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Supplement of

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

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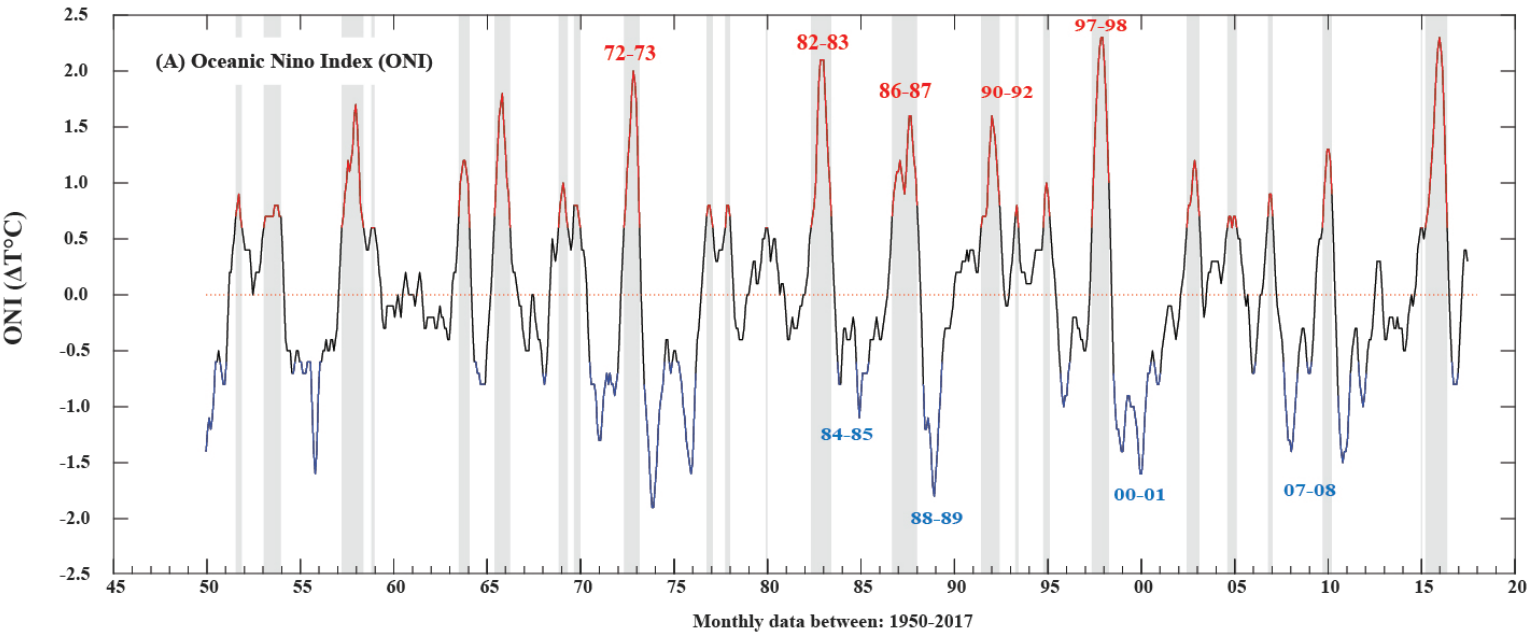
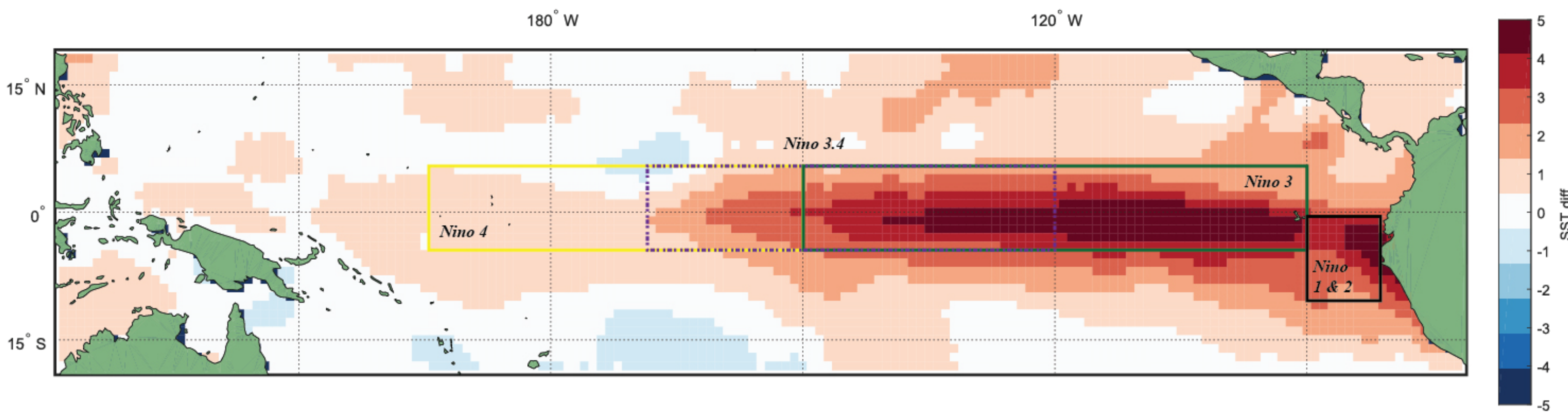
S1. Oceanic Nino Index (ONI) index

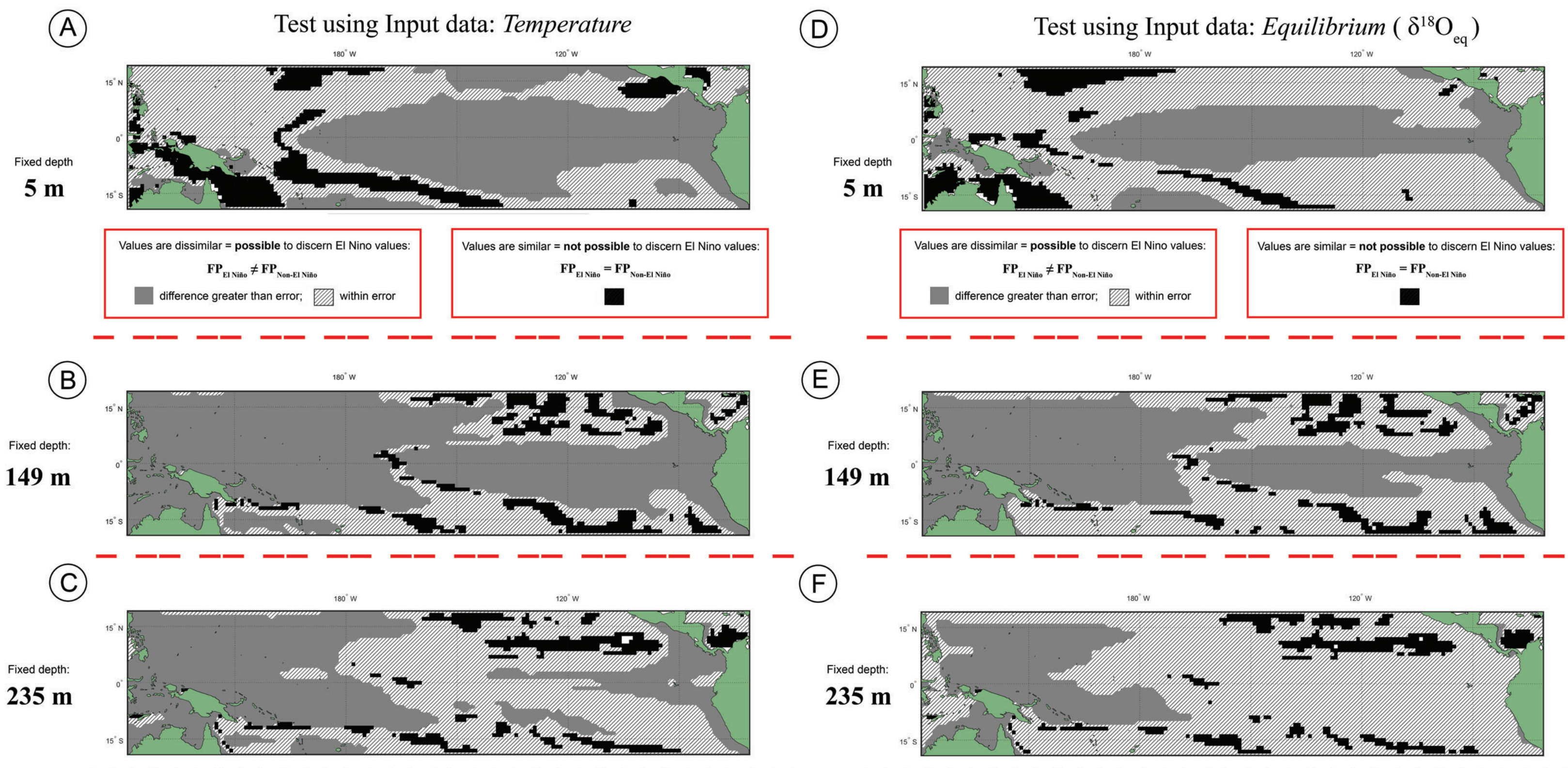
Supplementary Figure 1 Oceanic Niño Index and the temperature anomaly for a single El Niño event. (Top) Oceanic Niño Index (ONI), sourced from a 3-month running mean of SST anomalies in ERSST.v5 of the Niño 3.4 region (Huang et al., 2017). Grey vertical bars represent the periods in which El Niño-like conditions exist using a simple one-month threshold. (Bottom) The sea surface temperature difference between week beginning 1st December 1997 minus the long-term climatic mean (1971 – 2000) for December. The 1997 – 1998 El Niño represents an EP-ENSO. The long term monthly climatology, the NOAA optimum interpolation (OI) SST V2, based upon the methodology of Reynolds and Smith (Reynolds and Smith, 1995) using two distinct climatologies for 1971 - 2000 and 1982 – 2000 (Reynolds et al., 2002). Boxes represent the Nino region: Niño 1 and 2 (0° - -10°S, 90°W - 80°W), Niño 3 (5°N - -5°S, 150°W - 90°W), Niño 3.4 (5°N - -5°S, 170°W - 120°W) and Niño 4 (5°N - -5°S, 160°E - 150°W).


(A) Oceanic Nino Index (ONI)
ONI (ΔT°C)
Monthly data between: 1950-2017
72-73
82-83
86-87
90-92
97-98
84-85
88-89
00-01
07-08
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
45
50
55
60
65
70
75
80
85
90
95
00
05
10
15
20


180° W
120° W
15° N
0°
15° S
Nino 3.4
Nino 4
Nino 3
Nino 1 & 2
SST diff.
5
4
3
2
1
0
-1
-2
-3
-4
-5

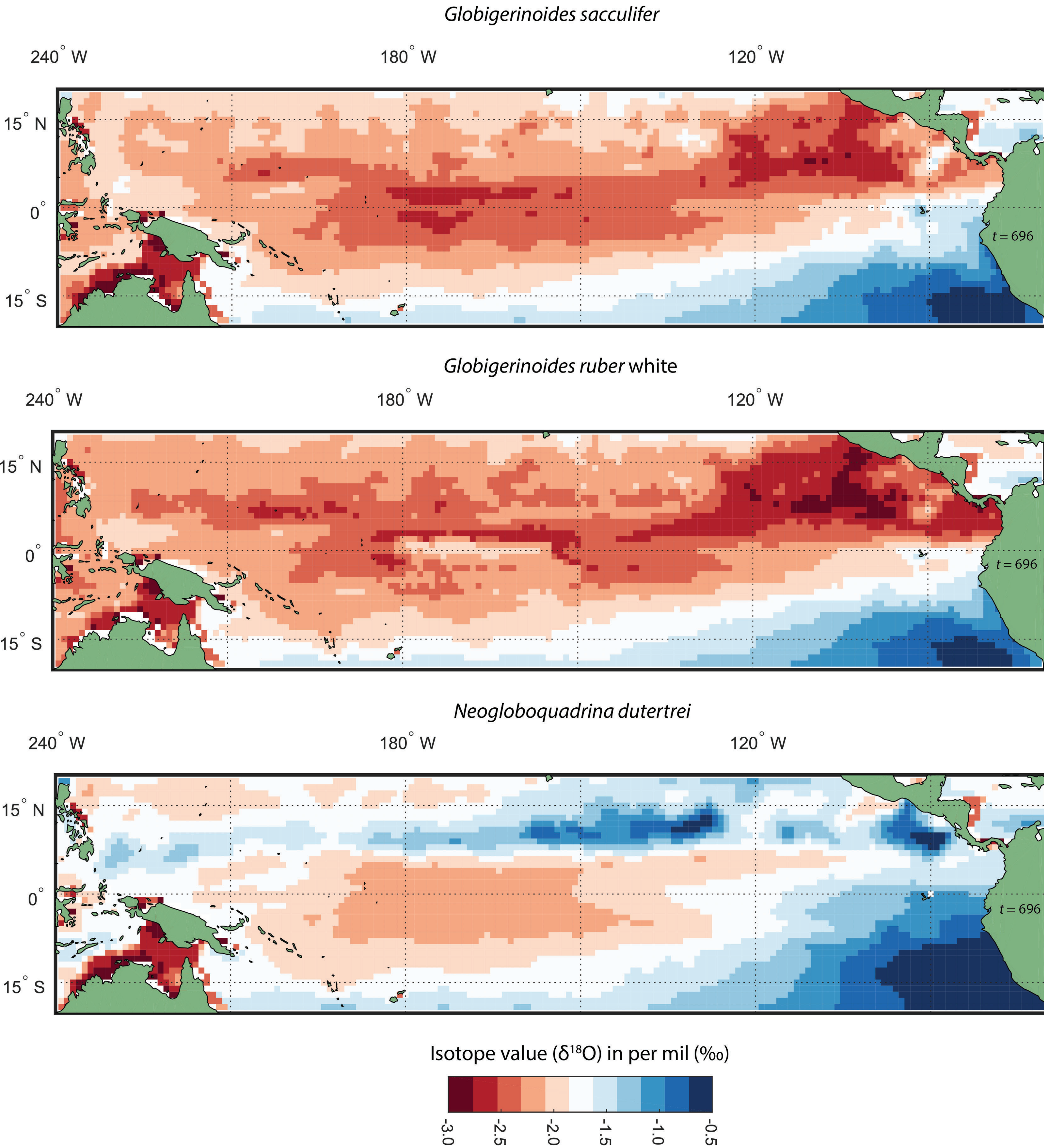
S2. Test of input (temperature and equilibrium)

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 (H_0), that the El Niño and Non- El Niño populations are not statistically different ($FP_{El\ Niño} = FP_{Non\text{-}El\ Niño}$), cannot be rejected. Gray regions represent grid points where the H_1 hypothesis is accepted, therefore the distributions of the foraminiferal population (FP) for El Niño and Non- El Niño can be said to be unique ($FP_{El\ Niño} \neq FP_{Non\text{-}El\ Niño}$). The hatched regions represent areas were the H_1 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 ($FP_{El\ Niño} \neq FP_{Non\text{-}El\ Niño}$), 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).


A
Test using Input data: *Temperature*
D
Test using Input data: *Equilibrium* ($\delta^{18}O_{eq}$)
180° W
120° W
15° N
0°
15° S
Fixed depth
5 m
Values are dissimilar = **possible** to discern El Nino values:
$FP_{El\ Niño} \neq FP_{Non\text{-}El\ Niño}$
difference greater than error;
within error
Values are similar = **not possible** to discern El Nino values:
$FP_{El\ Niño} = FP_{Non\text{-}El\ Niño}$
B
E
Fixed depth:
149 m
C
F
Fixed depth:
235 m

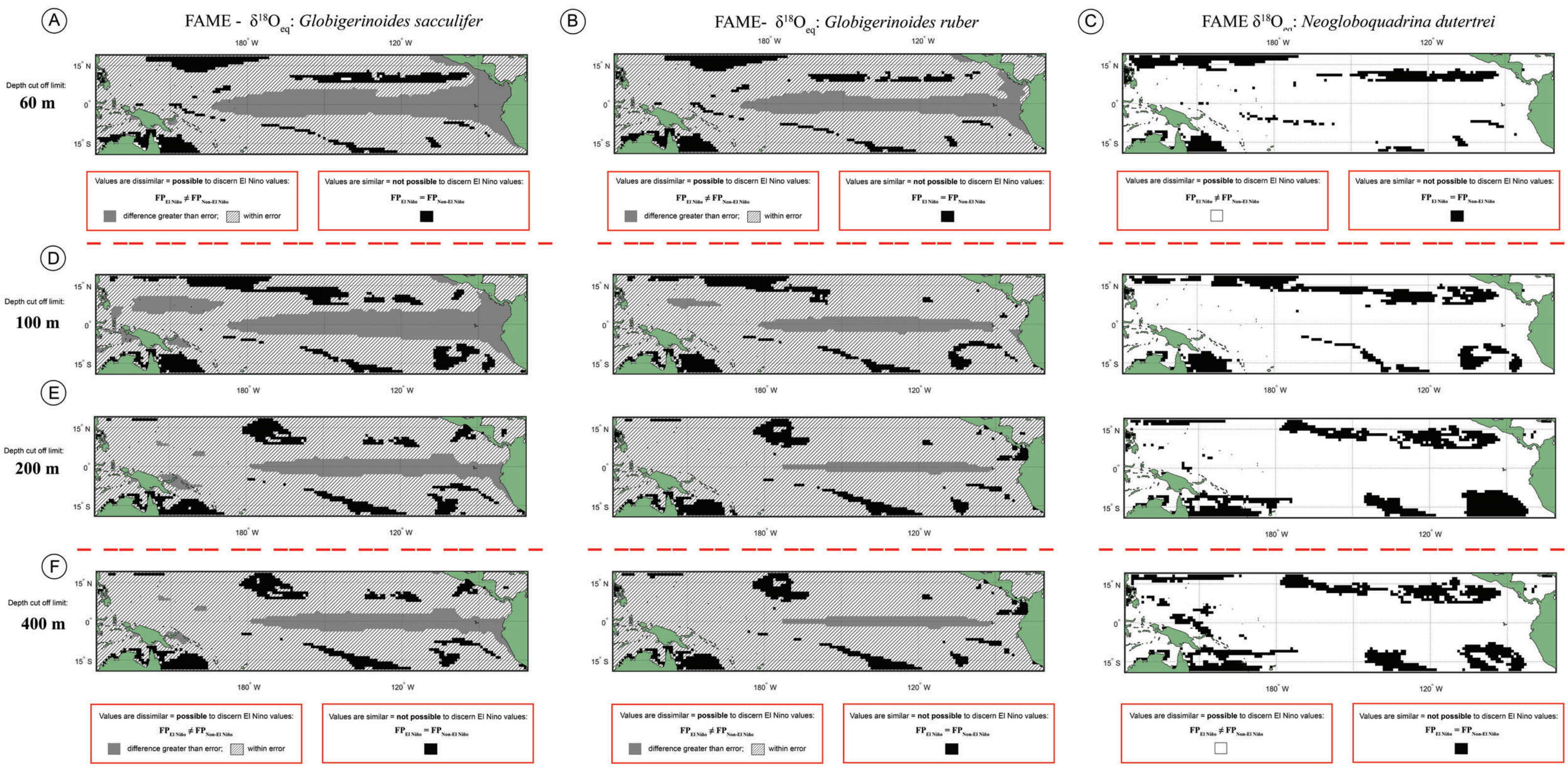
S3. FAME Output:

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)



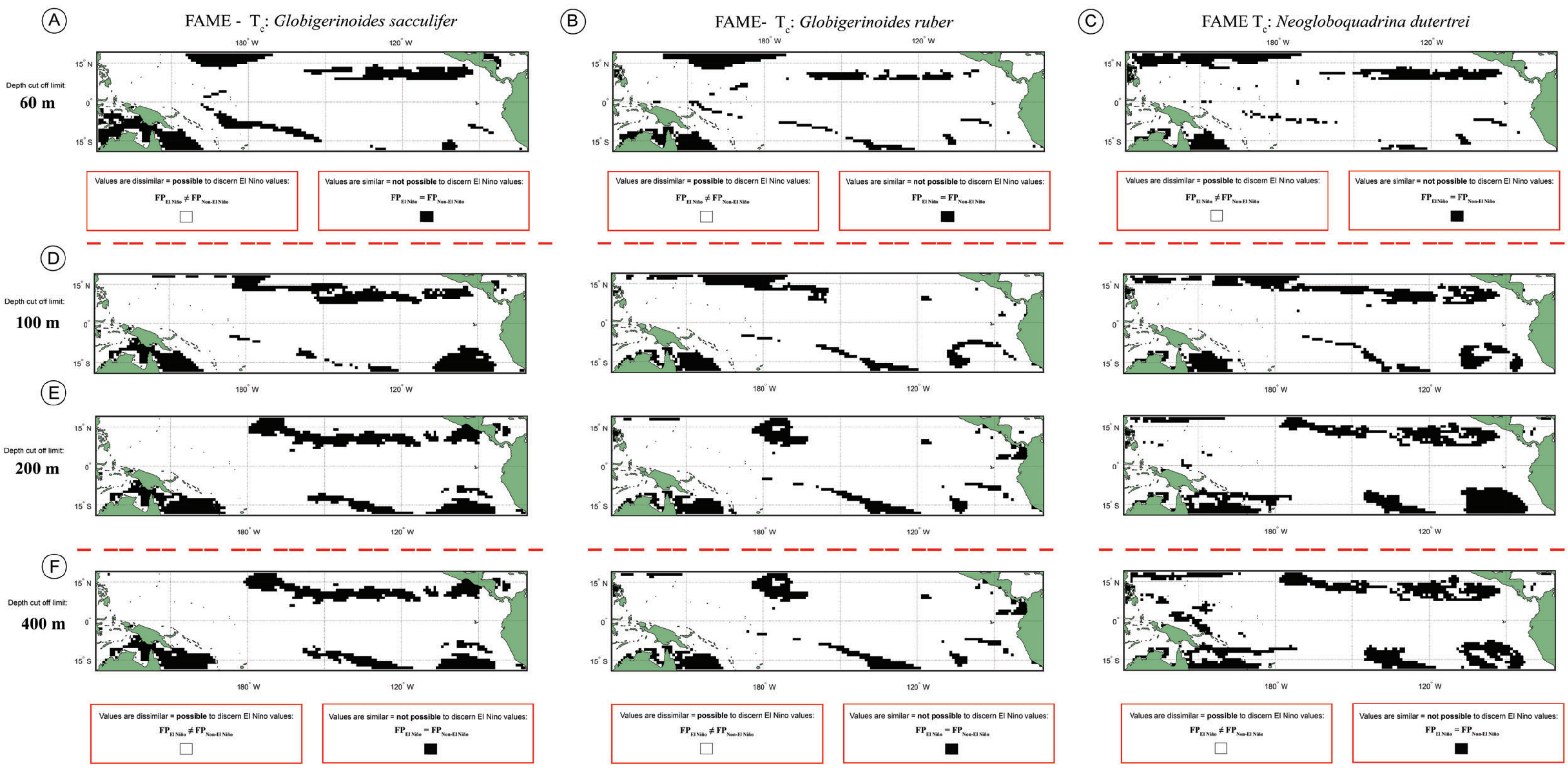
Globigerinoides sacculifer
240° W
180° W
120° W
15° N
0°
15° S
t = 696
Globigerinoides ruber white
240° W
180° W
120° W
15° N
0°
15° S
t = 696
Neogloboquadrina dutertrei
240° W
180° W
120° W
15° N
0°
15° S
t = 696
Isotope value (δ18O) in per mil (‰)
-3.0
-2.5
-2.0
-1.5
-1.0
-0.5

Supplementary Figure 4 Anderson-Darling Results for modelled FAME-$\delta^{18}O_{eq}$: Panels representing locations of where dissimilar and similar values of FAME modelled species δ^{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 ($FP_{\text{El Niño}} = FP_{\text{Non-El Niño}}$). The results in which the H_1 hypothesis is accepted, in which the, therefore the distributions can be said to be different ($FP_{\text{El Niño}} \neq FP_{\text{Non-El Niño}}$), 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.



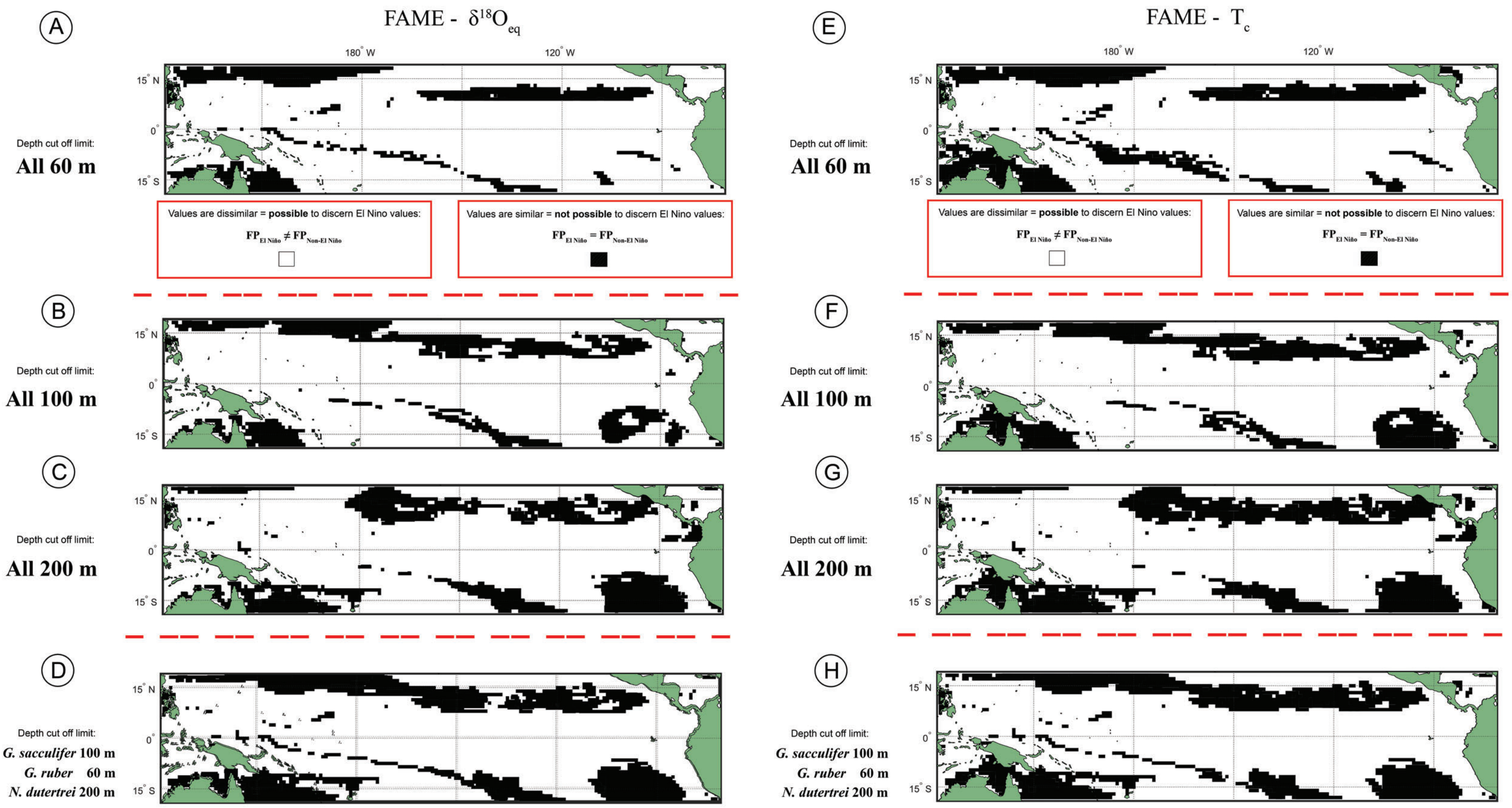
A
FAME - δ18Oeq: Globigerinoides sacculifer
B
FAME- δ18Oeq: Globigerinoides ruber
C
FAME δ18Oeq: Neogloboquadrina dutertrei
180° W
120° W
15° N
0°
15° S
Depth cut off limit:
60 m
Values are dissimilar = possible to discern El Nino values:
FP El Niño ≠ FP Non-El Niño
difference greater than error;
within error
Values are similar = not possible to discern El Nino values:
FP El Niño = FP Non-El Niño
D
Depth cut off limit:
100 m
E
Depth cut off limit:
200 m
F
Depth cut off limit:
400 m

Supplementary Figure 5 Anderson-Darling Results for modelled FAME-T_c: 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 (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 ($FP_{\text{El Niño}} = FP_{\text{Non-El Niño}}$). The results in which the H_1 hypothesis is accepted, in which the distributions can be said to be different ($FP_{\text{El Niño}} \neq FP_{\text{Non-El Niño}}$), 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.

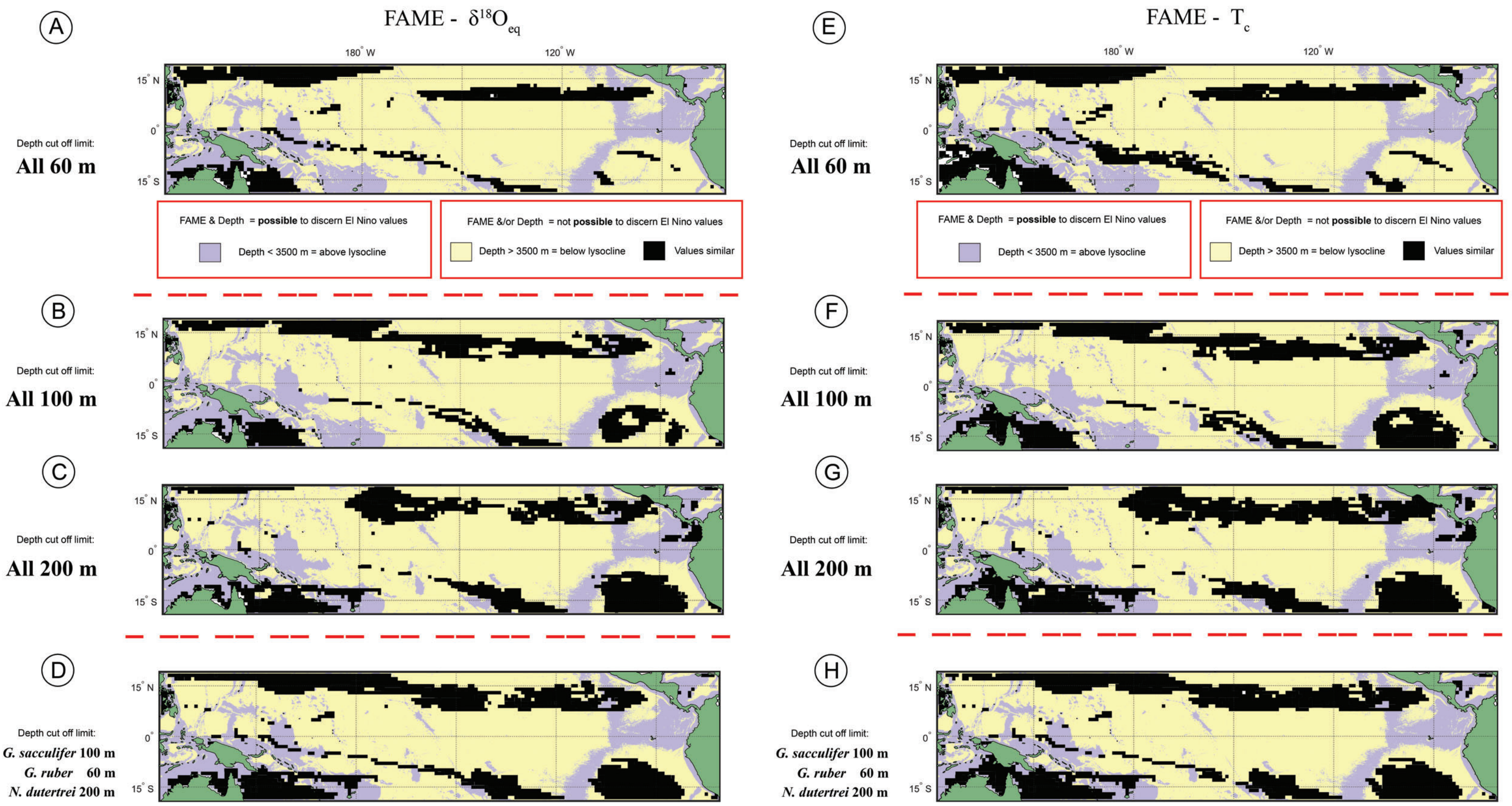


A
FAME - T_c: *Globigerinoides sacculifer*
B
FAME- T_c: *Globigerinoides ruber*
C
FAME T_c: *Neogloboquadrina dutertrei*
Depth cut off limit:
60 m
100 m
200 m
400 m
D
E
F
180° W
120° W
15° N
0°
15° S
Values are dissimilar = **possible** to discern El Nino values:
$FP_{El\ Niño} \neq FP_{Non\text{-}El\ Niño}$
Values are similar = **not possible** to discern El Nino values:
$FP_{El\ Niño} = FP_{Non\text{-}El\ Niño}$

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 (Tc) 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 ($FP_{El\ Niño} = FP_{Non\text{-}El\ Niño}$).


A
FAME - δ18Oeq
E
FAME - Tc
180° W
120° W
15° N
0°
15° S
Depth cut off limit:
All 60 m
Values are dissimilar = possible to discern El Nino values:
FP El Niño ≠ FP Non-El Niño
Values are similar = not possible to discern El Nino values:
FP El Niño = FP Non-El Niño
B
F
Depth cut off limit:
All 100 m
C
G
Depth cut off limit:
All 200 m
D
H
Depth cut off limit:
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 ($FP_{El\ Niño} \neq FP_{Non\text{-}El\ Niño}$), 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).

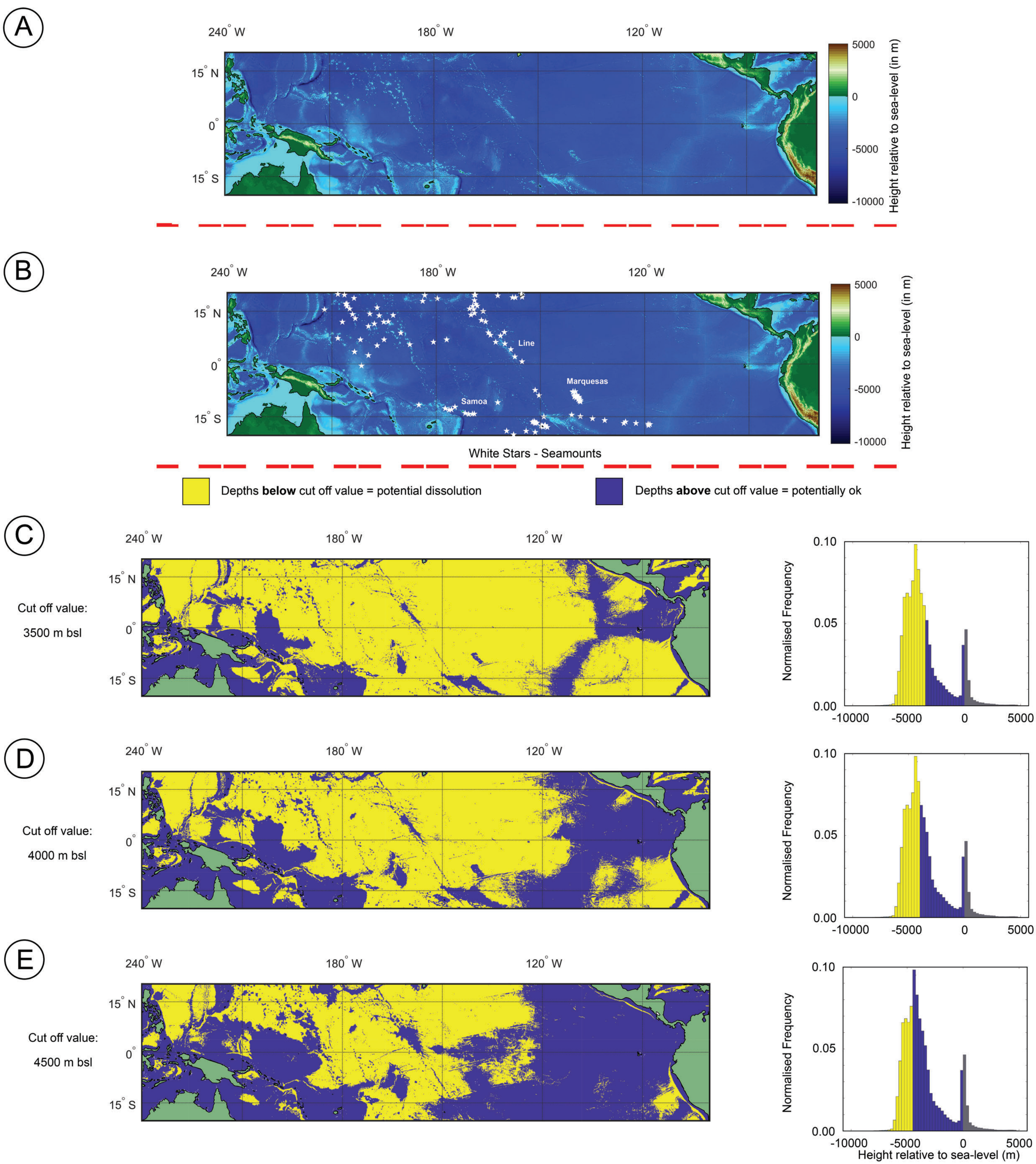


A
FAME - δ18Oeq
180° W
120° W
15° N
0°
15° S
Depth cut off limit:
All 60 m
FAME & Depth = possible to discern El Nino values
Depth < 3500 m = above lysocline
FAME &/or Depth = not possible to discern El Nino values
Depth > 3500 m = below lysocline
Values similar
B
Depth cut off limit:
All 100 m
C
Depth cut off limit:
All 200 m
D
Depth cut off limit:
G. sacculifer 100 m
G. ruber 60 m
N. dutertrei 200 m
E
FAME - Tc
F
G
H

S4. Sedimentation: Bioturbation and Dissolution

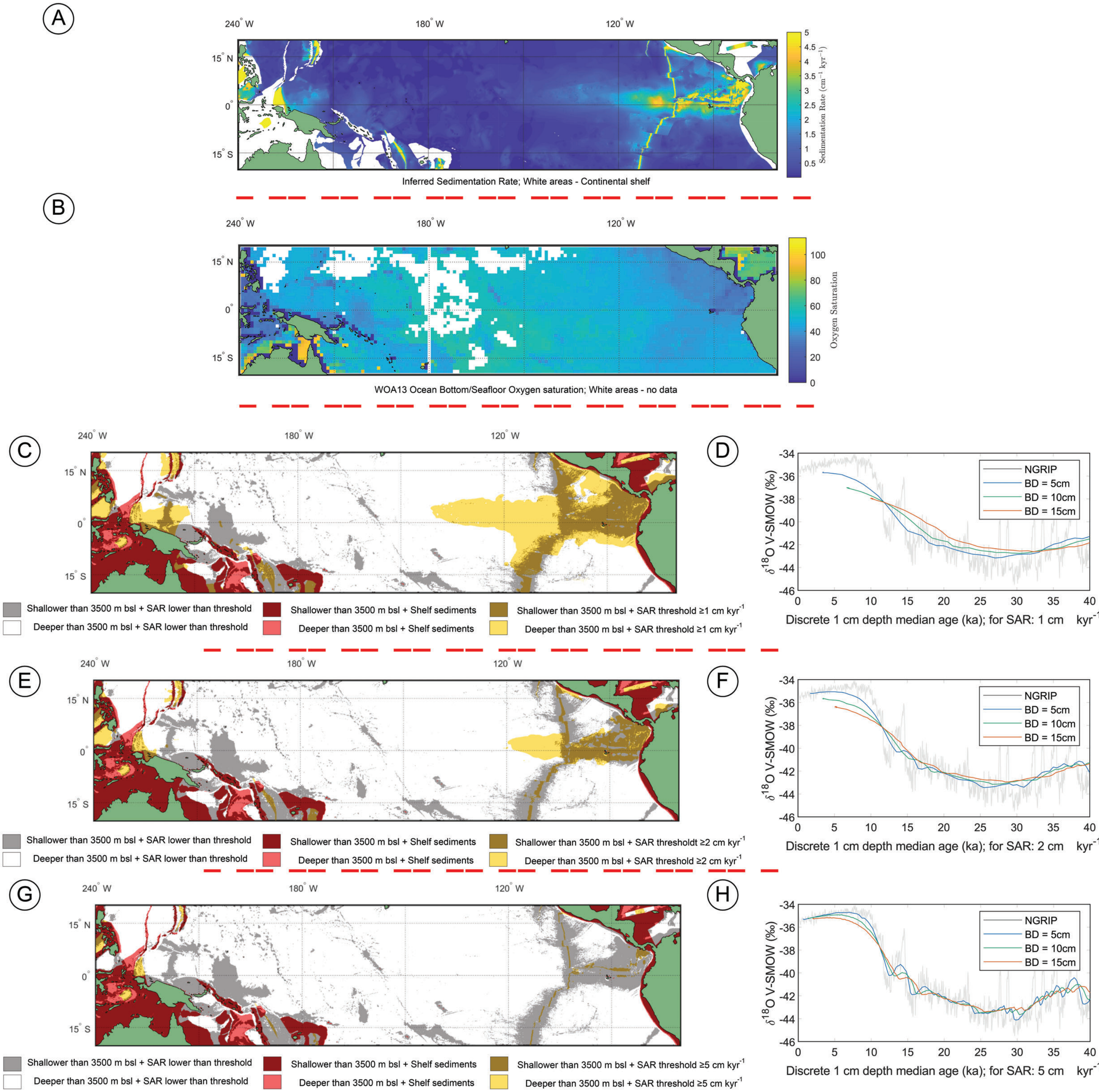
S4.1 Bathymetry

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.


A
240° W
180° W
120° W
15° N
0°
15° S
5000
0
-5000
-10000
Height relative to sea-level (in m)
B
240° W
180° W
120° W
15° N
0°
15° S
Line
Marquesas
Samoa
5000
0
-5000
-10000
Height relative to sea-level (in m)
White Stars - Seamounts
Depths **below** cut off value = potential dissolution
Depths **above** cut off value = potentially ok
C
Cut off value:
3500 m bsl
240° W
180° W
120° W
15° N
0°
15° S
Normalised Frequency
0.10
0.05
0.00
-10000
-5000
0
5000
D
Cut off value:
4000 m bsl
240° W
180° W
120° W
15° N
0°
15° S
Normalised Frequency
0.10
0.05
0.00
-10000
-5000
0
5000
E
Cut off value:
4500 m bsl
240° W
180° W
120° W
15° N
0°
15° S
Normalised Frequency
0.10
0.05
0.00
-10000
-5000
0
5000
Height relative to sea-level (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 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.



A
240° W
180° W
120° W
15° N
0°
15° S
Sedimentation Rate (cm^{-1} kyr^{-1})
Inferred Sedimentation Rate; White areas - Continental shelf
B
Oxygen Saturation
WOA13 Ocean Bottom/Seafloor Oxygen saturation; White areas - no data
C
D
NGRIP
BD = 5cm
BD = 10cm
BD = 15cm
δ^{18}O V-SMOW (‰)
Shallower than 3500 m bsl + SAR lower than threshold
Deeper than 3500 m bsl + SAR lower than threshold
Shallower than 3500 m bsl + Shelf sediments
Deeper than 3500 m bsl + Shelf sediments
Shallower than 3500 m bsl + SAR threshold ≥1 cm kyr^{-1}
Deeper than 3500 m bsl + SAR threshold ≥1 cm kyr^{-1}
Discrete 1 cm depth median age (ka); for SAR: 1 cm kyr^{-1}
E
F
Shallower than 3500 m bsl + SAR thresholdt ≥2 cm kyr^{-1}
Deeper than 3500 m bsl + SAR threshold ≥2 cm kyr^{-1}
Discrete 1 cm depth median age (ka); for SAR: 2 cm kyr^{-1}
G
H
Shallower than 3500 m bsl + SAR threshold ≥5 cm kyr^{-1}
Deeper than 3500 m bsl + SAR threshold ≥5 cm kyr^{-1}
Discrete 1 cm depth median age (ka); for SAR: 5 cm kyr^{-1}

S4.2.1 Oxygen saturation state of the Pacific Ocean

Extracting the oxygen saturation (**SO_2**) 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.