Causes of Higher Climate Sensitivity in CMIP6 Models

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Causes of Higher Climate Sensitivity in CMIP6 Models

Mark D. Zelinka¹, Timothy A. Myers¹, Daniel T. McCoy², Stephen Po-Chedley¹, Peter M. Caldwell¹, Paulo Ceppi³, Stephen A. Klein¹, and Karl E. Taylor¹

¹Lawrence Livermore National Laboratory, Livermore, CA, USA, ²Institute of Climate and Atmospheric Sciences, University of Leeds, Leeds, UK, ³Grantham Institute, Imperial College London, London, UK

Key Points:
- Climate sensitivity is larger on average in CMIP6 than in CMIP5 due mostly to a stronger positive low cloud feedback
- This is due to greater reductions in

\[
\begin{align*}
N=27 & \quad \text{Nov 2019} \\
N=40 & \quad \text{June 2020}
\end{align*}
\]
Equilibrium Climate Sensitivity

What is it?
• The equilibrated global surface temperature change in response to a doubling of atmospheric CO$_2$

Why do I care?
• Highly relevant to future climate warming (Grose et al., 2018)
• Crucial for determining CO$_2$ stabilization targets to avoid crossing dangerous global temperature thresholds (Rogelj et al., 2014)
• Encapsulates substantial information about the climate system and how it responds to perturbations.

How do we quantify it?
• Paleoclimate
• Instrumental record
• Global climate models
Radiative Forcing

\[ R = F + \lambda T \]

Global Mean T_{sfc} Anomaly

Incoming Net Radiation \((R)\)

Radiative Feedback

ECS is the equilibrium \((R=0)\) response of \(T\) to the radiative forcing from a doubling of CO\(_2\) \((F_{2x})\):

\[ ECS = -\frac{F_{2x}}{\lambda} \]

Can diagnose \(F_{2x}, \lambda,\) and \(ECS\) by scatter plotting \(R\) against \(T\) in abrupt CO\(_2\) quadrupling experiments, following Gregory et al. (2004)
Forcing, Feedback, Sensitivity

\[ R = F + \lambda T \]

\[ ECS = -F_{2x}/\lambda \]

To aid understanding, it is helpful to break \( \lambda \) down into components...

\( F_{2x} = 2xCO_2 \) radiative forcing \( \approx 3.7 \text{ W/m}^2 \)

\( ECS \) = effective climate sensitivity \( \approx 5.6 \text{ K} \)
Forcing, Feedback, Sensitivity

\[ R = F + \lambda T \]

Planck: A warmer planet emits more LW radiation to space (negative)

Surface Albedo: A warmer planet has less snow and ice; absorbs more SW radiation (positive)

Water Vapor: A warmer atmosphere is more moist (assuming RH unchanged); larger greenhouse effect (positive)

Clouds: ??
Why are we comparing CMIP5 and CMIP6 ECS?

• As models continuously get developed and refined (improved?), it is important to assess whether their climate sensitivities have changed, perhaps giving a more accurate view of Earth’s future climate.

• The notion that ECS increased in CMIP6 got a lot of press as early models came into the archive. We wanted to know whether this was actually statistically significant.

• IPCC AR6 needs this information
ECS, Forcings, & Feedbacks Diagnosis

• Data from abrupt CO₂ quadrupling experiments conducted by GCMs as part of the Coupled Model Intercomparison Project phases 5 & 6 (CMIP5/6)
  • Anomalies are with respect to coincident pre-industrial control simulations

• Regress TOA radiation anomalies on $T_{sfc}$ anomalies from all 150 yrs of the abrupt-4xCO₂ simulations [Gregory et al. 2004]
  • Regression slope = radiative feedback parameter ($\lambda$)
  • Y-intercept/2 = 2xCO₂ Effective Radiative Forcing (ERF$_{2x}$)
  • X-intercept/2 = Effective Climate Sensitivity (ECS)

• Decompose $\lambda$ into individual feedback components using radiative kernels
  • Kernels quantify the impact of $\Delta T$, $\Delta q$, $\Delta$albedo on TOA radiation
  • All kernels give consistent results; Huang et al [2017]'s yield smallest residuals
  • We report constant RH feedbacks [Held & Shell 2012]
**ECS, Forcings, & Feedbacks**

**CMIP5 vs CMIP6**

Mean ECS: 3.3 → 3.8

ECS > 4.5 in 14 models

Current: 40 models from 22 centers
Expected: 102 models from 35 centers
ECS, Forcings, & Feedbacks
CMIP5 vs CMIP6

Mean ECS: 3.3 → 3.8
ECS > 4.5 in 14 models

Means are deemed significantly different if the 2-tailed p value of the Welch's t-test for equal means is less than 0.05.

Variances are deemed significantly different if the p value of Bartlett's test for equal variances is less than 0.05.

Current: 40 models from 22 centers
Expected: 102 models from 35 centers
ECS, Forcings, & Feedbacks
CMIP5 vs CMIP6

Mean ECS: 3.3 → 3.8
ECS > 4.5 in 14 models
Highest & lowest ECS values come from unique forcing-feedback combos

\[ ECS = -\frac{ERF_{2x}}{\lambda} \]

Weak radiative damping

Strong

See also Andrews et al., JAMES (2019)
CESM2 & E3SM are among the models w/ highest ECS

**Equation:** $\text{ECS} = -\text{ERF}_{2x}/\lambda$

- Weak radiative forcing
- Strong radiative forcing

---

[Graph showing scatter plot of Net Feedback vs. ERF$_{2x}$ with model markers and lines for different ECS values (2K, 3K, 4K, 5K, 6K).]
What is the relative importance of \( \Delta \text{Forcing}, \Delta \text{Feedback}, \& \Delta \text{Covariance} \) in Causing Higher ECS in CMIP6?

\[
\text{ECS} = - \frac{\text{ERF}_{2x}}{\lambda}
\]

Weak ----------- radiative forcing ----------- Strong
What is the relative importance of $\Delta$Forcing, $\Delta$Feedback, & $\Delta$Covariance in Causing Higher ECS in CMIP6?

$$\text{ECS} = -\frac{\text{ERF}_{2x}}{\lambda}$$

Weak ---------- radiative forcing ---------- Strong
Hereafter we focus on the red portion, which is entirely due to more positive cloud feedback.
Summary so far

• The mean and inter-model spread in ECS has increased markedly in CMIP6.
  • Neither of these changes are statistically significant at 95% confidence
  • ECS $> 4.5^\circ$C in 14 of 40 CMIP6 models, including E3SM and all CESM2 variants

• Highest ECS values arise from strong positive feedbacks + moderate forcing.

• Increase in mean ECS in CMIP6 is attributable to…
  …stronger forcing (19%)
  …stronger positive feedbacks (52%), and
  …“steeper” anti-correlation between forcing and feedback (29%)

So why has the [cloud] feedback increased in CMIP6?
Why has the cloud feedback increased in CMIP6?

We use two methods in concert to detail the cloud feedback:

- *Webb et al (2006)* technique to separate feedback into contributions from low and non-low clouds

- APRP method of *Taylor et al (2007)* to separate SW cloud feedback into contributions from cloud amount & scattering
Cloud Feedbacks
CMIP5 vs CMIP6

5→6: Greater low cloud amount reductions
5→6: Low cloud albedo decreases rather than increases
Cloud Feedbacks

CMIP5 vs CMIP6

CMIP6 mean SW low cloud amount and scattering feedbacks (and their sum) are substantially more positive at middle-high latitudes.

Latitudes where at least 80% of the models agree on the sign of the feedback are plotted with a solid line. Multi-model mean differences are shown in black lines, which are solid where differences are significant.
Cloud Feedbacks

CMIP5 vs CMIP6
Cloud Feedbacks
CMIP5 vs CMIP6

Global- or Regional-Mean Cloud Feedbacks

- CESM2
- CESM2-FV2
- CESM2-WACC
- CESM2-WACC-FV2
- E3SM-1-0

W m$^{-2}$ K$^{-1}$

Net Non-low  |  Net Low  |  SW Low  |  SW Low Amount  |  SW Low Scattering
Cloud Feedbacks
CMIP5 vs CMIP6
+Individual CMIP6 models
Cloud Feedbacks  
CMIP5 vs CMIP6  
+Individual CMIP6 models

CESM2* among the models with largest SH low cloud feedbacks, especially in the extratropics
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- Stronger positive feedback in CMIP6 is due to stronger decreases in low cloud coverage and albedo in the extratropics.

So why has the extratropical cloud feedback increased in CMIP6?
Why has the extratropical low cloud scattering feedback increased in CMIP6?

Models with larger positive SW low cloud scattering feedbacks have larger decreases in LWP$_{\text{low}}$

So let’s perform cloud controlling factor analysis on LWP$_{\text{low}}$ over the SH oceans (30-60°S)
Cloud-Controlling Factor Analysis

\[
\frac{dLWP_{\text{low}}}{dT_g} = \sum_i \frac{\partial LWP_{\text{low}}}{\partial x_i} \frac{dx_i}{dT_g}
\]

\(x_i \in \{\text{SST, inversion strength, advection, etc.}\}\)

Low-latitude studies
Qu et al. (2014, 2015)
Zhai et al. (2015)
Zhou et al. (2015)
Myers & Norris (2016)
Brient & Schneider (2016)
McCoy et al. (2017)
And reviewed by Klein et al. (2017)

Extra-tropical studies
Gordon and Klein (2014)
Terai et al. (2016)
Ceppi et al. (2016)
Grise & Medeiros (2016)
Zelinka et al. (2018)
Miyamoto et al. (2018)
Kelleher & Grise (2019)
Why has extratropical low cloud scattering feedback increased in CMIP6?

In CMIP6, the LWP\textsubscript{low} increase with SST in the piControl climate is much weaker.

Basically the same story for low cloud cover (& amount feedback)
Why has extratropical low cloud scattering feedback increased in CMIP6?

In CMIP6, the LWP\textsubscript{low} increase with SST in the piControl climate is much weaker.

This overwhelms the slightly larger SST increase…

Basically the same story for low cloud cover (& amount feedback)
Why has extratropical low cloud scattering feedback increased in CMIP6?

In CMIP6, the $LWP_{\text{low}}$ increase with SST in the piControl climate is much weaker.

This overwhelms the slightly larger SST increase…

…causing markedly weaker SST-driven increases in $LWP_{\text{low}}$.

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In CMIP6, the LWP\textsubscript{low} increase with SST in the piControl climate is much weaker.

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...causing markedly weaker SST-driven increases in LWP\textsubscript{low}.

The multi-linear regression model predicts that \(\Delta\text{LWP}_{\text{low}}\) changes sign from positive in CMIP5 to negative in CMIP6.

Basically the same story for low cloud cover (& amount feedback)
Why has extratropical low cloud scattering feedback increased in CMIP6?

In CMIP6, the $LWP_{\text{low}}$ increase with SST in the piControl climate is much weaker.

This overwhelms the slightly larger SST increase…

…causing markedly weaker SST-driven increases in $LWP_{\text{low}}$.

The multi-linear regression model correctly predicts that $\Delta LWP_{\text{low}}$ changes sign from positive in CMIP5 to negative in CMIP6.

It also predicts $LWP_{\text{low}}$ changes that are significantly correlated with actual model-produced values.

Basically the same story for low cloud cover (& amount feedback)
Cloud phase as a potential root cause of increased extratropical cloud feedbacks

Models with larger mean-state liquid condensate fraction (LCF) have been shown to experience weaker LWP increases with warming (McCoy et al., 2015).

CAM5 modified to produce higher mean-state LCF have more positive extratropical scattering (Tan et al. 2016) and amount (Frey and Kay, 2017) feedbacks.

Increased mean-state LCF is implicated in causing increased cloud feedback in HadGEM2 (Bodas-Salcedo et al., 2019) and CESM2 (Gettelman et al., 2019).
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CMIP6 models have higher LCF on average.
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CMIP6 models have higher LCF on average.
CESM2 & E3SM among the supercool kids ...may have overshot
Cloud phase as a potential root cause of increased extratropical cloud feedbacks

\[ \Delta \text{LWP}_{\text{low}} [30-60^\circ S] \]

Less mean-state supercooled liquid, larger increase in LWP with warming.

More mean-state supercooled liquid, larger decrease in LWP with warming.
Conclusions

• The mean and inter-model spread in ECS has increased markedly in CMIP6.
  • Neither of these changes are statistically significant at 95% confidence
  • ECS > 4.5°C in 14 of 40 CMIP6 models, including E3SM and all CESM2 variants

• Highest ECS values arise from strong positive feedbacks + moderate forcing.

• Increase in mean ECS in CMIP6 is attributable to…
  …stronger forcing (19%)
  …stronger positive feedbacks (52%), and
  …“steeper” anti-correlation between forcing and feedback (29%)

• Stronger positive feedback in CMIP6 is due to stronger decreases in low cloud coverage and albedo in the extratropics.
  • Both of these changes are tied to models' physical representation of clouds, with CMIP6 models showing weaker increases in extratropical low cloud cover and water content with SST.
  • Could be related to increased mean-state supercooled liquid fraction in CMIP6.
  • E3SM and CESM2: lots of supercooled liquid & big extratropical cloud feedbacks
Implications

- Global non-low cloud feedbacks are uniformly positive.
- Tropical low cloud feedbacks are uniformly positive.
- Extratropical low cloud scattering feedback has shifted to more positive values, possibly related to improved cloud phase.

All of these are qualitatively consistent with GCMs achieving a better match with theory, observations, and/or high-res modeling. So is ECS higher than we previously thought?
Implications

✓ Global non-low cloud feedbacks are uniformly positive.
✓ Tropical low cloud feedbacks are uniformly positive.
✓ Extratropical low cloud scattering feedback has shifted to more positive values, possibly related to improved cloud phase.

*All of these are qualitatively consistent with GCMs achieving a better match with theory, observations, and/or high-res modeling.*

*So is ECS higher than we previously thought?*

Not necessarily.

1) We need to determine whether models’ individual cloud feedbacks quantitatively agree with other constraints.
2) Moreover, any model-based inference that ECS is high needs to be evaluated alongside independent evidence [paleo, historical record].
https://github.com/mzelinka/cmip56_forcing_feedback_ecs
or just google “Mark Zelinka github”

Summary

Two tables and a JSON file are provided containing effective climate sensitivity, effective 2xCO₂ radiative forcing, and radiative feedbacks for all CMIP5 and CMIP6 models that have published output from abrupt CO₂ quadrupling experiments. Also provided is a figure showing Gregory plots for the CMIP6 models. Methodology is described in Zelinka et al. (2020), but the CMIP6 results are regularly updated as new models are published.

Table Contents

For each model, the following global mean values are provided:

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECS</td>
<td>effective climate sensitivity</td>
<td>K</td>
</tr>
<tr>
<td>ERF2x</td>
<td>2xCO₂ effective radiative forcing</td>
<td>Wm⁻²</td>
</tr>
</tbody>
</table>
Conclusions

• Average ECS has increased by 0.5°C in CMIP6; values > 4.5°C in 14 of 40 models.
  - Neither the increase in multi-model mean, nor the increase in inter-model spread is statistically significant at 95% confidence

• Highest ECS values arise from weak radiative damping + moderately strong forcing.

• Increase in mean ECS in CMIP6 is attributable to…
  …stronger forcing (19%)
  …stronger positive feedbacks (52%), and
  …“steeper” anti-correlation between forcing and feedback (29%)

• Stronger positive feedback in CMIP6 is due to stronger decreases in low cloud coverage and albedo in the extratropics.
  - Both of these changes are tied to models' physical representation of clouds, with CMIP6 models showing weaker increases in extratropical low cloud cover and water content with SST.
  - Could be related to increased mean-state supercooled liquid fraction in CMIP6.
Extras
Note, these are for 4xCO2, so ECS and F are ½ of the intercepts
Evolution of CMIP6 mean ECS

Dates are roughly when enough complete data were present @PCMDI for a model to be included in my analysis
High confidence in **positive** feedback from high clouds rising with warming.

- **Observational** support from tropical inter-annual variability
- **Fine-scale model** support from simulations of tropical radiative convective equilibrium
- **Theory**: High cloud tops rise as a consequence of radiative-convective equilibrium, as articulated in the fixed anvil temperature (FAT) hypothesis [Hartmann & Larson, 2002].
Observations and high-resolution modeling agree that tropical low cloud feedbacks should be positive.

Cloud controlling factor predictions from observations:

Large Eddy Simulations:

Global Climate Models:

Tropical Low Cloud Feedback [W/m²/K]

Qu et al. (2015)
Zhai et al. (2015)
Myers & Norris (2016)
Brient & Schneider (2016)
McCoy et al. (2017)

Modified from Klein et al., Surv. Geophys. [2017]
Models lack sufficient super-cooled liquid. Eliminating this bias increases ECS.

- Observational analyses indicate that models exaggerate extratropical clouds brightening with warming.
- Part of this is likely related to a too-strong ‘phase feedback’ from ice transitioning to liquid.
- Increasing the present-day amount of super-cooled liquid in accord with Calipso observations increases climate sensitivity markedly in CAM5 (Tan et al. 2016; Frey & Kay 2017).
- Multi-model analysis supports this view (McCoy et al. 2016).
Cloud-Controlling Factor Analysis: An example w/ cloud optical depth

**Punchline**: current-climate sensitivities are highly relevant for long-term response...so observations of the former can help constrain the latter.
Simulations by Xue Zheng (LLNL) loosely following Kay et al (2016)