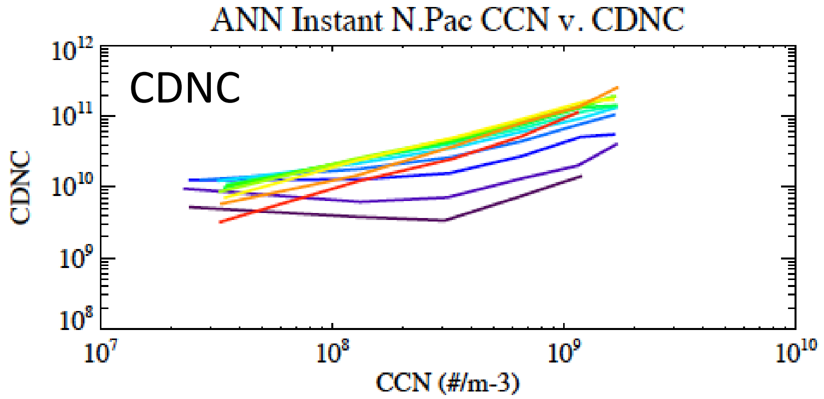
CCN v Cloud Albedo, Re and CDNC


ANN Instant N.Pac CCN v. Tau

ANN Instant N.Pac CCN v. SWCRE

ANN Instant N.Pac CCN v. Cld Albedo

ANN Instant N.Pac CCN v. Rel

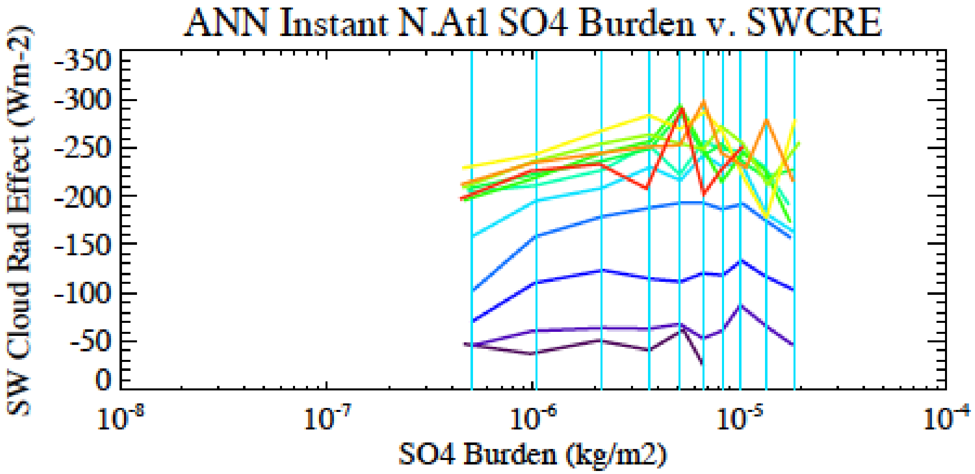

ANN Instant N.Pac CCN v. CDNC

Clear relationships with CDNC & Re, but
Translation to SWCRE not direct
τ and α change only in some LWP ranges
Even CDNC v. CCN not direct

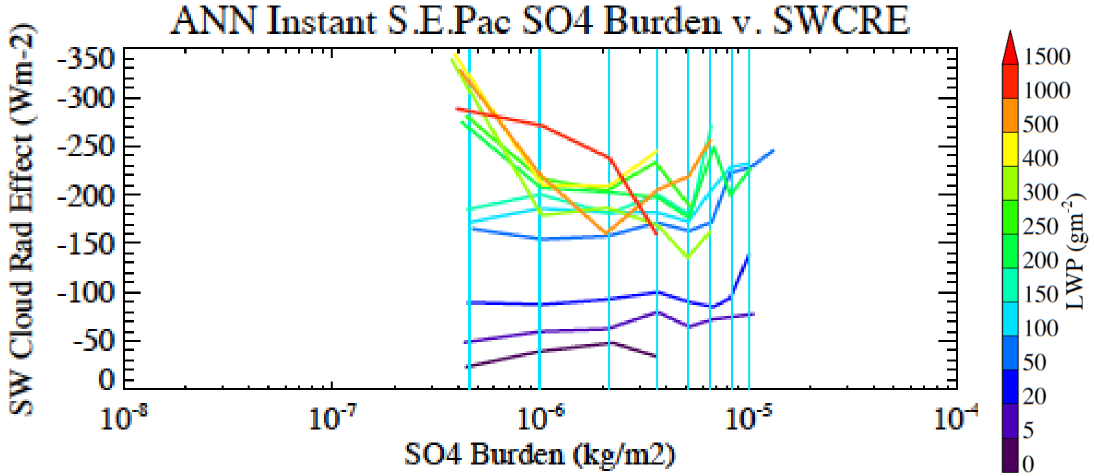
Microphysics matters!

SO_4 v. SWCRE Regional

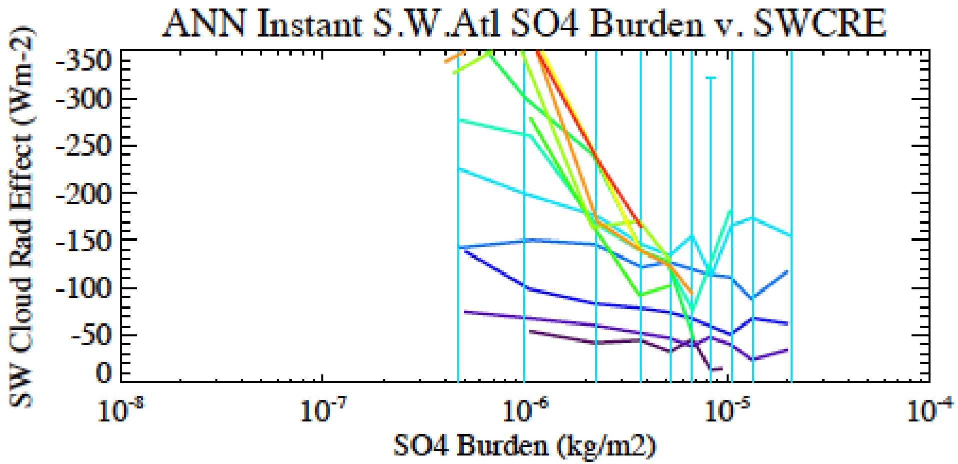
N. Atl Storm Track
(N. Pacific Similar)



VOCALS: S. E. Pacific



Barbados: Tropical Atlantic

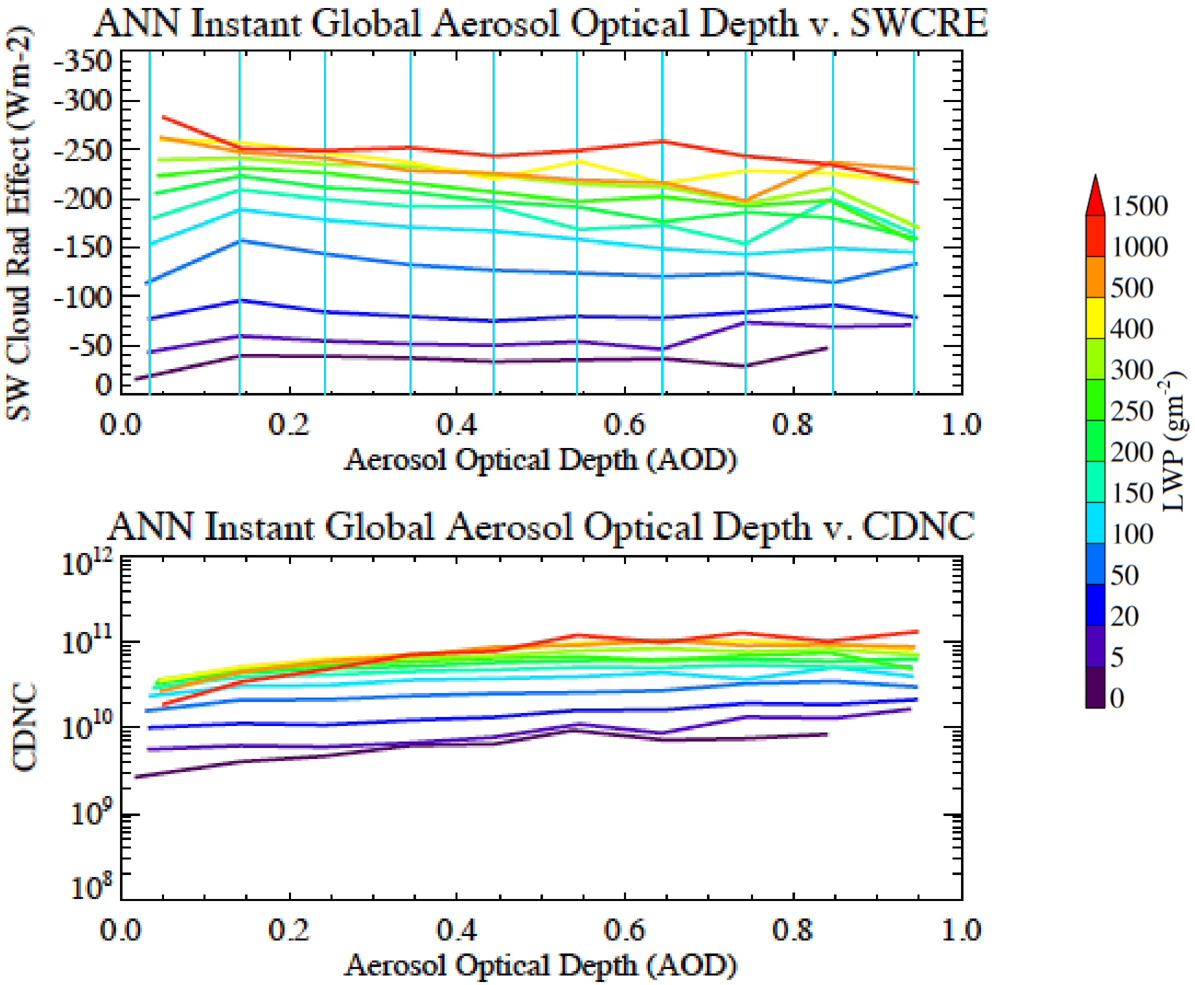


“Cloud Thinning” with higher SO_4

SO_4-Cloud Relationships

- SWCRE increases (more neg) with + SO_4 in many regions
  - Mostly moderate LWP (125-300 gm^{-2})
- Correlations stronger in Arctic and S. Ocean , N Atl, Global
- Shallow clouds: (SW Atlantic: Barbados): SWCRE decreases (less neg) in SWCRE with increasing SO_4
  - Is this a cloud burn off mechanism? (Ackerman)
  - GCM may be able to do `buffering…’ (Stevens & Feingold, 2009)

AOD-Cld (Global, Instant, sort by LWP)



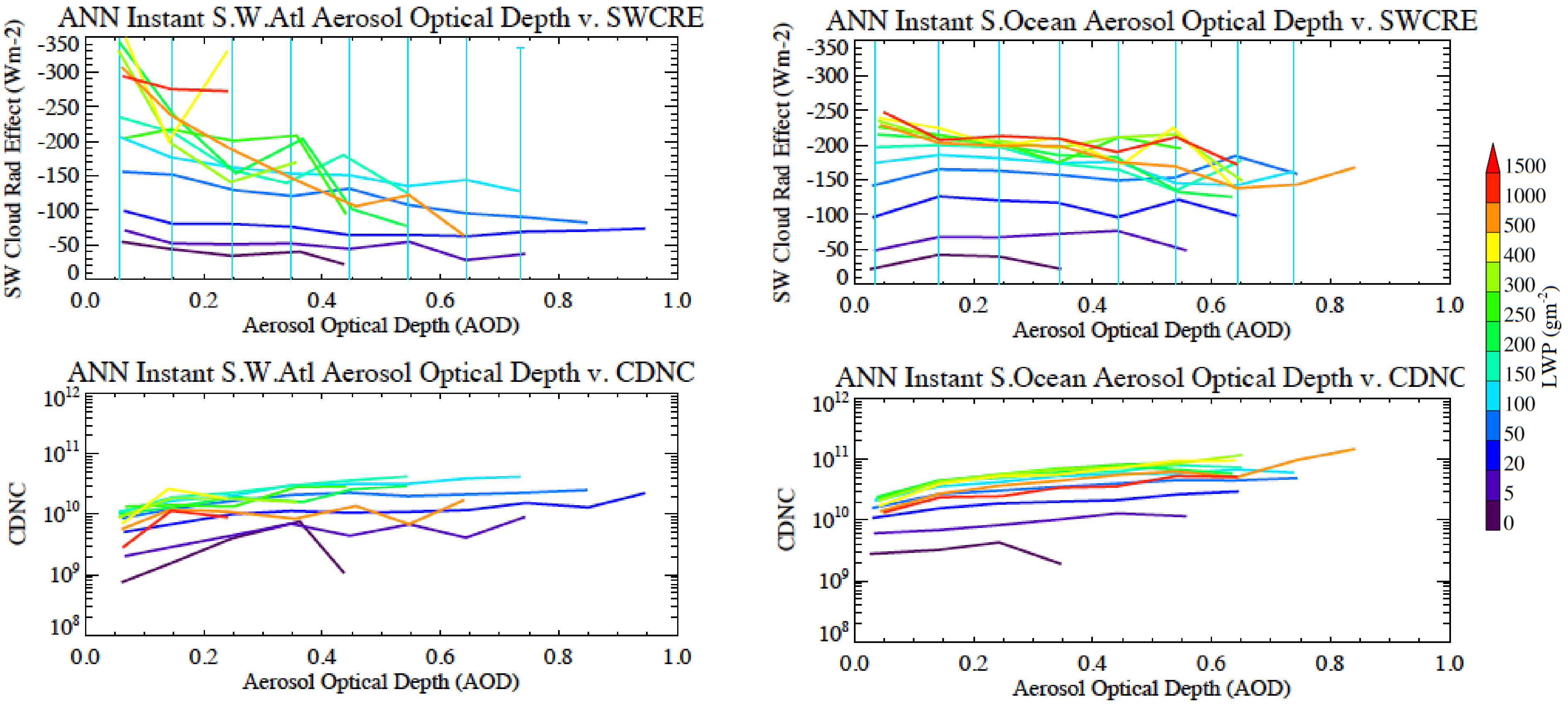
See some relationships: But SWCRE decreases with AOD even as CDNC increases?

AOD v. SWCRE or CDNC

Increases in CDNC with AOD

Shallow clouds: Reductions in SWCRE with higher AOD at higher LWP.
Storm Tracks Similar

What is going on? Also seasonal effects



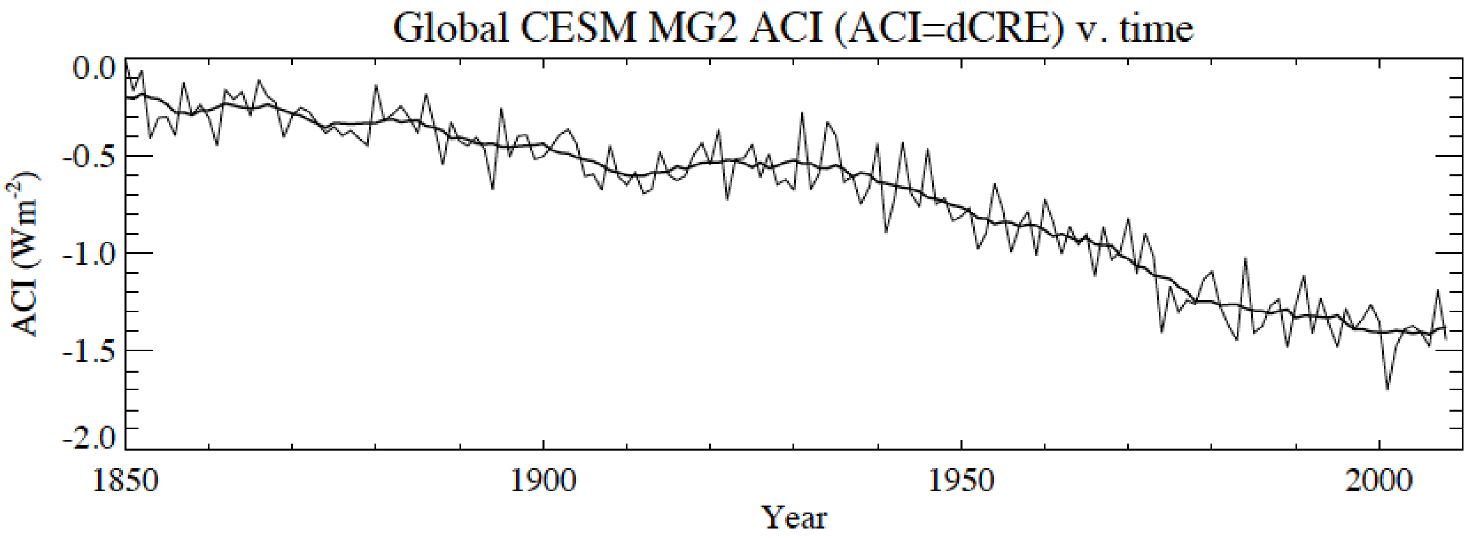
Summary

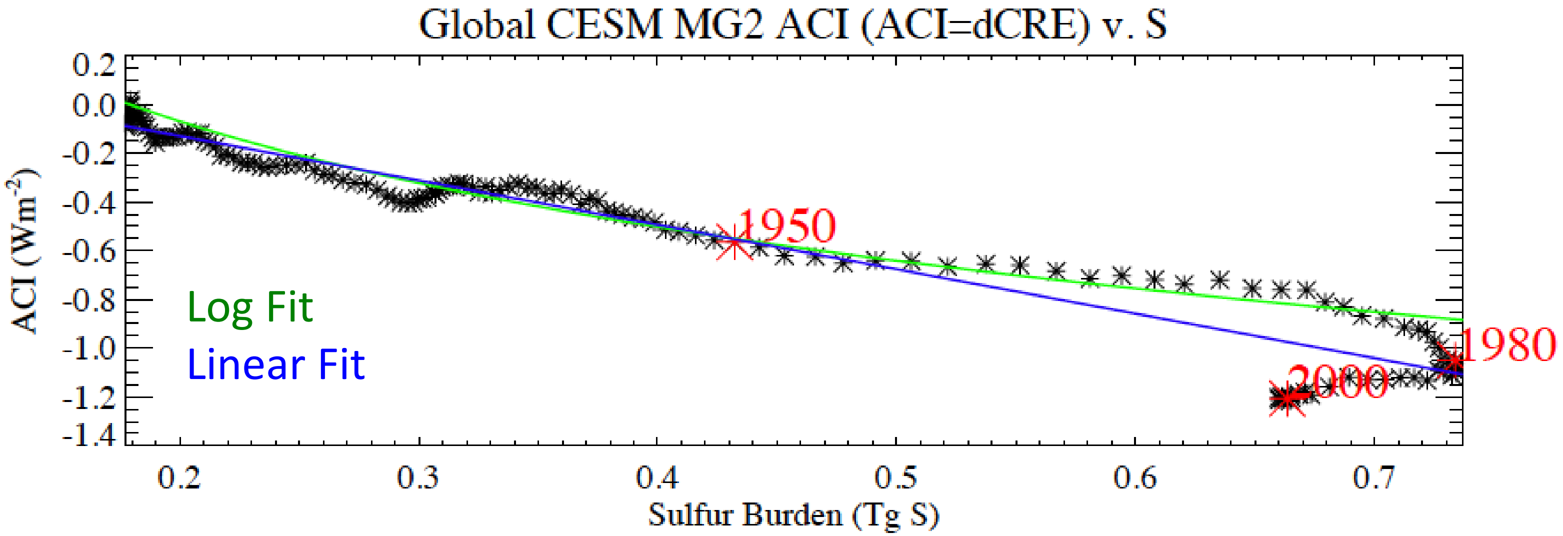
- Link from CDNC→ albedo seen in a comprehensive model
- Albedo or τ → Forcing (SWCRE) is a weak link
  - Effects vary by LWP (proxy for cloud regime?)
- Complex relationships by cloud regime
  - Large scale patterns depend on regions and seasons
  - E.g.: SWCRE has a seasonal dependence
- Beyond the albedo effect
  - In trade cumulus regime: simulations have negative correlations between SWCRE & SO_4 or AOD (+aerosol → dimmer cloud)
- Cloud relationships with AOD are weaker than with SO_4
  - Other species (sea salt, dust, BC) contribute to AOD
- Non-linearity implies cloud responses are:
  - Not stationary over time
  - Vary with source pattern

Cloud Effects v. Sulfur (and Time)

ACI over time also changes

Pattern of emissions changes will have an impact….



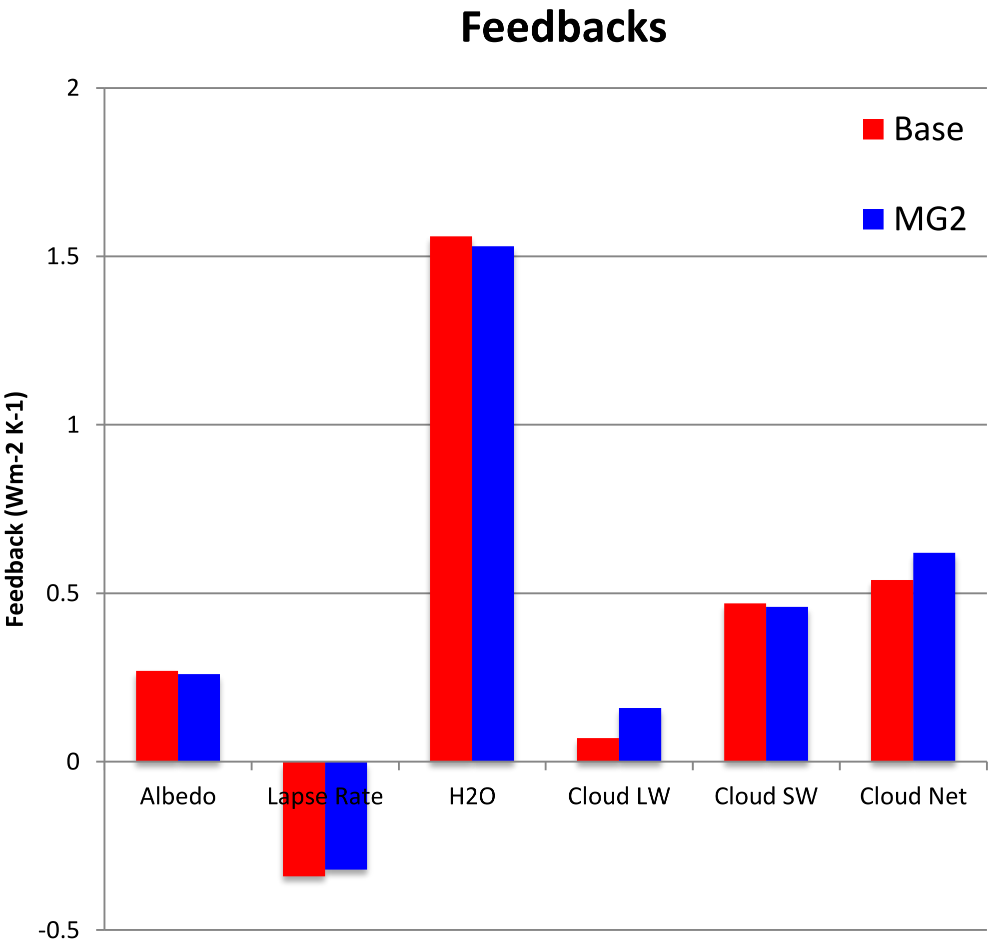


Microphysics and Cloud Feedbacks

	ΔTs (K)	λ_{eff} ($Wm^{-2}\ K^{-1}$)
MG1	3.94	0.92
MG2	4.47	0.81

Slab Ocean Model Simulations
720 v. 360 ppm CO_2

Base (MG1) v. MG2: +0.5K increase in climate sensitivity



Using Prognostic Precipitation (MG2), climate sensitivity goes up by 0.5K

Why? Cloud Feedbacks

A) SW feedbacks in S. Ocean
B) LW Feedbacks in Tropics

Microphysical view of Cloud Feedbacks

Cloud forcing (R_{CLD}) is observed and ‘well known’

$R_{CLD} = f(a,\tau)$ (a= fraction, $\tau =$ optical depth)

Satellites have different *a* (viewing geometry & sensitivity)

Can correct for this with ‘simulators’

Both a,τ are ‘known’ from observations outside of the Arctic

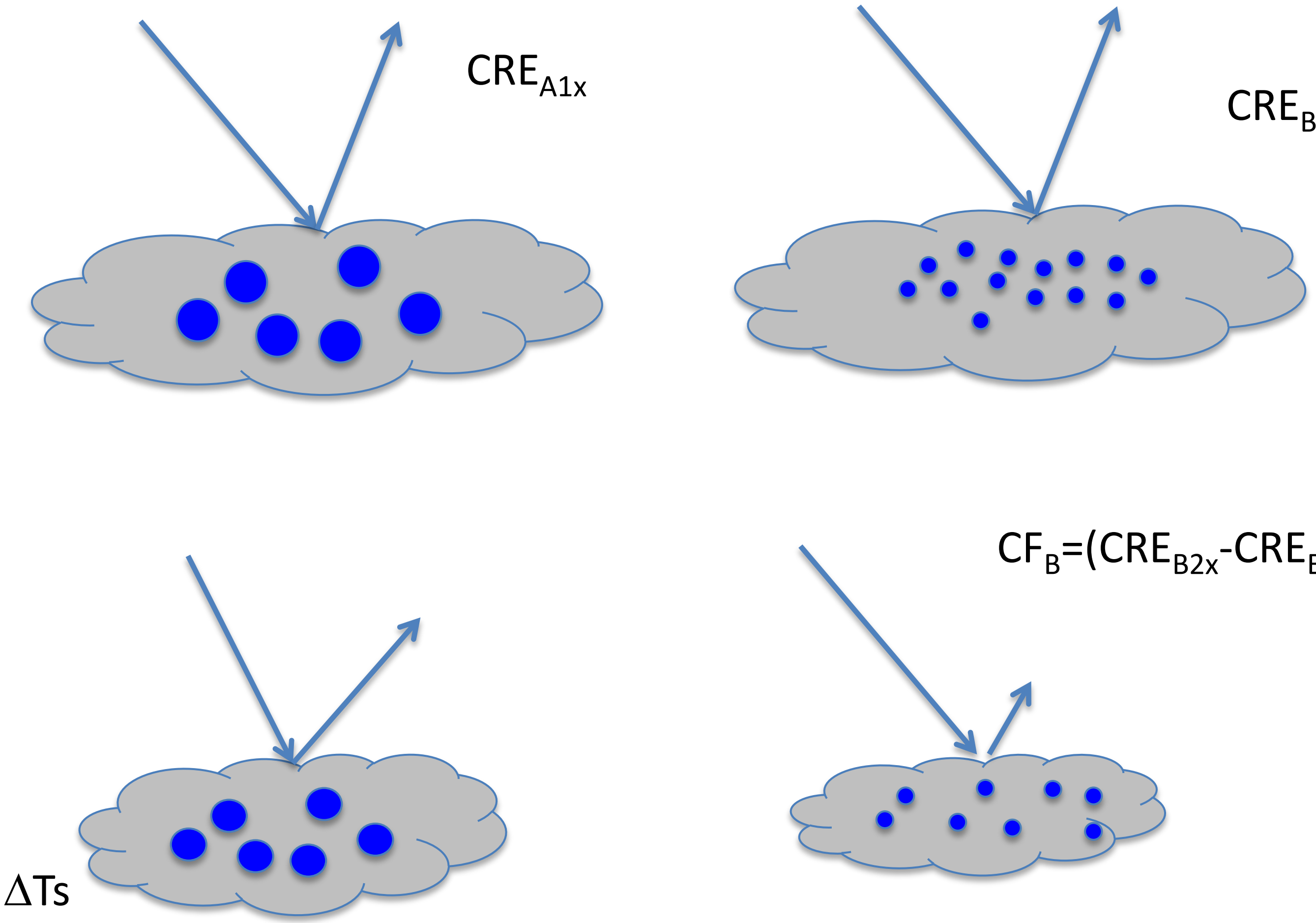
But:

$\tau = f(N_c, LWP)$ [mass,#]

Satellites measure τ, assume N_c to get LWP

Non unique function of N_c, LWP (multiple possible states)

Cloud Feedback (CF) and Mean State



CRE_{A1x}

$\text{CRE}_{B1x}=\text{CRE}_{A1x}$

1xCO_2
Ts

$\text{CF}_B=(\text{CRE}_{B2x}-\text{CRE}_{B2x})/\Delta T_s$

$\text{CF}_A>\text{CF}_B$

2xCO_2
$\text{Ts}=\text{Ts} + \Delta\text{Ts}$

$\text{CF}_A=(\text{CRE}_{A2x}-\text{CRE}_{A1x})/\Delta T_s$

Conclusions

- Climate forcing is uncertain *due to aerosols* (ACI)
- Aerosol effects are complex
  - Vary by cloud type and regime
  - Use this to better constrain global models
  - Can we simulate and evaluate this complexity?
  - Compare to detailed models?
- Cloud feedbacks likely determined by cloud state
  - ‘Microphysical’ example: aerosols affect cloud state
- Key to progress: understand key cloud regimes
  - Shallow Cumulus
  - Mixed phase synoptic & stratiform clouds

aerosol **CLOUD** interactions (aCi)

- Cloud microphysics alters aCi
  - Prognostic precipitation changes process rates
  - Also may change aerosol processing
- Cloud response to aerosols (aCi) is critical
  - For aerosol forcing
  - Also for cloud state, hence feedbacks & sensitivity
  - Future aCi affects feedbacks (‘aerosol feedback’?)
- Current ‘state of clouds’ not sufficiently constrained
  - Need to know how the cloud radiative effects (τ) are maintained