Historical Pattern Effects and Climate Sensitivity Revisited with Novel Constraints on Past Warming Patterns

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Motivation

- Climate **feedbacks depend on spatial patterns** of SST and sea ice
- But there are **disagreements between existing SST datasets** resulting from different methods for infilling the gaps between sparse observations
  - **Recent studies have questioned the historical pattern effect:** is it a result of issues with historical SST datasets?
  - What is the uncertainty in historical feedbacks from uncertain SST patterns?
- Do we know how recent trends from 1980–present compare to pre-1980 variability? **How unusual is the recent evolution of circulation, SST, and sea ice?**
- There is an **opportunity to combine observations** of SST, land-based air temperature, and sea-level pressure **using *coupled data assimilation***
- With **new constraints on historical SST, sea ice, and SLP patterns**, we can revisit historical feedbacks, pattern effects, and implications for ECS

Method of Historical Reconstruction

Linear Inverse Model (LIM) and Observation Network

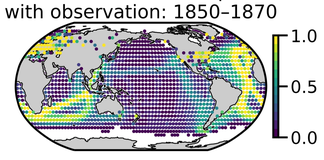
- LIMs are empirical climate models with **linear dynamics** (**L**) and **stochastic noise** (**S**$\boldsymbol{\eta}$), and they reproduce the climate statistics of the training data
- We build 8 "cyclostationary" (monthly) LIMs separately for CESM2, E3SMv2, HadGEM3, GFDL-ESM4, EC-Earth3, NorESM2, UKESM1, SAM0-UNICON

$$\mathbf{x} = \begin{bmatrix} SST \\ T \\ SLP \\ SIC \end{bmatrix} \qquad \frac{d\mathbf{x}}{dt} = \mathbf{L}\mathbf{x} + \mathbf{S}\boldsymbol{\eta}$$

$$\mathbf{L}_j = \tau^{-1}\ln\left[\mathbf{C}_j(\tau)\mathbf{C}_j(0)^{-1}\right], \quad j = 1, \ldots, 12\ (months);\ \tau = 1$$

- We include observations of:
  - SST (HadSST4)
  - Land T (CRUTEM5)
  - SLP (ICOADS)
  - Sea ice (NSIDC satellite)

Fraction of timesteps with observation: 1850–1870



Coupled Data Assimilation (DA)

- **LIM** produces monthly "prior" forecasts, and the **Kalman filter** produces the "posterior" analysis (accounting for model and observation uncertainty)
- Forecasts are initialized from previous analysis (i.e., this **framework has "memory" of past observations**)

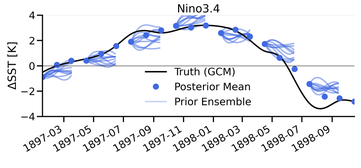
Ensemble Mean (x) $\quad \mathbf{G}_j = \exp(\mathbf{L}_j \delta t)$

1) Forecast: $\mathbf{x_f}(t+\delta t) = \mathbf{G}_j \mathbf{x_a}(t) + \boldsymbol{\not{\eta}}$
2) Assimilation: $\mathbf{x_a} = \mathbf{x_f} + \mathbf{K}(\mathbf{y} - \mathbf{H}\mathbf{x_f})$
$\mathbf{K} = \mathbf{P_f}\mathbf{H}^{\mathrm{T}}[\mathbf{H}\mathbf{P_f}\mathbf{H}^{\mathrm{T}} + \mathbf{R}]^{-1}$

Covariance (P)

1) Forecast: $\mathbf{P_f}(t+\delta t) = \mathbf{G}_j \mathbf{P_a} \mathbf{G}_j^{\mathrm{T}} + \mathbf{N}_j$
$\mathbf{N}_j = \boldsymbol{C}_{j+1}(0) - \mathbf{G}_j \boldsymbol{C}_j(0) \mathbf{G}_j^{\mathrm{T}}$
2) Assimilation: $\mathbf{P_a} = (\mathbf{I} - \mathbf{K}\mathbf{H})\mathbf{P_f}$

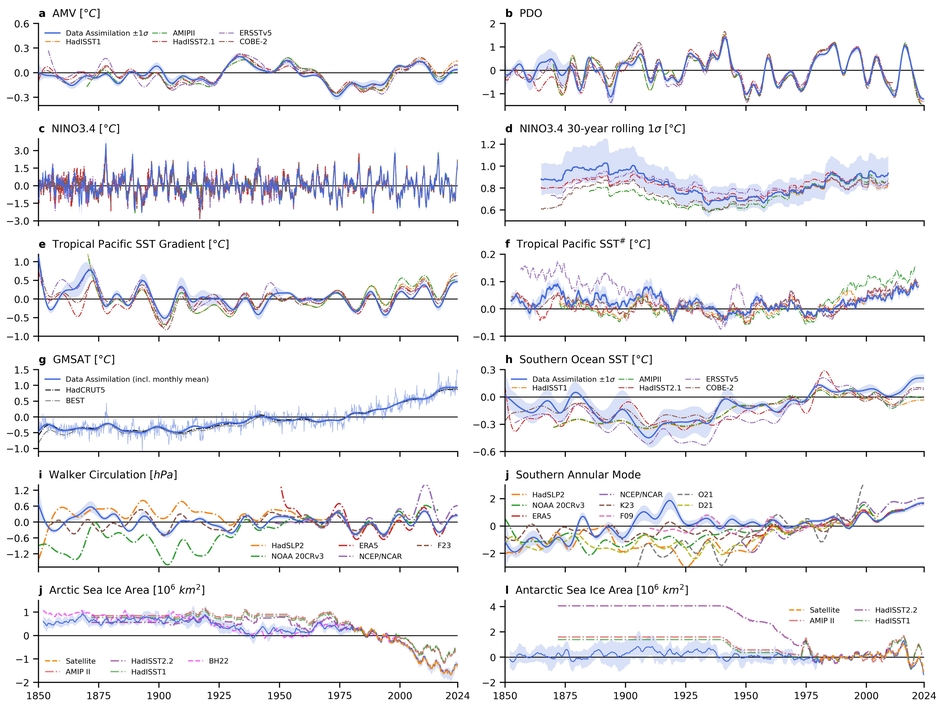
Illustration of LIM + DA Method



Results: Historical Reconstruction

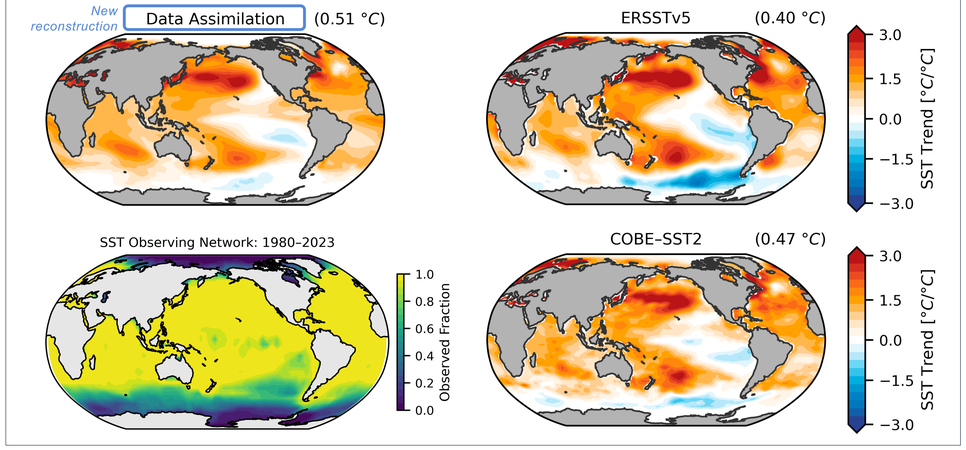
Variability in SST, Sea-Level Pressure, and Sea Ice

- With these constraints on past variability, we may need to revise interpretation of recent trends in **tropical SST, Walker Circulation, SAM, Southern Ocean SST, and Antarctic sea ice**



SST Trends 1980–2023

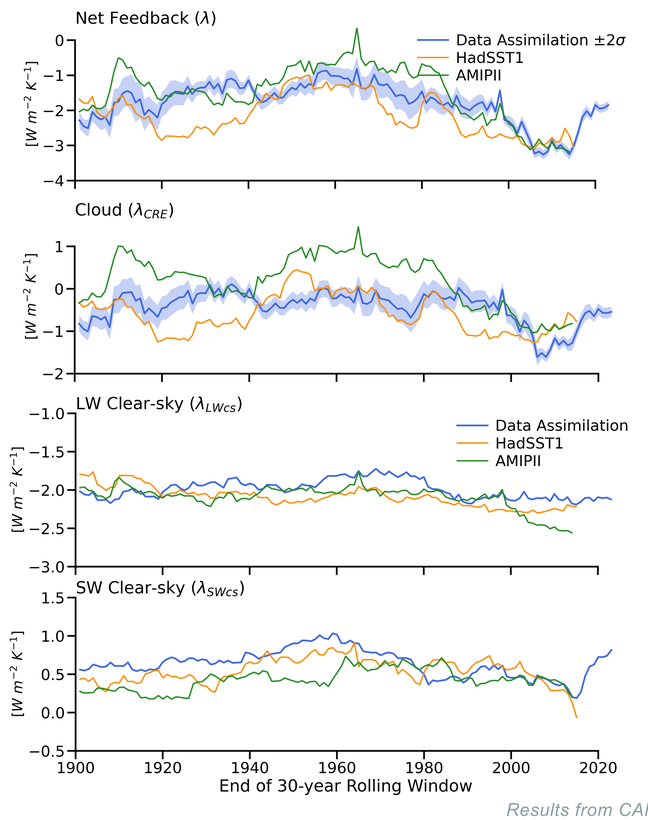
- Southern ocean cooling: perhaps this recent trend is not so extreme?



Results: Historical Feedbacks and Pattern Effects

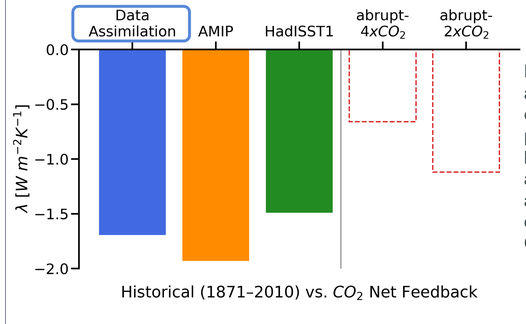
Time-varying Radiative Feedbacks

- Comparing feedbacks from our new reconstruction vs. other SST datasets, we find **more consistent feedbacks pre-1980** and a **more extreme negative feedback in recent decades**



Results from CAM6

Implications: Historical Pattern Effect and Climate Sensitivity



Historical data assimilation **confirms large pattern effect**: historical feedbacks are more stabilizing and negative compared to abrupt-CO_2 feedbacks

Results from CAM6

Conclusions & Next Steps

- We combine models and observations to produce **globally resolved monthly SST, surface air temperature, sea ice fraction,** and **sea-level pressure** back to **1850**
  - Method accurately reconstructs out-of-sample climate model *(not shown)*
- Historical reconstruction captures large-scale variability and trends, but perhaps more importantly, **quantifies uncertainty and its spatial fingerprints**
- **Southern Ocean** recent cooling is muted, recent **Walker Circulation** is consistent with past variability, and changes in **Antarctic sea ice** from 1850–present are smaller than existing estimates
- Radiative **feedbacks are more consistent across the historical record** in our reconstruction
  - But the **recent (post-1980) negative feedback now appears even more unusual**, requiring further investigation
- New constraints on past warming patterns confirm a **large historical pattern effect**, supporting recent ECS assessments
  - More work needed on mechanisms, and more experiments in AGCMs needed to quantify uncertainty using new reconstruction

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