Cloud Feedback and Aerosol Radiative Forcing in the IPCC AR4 Models

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Introduce “Radiative Kernels” to describe the differential response of radiation to changes in state variables.

Use Kernels to:

- Analyze cloud feedbacks for IPCC AR4 GCMs.
- Analyze radiative forcings for IPCC AR4 scenarios.
- Details: Soden et al., 2008, J. Climate, in press.
What is the Range of Cloud Feedback?

Cess et al. (1996)  
ΔCRF Method

- 8 of 18 models have negative cloud feedback

Colman (2003)  
Radiative Perturbation Method

- 1 of 10 models has negative cloud feedback
Climate Feedbacks using Radiative Kernels

\[ \Delta T_s = \frac{G}{\lambda} \]

\( G = \) radiative forcing
\( \lambda = \) climate sensitivity
\( R = \) net radiation at TOA

\[ \lambda = \frac{\delta R}{\delta T} \frac{dT}{dT_s} + \frac{\delta R}{\delta W} \frac{dW}{dT_s} + \frac{\delta R}{\delta C} \frac{dC}{dT_s} + \frac{\delta R}{\delta \alpha} \frac{d\alpha}{dT_s} \]

- Temperature Feedback
- Water Vapor Feedback
- Cloud Feedback
- Sfc Albedo Feedback

Climate Feedback = \( \frac{\delta R}{\delta X} \times \frac{dX}{dT_s} \)

Radiative Transfer (Kernel) Climate Response
Multi-Model Ensemble Mean Feedbacks: IPCC AR4 GCMs
Global Mean Feedbacks: IPCC AR4 GCMs

- Range cloud feedback is ~4 times larger than other feedbacks.
- Cloud feedback is neutral to positive in all models, even though ΔCRF is not.
Cloud Feedback vs $\Delta$ Cloud Forcing

Adjusted Change in Cloud Forcing (0.70 W/m²/K)

Changes in cloud radiative forcing include effects from changes in other variables (e.g., CO2).

Cloud Feedback (0.77 W/m²/K)

Change in Cloud Forcing (−0.22 W/m²/K)
LW cloud feedback is consistently positive in all models.

SW cloud feedback ranges from modest negative to strong positive.

Ensemble Mean Cloud Feedback: SW vs LW

Net Cloud Feedback
Ens. Mean: 0.66 W/m²/K  Intermodel Range: 0.2 to 1.3

LW Cloud Feedback
Ens. Mean: 0.40 W/m²/K  Intermodel Range: 0.1 to 0.5

LW cloud feedback is consistently positive in all models.

SW Cloud Feedback
Ens. Mean: 0.26 W/m²/K  Intermodel Range: -0.5 to 1.3

SW cloud feedback ranges from modest negative to strong positive.
Ensemble Mean Cloud Feedback: High vs Low

**High Cloud Feedback**
- Ens. Mean: 0.18 W/m²/K
- Intermodel Range: 0.1 to 0.3

**Mixed Cloud Feedback**
- Ens. Mean: 0.18 W/m²/K
- Intermodel Range: 0.1 to 0.3

**Low Cloud Feedback**
- Ens. Mean: 0.30 W/m²/K
- Intermodel Range: -0.1 to 0.9

Roughly 50% of net feedback is from low clouds.
Which Clouds Contribute to the Intermodel Spread in Global Mean Cloud Feedback?

Intermodel spread in net cloud feedback is dominated by SW feedback from low clouds.
Regional contribution to intermodel spread in global mean cloud feedback is dominated by stratocumulus.
Are these changes detectable in observations?
Intermodel Differences in Radiative Forcing: 20th Century (20C3M)
GFDL AM2 Simulations with Prescribed SST: 1850-2000
IPCC AR4 20th Century Model Projections (20C3M)

Surface temperature increases in all models.

Precipitation may increase, decrease or remain unchanged.
Cloud feedback is neutral to positive in all models. Why?

SW feedback from stratocumulus clouds is the primary cause of intermodel differences in cloud feedback … and thus climate sensitivity.

Long-term, stable ERB measurements will be needed to reduce uncertainty in cloud feedback.

Intermodel differences in aerosol radiative forcing are a significant source of uncertainty in both 20th and 21st Century climate projections.
Extra Slides
Intermodel Differences in Radiative Forcing: 21st Century (A1b)

3.2 W/m²
CCSM4 (3.21)

CNRM (4.66)
GFDL CM2.0 (5.54)
HADCM3 (4.53)

GISS EHR (4.10)
GISS EHR (4.01)
INMCM3 (2.78)
IPSL (4.18)

MIROC ECHAM (4.41)
MPI (6.01)
MRI (4.05)
NCAR CCSM3 (4.03)

6.0 W/m²
Water Vapor Feedback using Kernels

Water Vapor Kernel
\( \frac{\delta R}{\delta W} \) from RT code

Water Vapor Response to 2xCO2
\( \frac{dW}{dT_s} \) from GCM

Water Vapor Feedback = Kernel x Response

\[ \text{Water Vapor Feedback} = \text{Kernel} \times \text{Response} \]
Intermodel Differences in Radiative Forcing: A1b vs 1% to 2XCO2

Uncertainty in CO2: ~0.5 W/m²

Uncertainty in Aerosol: ~3 W/m²
Ensemble Mean Cloud Feedback: Robustness

Number of models with a positive cloud feedback in each grid box (out of a total of 12).
Intermodel spread in net cloud feedback is dominated by SW feedback.
How FAT is Cloud Feedback in AR4 GCMs?

High clouds do warm in response increased CO2, but do so more slowly than a fixed cloud response.
Comparison Feedback Calculations: PRP vs. Kernel Method

<table>
<thead>
<tr>
<th>Feedback</th>
<th>Kernel</th>
<th>Forward PRP</th>
<th>Reverse PRP</th>
<th>Average PRP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>-4.06</td>
<td>-4.42</td>
<td>-3.64</td>
<td>-4.03</td>
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<tr>
<td>Water Vapor</td>
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<td>2.12</td>
<td>1.78</td>
<td>1.95</td>
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<tr>
<td>Surface Albedo</td>
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<td>0.17</td>
<td>0.13</td>
<td>0.15</td>
</tr>
<tr>
<td>Clouds</td>
<td>0.37</td>
<td>0.28</td>
<td>0.39</td>
<td>0.34</td>
</tr>
</tbody>
</table>

Feedback calculations agree to within ~10% of conventional PRP.
Regional contribution to intermodel spread in global mean cloud feedback is dominated by stratocumulus.
Water Vapor Kernel: $\delta R/\delta W$ (zonal, annual mean)

Change in OLR due to constant RH increase in WV

Total Sky

Clear Sky

W/m²/K/100 mb