Supplement of

A proxy modelling approach to assess the potential of extracting ENSO signal from tropical Pacific planktonic foraminifera

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S1. Oceanic Niño Index (ONI) index

S2. Test of input (temperature and equilibrium)

Supplementary Figure 2 Anderson-Darling Results for Input datasets of Temperature and Equilibrium $\delta^{18}$O ($\delta^{18}$O$_{eq}$). Results of the test in which input variables underwent the same statistical procedure (see section 2.0) as the modelled data for (A-C) temperature and (D-F) $\delta^{18}$O$_{eq}$ values. Here, model input data was extracted for three fixed depths ([A & D] 5 m; [B & E] 149 m; [C & F] and 235 m) without any growth weighting applied. Black regions are those grid points in which the null hypothesis (H0), that the El Niño and Non-El Niño populations are not statistically different (FP$_{El Niño} = FP_{Non-El Niño}$), cannot be rejected. Gray regions represent grid points where the H1 hypothesis is accepted, therefore the distributions of the foraminiferal population (FP) for El Niño and Non-El Niño can be said to be unique (FP$_{El Niño} \neq FP_{Non-El Niño}$). The hatched regions represent areas were the H1 hypothesis can be accepted, therefore the distributions of the foraminiferal population (FP) for El Niño and Non-El Niño can be said to be unique (FP$_{El Niño} \neq FP_{Non-El Niño}$), though the difference between the means of tested distribution are less than (A-C) 0.5°C or (D-F) 0.1‰. Each panel represents a single depth (5, 149 and 235 m).
Test using Input data: Temperature

Fixed depth: 5 m

Values are dissimilar = possible to discern El Nino values:
$FP_{1979} \neq FP_{1980-1982}
$

Values are similar = not possible to discern El Nino values:
$FP_{1979} = FP_{1980-1982}
$

Value difference greater than error: \[ \square \]

Value within error: \[ \square \]

Test using Input data: Equilibrium ($\delta^{18}O_{eq}$)

Fixed depth: 5 m

Values are dissimilar = possible to discern El Nino values:
$FP_{1979} \neq FP_{1980-1982}
$

Values are similar = not possible to discern El Nino values:
$FP_{1979} = FP_{1980-1982}
$

Value difference greater than error: \[ \square \]

Value within error: \[ \square \]

Fixed depth: 149 m

Fixed depth: 235 m
S3. FAME Output:

Supplementary Figure 3 A snapshot of the output of FAME. Each panel represents an individual species (Top Panel *G. sacculifer*; Middle Panel *G. ruber* and Bottom Panel *N. dutertrei*) $\delta^{18}O$ for a single time step ($t = 696$). The species $\delta^{18}O$ for each grid-point is based upon the integrating the $\delta^{18}O_{eq}$ values using a growth-rate based weighting (FAME; Roche et al., 2018). Values are in per mil (‰ V-PDB)
Supplementary Figure 4 Anderson-Darling Results for modelled FAME-$\delta^{18}$Oeq: Panels representing locations of where dissimilar and similar values of FAME modelled species $\delta^{18}$O occur between climate states, for (columns) particular species and (rows) particular model depth cut-off limits. Each panel represents the Anderson-Darling test result, which are plotted with ([A] *Globigerinoides sacculifer* and [B] *Globigerinoides ruber*) and without ([C] *N. dutertrei*) model derived error. For all panels black areas reflect latitudinal and longitudinal grid points that failed to reject the null hypothesis ($H_0$) and therefore the foraminiferal population (FP) of the El Niño is similar to the Non-El Niño (FP$_{El Niño}$ = FP$_{Non-El Niño}$). The results in which the $H_1$ hypothesis is accepted, in which the, therefore the distributions can be said to be different (FP$_{El Niño}$ $\neq$ FP$_{Non-El Niño}$), are plotted as either: (A – *G. sacculifer*, B – *G. ruber*) grey and hatched or (C – *N. dutertrei*) solely as white regions. For species with calculatable error, grey regions represent values where the difference between the two means of the population is greater than species-specific standard deviation of the FAME model and hatched regions represent those in which the means are less than this standard deviation (Roche et al., 2018). For species without a calculatable error, the regions are plotted in white. The rows represent the model runs with a depth cut-off limit at: (A-C) 60 m; (D) 100 m; (E) 200 m; and (F) 400 m.
Supplementary Figure 5 Anderson-Darling Results for modelled FAME-Tc: Panels representing locations of where dissimilar and similar values of FAME modelled temperature recorded in the calcite shells (Tc) occur between climate states, for (columns) particular species and (rows) particular model depth cut-off limits. Each panel represents the Anderson-Darling test result, which are plotted with ([A] Globigerinoides sacculifer and [B] Globigerinoides ruber) and without ([C] N. dutertrei) model derived error. For all panels black areas reflect latitudinal and longitudinal grid points that failed to reject the null hypothesis (H0) and therefore the foraminiferal population (FP) of the El Niño is similar to the Non-El Niño, and therefore the distribution between the neutral climate and El Niño cannot be said to be different (FPEl Niño = FPNon-El Niño). The results in which the H1 hypothesis is accepted, in which the distributions can be said to be different (FPEl Niño ≠ FPNon-El Niño), are plotted as white regions. The rows represent the model runs with a depth cut-off limit at: (A-C) 60 m; (D) 100 m; (E) 200 m; and (F) 400 m.
Supplementary Figure 6 Combined A-D plots. As Supplementary Figure 4 and figure 5, in that panels represent locations of where dissimilar and similar values for the two climate states for (a-d) FAME-$\delta^{18}$O$_{eq}$ modelled oxygen isotope values or (e-h) FAME-$T_c$ modelled temperature recorded in the calcite shells ($T_c$) occur. Each panel represents the Anderson-Darling test result, the results for *Globigerinoides sacculifer*, *Globigerinoides ruber* and *N. dutertrei* are overlaid. For all panels black areas reflect latitudinal and longitudinal grid points that failed to reject the null hypothesis ($H_0$) and therefore the foraminiferal population (FP) of the El Niño is similar to the Non-El Niño, and therefore the distribution between the neutral climate and El Nino cannot be said to be different (FP$_{El \text{ Niño}} = $ FP$_{Non-El \text{ Niño}}$).
FAME - $\delta^{18}$O

Depth cut-off limit:

A. All 60 m

Values are dissimilar = possible to discern El Niño values.

B. All 100 m

Values are similar = not possible to discern El Niño values.

C. All 200 m

FAME - $T_c$

Depth cut-off limit:

E. All 60 m

Values are dissimilar = possible to discern El Niño values.

F. All 100 m

Values are similar = not possible to discern El Niño values.

G. All 200 m

H. G. sacculifer 100 m

G. ruber 60 m

N. dutertrei 200 m
Supplementary Figure 7 Same as Supplementary Figure 6 except: the results in which the $H_1$ hypothesis is accepted, in which the distributions can be said to be different ($F_{\text{El Niño}} \neq F_{\text{Non-El Niño}}$), are plotted as yellow where the depth is deeper than 3500 m bsl or purple where the depth is shallower than 3500 m bsl (see Figure 8). Purple locations are where our results suggest that the signal of ENSO has different values and the water depth allows for preservation – although this purple region will be smaller when inferred SAR is taken into account (see Figure 5). The rows represent the model runs with a depth cut-off limit at: (A and E) 60 m; (B and F) 100 m; (C and G) 200 m; and (D and H) where a combination of depths were utilised (Pracht et al., 2019).
S4. Sedimentation: Bioturbation and Dissolution

S4.1 Bathymetry

Supplementary Figure 8. Bathymetric map of the Tropical Pacific Ocean highlighting the areas above and below the Lysocline and/or Calcite compensation depth (CCD). (A) GEBCO map of height relative to 0 m; (B) same as (A) with location of seamounts plotted (white stars); (C-E) binary colour map of GEBCO data, yellow is values below cut-off depth value ([C] 3500 m below sea-level (bsl); [D] 4000 m bsl; and [E] 4500 m bsl respectively) and purple above the cut-off depth value. The histograms represent the normalised frequency of grid cell height in bins of 250 m wide, yellow is values below cut off value ([C] 3500 m below sea-level (bsl); [D] 4000 m bsl; and [E] 4500 m bsl respectively), purple above cut off value. The grey bins in each histogram are those above 0 m.
S4.2 Bioturbation

Supplementary Figure 9. Map of the sedimentation rate and oxygen saturation for the Tropical Pacific. (A) Inferred sedimentation rate (Olsen et al. 2016). White regions represent continental shelf. (B) Oxygen saturation of the bottom grid layer of World Ocean Atlas 2013 (data from: https://www.nodc.noaa.gov/cgi-bin/OC5/woa13/woa13oxnu.pl ). (C, E, G) Overlay between water depth and inferred SAR, Red / Pink: Continental shelf sediments that are (Red) shallower or (Pink) deeper than 3500 mbsl; Gray / White: grid point SAR is lower than SAR threshold and the seafloor depth is (grey) shallower or (white) deeper than 3500 mbsl; Light Yellow/Gold: Light yellow represents areas where the SAR is above the threshold but the water depth is deeper than 3500 mbsl in comparison Gold represents areas where the SAR is above the threshold and the water depth is deeper than 3500 mbsl. The ideal locations are therefore plotted as Gold. Cut-off limits for SAR are (C) ≥1 cm kyr⁻¹; (E) ≥2 cm kyr⁻¹ and (G) ≥5 cm kyr⁻¹, (D, F, H) alongside the maps the bioturbation simulations for the minimum SAR threshold is plotted (see Figure 8 and Figure 9 for the output of SEAMUS). Each plot gives the input values of NGRIP (grey) and for each SAR three analysis were performed with different bioturbation depths (BD) these are (Blue) 5 cm; (Green) 10 cm; and (Orange) 15 cm.
S4.2.1 Oxygen saturation state of the Pacific Ocean

Extracting the oxygen saturation (SO2) state, of the Pacific Ocean bottom waters from the Annual Climatology WOA13 give values that are predominantly >40 % (Supplement Figure 9). Oxygen saturation is the concentration of Oxygen in a medium against the maximum that can be dissolved in the same medium. Whilst annual variability may exist, it is unlikely that bioturbation would be prevented by low oxygen.