Variability in Sea-Surface Temperature and Sea Ice Patterns from Coupled Data Assimilation, 1850–present

Vincent Cooper[1], Gregory Hakim[1], and Kyle Armour[1]

[1]Department of Atmospheric Sciences, University of Washington

Motivation

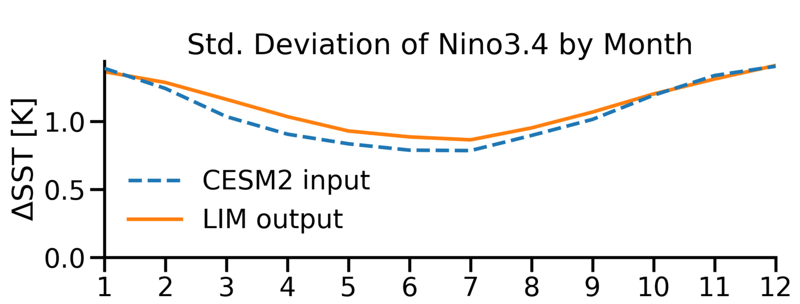
- *First, see HadISST vs. NOAA ERSST trends in SST (**bottom-right figure**)*
- Climate **feedbacks depend on spatial patterns** of SST and sea ice
- Substantial **disagreements across existing SST datasets** come from different infilling methods applied to unobserved regions
- **We don't know how satellite-era trends compare to pre-1980 variability** because of the disagreements across datasets
- We **need to quantify uncertainty** in SST and sea-ice patterns
  - And **identify where additional data could help** constrain past variability
- There is an **opportunity to combine obs** of ship-based SST, land-based air temperature, and sea-level pressure **using *coupled data assimilation***

Methods

Linear Inverse Model (LIM)

- Coupled online data assimilation (DA) with climate models is not feasible, so we build **linear inverse models (LIMs)** to represent climate models
- LIMs contain **linear dynamics (L)** and **stochastic noise (S)**, which together can reproduce the original statistics of the input climate model

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



- We build "cyclostationary" (monthly) LIMs separately for:
  - **CESM1, CESM2, MRI-ESM2-0, HadCM3, GISS-E2R**

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

(Shin et al. 2021; Penland & Sardeshmukh 1995)

Data Assimilation (DA)

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

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

1) Forecast: $\mathbf{x_f}(t+\delta t) = \mathbf{G}_j\mathbf{x_a}(t) + \cancel{\mathbf{n}}$
2) Assimilation: $\mathbf{x_a} = \mathbf{x_f} + \mathbf{K}(\mathbf{y} - \mathbf{H}\mathbf{x_f})$

$\mathbf{K} = \mathbf{P_f}\mathbf{H}^{\mathrm{T}}[\mathbf{H}\mathbf{P_f}\mathbf{H}^{\mathrm{T}} + \mathbf{R}]^{-1}$

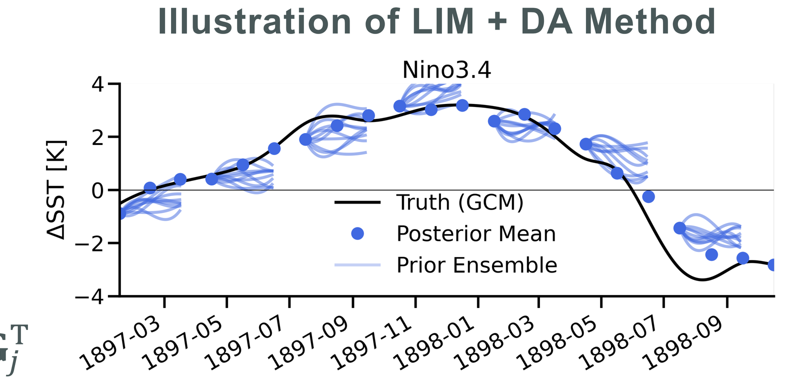
Covariance (P)

1) Forecast: $\mathbf{P_f}(t+\delta t) = \mathbf{G}_j\mathbf{P_a}\mathbf{G}_j^{\mathrm{T}} + \mathbf{N}_j$

$\mathbf{N}_j = C_j(0) - \mathbf{G}_j C_j(0)\mathbf{G}_j^{\mathrm{T}}$

2) Assimilation: $\mathbf{P_a} = (\mathbf{I} - \mathbf{KH})\mathbf{P_f}$

Illustration of LIM + DA Method

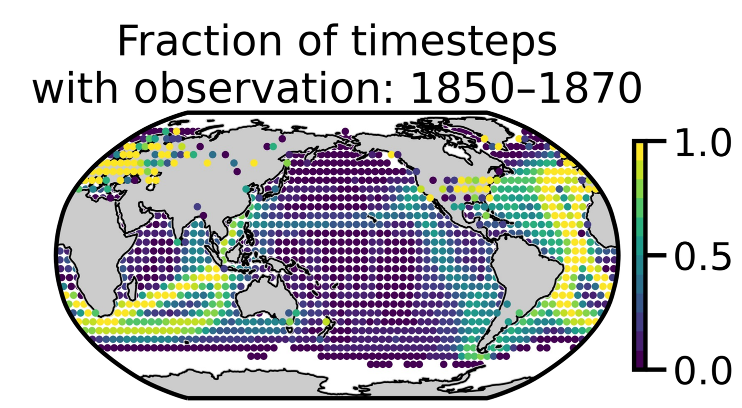


(Hakim et al. 2022)

Results: Test Reconstruction of Climate Model

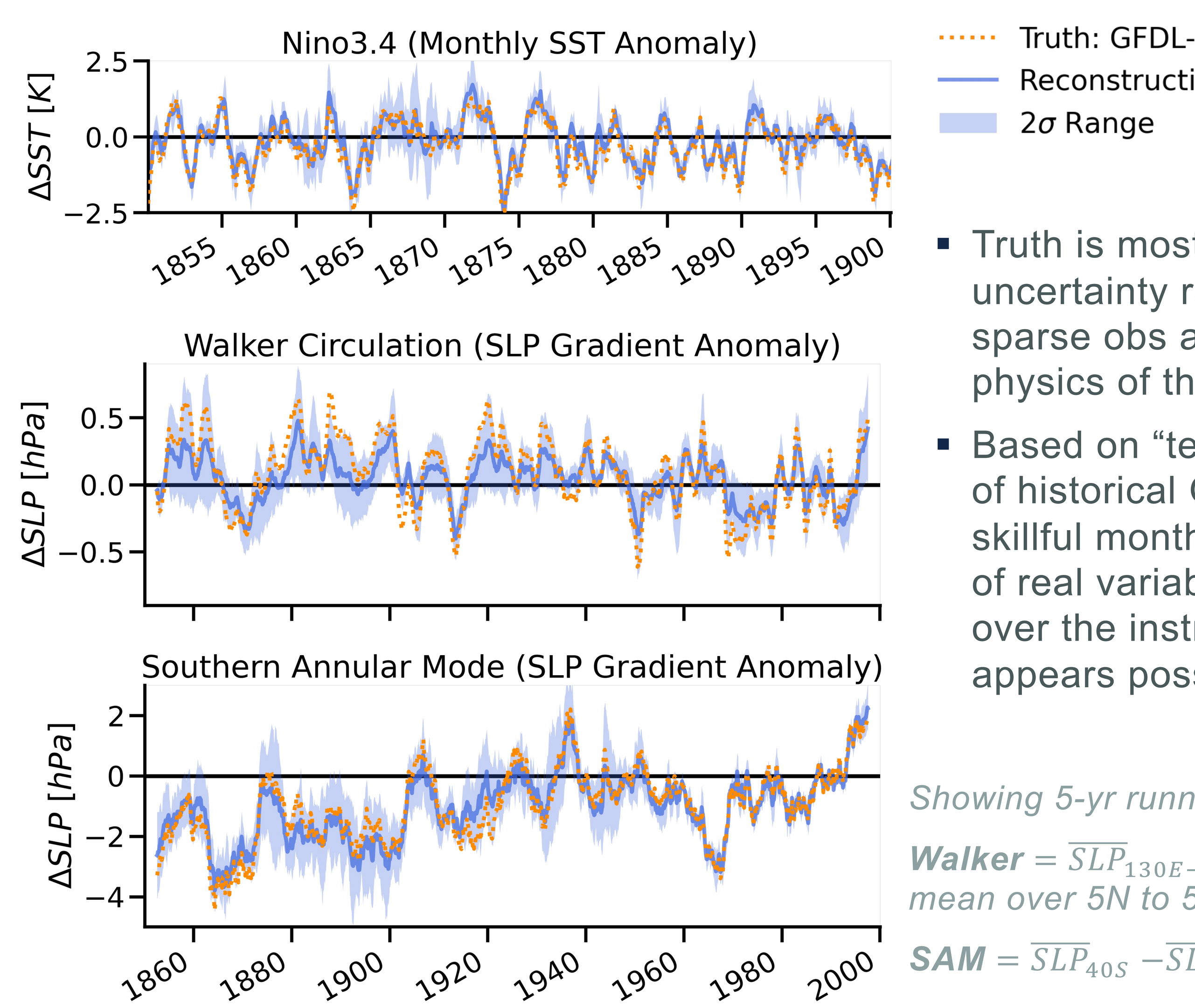
Observation Network

- Monthly mean **SST**, 2-m air **temperature**, and **sea-level pressure** are assimilated from HadSST4, CRUTEM5, and HadSLP2 (1850–2000)
- **Imperfect model "test" reconstructions:** draw obs from a target climate model (**GFDL-CM4** shown below)
  - Locations and errors of the "test" obs (from the target model) are specified to replicate the actual obs



Including HadSST4 and CRUTEM5 (HadSLP2 not plotted)

Validation vs. True Variability in GFDL CM4



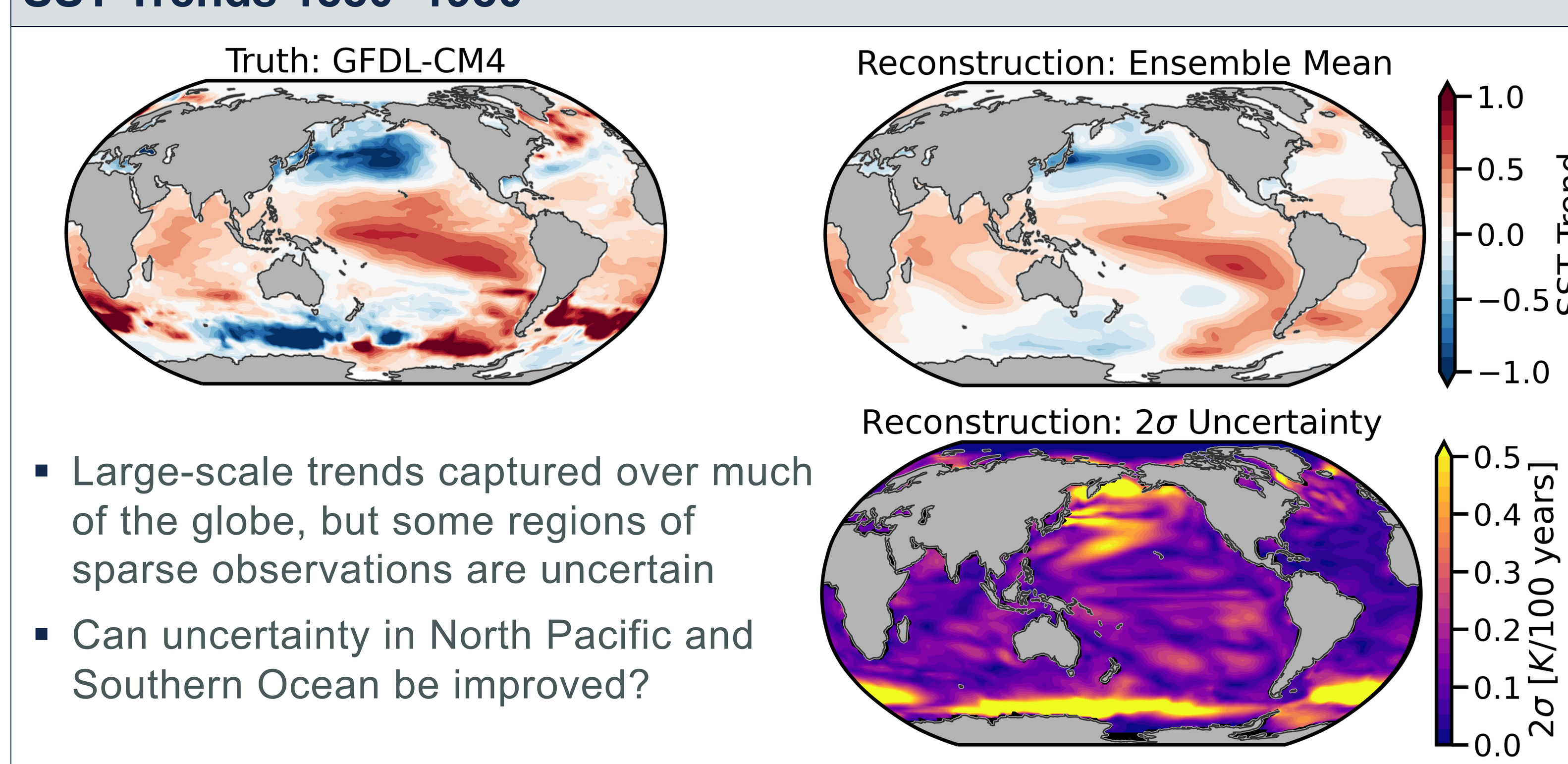
- Truth is mostly within uncertainty range, despite sparse obs and unknown physics of the target model
- Based on "test" reconstruction of historical GFDL-CM4, a skillful monthly reconstruction of real variability and trends over the instrumental era appears possible

Showing 5-yr running mean (anomaly)

Walker $= \overline{SLP}_{130E-150E} - \overline{SLP}_{160W-120W}$ mean over 5N to 5S

SAM $= \overline{SLP}_{40S} - \overline{SLP}_{65S}$

SST Trends 1880–1980

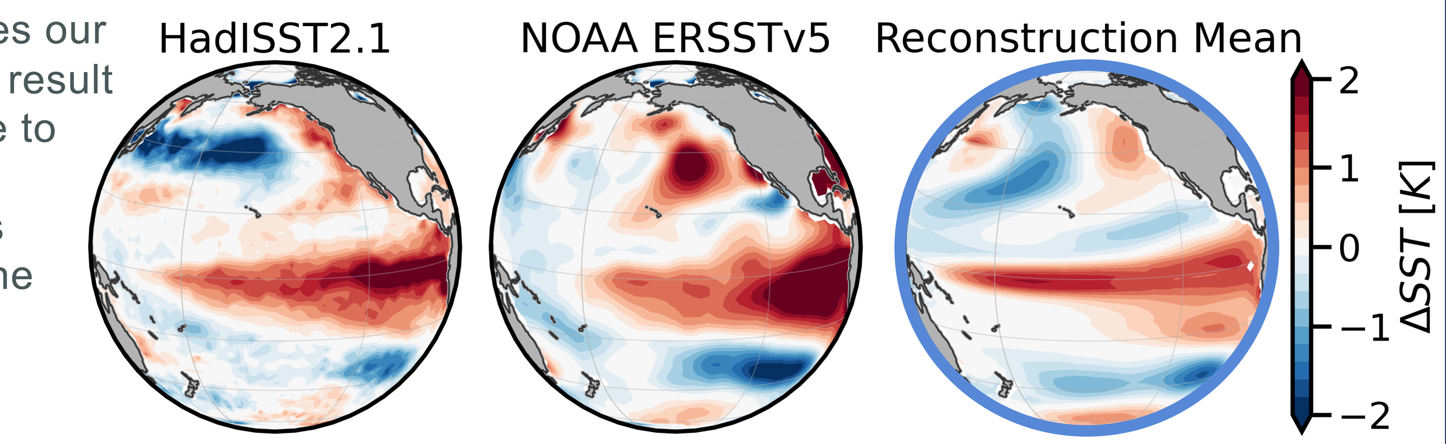


- Large-scale trends captured over much of the globe, but some regions of sparse observations are uncertain
- Can uncertainty in North Pacific and Southern Ocean be improved?

Results: Real Reconstruction with Instrumental Obs.

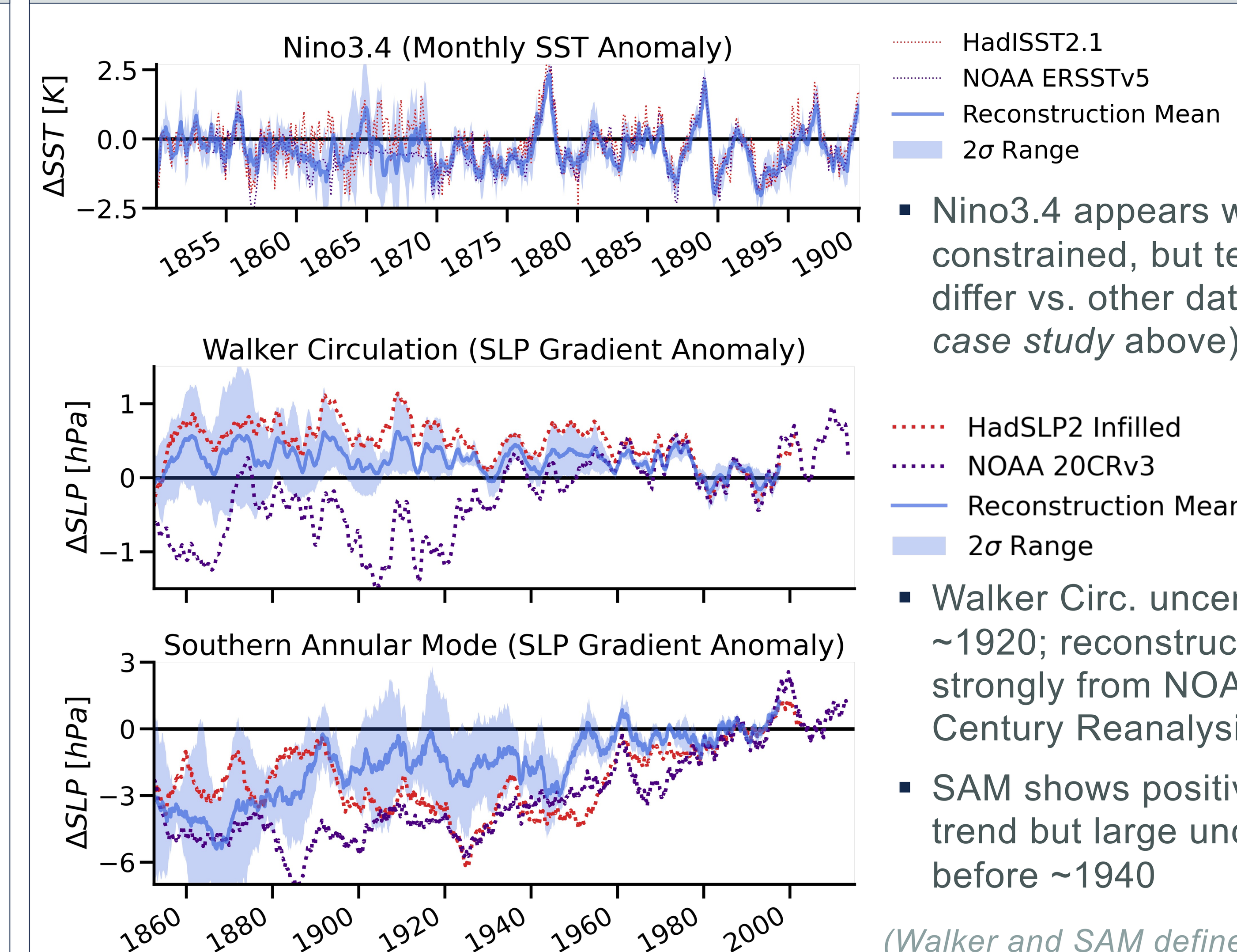
Case Study: Onset of Major ENSO (July 1877)

- How does our LIM+DA result compare to existing datasets during the 1877/78 ENSO?



- Despite similar Nino3.4 values, spatial patterns of SST anomalies vary significantly across existing infilled datasets and vs. our reconstruction

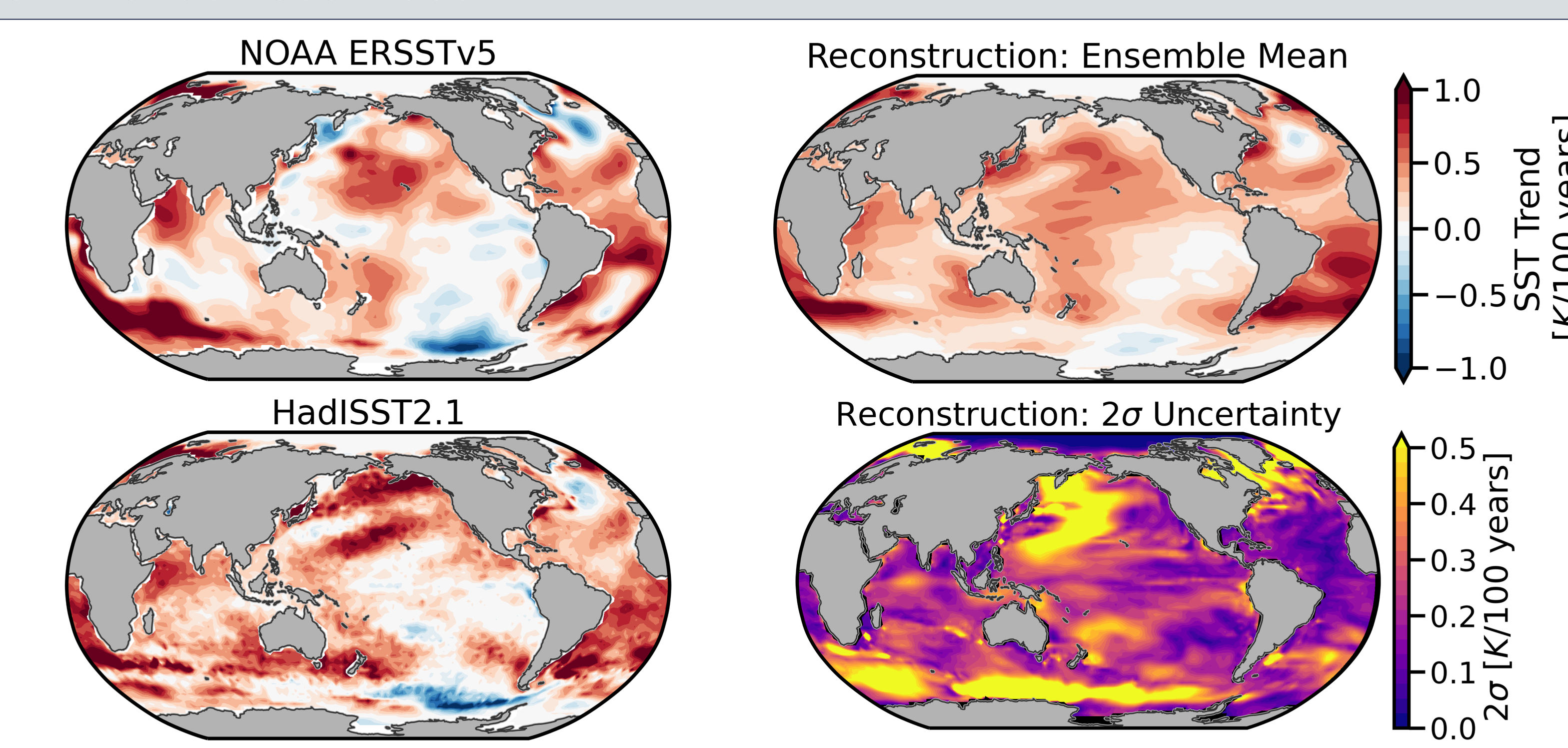
Reconstruction of ENSO, Walker Circulation, and Southern Annular Mode



- Nino3.4 appears well constrained, but teleconnections differ vs. other datasets (see *case study* above)
- Walker Circ. uncertain before ~1920; reconstruction differs strongly from NOAA 20th Century Reanalysis
- SAM shows positive long-term trend but large uncertainty before ~1940

(Walker and SAM defined in box to left)

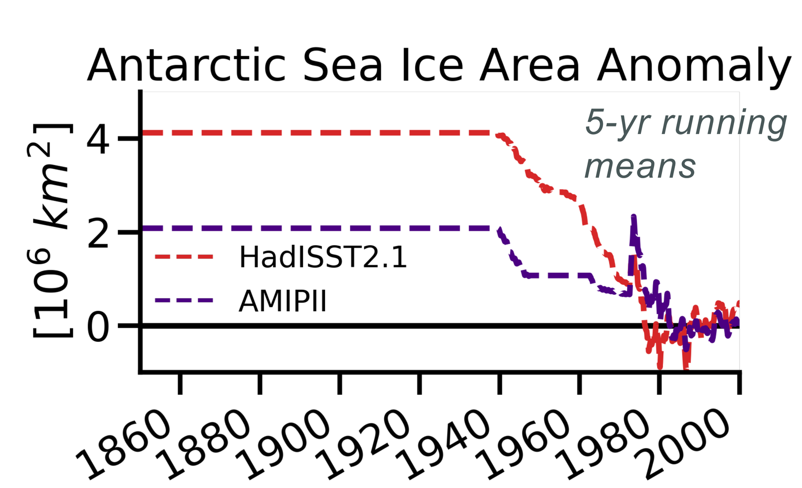
SST Trends 1880–1980



- Existing datasets (*left*) that are currently used as boundary conditions for AGCMs (e.g., in AMIP-type simulations) differ from our reconstruction
- Reconstruction quantifies spatial distribution of uncertainty: could proxies help?

Conclusions & Next Steps

- We combine models and observations to produce **spatially complete monthly SST, 2-m air temp., and sea-level pressure back to 1850**
- LIM+DA method captures large-scale variability and trends, but perhaps more importantly, **quantifies uncertainty and its spatial fingerprints**
- Results could be used in **atmospheric GCMs** to investigate uncertainty in **historical feedbacks** and its sources in the Tropics, Southern Ocean, etc.
- Method could be extended to investigate past variability in the **hydrologic cycle** *(P–E)*
- Reconstruction of **sea ice is a work-in-progress**: challenges come from different mean states and physics in models vs. reality
- Uncertainties in sea ice (and implications for feedbacks) need to be quantified given differences in existing gridded datasets (*see figure at right*)



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Contact: vcooper@uw.edu **Website:** vtcooper.github.io