Using observational simulations to distinguish low-cloud feedbacks in CCSM3 and CESM

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Uncertain Low-Cloud Feedbacks

- Low-cloud feedbacks have been identified as a major source of uncertainty in determining climate sensitivity.
- The parameterizations of shallow convection in the subtropics are uncertain but are an area of active research.
- What measurements can inform the model development?

Bony, et al, 2006
Variable Resolution Simulations

- We have analyzed CCSM3 simulations forced only with CO\textsubscript{2} increasing at 1% per year.
- Simulations are at T31 (~3.75°), T42 (~2.8°), and T85 (~1.4°) horizontal resolutions.
- Cloud feedbacks are stronger for higher spatial resolution models
  - Due to boundary-layer parameterizations that lead to over-prediction of low-level cloud fraction from inefficient mixing of drier air in the boundary layer.

<table>
<thead>
<tr>
<th>CCSM3 Feedback strengths (W/m\textsuperscript{2}/°C)</th>
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<tbody>
<tr>
<td>Model</td>
</tr>
<tr>
<td>T31</td>
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<tr>
<td>T42</td>
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<tr>
<td>T85</td>
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</tbody>
</table>

Adapted from Kiehl, et al, 2006
Results of Different Resolution Runs at 2xCO2

- Identical physics except for low-cloud and ice albedo feedbacks and resolution effects.
  - Highest-res (T85) run has 17% higher equilibrium climate sensitivity than lowest-res (T31) run.

- How long does it take to differentiate these results using measurements?
Observing System Simulation Experiments (OSSEs)

- Climate models integrations (e.g., CCSM3 & CESM) represent possible realizations of the climate system.
  - The physics, inputs, and outputs are completely known.
  - Realistic simulated measurements derived from the climate model (from MODTRAN [Berk et al, 1999]) can determine observational signals of underlying climate change and detectability.
SW Reflectance & LW Radiance Spectra

- Surface reflection, aerosols, (low) clouds and water vapor can be seen in SW spectra.
- Temperature, water vapor, trace gas profiles and (high) clouds can be seen in LW spectra.
- SW and LW spectra will change under climate change scenarios.
- The CLimate Radiance and Refractivity Observatory (CLARREO) is a proposed NASA mission that will make benchmark measurements with NIST-like calibration.

Pan-spectral globally-averaged all- and clear-sky spectra

Feldman et al, submitted
Radiation Cross-checks between CCSM & OSSE

Consistency check

CCSM IPCC AR4 Simulations

Consistency check

CCSM Instantaneous Fluxes

OSSE Fluxes and Reflectances

Same radiation scheme

Same condensate optics and surface BCs

- Checks ensure correct operation of radiative transfer calculations.
- Checks ensure that forcing and spectral signatures are consistent.
Consistent OSSE and Climate Model Fluxes

- Given substantial differences in radiative transfer between MODTRAN and CCSM, discrepancies are small and indicative of a well-performing instrument emulator.

\[ r^2 = 0.9998 \mu = -0.61\% \sigma = 0.93\% \]
Comparison with Modern Instrumentation

- Comparisons with data from SCIAMACHY indicate that the OSSE is capturing most of the natural variability in shortwave reflectance spectra.
Δ Clear-sky OLR

Broadband trends in OLRC are associated with water vapor and temperature. Increases in OLRC from surface and tropospheric temperature rise in arctic. Decreases in OLRC at tropics and subtropics from water vapor due to thermo.
Broadband trends are associated with water vapor, temperature, and UT clouds. Polar amplification blunted by clouds. Increases in water vapor offset by subtropical clouds. Dipole in OLR around ITCZ.
Δ Clear-sky broadband albedo

Broadband trends are associated with changes in snow, and sea ice and H$_2$O.
Little change in albedo at low latitudes.
Snow and ice changes are significant at poles.
Δ All-sky broadband albedo

Broadband trends are associated with changes in clouds, snow, and sea-ice.

Clouds offset loss of sea-ice in T31 run.
No significant increase in low-latitude clouds in T85 run.
Time Series Comparison Analysis

• We utilize the formulae from Weatherhead et al [1998] and described in Feldman et al [JGR, 2011b] to estimate the time required to differentiate two time series.
  • AR(1) noise process.
  • Linear secular trend derived from the difference of the two time series.
  • Trend and noise assumed to be stationary.
Formula for Change Detection

- The time required to say that one time-series differs from another requires estimates of:
  - Natural variability
  - Measurement uncertainty
  - Uncertainty in noise and trend estimation from a short time series.

\[
\begin{align*}
   n^* & \approx e^{\beta/\sqrt{M}} \\
   & \quad \left[ \frac{3.96 \sigma_c}{\omega_o (1 - \varphi)} \right]^{2/3} \\
   & \quad \left( 1 + \frac{\sigma_{meas}^2}{\sigma_w^2} \right)^{1/3}
\end{align*}
\]

- Detection time
- Scaling factor for length of record
- Std dev of noise process
- Measurement uncertainty
- Difference trend
- AR(1) of noise process
- Correlated natural variability
Model Differentiation with OLR and Albedo

Differences in arctic warming and atmospheric H₂O seen in clear-sky OLR and albedo. ITCZ and storm track movement seen in all-sky OLR and albedo.
Comparing Trends in Albedo and OLR

- For variable resolution runs, differentiation requires decades of continuous measurements because trends in broadband quantities are similar except in the arctic (α and OLR) and NH tropics (OLR).

1% per year CO₂ increase trend comparisons: Clear-sky OLR

1% per year CO₂ increase trend comparisons: Clear-sky albedo
Trends in All-sky Spectral Data

- Models with different cloud feedbacks produce different signals in
  - Window and H$_2$O overtone bands in SW.
  - Window bands and H$_2$O $\nu_3$ band in LW.
Model Differentiation with Pan-spectral (SW+LW) Data

- Colors indicate where spectral measurements differentiate models faster than broadband.
- Multi-decadal continuous records are required. No calibration drift allowed.
Low Clouds in CESM

- Climate sensitivity has increased from CAM3 to CESM.
  - Largely due to parameterizations related to low clouds.
- OSSE framework can be utilized to determine the observational signals from the different low-cloud feedback.

Using Data in Hand

• Existing, high-quality observational records from AIRS and SCIAMACHY should be analyzed and may provide observational constraints.
  – Long-term performance of these instruments needs to be considered.
• Use of multi-decadal records such as ISCCP should be handled with care.
• COSP results can also be used to understand if other existing instruments provide low-cloud observational constraints.
  – Evaluate the length of record required to (potentially) reject outliers.
  – Currently no hyperspectral simulator.
    • SW NIR H₂O bands, in particular, are not included.
OSSE Computational Expense: A Rate-Limiting Step

- OSSEs are computationally-expensive and are generally rate-limited by the radiative transfer calculations for instrument emulator
  - 100-year simulation of monthly-mean shortwave spectrally-resolved radiance spectra with cloud overlap at 1.4° x 1.4° requires 3.1 million CPU-hours.
  - Simulation of CMIP3 archive would require ~1 billion CPU-hours.
  - OSSEs with CMIP5 currently computationally infeasible.
- Look-up tables or novel hardware (perhaps GPUs) will be required to reduce the computational burden substantially.

Photo by Marco Librero, NASA Ames Research Center.
Discussion

- Observational simulations suggest which measurements can be used to differentiate climate models.
- Decades of continuous, calibration drift-free measurements are necessary to reject a version of CCSM3 based on (slightly) incorrect low-cloud feedbacks.
  - Larger differences (e.g., between CCSM3 and CESM) will be detectable with shorter records.
- Existing (long-term) measurement records should be considered as potential observational constraints.
- We have several TB of simulations for those who are interested.

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