Can we directly estimate ECS using reconstructions of the LGM?

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ECS & paleoclimate constraints

- Equilibrium climate sensitivity (ECS): global surface temperature response (ΔT) to 2×CO2 (F_{2CO2}) after accounting for **fast feedback processes**

- Paleoclimate constraints can be used to inform ECS
  - Real-world data with large forcing/response, e.g. Cenozoic CO_2 (190–1500) & GMST [8–30°C]
  - Paleo-temperatures integrate effects across **fast and slow timescales**

- The PALAEOSENS approach (Rohling et al., 2012, *Nature*)
  - **Slow processes are treated as forcings and independent from fast feedbacks**

$$\mathrm{ECS} = \frac{\Delta T}{F_{\mathrm{GHG}} + F_{\mathrm{LIS}} + \cdots} \times F_{2\mathrm{CO2}}$$

The LGM application: requirements/assumptions

$$\mathrm{ECS} = \frac{\Delta T}{F_{\mathrm{GHG}} + F_{\mathrm{LIS}} + \cdots} \times F_{2\mathrm{CO2}}$$

1. LGM cooling (ΔT): 3–8°C (IPCC AR5); 6.1±0.4°C (Tierney, Zhu, et al., *Nature, accepted*)

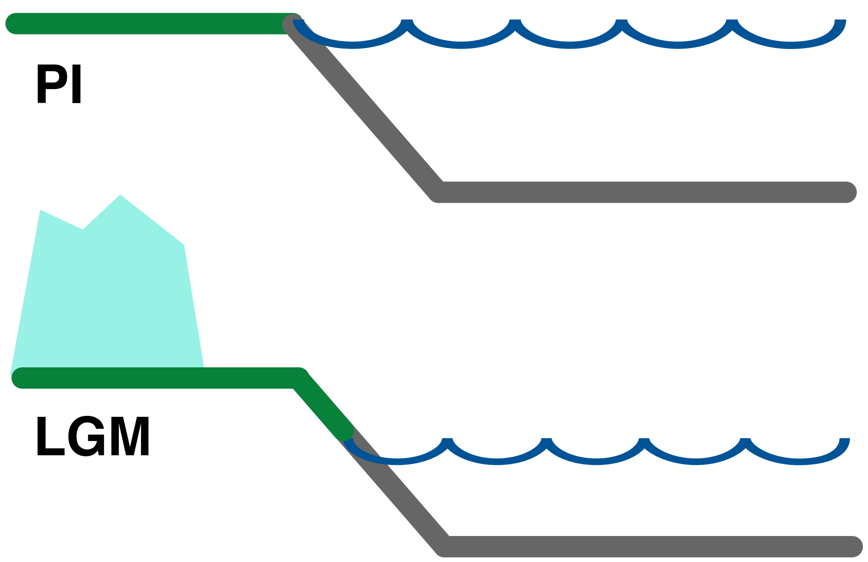
2. **Knowledge of forcings**
   - Non-GHG forcings are challenging to quantify, e.g. LIS
   - Different forcing agents have the same efficiency in change ΔT.

3. **Fast feedbacks are independent on slow processes**

This study examines items 2&3 in a "perfect-model scenario" in CESM1.2

Pathways of land ice sheet (LIS) forcing

- Radiative pathways
  - SW albedo over ice / new land
  - **LW emission at higher elevation & colder T**
- Non-radiative pathways
  - **Dynamical wind shifts**
  - **"Surface" defined at different elevation**

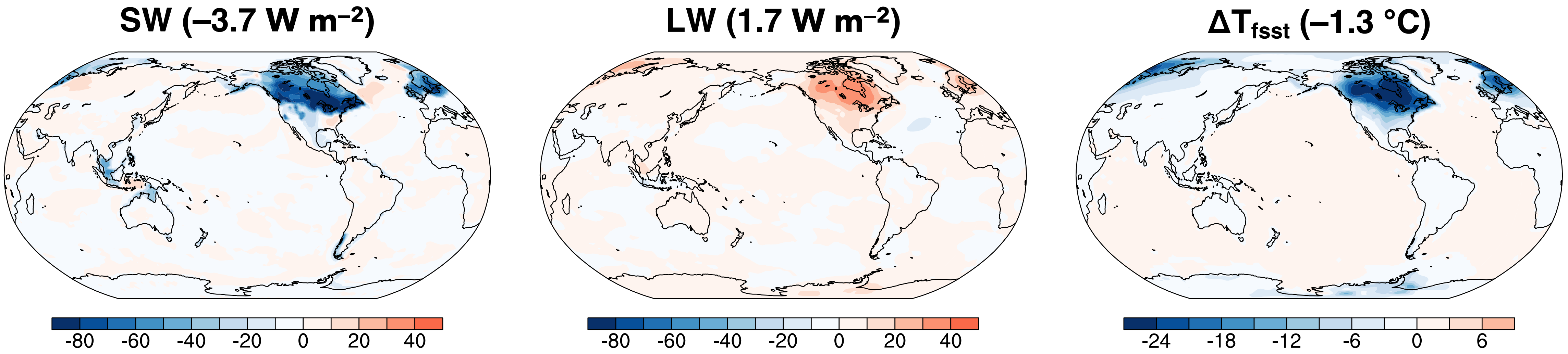


→ Solution: **effective radiative forcing/efficacy**

$$\mathrm{ECS} = \frac{\Delta T}{\boldsymbol{\varepsilon}_{\mathbf{GHG}} \times ERF_{\mathrm{GHG}} + \boldsymbol{\varepsilon}_{\mathbf{LIS}} \times ERF_{\mathrm{LIS}} + \cdots} \times F_{2\mathrm{CO2}}$$

Effective radiative forcing (ERF)

- Fixed-SST simulation: **ATM_LIS** (CESM1.2-CAM5 + PI SST + LGM LIS; 30 yrs)
  - ΔR_{TOA}: **ERF_{fsst} = –1.9±0.2 W m^{-2}**



For more on the adjusted framework: see Sherwood et al. (2015)

Correction of ERF_{fsst} & efficacy of forcing

- $ERF = ERF_{\mathrm{fsst}} - \Delta T_{\mathrm{fsst}} \;/\; \lambda$
  - **SOM_LIS** (CESM1.2 + SOM with PI "qflux" + LGM LIS; 60 yrs)
  - $\lambda = \frac{\Delta T_{\mathrm{SST\_mediated}}}{ERF_{\mathrm{fsst}}} = \frac{\Delta T_{\mathrm{SOM}} - \Delta T_{\mathrm{fsst}}}{ERF_{\mathrm{fsst}}}$

- $\varepsilon_{\mathrm{LIS}} = \frac{(\frac{\Delta \mathrm{T}_{\mathrm{SOM}}}{ERF})_{\mathrm{LIS}}}{(\frac{\Delta \mathrm{T}_{\mathrm{SOM}}}{ERF})_{\mathrm{2CO2}}}$
  - With ATM_2CO2 & SOM_2CO2
  - Similarly, ATM_GHG & SOM_GHG

Results: ERF and efficacy

- $\boldsymbol{ERF}_{\mathbf{LIS}}$ = **–3.2±0.2 Wm^{-2},** $\boldsymbol{\varepsilon}_{\mathbf{LIS}} = \mathbf{1.1}$
- $\boldsymbol{ERF}_{\mathbf{GHG}}$ = **–2.8±0.3 Wm^{-2} ,** $\boldsymbol{\varepsilon}_{\mathbf{GHG}} = \mathbf{0.9}$

- With 6 simulations (*270 years*)
  - a complete quantification of forcing/efficacy of GHG and LIS
  - consistent with the concept of ECS and requirements of forcing-feedback framework (ΔR_{TOA}~ΔT)

Low ε_{GHG} (0.9) attributed to the cloud-phase feedback

Exp.	ERF_λ	λ_{Planck}	λ_{Alb}	λ_{WV+LR}	λ_{CLD_LW}	$\boldsymbol{\lambda_{CLD\_SW}}$
SOM_2CO2	+3.9	–3.57	0.42	1.51	0.13	**0.33**
SOM_GHG	–2.8	–3.52	0.41	1.52	0.13	**0.19**

Pendergrass et al. (2018) kernels are used.

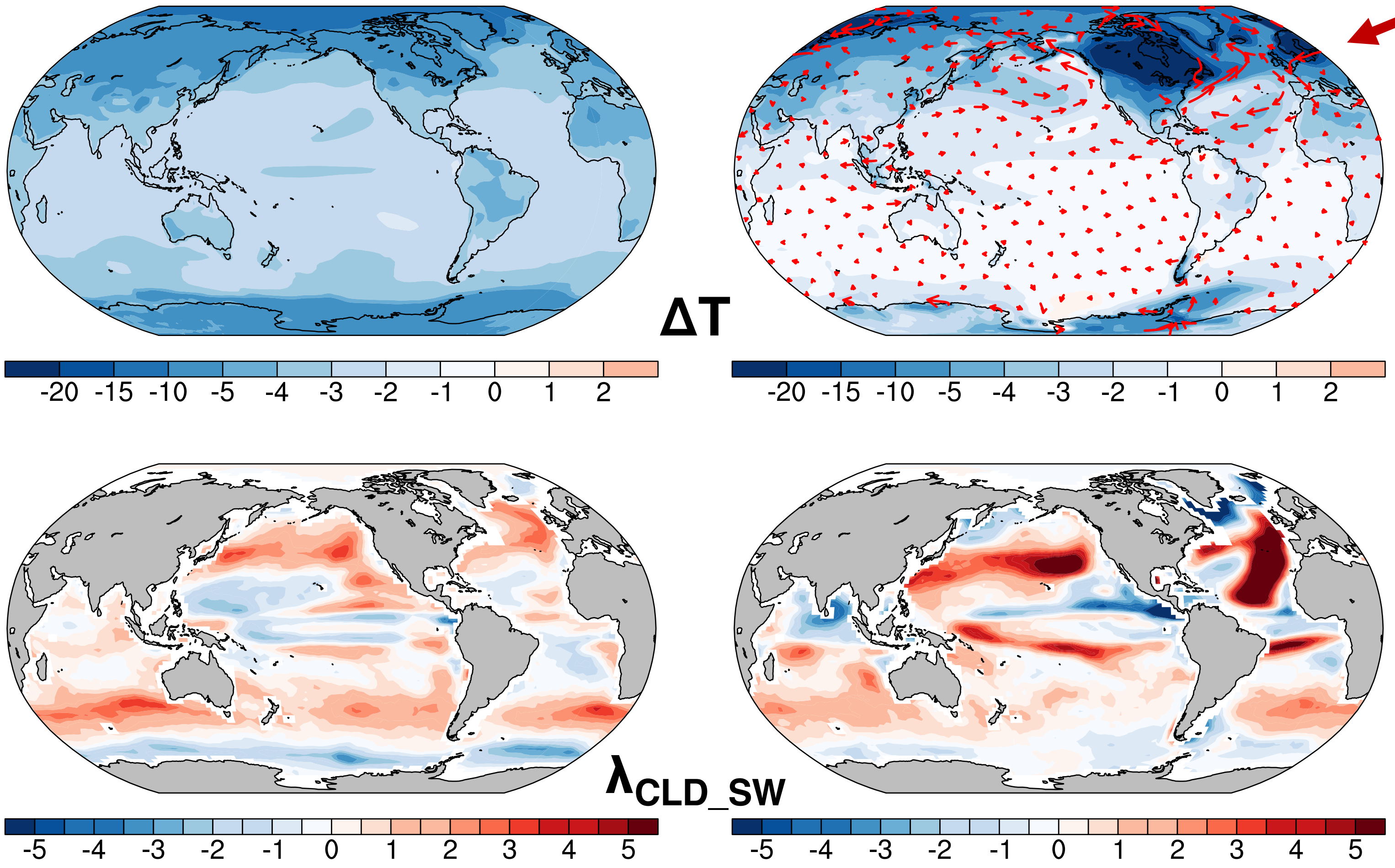
- High-latitude cloud-phase feedback
  - Mitchell, Senior, & Ingram, 1989
  - Tan, Storelvmo, & Zelinka, 2016
  - Frey & Kay, 2018
  - …

High ε_{LIS} (1.1) linked to adjustments, coupled and cloud feedbacks

SOM_2CO2 * –1

SOM_LIS

850-wind changes from *ATM_LIS*



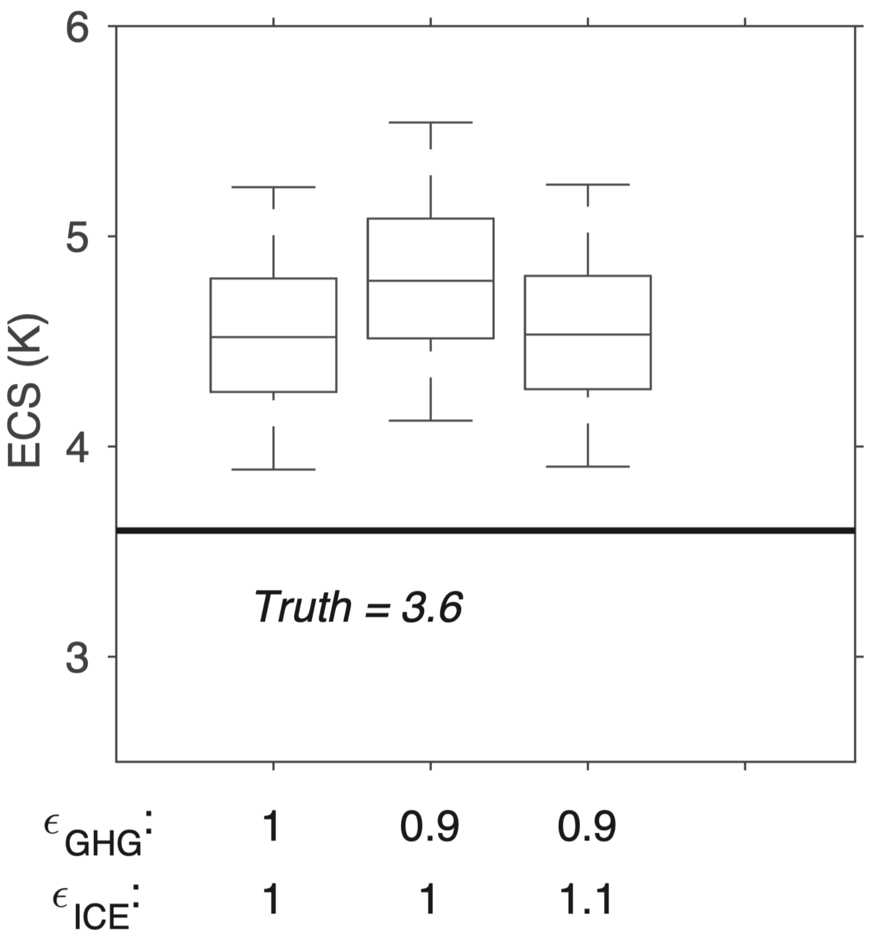
- **Wind-Evaporation-SST**
- **λ_{CLD} & SST pattern effect** (e.g. Zhou et al., 2017)

	SOM_2CO2	SOM_LIS
ERF	+3.9	–3.2
ΔT_{fsst}	**0.3**	**–1.3**
$\lambda_{CLD\_SW\_OCN}$	**0.21**	**0.30**

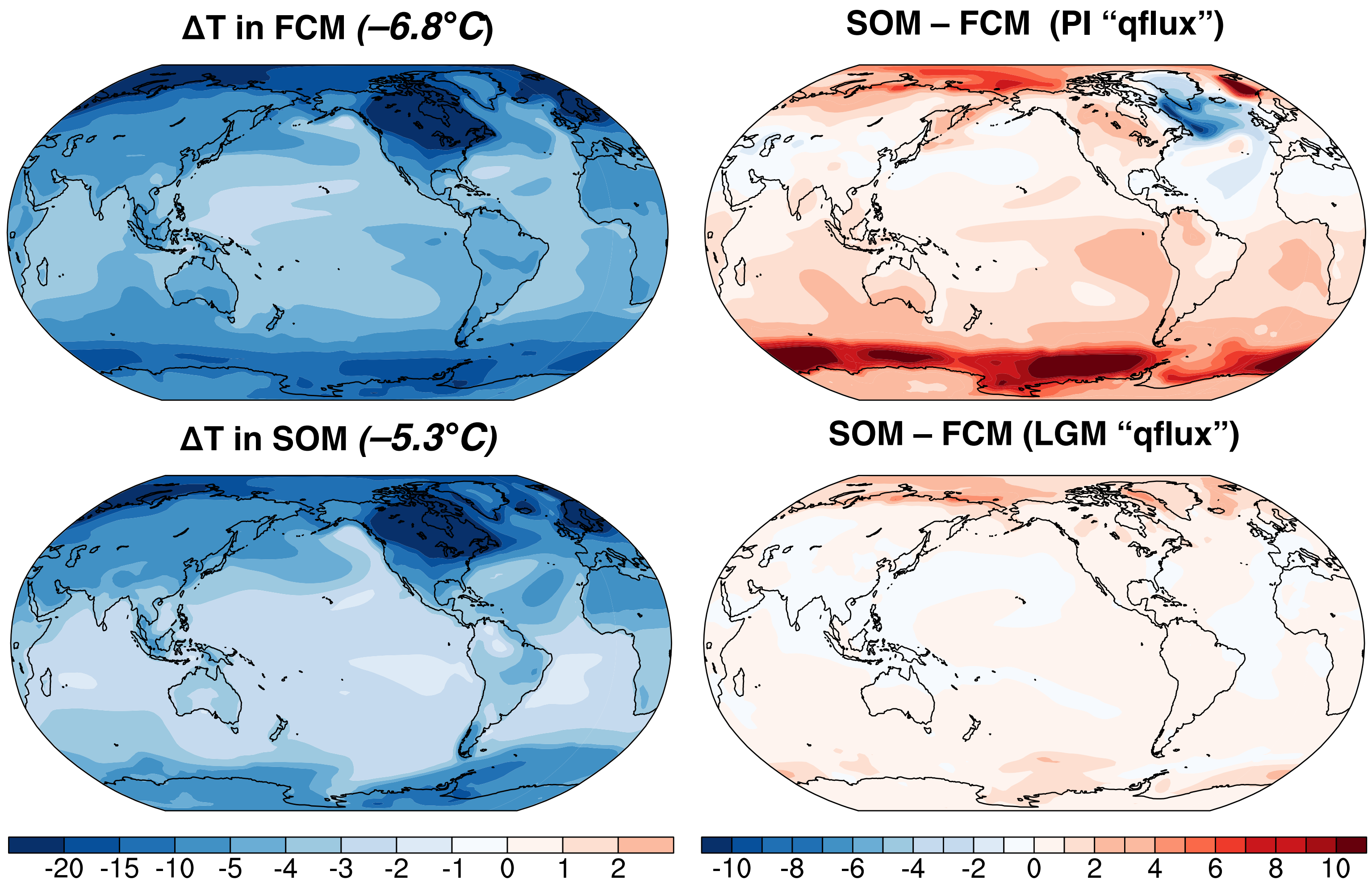
Direct ECS calculation in "a perfect model"

- **"Truth" in ΔT = –6.8°C**
  - **FCM_LGM:** CESM1.2 + LGM GHG & LIS
  - Close to equilibrium ($R_{TOA} < 0.06\ Wm^{-2}$)
- **"Truth" in ECS = 3.6°C**
  - ΔT (SOM_2CO2 – SOM_PI)

$$ECS = \frac{\Delta T}{\varepsilon_{GHG} \times ERF_{GHG} + \varepsilon_{LIS} \times ERF_{LIS}} \times ERF_{2CO2}$$



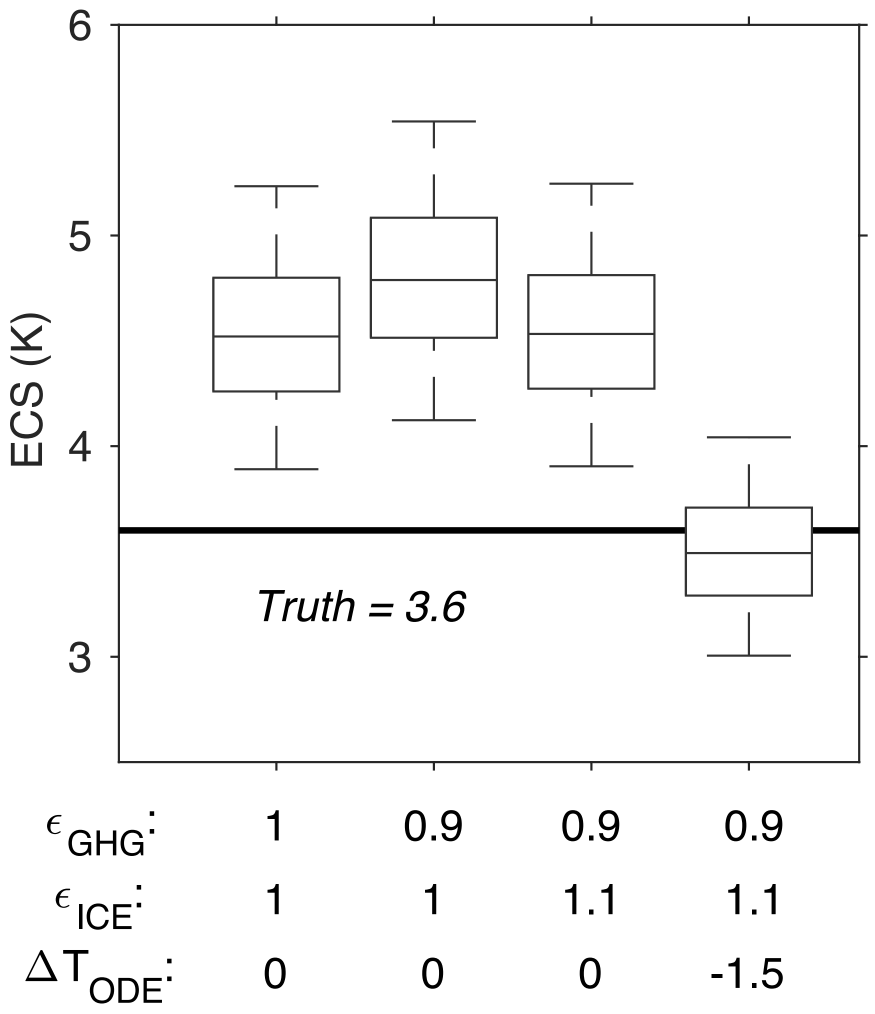
The missing piece: ocean dynamical effect (–1.5°C)



Slow ocean dynamics amplify LGM cooling through impacting fast feedbacks.

Direct calculation of ECS in a "perfect model"

$$\mathrm{ECS} = \frac{\Delta \mathrm{T} - (\mathbf{-1.5})}{\varepsilon_{\mathrm{GHG}} \times \mathrm{ERF}_{\mathrm{GHG}} + \varepsilon_{\mathrm{LIS}} \times \mathrm{ERF}_{\mathrm{LIS}}} \times \mathrm{ERF}_{2\mathrm{CO2}}$$



Conclusion

- Paleoclimates contain invaluable real-world data, ***but climate models are needed***:
  - **To provide a complete quantification of forcing/efficacy**
  - **To explore the state dependence of fast feedbacks, e.g. the interactions with slow ocean dynamics.**

Thank you for your attention!

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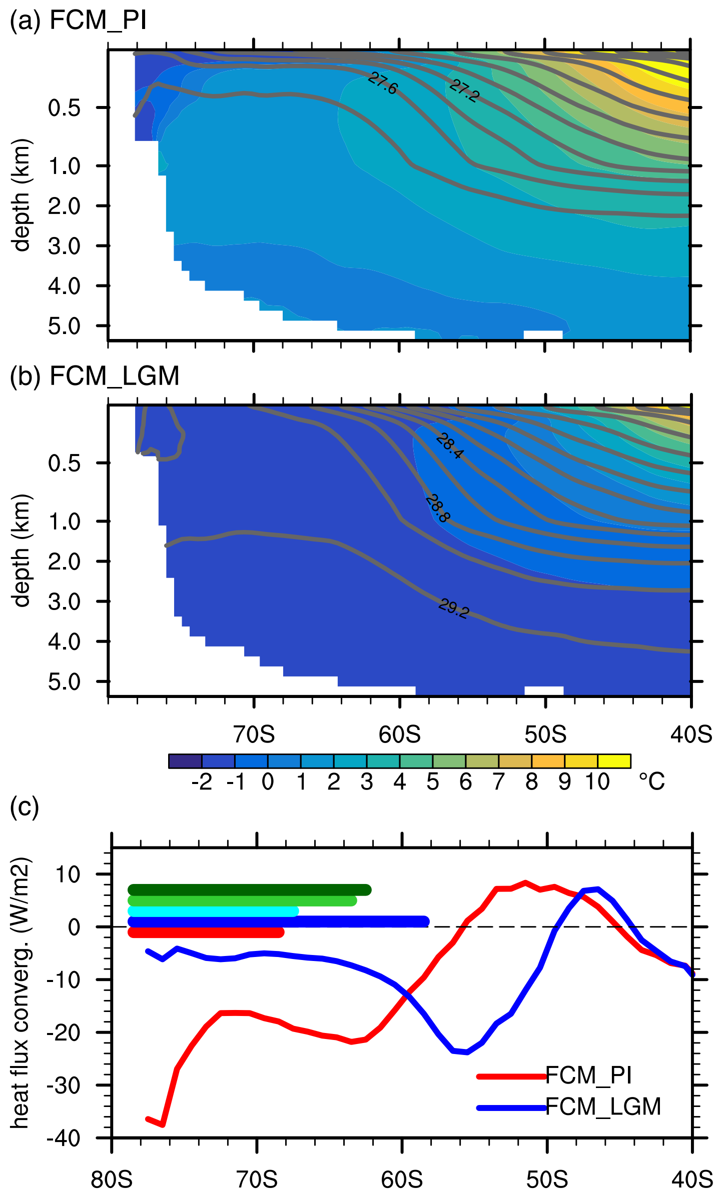
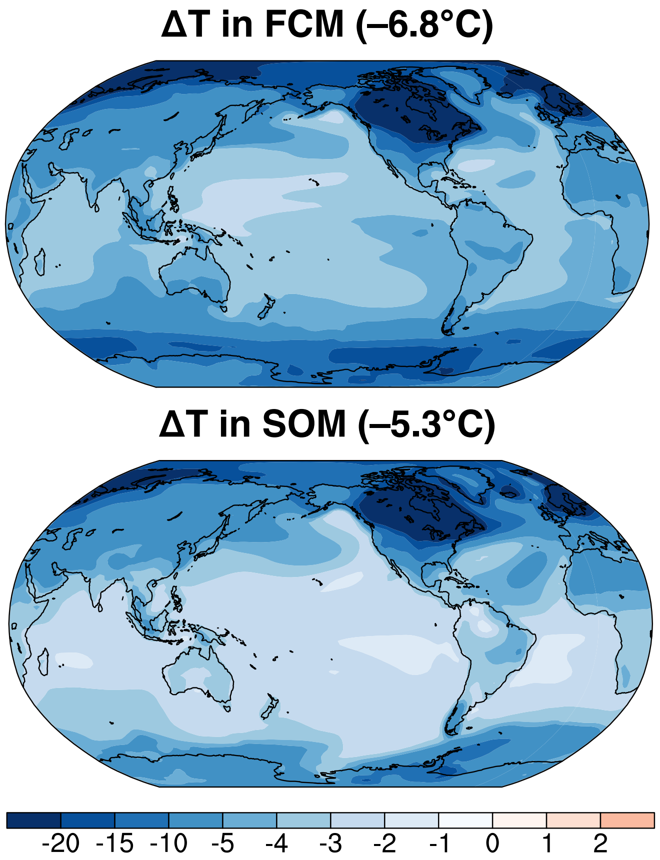
Table of simulations

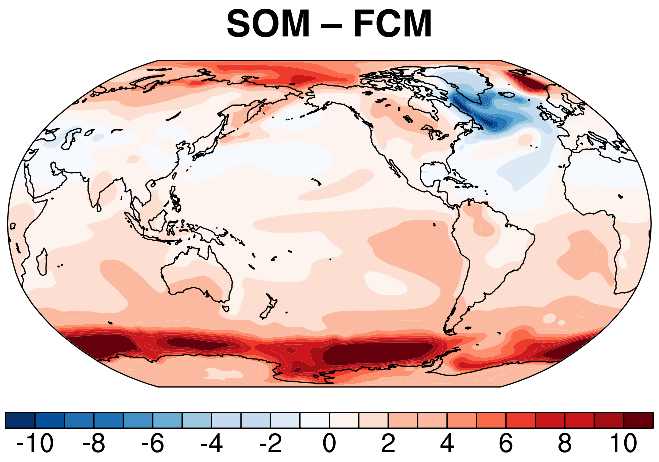
Experiment	GHG	ICE	Length (yrs)	GMST / ΔGMST (°C)	ERF_{fsst} ($W\ m^{-2}$)	ERF_{λ} ($W\ m^{-2}$)	ERF_{kernel} ($W\ m^{-2}$)	ε
FCM_PI	PI	PI	900+	15.1				--
FCM_LGM	21ka	21ka	900+	–6.8				--
ATM_PI	PI	PI	30	14.9±0.03	--	--	--	--
ATM_2CO2	2×PI	PI	30	+0.3±0.05	3.7±0.3	+3.9±0.3	+4.0	--
ATM_GHG	21ka	PI	30	–0.2±0.04	–2.6±0.2	**–2.8±0.3**	–2.8	--
ATM_LIS	PI	21ka	30	–1.3±0.03	–1.9±0.2	**–3.2±0.2**	--	--
ATM_LGM	21ka	21ka	30	–1.5±0.05	–4.4±0.3	–6.1±0.3	--	--
SOM_PI	PI	PI	60	14.9±0.06	--	--	--	--
SOM_2CO2	2×PI	PI	60	+3.6±0.06	--	--	--	1.00
SOM_GHG	21ka	PI	60	–2.2±0.11	--	--	--	**0.9±0.1**
SOM_LIS	PI	21ka	60	–3.2±0.09	--	--	--	**1.1±0.1**
SOM_LGM	21ka	21ka	60	–5.3±0.09	--	--	--	0.9±0.1

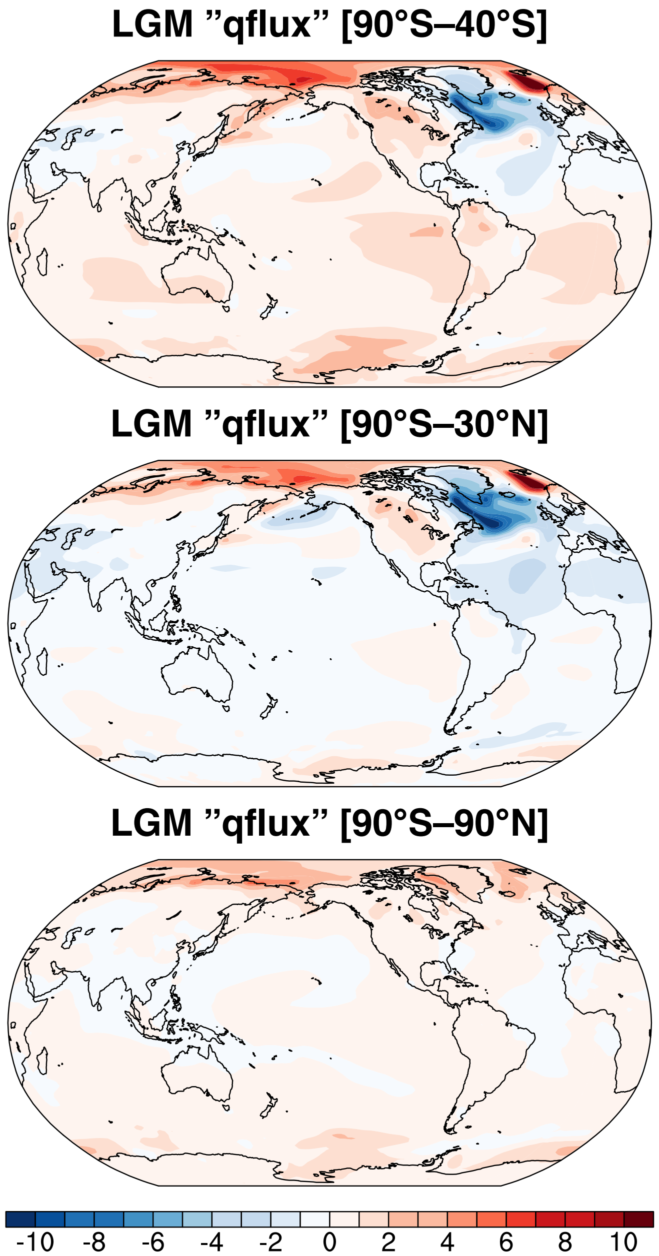
The missing physics—ocean dynamics



The missing piece: ocean dynamical effects (–1.5°C)







Slow ocean dynamical changes regulate LGM cooling through interactions with fast feedbacks.