Sensitivity of tropical water and energy cycle to SST increase and doubling CO$_2$ as simulated with an upgraded Multiscale Modeling Framework

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Objectives

- to improve the simulation of low-level clouds using a multiscale modeling framework (MMF) with a third-order turbulence closure in its CRM component
- to understand climate sensitivity and cloud response from this MMF
- to compare with studies using an MMF with a simple first-order turbulence closure

Cheng and Xu (2011; JGR); Xu and Cheng (2013a,b; J. Climate)
Cheng and Xu (2013a; J. Climate); Cheng and Xu (2013b; JGR)
Cheng and Xu (2014, JGR); Painemal et al. (2015; J. Climate)
Cheng and Xu (2015, J. Climate)
Outline

1. Why focus on low clouds?
2. Model description and simulation setup
3. Results from control and sensitivity simulations
4. Comparison with earlier studies
5. Summary and conclusions
Uncertainties in cloud feedback remain in GCMs

Soden and Vecchi (2011):

• Low cloud cover is responsible for ~3/4 of the difference in global-mean net cloud feedback among AR4 models, with the largest contributions associated with low-level subtropical marine cloud systems;

The low-cloud inconsistency and deficiency in most of the models.
SE Pacific Stratocumulus

Subtropical stratocumulus
4 September 2009 at 20:45 UTC

from Wood (2012; Mon. Wea. Rev.)
Processes associated with stratocumulus

Coupled boundary layer

Decoupled boundary layer

from Wood (2012; *Mon. Wea. Rev.*)
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IPHOC: Intermediately-prognostic higher-order turbulence closure for cloud-resolving model (CRM)

Advance 12 prognostic equations

\[ \bar{w}, \bar{q}_t, \bar{\theta}_l, \bar{w}^2, \bar{q}_t^2, \bar{\theta}_l^2, \bar{w}'q_t, \bar{w}'\theta_l, \bar{q}_t^3, \bar{\theta}_l^3 \]

Use PDF to close higher-order moments, buoyancy terms

\[ \bar{w}'q_t^2, \bar{w}'\theta_l^2, \bar{w}'q_t\theta_l, \bar{w}'\theta_l^3, \bar{w}'^2 q_t, \bar{w}'^2 \theta_l, \bar{w}'q_t^3, \bar{w}'\theta_l^3, \bar{w}'^4, \bar{w}'q_t^3, \bar{w}'\theta_l^3 \]

Select PDF from given family to match 12 moments

Diagnose cloud fraction, liquid water from PDF

Golaz et al. (2002); Cheng & Xu (2006, 2011)
The Multiscale Modeling Framework
(Grabowski 2001; Khairoutdinov and Randall 2001; Cheng & Xu 2011; Xu and Cheng 2013a)

- A CRM is embedded at each grid column (~100s km) of the host GCM to represent cloud physical processes
- The CRM explicitly simulates cloud-scale dynamics (~1s & km) and processes
- Periodic lateral boundary condition for CRM (not extended to the edges)

Upgraded CRM with a third-order turbulence closure (IPHOC):
- Double-Gaussian distribution of liquid-water potential temperature ($\theta_l$), total water mixing ratio ($q_t$) and vertical velocity ($w$), pdf = $a G_1 (w, q_t, \theta_l) + (1-a) G_2 (w, q_t, \theta_l)$
- Skewnesses, i.e., the three third-order moments, predicted
- All first-, second-, third- and fourth-order moments, subgrid-scale condensation and buoyancy based on the same PDF
- Advantages over CLU BB (Golaz et al.)
  1) two extra third-order moments
  2) Widths of two Gaussian unequal
  3) Merge to a single Gaussian if $sk = 0$
SPCAM-IPHOC climate simulations

- **SPCAM-IPHOC**
  - CAM3.5 with finite-volume dynamic core as the host GCM
  - 2-D version of System for Atmospheric Modeling (SAM) CRM with IPHOC
  - The CRM grid spacing is 4 km, with 32 columns, within a GCM grid box
  - The GCM grid spacing is 1.9°x2.5° with 32 vertical levels (12 below 700 hPa)

- **Control simulation**
  - Forced with climatological SST and sea ice distributions (not an AMIP-type simulation) with present-day CO$_2$ concentration
  - Simulation duration is 10 years and 3 months, with last nine years analyzed

- **Doubled CO$_2$ (2xCO$_2$) simulation**
  - Same as the control except that CO2 is doubled; SST and sea ice are fixed

- **+2 K SST (I2K) simulation**
  - Same as the control except that sea surface temperature is increased by 2 K
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Low-level (surface -- 700 hPa) cloud fraction (%) from 10-yr control simulation and changes in sensitivity simulations

More in cumulus regions in I2K; but stratocumulus regions in 2xCO₂
More in poleward of storm track in I2K, but equatorward in 2xCO₂
Longwave Cloud Radiative Forcing from 10-yr control simulation and changes in sensitivity simulations

Changes in LW CRE are larger in I2K (higher clouds due to higher SSTs); Storm tracks moves polarwards and stronger SPCZ in I2K
Increases at ITCZ and SPCZ (polarward movements) in I2K;
General small decreases in tropics and over lands in 2xCO$_2$
Shortwave Cloud Radiative Forcing from 10-yr control simulation and changes in sensitivity simulations

Changes in SW CRE reflect mostly the changes in low cloud fraction in both sensitivity simulations; some due to high clouds.
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Low-level (surface -- 700 hPa) cloud fraction (%) changes in sensitivity simulations (Bretherton et al. 2014)

Differences appear in cumulus regions in +SST simulations. There are large differences in CO₂ simulations everywhere.
Similar increases at ITCZ and SPCZ in +SST simulations; More increases over lands in 2xCO$_2$ than in 4xCO$_2$. 

Surface Precipitation Rate changes in sensitivity simulations (Bretherton et al., 2014)
Changes in the tropical land and ocean (30° N/S) from CO₂ sensitivity simulations

<table>
<thead>
<tr>
<th>Change</th>
<th>Value</th>
<th>Change</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔIWP</td>
<td>+5.0</td>
<td>ΔLWP</td>
<td>+2.8</td>
</tr>
<tr>
<td>ΔIWP</td>
<td>+4.8</td>
<td>ΔLWP</td>
<td>+1.8</td>
</tr>
<tr>
<td>ΔLWP + ΔIWP</td>
<td>+7.8</td>
<td>ΔLWP + ΔIWP</td>
<td>+6.6</td>
</tr>
</tbody>
</table>

Number in Green 2×CO₂ from SPCAM-IPHOC multiplied by 2
Red number from 4×CO₂ in Bretherton et al. (2014)

Deep convection is enhanced over land.

Δω₅₀₀ = hPa day⁻¹

ΔLWP + ΔIWP = g m⁻²

ΔCO₂ increases downward LW at land and ocean surface.

ΔIWP = 0.8 K
ΔLWP = 0.8 K

Land surface warms.
Summary and conclusions

- The low cloud fractions increase in the tropics/subtropics in both sensitivity simulations, but for different reasons.
  - Enhanced inversion strength due to free tropospheric warming from 2XCO$_2$;
  - Increased instability results in more shallow convection in +2K SST
- The polarward displacement of storm tracks results in large changes (+ve polarward and –ve equatorward) in cloud fraction and cloud radiative effects in +2K SST simulation
- Precipitation increases in +2K SST are pronounced, especially ITCZ and SPCZ, but almost no increases in the global mean of 2xCO$_2$ simulation, in which the local changes are dis-similar to those of +2K SST in most continents
- There are many similarities with the MMF without the higher-order turbulence closure, but there are some differences
  - shallow cumulus increase more over ocean
  - stronger convection over lands and weaker convection over ocean
  - stronger lower tropospheric moisture transport over land is the reason
Temperature differences at surface and 850 hPa between sensitivity and control simulations

Increased stability in the stratocumulus regions of 2xCO$_2$
But the cumulus regions in I2K do not show much change