Uncertainty in model climate sensitivity traced to representations of cumulus precipitation microphysics

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Recent GFDL GCMs produce a wide range of estimates of the ECS based on the CESS equilibrium climate sensitivity parameter. AM3, HIRAM, AM4-H show marked increase in climate sensitivity compared to AM2.

Estimate of equilibrium climate sensitivity parameter using the CESS EXP (unified 2K warming) yields:

\[ \lambda : \text{(Km}^2/\text{W}) \]

- AM2: 0.58
- AM3: 0.68
- HIRAM: 0.80
- AM4-H: 0.82

\( \Delta \): warming minus control
\( G \): change in net TOA radiative flux
Convective detrainment efficiency may be a key in affecting GCM simulated clouds and cloud feedback.

Convective detrainment efficiency (Zhao 2014, J. Climate)

\[ \kappa_c = \frac{C_c - P_c}{P_c} = \frac{1}{e_c} - 1, \quad e_c = \frac{P_c}{C_c}, \quad \kappa_c = f(\text{mixing, microphysics, ...}) \]

![Graph showing relationship between TCRE and Convective detrainment efficiency](image1)

![Graph showing changes in detrainment efficiency](image2)
Can we create a low sensitivity AM4 with minimum changes to model formulation?

AM3, HIRAM, AM4-H show marked increase in climate sensitivity compared to AM2.

The equilibrium climate sensitivity parameter based on the CESS EXP (unified 2K warming) yield

\[ \lambda: \text{(Km}^2/W) \]

AM2: 0.58
AM3: 0.68
HIRAM: 0.80
AM4-H: 0.82
AM4-M: 0.54
AM4-L: 0.48

\[ \Delta: \text{warming minus control} \]
\[ G: \text{change in net TOA radiative flux} \]

\[ \lambda: \text{climate sensitivity parameter} \]
\[ \text{TCRE: total cloud radiative forcing} \]
\[ G: \text{change in net TOA radiative flux} \]

Cloud feedback parameter
Modifications in convective precipitation treatment

AM4-H uses modified UW convection scheme (Bretherton et. al 20014)

- Threshold removal in AM4-H: *(Emanuel & Zivkovic-Rothman 1999)*

\[
P = M_c \max(q_c - q_{c0}, 0), \quad q_{c0} = \begin{cases} 
q_0 & T \geq 0^\circ C \\
q_0 \left(1 - \frac{T}{T_{\text{crit}}} \right) & T_{\text{crit}} < T < 0^\circ C \\
0 & T \leq T_{\text{crit}}
\end{cases}
\]

- Fractional removal in AM4-M, AM4-L:

\[
P = M_c (\beta \Delta p) \max(q_c - q_{c0}, 0), \quad \beta(T) = \begin{cases} 
\beta_i, & q_{c0} = q_0, \quad T \geq -5^\circ C \\
\beta_i + \frac{-5-T}{-5+25} (\beta_i - \beta_i), & q_{c0} = 0, \quad -25^\circ C < T < -5^\circ C \\
\beta_i, & q_{c0} = 0, \quad T \leq -25^\circ C
\end{cases}
\]

\[
\beta_{\text{deep}} = \alpha \beta_{\text{shallow}}
\]

- Fractional removal in AM2 RAS: *(GFDL GAMDT 2004)*

\[
P = M_c \beta q_c, \quad \beta(p_T) = \begin{cases} 
0.975, & p_T \leq 500\text{hPa} \\
0.5 + \frac{800 - p_T}{800 - 500} (0.975 - 0.5), & 800\text{hPa} < p_T < 500\text{hPa} \\
0.5, & p_T \geq 800\text{hPa}
\end{cases}
\]

**Parameters**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>H</th>
<th>M</th>
<th>L</th>
</tr>
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<tbody>
<tr>
<td>(q_0) (g/kg)</td>
<td>1.5</td>
<td>0.8</td>
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<tr>
<td>(T_{\text{crit}}) (°C)</td>
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<td>N/A</td>
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<tr>
<td>(\beta_i) (Pa⁻¹)</td>
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<td>4.0e-5</td>
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<tr>
<td>(\alpha)</td>
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<td>4</td>
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</table>

\(p_T\): unit in Pa; \(c\text{crit}\), \(c\text{shallow}\), \(c\text{deep}\)
Comparison of simulated LW and SW cloud radiative effect with the CMIP5 ensemble and the CERES observational estimate

Red: AM4-H
Blue: AM4-M
Green: AM4-L
black: CMIP5 mean
light shading: CMIP5 1-std
dashed: CERES
dark shading: CMIP5 min/max
Comparison of the normalized RMSE of selected fields with CMIP5 ensemble (CREs: CRERES; PCP: GPCPv2; SAT, SLP, TAUX: ERA-INTERIM)

Red: AM4-H boxplot: CMIP ensemble
Blue: AM4-M red line: median; blue edge: 25th and 75th
Green: AM4-L whiskers: CMIP5 min/max

AM4- M&L produce large reductions in total CRE, which may be explained by changes in convective detrainment efficiency.
Changes in total CRE are dominated by tropical SW CRE.
Changes in cloud responses are dominated by tropical low+middle cloud fraction and liquid+ice water path.

Percentage changes in cloud water and cloud fraction (%)/K.

- Blue: Liquid water path
- Cyan: Ice water path
- Yellow: low+middle cloud fraction
- Red: high cloud fraction

Global mean vs. Tropical mean.
Latitudinal distribution of changes in SW CRE
(changes in AM4-M & AM4-L are more like AM2 than AM4-H)

Changes in annual mean SW CRE (area weighted at each latitude)
Latitudinal distribution of changes in IWP+IWP
(changes in AM4-M & AM4-L are more like AM2 than AM4-H)

Changes in liquid+ice water path (area weighted at each latitude)

Red: AM4-H
Green: AM4-M
Blue: AM4-L
Black: AM2
Latitudinal distribution of changes in low+mid cloud fraction
(changes in AM4-M & AM4-L are more like AM2 than AM4-H)

Changes in low+middle cloud fraction (area weighted at each latitude)

Δ low+middle cloud fraction (%/K)

latitude

Red: AM4-H
Green: AM4-M
Blue: AM4-L
Black: AM2
Changes in total CRE partitioned into different large-scale regimes characterized by $\omega_{500}$

- Red: AM4-H
- Green: AM4-M
- Blue: AM4-L
Changes in tropical low+middle cloud fraction and LWP+IWP partitioned into different large-scale regimes characterized by $\omega_{500}$

Red: AM4-H
Green: AM4-M
Blue: AM4-L
Changes in convective detrainment efficiency partitioned into different large-scale regimes characterized by $\omega_{500}$
Cloud feedback and climate sensitivity can be strongly affected by model parameterization of convective precipitation. The effect comes through both ascent and decent regions, and may be understood through bulk convective detrainment efficiency.

Compared to the threshold remover scheme in AM4-H, the fractional remover and associated treatment in mixed and ice-phase clouds in AM4 M&L tend to produce much reduced positive (or negative) cloud feedback.

Given the uncertainty in parameterizing convective precipitation microphysics, the result suggests that one can engineer climate sensitivity. Explicitly constructed low & high sensitivity models may be useful for studying historical climate variability and future projections.
End
Changes in convective detrainment partitioned into different large-scale regimes characterized by $\omega_{500}$