Validating and Understanding Feedbacks in Climate Models

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In collaboration with
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Why Feedbacks?

- Feedbacks determine the sensitivity of the climate system to anthropogenic forcing

- Feedbacks determine the amplitude of the natural variability in the climate system

- Feedbacks determine the equilibrium state of the climate system--the time-mean climate
Methodology

• The initial analysis is focused on the equatorial Pacific cold-tongue region.

• Use ENSO as the forcing signal and obtain the feedbacks by examining the response of various energy fluxes to El Nino warming.
Data

- Observational data: ERBE, NCEP/NCAR reanalysis, ISCCP
- Model outputs: AMIP and fully coupled runs of climate models
The Physical Processes

\[ S = S_c + C_s \]

\[ F = E - G = \sigma T^4 - G_a - C_l \]

\[ N_T = S - F \]

Atmosphere

\[ -D_a \]

Ocean

\[ F_s \]
The Water Vapor Feedback
The Dynamical Feedback
The Cloud Feedbacks
The Cloud Feedbacks

NCAR CAM2

NCAR CAM3
The Cloud Feedbacks

[Graph showing time series of cloud feedbacks with time on the x-axis and cloud forcing on the y-axis, labeled NCAR CAM3 (T85)]
Atmospheric feedbacks in observations and the NCAR models

<table>
<thead>
<tr>
<th>Name of Process</th>
<th>Observation</th>
<th>NCAR/CAM1</th>
<th>NCAR/CAM2</th>
<th>NCAR/CAM3</th>
<th>CAM3 (T85)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{\partial G_a}{\partial T}$</td>
<td>6.72 ± 0.27</td>
<td>9.10 ± 0.43</td>
<td>8.39 ± 0.41</td>
<td>8.89 ± 0.39</td>
<td>9.69 ± 0.36</td>
</tr>
<tr>
<td>$\frac{\partial C_L}{\partial T}$</td>
<td>12.21 ± 1.03</td>
<td>15.94 ± 1.35</td>
<td>6.64 ± 0.63</td>
<td>7.21 ± 0.72</td>
<td>12.63 ± 0.82</td>
</tr>
<tr>
<td>$\frac{\partial C_z}{\partial T}$</td>
<td>-10.93 ± 1.37</td>
<td>-4.98 ± 0.60</td>
<td>1.87 ± 0.96</td>
<td>-0.56 ± 0.78</td>
<td>-9.72 ± 1.09</td>
</tr>
<tr>
<td>$\frac{\partial D_v}{\partial T}$</td>
<td>-16.69 ± 1.51</td>
<td>-13.63 ± 1.76</td>
<td>-9.18 ± 1.40</td>
<td>-9.02 ± 1.20</td>
<td>-14.34 ± 1.23</td>
</tr>
<tr>
<td>$\frac{\partial F_a}{\partial T}$</td>
<td>-8.69 ± 1.76</td>
<td>6.42 ± 1.24</td>
<td>7.72 ± 1.12</td>
<td>6.53 ± 1.00</td>
<td>-1.75 ± 1.23</td>
</tr>
<tr>
<td>$\frac{\partial F_z}{\partial T}$</td>
<td>-14.89 ± 1.83</td>
<td>0.44 ± 1.24</td>
<td>1.48 ± 1.13</td>
<td>0.30 ± 1.02</td>
<td>-8.08 ± 1.25</td>
</tr>
</tbody>
</table>

* The net atmospheric feedback $\frac{\partial F_a}{\partial T} = \frac{\partial G_a}{\partial T} + \frac{\partial C_L}{\partial T} + \frac{\partial C_z}{\partial T} + \frac{\partial D_v}{\partial T}$
How are other models doing in simulating the feedbacks?

## Atmospheric Feedbacks in Models and Observations

<table>
<thead>
<tr>
<th>Name of Process</th>
<th>Feedback (Wm⁻²K⁻¹)</th>
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<tbody>
<tr>
<td></td>
<td>Observation</td>
</tr>
<tr>
<td>( \frac{\partial (G_e)}{\partial T} )</td>
<td>6.72 ± 0.27</td>
</tr>
<tr>
<td>( \frac{\partial (C_L)}{\partial T} )</td>
<td>12.21 ± 1.03</td>
</tr>
<tr>
<td>( \frac{\partial (C_S)}{\partial T} )</td>
<td>-10.93 ± 1.37</td>
</tr>
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<td>-16.69 ± 1.51</td>
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<tr>
<td>( \frac{\partial (F_u)}{\partial T} )</td>
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<td>( \frac{\partial (F_L)}{\partial T} )</td>
<td>-14.89 ± 1.83</td>
</tr>
</tbody>
</table>

* The net atmospheric feedback \( \frac{\partial (F)}{\partial T} = \frac{\partial (G)}{\partial T} + \frac{\partial (C_L)}{\partial T} + \frac{\partial (C_S)}{\partial T} + \frac{\partial (D)}{\partial T} \)
Precipitation Response to El Nino Warming
Cloud Cover Response to El Nino Warming
The Water Vapor Response

Percentage response of specific humidity to El Nino warming (%/K)
Preliminary results from fully coupled runs

### Atmospheric Feedbacks in Models and Observations

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<th>Name of Process</th>
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<th>Observation</th>
<th>NCAR/CCSM1</th>
<th>NCAR/CCSM2</th>
<th>NCAR/CCSM3</th>
<th>CCM3 (T85)</th>
<th>UKMO/HadCM3</th>
<th>IPSL/CM4</th>
<th>GFDL/CM2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{\delta(G_a)}{\delta T}$</td>
<td>6.72 ± 0.27</td>
<td>8.89 ± 0.40</td>
<td>8.43 ± 0.16</td>
<td>9.71 ± 0.22</td>
<td>9.37 ± 0.37</td>
<td>8.73 ± 0.24</td>
<td>9.72 ± 0.18</td>
<td>8.97 ± 0.19</td>
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</tr>
<tr>
<td>$\frac{\delta(C_a)}{\delta T}$</td>
<td>12.21 ± 1.03</td>
<td>11.84 ± 0.96</td>
<td>7.07 ± 0.28</td>
<td>10.33 ± 0.55</td>
<td>12.64 ± 0.97</td>
<td>6.09 ± 0.41</td>
<td>12.31 ± 0.76</td>
<td>11.56 ± 0.70</td>
<td></td>
</tr>
<tr>
<td>$\frac{\delta(G_a + C_a)}{\delta T}$</td>
<td>18.93 ± 1.17</td>
<td>20.73 ± 1.31</td>
<td>15.50 ± 0.38</td>
<td>20.03 ± 0.72</td>
<td>22.01 ± 1.24</td>
<td>14.82 ± 0.64</td>
<td>22.03 ± 0.82</td>
<td>20.52 ± 0.79</td>
<td></td>
</tr>
<tr>
<td>$\frac{\delta(C_e)}{\delta T}$</td>
<td>-10.93 ± 1.37</td>
<td>-3.50 ± 0.62</td>
<td>-0.93 ± 0.57</td>
<td>-6.90 ± 1.03</td>
<td>-7.46 ± 1.41</td>
<td>-4.56 ± 0.64</td>
<td>-8.32 ± 0.74</td>
<td>-7.64 ± 1.00</td>
<td></td>
</tr>
<tr>
<td>$\frac{\delta(D_e)}{\delta T}$</td>
<td>-16.69 ± 1.51</td>
<td>-17.84 ± 1.32</td>
<td>-14.12 ± 0.65</td>
<td>-17.09 ± 1.07</td>
<td>-17.87 ± 1.42</td>
<td>-12.35 ± 0.84</td>
<td>-16.45 ± 1.09</td>
<td>-19.96 ± 0.99</td>
<td></td>
</tr>
<tr>
<td>$\frac{\delta(F_e)}{\delta T}$</td>
<td>-8.69 ± 1.76</td>
<td>-0.61 ± 1.20</td>
<td>0.45 ± 1.02</td>
<td>-3.96 ± 1.38</td>
<td>-3.32 ± 1.67</td>
<td>-2.09 ± 0.87</td>
<td>-2.74 ± 1.02</td>
<td>-7.08 ± 1.35</td>
<td></td>
</tr>
</tbody>
</table>

The net atmospheric feedback $\frac{\delta(F_e)}{\delta T} = \frac{\delta(G_a)}{\delta T} + \frac{\delta(C_a)}{\delta T} + \frac{\delta(C_e)}{\delta T} + \frac{\delta(D_e)}{\delta T}$
SST-Precipitation Relationship in coupled models
Summary

• The models tend to overestimate the positive feedback from water vapor in El Nino warming.

• The models tend to underestimate the negative feedback from cloud albedo in El Nino warming.
Questions Highlighted

• What are the factors that control the upper tropospheric water vapor?

• How is the vertical distribution of clouds determined?

• What are the factors that control the sensitivity of the precipitation to SST forcing?
Some Other Questions We Are Addressing

• What are the impacts of these biases in the cloud and water vapor feedbacks on the large-scale tropical ocean-atmosphere interaction?

• Will these biases in the cloud and water vapor feedbacks affect the model’s projection of the response of the coupled tropical climate system to global warming?

• What are the implications of the reduced sensitivity of precipitation to SST forcing in the models for the teleconnection between the tropics and the extratropics?
Cloud Cover Response to El Nino Warming

Spatial Pattern of Response of Cloud Cover to El Nino Warming

Observation

High Cloud

NCAR CAM2

High Cloud

Middle Cloud

Middle Cloud

Low Cloud

Low Cloud

Longitude (degree)

Latitude (degree)
Cloud Cover Response to El Nino Warming
Cloud Cover Response to El Nino Warming
The Excessive Cold-tongue in Coupled models
The idea of a weaker regulating effect from the model atmosphere
The effect of a less negative net atmospheric feedback on the cold-tongue SST bias

\[ T - T_0 = \frac{H(T_0)}{4\sigma T_0^3} - \left( \frac{\partial G_a}{\partial T} + \frac{\partial C_l}{\partial T} + \frac{\partial C_s}{\partial T} + \frac{\partial D_a}{\partial T} \right) - \frac{\partial D_o}{\partial T} \]

SST Bias

Atmospheric Feedbacks

Ocean feedback

Net flux error at \( T_0 \)
A further assessment of the effect of feedback errors on the cold-tongue SST

Coupled model used: NCAR Pacific basin model coupled with an empirical atmosphere (Sun 2003)