Temperature reconstructions for the last glacial maximum as constraints for climate sensitivity

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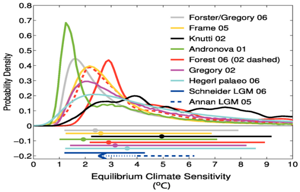

Source: IPCC AR 4, 9.6.2.1

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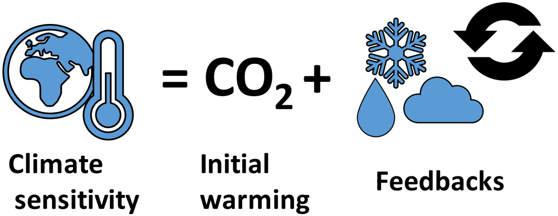
Climate sensitivity

A key number in climate science

Definition

Climate sensitivity is the most probable global warming in response to doubling the CO_2 concentration of the atmosphere.



Source: Femkemilene, CC BY-SA 4.0, via Wikimedia Commons

- Charney report (1979): 1.5 – 4.5°C
- IPCC AR 5 (2014): 1.5 – 4.5°C

ECS and TCR

Short and long-term effects

Equilibrium climate sensitivity (ECS)

- Warming until a new equilbrium is reached
- Timescale: up to thousand years
- Takes into account long term feedbacks

Transient climate response (TCR)

- Gradual CO_2 increase by 1% / year
- Timescale: several decades
- Favored to describe anthropogenic impact on climate

Closely related: Transient climate response to cumulative carbon emissions (TCRE) [°C / tons of carbon]

ECS in terms of forcings

Simple energy (im)balance:

$$\Delta Q = \Delta F - \frac{1}{\lambda}\Delta T \tag{1}$$

ΔQ Heat Flux (0 for Equilibrium) [W/m^2]

ΔF Radiative forcing [W/m^2]

ΔT Temperature Change [$^\circ$C]

$\lambda = \frac{\Delta T}{\Delta F - \Delta Q}$ Climate sensitivity parameter [$^\circ$C/ W/m^2]

ΔF_{2xCO_2} Forcing due to doubled CO_2 concentration [W/m^2]

Formal definition

$$ECS = \Delta T_{2xC0_2} = \Delta F_{2xCO_2} \cdot \frac{\Delta T}{\Delta F - \Delta Q} \tag{2}$$

ECS in terms of feedback mechanisms

Temperature increase without feedbacks:

$$\Delta T_0 = \lambda_0(\Delta F - \Delta Q) = \lambda_0 \Delta R \qquad (3)$$

Feedback f: Energy that goes back to input.
Linear model:

$$\Delta T = \lambda_0(\Delta R + \sum c_i \Delta T) \qquad (4)$$

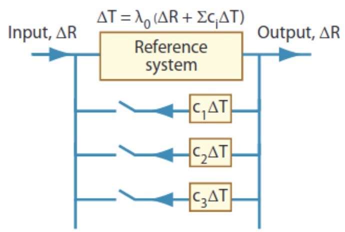
$$= \lambda_0 \Delta R + f \Delta T \qquad (5)$$

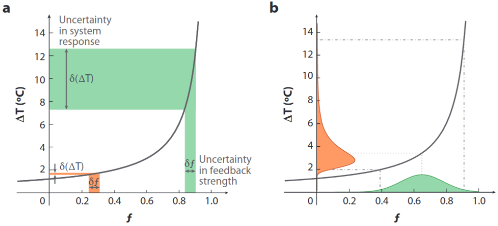
$$\Longrightarrow \Delta T = \Delta T_0 \cdot \frac{1}{1-f} \qquad (6)$$

This simple model tells us a lot regarding uncertainties:

$$\delta(\Delta T) = \Delta T_0 \cdot \frac{1}{(1-f)^2} \cdot \delta f \qquad (7)$$

$\Rightarrow$ PDF for ECS gets characteristic long tail





Source: Roe 2009

Bayesian Inference

Updating PDFs in light of new information

Bayes Theorem

H stands for hypothesis, E stands for evidence (new data)

$$P(H|E) = \frac{P(E|H) \cdot P(H)}{P(E)} \tag{8}$$

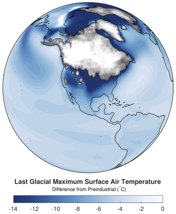
- $P(H)$ Prior probability
- $P(H|E)$ Posterior probability
- $P(E|H)$ Likelihood
- $P(E)$ Marginal likelihood (normalization factor)

$$P(H|E) \sim P(E|H)P(H) \tag{9}$$

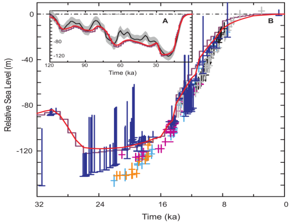
The Last Glacial Maximum

A playground for climatologists

- Approx. 21ka before present
- Maximal glacier extent $\equiv$ minimal sea level
- Most significant differences in greenhouse gas content and icesheet conditions
- Approx. 3°C to 5°C cooler
- Largest uncertainties regarding cooling in the tropics



Source: Tierney 2020



Source: IPCC AR 4 6.4.3

Reasons for using the LGM for ECS estimations

following Schneider von Deimling 2006

1. Large GHG changes
2. Large climate signal
3. Persisting cold climate $\equiv$ equilibrium
4. Well known forcing and response
5. Many glacial climate simulations available

Estimating ECS with climate model ensembles

Idea

Run an intermediate complexity climate model for perturbed parameters.

Steps

1. Choose model parameters to perturb
2. Run model for present-day/preindustrial conditions
3. Run model for doubled CO_2 concentration $\rightarrow$ Climate sensitivity
4. Run model for LGM boundary conditions
5. Compare modeled LGM to proxy data

$\rightarrow$ Probability distribution for equilibrium climate sensitivity

Model-proxy data comparison

Main Tool: Bayesian Inference

$$P(ECS|T_{obs}) \sim P(T_{obs}|ECS)P(ECS) \tag{10}$$

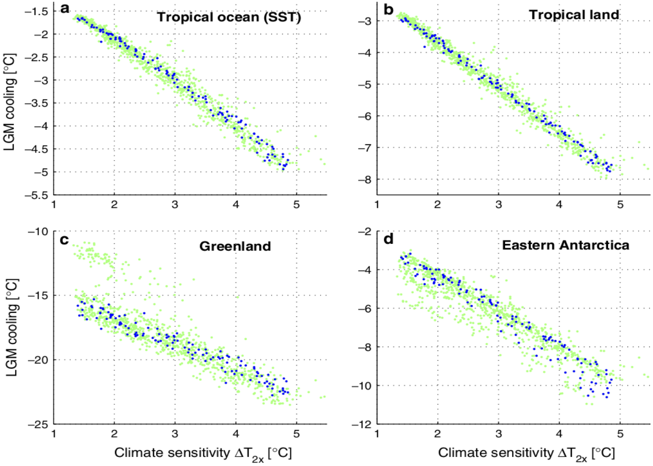
Requires

- likelihood function
- assumptions on distributions, relation of T_{obs} and T_{mod}
- error estimations

Advanced methods used to evaluate likelihood function.

LGM cooling - $2xCO_2$ warming correlation

In the study by Schneider von Deimling (2006) ECS could simply be estimated with a linear fit.



Source: Schneider von Deimling (2006)

Research Results

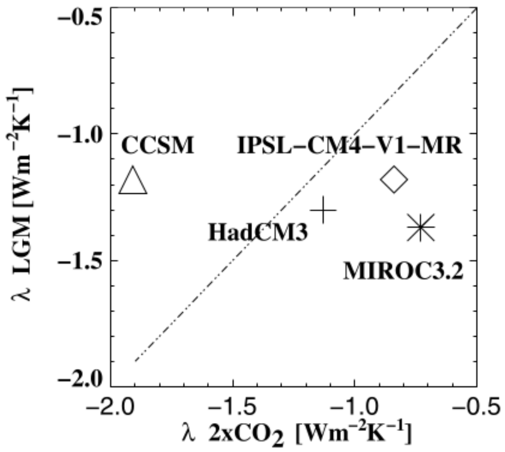
Study	Year	Proxy data	ECS estimation
Annan and Hargreaves	2006	Tropical SST	$P(ECS > 6^\circ C) < 7\%$
Schneider von Deimling	2006	Tropical SST	$1.2 - 4.3^\circ C$
Schmittner	2011	Global reconstruction	$1.7 - 2.3^\circ C$

Table 1: ECS estimates from selected studies

- Modeling approach allows for excluding really high sensitivites
- Models give us way more information than ECS
- Proxy data is key!

Pitfalls

Varying climate sensitivities for different models



Source: Crucifix 2006

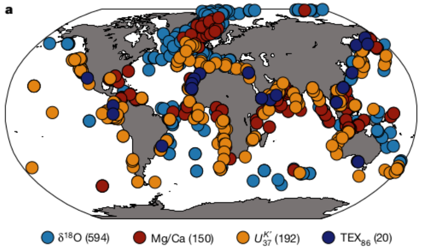
Reconstructing LGM climate with proxy data

- Recall Climate sensitivity definition: $ECS = \Delta F_{2xCO_2} \cdot \frac{\Delta T}{\Delta F - \Delta Q}$

- The question is:
  How cool was the LGM, especially in the tropics?

- Tierney et al. (2020) reconstructed LGM SST and SAT globally.

$\rightarrow$ Paleoclimate data assimilation: Combination of proxy data and models

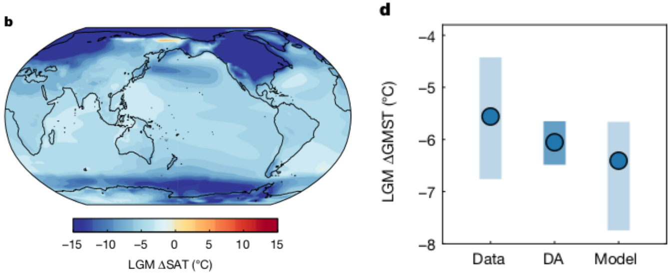


Source: Tierney 2020

Data assimilation
Combining model and proxy data

- Model: iCESM (isotope-enabled)
- Prior probability: 50 year average states from LGM simulations
- Updated with time series of proxy records
- Verification via δ^{18}O-data

$\rightarrow$ LGM cooling of 6.1°C $\equiv$ ECS 3.4°C (2.4 - 4.5 °C)



Source: Tierney 2020

x represents the model, y the measurement.

$$P(x|y) = \frac{P(y|x) \cdot P(x)}{P(y)} \tag{11}$$

Assume gaussian statistics:

$$\left.\begin{aligned} P(y|x) &= c_1 e^{-\frac{1}{2}\left(\frac{y-x}{\sigma_y}\right)^2} \\ P(x) &= c_2 e^{-\frac{1}{2}\left(\frac{x-x_0}{\sigma_0}\right)^2} \end{aligned}\right\} P(x|y) = c_3 e^{-\frac{1}{2}\left(\left(\frac{y-x}{\sigma_y}\right)^2 + \left(\frac{x-x_0}{\sigma_0}\right)^2\right)} = c_3 e^{-J(x)}$$

Maximizing Likelihood $\equiv$ Minimizing cost function $J(x)$

$$\frac{\partial J}{\partial x} = 0 \rightarrow \bar{x} = \left(\frac{{\sigma_y}^2}{{\sigma_y}^2 + {\sigma_0}^2}\right) x_0 + \left(\frac{{\sigma_0}^2}{{\sigma_y}^2 + {\sigma_0}^2}\right) y \tag{12}$$

Formulation as an update equation:

$$\bar{x} = x_0 + K \underbrace{(y - x_0)}_{innovation} \tag{13}$$

$$K = \frac{{\sigma_0}^2}{{\sigma_0}^2 + {\sigma_y}^2} \tag{14}$$

K is called the Kalman gain.

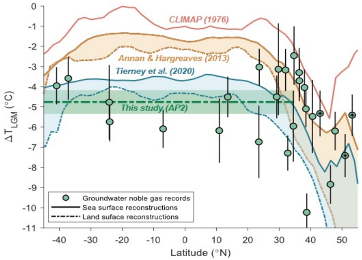
IUP Research: Noble gas temperature reconstructions

Widespread 6° C Cooling on Land During the Last Glacial (accepted publication)

Noble gases as paleothermometers

- Solubility of noble gases Ne, Ar, Kr, and Xe depends on temperature (and pressure)
- Thermometer for time of groundwater recharge
- Conversion from groundwater to atmospheric temperature necessary
- Rarely used in model-data comparisons so far

Tierney et al. motivated noble gas experts to gather their data.
→ Research supports strong cooling trend as inferred by Tierney.



Source: Seltzer 2021

Summary

- LGM is a promising period for constraining climate sensitivity
- LGM studies allow for cutting upper end of ECS
- Research shows correlation between tropical LGM cooling and ECS
- Bayesian Inference is a widely used tool in climate science

Future goals:

- Improve LGM temperature reconstructions: embed different proxies
- Enhance climate model comparisons

Questions and Discussion!

Bibliography I

Knutti, Reto, and Gabriele C. Hegerl.
The equilibrium sensitivity of the Earth's temperature to radiation changes
Nature Geoscience 1.11 (2008): 735-743.

Crucifix, Michel.
Does the Last Glacial Maximum constrain climate sensitivity?.
Geophysical Research Letters 33.18 (2006).

Annan, James D., and Julia C. Hargreaves.
Using multiple observationally-based constraints to estimate climate sensitivity.
Geophysical Research Letters 33.6 (2006).

von Deimling, Thomas Schneider, et al.
Climate sensitivity estimated from ensemble simulations of glacial climate.
Climate Dynamics 27.2-3 (2006): 149-163.

Bibliography II

Schmittner, Andreas, et al.
Climate sensitivity estimated from temperature reconstructions of the Last Glacial Maximum.
Science 334.6061 (2011): 1385-1388.

Tierney, Jessica E., et al.
Glacial cooling and climate sensitivity revisited.
Nature 584.7822 (2020): 569-573.

Seltzer, Alan et al.
Widespread 6°C Cooling on Land During the Last Glacial
Nature (accepted publication)

Roe, Gerard
Feedbacks, timescales, and seeing red.
Annual Review of Earth and Planetary Sciences 37 (2009): 93-115.

Bibliography III

Solomon, Susan, et al.
Climate change 2007-the physical science basis: Working group I contribution to the fourth assessment report of the IPCC. Vol. 4.
Cambridge university press, 2007.

Stocker, Thomas, ed.
Climate change 2013: the physical science basis: Working Group I contribution to the Fifth assessment report of the Intergovernmental Panel on Climate Change.
Cambridge university press, 2014.

Kutz, Nathan.
Lecture on data assimilation
https://www.youtube.com/watch?v=Pn3ffYPtzyE7