

The Response of ENSO Diversity and Asymmetry to Mid-Holocene Climate: Revealed by Proxy Records and Isotope-Enabled Earth System Model Simulations

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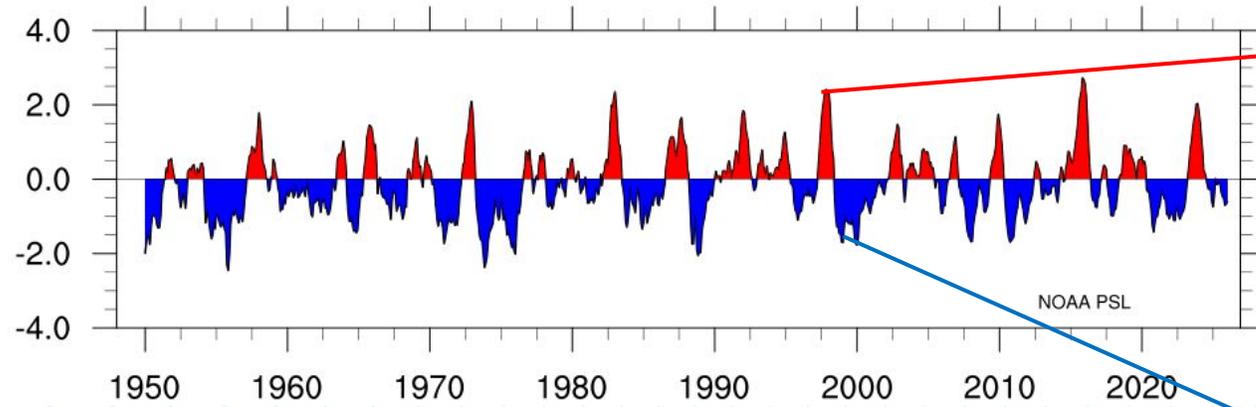
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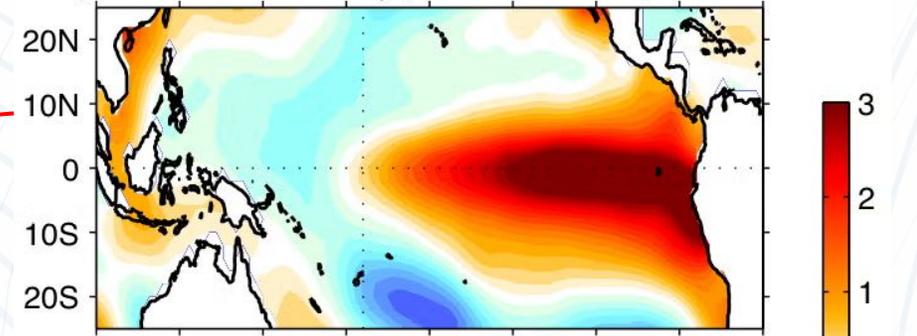
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Niño 3.4

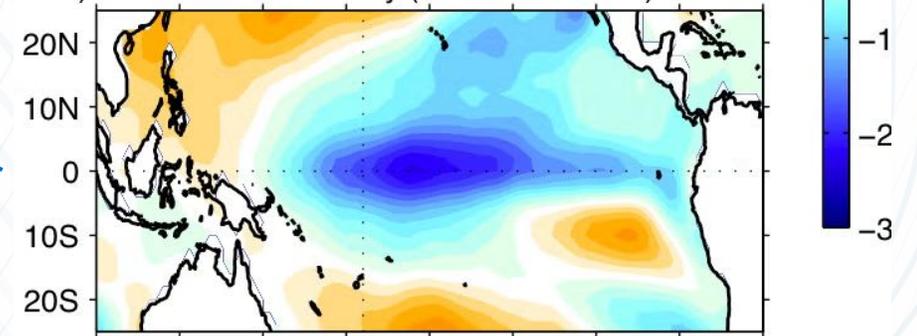


<https://psl.noaa.gov/enso/dashboard.html>

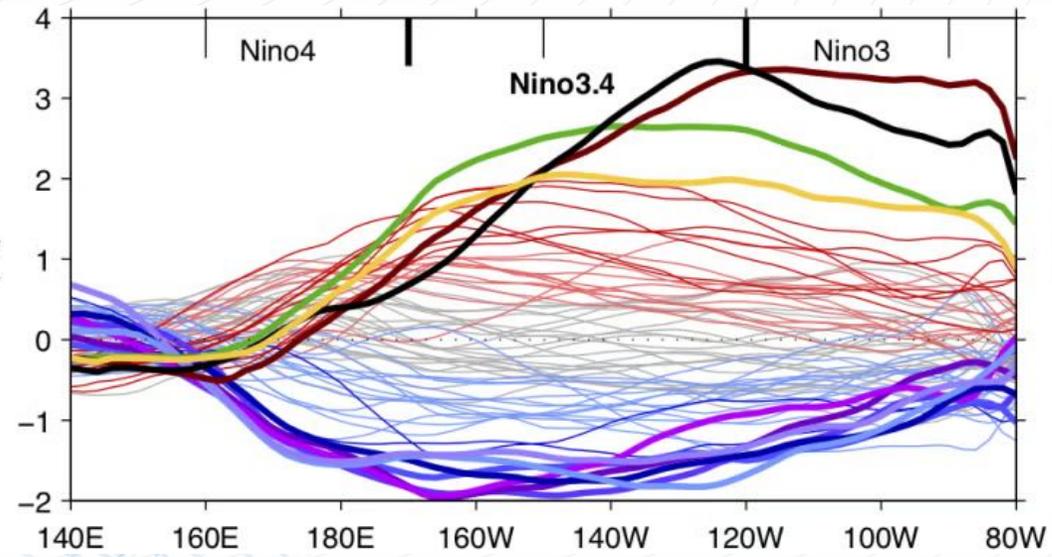
b) El Niño SST anomaly (12/1997–2/1998)



c) La Niña SST anomaly (12/1998–2/1999)



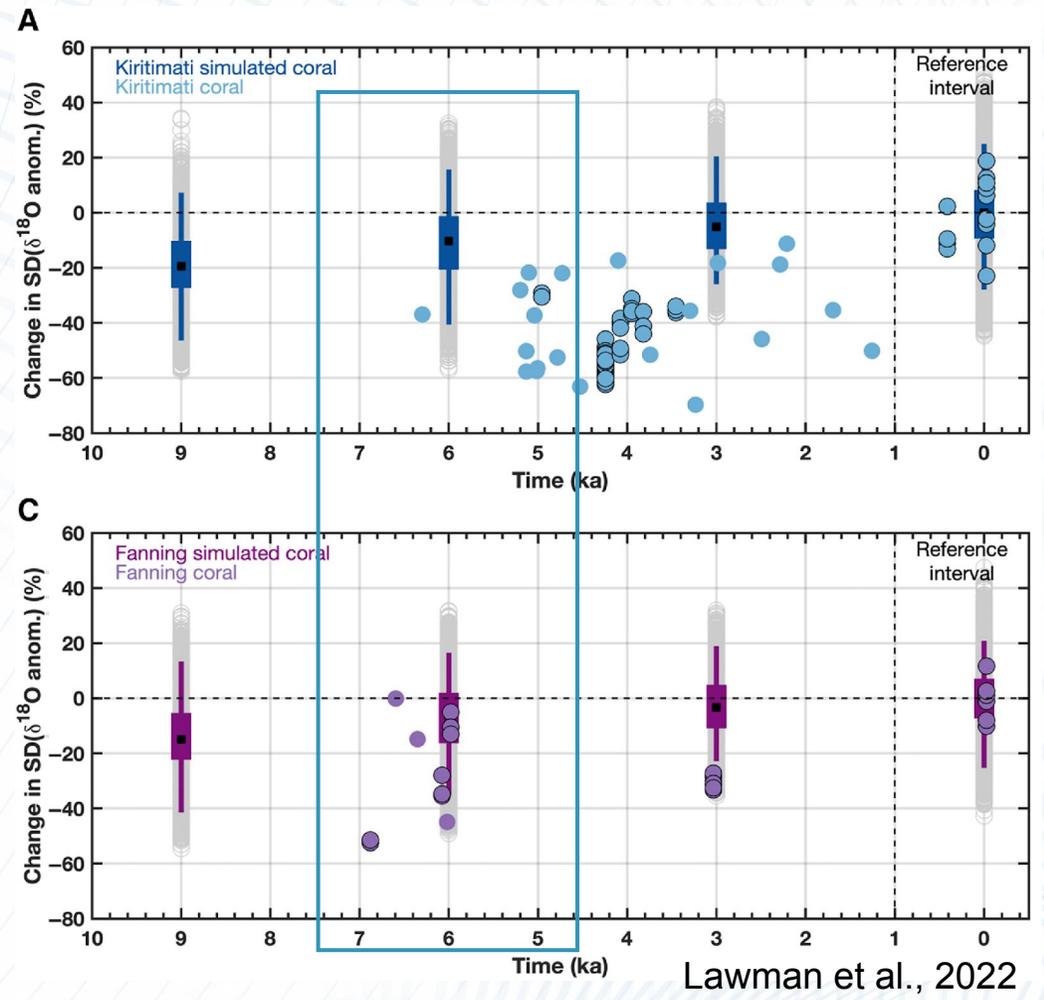
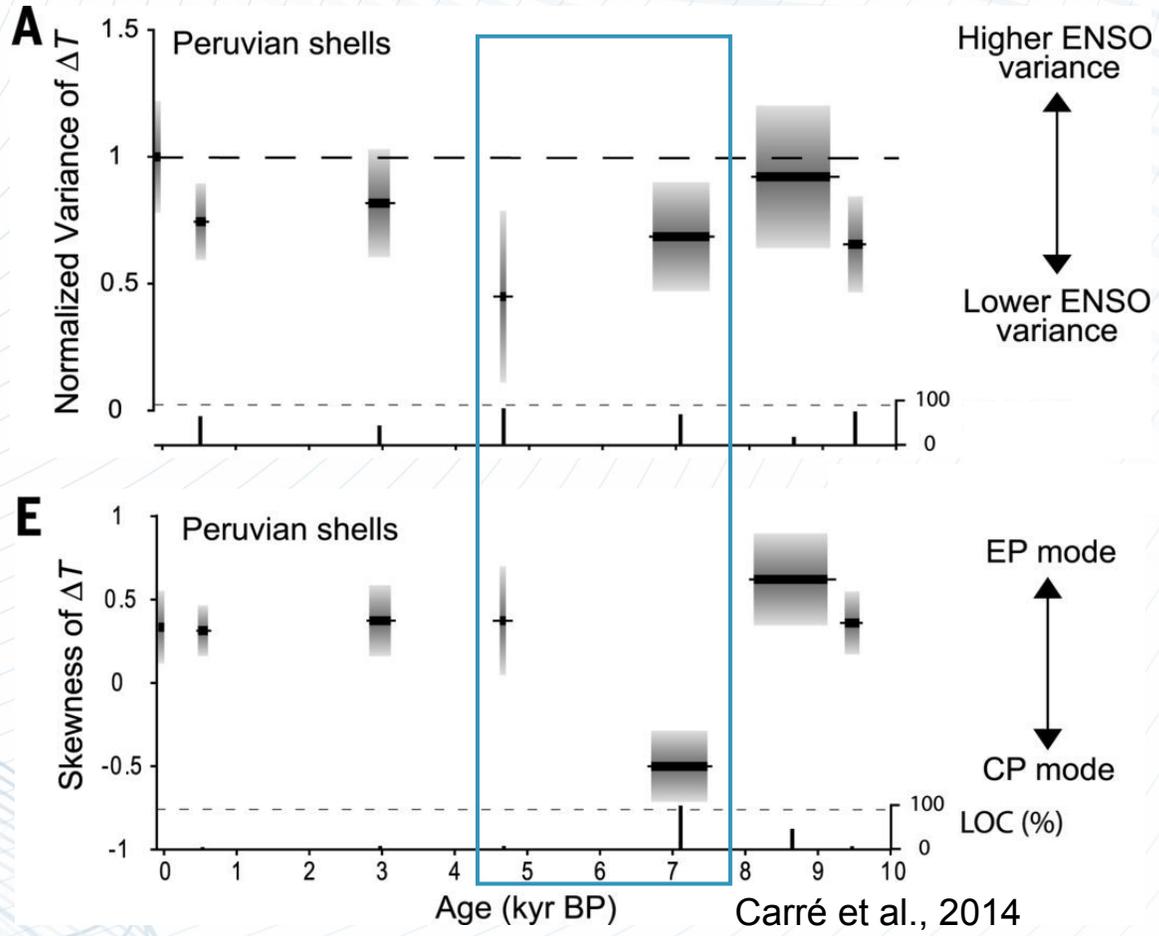
Santoso and NCAR (2022)



Santoso and NCAR (2022)

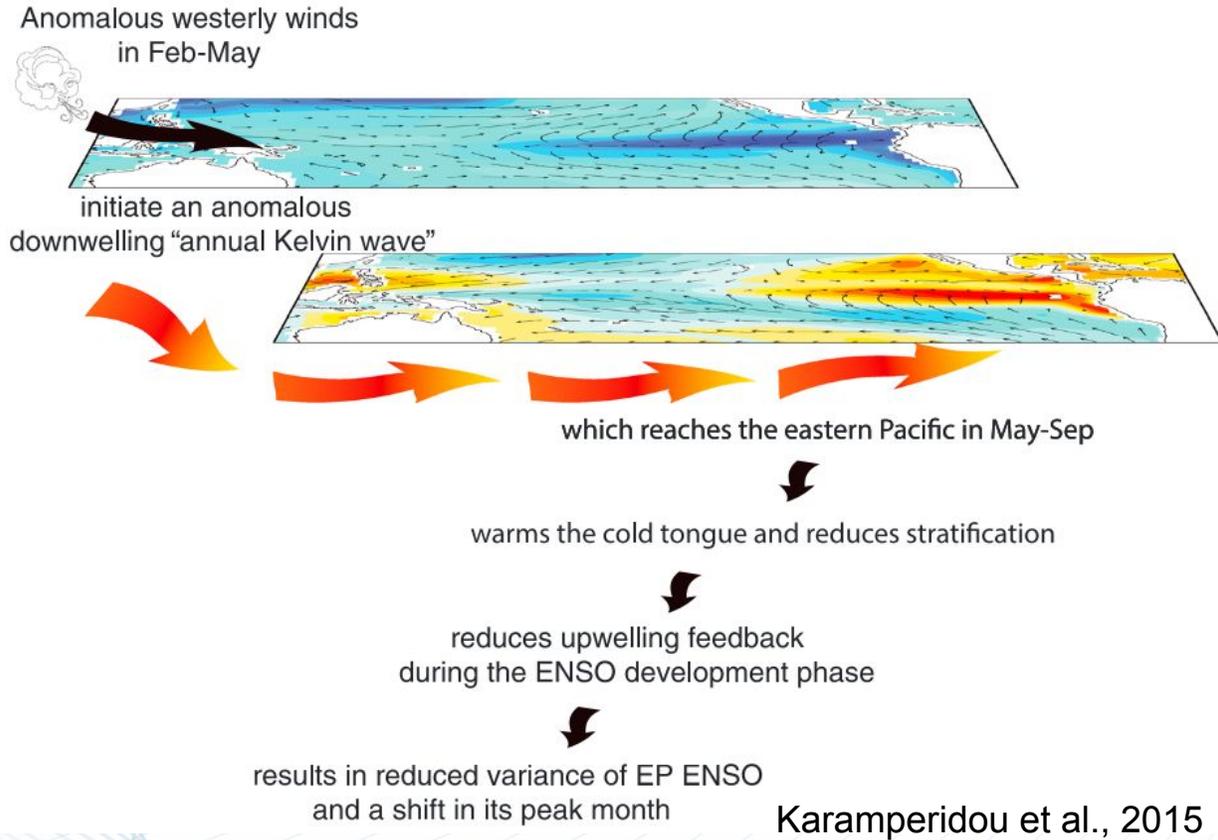
- Strong interannual variability
- ENSO asymmetry – typically stronger El Niño than La Niña events
- ENSO diversity – spatial pattern and amplitude of ENSO events

ENSO variability & asymmetry during the mid-Holocene (6ka)

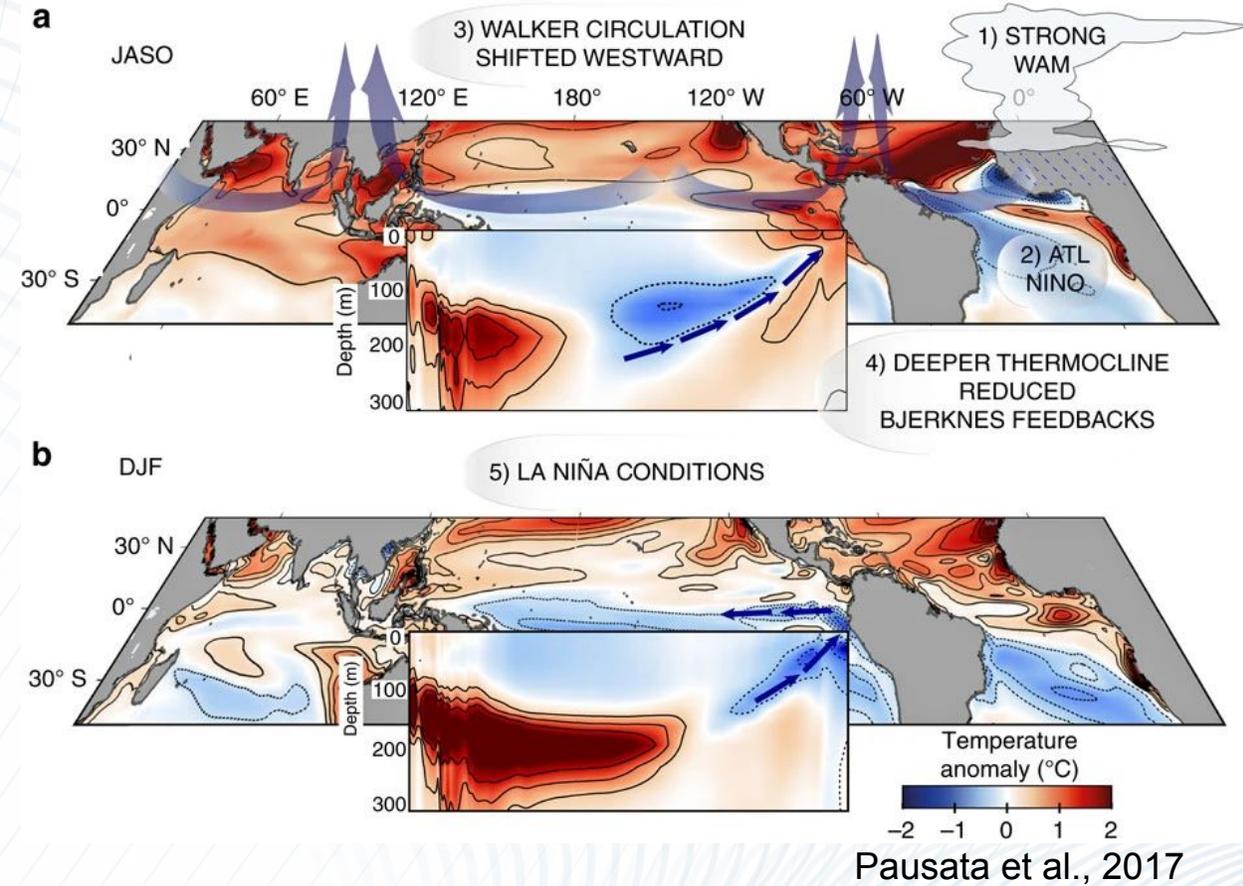


- Proxy records and climate models show reduced ENSO variability & asymmetry during the mid-Holocene.
- Climate models underestimate the ENSO variability reduction.

□ Orbital forcing



□ Green Sahara forcing



Reduced ENSO variability due to

- (1) Anomalous westerly winds (Karamperidou et al., 2015; Karamperidou and Dinezio, 2022),
- (2) Changes in Walker Circulation caused by the Green Sahara (Pausata et al., 2017; Tiwari et al., 2025)
- (3) Warm water subduction from the southern subtropical Pacific (Iwakiri and Watanabe, 2019)

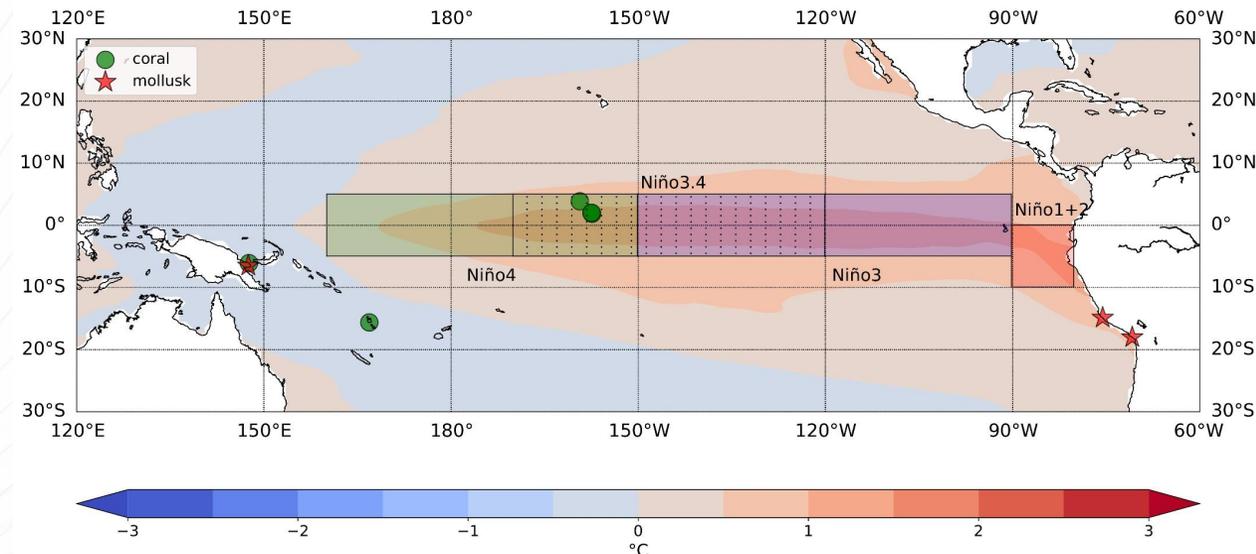
- ❑ Previous studies:
 - Different amplitude and spatial pattern of ENSO types, especially La Nina types during the mid-Holocene remain unclear.
 - The relationships between different types of ENSO and the ENSO variability and asymmetry during the mid-Holocene are also not well understood.
 - Climate models often underestimate the reduction of ENSO variability during the mid-Holocene.

- ❑ This study:
 - ❑ It is focused on how the amplitude and spatial pattern of different ENSO types were changed during the mid-Holocene.
 - ❑ It investigates the mechanisms of how ENSO diversity impacted the overall ENSO variability and asymmetry changes, incorporating the Green Sahara forcing as well.
 - ❑ A direct proxy-model comparison using an isotope-enabled climate model is introduced.

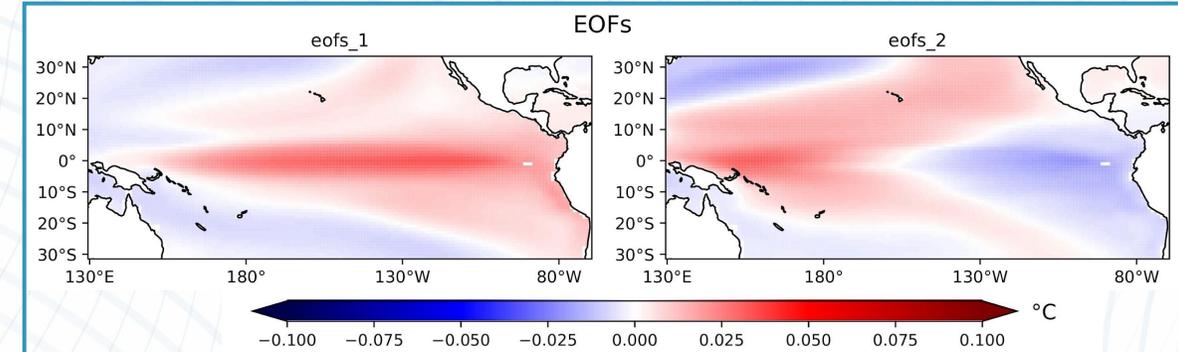
- Model simulations **isotope-enabled Community Earth System Model version 1.2 (iCESM1.2; Brady et al., 2019; Zhu et al., 2017)**
 - $1.9^\circ \times 2.5^\circ$ (latitude \times longitude) for the atmosphere and land, and the $1^\circ \times 1^\circ$ for the ocean
 - piControl: orbital parameters, GHG concentrations, aerosols are prescribed to the pre-industrial era (AD 1850)
 - 6ka: Following the PMIP4 protocol
 - **6ka ORB**
 - **6ka ORB+GS** - incorporates Green Sahara forcing (prescribing a 100% spatial coverage of shrub and C4 grass at $10^\circ\text{--}25^\circ\text{N}$ and $25^\circ\text{--}35^\circ\text{N}$, respectively)
 - Last 200 years of outputs are used.

□ Proxy Data Comparison

Published high-resolution monthly mollusk and coral oxygen isotope ($\delta^{18}O$) records across the tropical Pacific, which span the mid-Holocene and modern era.



- ❑ Previous studies:
 - The E and C indices (Takahashi et al., 2011), based on SST EOF1 and EOF2 patterns, are used to capture different El Niño types.
 - The EOF1 and EOF2 (from which PC1 and PC2 are derived to calculate E and C indices) can differ greatly between observations and model simulations and between different climate intervals.



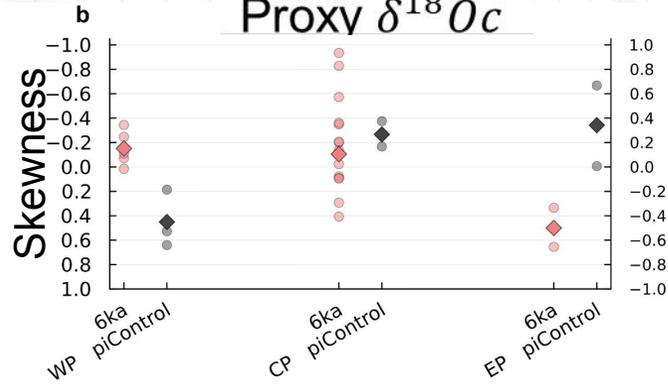
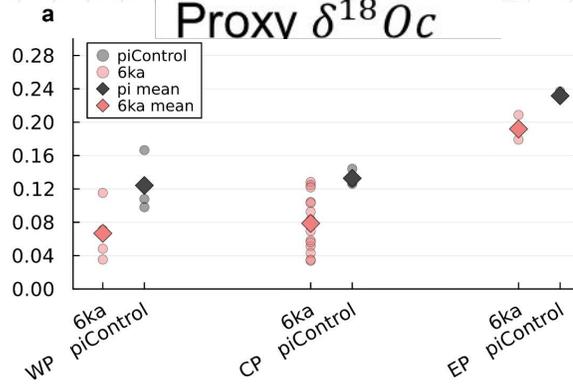
1. First 2 principal components (64% variance) from piControl
2. Projecting monthly SSTA from 6ka onto the first 2 EOFs from piControl
=> A direct comparison between 6ka and piControl by obtaining 2 PCs for the 6ka under the same latent space as the piControl
3. El Niño and La Niña boreal winter months (DJF) were selected from the PCs time series, based on Niño3.4 index exceeding ± 0.5 °C.

- ❑ **Gaussian Mixture Model (GMM) clustering:**
It captures multiple ENSO types in the PC1-PC2 latent space by detecting Gaussian distributions of ENSO events.
=> Both El Niño and La Niña types

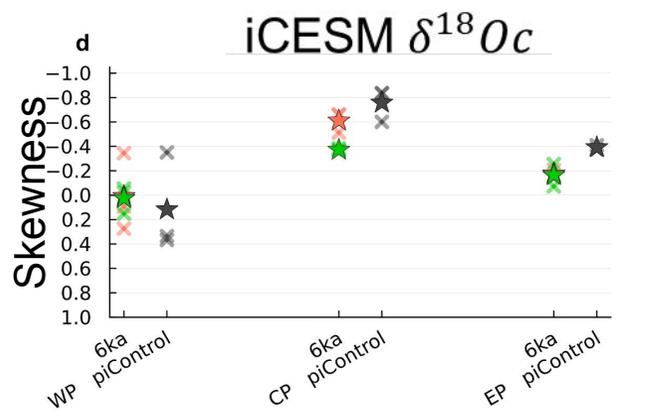
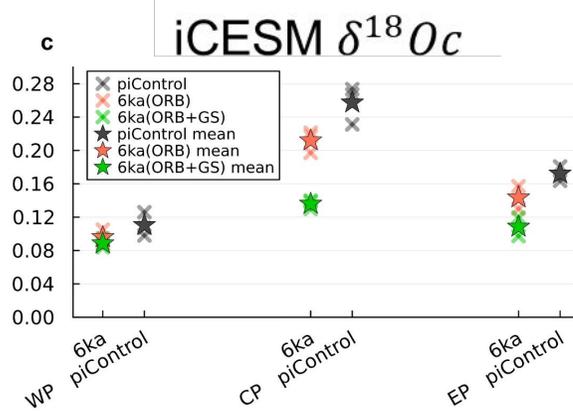
Variability

Asymmetry

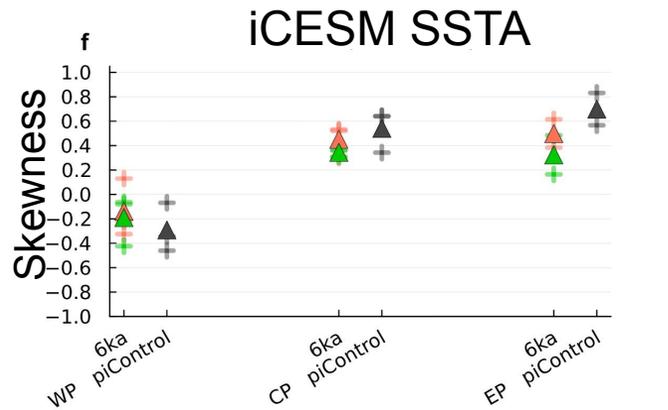
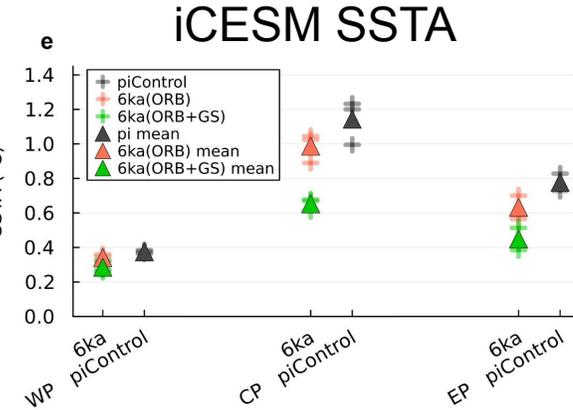
Standard deviation $\delta^{18}O_c$ (‰)



Standard deviation $\delta^{18}O_c$ (‰)



Standard deviation SSTA (°C)



*Simulated $\delta^{18}O_{sw}$ is converted to $\delta^{18}O_c$.

Reduction% of ENSO variability (piControl-6ka)	WP	CP	EP
Proxy $\delta^{18}O_c$	46%	41%	17%
iCESM $\delta^{18}O_c$ (ORB)	13%	18%	17%
iCESM $\delta^{18}O_c$ (ORB+GS)	20%	47%	37%

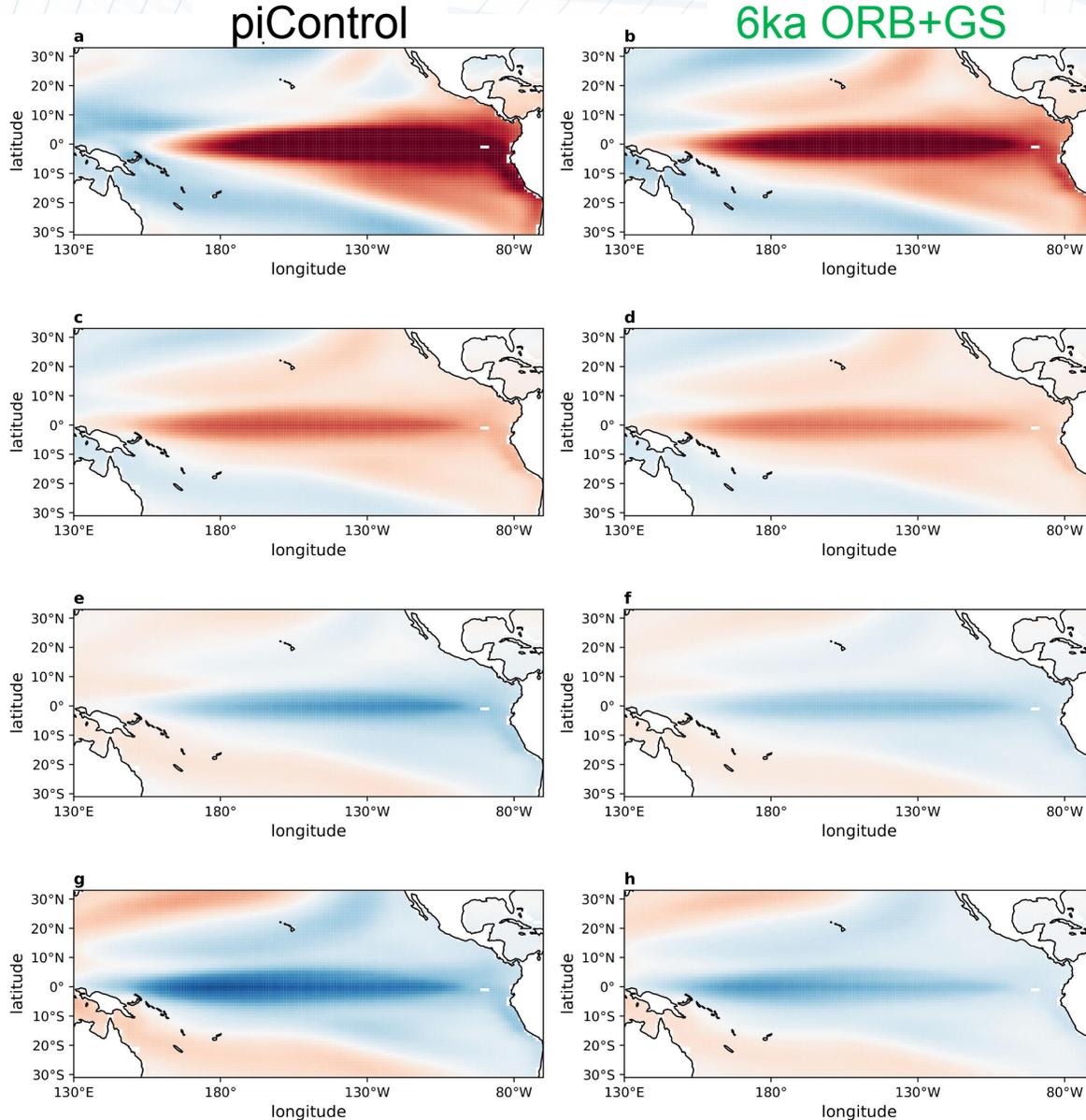
- ENSO variability and asymmetry were both reduced during the mid-Holocene across the tropical Pacific.
- Better proxy-model consistency was found in the **6ka ORB+GS**.

Extreme El Niño

CP El Niño

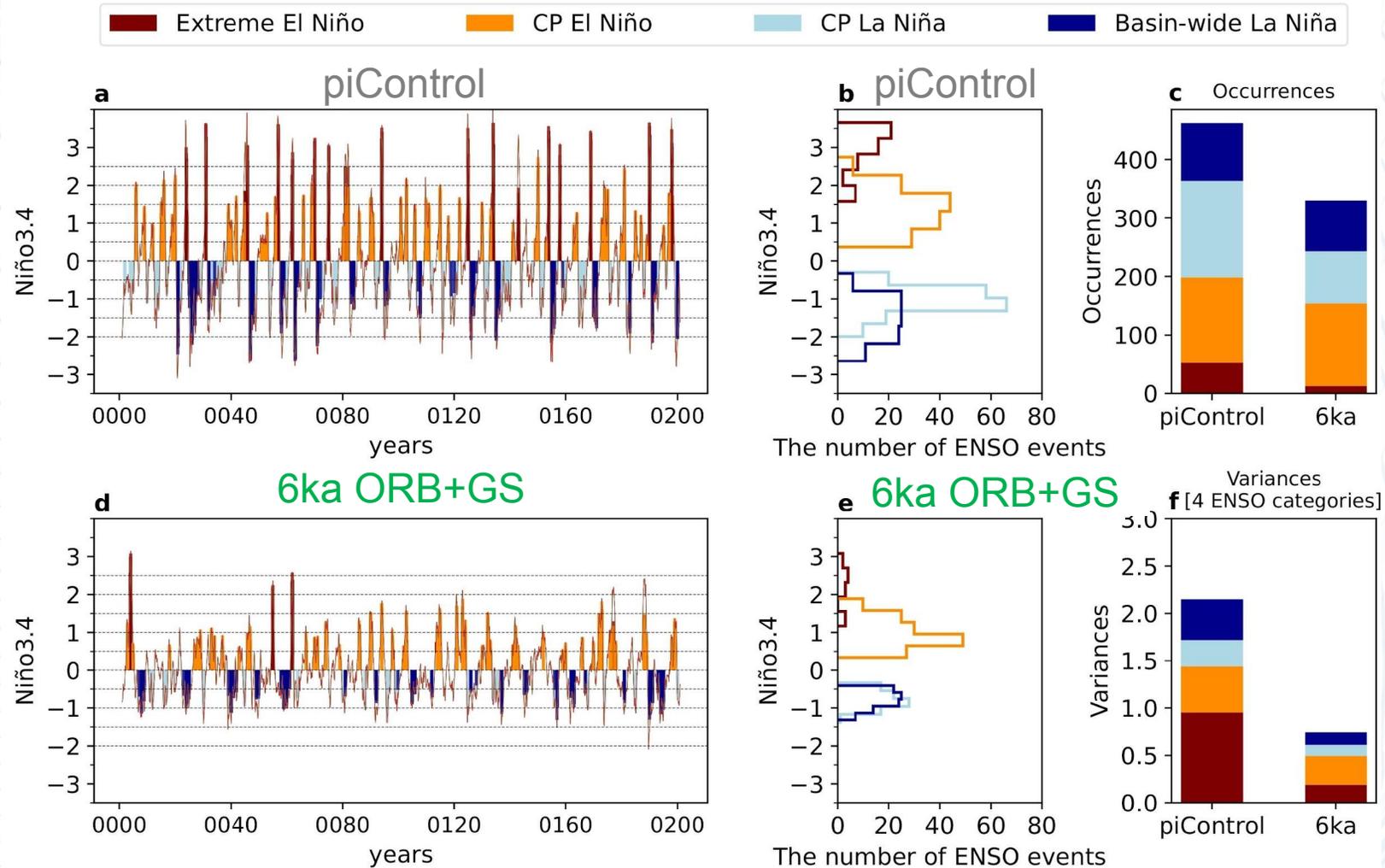
CP La Niña

Basin-wide La Niña



- **Extreme El Niño:** Strongly positive SSTAs extending across the EP-CP
 - **Central Pacific (CP) El Niño:** Moderate positive SSTAs over the CP
 - **Central Pacific (CP) La Niña:** Moderate negative SSTAs over the CP
 - **Basin-wide La Niña:** Strongly negative SSTAs over WP-CP
- Major changes during the mid-Holocene
- **Extreme El Niño:** Absence of strong positive SSTAs off the South American coast and weaker latitudinal extent
 - **CP El Niño/CP La Niña:** Slightly weakened
 - **Basin-wide La Niña:** Weaker negative SSTAs over WP

The impacts of ENSO diversity on ENSO variability

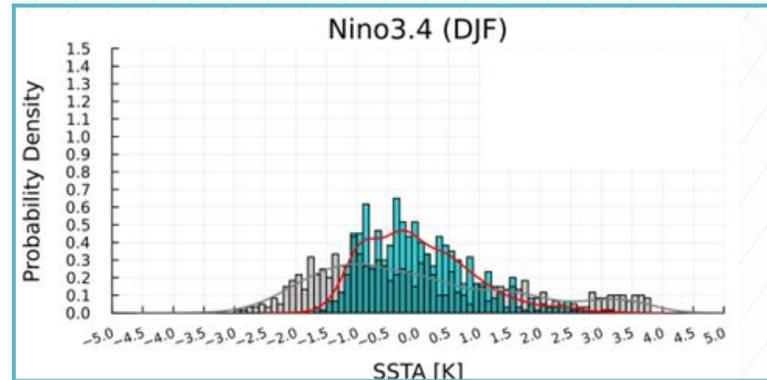
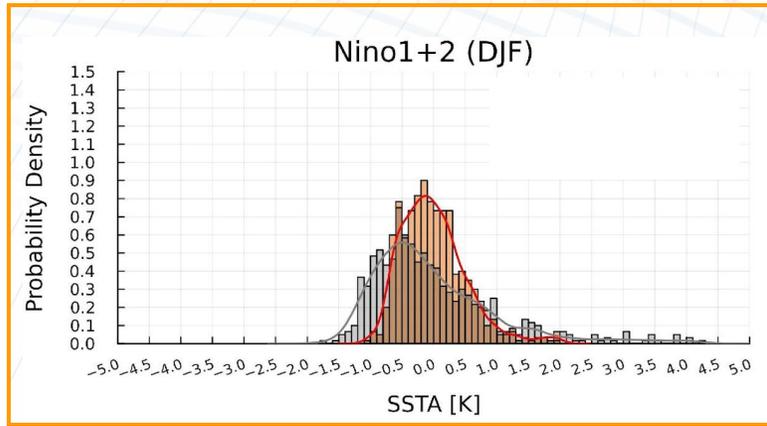
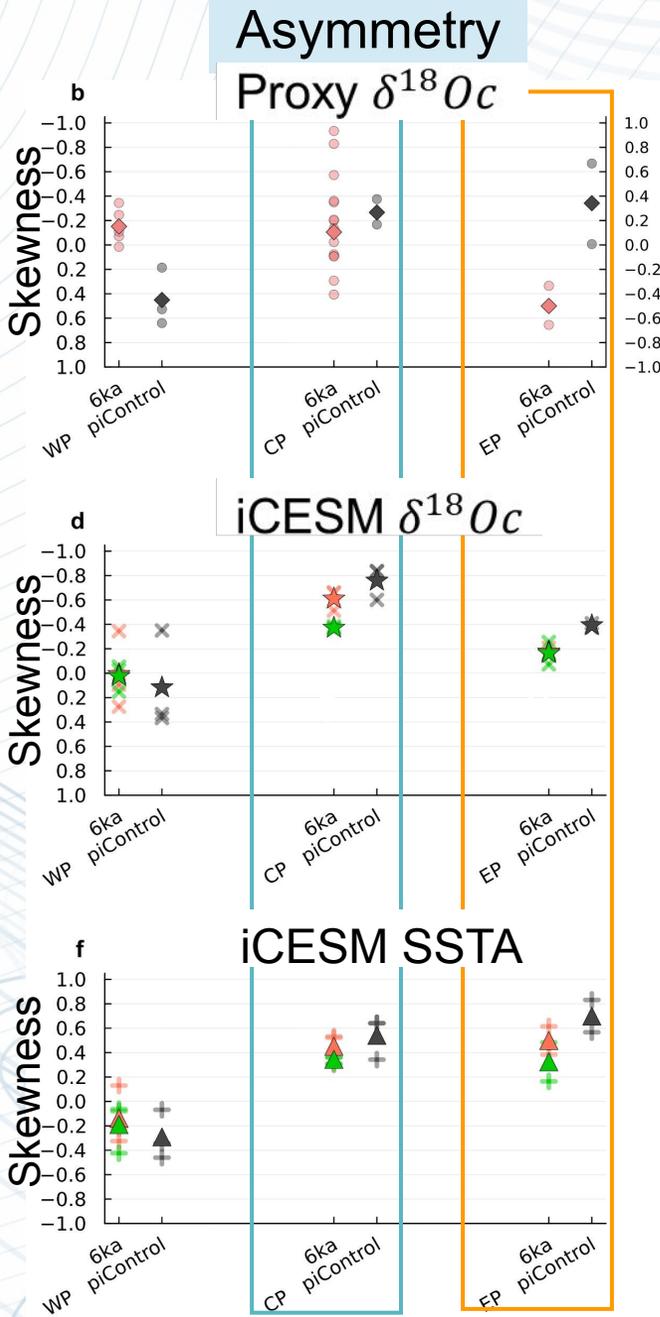


- Less frequent & weaker Extreme El Niño events
- (Slightly weaker CP El Niño and La Niña events)
- Weaker Basin-wide La Niña events



Reduced ENSO variability

The impacts of ENSO diversity on ENSO asymmetry



Gray: piControl
Orange/blue: 6ka ORB+GS

- Less frequent & weaker Extreme El Niño events
- (Slightly weaker CP El Niño and La Niña events)
- Weaker Basin-wide La Niña events

• EP:
large impacts of Extreme El Niño vs small influence from La Niña => significant reduction in ENSO asymmetry

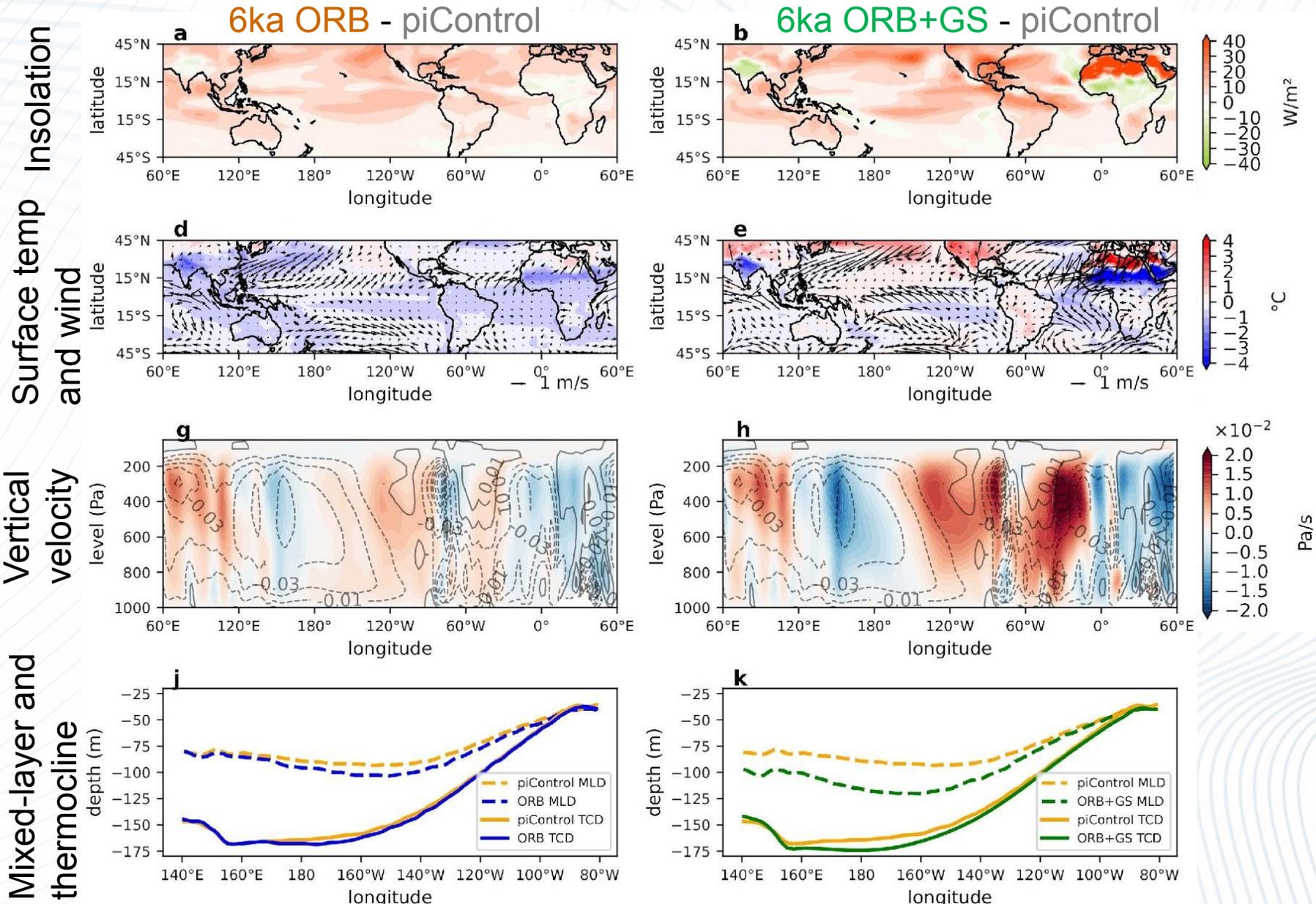
• CP:
large impacts of CP ENSO and Basin-wide La Niña vs small influence from Extreme El Niño => relatively small reduction in ENSO asymmetry

The mechanisms – changes in the mean state

June-July-August

- Anomalous westerly winds over the WP
- Strengthened Pacific Walker Circulation
- The deeper thermocline over the CP-EP

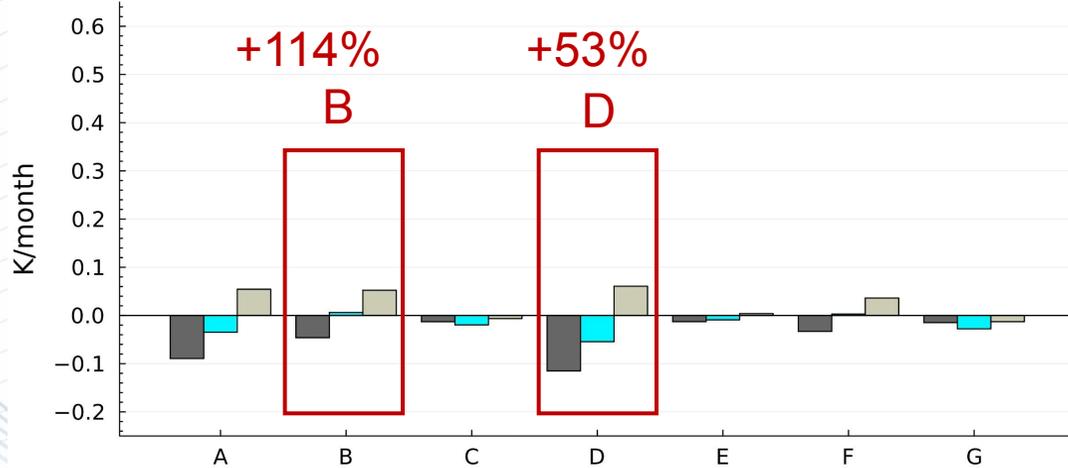
- 6ka ORB+GS shows more pronounced changes.



$$\frac{\partial T'}{\partial t} = - \left(\bar{u} \frac{\partial T'}{\partial x} + \boxed{u' \frac{\partial \bar{T}}{\partial x}} + u' \frac{\partial T'}{\partial x} \right) - \left(\bar{v} \frac{\partial T'}{\partial y} + v' \frac{\partial \bar{T}}{\partial y} + v' \frac{\partial T'}{\partial y} \right) - \left(\bar{w} \frac{\partial T'}{\partial z} + \boxed{w' \frac{\partial \bar{T}}{\partial z}} + w' \frac{\partial T'}{\partial z} \right) + \frac{Q'_{net}}{\rho C_p H} + R$$

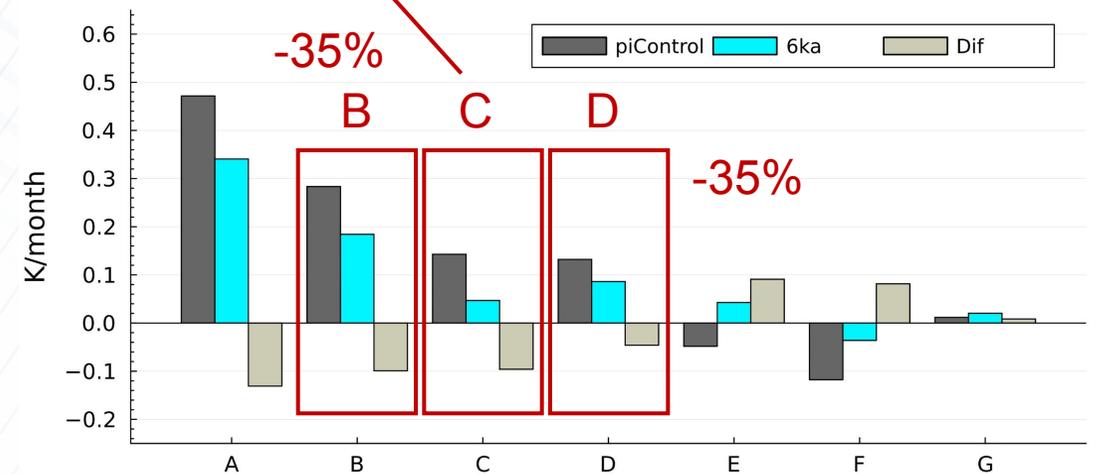
D: zonal advection
B: Thermocline
C: Upwelling

Basin-wide La Niña



- Weaker thermocline feedback (B)
- Weaker zonal advective feedback (D)

Extreme El Niño



- Weaker thermocline feedback (B)
- Weaker upwelling feedback (C)
- Weaker zonal advective feedback (D)

- Both proxy records and iCESM simulations show reduced ENSO variability and asymmetry across the tropical Pacific during the mid-Holocene.
- **6ka ORB+GS simulation** provides closer agreement with proxy records in terms of the magnitude of the reduction in ENSO variability and asymmetry, highlighting the significant role of vegetation-related feedbacks.
- GMM clustering analysis revealed the changes in ENSO diversity, including La Niña events. Less frequent and weaker **Extreme El Niño**, along with weaker **Basin-wide La Niña** events, contributed to the reduced ENSO variability and asymmetry.
- Heat budget analysis suggests that less frequent and weaker **Extreme El Niño** events are primarily driven by weaker **vertical advections**, while weaker **zonal advection** and **vertical advection** contributed to weaker **Basin-wide La Niña** events.

- What is the GMM?
 - A probabilistic clustering method using Gaussian distributions.
 - It allows overlapping classifications (Ayar et al., 2023; Schlör et al., 2024).
 - The probability distribution of latent states $p(z)$ is expressed as the mixture of Gaussians:

$$p(z) = \sum_{k=1}^K w_k \mathcal{N}(z | \mu_k, \Sigma_k)$$

Where

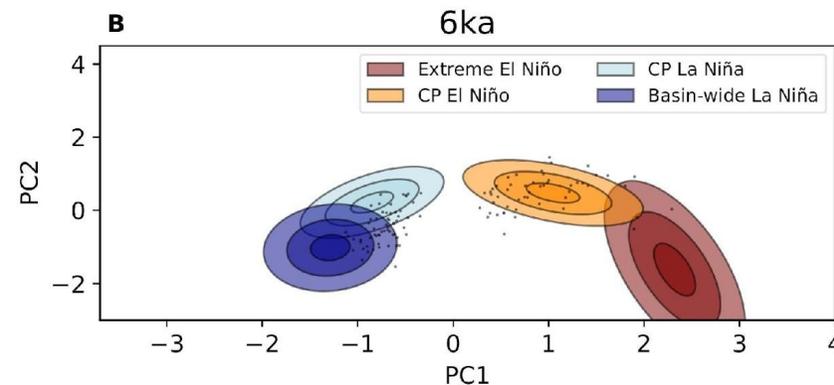
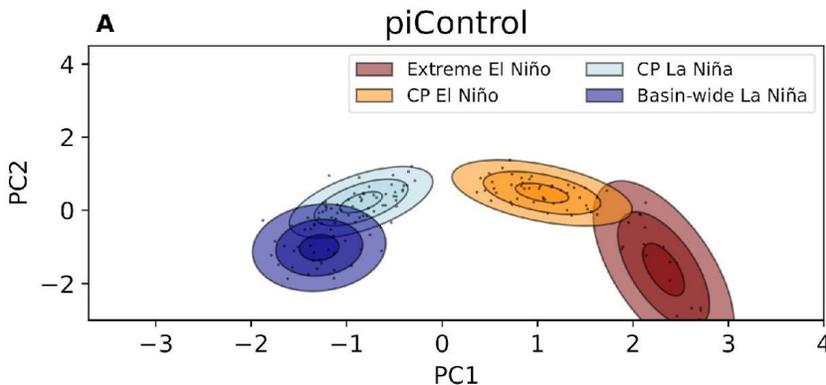
k is the number of Gaussians

π_k is the probability of Gaussian k

μ_k and Σ_k are the mean and covariance of Gaussian k

STEPS:

1. Reducing the dimensionality of the tropical Pacific SSTA field using PCA.
2. Applying the GMM and getting the probability for each data point.
3. Assigning an ENSO type to each Gaussian.



*Expectation Maximization (EM) is done 250 iterations to obtain the Gaussian parameters.

$$BIC(K) = p \log n - 2 \log L$$

where

k is the number of clusters

L is the likelihood of the parametrized mixture model

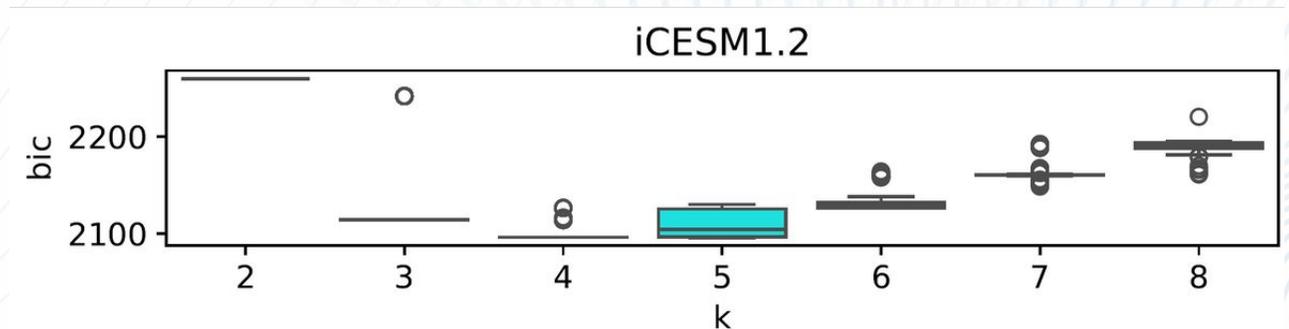
p is the number of parameters of the GMM to estimate

n is the sample size



- We fit 250 GMMs with random initialization for each number of Gaussians (k) and compute the BIC.
- The model with the lowest BIC represents the best trade-off between model complexity and fit quality (Ayar et al., 2023; Schlör et al., 2024).

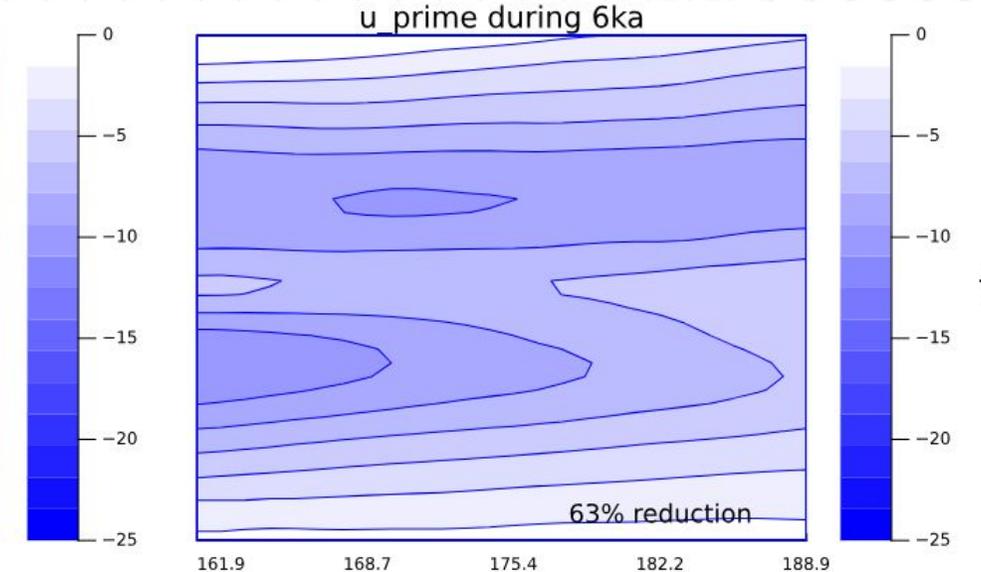
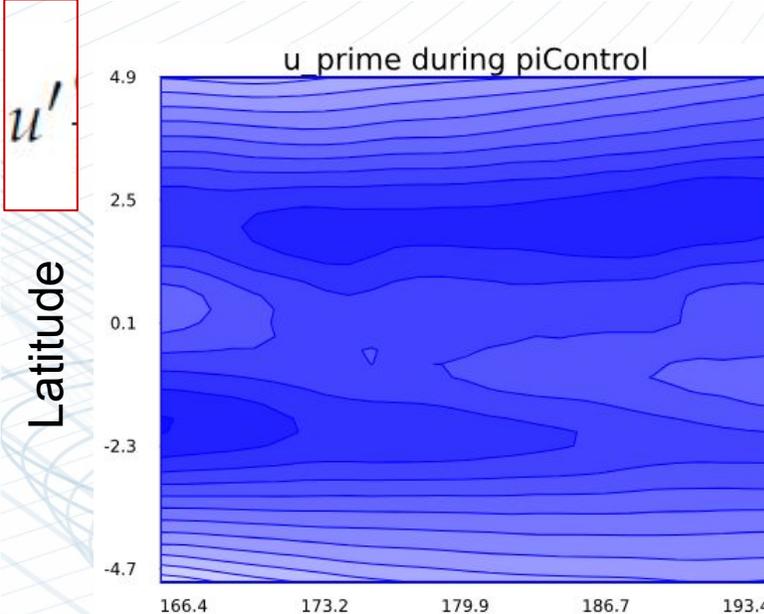
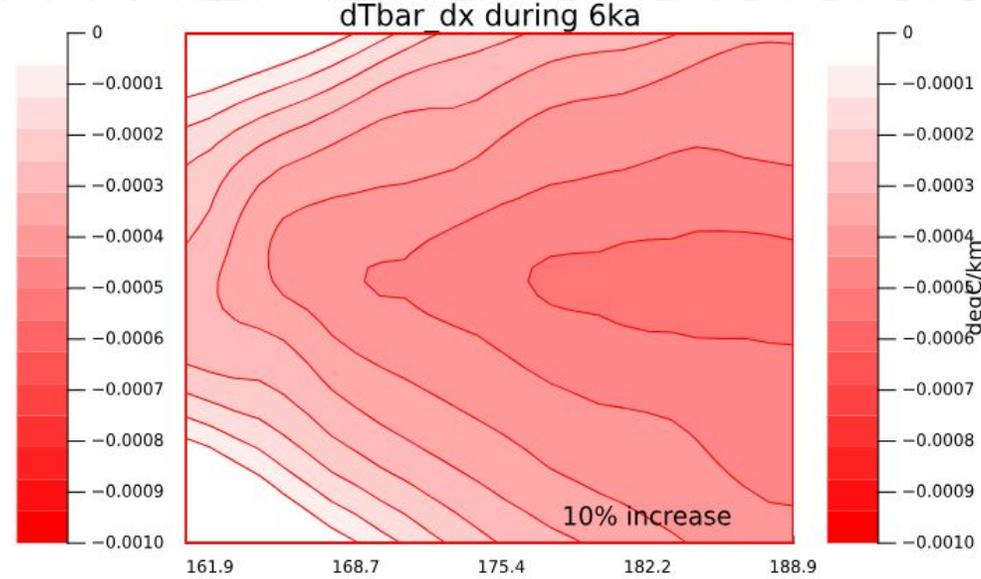
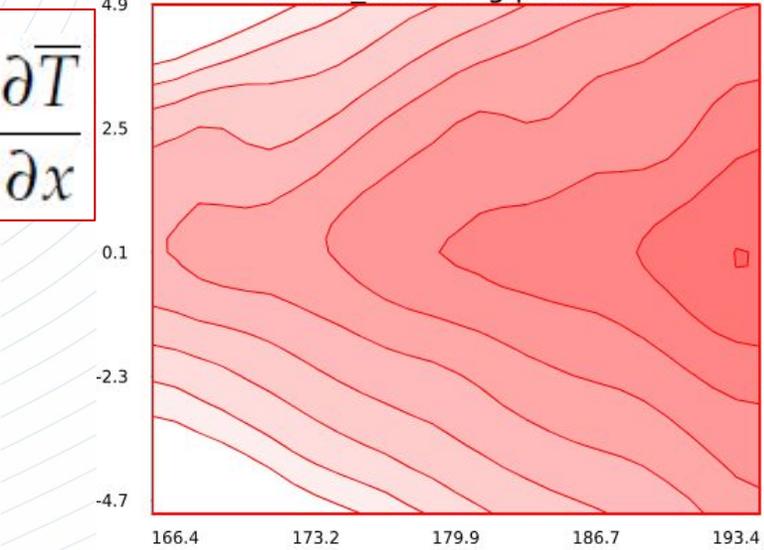
- The Bayesian Information Criterion (BIC; Schwarz (1978)) is a traditional tool to get the optimal number of clusters k .
- The BIC is used for model selection and helps to prevent overfitting by introducing penalty terms for the complexity of the GMM (i.e., the number of parameters). It balances model complexity and fit quality.



Why weaker zonal advection during Basin-wide La Niña?

$$u' \frac{\partial \bar{T}}{\partial x}$$

D: zonal advection



- Stronger Walker circulation and warm pool
 - The region with the highest SSTA shifted westward
- => enhanced zonal temperature gradient over the region



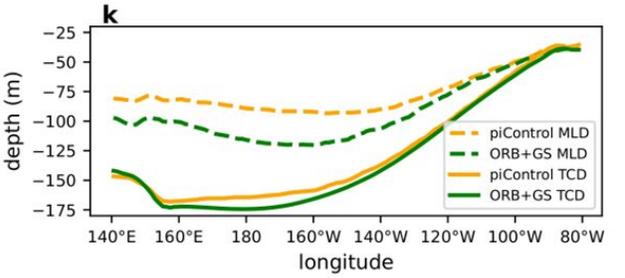
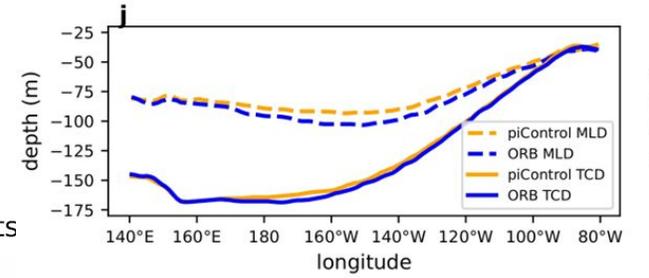
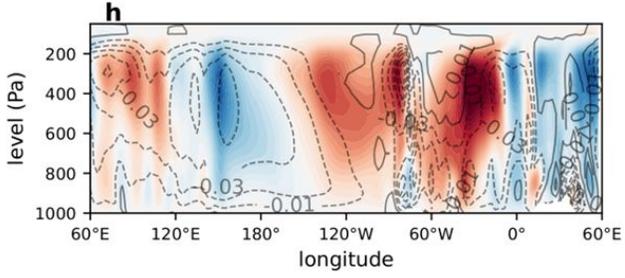
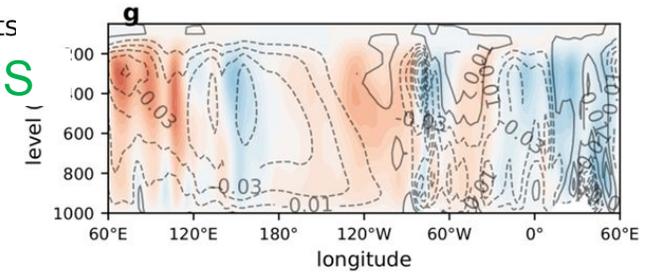
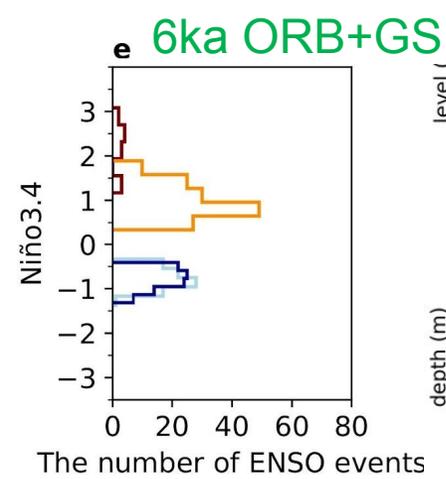
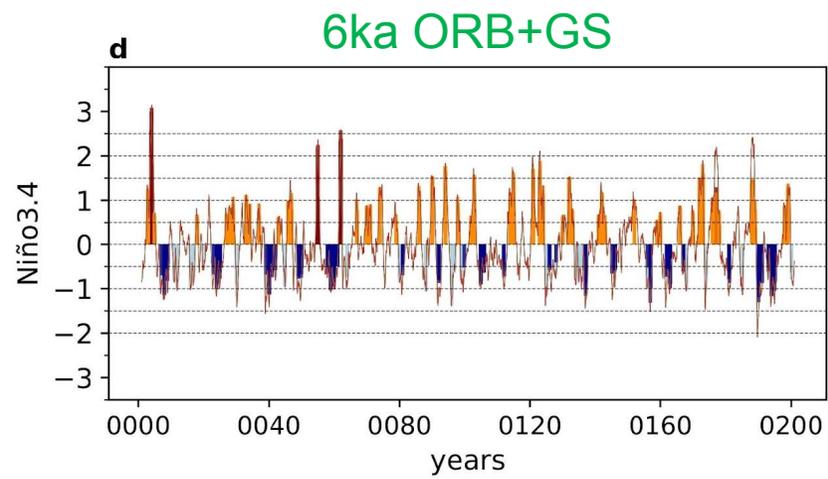
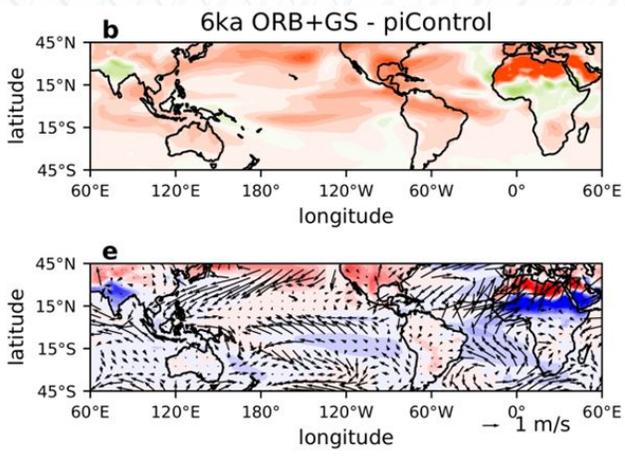
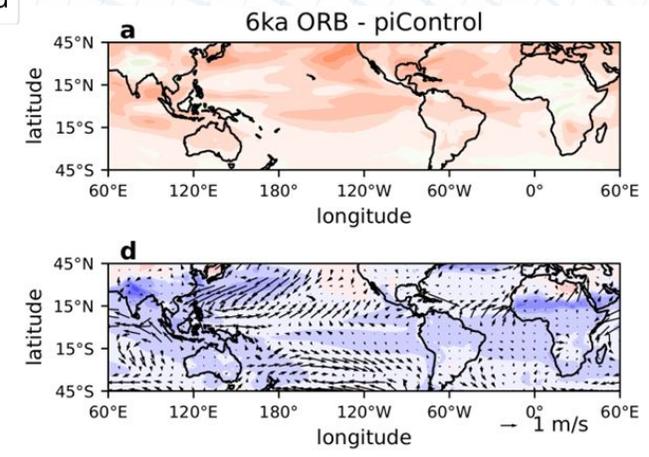
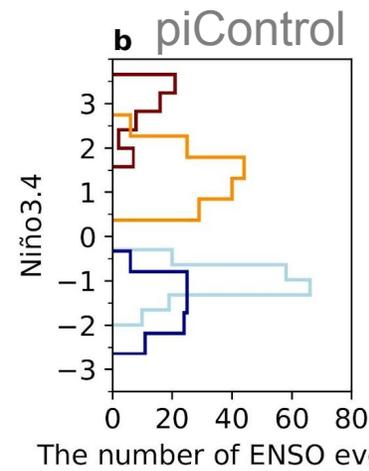
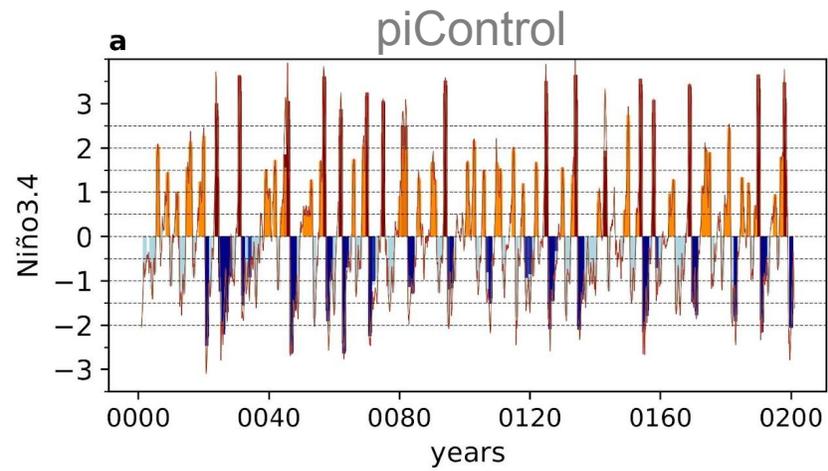
- **Weaker westward current anomalies**

During Basin-wide La Niña development season

Longitude

La Niña-like mean state <-> weaker La Niña events?

■ Extreme El Niño
 ■ CP El Niño
 ■ CP La Niña
 ■ Basin-wide La Niña

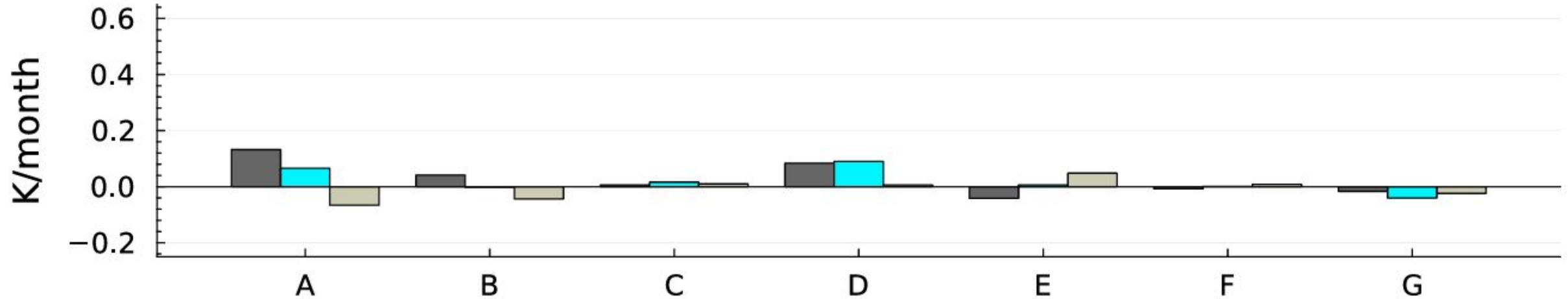


□ Weaker & less frequent Extreme El Niño events

□ Strengthened PWC

□ Deepened thermocline and mixed-layer directly contributed to weakening La Niña events during the mid-Holocene.

CP El Niño



CP La Niña

