Understanding the spread of climate sensitivity and cloud responses in CMIP6 models

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Sandrine Bony, and
Jean-Louis Dufresne, LMD, Paris, France

René Magritte, The Embellishment, 1962
A more bimodal ECS distribution in CMIP6?

- ECS values calculated with Gregory regression (2004)
- CMIP6 range [2.6 - 5.6K], mean 4K
- CMIP5 range [2.1 - 4.7K], mean ~3K (Andrews et al, 2012)
- Not spanning possible ECS range due to feedback and forcing compensations (Huybers 2010), and under-explored parameter spaces (Stainforth et al, 2005)
In CMIP6, spread in ECS still largely driven by varying cloud responses

\[ r = 0.77 \]

\[ R^2 = 0.60 \]
Tropical CRE variability can largely explain global CRE variability

<table>
<thead>
<tr>
<th>r ($R^2$)</th>
<th>ECS</th>
<th>Global CRE</th>
<th>Extratropical CRE</th>
<th>Tropical CRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECS</td>
<td>1</td>
<td>0.77 (60%)</td>
<td>0.43 (19%)</td>
<td>0.73 (54%)</td>
</tr>
<tr>
<td>Global CRE</td>
<td>1</td>
<td>0.55 (31%)</td>
<td></td>
<td>0.87 (76%)</td>
</tr>
<tr>
<td>Extratropical CRE</td>
<td>1</td>
<td></td>
<td>0.27 (8%)</td>
<td></td>
</tr>
<tr>
<td>Tropical CRE</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

NASA MODIS image of cloud cover
Tropical SW and LW CRE strongly anticorrelated

Tropical contribution to global cloud feedback

- Net CRE
  - SW CRE
  - LW CRE

<table>
<thead>
<tr>
<th></th>
<th>Net CRE</th>
<th>SW CRE</th>
<th>LW CRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>r (R²)</td>
<td>1</td>
<td>0.87</td>
<td>-0.40</td>
</tr>
<tr>
<td></td>
<td>(76%)</td>
<td>(16%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>-0.80</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>(63%)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

CMIP6 models

GISS-E2-G, GISS-E2-H, IPSL-CM6A-LR, MIROC5, GFDL-CM4, BCC-CSM2, MIH-ESM2, CNRM_ESM1_1, CNRM_CM6_1, CESM2-WACCM, SAM0, HadGEM3-GC31
Which dynamical regimes are contributing to the spread in CRE?

\[ Y_{150} - \text{piControl} \]
Stratify cloud feedbacks by low and high sensitivity models

Low sensitivity
ECS < 4 °C
[GISS-E2-G, GISS-E2-H, MIROC6, MRI-ESM2, BCC-CSM2, SAM0, GFDL-CM4]

High sensitivity
ECS > 4 °C
[CNRM-CM6, CNRM-ESM, IPSL-CM6A, HadGEM3, CESM2]
Strongest divergence of early cloud feedback in subsidence regimes

Y10 - piControl

\[ \omega_{500} \text{ hPa/day} \]

- Low ECS
- High ECS

W/m²/°C
Thermodynamic contribution $P_\omega \Delta C_\omega$ to later cloud feedback

$$\delta C_\omega = \sum_\omega C_\omega \Delta P_\omega + \sum_\omega P_\omega \Delta C_\omega + \sum_\omega \Delta P_\omega \Delta C_\omega$$


$\overline{Y_{150} - Y_{10}}$
Subsidence regimes’ thermodynamic feedback most correlated with tropical cloud feedback

\[ \overline{\delta C_\omega} = \sum_\omega C_\omega \Delta P_\omega + \sum_\omega P_\omega \Delta C_\omega + \sum_\omega \Delta P_\omega \Delta C_\omega \]


### Thermodynamic feedback per circulation regime:

<table>
<thead>
<tr>
<th>r (R²)</th>
<th>Strong ascent</th>
<th>Weak ascent</th>
<th>Weak subsidence</th>
<th>Strong subsidence</th>
<th>Net</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical feedback</td>
<td>-0.40 (16%)</td>
<td>0.67 (45%)</td>
<td>0.88 (77%)</td>
<td>0.95 (91%)</td>
<td>0.92 (85%)</td>
</tr>
</tbody>
</table>
High sensitivity models associated with stronger weakening of the tropical overturning circulation

\[ p_\omega \]

\[ \omega \]

\[ \delta p_\omega \]

\[ I \equiv \overline{\omega}^\downarrow - \overline{\omega}^\uparrow \]

\[ I: \text{tropical circulation intensity (Bony et al, 2013)} \]

ECS and \( dI/dT \): \( r = -0.56 \quad (R^2 = 32\%) \)
Towards tropical cloud ‘storylines’ to discriminate between low and high sensitivity models

<table>
<thead>
<tr>
<th></th>
<th>Low ECS &lt; 4K</th>
<th>High ECS &gt; 4K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial cloud response in subsidence regimes</td>
<td>-/0</td>
<td>+</td>
</tr>
<tr>
<td>Thermodynamic cloud feedback in subsidence regions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weakening of the tropical circulation intensity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SST pattern effect and EIS?</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Evaluating CMIP6 low cloud responses with EUREC$^4$A field campaign data

• EUREC$^4$A multi-platform field campaign: Jan. 20 - Feb. 20, 2020 in Barbados
• Leverage EUREC$^4$A data to evaluate low cloud responses in CMIP6 models
• Simple mixed-layer model to understand what controls the cloudiness in the trades, constrained with EUREC$^4$A observations
Supplementary
Greater moistening around 500hPa in ascending regions in high sensitivity models — increased cloudiness as well?

Relative humidity anomalies (%)  
Cloud fraction anomalies (%)
Heterogeneities in $\Delta$SST by circulation regime?

**High sensitivity model**

*CNRM-CM6A*

**Low sensitivity model**

*MRI-ESM*
Decompose tropical cloud feedbacks into discrete tropical circulation regimes (defined by $\omega_{500}$ hPa/day).

- $\omega_{500}$ (hPa/day), vertical pressure velocity at 500 hPa, acts as proxy for large-scale atmospheric circulation
- Negative for ascending motions
- Positive for subsiding motions
- $\omega_{500}$ increases with decreasing SST, moving from regions of regions of large-scale ascent (deep convection) to regions of large-scale subsidence (trade cumulus and stratocumulus regions)

$P_\omega$: discrete distribution of tropical circulation (pre-industrial)

- Colored shading is one standard deviation ($\sigma$) of monthly values around 20-year climatology
- Peak in distribution of in regions of weak subsidence (0-30 hPa/day), dominated by trade wind cumulus clouds
- Strength of peak in weak subsidence regimes trades off with frequency of extreme circulations
- Compare $P_\omega$ in historical runs with ERAI $P_\omega$
Tropical circulation changes $\delta P_\omega$: abrupt4xCO$_2$ - piControl

- $\delta P_\omega$ illustrates the robust weakening of the tropical circulation with warming — decreased frequency of strong updrafts and strong subsidence and increased frequency of weak updrafts and weak subsidence (i.e. Vecchi and Soden, 2006)
- Demonstrates the shift in frequency towards weaker large-scale subsidence in trade wind cumulus regimes (0, 30 hPa)
- IPSL-CM6A peak in regions of weak ascent (-30, 0 hPa) might result from strong double ITCZ bias
What could explain this compensatory behavior between SW and LW CRE in the tropics?

- Result of tuning?
- Two examples of possible physical mechanisms
  - ITCZ narrowing
  - Lower tropospheric mixing
Strength of lower tropospheric mixing

Sherwood et al, 2014

Stronger mixing dehydrates boundary layer moisture needed to sustain low cloud cover, positive SW CRE

Induces deep circulation changes? Aggregation, iris effect to have negative LW CRE?
ITCZ narrowing to interpret SW and LW CRE anticorrelation?

ITCZ narrows?
- Fewer cirrus clouds, iris effect, **negative LW CRE**
- Greater low cloud fraction exposed in subsidence regimes, **positive SW CRE**

Test descent vs. ITCZ area changes in CMIP6 models

Byrne et al (2016)
Correlation dynamic change $C_{\omega} \delta P_{\omega}$ and $\lambda_c$ in primary circulation regimes

$$\delta C_{\omega} = \sum_{\omega} C_{\omega} \Delta P_{\omega} + \sum_{\omega} P_{\omega} \Delta C_{\omega} + \sum_{\omega} \Delta P_{\omega} \Delta C_{\omega}$$

$\lambda_c$ Net tropical cloud feedback

- Region 1 and $\lambda_c$ r=0.35 (12%)
- Region 2 and $\lambda_c$ r=0.08 (0.5%)
- Region 3 and $\lambda_c$ r=0.48 (23%)
- Region 4 and $\lambda_c$ r =-0.15 (2%)
- Dynamic component and $\lambda_c$ r = 0.63 (40%)
Thermodynamic, dynamic and covariance contributions to each model’s net tropical cloud feedback

\[ \sum_{\omega} P_{\omega} \Delta C_{\omega} = \sum_{\omega} C_{\omega} \Delta P_{\omega} + \sum_{\omega} \Delta P_{\omega} \Delta C_{\omega} \]

<table>
<thead>
<tr>
<th>Model</th>
<th>Thermodynamic</th>
<th>Dynamic</th>
<th>Covariance</th>
<th>Net tropical cloud feedback</th>
</tr>
</thead>
<tbody>
<tr>
<td>GISS-G</td>
<td>-0.17</td>
<td>-0.05</td>
<td>-0.004</td>
<td>-0.22</td>
</tr>
<tr>
<td>CNRM CM6</td>
<td>0.19</td>
<td>-0.06</td>
<td>-0.002</td>
<td>0.13</td>
</tr>
<tr>
<td>CNRM ESM</td>
<td>0.18</td>
<td>-0.07</td>
<td>-0.002</td>
<td>0.11</td>
</tr>
<tr>
<td>MRI</td>
<td>0.14</td>
<td>0.06</td>
<td>-0.021</td>
<td>0.17</td>
</tr>
<tr>
<td>IPSL</td>
<td>0.03</td>
<td>0.24</td>
<td>-0.012</td>
<td>0.26</td>
</tr>
<tr>
<td>BCC</td>
<td>0.06</td>
<td>0.04</td>
<td>-0.023</td>
<td>0.07</td>
</tr>
<tr>
<td>GFDL</td>
<td>0.05</td>
<td>0.09</td>
<td>-0.006</td>
<td>0.14</td>
</tr>
<tr>
<td>MIROC</td>
<td>0.01</td>
<td>-0.04</td>
<td>0.007</td>
<td>-0.03</td>
</tr>
</tbody>
</table>
Conceptual model of trade wind boundary layer

1D framework:

**Temperature**

\[
\frac{\partial \theta_{BL}}{\partial t} = Q_{BL} + \frac{1}{h}(w_e \Delta \theta + F_\theta)
\]

(1)

with

\[
\Delta \theta = \theta_0 + \Gamma h - \theta_{BL}
\]

(2)

\[
F_\theta = C_a V (\theta_{slc} - \theta_{BL})
\]

(3)

**Humidity**

\[
\frac{\partial q_{BL}}{\partial t} = \frac{1}{h}(w_e \Delta q + F_q)
\]

(4)

with

\[
\Delta q = q_{FT} - q_{BL}
\]

(5)

\[
F_q = C_a V (q_{slc} - q_{BL})
\]

(6)

**Boundary layer height**

\[
\frac{\partial h}{\partial t} = w_{FT} + w_e + w_m = \frac{Q_{FT}}{\Gamma} + A \frac{F_B}{\Delta \theta_v} + w_m
\]

(7)

with

\[
\Delta \theta_v = (\theta_0 + \Gamma h)(1 + \epsilon q_{FT}) - \theta_{v,BL}
\]

(8)

\[
F_B = F_\theta + \epsilon \theta_{BL} F_q
\]

(9)

\[
w_m = \begin{cases} 
\frac{h - LCL}{\tau} & \text{if } LCL < h \\
0 & \text{if } LCL \geq h 
\end{cases}
\]

(10)
Rapid adjustments (abrupt$4\times CO_2_{yr.20}$ - pre-industrial mean) filtered by high and low sensitivity models and weighted by $P_\omega$.
Using years 0-150 of abrupt4xCO2 experiment for consistency across models

Ex. Role of time period in calculating ECS in IPSL-CM6A-LR

ECS (150 yrs) = 4.5 (4.0, 5.1) K
ECS (300 yrs) = 4.8 (4.3, 5.2) K
ECS (900 years) = 5.0 (4.8, 5.3) K
ECS (last 600 years) = 5.1 (4.2, 6.3) K