Distribution of equilibrium climate sensitivity and transient climate response found in the latest climate model ensemble

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Studies on mitigation pathways

Complex multi-model ensemble and other evidence
CMIP provides fundamental resources

Climate model emulator
providing probabilistic climate projections

Mitigation pathways
assessed for consistency with a given temperature goal

CMIP5, C4MIP
↓
CMIP6

MAGICC6
↓
MAGICC6, FaIR-1.3 for non-CO₂ forcing

RCMIP (?)

AR5DB
↓
SR15DB
↓
AR6DB

updates on forcing and sensitivity
adapted through openscm
Research objectives

– diagnose forcing-response properties of CMIP6 models in idealized CO₂ scenarios
  • abrupt quadrupling of concentration (step forcing)
  • 1%/y increase of concentration (ramp forcing)

– compare CMIP6 and CMIP5 focusing on climate sensitivity
  • equilibrium climate sensitivity (ECS)
  • transient climate response (TCR)

– consider revising the methodology of probabilistic climate projections considering assessed likely range of key metrics
Method — Impulse Response Model (IRM)

\[ T_k(t) = \int_0^t \frac{F(t')}{\lambda} \sum_i \frac{A_{ki}}{\tau_i} \exp \left( -\frac{t - t'}{\tau_i} \right) \, dt' \]

\[ \sum_i A_{ki} = 1 \quad (k = S, 1, \ldots; i = 0, 1, \ldots) \]

\( \lambda \): climate feedback parameter
\( A_{ki}, \tau_i \): three normalized amplitudes and time constants
= six independent parameters

converted from a 3-box model for Earth’s energy balance including explicit ocean heat uptake

\[ T_s, T_1, T_2: \text{Temp. anomaly} \]
\( \lambda, \lambda_1, \lambda_2: \text{Exchange coeff.} \]
\( C_s, C_1, C_2: \text{Heat capacity} \)
Characteristics of IRM method

- simplicity and accuracy
  - easy to be handled for calibration and probabilistic analyses
  - two exponentials are usually sufficient, three are better for volcanic forcing and CDR scenarios

- transparency and consistency
  - calibrated parameters provide a general quantity of transient temperature response, from which TCR is derived as a realized warming fraction
  - tool for both emulating and diagnosing complex models, ensuring methodological consistency
Calibration and diagnosing sensitivity

Use **timeseries fitting for N and T_s** from 4x and 1%/y experiments, instead of the conventional N-T_s regression for 4x experiment.

Effective radiative forcing of CO₂ considers **logarithmic proportionality** with a factor of \( \alpha \) and **amplification** from first doubling to second doubling with a factor of \( \beta \).

Up to doubling:

\[
F_x = \alpha \ln(x)
\]

Greater levels:

\[
\tilde{F}_x = \beta F_x + (\beta - 1)(F_x - 2F_2) \left( \frac{2F_x}{F_2} - 1 \right)
\]
Emulation for 25 CMIP5 models

Panels share a common vertical range
Emulation for 22 CMIP6 models as of mid October

The vertical range is the same as in the previous page.
Multi-model distribution of TCR and ECS

CMIP6 inter-model variation is still large

CMIP6 models spread toward higher sensitivities than CMIP5 models

TCR-to-ECS ratio (realized warming fraction) is smaller in high-sensitivity models

WGCM, representing the CMIP6 community, is leading a paper to better understand ECS from the CMIP6 models
## Ensemble-mean changes

<table>
<thead>
<tr>
<th></th>
<th>CMIP5</th>
<th>CMIP6</th>
<th>%-change</th>
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</thead>
<tbody>
<tr>
<td><strong>ECS</strong></td>
<td>3.10 K</td>
<td>3.65 K</td>
<td>18%</td>
</tr>
<tr>
<td></td>
<td>(3.29 K)</td>
<td>(3.99 K)</td>
<td>(21%)</td>
</tr>
<tr>
<td><strong>TCR</strong></td>
<td>1.85 K</td>
<td>2.09 K</td>
<td>13%</td>
</tr>
</tbody>
</table>

Numbers in parentheses are conventional ECS estimates, i.e., halved equilibrium response to 4x CO₂

- The numbers are subject to **data availability**, including potential biases due to "**ensemble of opportunity**", and should be examined with advanced weighting and constrain approaches.

- The **relatively smaller change in TCR** is robust and resulted from the tendency of the realized warming fraction (RWF), consistent with the relationship between feedback strength and response timescale.
Decomposition of sensitivity variation

Fractional variation $\equiv \frac{\delta \alpha}{\alpha} + \frac{\delta \beta}{\beta} + \frac{\delta (1/\lambda)}{(1/\lambda)} + \frac{\delta \text{RWF}_{2x}}{\text{RWF}_{2x}}$

$\alpha$: forcing scale, $\beta$: forcing amplification, $1/\lambda$: feedback strength, RWF: ocean heat uptake

$\lambda$ is further decomposed into individual feedback terms (out of scope in this study)

Dependency on decomposes terms:

<table>
<thead>
<tr>
<th>Term</th>
<th>Terms</th>
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<tbody>
<tr>
<td>ECS</td>
<td>$\alpha, 1/\lambda$</td>
</tr>
<tr>
<td>ECS*</td>
<td>$\alpha, \beta, 1/\lambda$</td>
</tr>
<tr>
<td>TCR</td>
<td>$\alpha, 1/\lambda, \text{RWF}$</td>
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</table>

ECS*: conventional estimation
Multi-model distributions of TCR-relevant parameters

1. Feedback strength \((1/\lambda)\) is the most dominant term
2. Its increase is somewhat compensated by RWF decrease
3. The negative correlation comes from the longest timescale \((A_2)\) variability

consistent with the theoretical relationship between the feedback strength and response timescales
How we consider CMIP6 in mitigation studies

– Climate sensitivity is not assessed from modelling study alone
  • AR6 authors will consider many lines of evidence

– New models generally incorporates new physical insights using new schemes for prognostic clouds and aerosol processes
  • which may lead to an upward revision of assessed climate sensitivity
Calibration to be consistent with assessed key metrics

Example: calibration to TCRE at 50% and 33–67% based on AR5 likely range

DEFAULT and PROB-33rd/67th are calibrated so that instantaneous TCRE at about 1200 GtC in 1pctCO2 is 1.65 K and 1.28/2.02 K based on percent points of a normal distribution for the AR5 likely range of 0.8 to 2.5 K

3 calibs selected based on PC analysis for 8 params
Conclusions

– Complex climate models can be emulated and characterized with sufficient accuracy and transparency by a reduced form of forcing-response representations
  • The present method has six and two parameters for thermal response and CO₂ forcing
  • balanced with simplicity and accuracy
– Although CMIP6 models show higher sensitivity than the CMIP5 models, realized warming (TCR) is not much different compared with estimated equilibrium response (ECS)
– Emulators can be adjusted to be consistent with assessed key metrics and the multi-model variation of forcing-response properties