Climate Sensitivity and Cloud Feedbacks in the Evolution of a GCM

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CESM Evolution

2xCO₂ SOM Climate Sensitivity

CCSM4/CESM1 (CAM4): 3.1K
CESM1 (CAM5): 4.5K

What is the difference?
40% Forcing
60% Feedbacks

Note: forcing confirmed by off line radiation calculations
‘Evolution’ of Feedbacks in CESM

CCSM4 = CAM4  CESM1-CAM5 = CAM5

Radiative Kernel Estimated Feedbacks

Climate Sensitivity:
CCSM4: 3.2K
CESM1: 4.1K

Soden, 2008 (also Colman, Bony)
Methodology

• CESM Development ensemble (21 experiment pairs)
• Estimate feedbacks with radiative kernels
  – $\lambda = \Delta F / \Delta T_s$ ($\lambda = 1/\gamma$)
  – $\lambda_x = \Delta F/\Delta X \Delta X/\Delta T_s$
  – ‘kernel’ $K = \Delta F/\Delta X (x,y,z,t)$
  – Cloud feedbacks: Kernel adjusted Cloud Radiative Forcing
• Correlate feedbacks (especially clouds) with sensitivity ($\gamma$)
• Also correlate with mean state of ‘critical’ parameters (show one example)
CESM Ensemble looks like ‘Earth’

21 CESM Experiments: CAM4 $\rightarrow$ CAM5
7 Slab Ocean (SOM), 14 Fixed SST (Cess): 1x & 2x CO$_2$
Model climates are ‘earth like’
Model feedbacks look like other CMIP3 models
Sensitivity ($\gamma$) and Cloud Feedback

- Look at individual Experiment pairs (SW is dominant)
- Slope, correlation and goodness of fit provide statistics
- Do also for a range of feedbacks/properties, and at different points
Which Feedbacks?

Global Feedback Correlations with Climate Sensitivity

Slope: Wm$^{-2}$ K$^{-2}$

Clouds and Albedo are significantly correlated with climate sensitivity.

Albedo has a small slope

<table>
<thead>
<tr>
<th>Feedback</th>
<th>Corr</th>
<th>$r^2$</th>
<th>Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net Cloud</td>
<td>0.67*</td>
<td>0.44</td>
<td>0.07</td>
</tr>
<tr>
<td>LW Cloud</td>
<td>-0.90*</td>
<td>0.80</td>
<td>-0.09</td>
</tr>
<tr>
<td>SW Cloud</td>
<td>0.84*</td>
<td>0.71</td>
<td>0.16</td>
</tr>
<tr>
<td>Albedo</td>
<td>-0.56*</td>
<td>0.32</td>
<td>-0.01</td>
</tr>
<tr>
<td>H2O + LR</td>
<td>0.21</td>
<td>0.04</td>
<td>-0.006</td>
</tr>
<tr>
<td>Temp + LR</td>
<td>-0.11</td>
<td>0.01</td>
<td>-0.01</td>
</tr>
<tr>
<td>TS</td>
<td>-0.45</td>
<td>0.20</td>
<td>-0.006</td>
</tr>
</tbody>
</table>
Which Parameterization Changes?

Zonal Mean Kernel Adjusted Cloud Feedback

Biggest changes:

1. Microphysics (CAM4 → +Micro)
2. Radiation (+F_{CO2}) (+Macro → +Rad)
3. PBL makes it more negative (+Aero → +PBL)
4. Shallow Convection (last step) has largest impact (+PBL → CAM5)

Regions: Subtropics, Storm tracks, Deep convection over land

Note: can also see this in divergence metrics of present state
Which Regimes?

Pattern Correlation between cloud feedback (each point) and global $\gamma$ (sensitivity) = Slope of the line on scatter plots (but $\lambda_{\text{cl}}$ at each point)

Where are highest correlations with sensitivity? In the storm tracks (especially subtropical edge)
Regressions

Regression of local cloud feedback on global cloud feedback in CESM ensemble

Regression on global sensitivity ($\gamma$) looks similar
Regressions: Compared to CMIP3

- CESM different than CMIP3 even with feedback sign change in Strato-cu regions...
- CMIP3: tied to sub-tropical descent regions (no correlation where forcing is large)

- CESM: looked at $\omega_{500}$: not strong correlations or regression
- CESM: more storm track focused (where forcing is large)
Sample regression of parameters on $\gamma$

Regression of mean 1xCO2 LWP and IWP on global climate sensitivity

- Large slope (correlation) with Liquid Water Path
  - Higher sensitivity associated with lower mean condensate
- Ice moderately correlated: patterns are a ‘feature’
  - Different treatment of convective water: land & ocean
What is happening in CESM?

- Change to shallow convection causes largest jump in climate sensitivity
- Due to shortwave cloud feedbacks
- Equator-ward branches of storm tracks
- Why? Change in shallow and deep convective detrainment into stratiform clouds
- Seen in cloud mean base state LWP, also some microphysical and deep convection parameters
- Different than CMIP3 ensemble (SV2011)
- This is parameterization dependent in CESM
- Process by which it occurs has a physical basis...
  - Mean state cloud optical depth is non-unique function of LWP/re, this affects feedbacks
γ correlated with mean state properties in CESM and SOM experiments.

Have looked at CMIP3: less conclusive

Others (e.g. Pincus et al 2008) have looked for different parameters or correlations: generally not seen them.

Why? Models have same forcing. Different balance to get there.
Why does LWP matter?

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

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

(a= fraction, $\tau$ = optical depth)

Both $a, \tau$ are ‘known’ outside of Arctic (not well known)

$$\tau = f(N_c, \text{LWP}) \quad [\text{mass, #}]$$

Satellites only measure $\tau$, make assumptions about $N_c$ to get LWP, and have different $a$ (viewing geometry).

Still 20-40% uncertainties in LWP (see plot again): may be able to use them to ‘rule out’ some ranges of climate sensitivity?

Bad news: CAM5 ($\gamma = 4K$) has much better clouds and low LWP
Cloud Feedback (CF) and Mean State

$1xCO_2$

$T_s$

$2xCO_2$

$T_s = T_s + \Delta T_s$

$CRF_{A1x} \rightarrow CRF_{A2x}$

$CRF_{B1x} = CRF_{A1x}$

$CRF_{B1x} < CRF_{A1x}$

$CF_A = (CRF_{A1x} - CRF_{A2x})/\Delta T_{sA}$

$CF_B = (CRF_{B1x} - CRF_{B2x})/\Delta T_{sB}$

$CF_B > CF_A$

References:
Conclusions

• Cloud feedbacks dominate CESM climate sensitivity spread
• Some other side notes: effects of ‘tuning’ parameters and aerosols on climate sensitivity are small
• SW cloud feedbacks on equator-ward part of the storm track: when shallow convection is introduced
• Less spread due to stratocumulus regions than CMIP3 results (even though these feedbacks change in CESM).
• Base state microphysical balance of clouds is different between CESM models: base state of cloud microphysics says something about climate sensitivity in CESM
• (Micro) Physical reasons why clouds matter: optical depth of clouds non unique (some relation of LWP and $r_e$)
• Unknown: Why should CESM ensemble be different than CMIP3 regions for variation in cloud feedback? Might be large S. Ocean improvements (Trenberth & Fasullo 2010)
Questions, Comments or ‘Feedback’?

CESM Net Cloud Feedback
High, Med, Low Cloud Feedback

CMIP3 (Soden & Vecchi 2011)

High Cloud Feedback

High

Medium

Low Cloud Feedback

Low

CAM4 (CCSM4)

A) CAM4 SOM

CESM1-CAM5

B) CAM5 SOM

Ensemble-mean Cloud Feedback (W m⁻² K⁻¹)
Change in Cloud Fraction

CMIP3 (Soden & Vecchi 2011)

CAM4 (CCSM4)

CESM1-CAM5

Change in Cloud Cover

Ensemble-mean Cloud Cover Change (%K')