An Atmospheric Chronology for the Glacial-Deglacial Eastern Equatorial Pacific

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Supplementary Information
Supplementary Figure 1.
Location of KNR176-GGC17/JPC30 in an expanded map with topography. Map made with Ocean Data View\textsuperscript{1}.
Supplementary Figure 2.
CT scanning of sediment core sections. Left: Sediment core sections being scanned by a CT machine in the Computerized Scanning and Imaging Facility at WHOI. Right: A CT scanning image revealing a twig buried in the sediments.
Supplementary Figure 3.
CT image showing a worm burrow. This hollow burrow extends more than 30 cm in the early Holocene sediments of GGC17.
Supplementary Figure 4.
Sedimentation rate of KNR176-GGC17/JPC30.
Strong surface ocean stratification near our site. (a) Temperature and salinity profiles from station KNR176-HC38 (5.00°N, 77.75°W) close to our site. According to a plankton tow study in the Panama Basin, *N. dutertrei* calcifies near the thermocline which is mainly influenced by subsurface currents from the west. (b) *N. dutertrei* and *G. ruber* δ¹⁸O from a nearby site (KNR176-JPC32, 4.67°N, 77.96°W; unpublished) suggesting strong and stable surface stratification from the LGM to the Holocene near the delta of San Juan River. The *N. dutertrei* δ¹⁸O data agree well with those from other locations in the EEP (e.g., an LGM-Holocene shift from ~2‰ to ~0.8‰ at ODP1240).
Supplementary Figure 6.
*N. dutertrei* (dots) and *Uvigerina* (squares) $\delta^{13}$C from GGC17/JPC30 compared to other EEP records (*N. dutertrei* $\delta^{13}$C from ODP1238 in the upwelling region and *Uvigerina* $\delta^{13}$C from KNR195-5 GGC43 at the same site as VM21-30; Fig. 1). For the large negative excursions of $\delta^{13}$C at ~17.4 kyr BP (isolated points), the carbon source is currently not clear.
Supplementary Figure 7.
Published near-surface $^{14}$C reservoir ages compared with the EEP thermocline and intermediate water ventilation ages from this study. Note that the EEP thermocline reservoir ages based on stratigraphic alignments (ODP1240$^7$ and TR163-23$^8$) for most of the LGM and many deglacial samples are even larger than the intermediate-depth ventilation age in this study. The reservoir ages recorded by *G. ruber* off Baja California$^9$, with chronologies based on the correlation of the third factor (after R-mode factor analysis) of diffuse spectral reflectance to Greenland ice cores$^10$, are much larger than our thermocline and intermediate-depth ventilation ages in the EEP during the deglaciation. For clarity, the errors bars are not plotted. See Fig. 3 for a sense of the uncertainties.
Supplementary Figure 8.

*G. ruber* δ¹⁸O from two EEP cores plotted with the age models determined from *N. dutertrei* ¹⁴C dates calibrated with a stable reservoir age (590+/−270 ¹⁴C yr averaged from this study) and from *G. ruber* δ¹⁸O aligned with Greenland ice core δ¹⁸O (GRIP data; Ref: ¹¹), respectively. Vertical dashed lines delineate the tie points used, which are different between the studies (Refs: ⁸ for TR163-23 (cyan) and ⁷ for ODP1240 (magenta)). Open symbols at the bottom show the ¹⁴C dates from the two cores (Refs: ⁸ for TR163-23 (blue) and ⁴,⁸ for ODP1240 (pink)). Note there are ¹⁴C age reversals in both cores (which produces very steep slopes in the *G. ruber* δ¹⁸O, e.g., ~13.5 kyr BP for TR163-23 and ~21 kyr BP for ODP1240), suggesting significant bioturbation influence.

There are uncertainties associated with selections of tie points and also the synchronicities between *G. ruber* δ¹⁸O in the EEP and Greenland ice core δ¹⁸O. For example, *G. ruber* δ¹⁸O based on calibrated ¹⁴C dates shows a general decreasing trend (note the inverted axis) during ~17.5-14.5 kyr BP for both records, suggesting a feature similar to the Antarctic rather than Greenland¹². In addition, *G. ruber* δ¹⁸O between the two sites do not always agree, which might indicate local complications of the proxy.
Supplementary Figure 9.
Locations of the intermediate-depth cores in the eastern tropical Pacific plotted with pre-bomb Δ¹⁴C distribution at 700 m (data from gridded GLODAP product¹). The modern Δ¹⁴C differences, which are also δ¹⁴R differences (Δ¹⁴C_{atm} = 0 for modern pre-bomb atmosphere in equation (3) of the Methods section), between these sites are no larger than 20‰. It is not plausible to maintain δ¹⁴R gradients larger than 200‰ between these sites from similar depths, especially between our site and Galapagos, if all the data in Fig. 3c represent large scale features. Figure made with Ocean Data View¹.
Supplementary Figure. 10.
Locations of the intermediate-depth cores with reference to active hydrothermal systems today. The observed sites of hydrothermal venting systems in the Eastern Equatorial and Northeastern Pacific are from InterRidge Vents Database Ver. 3.3 (http://vents-data.interridge.org/ventfields_list_all). Strengthened hydrothermal activities\textsuperscript{14} and/or increased intermediate-depth temperatures\textsuperscript{15} could lead to greater release of geological carbon near the ridges during the deglaciation. Note this map only shows the active venting sites today. There were likely more active sites during the deglaciation\textsuperscript{14} and some could be very close to the sites of the Galapagos and Baja California records. Figure made using Ocean Data View\textsuperscript{1}. 
**Supplementary Table 1.**
Modern fraction (Fm) and $^{14}$C age of wood, planktonic and benthic foraminifera samples from KRN176-GGC17/JPC30

| Depth (cm) | Wood | N. dutertrei | Uvigerina |
|------------|------|--------------|-----------|
|            | Fm   | $1 \text{ s.d.}$ | $^{14}$C age (yr) | $1 \text{ s.d.}$ | $^{14}$C age (yr) | $1 \text{ s.d.}$ | $^{14}$C age (yr) | $1 \text{ s.d.}$ | $^{14}$C age (yr) | $1 \text{ s.d.}$ |
| 53         | 0.6678 | 0.0018 | 3240 | 20 | 0.6098 | 0.0016 | 3970 | 20 |
| 129.5      | 0.5068 | 0.0016 | 5560 | 25 | 0.4654 | 0.0015 | 6410 | 25 |
| 161*       | 0.4454 | 0.0014 | 6500 | 25 | 0.3773 | 0.0014 | 7830 | 30 | 0.2781 | 0.0014 | 10300 | 40 |
| 204.5*     | 0.3178 | 0.0018 | 9210 | 45 | 0.2949 | 0.0015 | 9810 | 40 | 0.2364 | 0.0016 | 11600 | 55 |
| 216.5*     | 0.3256 | 0.0016 | 9010 | 40 |           |           |       |       |           |           |       |       |
| 226.5      | 0.2671 | 0.0015 | 10600 | 45 | 0.2747 | 0.0014 | 10400 | 40 | 0.2320 | 0.0014 | 11750 | 50 |
| 238        | 0.2216 | 0.0010 | 12100 | 35 | 0.2183 | 0.0012 | 12250 | 45 | 0.2026 | 0.0015 | 12800 | 60 |
| 243.5**    | 0.2135 | 0.0019 | 12400 | 70 | 0.2039 | 0.0012 | 12750 | 50 | 0.1924 | 0.0011 | 13250 | 45 |
| 254**      | 0.2144 | 0.0011 | 12350 | 40 | 0.1958 | 0.0012 | 13100 | 50 | 0.1852 | 0.0012 | 13550 | 55 |
| 271        | 0.2042 | 0.0012 | 12750 | 45 | 0.1947 | 0.0012 | 13150 | 50 | 0.1722 | 0.0015 | 14150 | 70 |
| 278.5      | 0.1979 | 0.0018 | 13000 | 75 | 0.1873 | 0.0012 | 13450 | 50 | 0.1841 | 0.0011 | 13600 | 45 |
| 306        | 0.1924 | 0.0019 | 13250 | 80 | 0.1782 | 0.0015 | 13850 | 70 | 0.1702 | 0.0011 | 14200 | 50 |
| 185        | 0.2799 | 0.0015 | 10250 | 45 | 0.2661 | 0.0015 | 10650 | 45 | 0.2382 | 0.0014 | 11550 | 50 |
| 192        | 0.2713 | 0.0017 | 10500 | 50 | 0.2457 | 0.0013 | 11300 | 45 | 0.2355 | 0.0015 | 11600 | 50 |
| 201        | 0.2464 | 0.0016 | 11250 | 55 | 0.2083 | 0.0016 | 12600 | 65 | 0.1917 | 0.0015 | 13250 | 65 |
| 209        | 0.2179 | 0.0023 | 12250 | 85 | 0.2136 | 0.0011 | 12400 | 45 | 0.1861 | 0.0015 | 13500 | 65 |
| 306        | 0.1806 | 0.0021 | 13750 | 95 | 0.1687 | 0.0016 | 14300 | 75 | 0.1559 | 0.0014 | 14950 | 70 |
| 333        | 0.1718 | 0.0022 | 14150 | 100 | 0.1604 | 0.0011 | 14700 | 55 | 0.1526 | 0.0016 | 15100 | 80 |
| 354.5      | 0.1682 | 0.0023 | 14300 | 110 | 0.1499 | 0.0012 | 15250 | 65 | 0.1404 | 0.0014 | 15750 | 80 |
| 379        | 0.1571 | 0.0021 | 14850 | 110 | 0.1468 | 0.0016 | 15400 | 85 | 0.1372 | 0.0015 | 15950 | 85 |
| 430.5      | 0.1422 | 0.0022 | 15650 | 130 | 0.1278 | 0.0016 | 16550 | 100 | 0.1221 | 0.0014 | 16900 | 90 |
| 466        | 0.1280 | 0.0022 | 16500 | 140 | 0.1204 | 0.0015 | 17000 | 100 | 0.1145 | 0.0015 | 17400 | 100 |
| 546.5      | 0.1137 | 0.0022 | 17450 | 160 | 0.1064 | 0.0012 | 18000 | 90 | 0.0986 | 0.0015 | 18550 | 120 |
| 578.5      | 0.1006 | 0.0011 | 18450 | 90 | 0.0911 | 0.0013 | 19250 | 120 | 0.0831 | 0.0012 | 20000 | 120 |
| 608        | 0.0894 | 0.0011 | 19400 | 100 | 0.0818 | 0.0013 | 20100 | 130 | 0.0767 | 0.0012 | 20650 | 130 |
| 663.5      | 0.0629 | 0.0008 | 22200 | 100 |           |           |       |       |           |           |       |       |
| 695        | 0.0394 | 0.0010 | 26000 | 210 |           |           |       |       |           |           |       |       |
| 741        | 0.0243 | 0.0011 | 29900 | 350 |           |           |       |       |           |           |       |       |

Note:
* Early Holocene samples that are significantly influenced by bioturbation (see Methods for details)
** These two wood $^{14}$C ages are the same within 1 s.d., so we combine data from the two samples.
Supplementary Table 2.

*N. dutertrei* and *Uvigerina* δ\(^{13}\)C of KRN176-GGC17/JPC30. Instrument precision of δ\(^{13}\)C is ~0.05‰.

| Depth (cm) | Cal age (kyr BP) | 1 s.d (kyr) | *N. dutertrei* δ\(^{13}\)C (‰) | *Uvigerina* δ\(^{13}\)C (‰) |
|------------|------------------|-------------|------------------|------------------|
| GGC17      |                  |             |                  |                  |
| 226.5      | 12.59            | 0.06        | 0.83             | -0.72            |
| 238        | 13.96            | 0.08        | 0.88             | -0.82            |
| 243.5-254  | 14.44            | 0.18        | 0.75             | -0.96            |
| 271        | 15.19            | 0.08        | 0.74             | -0.97            |
| 278.5      | 15.55            | 0.14        | 0.73             | -0.92            |
| 306        | 15.93            | 0.13        | 0.63             | -0.92            |
| JPC30      |                  |             |                  |                  |
| 185        | 11.99            | 0.10        | 0.83             | -0.7             |
| 192        | 12.45            | 0.10        | 0.95             | -0.72            |
| 201        | 13.12            | 0.05        | 0.85             | -0.96            |
| 209        | 14.23            | 0.19        | 0.87             | -0.93            |
| 306        | 16.62            | 0.17        | 0.97             | -0.65            |
| 333        | 17.22            | 0.16        | 1.09             | -0.81            |
| 354.5      | 17.41            | 0.16        | 0.36             | -2.03            |
| 379        | 18.07            | 0.14        | 1.1              | -0.88            |
| 430.5      | 18.92            | 0.15        | 1.17             | -0.93            |
| 466        | 19.91            | 0.18        | 1.24             | -0.83            |
| 546.5      | 21.09            | 0.23        | 1.08             | -0.66            |
| 578.5      | 22.31            | 0.12        | 1.33             | -0.86            |
| 608        | 23.35            | 0.16        | 1.15             | -0.7             |
Supplementary References

1. Schlitzer, R. Ocean Data View. http://odv.awi.de (2016).
2. Fairbanks, R. G., Sverdlov, M., Free, R., Wiebe, P. H. & Bé, A. W. H. Vertical distribution and isotopic fractionation of living planktonic foraminifera from the Panama Basin. Nature 298, 841-844 (1982).
3. Kessler, W. S. The circulation of the eastern tropical Pacific: A review. Prog. Oceanogr. 69, 181-217 (2006).
4. Pena, L. D., Cacho, I., Ferretti, P. & Hall, M. A. El Niño–Southern Oscillation–like variability during glacial terminations and interlududinal teleconnections. Paleoceanography 23, PA3101 (2008).
5. Martínez-Botí, M. A. et al. Boron isotope evidence for oceanic carbon dioxide leakage during the last deglaciation. Nature 518, 219-222 (2015).
6. Bova, S. C. et al. Links between eastern equatorial Pacific stratification and atmospheric CO2 rise during the last deglaciation. Paleoceanography 30, 1407-1424 (2015).
7. de la Fuente, M., Skinner, L., Calvo, E., Pelejero, C. & Cacho, I. Increased reservoir ages and poorly ventilated deep waters inferred in the glacial Eastern Equatorial Pacific. Nat. Commun. 6, 7420 (2015).
8. Umling, N. E. & Thunell, R. C. Synchronous deglacial thermocline and deep-water ventilation in the eastern equatorial Pacific. Nat. Commun. 8, 14203 (2017).
9. Lindsay, C. M., Lehman, S. J., Marchitto, T. M. & Ortiz, J. D. The surface expression of radiocarbon anomalies near Baja California during deglaciation. Earth Planet. Sci. Lett. 422, 67-74 (2015).
10. Marchitto, T. M., Lehman, S. J., Ortiz, J. D., Fluckiger, J. & van Geen, A. Marine radiocarbon evidence for the mechanism of deglacial atmospheric CO2 rise. Science 316, 1456-1459 (2007).
11. Rasmussen, S. O. et al. A stratigraphic framework for abrupt climatic changes during the Last Glacial period based on three synchronized Greenland ice-core records: refining and extending the INTIMATE event stratigraphy. Quat. Sci. Rev. 106, 14-28 (2014).
12. Koutavas, A. Temperature correlations between the eastern equatorial Pacific and Antarctica over the past 230,000 years. Earth Planet. Sci. Lett. 485, 43-54 (2018).
13. Key, R. M. et al. A global ocean carbon climatology: Results from Global Data Analysis Project (GLODAP). Global Biogeochem. Cycles 18, GB4031, doi:10.1029/2004GB002247 (2004).
14. Lund, D. C. et al. Enhanced East Pacific Rise hydrothermal activity during the last two glacial terminations. Science 351, 478-482 (2016).
15. Stott, L. & Timmermann, A. in Abrupt Climate Change: Mechanisms, Patterns, and Impacts (eds Harunur Rashid, Leonid Polyak, & Ellen Mosley-Thompson) 123-138 (AGU Geophysical Monograph Series vol. 193, American Geophysical Union, 2011).