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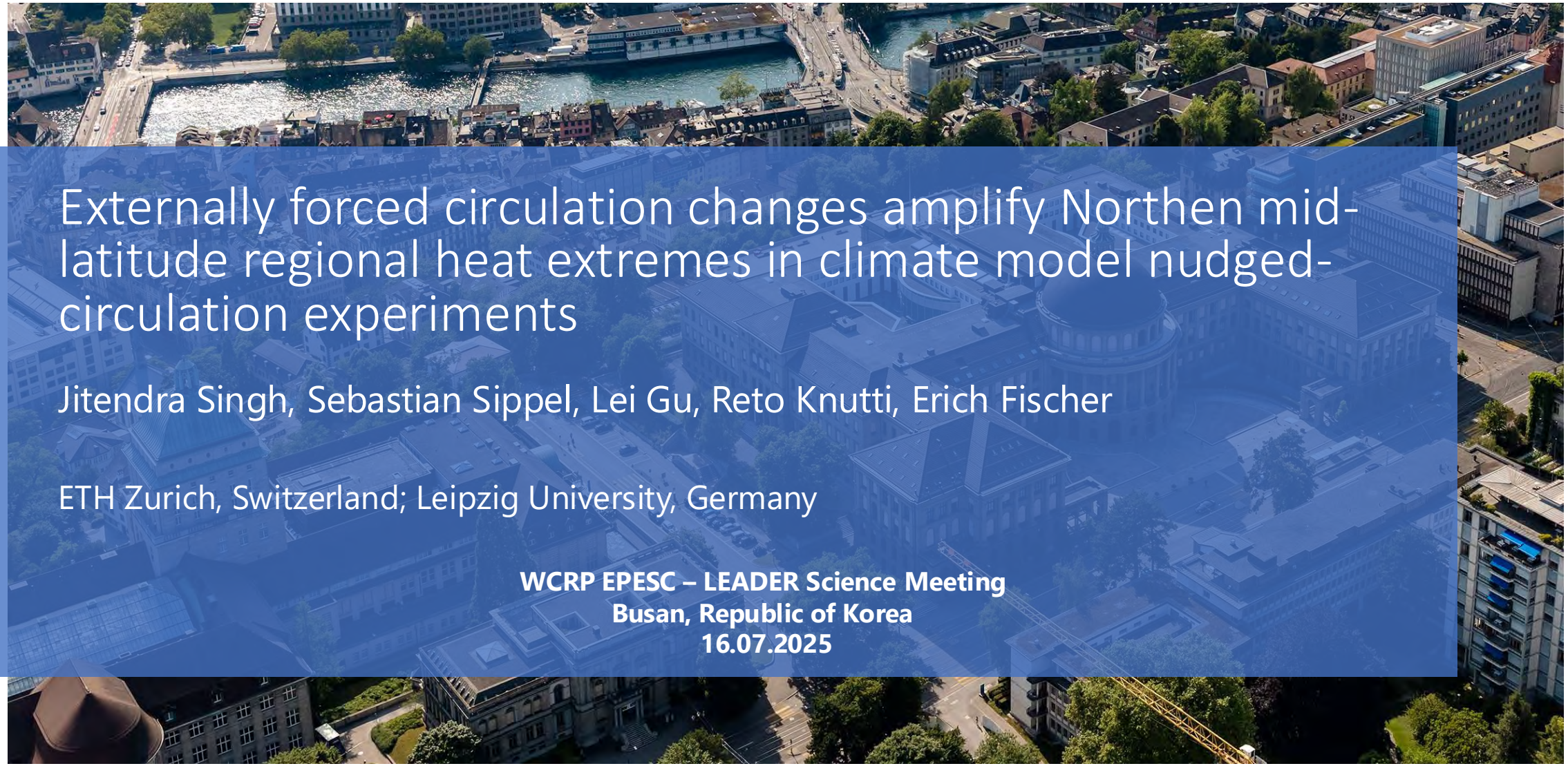

Externally forced circulation changes amplify Northen mid-latitude regional heat extremes in climate model nudged-circulation experiments

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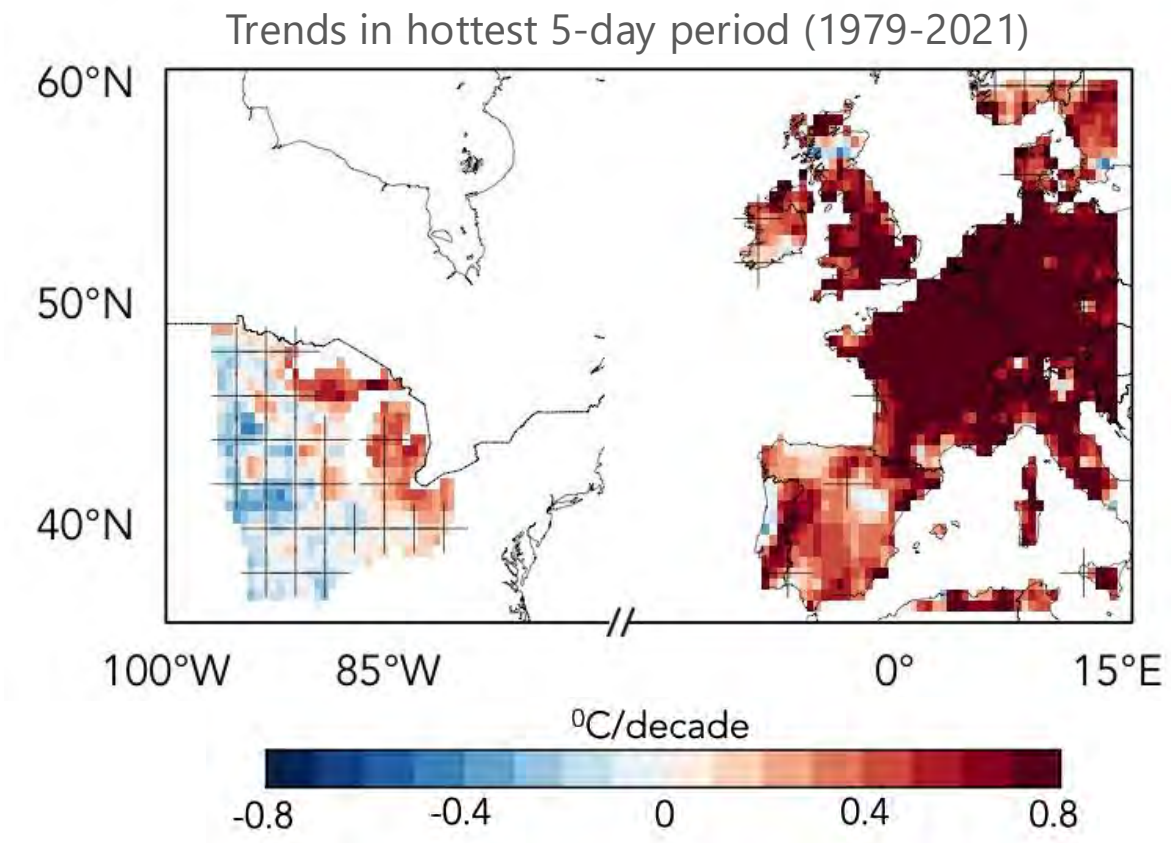
Motivation: Contrasting Trends in Western Europe and the Midwest USA

Robust warming over Western Europe (WEU); Weak cooling over the Midwest USA (MUS)



Tx5d **intensify >3°C in WEU** and **lessen by ~1°C in the MUS** for each 1°C increase in GMST

Singh *et al.* (2023)

Question: Why do observed trends in heat extremes intensity over the MUS and WEU differ so remarkably? What do these trends imply for future?

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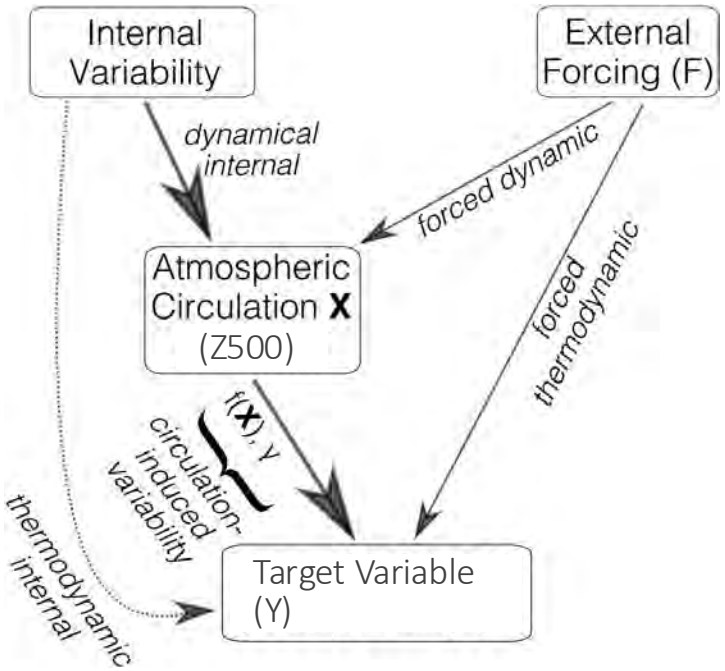
Machine learning based dynamical adjustment

Estimate the variability in a target variable due to atmospheric circulation changes



Circulation component:

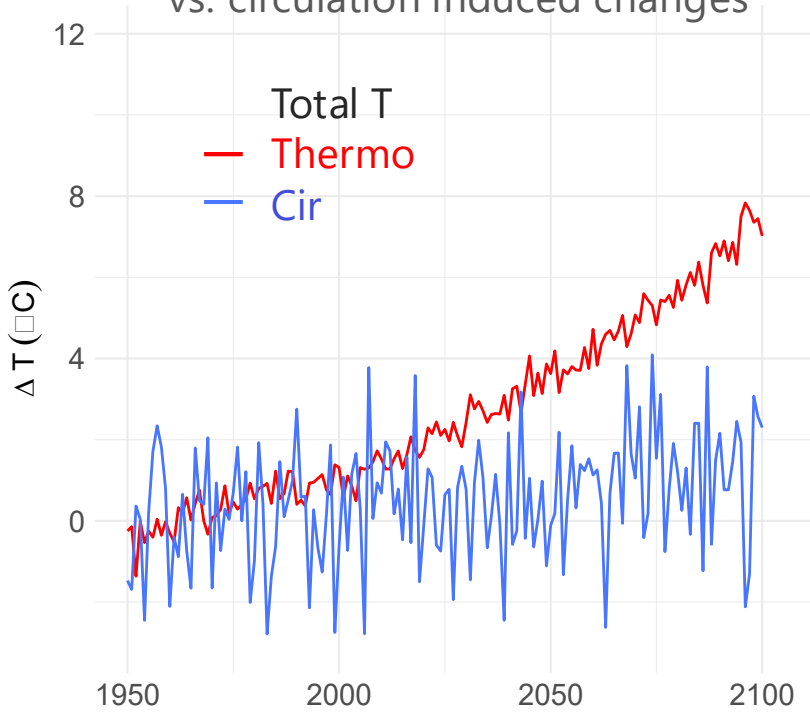
$$\widehat{T_X} = \mathcal{F}(Z500_d) \approx \hat{\gamma} Z500_d$$

Thermodynamic component:

$$\text{Residual } (\varepsilon) = TX - \widehat{T_X}$$

$Z500_d$ - de-trended geopotential height at 500 hPa pressure level

Illustration of thermodynamic vs. circulation induced changes



Singh *et al.* (2023)

Regularized ridge regression model is trained on 2400 years of CESM2 pre-industrial control simulations

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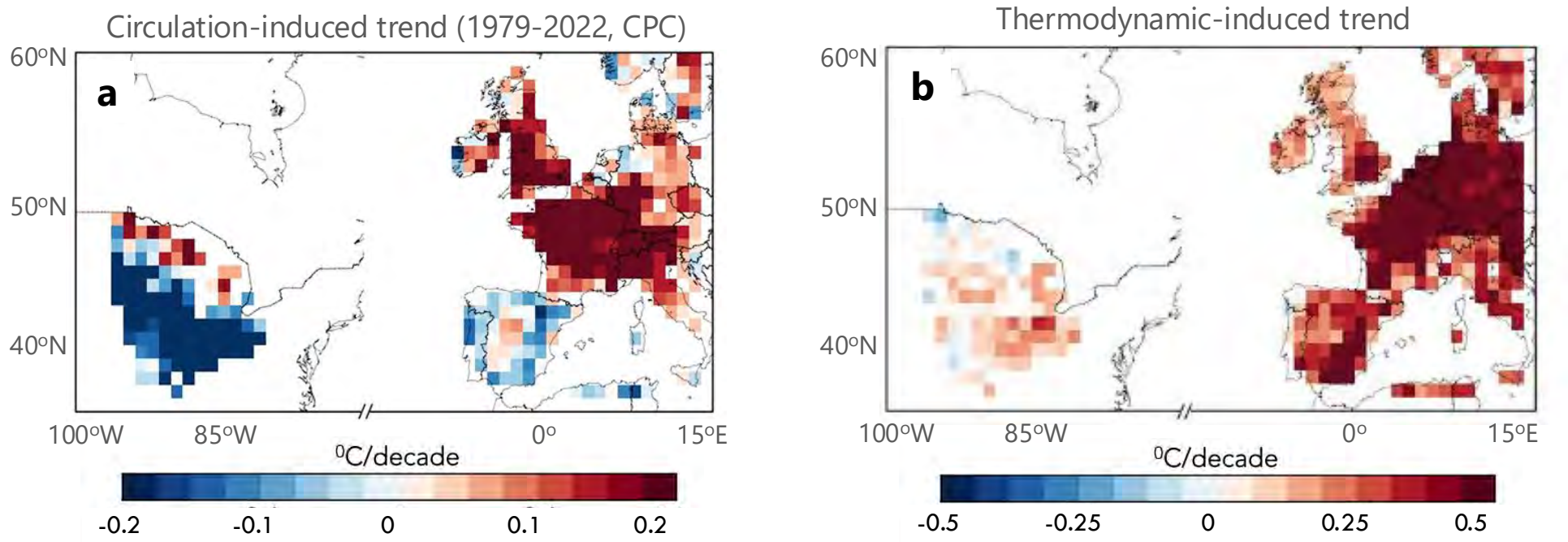
Circulation amplified heat extremes over WEU and dampened over the MUS



Singh *et al.* 2023
(Communications Earth & Env)

- Circulation offsets thermodynamic warming in the MUS
- Thermodynamic dominates heat extremes trends in WEU

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How circulation will shape the heat extremes in coming decades. It depends…

- If they are forced, it may increase heat extremes in WEU, while counteracting warming could lead to continued weak trends in the MUS

- If the trends are due to internal variability, they may reverse within decades, potentially slowing heat extremes rise in WEU and causing warmer conditions in the MUS

To what extent are circulation trends primarily forced or due to internal variability??

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Role of externally forced atmospheric circulation change in heat extremes

Constrains large-scale atmospheric circulation to transient climate while keeping all other forcings at pre-industrial levels

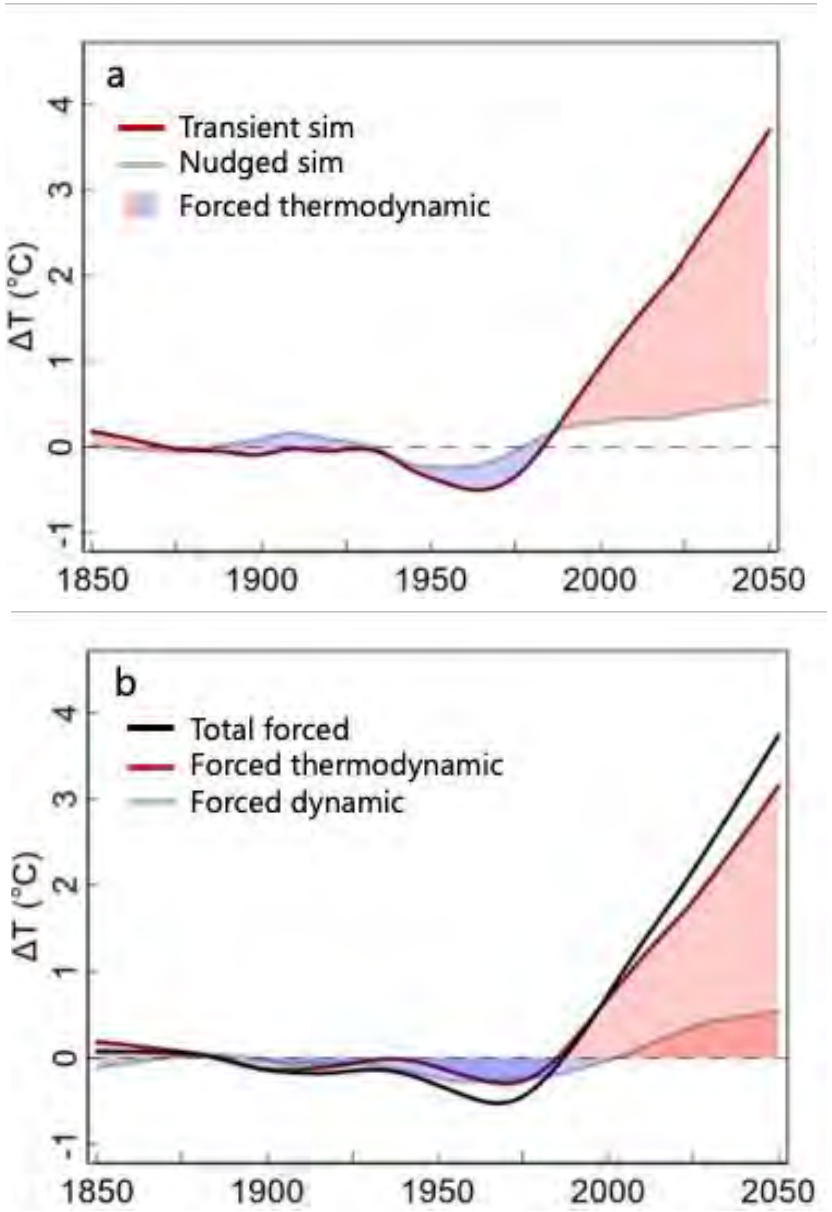
$T_i = TD_F + D_F + IV_i$ T_i: i^{th} simulation, IV: internal variability

$T_{N_i} \approx D_F + IV_i; \quad as \; TD_{pi} \approx 0$

T_{N_i}: i^{th} nudged simulation, TD_{pi}: thermodynamic at pre-industrial level

$\boldsymbol{TD_F = \frac{1}{k}\sum_{i=1}^{k}(T_i - T_{N_i})}$ *k:* no of nudged simulations

$\boldsymbol{D_F = T_{tot} - TD_F}$ T_{tot}: total forced (large ensemble mean)



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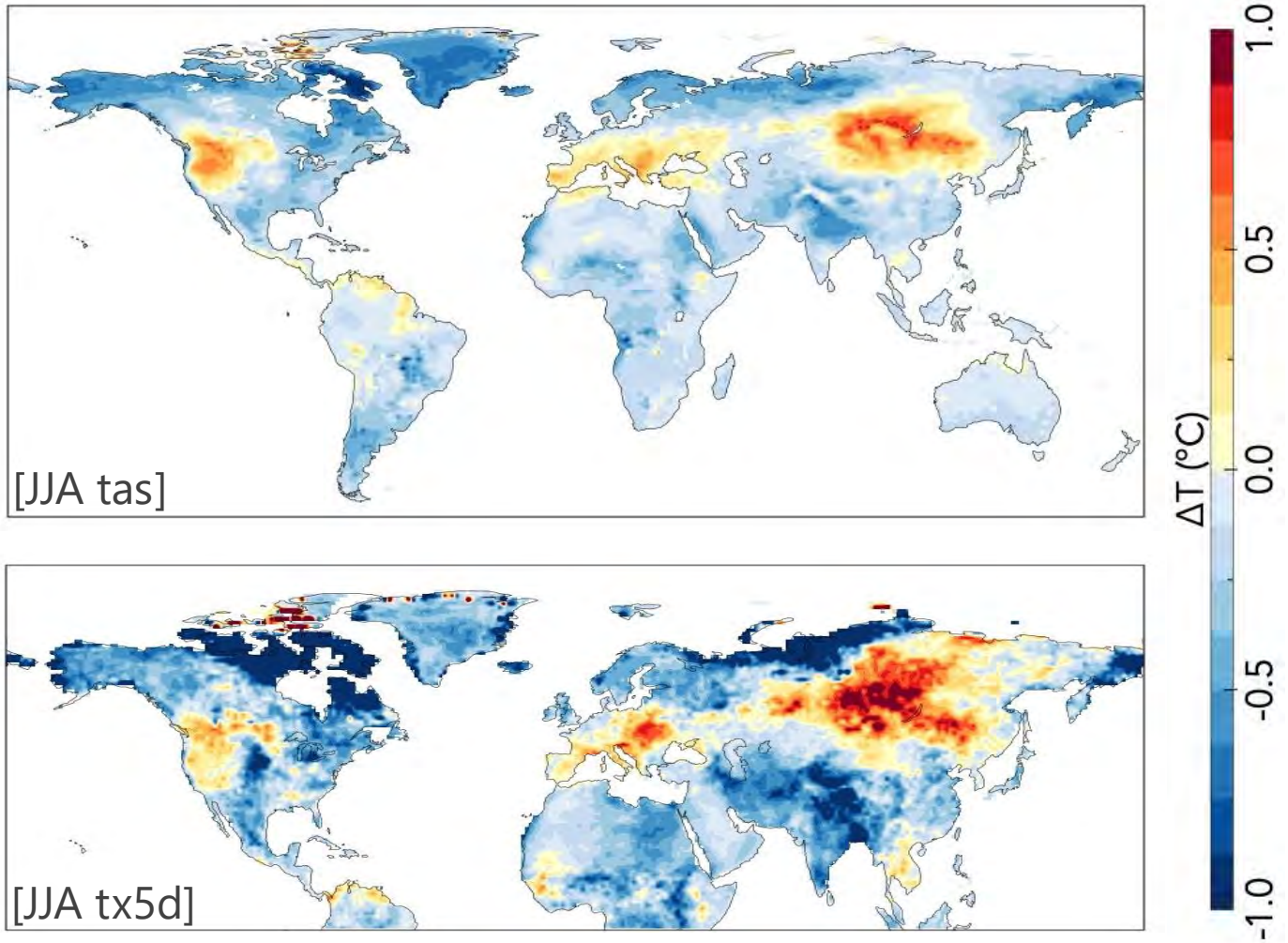
Forced dynamic induced trends in heat extremes



- A substantial proportion of circulation-driven summer heat extremes is externally forced, contributing up to 1°C warming since 1979 in several northern mid-latitude regions

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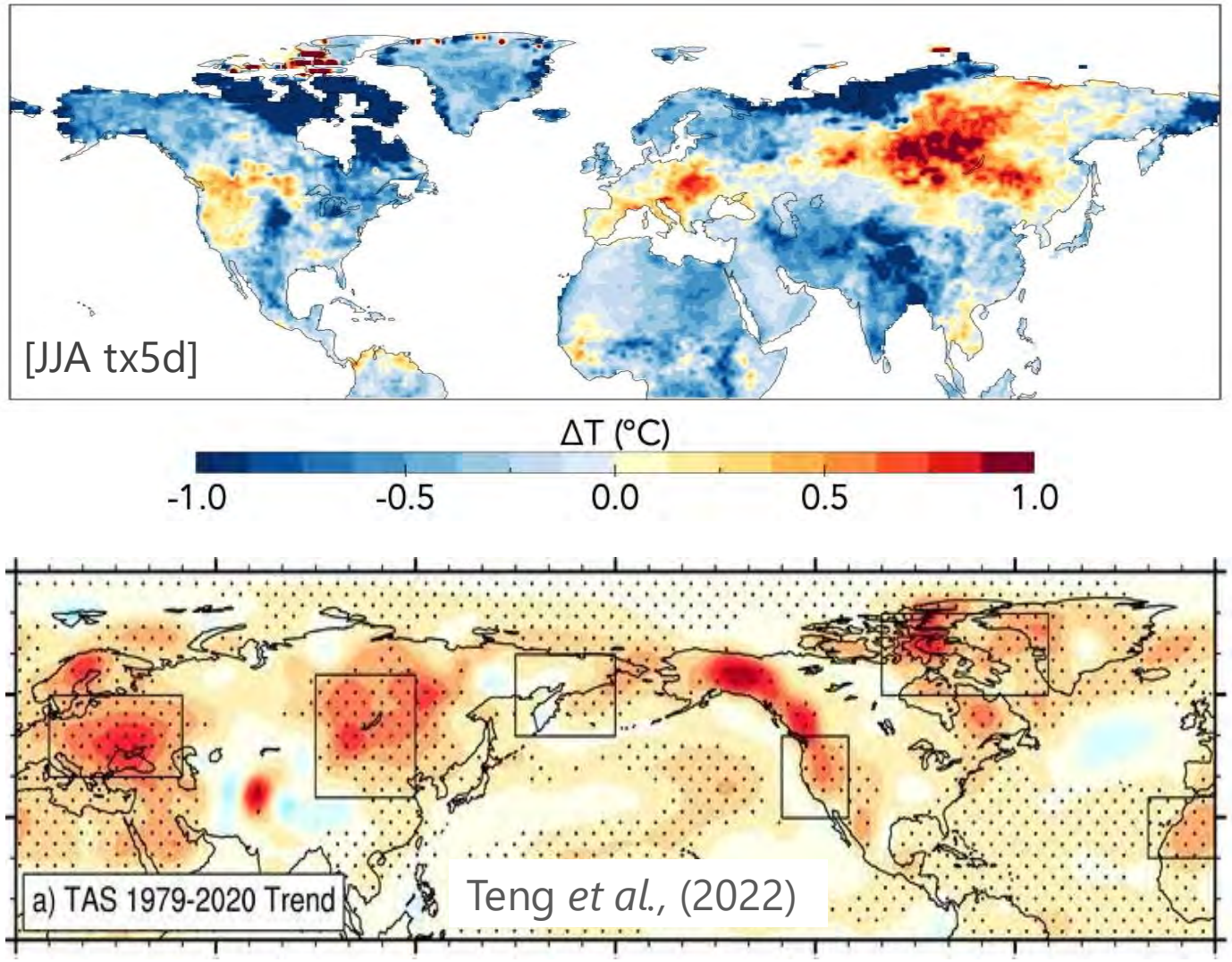
Model-based evidence of circulation-linked warming hotspots aligns with observations, yet to be fully validated



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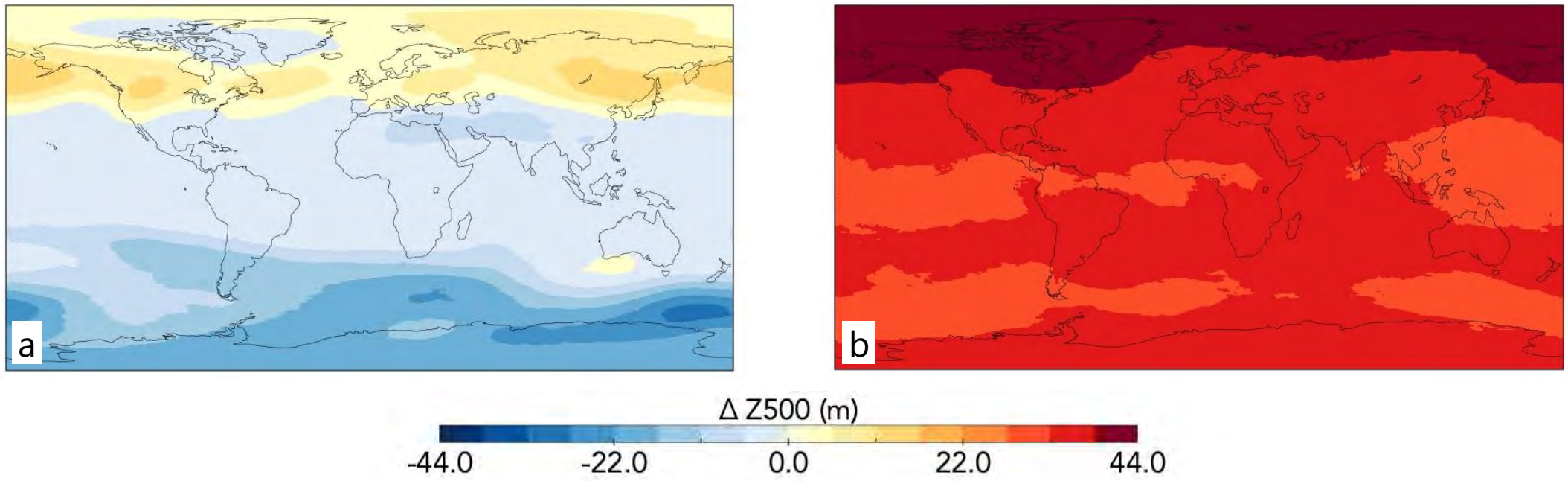
Forced responses in geopotential hight at 500 hPa (Z500)

Strengthening high-pressure systems over Northen mid-latitudes

Forced dynamic

Forced thermodynamic



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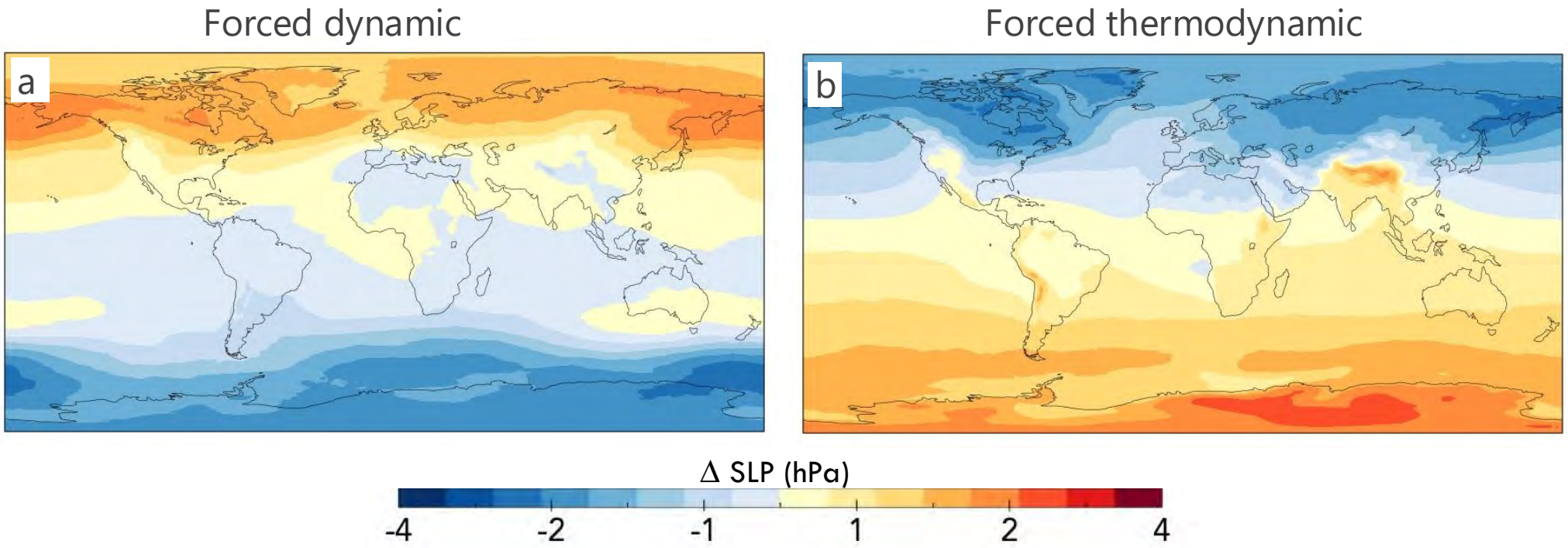
Forced responses in seal level pressure

Dynamically forced SLP trends show a distinct hemispheric asymmetry



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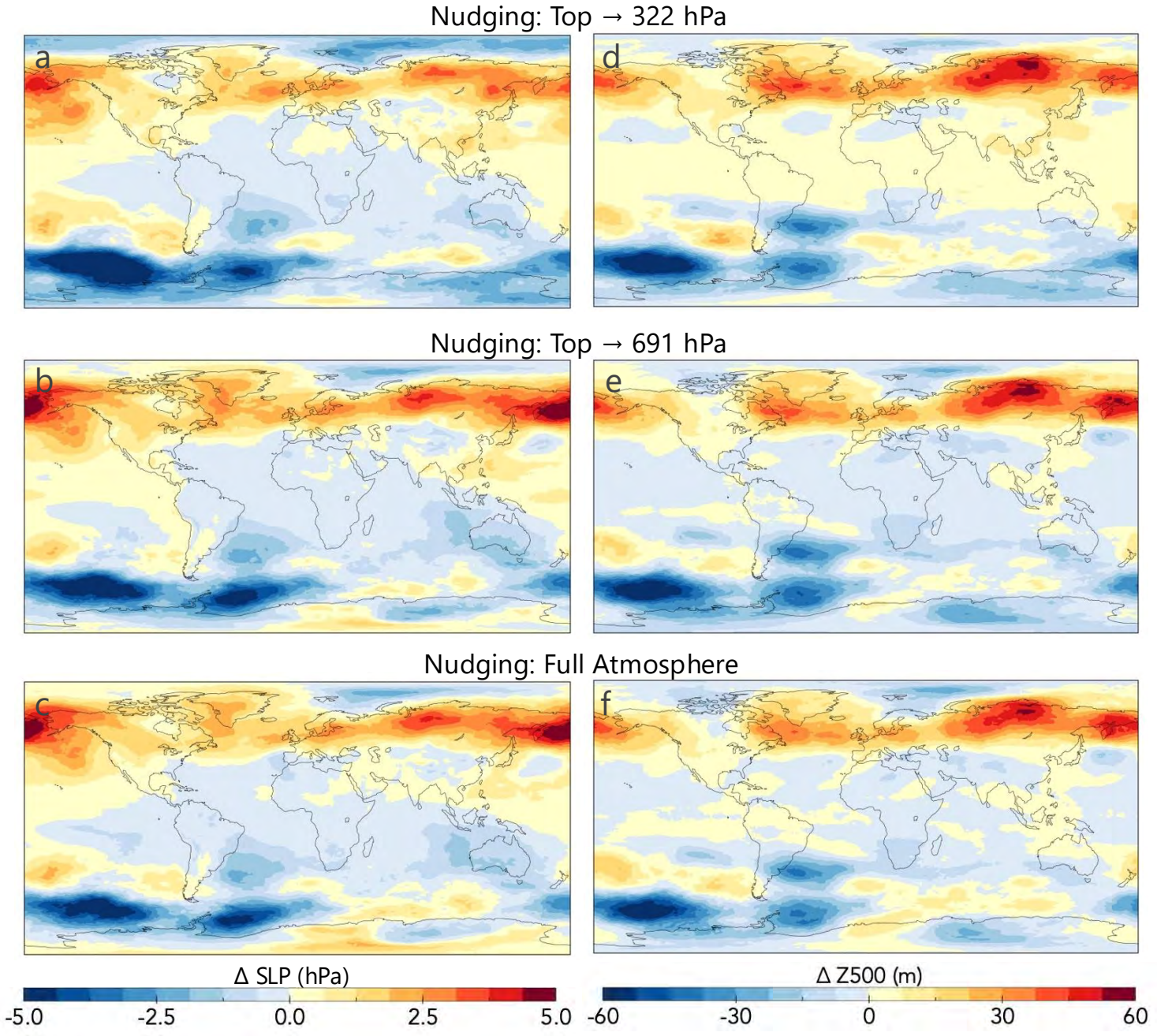
Senstitivity test of nudging setup - how important is the level on which we nudge?

Trend patterns in SLP and Z500 remain largely consistent across different nudging configurations



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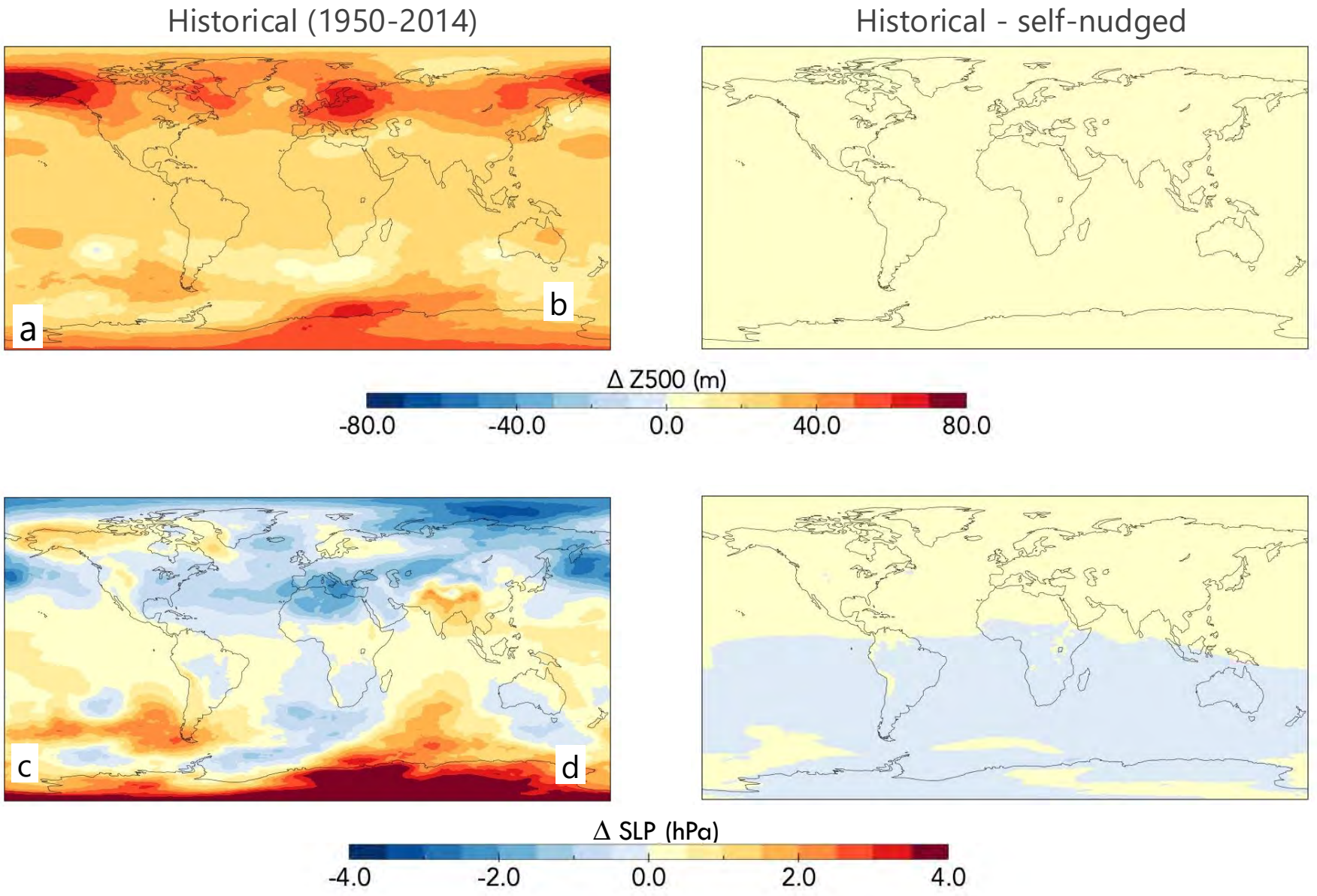
Thermodynamic feedback in surface temperature in nudging setup



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Key Takeaway

- Northern mid-latitudes are key heatwave hotspots, where atmospheric circulation plays a dominant role in driving heat extremes
- A substantial part of these circulation trends is externally forced, not just internal variability
- Our approach allows for a clean separation of forced thermodynamic and dynamic signals, and can be used by other modeling groups to assess forced heat extreme responses across models
- **Limitation:** Some feedbacks (like wind–SLP interactions) may not fully evolve, which is a common challenge in nudging-based experiments

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Thank you for listening