Unraveling forced responses of extreme El Niño variability over the Holocene

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Motivation:

Uncertainty surrounding the future response of El Niño–Southern Oscillation (ENSO) variability to anthropogenic warming motivates the study of past ENSO sensitivity to different climate forcings over geological history. The Holocene (11.65 thousand years ago to the present) provides an opportunity to explore the sensitivity of ENSO to changes in orbital forcing.

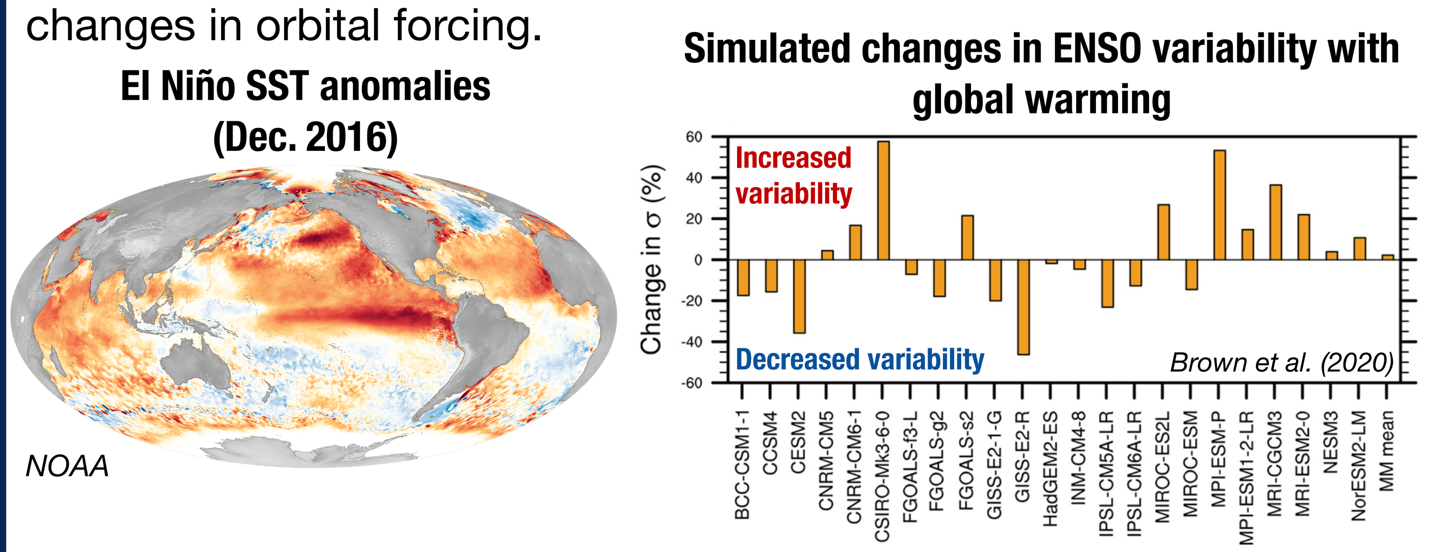
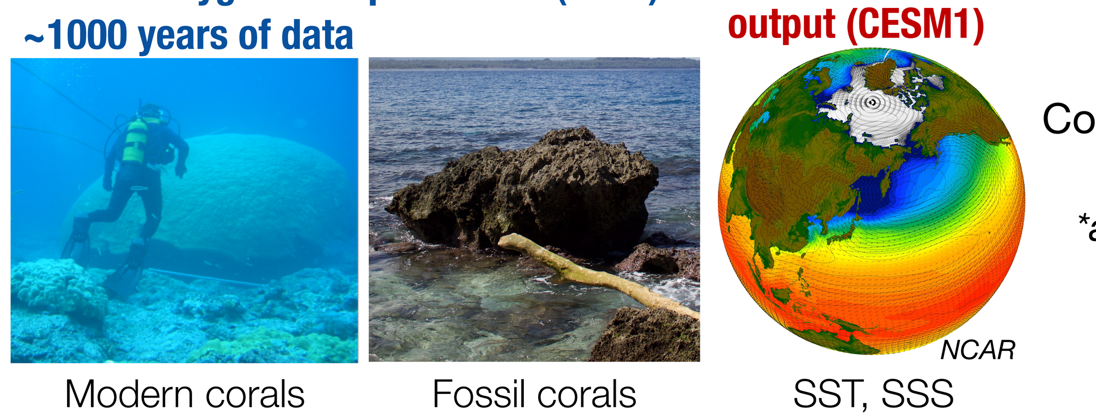


Fig. 1. (A) Sea-surface temperature (SST) anomalies during the 2015-2016 El Niño event. (B) Simulated change in ENSO amplitude relative to pre-industrial control for an abrupt quadrupling of carbon dioxide for climate models that participated in phases 5 and 6 of the Coupled Model Intercomparison Project (CMIP5/CMIP6).

Model-data comparison for Holocene ENSO:

Goal: Clarify the response of Holocene ENSO to external forcing using

1. Coral oxygen isotope records ($\delta^{18}O$) ~1000 years of data
2. Paleoclimate model output (CESM1)
3. A coral proxy system model (PSM)



Coral $\delta^{18}O$ = $a_1SST + a_2SSS$

and additional coral uncertainties

Simulated corals
Lawman et al. (2020)

Tropical Pacific SST anomalies:

Simulated Niño 3.4 SST anomalies (CESM1 0 ka):

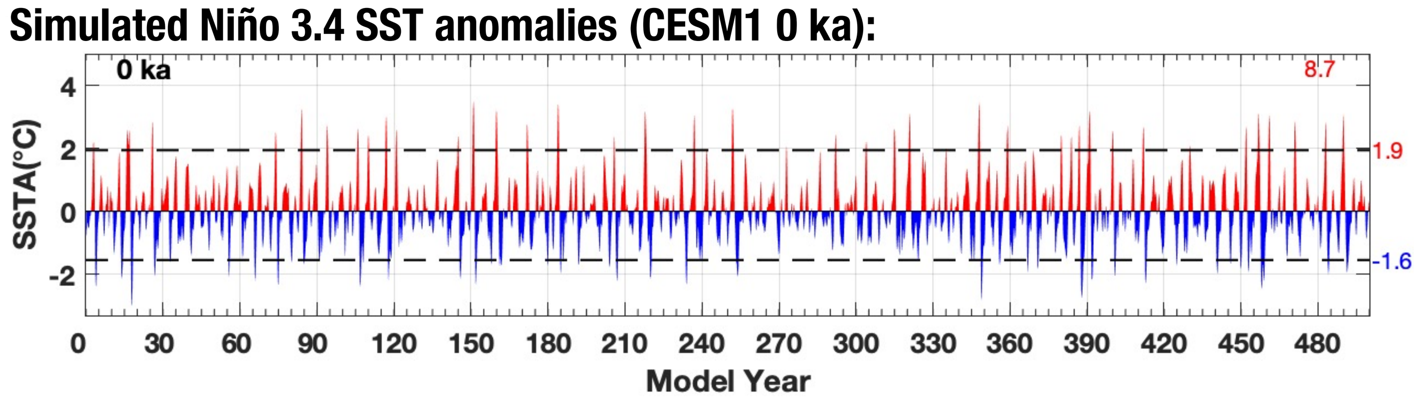


Fig. 2. Simulated Niño 3.4 SST anomalies (SSTA) for 0 ka. The first 500 years of the 1500-year-long simulation are shown. Horizontal dashed lines indicate the 5th (lower line), and 95th (upper line) percentiles. The number of extreme El Niño events/century is indicated in the upper right corner.

Tropical Pacific SST variability:

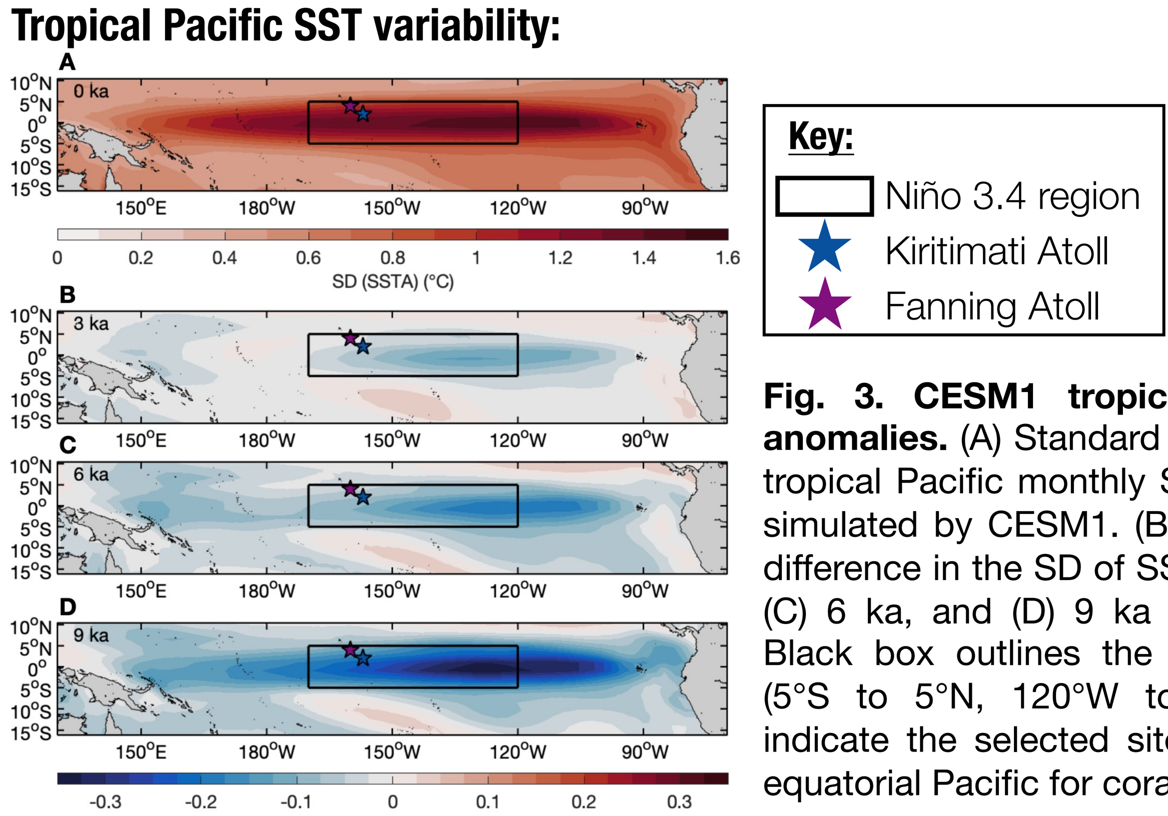


Fig. 3. CESM1 tropical Pacific SST anomalies. (A) Standard deviation (SD) of tropical Pacific monthly SSTA for 0 ka as simulated by CESM1. (B to D) Simulated difference in the SD of SSTAs for (B) 3 ka, (C) 6 ka, and (D) 9 ka relative to 0 ka. Black box outlines the Niño 3.4 region (5°S to 5°N, 120°W to 170°W). Stars indicate the selected sites in the central equatorial Pacific for coral proxy data.

Simulated changes in Holocene ENSO variability:

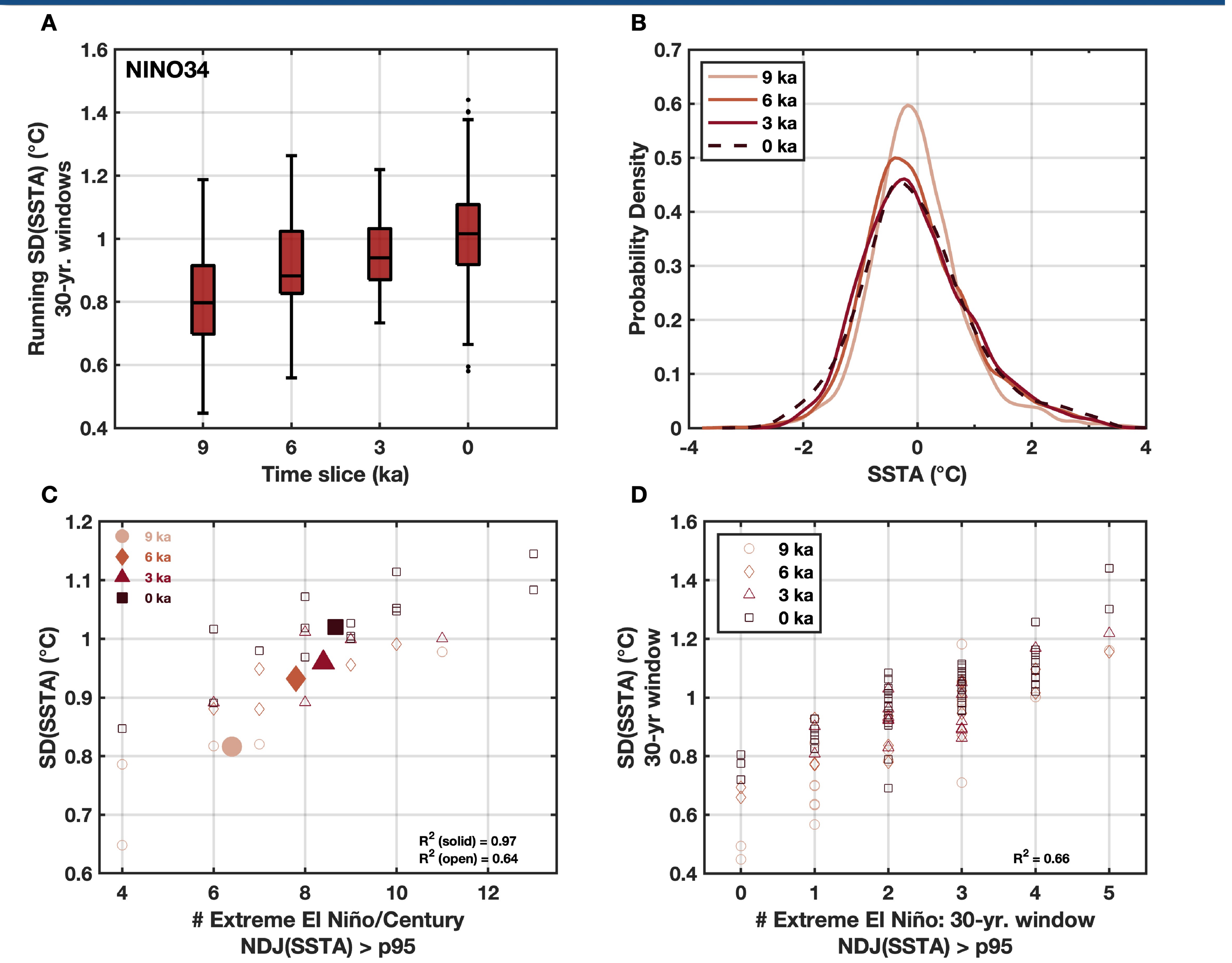


Fig. 4. CESM1 simulated changes in Holocene ENSO variability. (A) The 30-year running SD of Niño 3.4 monthly SSTA for 9, 6, 3, and 0 ka. Lower and upper bounds of the boxes respectively correspond to the 25th and 75th percentiles, and the center line indicates the median (50th percentile). (B) Probability density functions (PDFs) of Niño 3.4 monthly SSTA for the Holocene time slices (see legend for labels). (C and D) Scatter plot of SD versus the number of extreme El Niño events in (C) 100-year and (D) 30-year windows. Solid symbols in (C) indicate the average number of events/century for the full-length time slice simulations. Open symbols in (C) and (D) represent individual nonoverlapping windows.

Coral comparison over the past 7000 years:

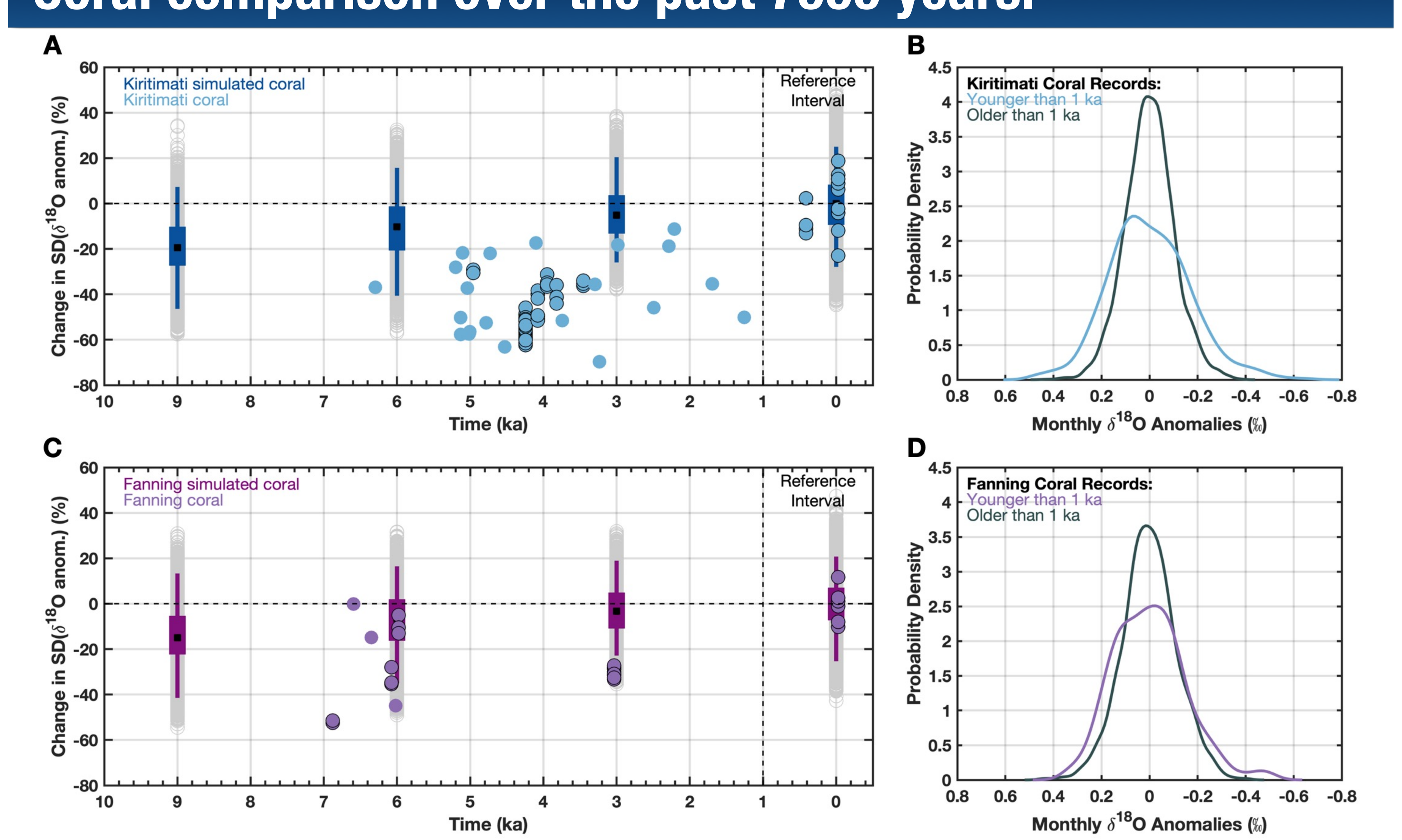


Fig. 5. Comparing simulated coral and coral proxy-inferred changes in Holocene ENSO variability. (A and C) Percent change in SD for simulated coral (n = 100 realizations) and measured coral $\delta^{18}O$ anomalies at (A) Kiritimati and (C) Fanning. Simulated coral $\delta^{18}O$ anomalies generated using a coral sensor model coupled with a process-based coral PSM (Lawman et al., 2020). Percent change relative to the median value for 0 ka (simulated coral output) and 1 to 0 ka for the coral data. Colored boxes show the 25th and 75th percentiles, and colored vertical lines indicate the 2.5th to 97.5th percentile range. Gray circles indicate the full range of simulated coral estimates. Colored circles indicate coral proxy records for each site, with full 30-year intervals outlined in black. Coral records <30 years are not outlined. (B and D) PDFs of monthly coral $\delta^{18}O$ anomalies for (C) Kiritimati and (D) Fanning in which all the individual $\delta^{18}O$ anomaly records are grouped into bins younger than 1 ka (blue, purple) and older than 1 ka (gray).

Constraining Holocene ENSO behavior (Q-Q analysis):

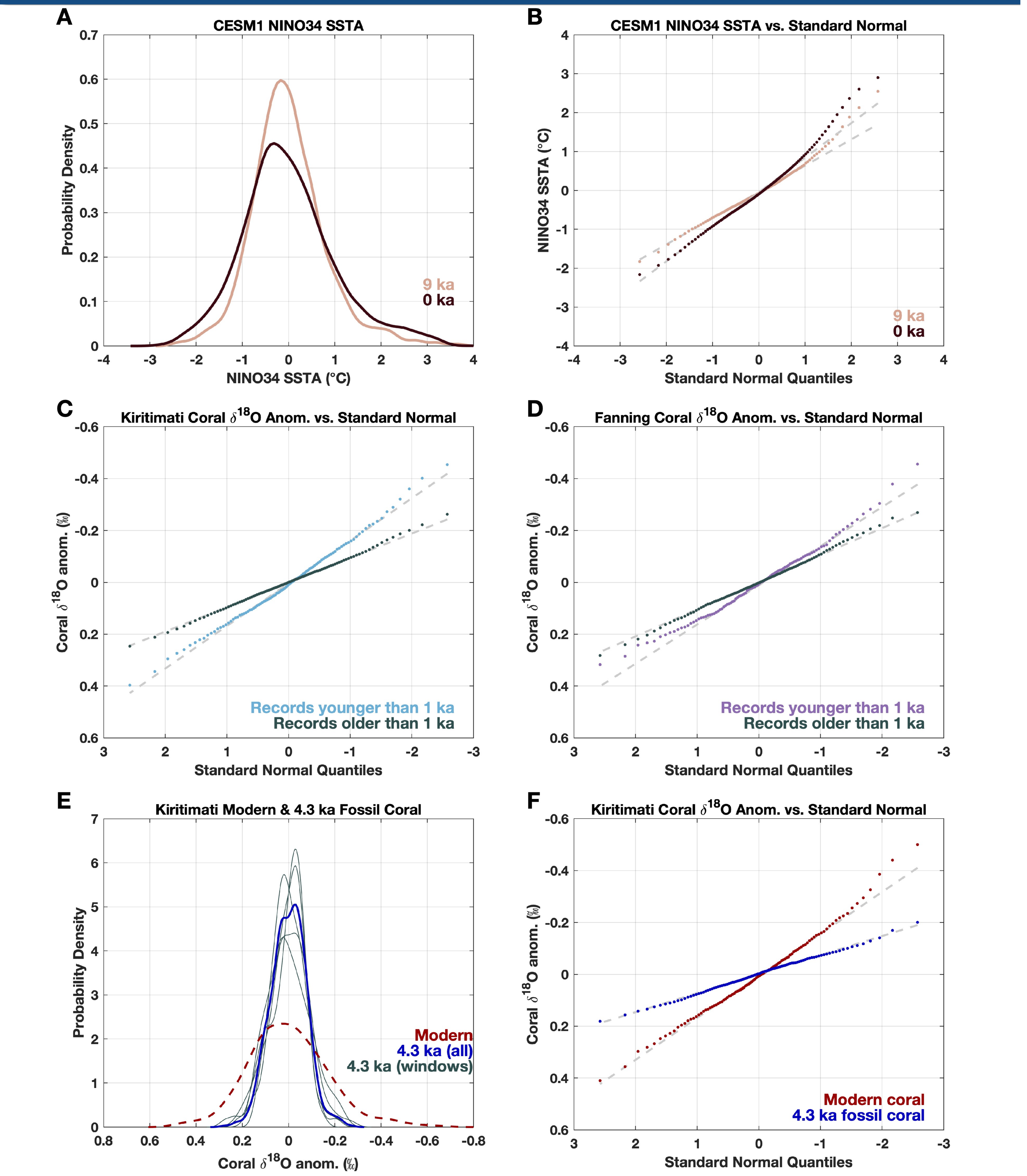


Fig. 6. Simulated and coral-inferred changes in extreme ENSO events. (A) PDFs of CESM1 simulated Niño 3.4 monthly SSTA for the 0 ka (dark red) and 9 ka (pink) intervals. (B to D) Q-Q plots for monthly (B) Niño 3.4 SSTA (0 and 9 ka). (C) Q-Q plots for coral $\delta^{18}O$ anomalies younger than 1 ka (blue) and older than 1 ka (gray) at Kiritimati versus standard normal quantiles. (D) Same as in (C) for Fanning, with 1- to 0-ka corals in purple. (E) PDF of the $\delta^{18}O$ anomalies for a long 177-year fossil coral from 4.3-ka (blue) from Kiritimati and nonoverlapping 30-year windows (gray). PDF of modern coral $\delta^{18}O$ from Kiritimati (red). (F) Q-Q plots for the 4.3-ka (blue) and modern (red) coral.

Conclusions:

- CESM1 simulates a modest increase in ENSO variability from the early to late Holocene (~2.1%/ka) driven by a change in the magnitude and frequency of extreme El Niño events
- Both the model and coral data indicate more recent ENSO variability eclipsed paleo-estimates, but diverge regarding the magnitude
- Large scatter in the coral data and large internal variability within simulated corals makes it difficult to quantify percent reduction

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References:

1. Lawman et al. (2022), Unraveling forced responses of extreme El Niño variability over the Holocene, *Science Advances*, doi: 10.1126/sciadv.abm4313.
2. Lawman et al. (2020), Developing a Coral Proxy System Model to Compare Coral and Climate Model Estimates of Changes in Paleo-ENSO Variability, *Paleoceanography and Paleoclimatology*, doi: 10.1029/2019pa003836.

Coral proxy data:
Grothe et al. (2020); Cobb et al. (2013); Evans (1999); Nurhati et al. (2009); McGregor et al. (2013); Woodroffe & Gagan (2000); McGregor et al. (2011); Woodroffe et al. (2003)