Simulating the Earth's Radiation Budget
What keeps me up at night

Andrew Gettelman & the 'CESM Development Team':

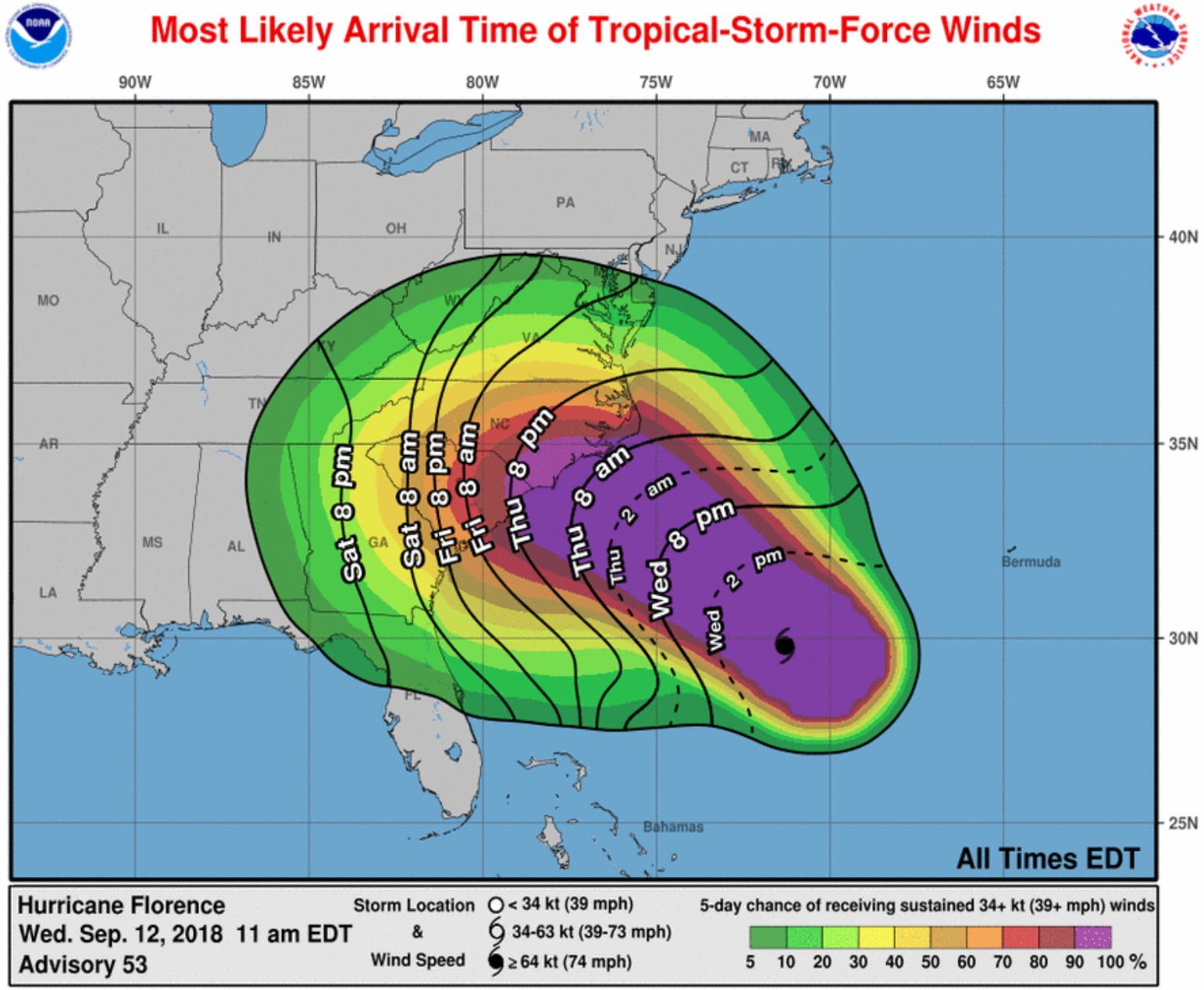
Esp: Lamarque, Bogenschutz, Hannay, Neale, Medeiros, Fasullo (NCAR),

Liu (UWy), Larson (UWM)

NCAR
NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

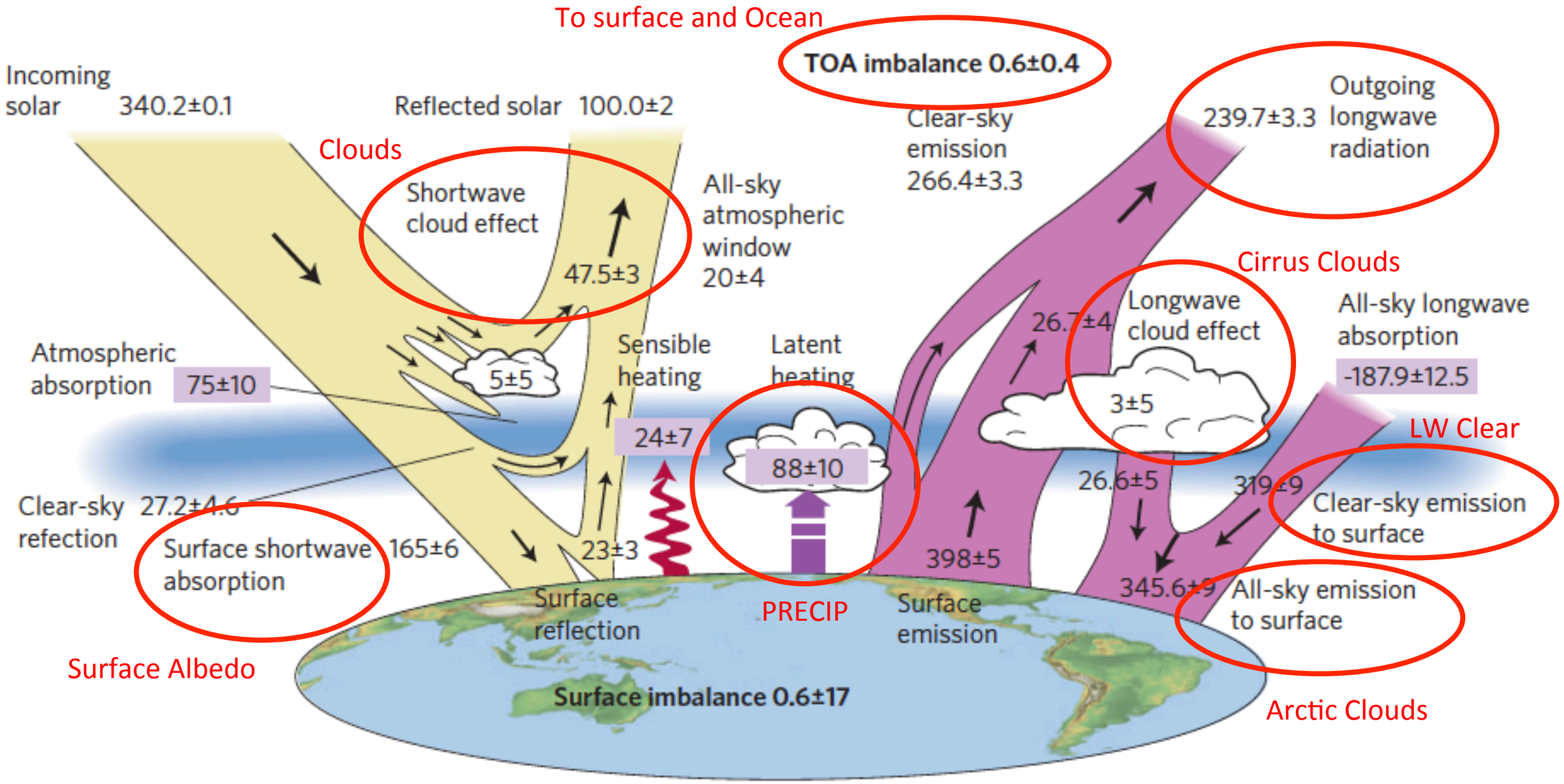
NSF

What keeps the CERES team up at night….



Outline

1. Motivation: Why worry about the Energy budget?
   Forcing and Feedback: how I think about the energy budget
2. CAM6/CESM2: where are we? Good, Bad or Ugly? (All of the above)
   Comparisons with observations
3. Forcing and Feedback from CESM2
4. How do we figure out forcing and feedback from observations?
5. Some complexities…
6. Summary



Stephens et al 2012

Motivation

- Understand forcing and feedbacks in CESM2
- Forcing is a balance between aerosol forcing and GHG forcing $F = F_{GHG} + F_{aero}$
- Feedbacks: response of the system
- Formally:

$$R = F - \lambda dT_s + dH$$

R= TOA imbalance, F=Forcing, λ= feedback parameter

H= Ocean Heat content, T_s = surface temperature

Using Observations

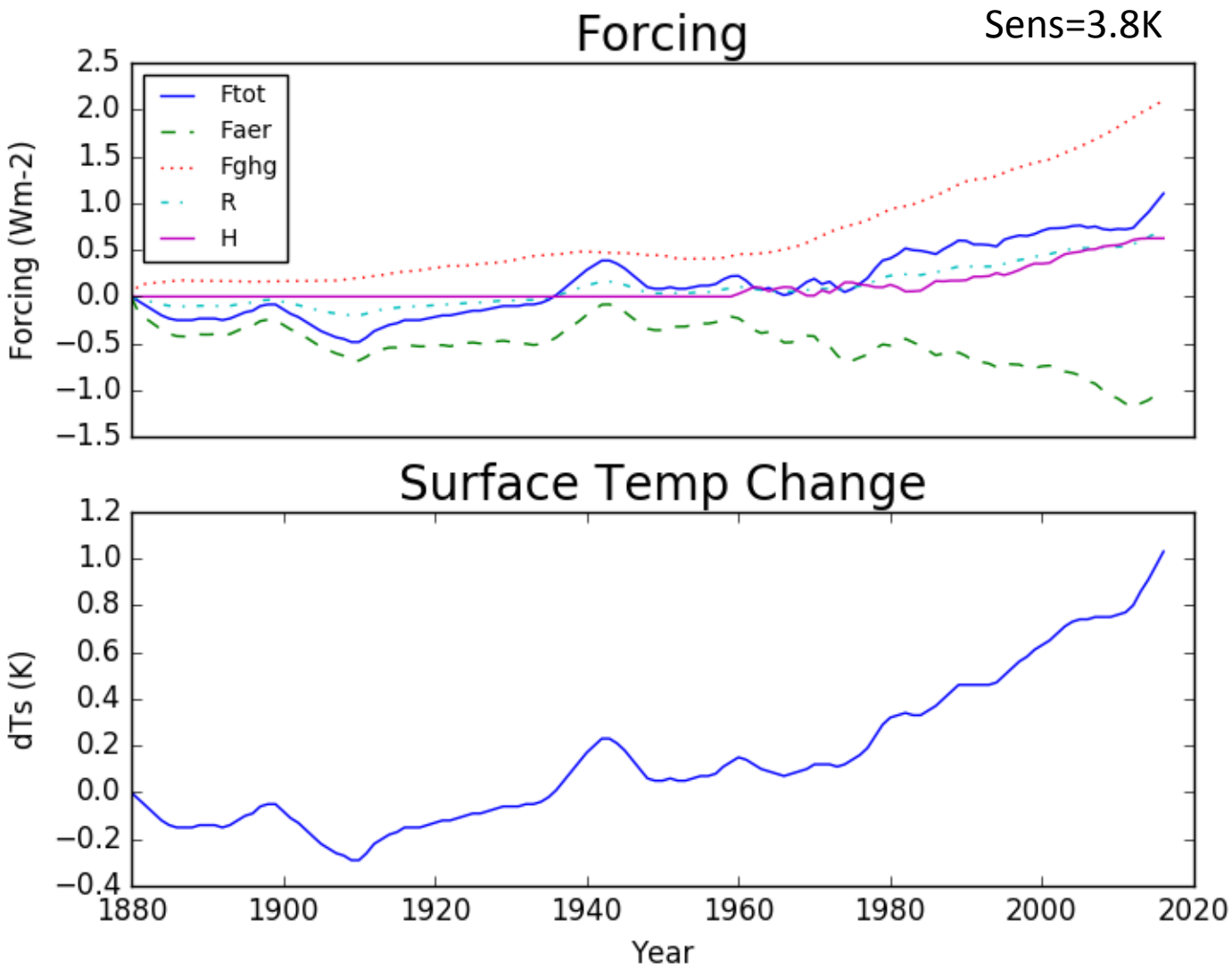
TOA imbalance = ocean heat uptake

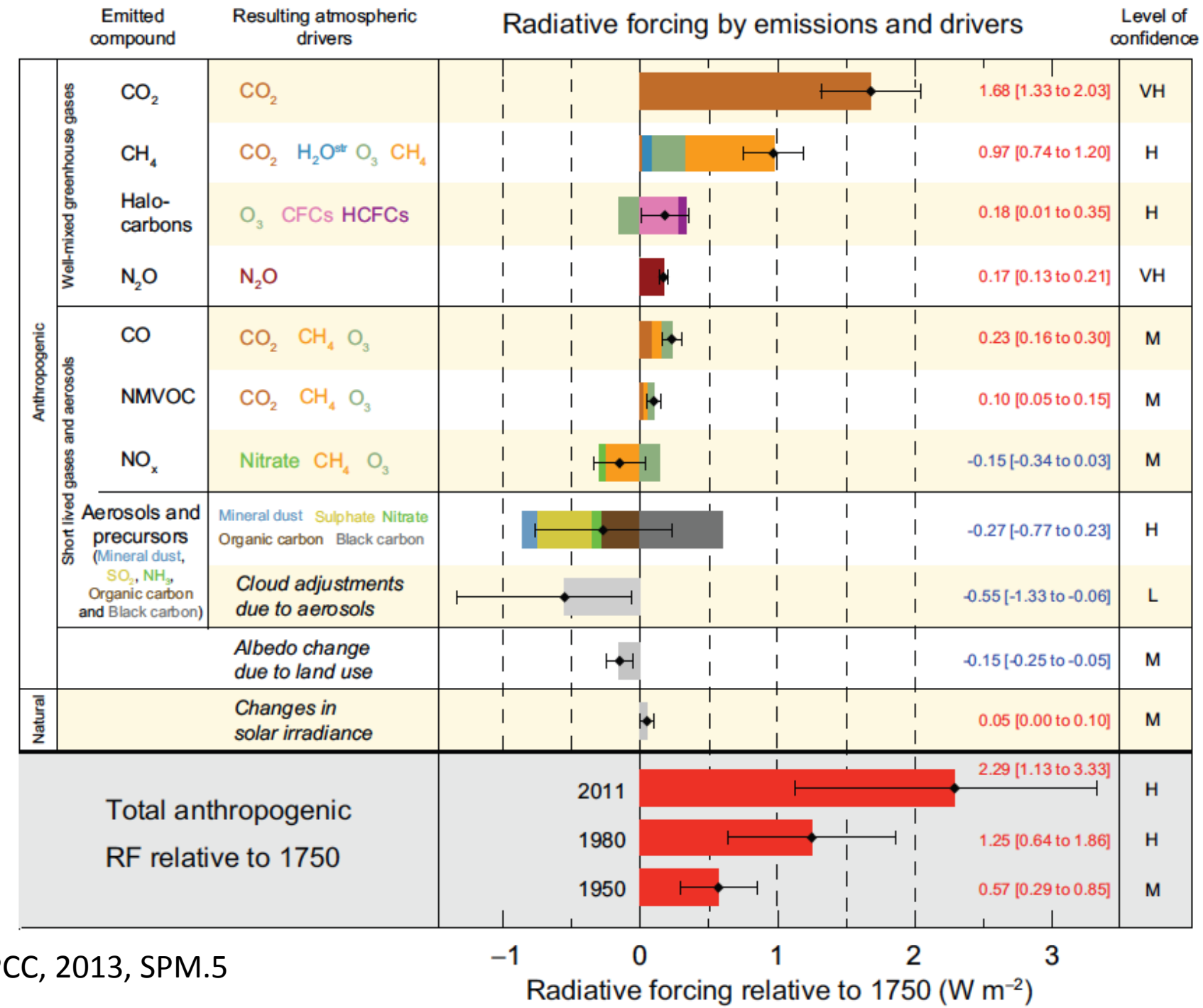
The ocean heat uptake (H) and the energy budget (R) may be able to constrain climate forcing (F) and feedbacks (λ).

Here: idealized, transient EB model.

$R = F_{aer} + F_{ghg} - \lambda Ts + H$ where all are *f(t)*

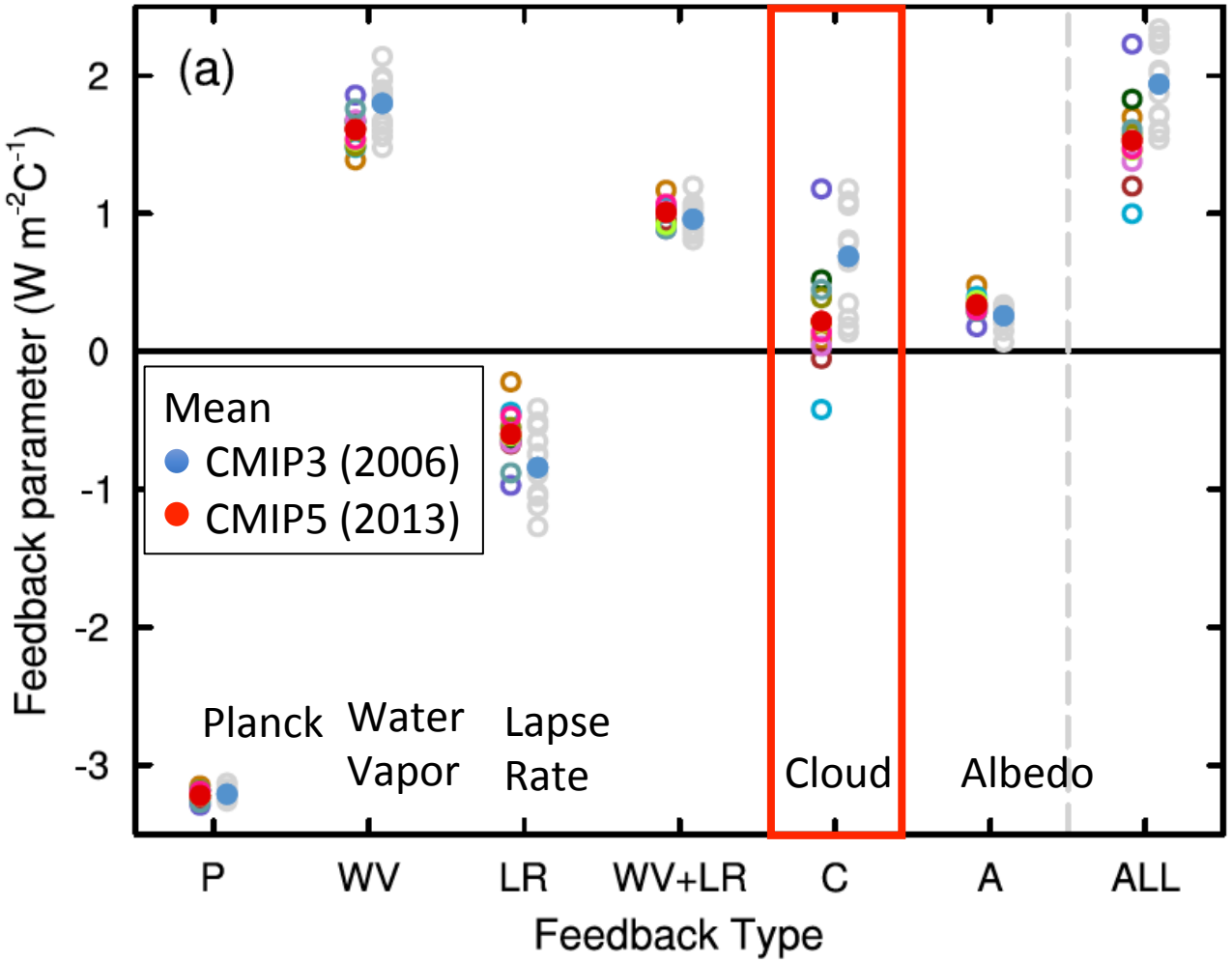
Specified F_{ghg}, and 'observed' Ts, H
R as a lag with set timescales
Assume λ to back out F_{aer}
H helps constrain λ and F_{aer} (+H → more $-F_{aer}$)





IPCC, 2013, SPM.5

Climate Feedbacks



Planck $\varepsilon = \sigma T^4$ (-)

Water Vapor
+T & RH=C → +H2O (+)

Lapse Rate (-)

Albedo (snow, ice)
+T → less snow, ice
-T → more snow, ice (+)

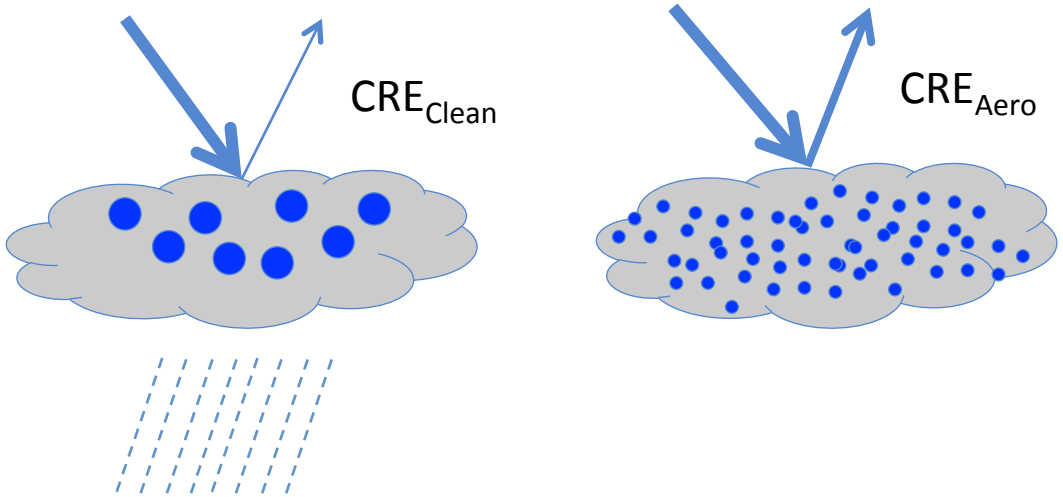
Clouds: Complicated (+)

IPCC, 2013 (Ch 9, Hartmann et al 2013) Fig 9.43. Updated from Coleman 2003

Aerosol Effects on Clouds

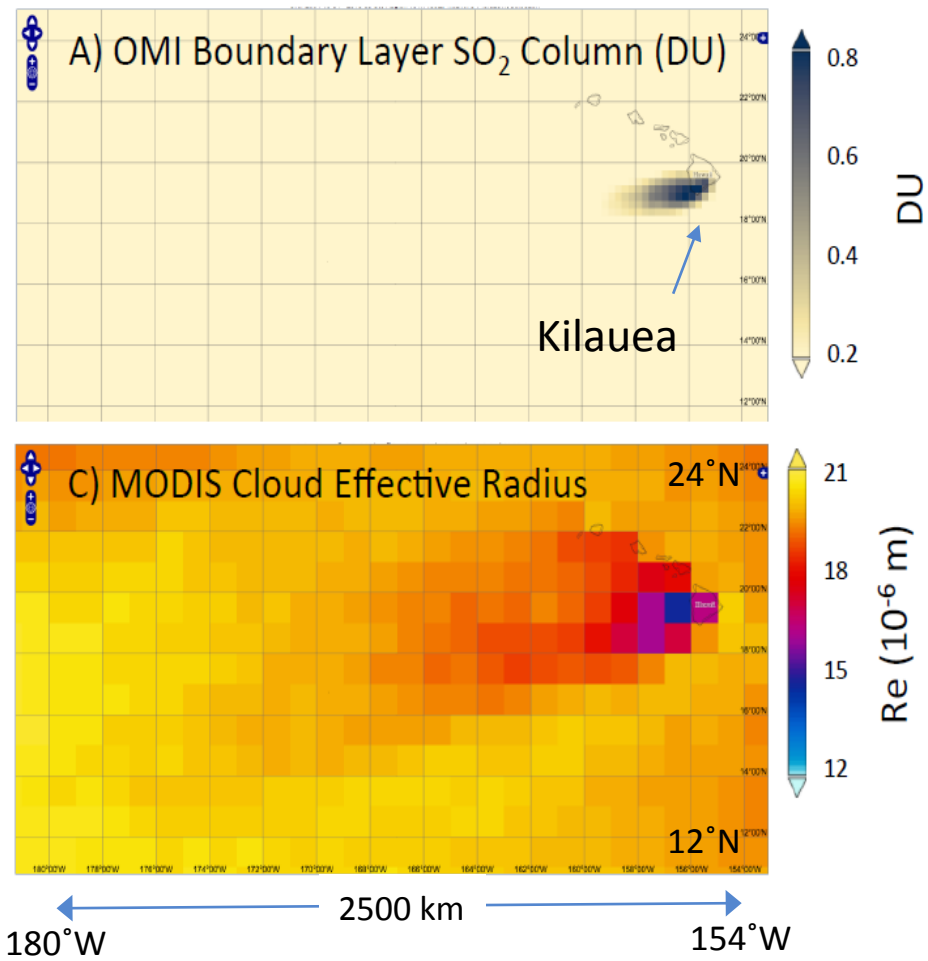
- Scattering & Absorption = Direct effects
- Aerosol – Cloud – Interactions (ACI)

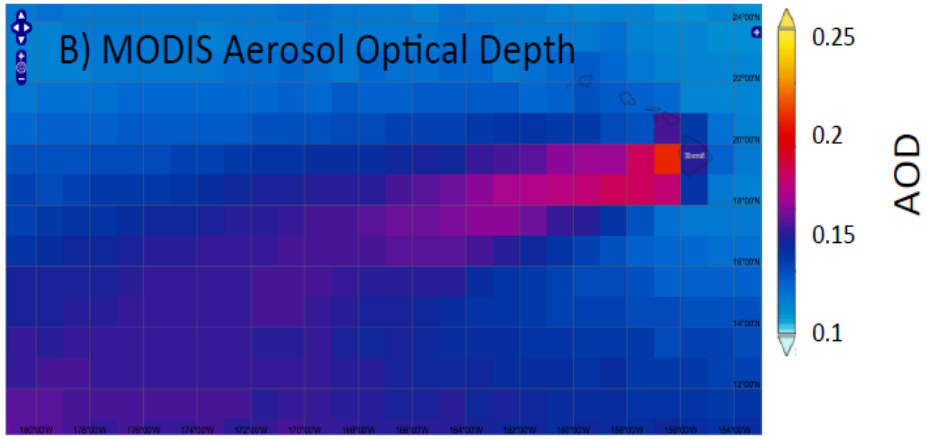
$$+\text{Aerosols} \rightarrow +\text{CCN} \rightarrow +N_c \rightarrow \Delta\text{CRE}$$



Brighter clouds (albedo effect) with smaller drops (S. Twomey 1977)
Also: delay in precipitation (B. Albrecht, 1989). Longer lived Clouds?

‘Volcano Tracks’: Satellite Climatology



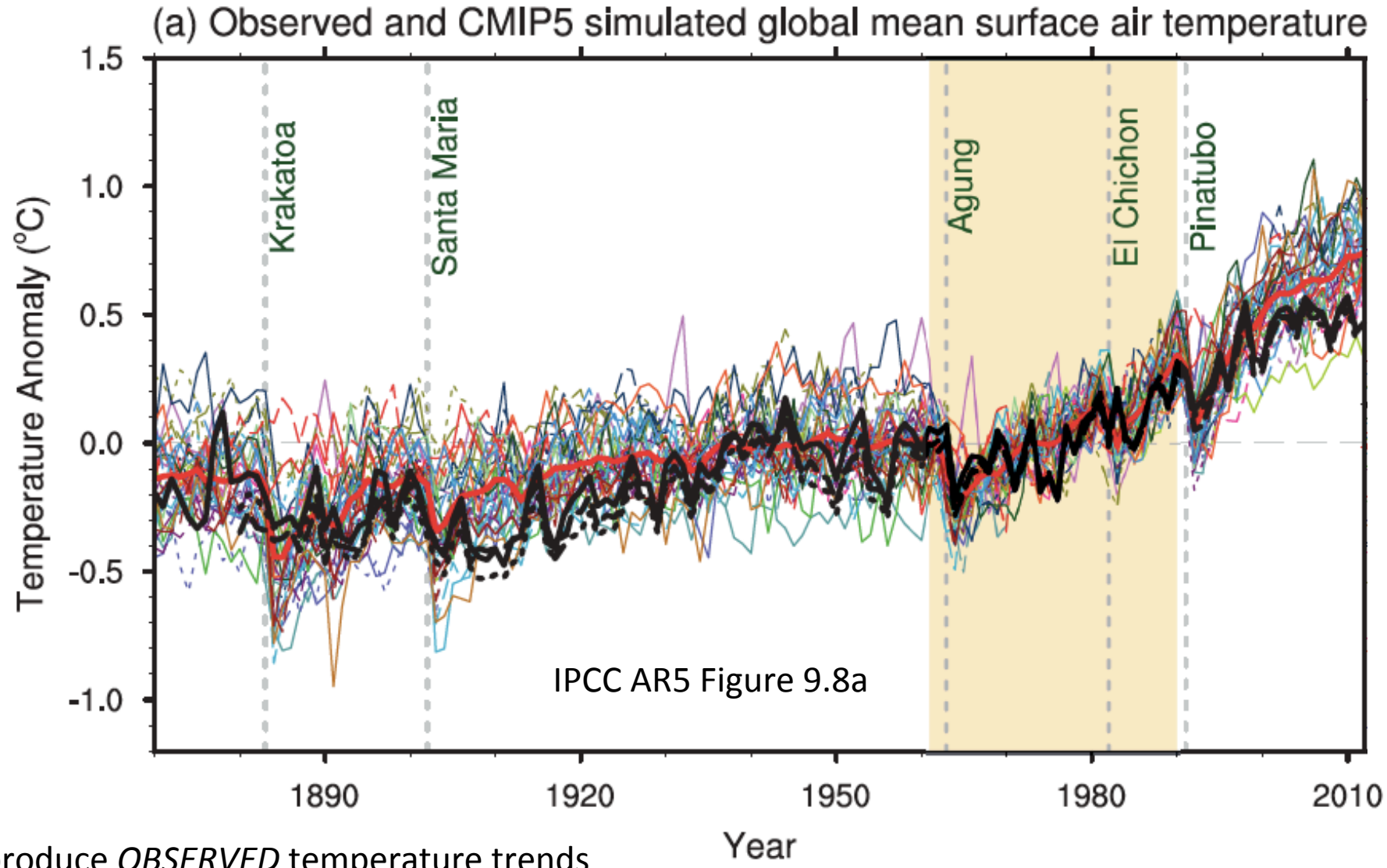


Satellite data for C. Pacific, 10 year climatology around the Hawaiian Islands

SO_2 is from Kilauea Volcano on Hawaii (Small-Griswold & Gettelman, in Prep)

Historical Record

$$R = F - \lambda dT_s + dH$$

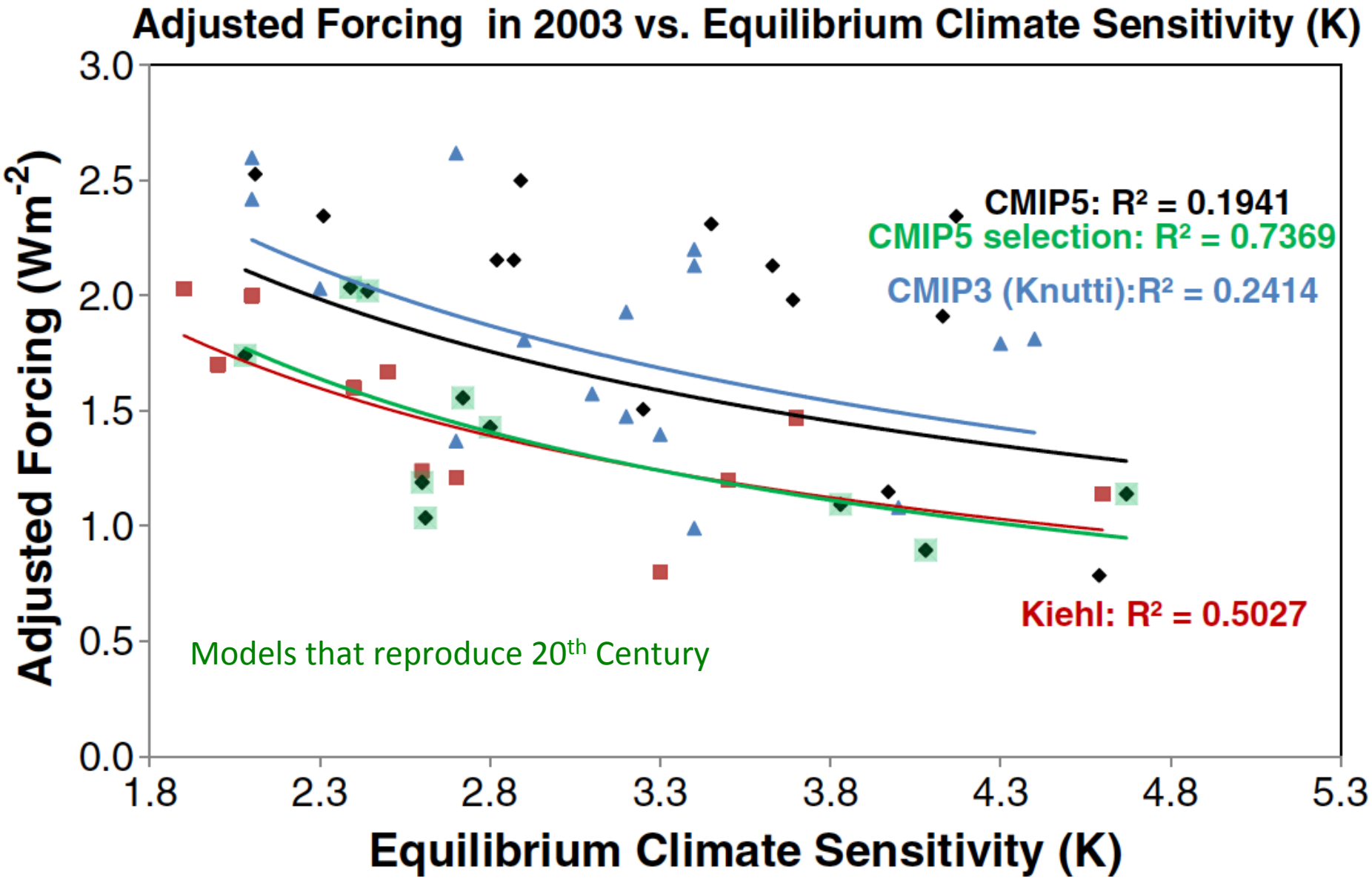


Models reproduce *OBSERVED* temperature trends

Note: secret hiding in plain sight….

Forcing Uncertainty

Forster et al 2013, Figure 7
Updated from Kiehl et al 2007

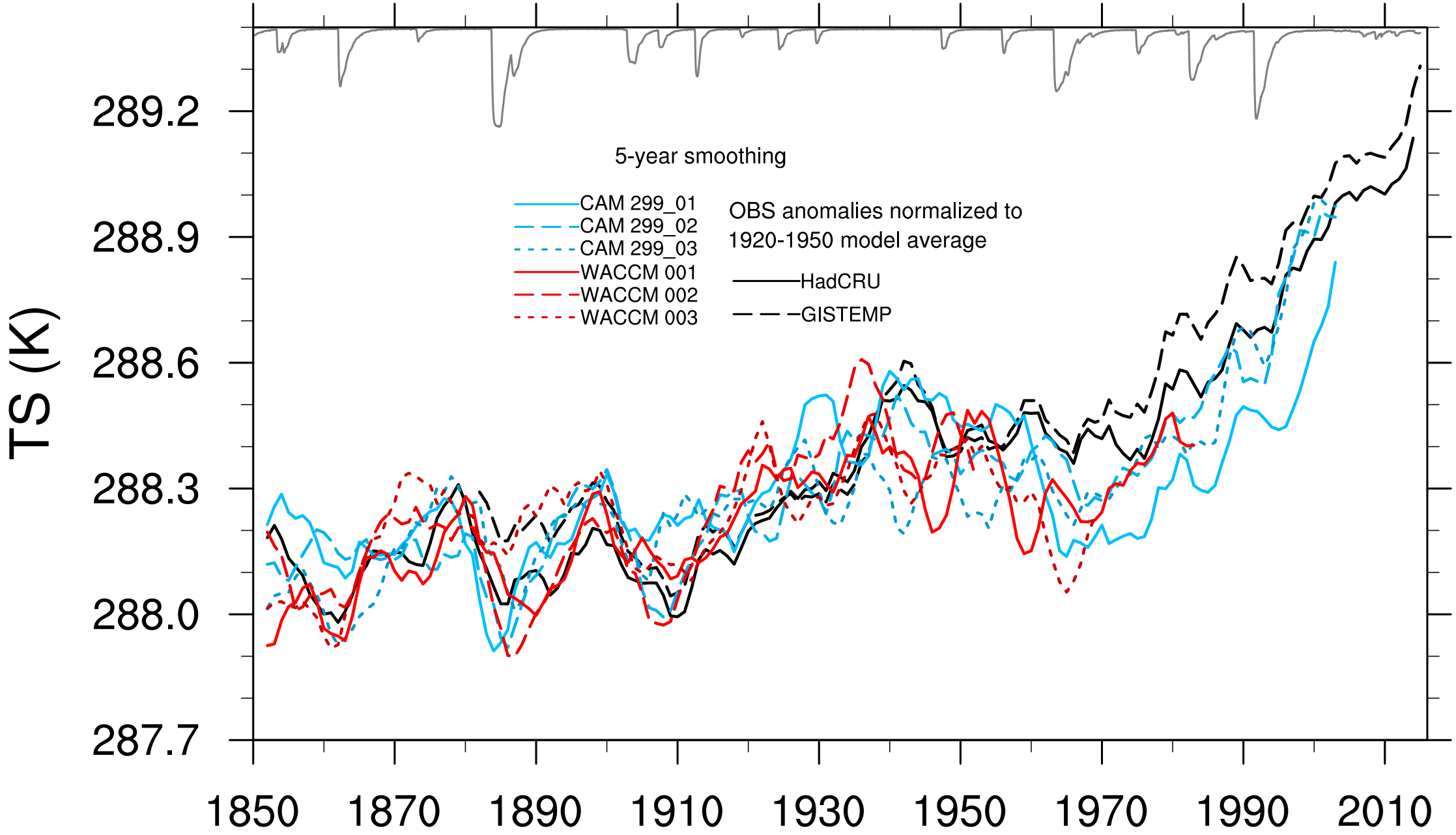


Key EEI/EB Issues for Modeling

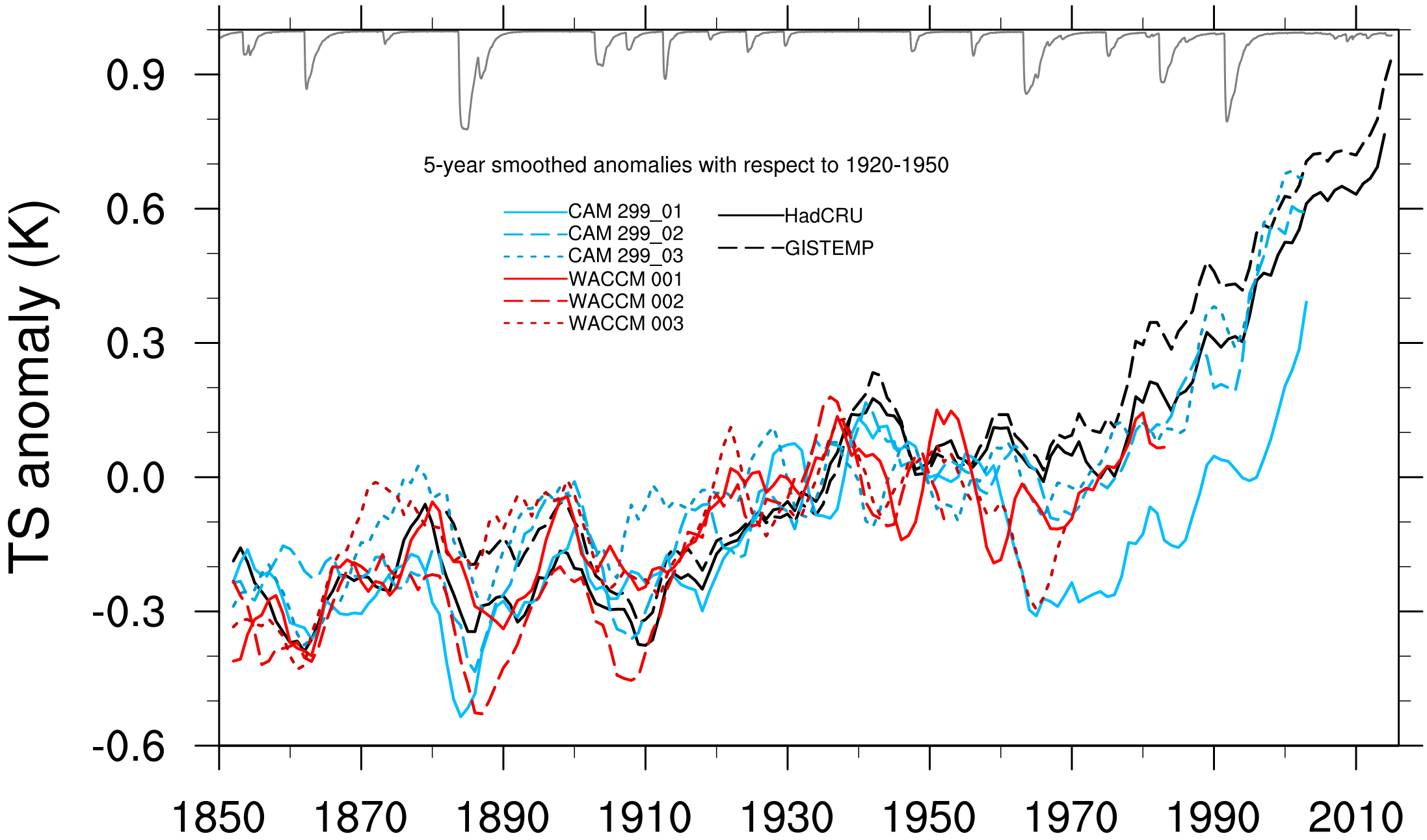
- My Bias: Clouds, Community Earth System Model (CESM)
  - Many of these issues are general across models
- TOA often hit the 'wrong' balance point. Better now.
- CESM2 2005 OLR ~ 239 Wm^{-2}, TOA imbalance +0.4 Wm^{-2}
  - CERES EBAF 2.8 OLR= 240 Wm^{-2}
- SH ASR Bias (too bright) reduced
  - In CESM: a supercooled liquid cloud problem
  - Remaining issues are around sea ice
- Latent Heat = Precipitation
- High Latitude: Surface radiation budget
  - Arctic low clouds especially

CESM2

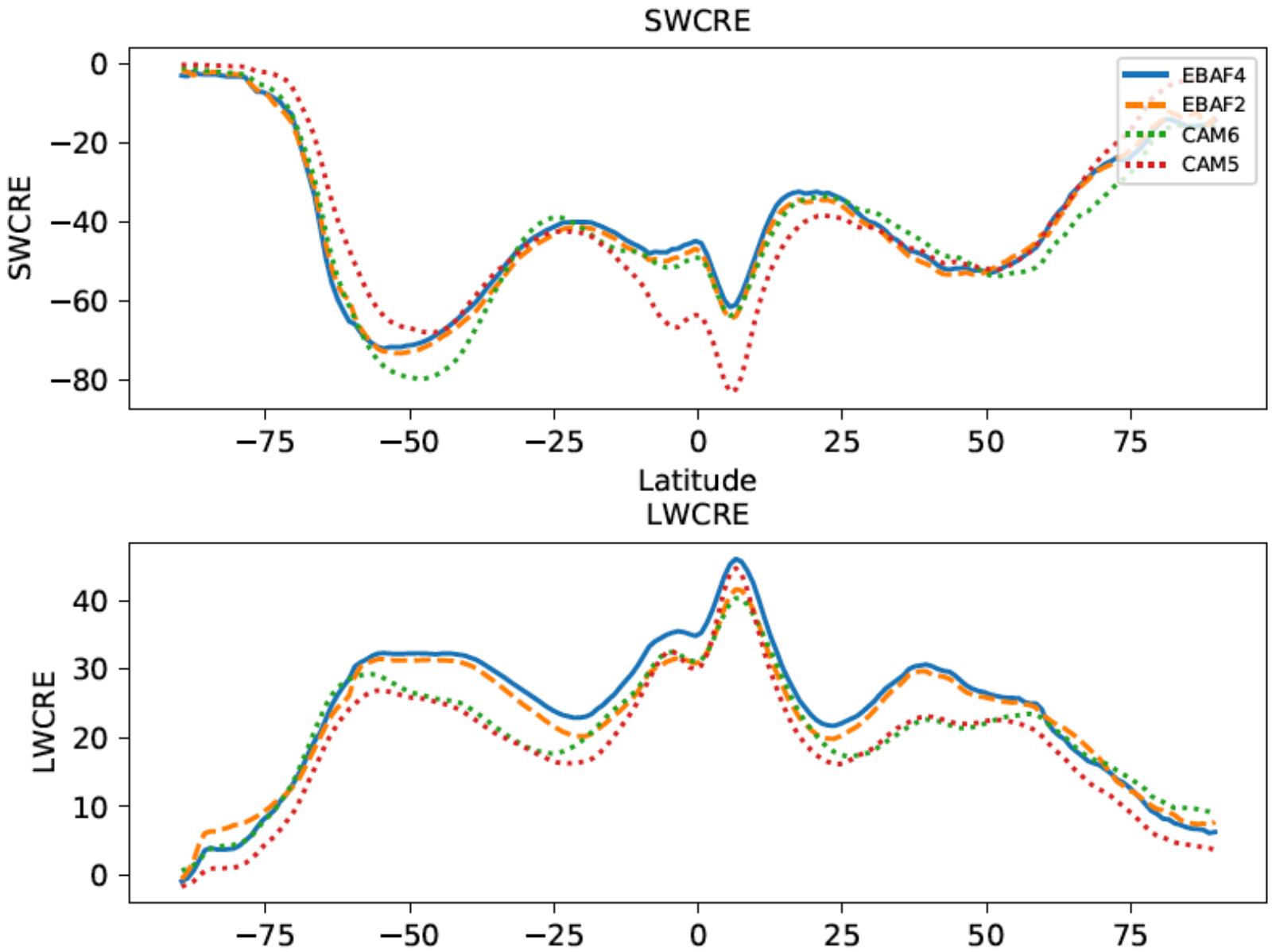
CMIP6 Historical runs, global surface temperature



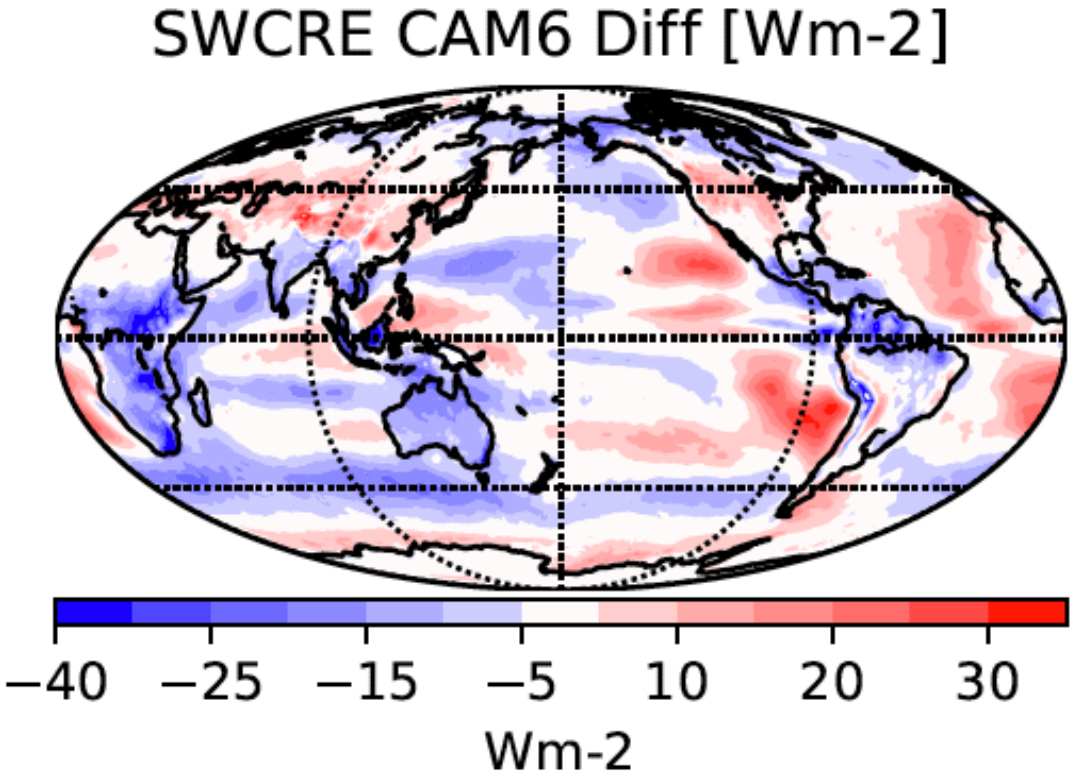
CMIP6 Historical runs, global surface temperature anomalies



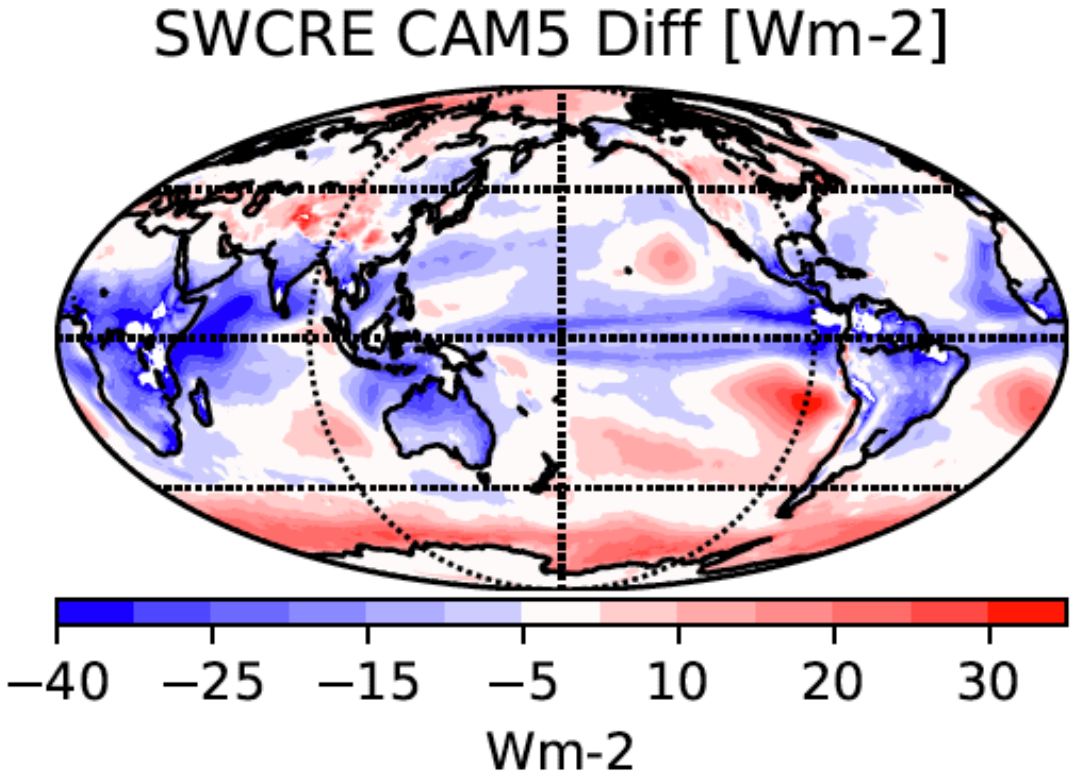
CESM2: Results (Global)



SW Cloud Biases (v. CERES EBAF4)

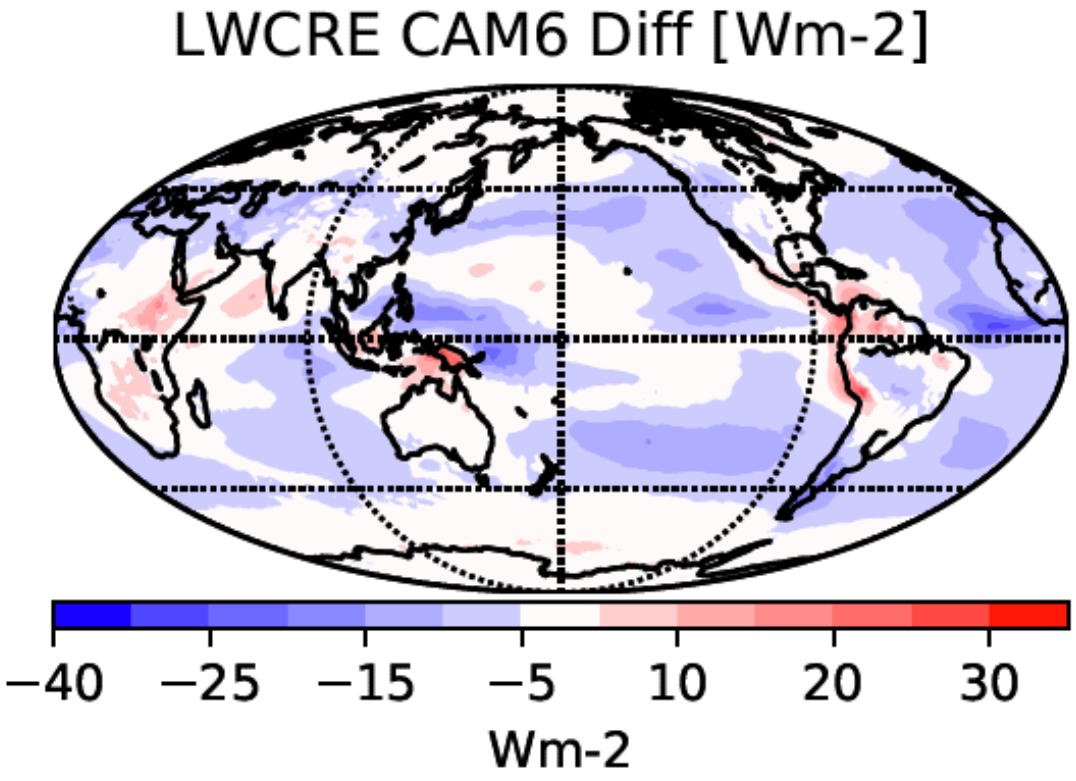


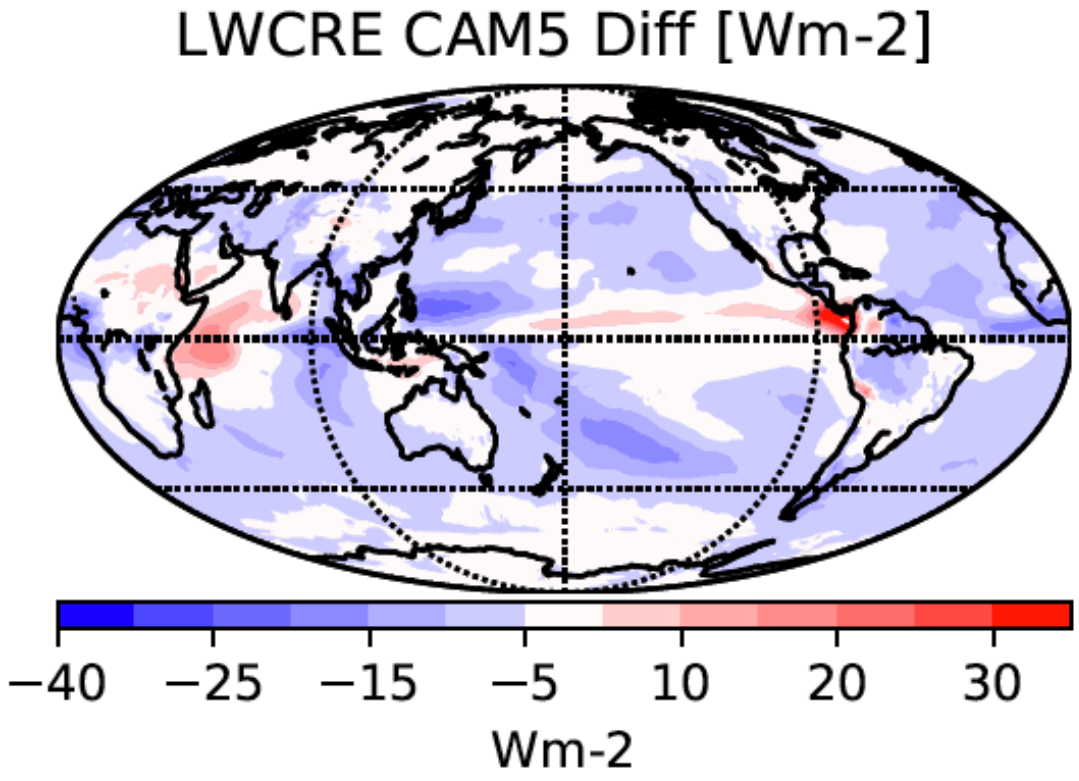
SWCRE RMSE v. EBAF4.0 = 9.05



SWCRE RMSE C5 v. EBAF4.0 = 12.57

LW Cloud Biases (v. CERES EBAF4)





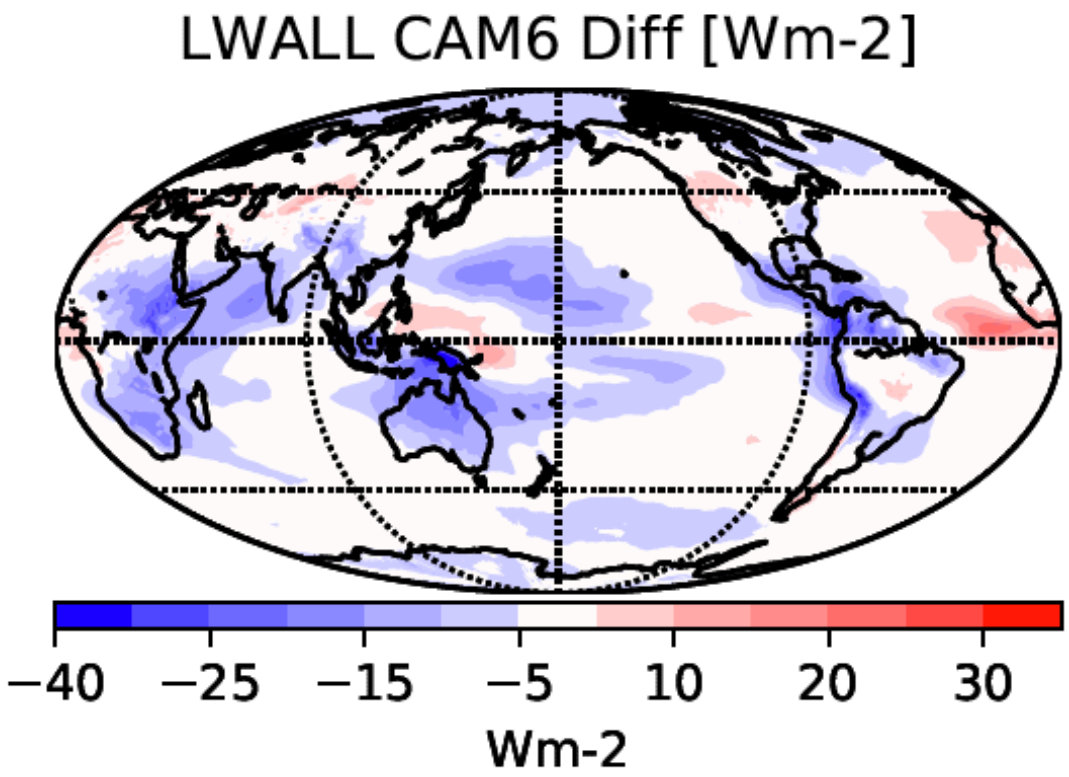
LWCRE RMSE v. EBAF4.0 = 5.93
LWCRE RMSE v. EBAF2.0 = 5.43

LWCRE RMSE C5 v. EBAF4.0 = 6.73

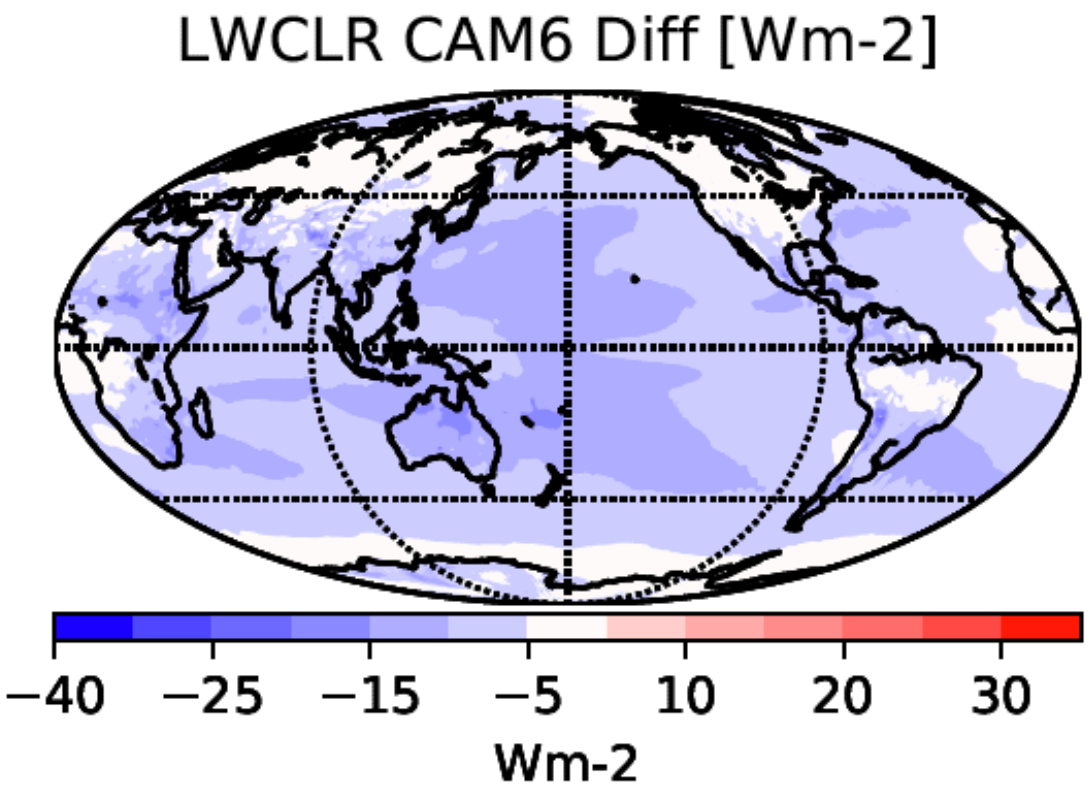
Note: RMSE actually larger v. EBAF4 than EBAF2.8

LW Biases (v. CERES EBAF4)

LW ALL Up



LW Clr Up



LWALL RMSE v. EBAF4.0 = 6.60

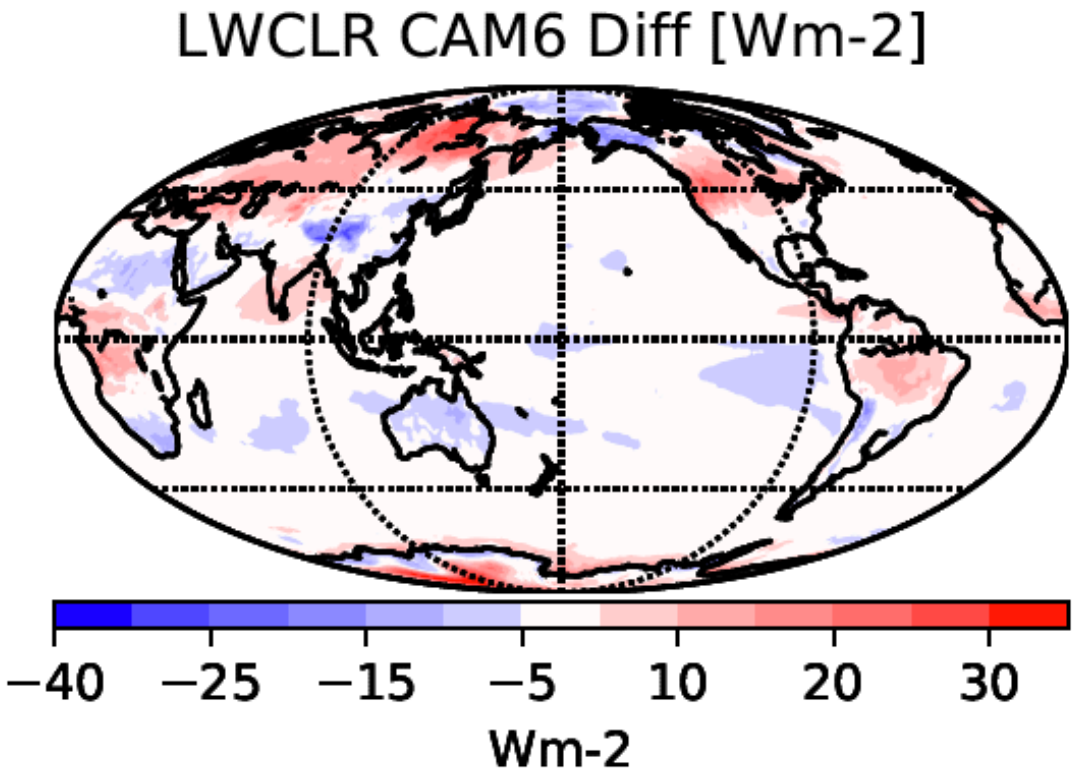
LWCLR RMSE v. EBAF4.0 = 7.81

RMSE larger for LW clear than LW all

This may not be a cloud problem, but a bias in water vapor.

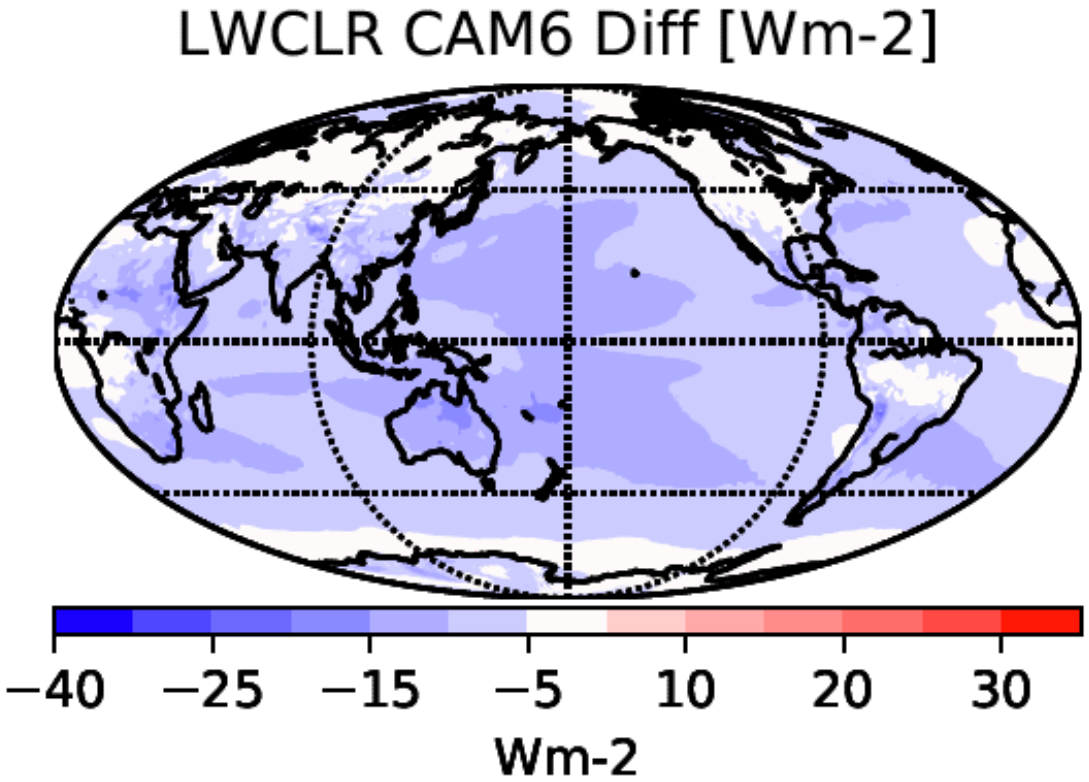
LW Clearsky Biases (v. CERES EBAF4)

SAMPLED for CLD < 0.1



LWCLR (Sampled) RMSE v. EBAF4.0 = 7.3

LW Clr Up



LWCLR RMSE v. EBAF4.0 = 7.81

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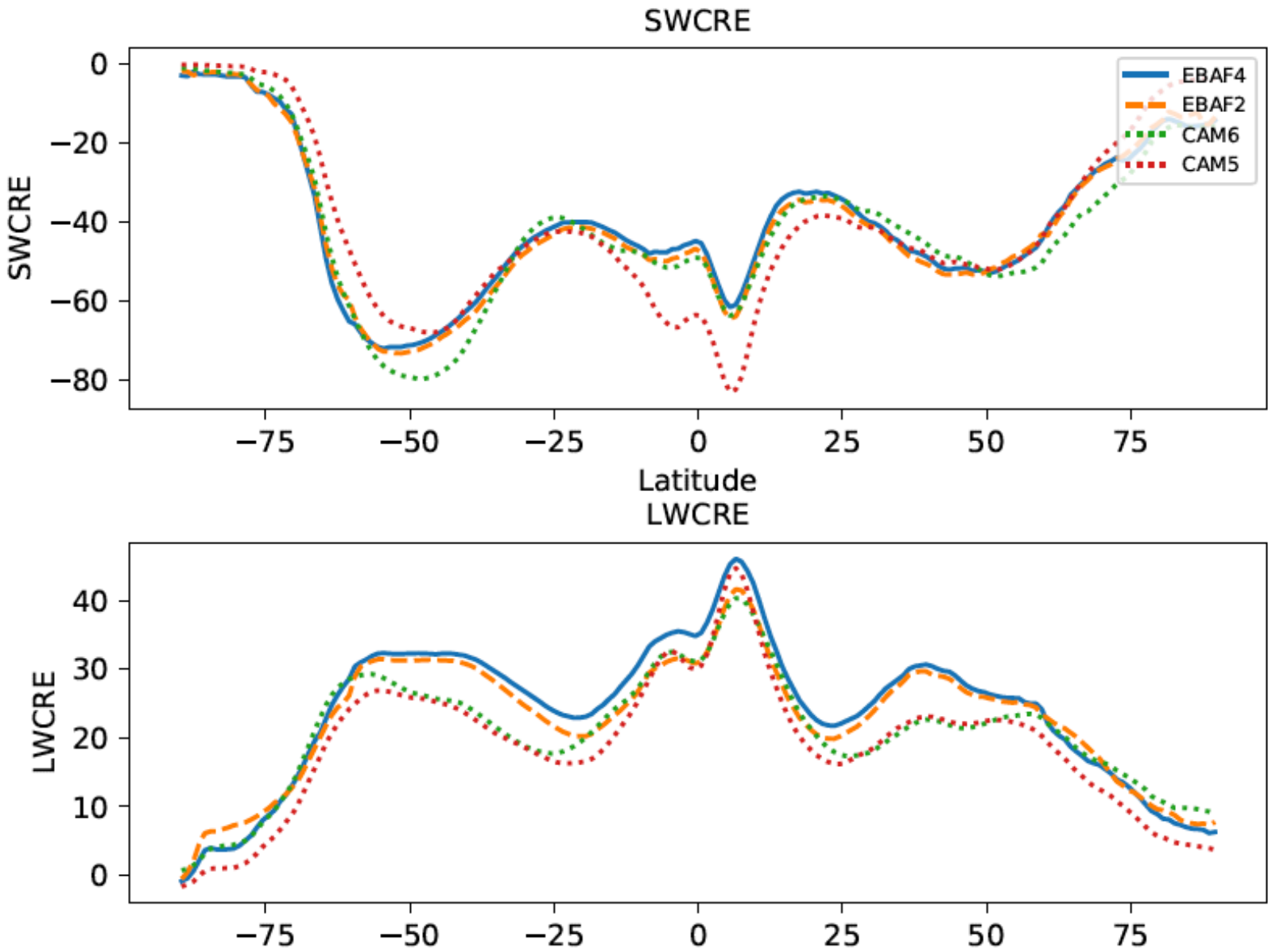
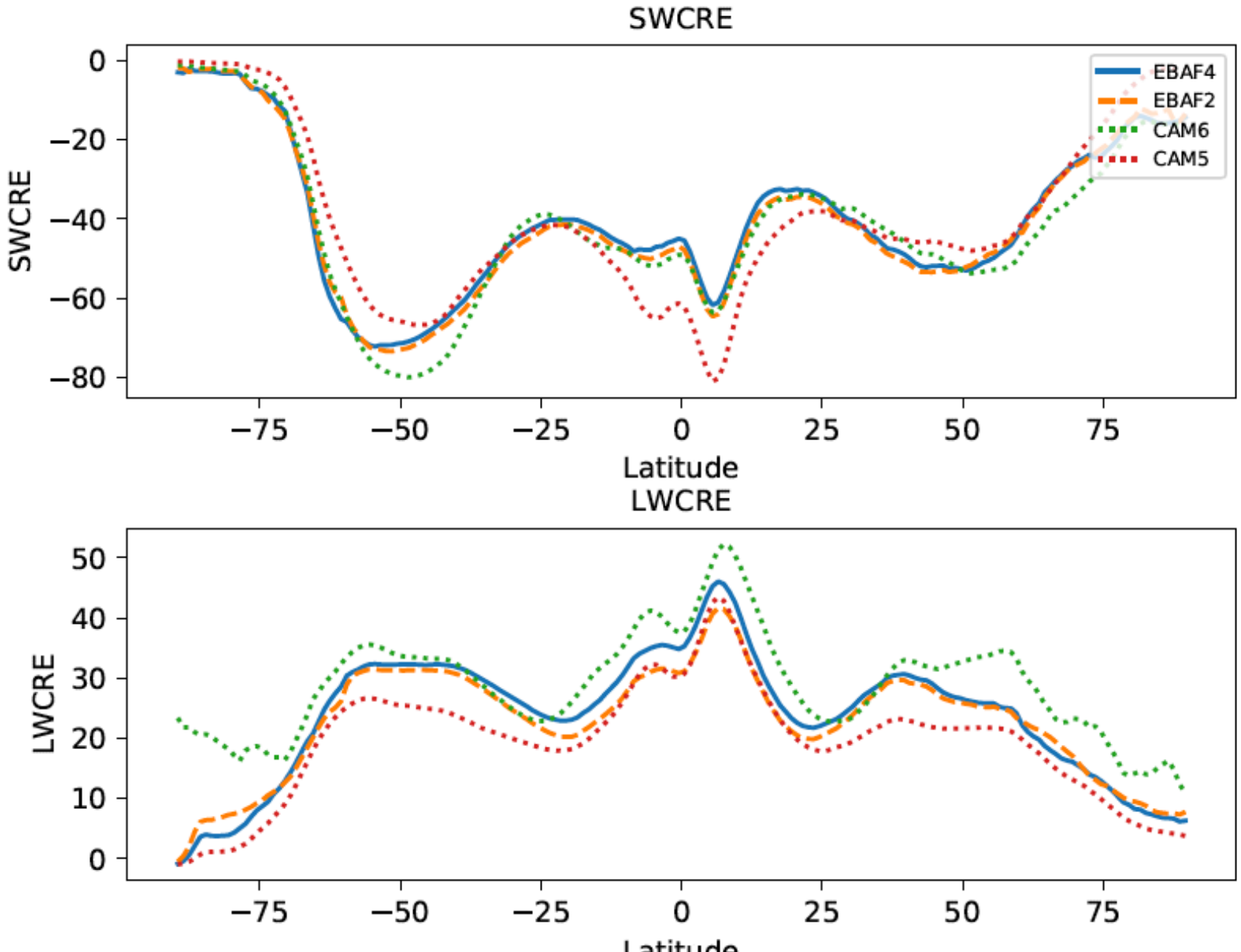
CESM2: Results (Global)

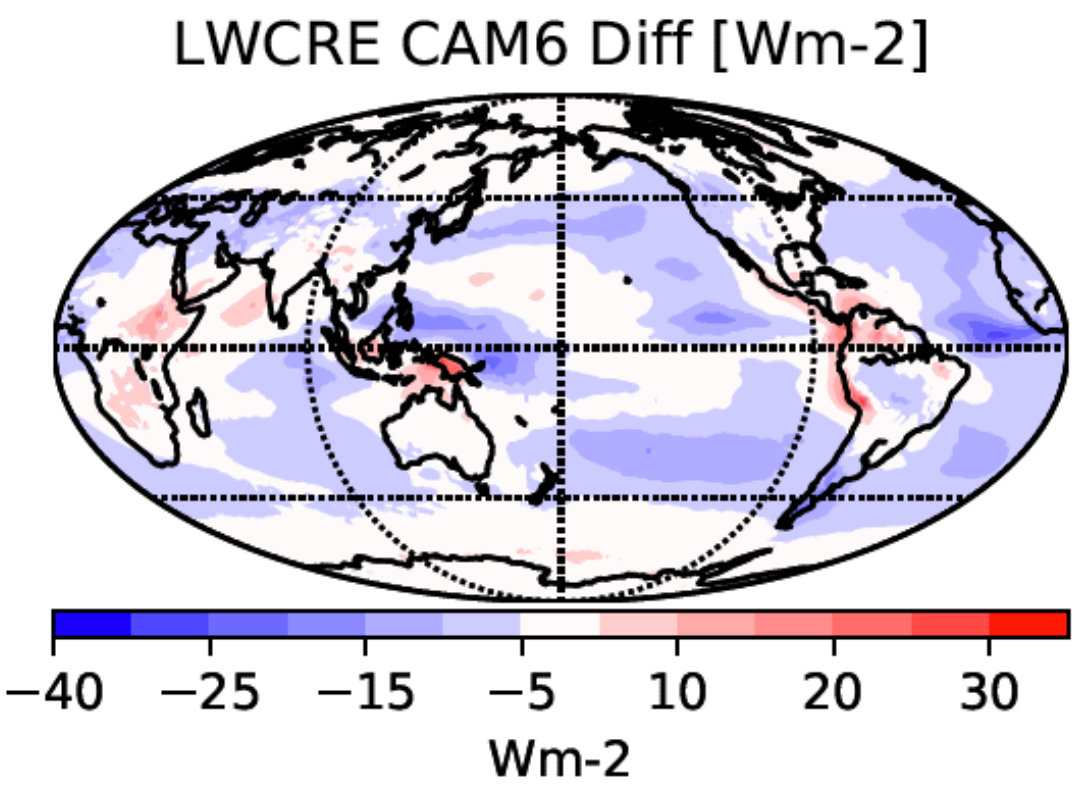


CESM2: LW CLR = Non-Cloudy Only

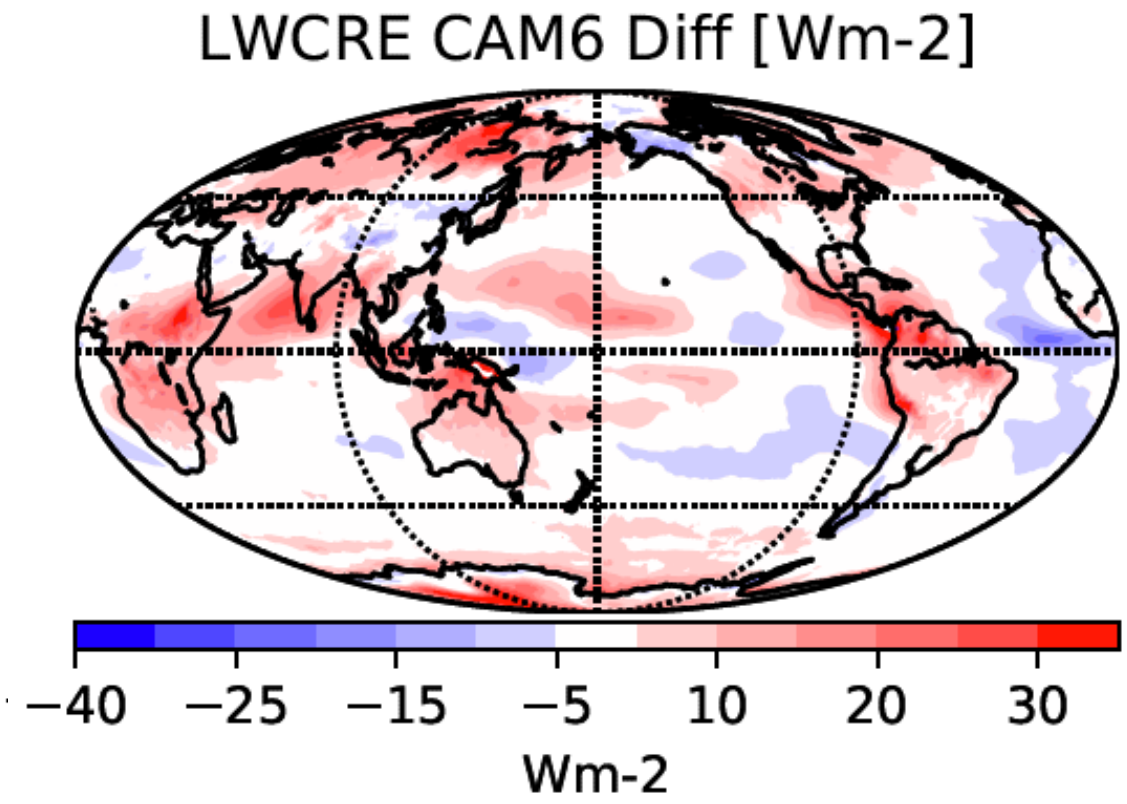


LW CRE Biases (v. CERES EBAF4)

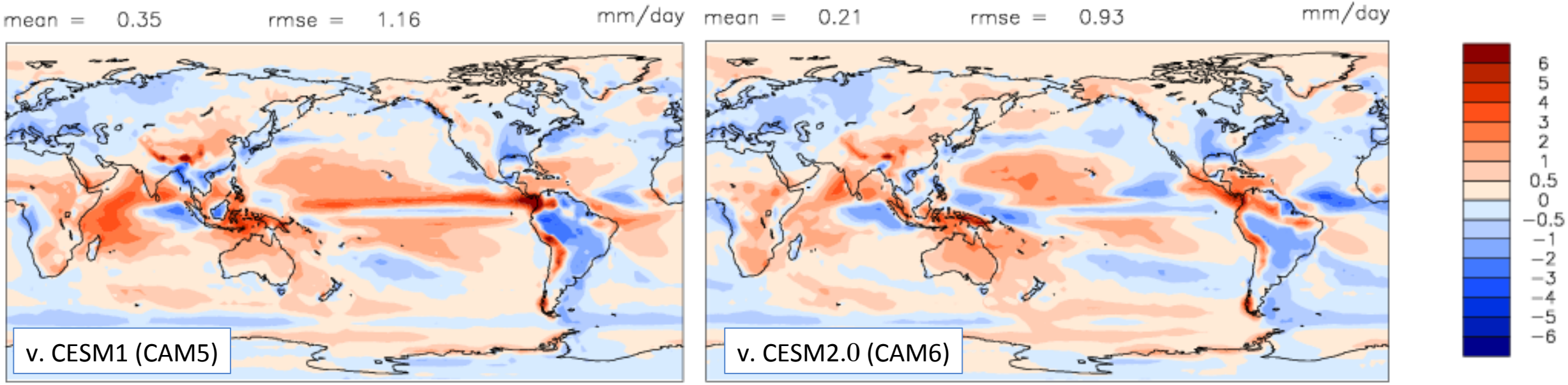
CLR Sky Everywhere



CLR SAMPLED for CLD < 0.1



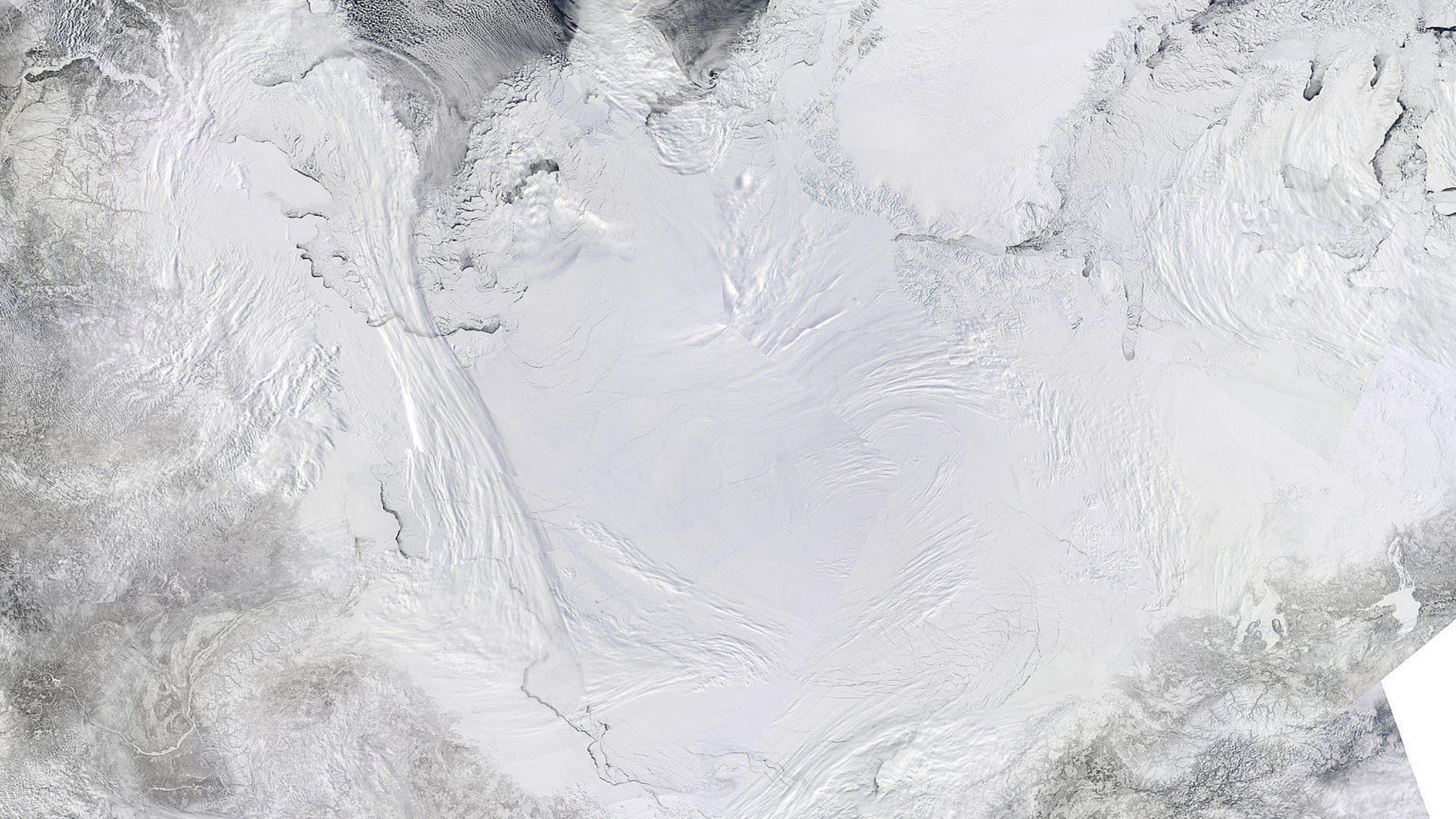
Precipitation
v. Ann GPCP



Mean is ~2.67 mm/d, so CAM still 5% high
Is CAM correct? Does GPCP miss light rain?
Probably (no and yes): answer somewhere in the middle
Again: this is a surface energy budget issue

Summary: TOA

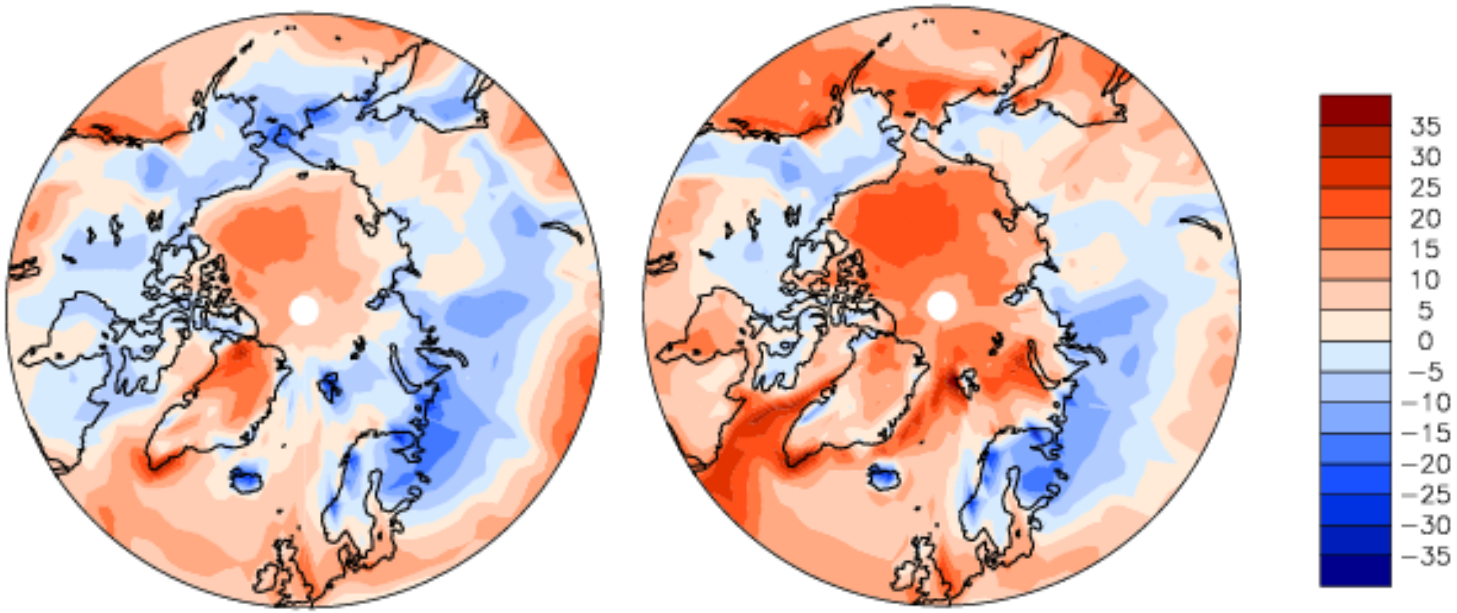
- Observations SHOULD be good for this (CERES)
  - But sampling is an issue
  - Model can help with this: Sample the model like observations.
- All Sky: good
- Clear Sky
  - A few remaining issues around sea-ice (Surface)
  - Leaks into cloud radiative effects (All − CLR).
- Appears that CAM has a LW CLR bias.
  - Most is a sampling issue!
- Note: TOA imbalance often NOT 0.6±0.4 Wm^{-2}(typically higher) with observed SSTs



Arctic LW Net Surface Radiation budget (DJF)

CAM6 – ISCCP FD

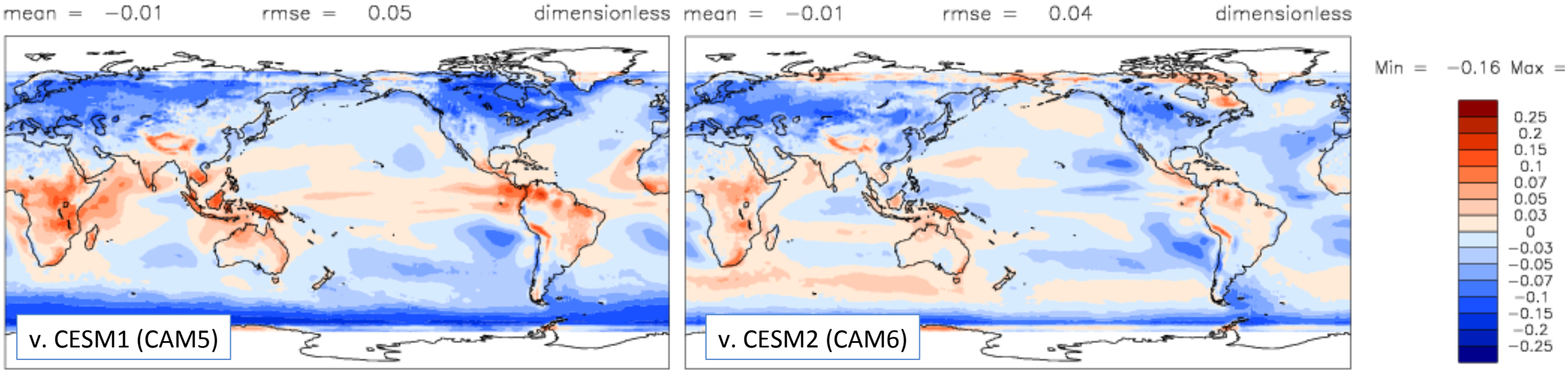
CAM5 – ISCCP FD



Still big biases (though observations have bias too), but improved

TOA Albedo v. CERES (EBAF2.8)

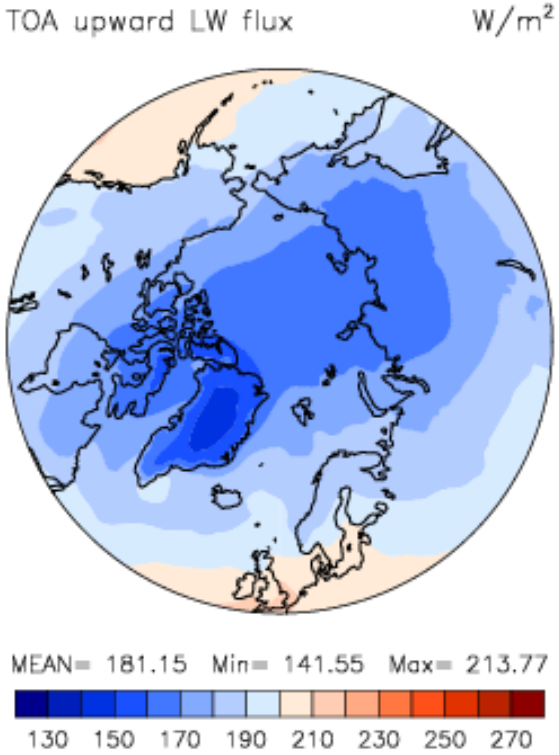
Much Better…High Latitude Land differences Remain



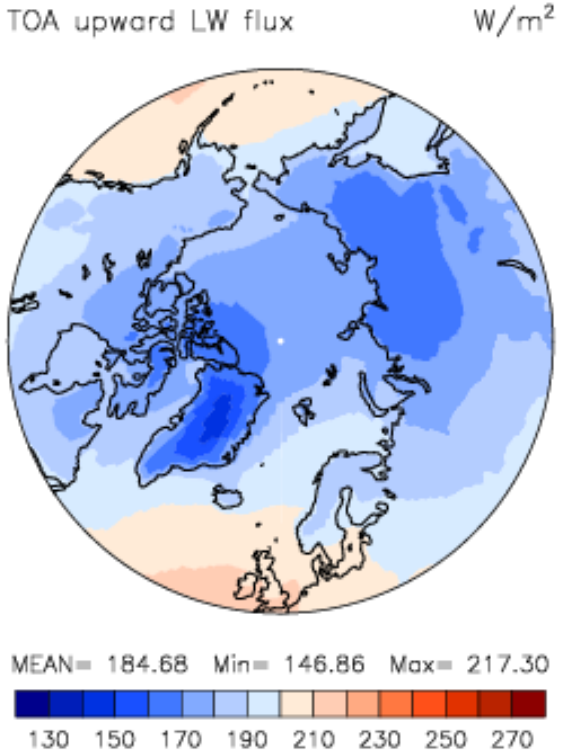
High latitude biases likely be due to snow (biggest issues are on land)
Still issues with snow albedo
Subtropical clouds too bright
Midlatitude land too bright (might be snow)

Winter (DJF) TOA LW

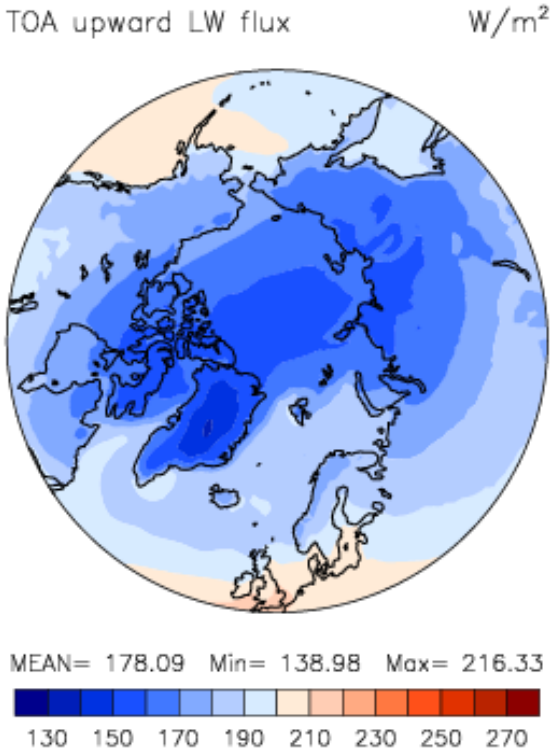
CAM6



CERES – EBAF2.8



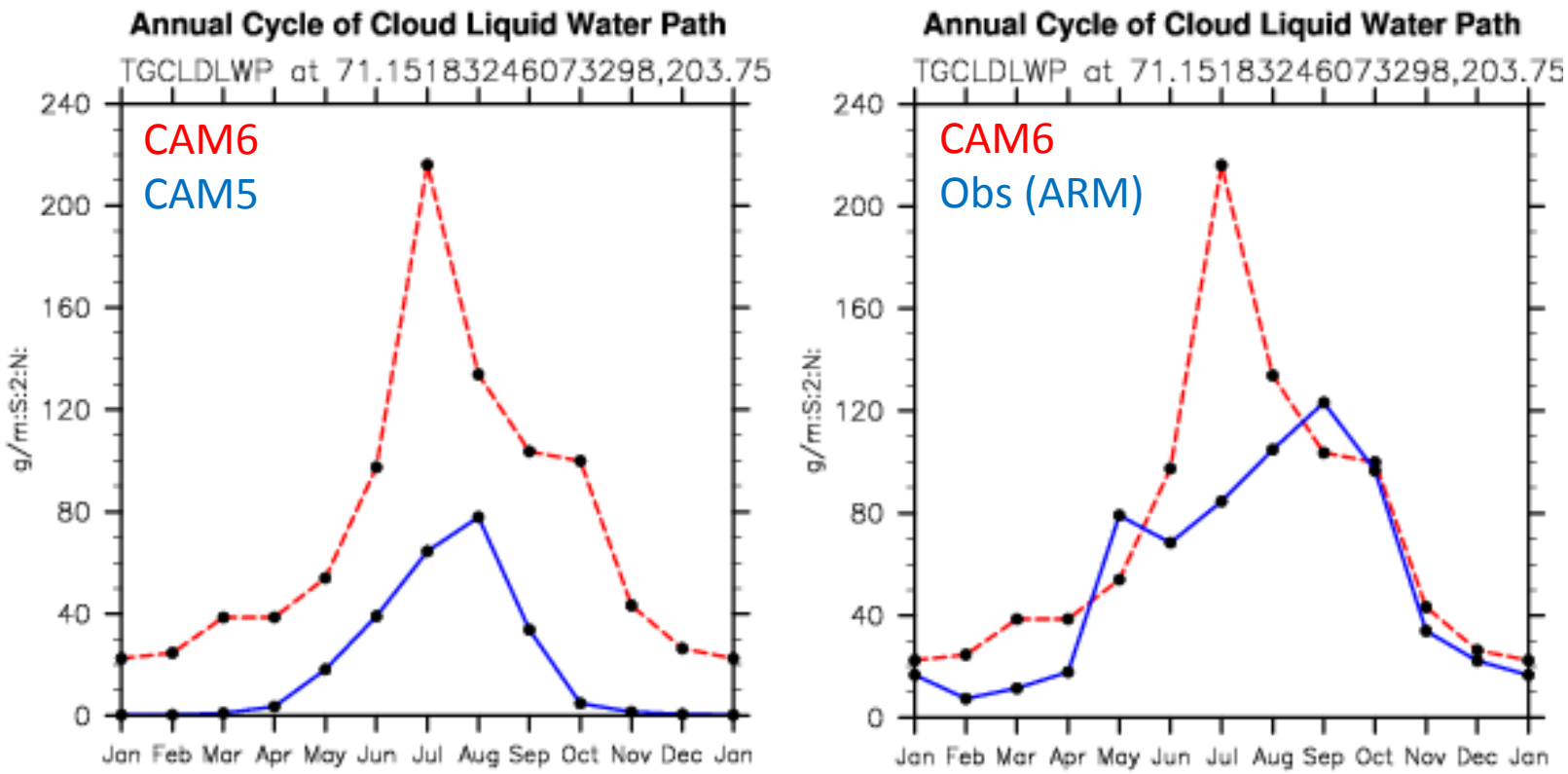
CAM5



Better, but biases of -10 Wm^{-2} remain (down from CAM5)

Why? Arctic Cloud Water

ARM Barrow, AK Site



Cloud water has improved, even in winter.
Now compares well to observations.

Arctic Clouds/Radiation Budget

- Clouds and surface albedo are big issues in the Arctic
  - Opinion: Clouds are more important
- Arctic Clouds: Know some things are better in CAM6
  - LWP: there is some
- TOA fluxes (LW): Still winter biases (consequence of LWP changes)
- Clouds: may be missing things from Obs
  - Best is CloudSat + CALIOP.
  - But issues with attenuation and surface clutter (lowest km)
  - Seeking more observations to get this right (e.g. Arctic IMPACT)

Summary

TOA

- Improved fluxes for CESM2 (Subtropics, Esp S. Ocean)
- We worry about SWCRE
- CAM (and other models) have a Clr Sky LW bias: sampling?

Surface Budget

- Big issue at high latitudes (Arctic, S. Ocean)
- Observations difficult (surface stations best): not sure yet how much to trust satellite based surface products (testing new EBAF4)
- Here the models are waiting on better observations, or better analyses
- Precipitation: not sure what to believe

Forcing and Feedback

$$R = F - \lambda dT_s + dH$$

$$dT_s = (F - R + dH)/\lambda$$

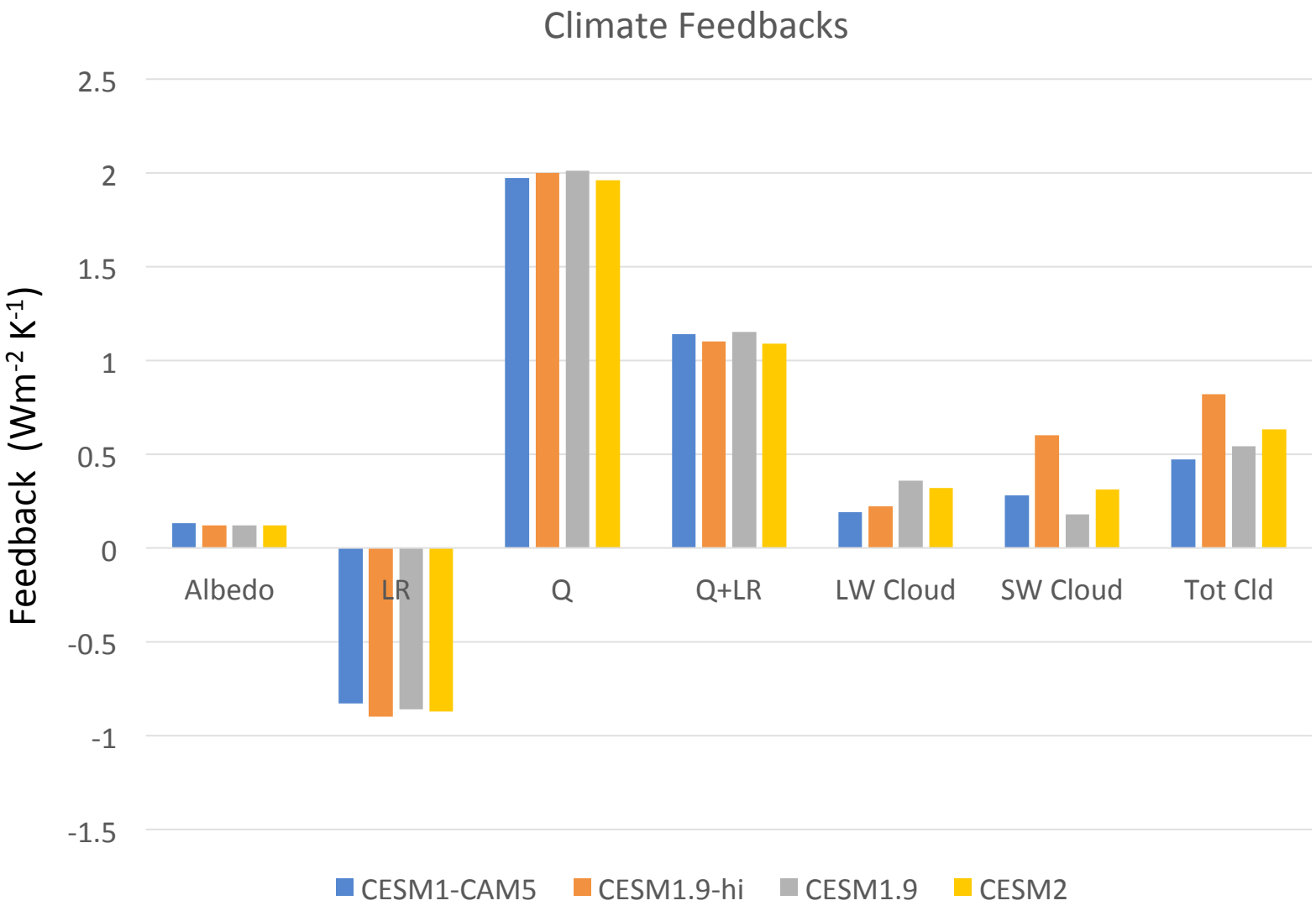
$$dT_s = (F_{ghg} + F_{aero} - R + dH)/\lambda$$

- Implication is that R (TOA imbalance) is critical for understanding
- Issues with all these terms, so hard to use this to constrain λ.

Methods

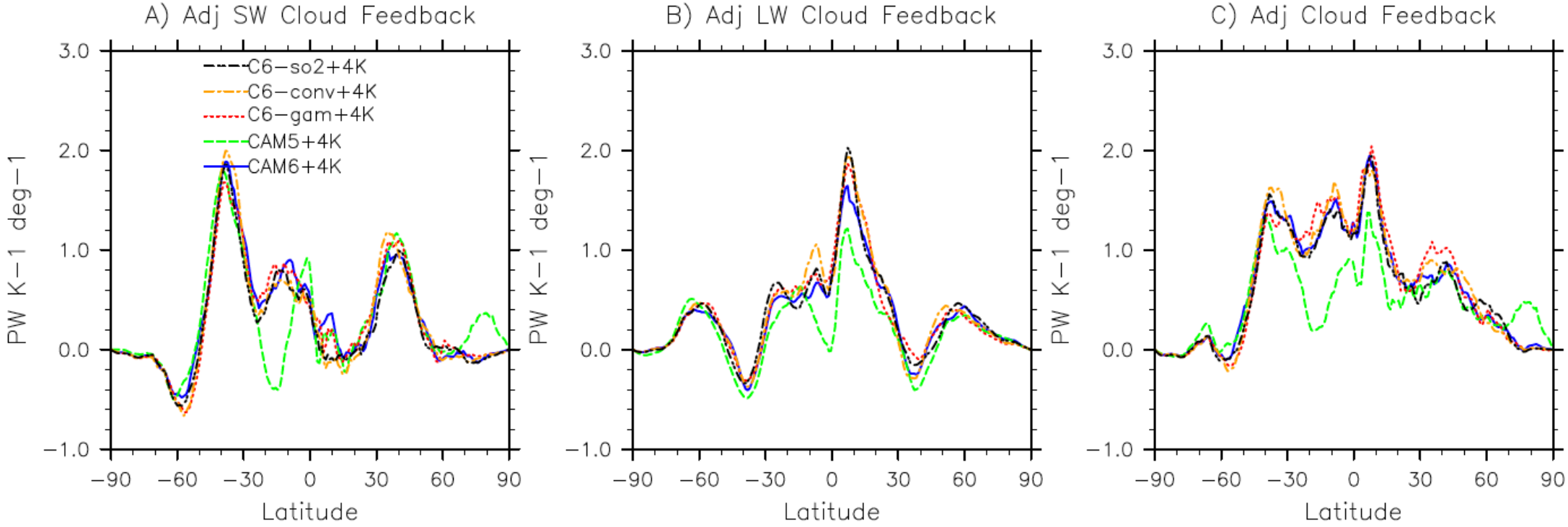
- Feedbacks: Radiative Kernels (Soden et al 2008)
  - Apply to SST +4K sensitivity tests (Fixed SST, 2 simulations)
  - CESM1-CAM5.3
  - CESM1.9: 2017
  - CESM1.9-hi
  - CESM2
- Forcing: Aerosol Forcing (total and indirect)
  - Indirect = Aerosol Cloud Interactions (ACI)
  - Use off line calculations (Fixed SST 2 simulations, different aerosols)
  - 'Clean Sky' aerosol forcing (Ghan et al 2013). Slightly higher than ΔCRE
  - Also: some coupled analysis (forcing interacts with feedbacks)

CESM2 Feedback Summary



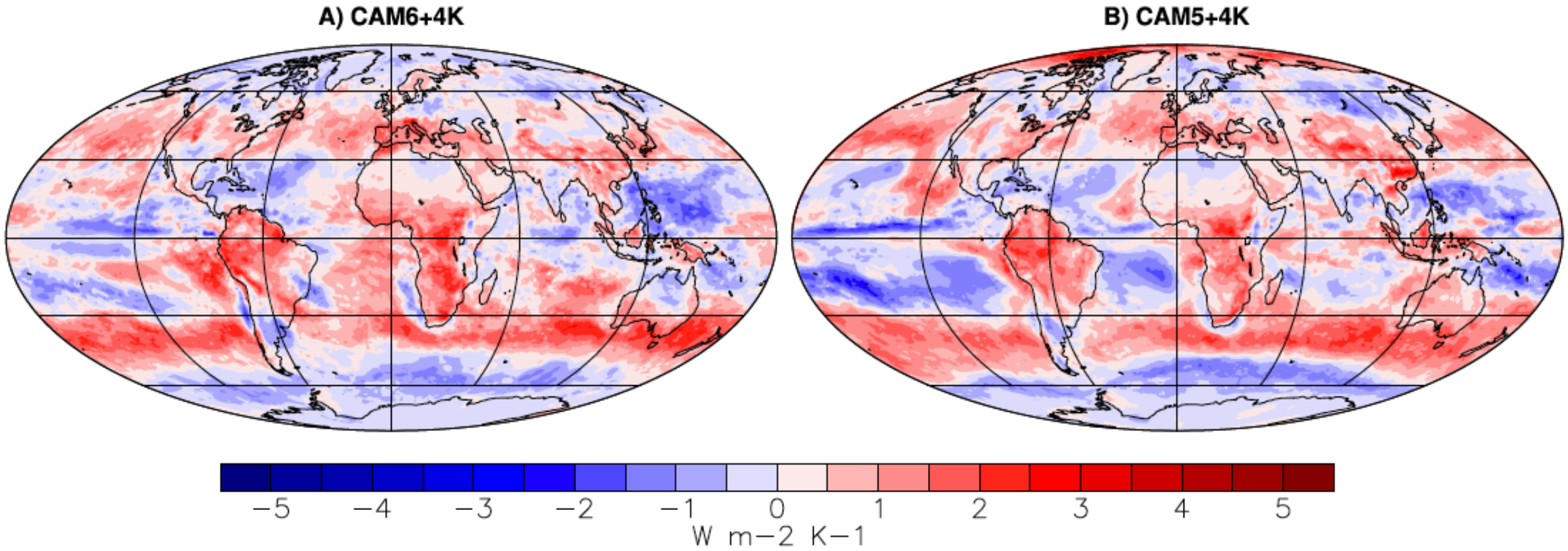
Cloud Feedback (Zonal Mean)

Fixed SST+4K simulations

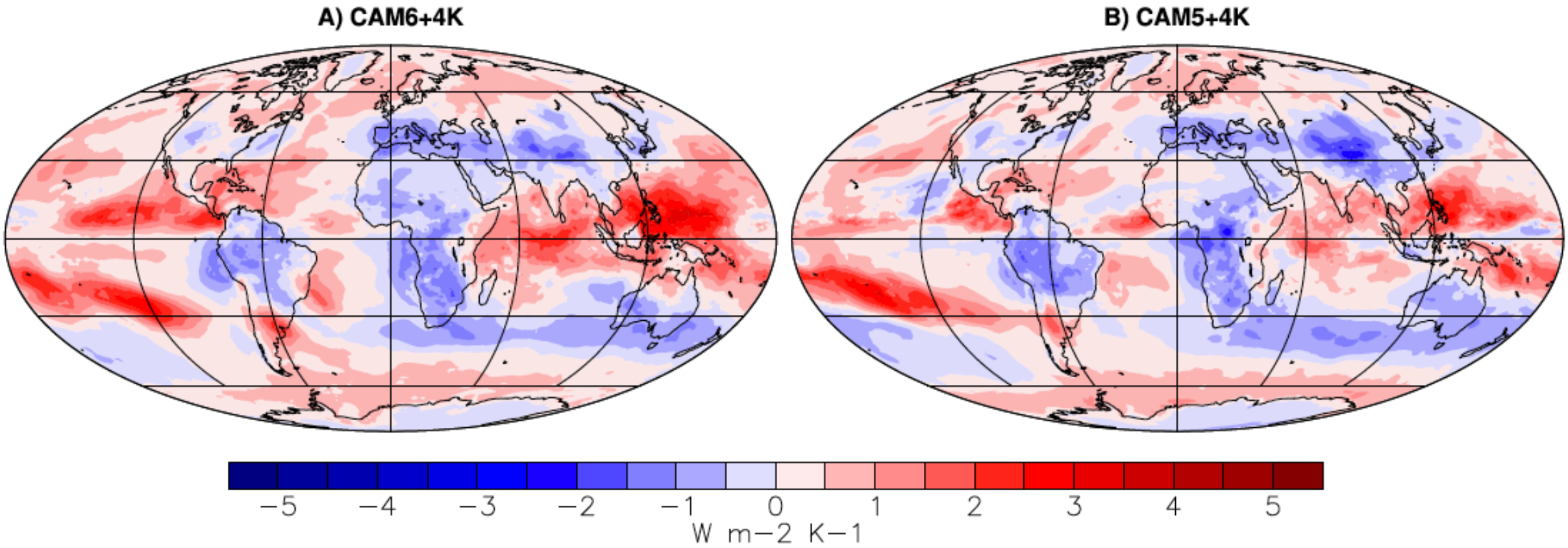


Feedbacks *appear* fairly constant
(more on this later, stay tuned)

SW Cloud Feedback

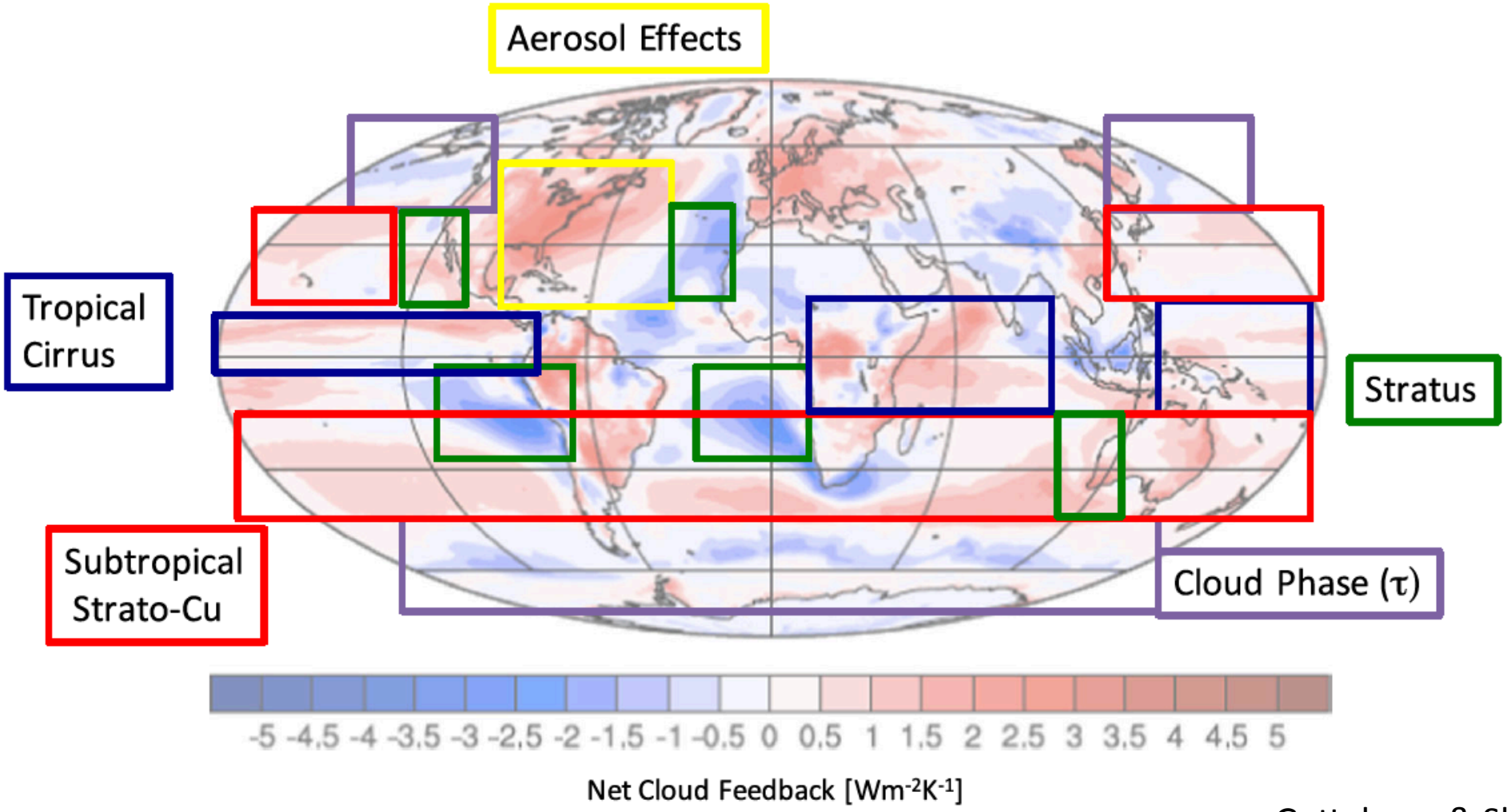


LW Cloud Feedback



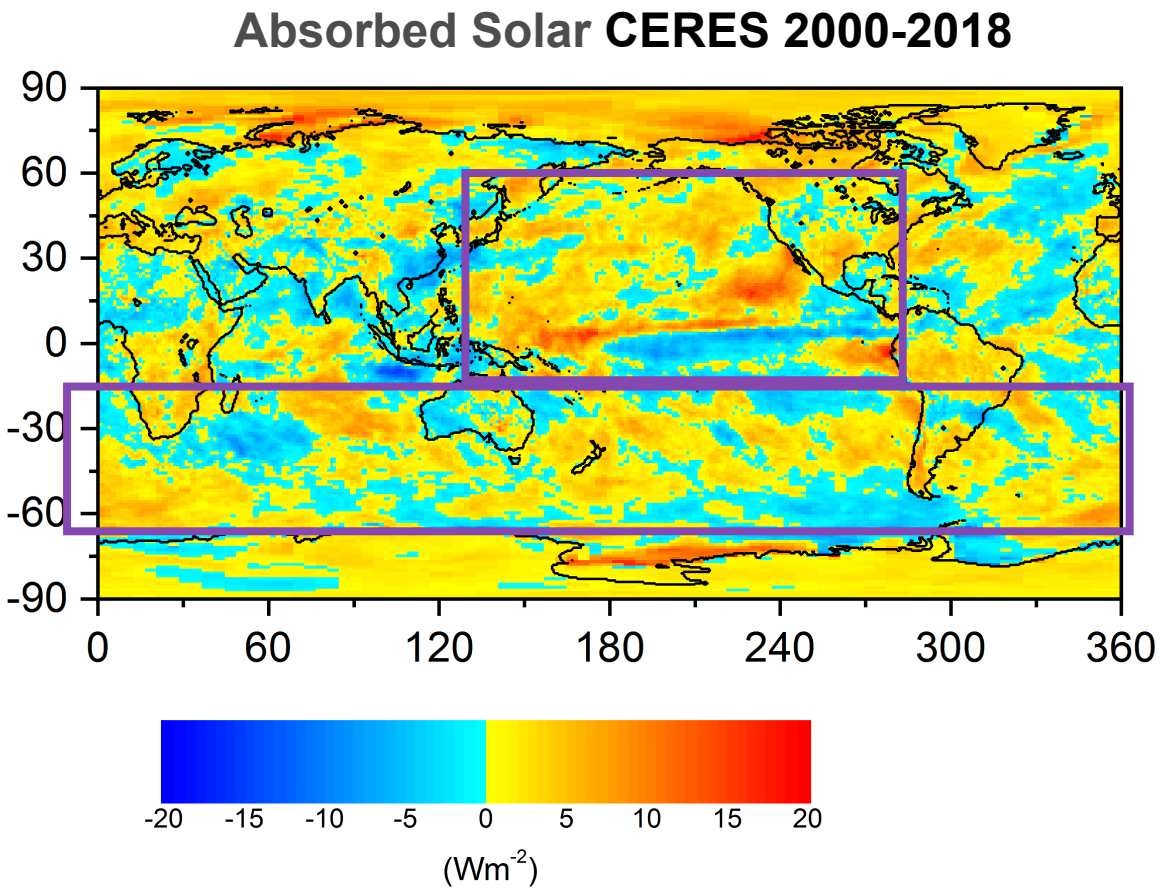
Processes responsible for Cloud Feedback

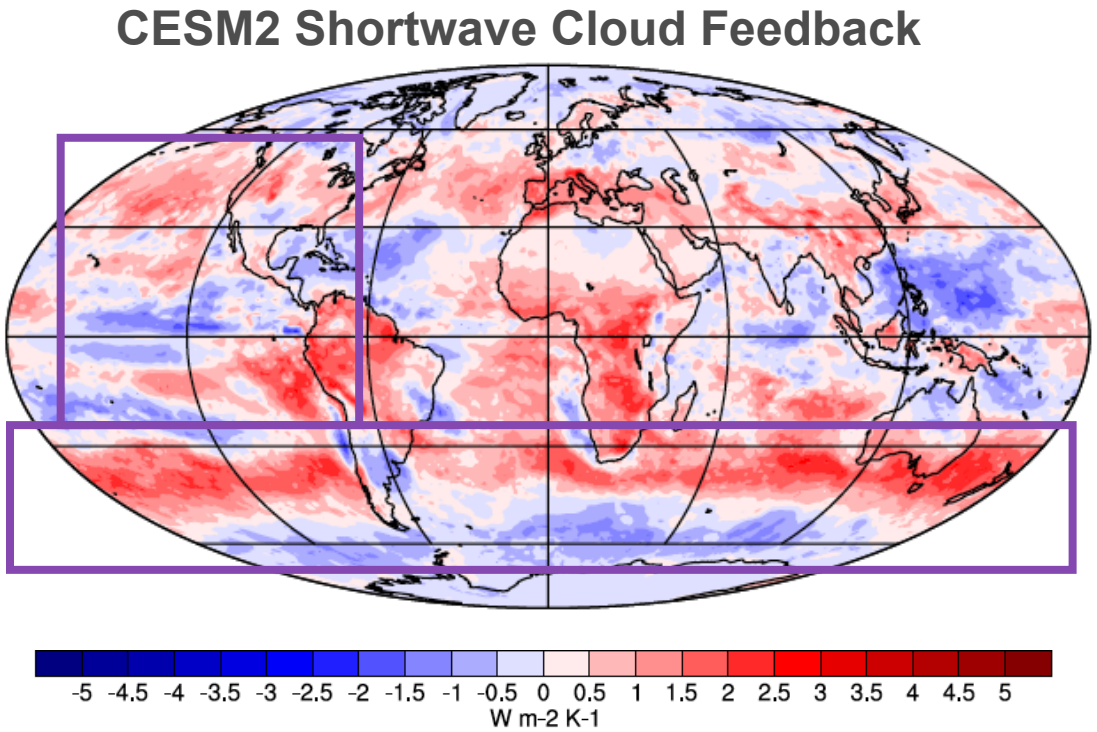
Cloud feedback is due to a series of different effects in different regimes.
They are somewhat independent, dealing with different processes.



Gettelman & Sherwood 2016

Methods for Using Observed trends



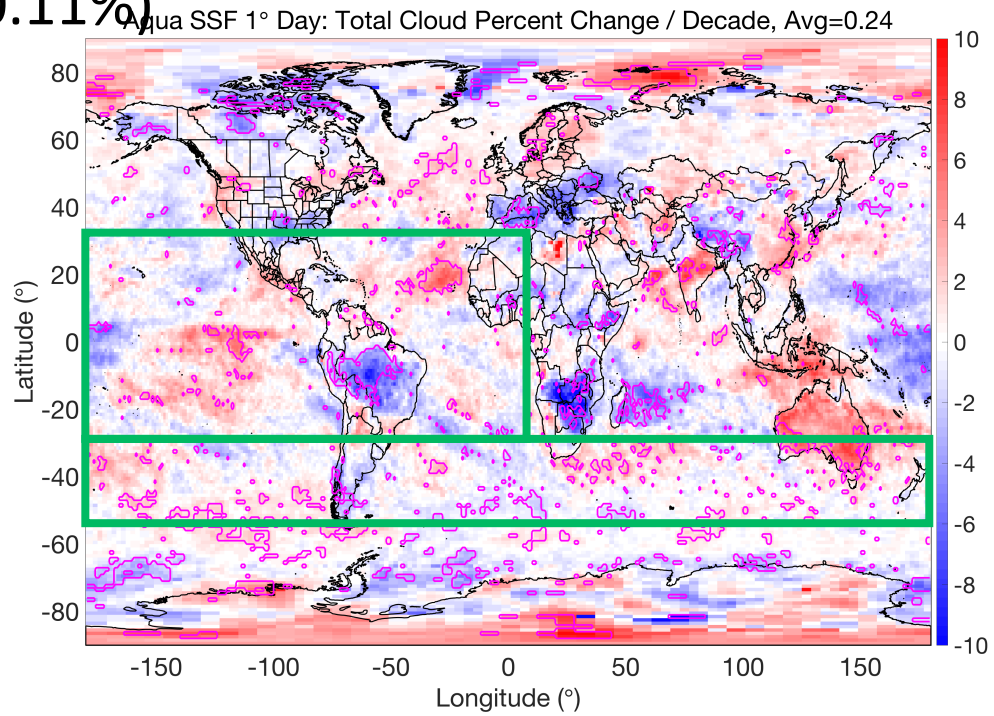


From Norman Loeb: Monday Talk

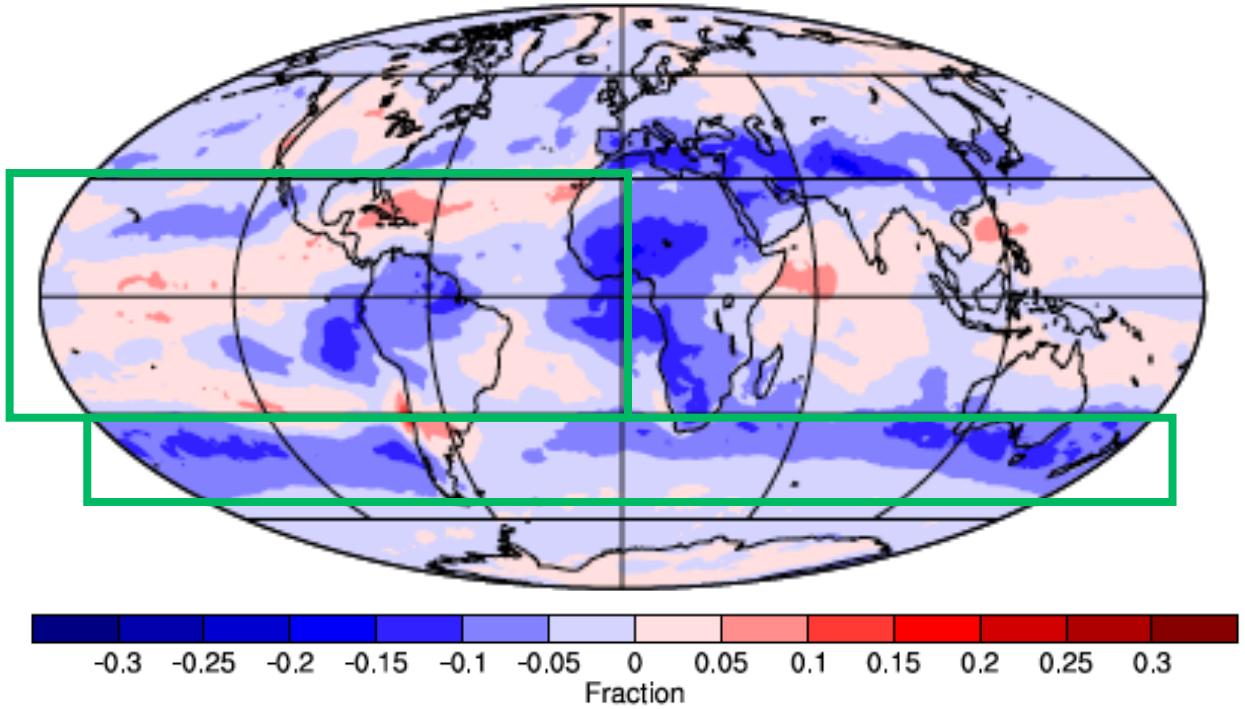
Are these patterns the same? Can we see ‘emergence’ of cloud feedback?

Cloud Fraction Trends

Aqua-MODIS 2003-2017
Total Cloud Percent Change/Decade
(0.11%)



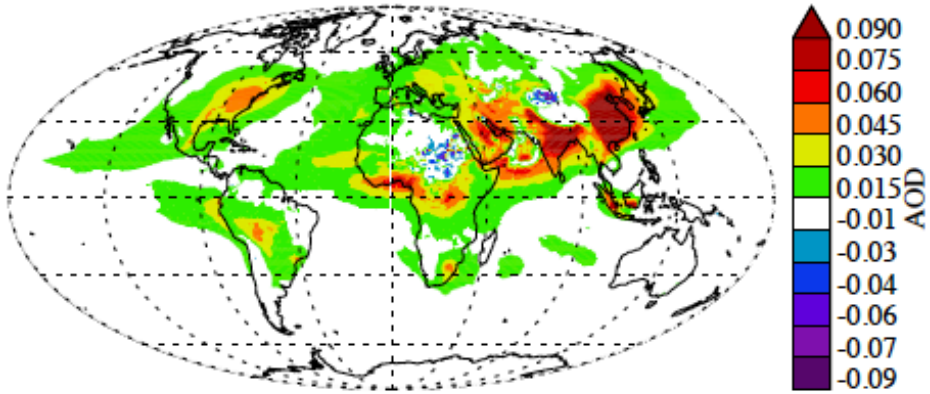
CESM2
Idealized climate change (SST+4K) ΔCLD



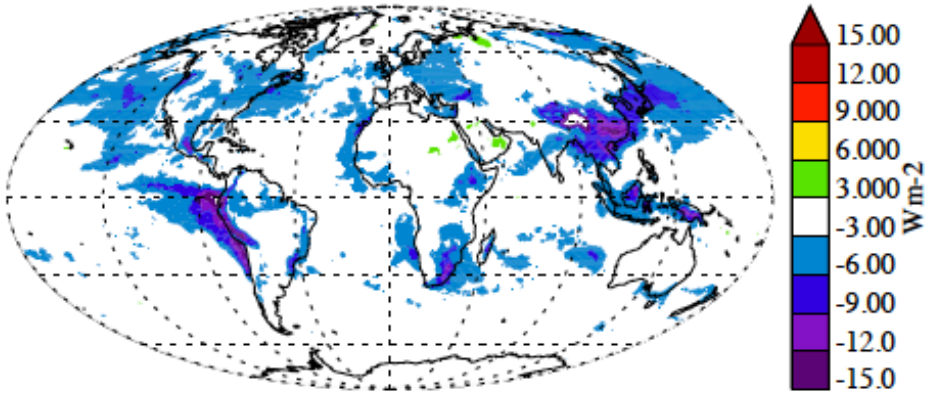
From Bill Smith, Monday Talk

Forcing: Aerosols

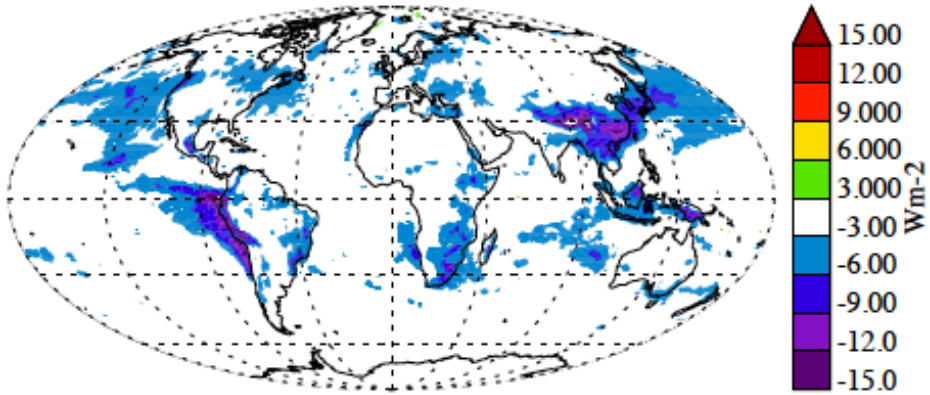
A) base 2000-1850 ΔAEROD



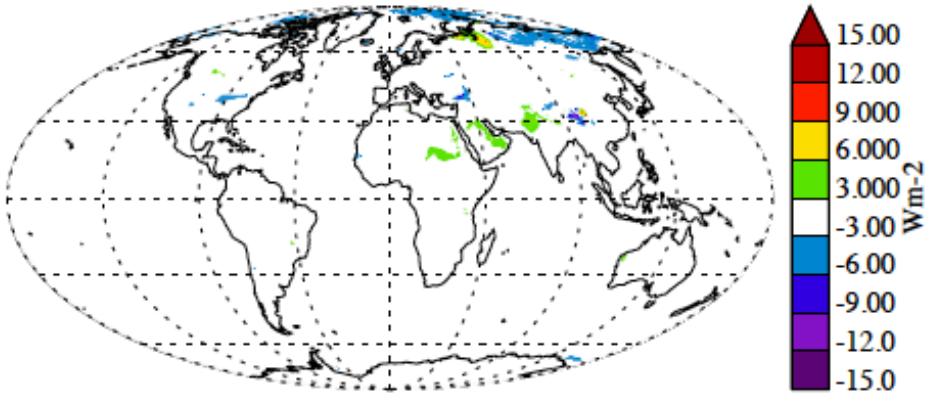
B) base 2000-1850 ΔTOA



C) base 2000-1850 ΔCRE (Indirect)

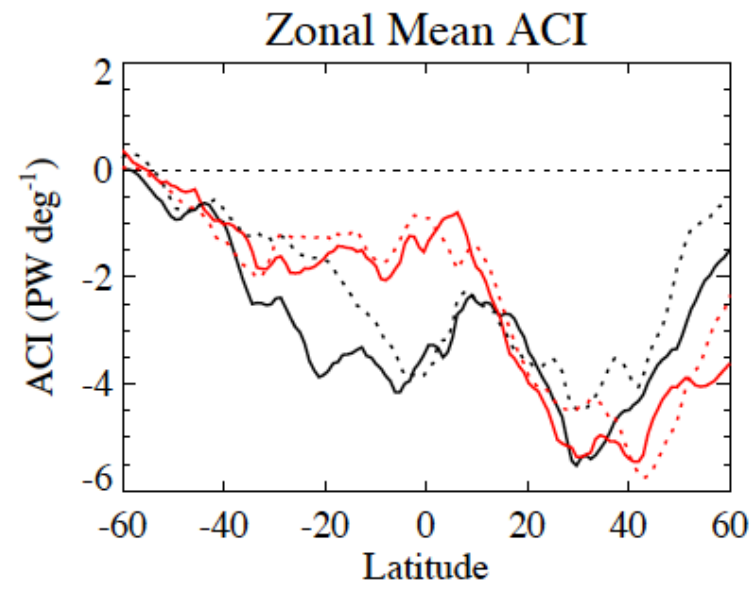


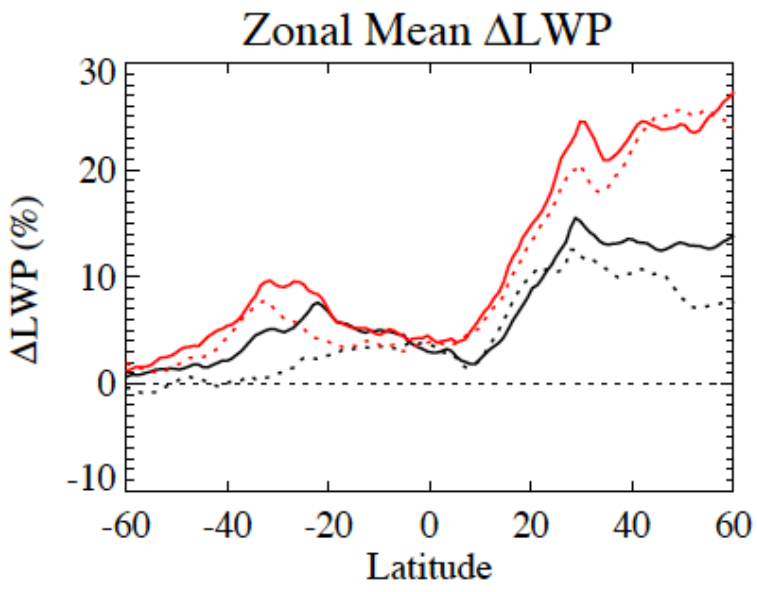
D) base 2000-1850 ΔDirect

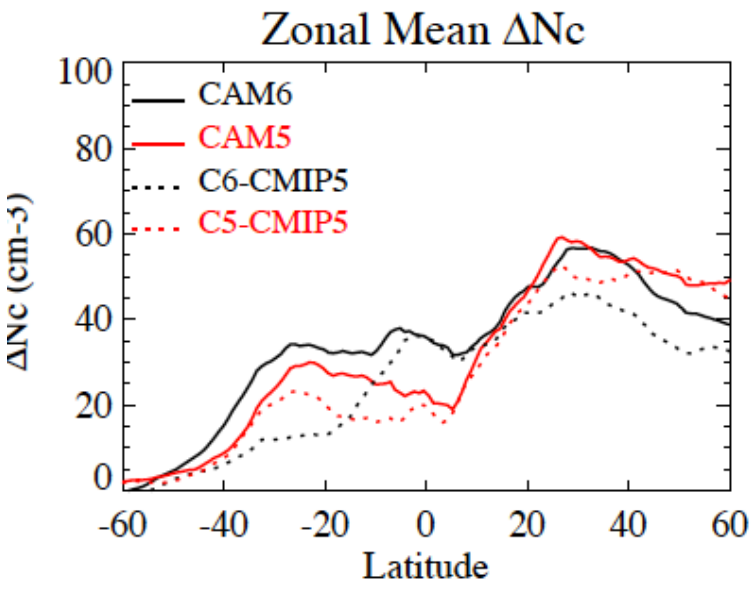


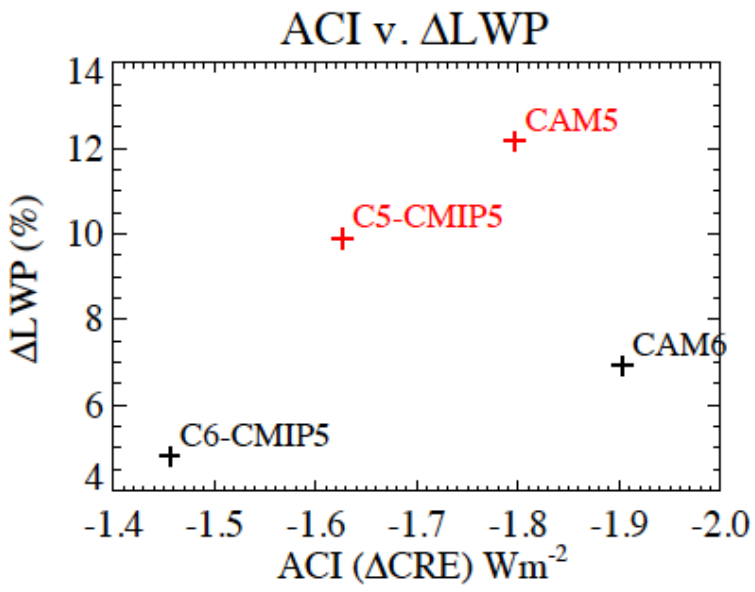
Aerosol Forcing: Sensitivity

- ACI most correlated with ΔLWP
- Emissions yield big differences
  - CMIP5→ CMIP6 Emissions
- Sensitivity: ~0.5 Wm-2
- How to constrain with observations?







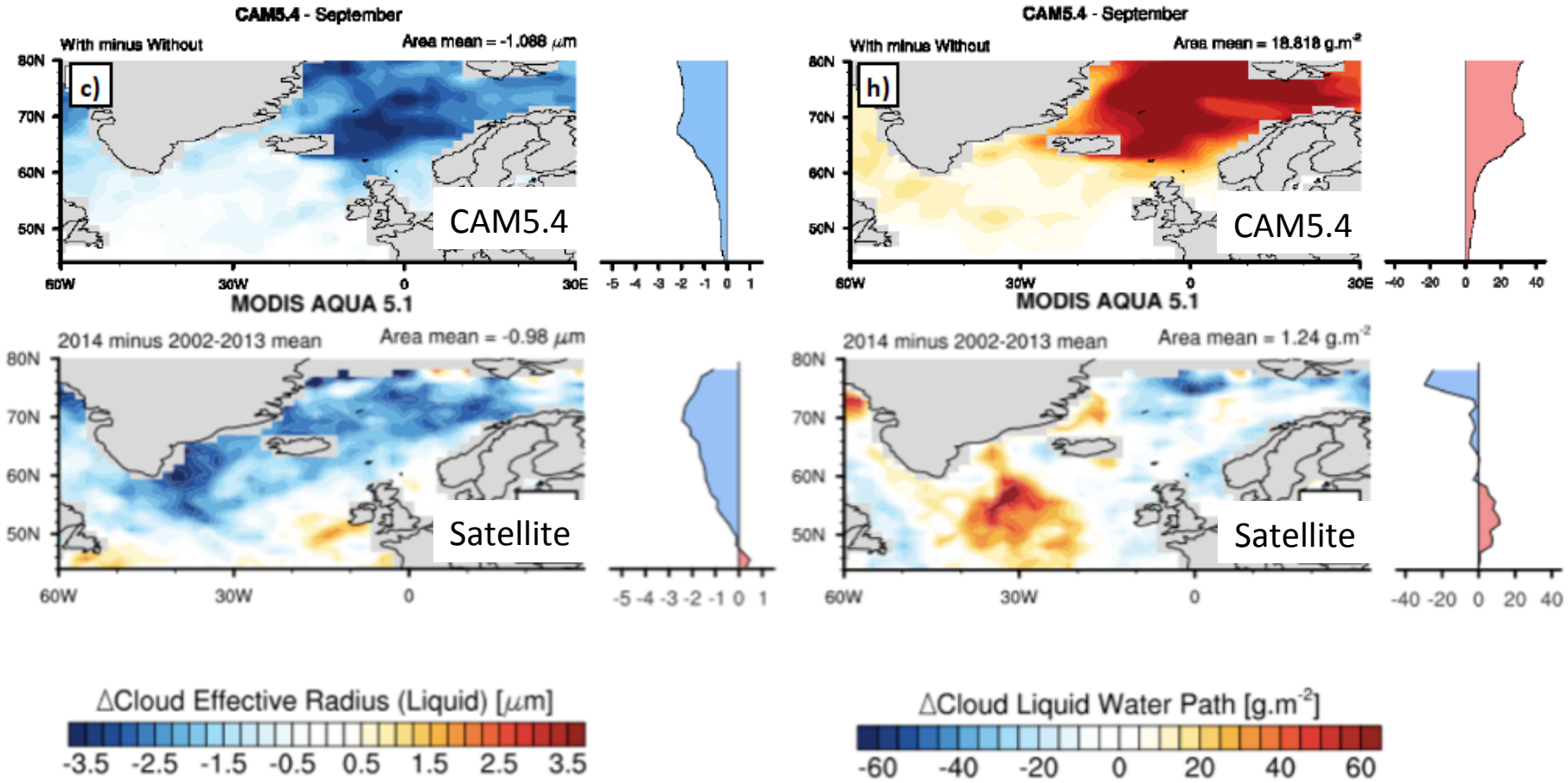


Constraining Forcing with Observations

CAM5.4 (and CAM6) show big increases in cloud water with elevated aerosols.
Here: an example from the Holurhaun eruption in Iceland in 2014.
Anomalies of Drop Size and Cloud Water for October 2014 from long term mean.
Smaller drops are seen, but no increase in cloud water from Satellites (MODIS)

Drop Size

Cloud Water



Malavelle et al 2017, Nature (in Press)

Process Level Forcing - Feedback Interaction

- Aerosols are affected by climate state
  - E.g.: Sea salt emissions depend on wind speed
- So, climate change causes 'Aerosol Mediated Cloud Feedbacks'
  - Sea salt changes affect cloud forcing = Feedback
- Aerosol Feedbacks contribute to spread in diagnosed cloud feedbacks!
- Aerosols may directly alter cloud feedback
- Also: Aerosols affect interpretation of observed records
  - Cloud brightening due to aerosol emissions, not temperature or climate modes (ENSO)

Gettelman, A., L. Lin, B. Medeiros, and J. Olson. *Climate Feedback Variance and the Interaction of Aerosol Forcing and Feedbacks*. Journal of Climate 29, (2016): 6659–75. doi: 10.1175/JCLI-D-16-0151.1.

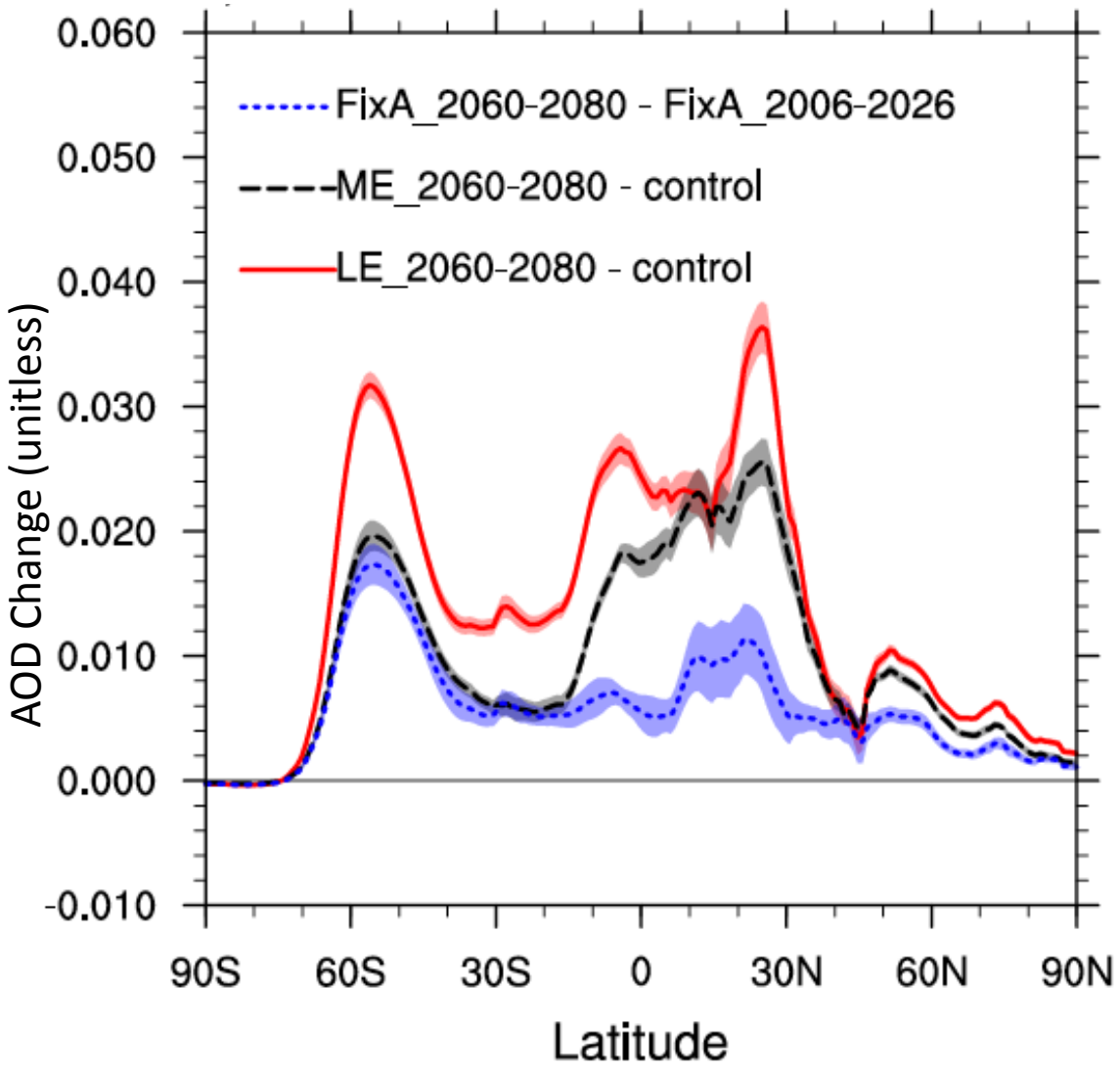
Models/Methods

- Test with 3 ensembles of CESM1-CAM5 (coupled)
  - 30 members with high forcing (RCP 8.5)
    - Large Ensemble = **LE**
  - 15 members with medium forcing (RCP4.5)
    - Medium Ensemble =**ME**
  - 15 members with high forcing (RCP8.5,2000 aerosols)
    - Fixed aerosol Ensemble = **FixA**
- Feedbacks
  - Kernel adjusted cloud feedback (Soden et al., 2008)
  - Difference 20 years of control with 2060-2080 (**LE**,**ME**)
  - Difference 1980-2000 with 2060-2080 (**FixA**)
  - Years do not affect results
  - Number of ensembles affects variance (spread)

Aerosol Mediated Cloud Feedback

- S. Ocean ΔAOD: not forced
- Tpcs & NH: forced
- **LE**: larger climate changes
- Sea salt and dust emissions depend on climate
- Aerosol lifetimes depend on climate (humidity, clouds)
- Affects CRE, but not a forcing (a feedback)
- Can this be factored out?

Change in AOD



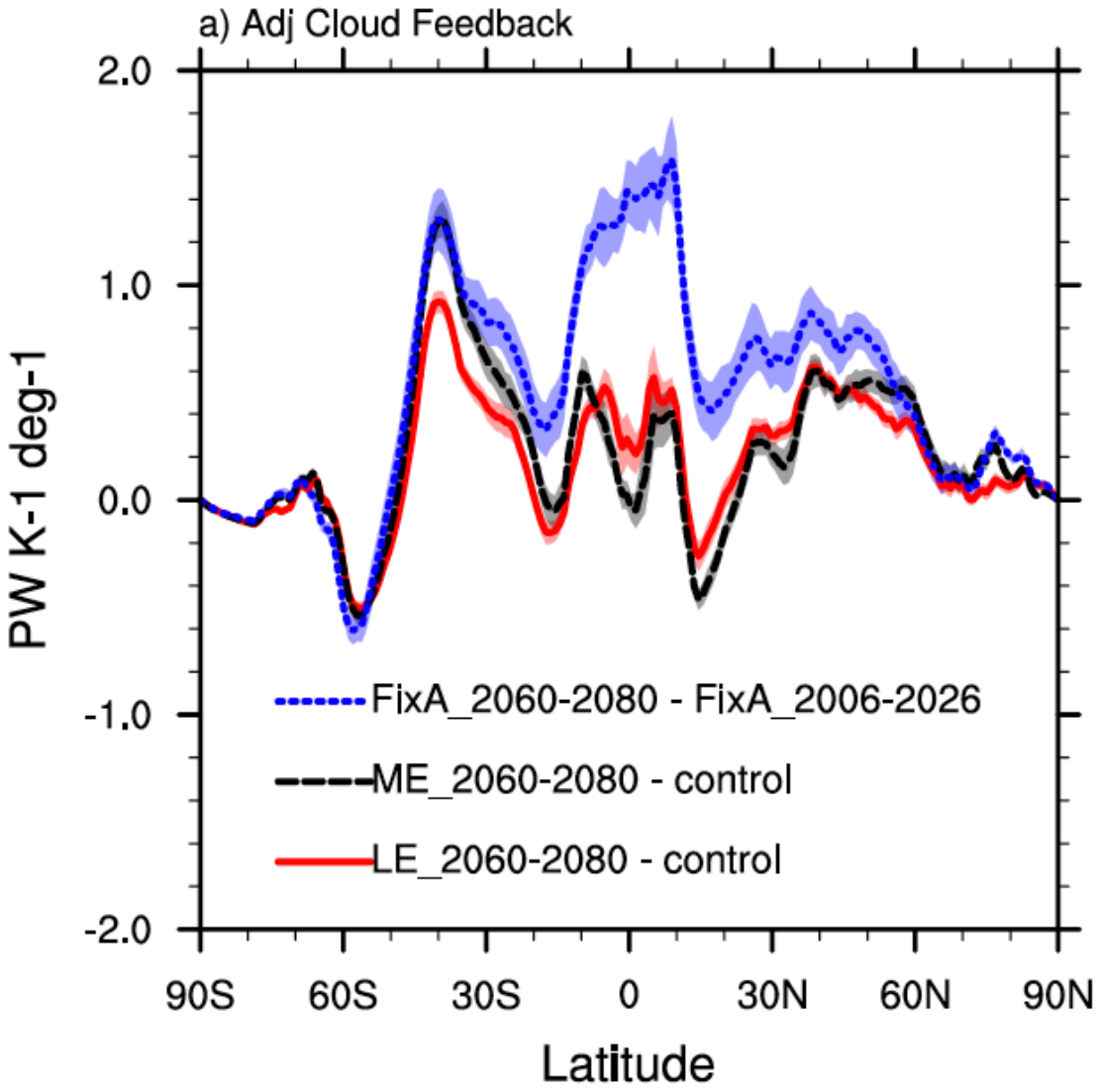
'control' = PI (1850)

Cloud Feedback

Total cloud feedbacks Includes differences in Aerosol

Now Apply Aerosol Kernel

Note that variability across the ensemble is SMALL. Applies to other feedbacks too.



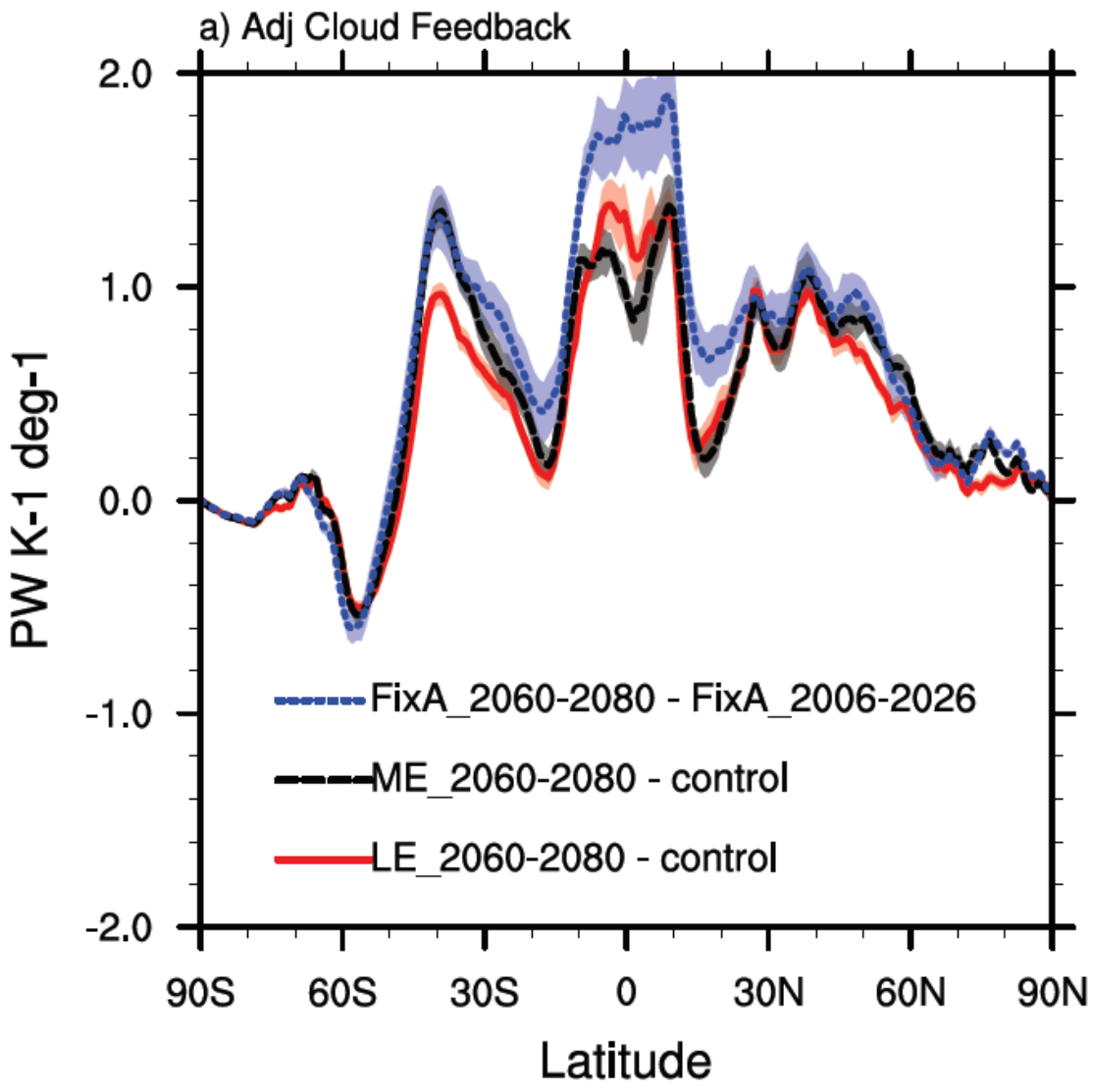
Cloud Feedback

Adjust Feedbacks for Aerosol

Feedbacks more positive (aerosol cooling from +ΔAOD misdiagnosed as feedback)

NH Mid-latitude feedback differences smaller

Tropical & Subtropical differences remain



Aerosol Effects on Clouds

Adjust Feedbacks for Aerosol

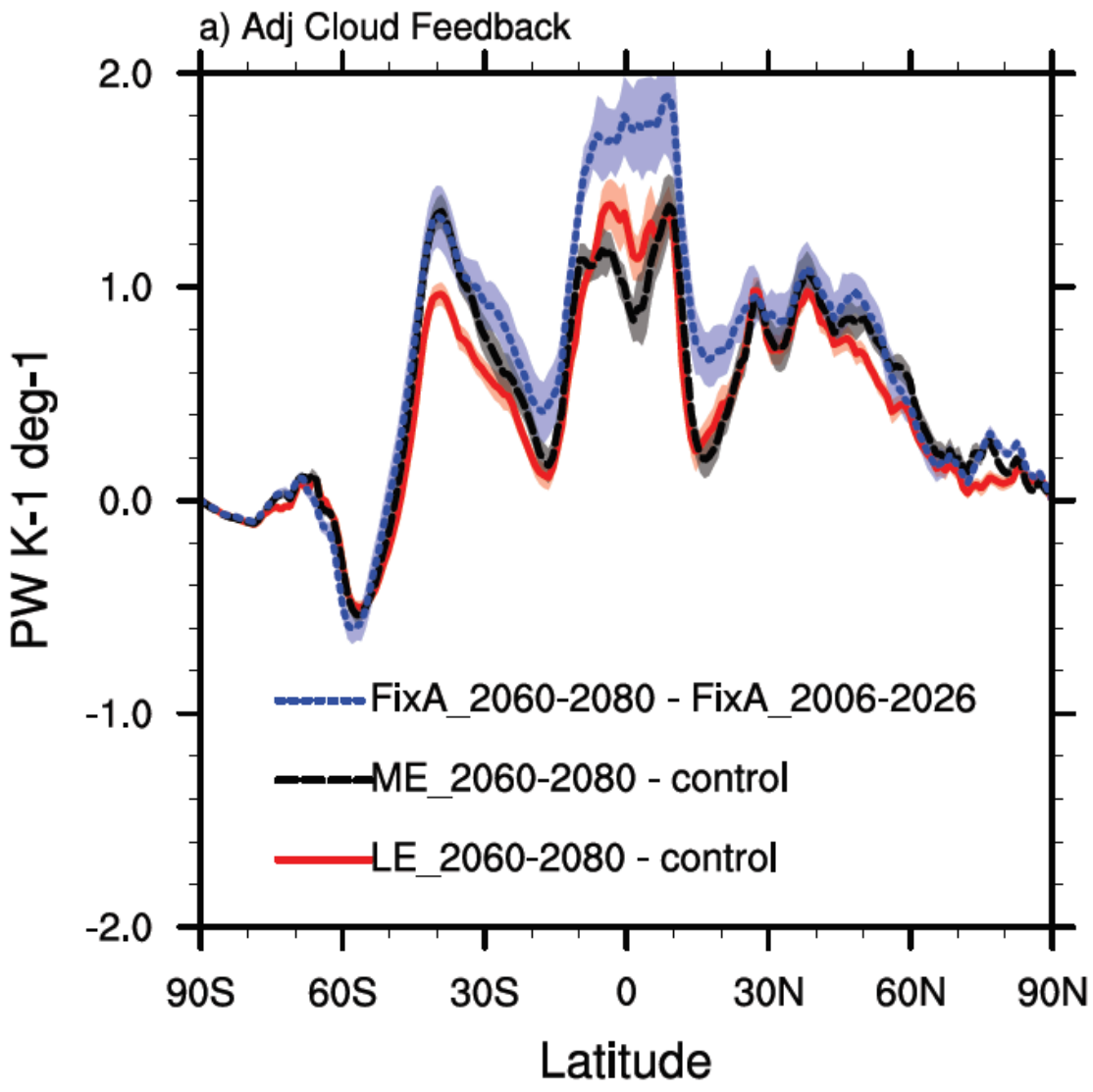
Tropical Changes:

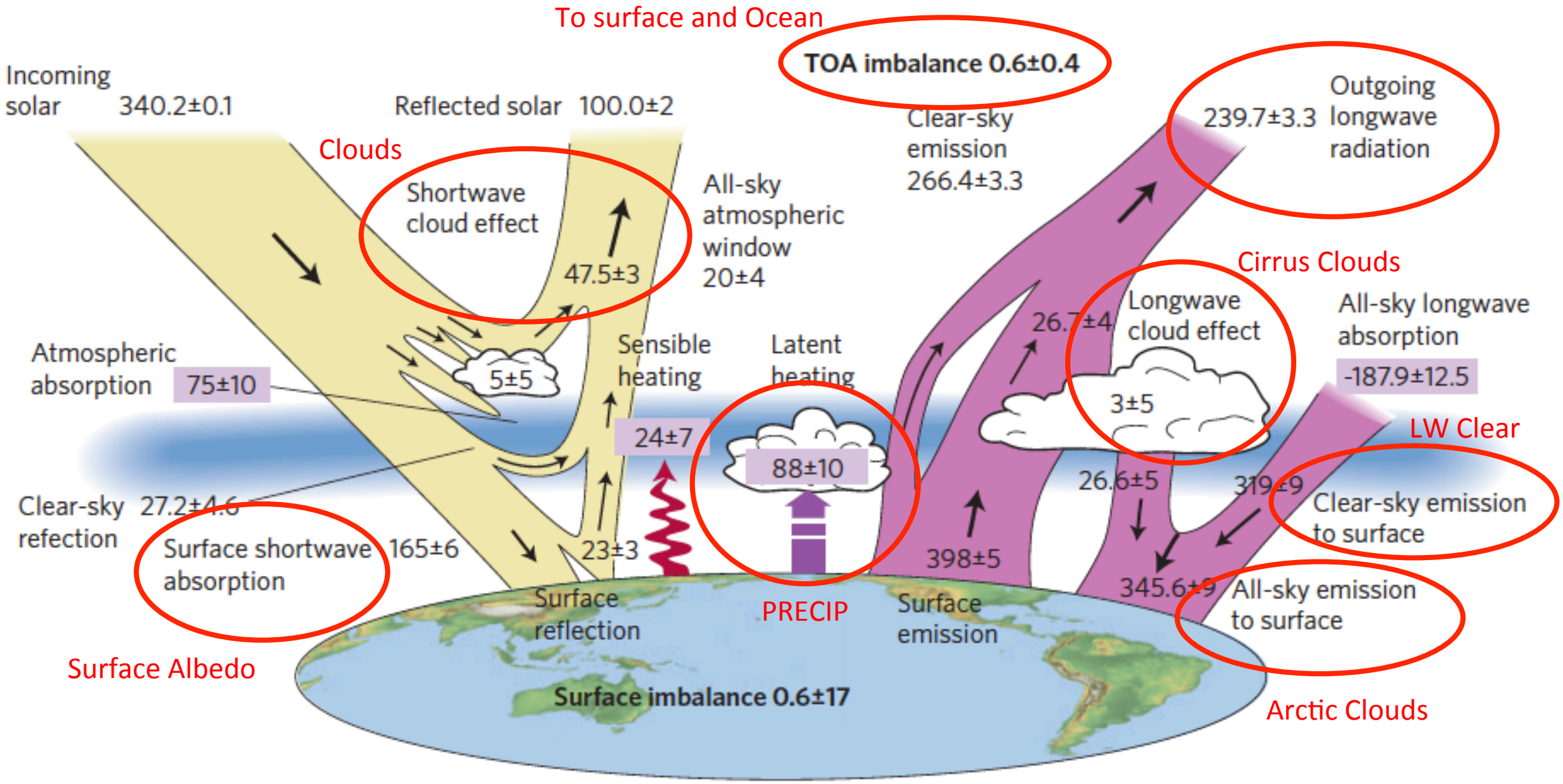
FixA ≠ **LE** or **ME**

Difference in feedbacks due to different cloud state (different LWP, drop #) = 20% of cloud feedbacks

S. Ocean difference is an aerosol feedback (**LE** larger AOD change, ~20%)

*Total difference between **LE** and **FixA** cloud feedbacks is 50% of cloud feedback!*




To surface and Ocean
TOA imbalance 0.6±0.4
Incoming solar 340.2±0.1
Reflected solar 100.0±2
Clouds
Shortwave cloud effect
47.5±3
All-sky atmospheric window 20±4
Clear-sky emission 266.4±3.3
239.7±3.3
Outgoing longwave radiation
Cirrus Clouds
Longwave cloud effect
All-sky longwave absorption
-187.9±12.5
26.7±4
3±5
Atmospheric absorption 75±10
5±5
Sensible heating
Latent heating
24±7
88±10
LW Clear
26.6±5
319±9
Clear-sky emission to surface
Clear-sky refection 27.2±4.6
Surface shortwave absorption 165±6
23±3
398±5
345.6±9
All-sky emission to surface
Surface reflection
PRECIP
Surface emission
Surface Albedo
Surface imbalance 0.6±17
Arctic Clouds

Summary

- CESM2 is pretty good [,bad & ugly]
  - Arctic is important
  - Shallow clouds are important
- Forcing and Feedback are uncertain
  - Both are important parts of the energy balance
- Interesting opportunities to constrain forcing and feedback with observations
  - Present day: process studies
  - Long records may provide opportunities (but observed feedback not climate change)
  - Can sort out modes of variability, might start to see cloud trends
- Complex interactions with forcing and feedback (e.g. aerosols)
  - Arise from coupled system
- Cloud feedbacks probably plural

One more Thing….The road not taken

- Removing liquid supersaturation from CLUBB was done with an ‘alternative’ cloud scheme
  - This resulted in higher sensitivity
- Also, relative variance was left in with SB2001
  - This configuration was not appropriate for SB2001
- Produced a reasonable 1850 climate, but…

Climate Sensitivity Perturbations

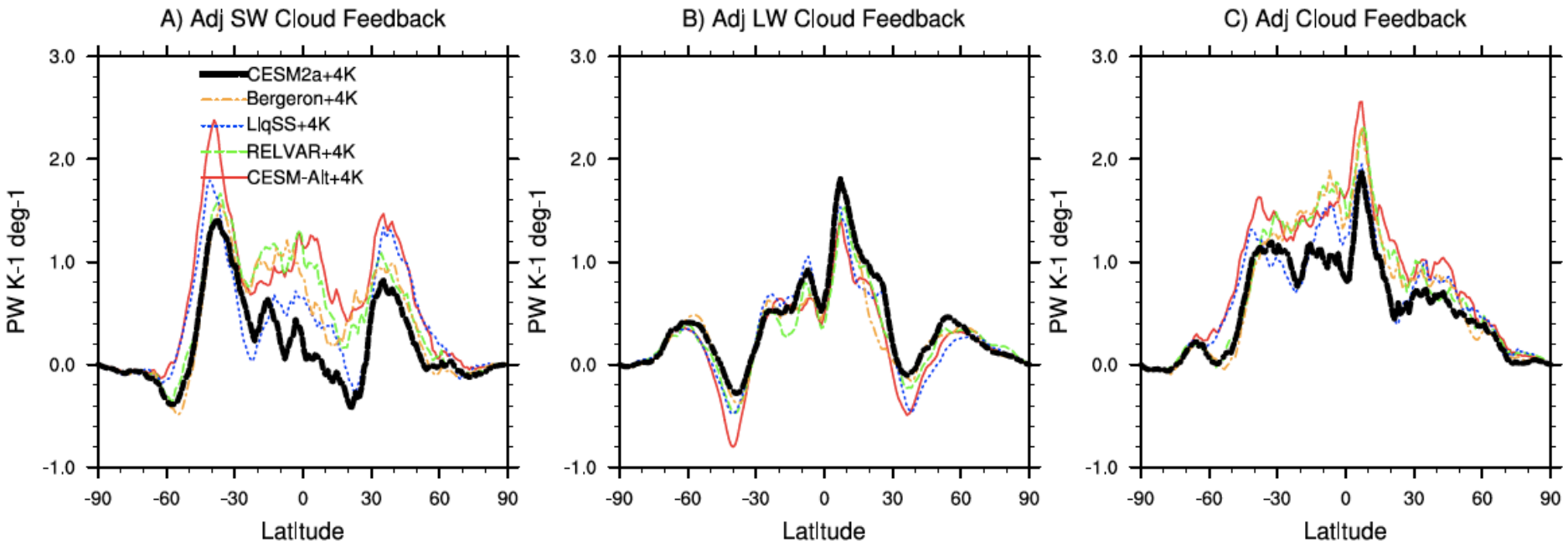
1. ‘High Sensitivity’: Changes to the low cloud scheme (subtropics)

   Inadvertently added a condensation scheme for low clouds to remove supersaturation

2. Lower Sensitivity’: Changes to stratiform clouds (high latitudes)
   1. Reducing excessive autoconversion/accretion
   2. Increasing efficiency of Bergeron process (less supercooled liquid)

Evolution of Cloud Feedback

SST+4K Experiments (Fixed SSTs)



CESM-Alt: 'High' Sensitivity (LiqSS+RELVAR)

LiqSS: Remove Liquid Supersaturation (LiqSS)

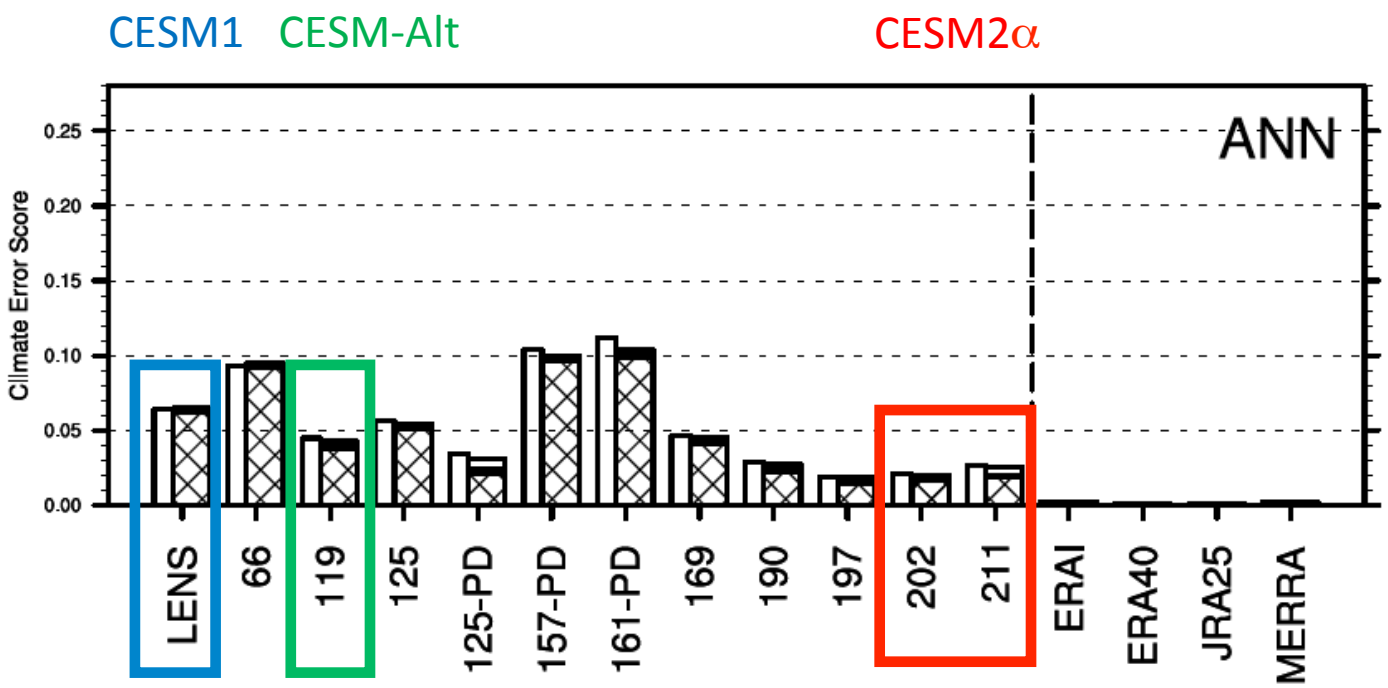
REVAR: Remove Relative Variance (RELVAR)

Bergeron: Increase efficiency of (Bergeron) Process (with LiqSS)

Baseline CESM2α (125)

Climate Skill Score

CESM-Alt is better than CESM1, close to CESM2



R. Neale

Phase errors (a)

Conditional bias (b)

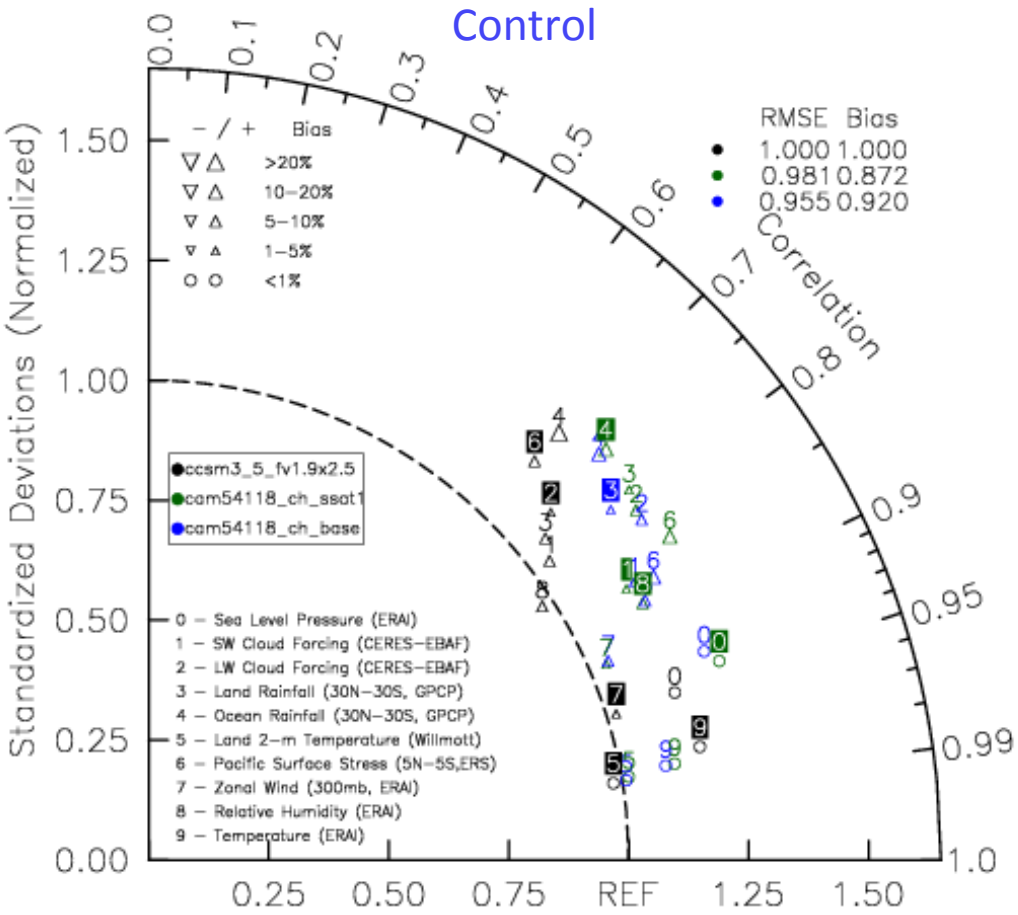
Unconditional bias (c)

Scaled variance ratio

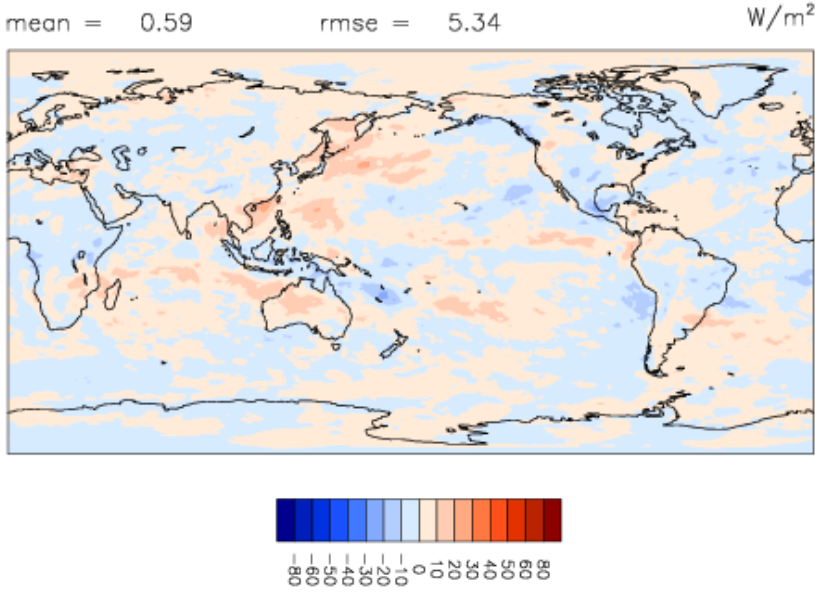
NMSE = (a)+(b)+(c)

Models are equally skillful

Reference
High Sensitivity
Control



Modified – Control SW CRE



How do you discriminate models?

Why does 119 have high Sensitivity?

CESM-Alt: 'High' Sensitivity was a tuned intermediate version with very good skill but ECS ~6K! Why high sensitivity?

1. Liquid Supersaturation (LiqSS) limiter added to CLUBB.

- Creates cloud between CLUBB sub-steps.
- This cloud often at top of PBL is very sensitive to surface temperature. Good simulation, but wrong reasons.

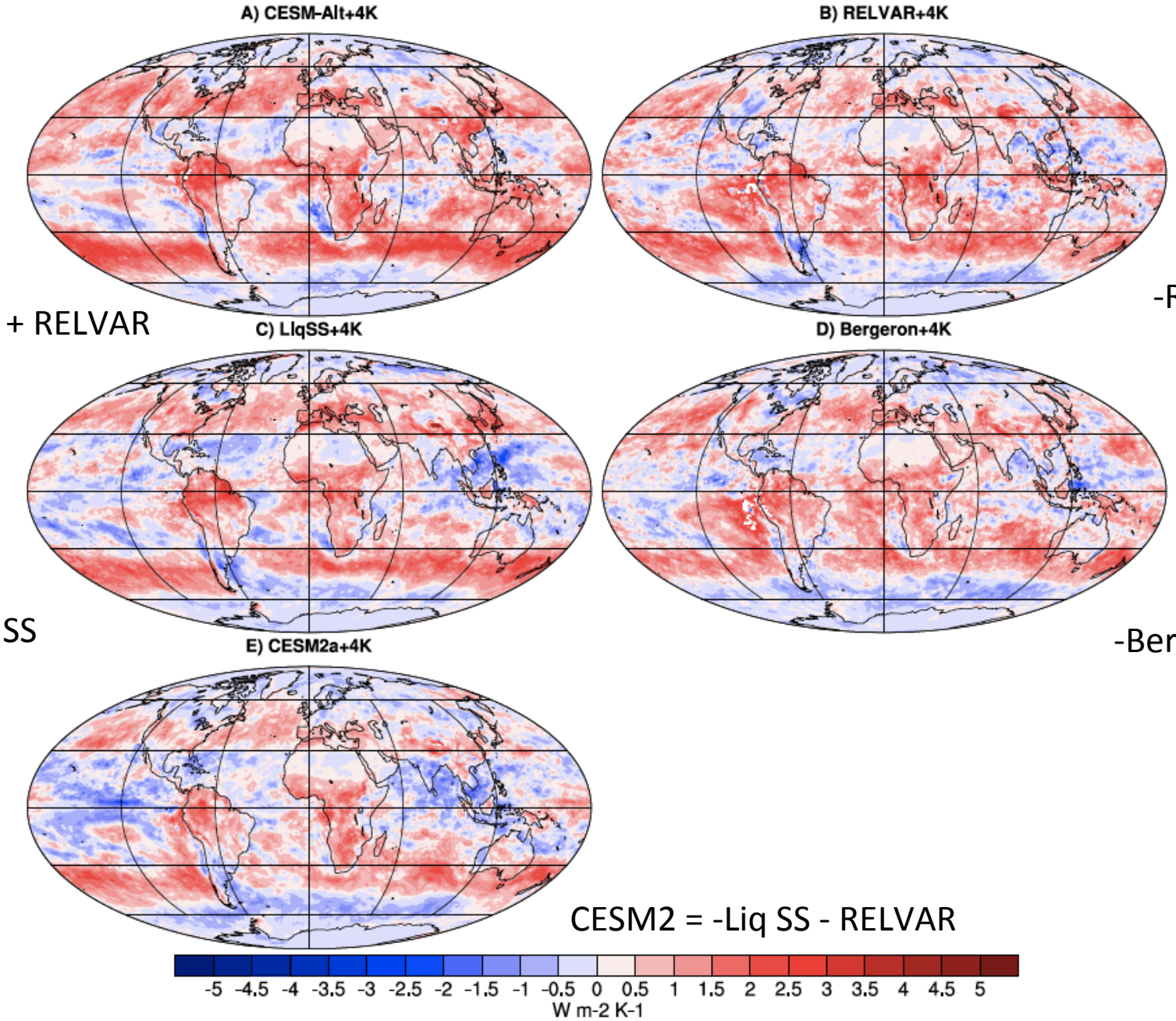
2. High Relative Variance (RELVAR)

- Boosts autoconversion (Au) & accretion (Ac): different Ac/Au balance.
- More autoconversion = more sensitive to increasing LWP when warmer. Limiting variance reduces cloud change (decrease) for higher latitude stratiform clouds.

Increased efficiency of (Bergeron) Process reduces super-cooled liquid.

Bigger cloud change when phase changes from ice→ liquid. Enhances negative high latitude cloud phase feedback, reducing sensitivity.

Adjusted Short Wave Cloud Feedback



Liq SS + RELVAR

-RELVAR

-Liq SS

-Bergeron

CESM2 = -Liq SS - RELVAR

Conclusions

- CESM2 is pretty good [,bad & ugly]
  - Arctic is important
  - Shallow clouds are important
- Forcing and Feedback are uncertain
- Interesting opportunities to constrain forcing and feedback with observations
- Complex interactions with forcing and feedback
- Constraining sensitivity is hard: high sensitivity models can ‘look good’