Constant equilibrium climate sensitivity (ECS) across a wide range of climates in extra-long CESM simulations

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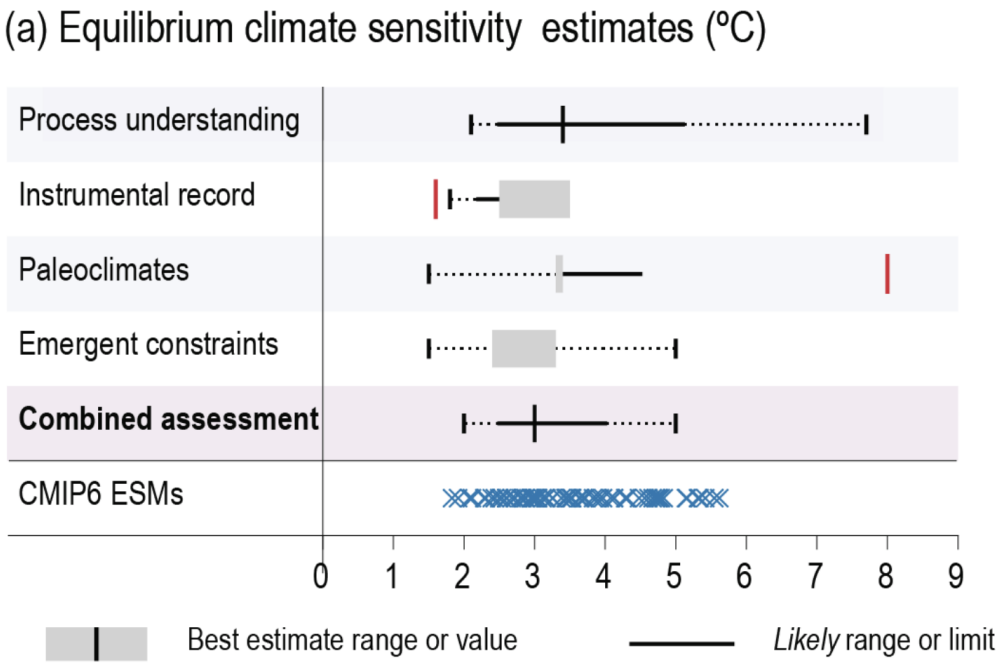
How High (or Low) is ECS?

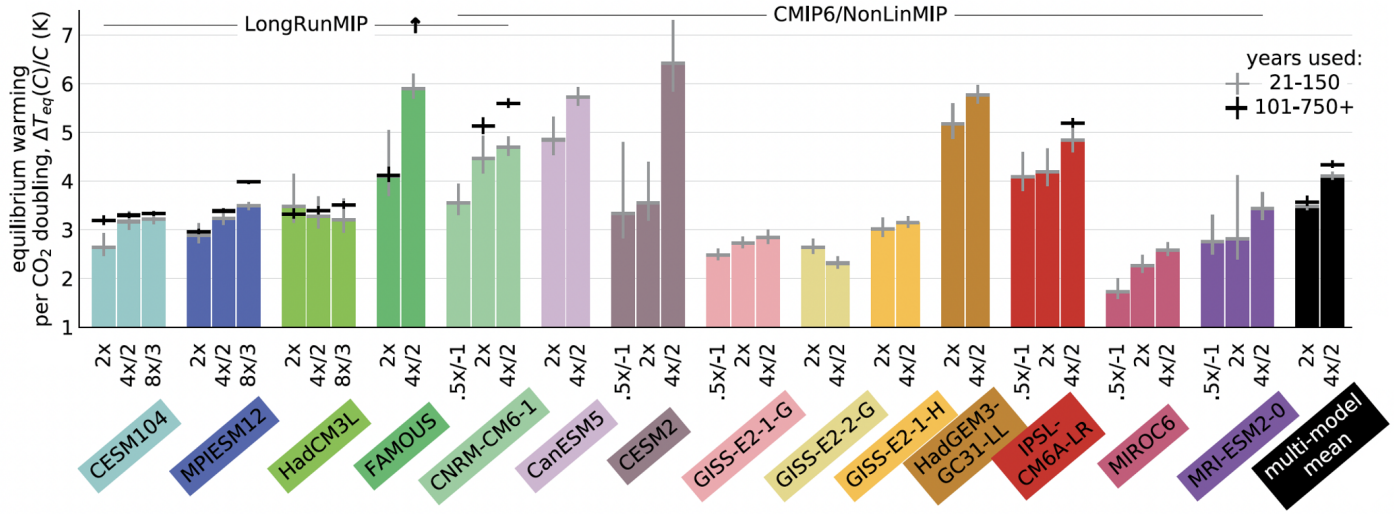
- **ECS**: The global mean temperature change (ΔT_{eq}) once the climate has equilibrated to a doubling in atmospheric CO_2 concentrations ($\mathcal{C}$).
- **IPCC AR6 2021:** *likely* 2.5°C $\leq$ ECS $\leq$ 4°C (below).
- **Sherwood *et al.* 2020:** 66% likelihood 2.6°C $\leq$ ECS $\leq$ 3.9°C.



- **One major uncertainty:** Lack of GCM simulations run towards equilibrium.

Obtaining ECS From Climate Models

- Only a handful of studies perform abrupt $n\times CO_2$ GCM experiments run towards equilibrium to get $\Delta T_{eq}/\mathcal{C}$.
- LongRunMIP simulations (below) suggest $\Delta T_{eq}/\mathcal{C}$ increases for larger instantaneous CO_2 increases.



- Are we running models for long enough?

CESM1 Experiments

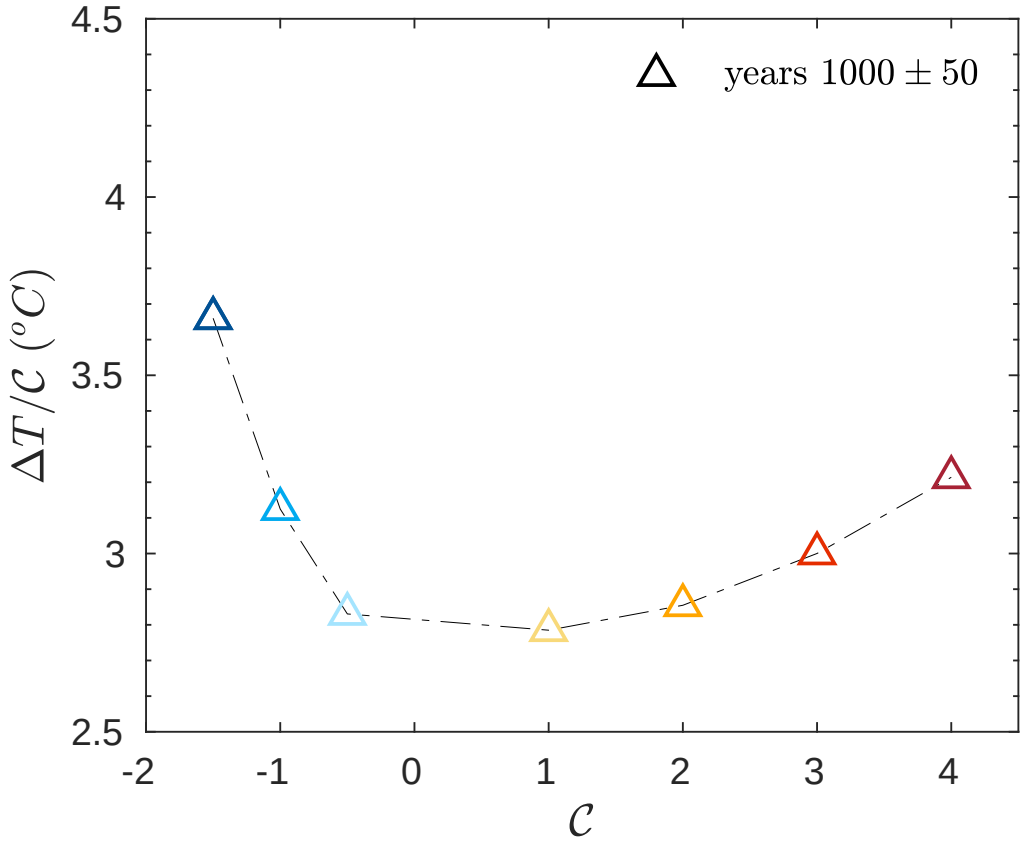
- Community Earth System Model version 1 (CESM1.0.4).
- In the atmosphere (CAM4): nominal resolution $\sim 3.75^o \times 3.75^o$ (T31).
- In the ocean (POP2): $\sim 0.5^o$ in the equator and high latitudes; $\sim 3^o$ elsewhere.
- Abrupt $n\times CO_2$ experiments (below), run to quasi-equilibrium.
- Part of a series of simulations totalling >80,000 years.

Experiment	**Integration Length (Years)**
$16\times CO_2$	4,250
$8\times CO_2$	10,000
$4\times CO_2$	6,895
$2\times CO_2$	9,100
piControl	6,375
$0.71\times CO_2$	4,200
$0.5\times CO_2$	7,000
$0.35\times CO_2$	6,000

- **Main advantage:** long timescales + consider global cooling.
- Longest experiments used to estimate ECS in a full-complexity GCM.

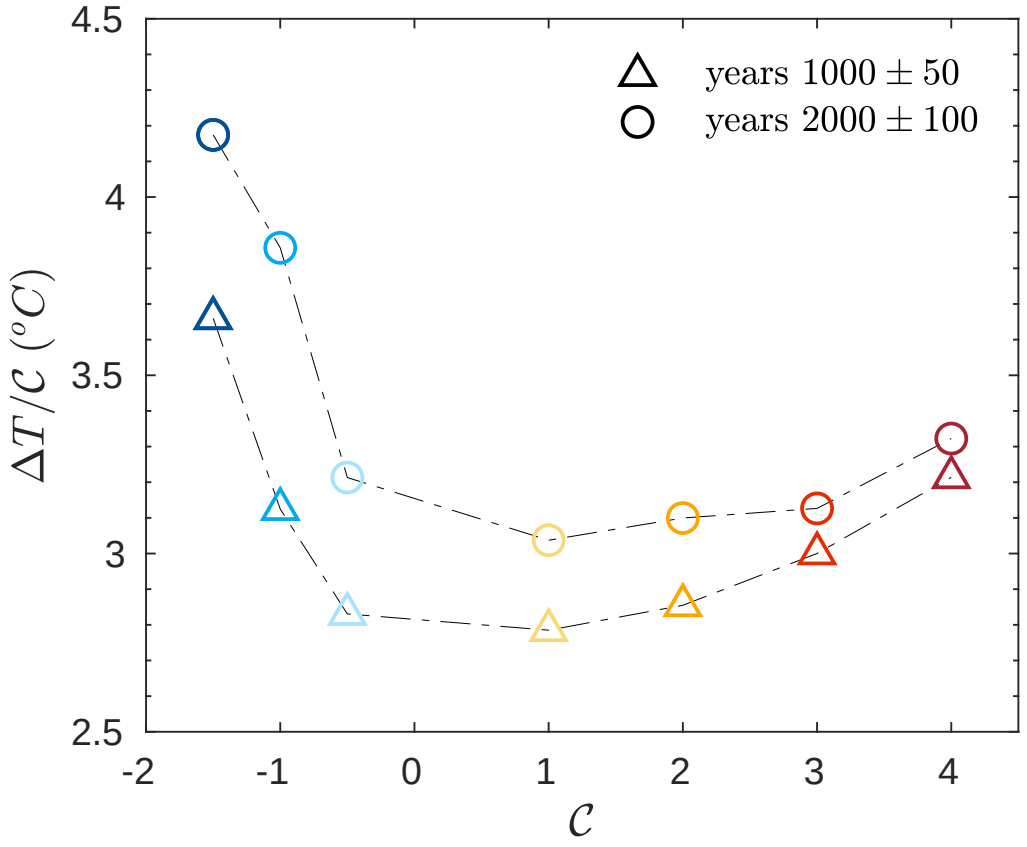
How Much Warming/Cooling and When?

- Normalised global mean surface air temperature change ($\Delta T/\mathcal{C}$) against the number of atmospheric CO_2 doublings ($\mathcal{C}$).
- **Is 1,000 years enough?**



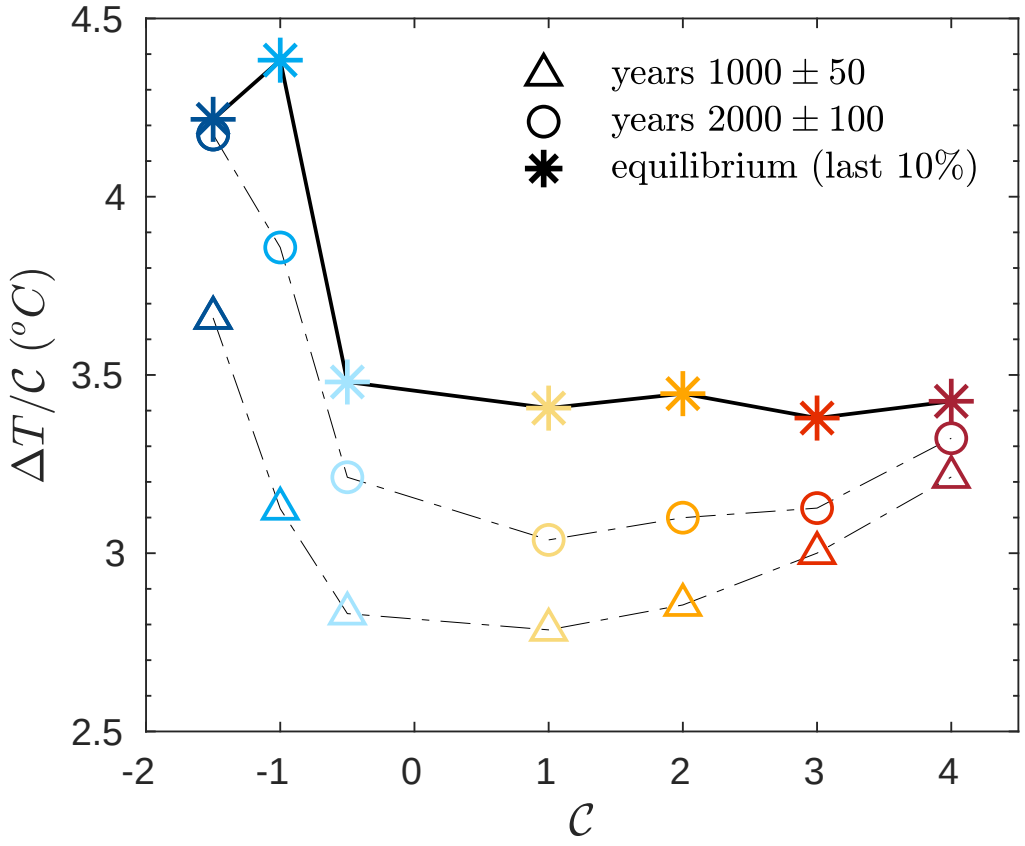
How Much Warming/Cooling and When?

- Normalised global mean surface air temperature change ($\Delta T/\mathcal{C}$) against the number of atmospheric CO_2 doublings ($\mathcal{C}$).
- **Is 2,000 years enough?**



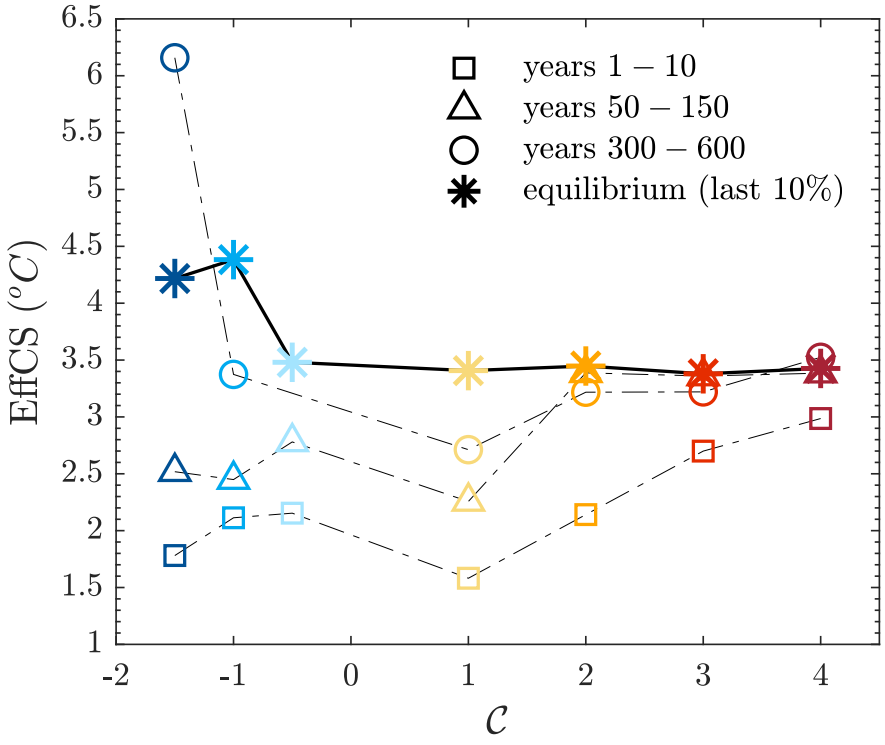
How Much Warming/Cooling and When?

- Normalised global mean surface air temperature change ($\Delta T/\mathcal{C}$) against the number of atmospheric CO_2 doublings ($\mathcal{C}$).
- **At quasi-equilibrium**: $\Delta T/\mathcal{C} \rightarrow$ constant for the 5 warmest experiments.



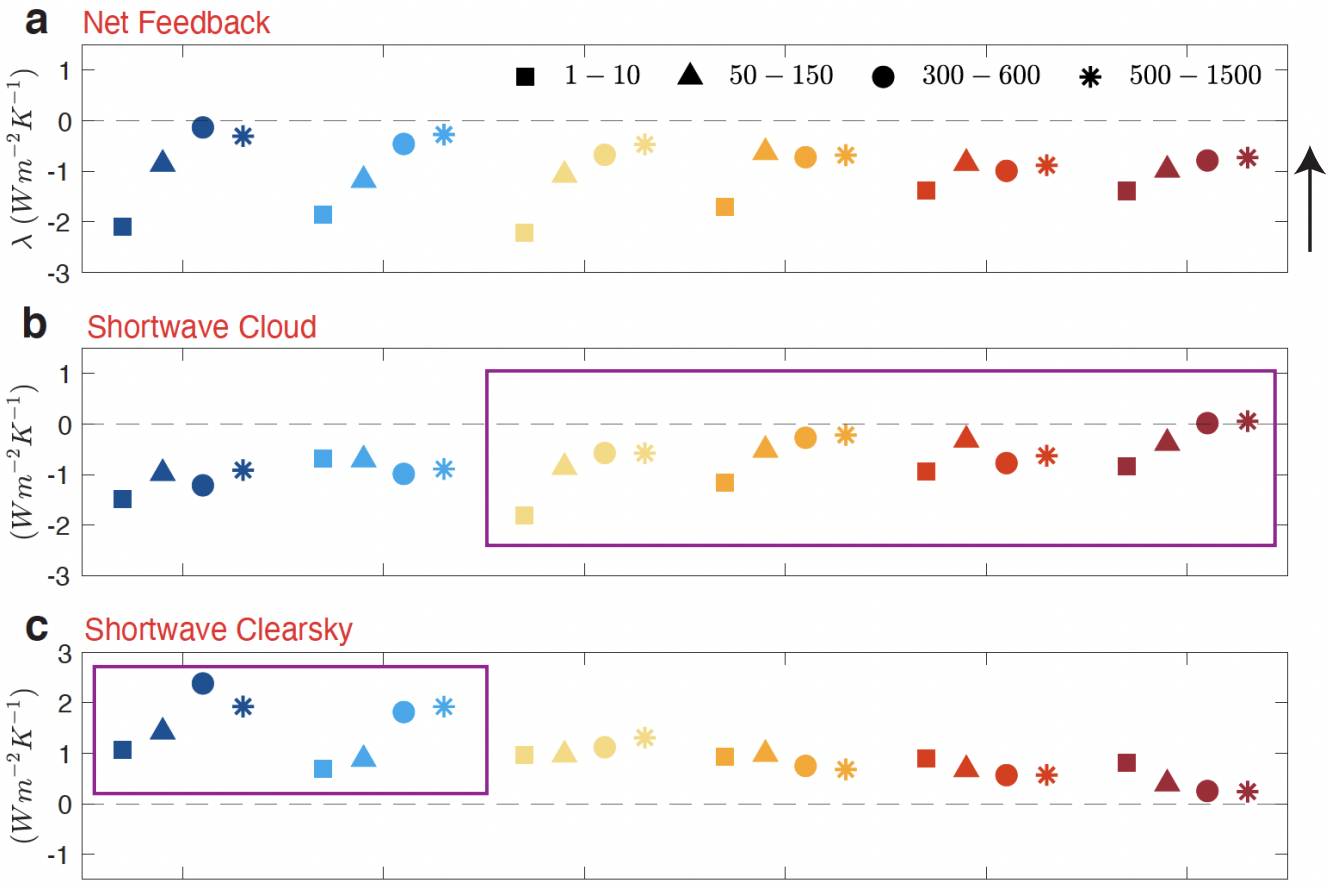
What Does Effective Climate Sensitivity (EffCS) Tell Us?

- Considering $N = F + \lambda \Delta T$: $\Rightarrow$ EffCS: An estimation to ECS.
- λ: obtained via a least-squares linear regression of N and ΔT over a given interval ('differential feedback' definition; Rugenstein and Armour, 2021).
- ΔT_{eq} estimated by extrapolating to $N = 0$.
- **EffCS**: Does well for warmest climates; very far from ECS in colder climates.
- Indicates large changes in λ during climate equilibration.



Shortwave (SW) Feedbacks Reduce λ

- Variations in λ mainly driven by SW feedbacks.
- In global warming: SW cloud feedbacks.
- In global cooling: SW clearsky feedback $\rightarrow$ albedo feedbacks.



Summary & Conclusions

- We determine a remarkably constant ECS $\sim 3.43^o$C across a wide range of climates with CO_2 ranging from $1/\sqrt{2}\times$ (285K) to $16\times$ (300K) pre-industrial.
- On long timescales: $\Delta T_{eq}/\mathcal{C}$ does not necesarily increase for higher $\mathcal{C}$.
- This takes $> 2,000 - 5,000$ years to emerge.
- Higher ECS $\sim 4.3^o$C in strongest global cooling experiments.
- EffCS becomes an increasingly poor indicator of ECS for colder climates.
- Run the models for as long as possible + consider global cooling

P. E. Curtis, A. V. Fedorov, & N. Feldl, Constant Equilibrium Climate Sensitivity (ECS) in Ultralong Simulations of a Wide Range of Climates. *Manuscript in review for Geophys. Res. Lett.*

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