Paleo Perspectives on the Pattern Effect on deep-time scales

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Using “deep-time” Paleoclimates to estimate Climate Sensitivity

Tierney et al. Science 2020
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It is important to distinguish between the role of:

• Fast feedbacks (Charney Sensitivity Feedbacks): water-vapor, clouds, lapse rate, snow and sea-ice feedbacks (~100 years in the modern context)

• Slow feedbacks: occur over much longer timescales e.g. land-ice and carbon cycle feedbacks (>1000 years)
Using “deep-time” Paleoclimates to estimate Climate Sensitivity

- It is important to distinguish between the role of:
  - Fast feedbacks (Charney Sensitivity Feedbacks): water-vapor, clouds, lapse rate, snow and sea-ice feedbacks (~100 years in the modern context)
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- This leads to the distinction being made between ECS and “Earth System Sensitivity” that includes some or all of the slow feedbacks (e.g. land ice and vegetation) in addition to the fast feedbacks

*Figure 1 | Charney sensitivity and Earth system sensitivity. a. CS = ΔTc (°C). b. ESS (°C) calculated from Supplementary Equations S16 and S17.*

Lunt et al. 2010
Using “deep-time” Paleoclimates to estimate Climate Sensitivity

• PALAEOSENS (Rohling et al. 2012) framework = constrain the fast feedbacks by treating the radiation changes due to the slow feedbacks as a forcing

• In practice however, paleoclimate modeling is needed to quantify the radiative influence of the slow feedbacks that need to be treated as forcing e.g. the radiative impacts of a very different paleogeography or atmospheric aerosol concentrations (Royer 2016)

\[ S_{[\text{CO}_2, P_1^s, \ldots, P_m^s]} = \frac{\Delta T}{\Delta R_{[\text{CO}_2]} + \sum_{j=1}^{m} \Delta R_{[P_j^s]}}, \]

\[ P^s = \text{slow feedback processes like land ice and vegetation changes} \]
Using Paleoclimates to estimate Climate Sensitivity

Sherwood et al. 2020

PALAEOSENS (Rohling et al. 2012)
State Dependence

based on climate models:
- Shaffer 2016 (LP / PETM)
- Caballero 2013 (Paleogene: 2-32×CO₂)
- Andrews 2012 (CMIP5 multi-model mean)

based on simpler models and data:
- Köhler 2016 (fullG / IG @2.1Ma)
- Anagnostou 2016 (LE / EE)
- Köhler 2015 (coldG / warmG @2.1Ma)
- Martinez-Boti 2015 (800ka Pleist. / Plio.)
- vdHeydt 2014 (coldG / warmG @800ka)

PALAEOSENS 2012 N (all@65Ma)

IPCC 2013 (90%CF range)

von der Heydt et al., 2016
State Dependence

Caballero & Huber, 2013

Zhu et al., 2019; Tierney et al. Science 2020
But what about the Pattern Effect?

• We know that the global top-of-atmosphere radiative response depends not only on *global* surface warming but also on the *spatial pattern* of surface warming – the so-called “pattern effect”

• Can we account for the pattern effect associated with a given deep-time paleoclimate state?
Global Radiative feedback response to local warming

CAM5 Green's Function (Zhou et al. 2017)
Pattern Effect for the LGM
Pattern Effect for the LGM

Fig. 1 | Locations of geochemical SST proxies used for the LGM climate reconstruction. a. Proxy sites for the LGM (956). b. Proxy sites for the late Holocene (LH; 879). Proxies are colour-coded by type and the number of each is shown in parentheses.

Tierney et al. 2021
LGM vs. 4xCO₂ SST Anomaly Patterns

Patterns are infilled to modern land mask and normalized by global mean SST anomaly
LGM vs. 4xCO$_2$ SST Anomaly Patterns

Patterns are infilled to modern land mask and normalized by global mean SST anomaly

Slide from Vince Cooper (UW)
Patterns are infilled to modern land mask and normalized by global mean SST anomaly.
Green’s Function for TOA response

CAM5 Green’s Function (Zhou et al. 2017)

Note: Green’s function plot values are scaled up by number of SST grid cells
LGM Pattern Effect

Preliminary results from AGCMs with prescribed SST/SIC

\[ \lambda' = \lambda_{4xCO_2} - \lambda_{LGM} \]

LGM feedback is weaker (less negative) than 4xCO₂ feedback

Slide from Vince Cooper (UW)
LGM Pattern Effect: Impact on Modern-day ECS

Preliminary results

- Adjust $\lambda_{LGM}$ for pattern effect $\lambda'$ when using LGM to estimate modern-day ECS:
  \[ ECS_{LGM} = \frac{\Delta F_{2xCO2}}{\lambda_{LGM} + \lambda'} \]

- $\lambda' < 0$ in all datasets and AGCM experiments
  - Accounting for pattern effect reduces modern-day ECS

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Poster session (Vince Cooper):
“The Last Glacial Maximum Pattern Effect”
Co-authors: Kyle Armour, Cristian Proistosescu, Philip Chmielewicz, Jessica Tierney, Matthew Osman, Yue Dong, Gregory Hakim, Daniel Amrhein, Natalie Burls, and Scott Knapp

Slide from Vince Cooper (UW)
What does the warm Pliocene tell us about how the tropical Pacific will respond to global warming?
Pattern Effect for the Late Pliocene?

3.264 - 3.025 Ma

Pliocene sea-surface temperature anomaly (PRISM)

PRISM; Dowsett et al. 2010

Tierney et al. (2019)
Pattern Effect for the Early Pliocene?

- **Fedorov et al., 2015 Zonal SST Gradient**
- **Tierney et al., 2019 Zonal SST Gradient**
- **Hansen et al., 2013 Global Temp**

Wycech et al., 2020
Pattern Effect for the Early Pliocene?

Burls and Fedorov, 2017
Modified Cloud Albedo and Abrupt CO$_2$ Sensitivity Experiments

Experimental Setup

- The Community Earth System Model (CESM)
- Modified Cloud albedo experiments
  Reflectivity of clouds changed by modifying the atmospheric liquid and ice water path, but only in the shortwave radiation scheme. The changes imposed are hypothetical.
- Abrupt 2x, 4x, 8x and 16x CO$_2$ experiments

Simulating a broad range of meridional SST gradients

Burls & Fedorov, Journal of Climate, 2014
Pattern Effect for the Early Pliocene?
Pattern Effect for the Pliocene?

Pliocene sea-surface temperature anomaly (PRISM)

PRISM; Dowsett et al. 2010

Abrupt4xCO₂ Feedback vs. LGM Feedback

Tierney et al. (2019)
What is needed?

- As seen for historical versus equilibrium warming, the pattern effects matter for paleoclimate estimates of ECS - a global-mean temperature reconstruction is not enough

- There is a need to differentiate between state dependance and the pattern effect

Challenges

- Accurate reconstructions of SST and sea ice patterns with uncertainty quantification, particularly in the tropical Pacific where the radiative response is very sensitive to the details of SST changes

- We have to deal with significant uncertainty in the forcing and its pattern in the deep-time paleoclimate context

- What is the pattern effect for the future? The pattern effect in climate model projections versus in paleoclimates
Insights from deep-time Paleoclimate

Paleoclimate warming is polar amplified and our models generally struggle to capturing the full extent of polar and subtropical warmth without warming the deep tropics too much.

Hollis et al., 2019, Lunt et al., 2020

Feng et al., 2020

Hollis et al., 2019, Lunt et al., 2020
Insights from deep-time Paleoclimate

The zonal SST gradient in the equatorial Pacific likely reduces in response to warming as equilibrium is approached (with modernish paleogeography)
Paleoclimates provide out-of-sample tests for Climate Models
Paleoclimates provide out-of-sample tests for Climate Models

Zhu et al., 2021; Zhu et al., 2022