CONSTRAINING CLIMATE SENSITIVITY:
TRANSIENT CLIMATE RESPONSE (TCR) AND EQUILIBRIUM CLIMATE SENSITIVITY (ECS)

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CMIP6 ensemble historical simulations.

Radiative forcing: \( N = F + \lambda T \).

- \( F \): Radiative forcing
- \( N \): Top of the atmosphere radiative imbalance
- \( T \): Temperature anomaly
- \( \lambda \): Climate feedback parameter

The model GHG signal was extremely weak compared to variance between 1960-1970 due to aerosols.
Temperature evolution

(a) Entire period: no clear pattern between warming and TCR
(b) Identified period: beautiful simplicity

Emergent constraint (EC)
- Observational error includes estimate of internal variability
- CMIP6 more variable.
- TCR: 1.68 [5-95%, 1.02 - 2.10]

Emergent constraint:
Each dot represents one model. Total of 24 CMIP6 models.

Internal variability explicit in observation. Estimated using model internal variability.

Extended to 2019 using SSP2-4.5
Emergent constraint on ECS: theory

<table>
<thead>
<tr>
<th>Approximation</th>
<th>Valid when</th>
<th>Equations</th>
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<tbody>
<tr>
<td>Full equations</td>
<td></td>
<td>( C \frac{dT}{dt} = - \lambda T + Q - \varepsilon \gamma (T - T_0) )</td>
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<td></td>
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<td>( C_0 \frac{dT_0}{dt} = \gamma (T - T_0) )</td>
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<tr>
<td>No deep ocean warming</td>
<td>&lt; century</td>
<td>Algebra</td>
</tr>
<tr>
<td>Upper ocean equilibrium</td>
<td>&gt; decade</td>
<td>Algebra</td>
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\( s' \): percentage doubling CO\(_2\)  
\( e' \): ocean heat uptake

\[ \text{ECS} = \frac{\Delta T}{(s' - e' \Delta T)} \]

TCR vs ECS

If emergent relationship steep: difficult to constraint ECS using observations

Behaviour parameters

Similar lines; but not possible to estimate parameters accurately:

- **CMIP5:**  
  - $e'$: 0.233  
  - $s'$: 0.420

- **CMIP6:**  
  - $e'$: 0.138  
  - $s'$: 0.315

**Model parameters:**

- **CMIP6:**  
  - $e'$: 0.240  
  - $s'$: 0.200

The emergent constraint:

- Final ECS CMIP5 weaker than CMIP6.
- Consistent upper bound
- ECS: 2.62 K  
  - [5-95%, 1.51 - 4.04]

Double check theory

- If theory perfect, all points would be on 1:1 line.

Comparing two two-layer models; with and without ocean heat uptake efficacy.

Checking with respect to theory.

1. Taking model DT
2. Fitted the ocean and forcing parameter per model.
3. Put in equation and compare real ECS
Very unlikely that ECS > 4.5 K and TCR > 2.5 K.

ECS can possibly be further restricted using ocean heat uptake, but theory may need refinement.

Emerging consensus on ECS (Cox et al. (2018), Goodwin (2016), Renault (2020))?

... and TCR (Jiménez-de-la-Cuesta (2019) and Tokarska (2020))?