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Millennial-scale ocean dynamics controlled export productivity in the subtropical North Pacific

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ABSTRACT

The integrated effects of ocean-climate dynamics on export production in the North Pacific have remained elusive. We present a 91 k.y. export productivity (EP) record based on sedimentary reactive phosphorus from the western subtropical North Pacific. On a millennial time scale, EP decreased during Northern Hemisphere cold events when atmospheric dust loading was high, and increased during warm episodes. The inferred antiphase relation between dust and EP suggests that the supply of macronutrients to the sunlit surface ocean, modulated by the penetration depth of North Pacific Intermediate Water and not eolian Fe, exerted a major control on EP in the subtropical North Pacific. A compilation of global EP records suggests that eolian Fe most likely played a role in stimulating EP regionally only in the Subantarctic zone of the Southern Ocean. Over the past 91 k.y., during the cold-south–warm-north phase of the bipolar seesaw, the biological pump in both hemispheres was enhanced synchronously, yet by different drivers; atmospheric Fe input for the Subantarctic and subsurface macronutrient supply for the North Pacific, including the tropical and/or subtropical Pacific, and the Antarctic zone of the Southern Ocean.

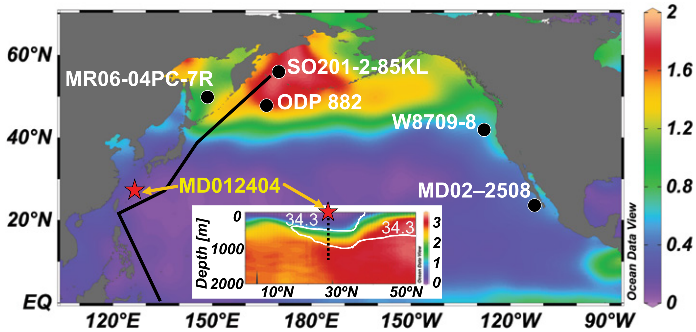

Figure 1. The modern phosphate concentration (µmol L⁻¹) at 20 m depth and of the upper 2000 m (the inset map) along the cross section (black solid line). Red star indicates core site MD012404 (Okinawa Trough); solid black dots indicate reference cores. White cvontour line in the inset map represents salinity. Phosphate data source is WOA2013 (http://www.nodc.noaa.gov/OC5/woa13/woa13data.html). Maps were generated with Ocean Data View software (R. Schlitzer, 2014, http://odv.awi.de/).

INTRODUCTION

In the modern North Pacific, North Pacific Intermediate Water (NPIW), characterized by a salinity minimum centered at a depth of 400–800 m (Fig. 1), acts as a barrier between the nutrient-depleted surface waters and nutrient-rich subsurface waters (see Fig. 1; see Fig. DR1 in the GSA Data Repository[1]). Thus, the penetration depth and nutrient content of NPIW could modulate the upward nutrient supply to the euphotic zone in this region. This hypothesis is supported by paleoclimate records and model simulations, both of which suggest that better ventilated NPIW was accompanied by reduced export productivity (EP) in the subarctic North Pacific during Heinrich Stadial 1 and the Last Glacial Maximum (Galbraith et al., 2007; Kohfeld and Chase, 2011; Schmittner, 2005). However, due to the lack of long-term, high-resolution records, the teleconnection patterns between the subtropical North Pacific and polar climate-ocean dynamics remain largely unconstrained, particularly during the last ice age when the bipolar seesaw, an asymmetric millennial time scale climate oscillation between the Northern and Southern Hemispheres (Wais Divide Project Members, 2015), prevailed. In addition, climate models show conflicting subtropical North Pacific EP responses as a consequence of a reduction in Atlantic Meridional Overturning Circulation (AMOC), as would be the case for Heinrich stadials (e.g., Mariotti et al., 2012; Schmittner, 2005).

The Okinawa Trough is in the western boundary of the North Pacific under the influence of the Kuroshio Current. Today, NPIW is the major source of Kuroshio intermediate water, which acts as the dominant nutrient source to the Okinawa Trough euphotic zone (Chen, 1996; Sarmiento et al., 2004; Zhang et al., 2007). As part of the oligotrophic North Pacific Gyre (characterized by very low surface phosphate concentrations; Fig. 1), dissolved nutrients in the Okinawa Trough euphotic zone are almost completely utilized by phytoplankton, and subsequently incorporated into the biomass through photosynthesis. Thus, EP reconstructions from the Okinawa Trough could provide useful archives to explore the temporal evolution of teleconnection patterns between the subtropical and subarctic North Pacific regions. Here we present a highly resolved sedimentary record of phosphorus speciation from the Okinawa Trough to infer the history of EP of the western subtropical North Pacific, and establish subarctic-subtropical teleconnection patterns on millennial time scales covering the past 91 k.y.

[1]GSA Data Repository item 2017211, study area, detailed methods, proxy interpretations, and Figures DR1–DR10, is available online at http://www.geosociety.org/datarepository/2017/, or on request from editing@geosociety.org.

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METHODOLOGY

In the euphotic zone, dissolved inorganic phosphate is incorporated into the living biomass through photosynthesis. Some of this biomass escapes remineralization and eventually accumulates in the underlying sediment. During sedimentary burial, the labile organic phosphorus (P) is converted through the process of sink-switching (Ruttenberg and Berner, 1993) to authigenic P mineral phases (Fe-bound and absorbed inorganic P and Ca-bound apatite). A selective solvent extraction method was employed to determine phosphorous speciation from International Marine Global Changes Study Program (IMAGES VII) core MD012404 (Fig. 1) retrieved from the Okinawa Trough. The reactive P ($P_{reactive} = P_{Fe\ oxide\ associated} + P_{authigenic} + P_{organic}$; for phosphorus speciation records, see Fig. DR3) was used to reconstruct downcore export productivity patterns (see the methods section of the Data Repository). Assuming that sedimentary titanium (Ti) is exclusively of detrital origin, we determine the $P_{reactive}$/Ti ratio to assess the influence of sedimentary dilution. Consistency between $P_{reactive}$ content and $P_{reactive}$/Ti variations is observed throughout the record (Fig. DR4), suggesting that sedimentary dilution is not the primary factor driving the reported sedimentary $P_{reactive}$ content. Therefore, we are confident that the sedimentary $P_{reactive}$ content can be applied as a robust EP proxy (for further details assessing the robustness of $P_{reactive}$ as productivity proxy, see the Data Repository).

RESULTS AND DISCUSSION

During the last glaciation, rapid millennial-scale climate fluctuations, known as Dansgaard–Oeschger oscillations and Heinrich stadials, were particularly prominent in the northern high latitudes (Böhm et al., 2015; Wais Divide Project Members, 2015). These climate episodes were characterized by a rapid warming usually lasting for a few tens to hundreds of years, followed by a more gradual cooling persisting for hundreds to thousands of years, revealing a bipolar seesaw pattern (antiphase climate variations between the Northern and Southern Hemispheres). In this specific interval, we report high and low $P_{reactive}$ values during millennial-scale warm and cold events within the uncertainty of our age model. Through the whole evolution of the last glaciation, these millennial oscillations of $P_{reactive}$ varied in sync with temperature variations in Greenland ice core records (Fig. 2C), but out of phase with the variations in eolian dust deposition (Fig. 2F). Throughout the record we identified 17 of the 20 cold excursions (Fig. 2), including 9 Heinrich events, to have low sedimentary $P_{reactive}$ content. According to our age model (for details, see "Material and age model" in the Data Repository), the benthic foraminiferal $\delta^{18}O$ record from core MD012404 (Fig. DR2) provides sufficiently high resolution (~115 yr on average) to constrain the millennial variability.

The cold episodes were characterized by intensified East Asian winter monsoon (Yang and Ding, 2014), which would have favored diapycnal mixing, hence promoting vertical nutrient supply to the euphotic zone; however, winter monsoon wind intensities were antiphased with $P_{reactive}$. Furthermore, considering the shallow and broad continental shelf characterizing the East China Sea, millennial sea-level fluctuations may have affected the terrestrial nutrient supply to the core site. However, higher terrestrial P, which could be an indicator of higher terrestrial input, was observed to coincide with low $P_{reactive}$ for both millennial cold events and orbital cold stages (Fig. DR3), excluding the possibility of terrestrial input in controlling EP variability. We thus suggest that EP in the Okinawa Trough was not linked to changes in local mixing intensity or sea-level fluctuations. As a result, the strong coherence between EP in the subtropical North Pacific and Arctic temperatures may imply a remote forcing originating from high- latitude ocean-atmosphere dynamics, specifically through NPIW production.

It has previously been reported that NPIW penetrated deeper during Heinrich stadial 1 and shoaled during the Bølling-Allerød (B-A) warm interval (Okazaki et al., 2010; Jaccard and Galbraith, 2013). Through atmospheric and oceanic teleconnections, North Atlantic and Greenland

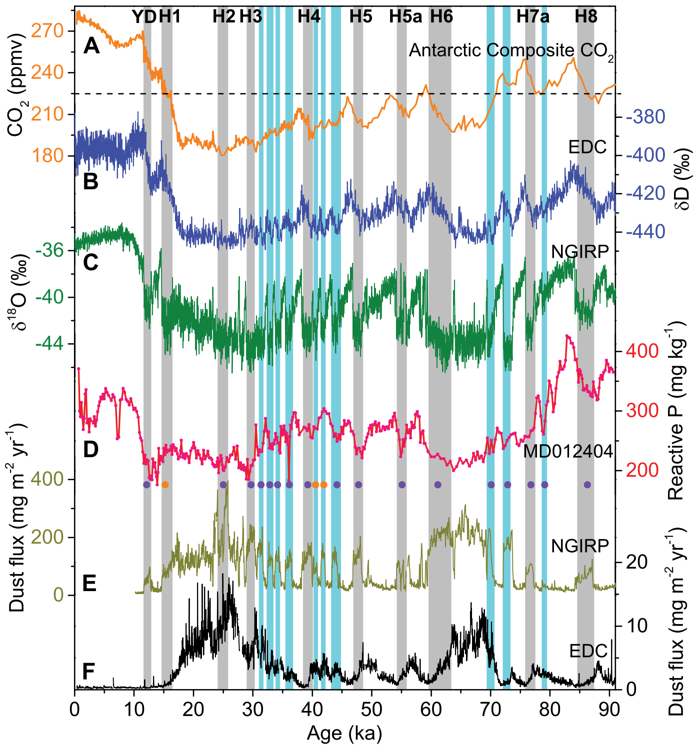

Figure 2. Temporal variations of paleorecords. YD—Younger Dryas; H1–H8—Heinrich stadials. A: Composite atmospheric CO_2 record from Antarctic ice cores (Bereiter et al., 2015). B: δD from Antarctic ice core EPICA (European Project for Ice Coring in Antarctica) Dome C (EDC) (Jouzel et al., 2007). C: $\delta^{18}O$ from North Greenland Ice Core Project (NGIRP) (North Greenland Ice Core Project Members, 2004). D: $P_{reactive}$ from International Marine Global Changes Study Program (IMAGES VII) core MD012404 (this study). E: Dust flux of NGRIP; dust flux was calculated using the published dust concentration data (Ruth et al., 2007), ice accumulation rate (Veres et al., 2013), and the density of ice (917 kg/m³). F: Dust flux from Antarctic EDC (Lambert et al., 2012). All ice core records are on AICC2012 age model (Antarctic ice core chronology; Veres et al., 2013). Dots indicate cold episodes; purple dots were in phase with $P_{reactive}$ and orange dots were not.

cooling would have induced deeper penetration of NPIW by the following proposed mechanisms. (1) The subarctic North Pacific sea-surface temperatures (SSTs) dropped simultaneously as Greenland climate cooled via atmospheric teleconnection (Okumura et al., 2009). Colder SSTs promoted sea ice formation in the Okhotsk (Nürnberg et al., 2011) and Bering Seas (Riethdorf et al., 2016), thereby increasing the density of surface waters, resulting in deeper penetration of NPIW (Okazaki et al., 2010). (2) The Pacific Intertropical Convergence Zone shifted southward during Northern Hemisphere cold events (Schneider et al., 2014), resulting in reduced precipitation, thereby increasing surface water salinity in the North Pacific. (3) During Greenland stadials, a significant weakening of the AMOC (Böhm et al., 2015) and associated North Atlantic SST cooling led to reduced moisture transport from the Atlantic to the Pacific and hence further increased the surface salinity and density in the NPIW formation regions (Krebs and Timmermann, 2007). Taken together, deeper penetration of NPIW during Northern Hemisphere cold events may have reduced the nutrient supply to the euphotic zone in large swaths of the North Pacific. This is supported by basin-wide reduced EP (see Fig. DR9) during Heinrich stadials, as reported from the Okinawa Trough ($P_{reactive}$ in Fig. 2D), the Okhotsk Sea (R/V *Mirai* cruise, core MR06–04 PC-7R) (Gorbarenko et al., 2012), and Bering Sea (R/V *Sonne* cruise SO201 KALMAR Leg 2, core SO201-2-85KL) (Riethdorf et al., 2013), and the eastern North Pacific region (core MD02–2508, R/V *Marion-Dufresne* IMAGES MD126-MONA cruise, and core W8709–8, National Science

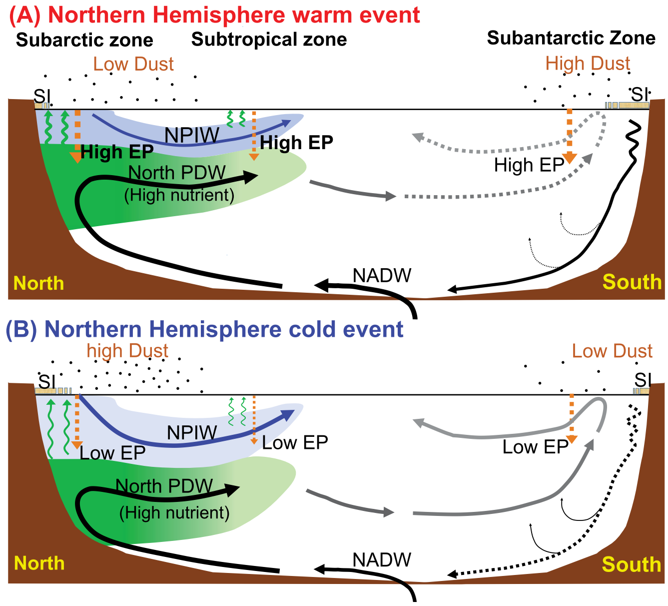

Figure 3. Schematic diagram for the teleconnection between high- and low-latitude regions on millennial climate events during bipolar seesaw. A: During the Northern Hemisphere warm events, the North Pacific Intermediate Water (NPIW) was weakened, thus permitting the North Pacific Deep Water (PDW) to reach shallower depths, promoting productivity in the subarctic as well as in the subtropical North Pacific. In the meantime, the Southern Ocean was cold and the reduction in deep-water ventilation around the Southern Ocean resulted in less emission of deeply sequestered CO_2. Meanwhile, relative higher dust deposition to the Subantarctic Ocean stimulated phytoplankton growth. EP—export productivity; SI—sea ice. B: During the Northern Hemisphere cold events, the deepened NPIW resulted in relatively lower EP in the subtropical North Pacific, while the Southern Ocean warmed; thus better ventilation of deep water and relatively low dust deposition around the Southern Ocean allowed more CO_2 to escape to the atmosphere. NADW—North Atlantic Deep Water.

Foundation Multitracers Project) (Cartapanis et al., 2014). Similar trends of low EP during cold periods have also been reported for the equatorial Pacific over longer time scales using biogenic barium and opal accumulation rates (Winckler et al., 2016). Combined with previous studies, we speculate that ocean dynamics, and not dust supply, primarily controlled EP in the North Pacific. Furthermore, based on our high temporal resolution record, we suggest that reduced nutrient supply caused by deepening of NPIW (and increased supply caused by shoaling) also operated on centennial to millennial time scales in the North Pacific during the last ice age. However, in contrast to higher productivity reported from large areas of the subarctic North Pacific during the B-A (14.7–13 ka) (Kohfeld and Chase, 2011), the sedimentary $P_{reactive}$ concentrations remained relatively low in our record (Fig. 2D). This might result from the relatively high nutrient utilization efficiency in the western subarctic Pacific during the B-A (Riethdorf et al., 2016), which led to lower preformed NPIW nutrient content. Alternatively, high respiration rates at the sediment-water interface may have remobilized P from the sediment during this specific interval. More work is certainly needed to further our understanding of nutrient dynamics associated with NPIW formation.

In contrast to the North Pacific, export production in the Subantarctic zone of Southern Ocean was controlled by dust deposition. During the last ice age, Antarctic millennial cold periods were characterized by high dust (Fe) deposition to the Antarctic continent (Fig. 2F) and the Southern Ocean (Martínez-García et al., 2014) (Fig. DR10B). Increased eolian Fe-bearing dust supply to the Subantarctic zone alleviated Fe limitation, thereby strengthening the biological pump there (Martínez-García et al., 2014). In contrast, during the Antarctic warm episodes, dust (Fe) flux and export productivity in the Subantarctic zone decreased in concert (Fig. DR10). Thus there are distinct spatial differences in the mechanisms controlling marine productivity on millennial time scales during the last glaciation.

The bipolar seesaw mechanism is commonly invoked to explain millennial-scale abrupt climatic variability and the asynchronous coupling of Greenland and Antarctic temperature variations during the last glaciation (WAIS Divide Project Members, 2015). When the bipolar seesaw operated (Fig. 2), high export production during warm episodes is observed in the North Pacific (Fig. DR9; Fig. 3). At the same time, temperatures were colder in the Subantarctic zone, where productivity was enhanced due to elevated dust input (Martínez-García et al., 2014). Thus, in spite of the decoupling of interhemisphere climate during the bipolar seesaw, the biological pump in both of these important regions functioned in the same direction, though by different drivers; i.e., from the bottom (NPIW penetration) in the North Pacific and from above (Fe via atmospheric dust deposition) for the Subantarctic (Fig. 3). Such a synergistic biological pump pattern is particularly important during the time interval when atmospheric pCO_2 was <225 ppmv (see Fig. 2). In this specific time interval, Antarctic ventilation was reduced (Jaccard et al., 2016) and carbon remained sequestered in the ocean interior. This study documents further evidence of the teleconnection of high-latitude climate and subtropical biological pump production, especially, on millennial scale, reinforcing the role of polar areas in operating the ocean-atmosphere interactions.

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REFERENCES CITED

Bereiter, B., Eggleston, S., Schmitt, J., Nehrbass-Ahles, C., Stocker, T.F., Fischer, H., Kipfstuhl, S., and Chappellaz, J., 2015, Revision of the EPICA Dome C CO_2 record from 800 to 600 kyr before present: Geophysical Research Letters, v. 42, p. 542–549, doi:10.1002/2014GL061957.

Böhm, E., Lippold, J., Gutjahr, M., Frank, M., Blaser, P., Antz, B., Fohlmeister, J., Frank, N., Andersen, M.B., and Deininger, M., 2015, Strong and deep Atlantic meridional overturning circulation during the last glacial cycle: Nature, v. 517, p. 73–76, doi:10.1038/nature14059.

Cartapanis, O., Tachikawa, K., Romero, O.E., and Bard, E., 2014, Persistent millennial-scale link between Greenland climate and northern Pacific Oxygen Minimum Zone under interglacial conditions: Climate of the Past, v. 10, p. 405–418, doi:10.5194/cp-10-405-2014.

Chen, C.-T.A., 1996, The Kuroshio intermediate water is the major source of nutrients on the East China Sea continental shelf: Oceanologica Acta, v. 19, p. 523–527.

Galbraith, E.D., Jaccard, S.L., Pedersen, T.F., Sigman, D.M., Haug, G.H., Cook, M., Southon, J.R., and Francois, R., 2007, Carbon dioxide release from the North Pacific abyss during the last deglaciation: Nature, v. 449, p. 890–893, doi:10.1038/nature06227.

Gorbarenko, S.A., Harada, N., Malakhov, M.I., Velivetskaya, T.A., Vasilenko, Y.P., Bosin, A.A., Derkachev, A.N., Goldberg, E.L., and Ignatiev, A.V., 2012, Responses of the Okhotsk Sea environment and sedimentology to global climate changes at the orbital and millennial scale during the last 350 kyr: Deep-Sea Research. Part II, Topical Studies in Oceanography, v. 61–64, p. 73–84, doi:10.1016/j.dsr2.2011.05.016.

Jaccard, S.L., and Galbraith, E.D., 2013, Direct ventilation of the North Pacific did not reach the deep ocean during the last deglaciation: Geophysical Research Letters, v. 40, p. 199–203, doi:10.1029/2012GL054118.

Jaccard, S.L., Galbraith, E.D., Martínez-García, A., and Anderson, R.F., 2016, Covariation of deep Southern Ocean oxygenation and atmospheric CO_2 through the last ice age: Nature, v. 530, p. 207–210, doi:10.1038/nature16514.

Jouzel, J., et al., 2007, Orbital and millennial Antarctic climate variability over the past 800,000 years: Science, v. 317, p. 793–796, doi:10.1126/science.1141038.

Kohfeld, K.E., and Chase, Z., 2011, Controls on deglacial changes in biogenic fluxes in the North Pacific Ocean: Quaternary Science Reviews, v. 30, p. 3350–3363, doi:10.1016/j.quascirev.2011.08.007.

Krebs, U., and Timmermann, A., 2007, Tropical air-sea interactions accelerate the recovery of the Atlantic Meridional Overturning Circulation after a major shutdown: Journal of Climate, v. 20, p. 4940–4956, doi:10.1175/JCLI4296.1.

Lambert, F., Bigler, M., Steffensen, J.P., Hutterli, M., and Fischer, H., 2012, Centennial mineral dust variability in high-resolution ice core data from Dome C, Antarctica: Climate of the Past, v. 8, p. 609–623, doi:10.5194/cp-8-609-2012.

Mariotti, V., Bopp, L., Tagliabue, A., Kageyama, M., and Swingedouw, D., 2012, Marine productivity response to Heinrich events: A model-data comparison: Climate of the Past, v. 8, p. 1581–1598, doi:10.5194/cp-8-1581-2012.

Martínez-García, A., Sigman, D.M., Ren, H., Anderson, R.F., Straub, M., Hodell, D.A., Jaccard, S.L., Eglinton, T.I., and Haug, G.H., 2014, Iron fertilization of the Subantarctic ocean during the Last Ice Age: Science, v. 343, p. 1347–1350, doi:10.1126/science.1246848.

North Greenland Ice Core Project Members, 2004, High-resolution record of Northern Hemisphere climate extending into the last interglacial period: Nature, v. 431, p. 147–151, doi:10.1038/nature02805.

Nürnberg, D., Dethleff, D., Tiedemann, R., Kaiser, A., and Gorbarenko, S.A., 2011, Okhotsk Sea ice coverage and Kamchatka glaciation over the last 350 ka—Evidence from ice-rafted debris and planktonic $\delta^{18}O$: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 310, p. 191–205, doi:10.1016/j.palaeo.2011.07.011.

Okazaki, Y., Timmermann, A., Menviel, L., Harada, N., Abe-Ouchi, A., Chikamoto, M.O., Mouchet, A., and Asahi, H., 2010, Deepwater formation in the North Pacific during the Last Glacial Termination: Science, v. 329, p. 200–204, doi:10.1126/science.1190612.

Okumura, Y.M., Deser, C., Hu, A., Timmermann, A., and Xie, S.-P., 2009, North Pacific climate response to freshwater forcing in the subarctic North Atlantic: Oceanic and atmospheric pathways: Journal of Climate, v. 22, p. 1424–1445, doi:10.1175/2008JCLI2511.1.

Riethdorf, J.R., Nürnberg, D., Max, L., Tiedemann, R., Gorbarenko, S.A., and Malakhov, M.I., 2013, Millennial-scale variability of marine productivity and terrigenous matter supply in the western Bering Sea over the past 180 kyr: Climate of the Past, v. 9, p. 1345–1373, doi:10.5194/cp-9-1345-2013.

Riethdorf, J.-R., Thibodeau, B., Ikehara, M., Nürnberg, D., Max, L., Tiedemann, R., and Yokoyama, Y., 2016, Surface nitrate utilization in the Bering sea since 180 kA BP: Insight from sedimentary nitrogen isotopes: Deep-sea Research. Part II, Topical Studies in Oceanography, v. 125–126, p. 163–176, doi:10.1016/j.dsr2.2015.03.007.

Ruth, U., Bigler, M., Röthlisberger, R., Siggaard-Andersen, M.-L., Kipfstuhl, S., Goto-Azuma, K., Hansson, M.E., Johnsen, S.J., Lu, H., and Steffensen, J. P., 2007, Ice core evidence for a very tight link between North Atlantic and east Asian glacial climate: Geophysical Research Letters, v. 34, L03706, doi:10.1029/2006GL027876.

Ruttenberg, K.C., and Berner, R.A., 1993, Authigenic apatite formation and burial in sediments from non-upwelling, continental margin environments: Geochimica et Cosmochimica Acta, v. 57, p. 991–1007, doi:10.1016/0016-7037(93)90035-U.

Sarmiento, J.L., Gruber, N., Brzezinski, M.A., and Dunne, J.P., 2004, High-latitude controls of thermocline nutrients and low latitude biological productivity: Nature, v. 427, p. 56–60, doi:10.1038/nature02127.

Schmittner, A., 2005, Decline of the marine ecosystem caused by a reduction in the Atlantic overturning circulation: Nature, v. 434, p. 628–633, doi:10.1038/nature03476.

Schneider, T., Bischoff, T., and Haug, G.H., 2014, Migrations and dynamics of the intertropical convergence zone: Nature, v. 513, p. 45–53, doi:10.1038/nature13636.

Veres, D., et al., 2013, The Antarctic ice core chronology (AICC2012): An optimized multi-parameter and multi-site dating approach for the last 120 thousand years: Climate of the Past, v. 9, p. 1733–1748, doi:10.5194/cp-9-1733-2013.

Wais Divide Project Members, 2015, Precise interpolar phasing of abrupt climate change during the last ice age: Nature, v. 520, p. 661–665, doi:10.1038/nature14401.

Winckler, G., Anderson, R.F., Jaccard, S.L., and Marcantonio, F., 2016, Ocean dynamics, not dust, have controlled equatorial Pacific productivity over the past 500,000 years: National Academy of Sciences Proceedings, v. 113, p. 6119–6124, doi:10.1073/pnas.1600616113.

Yang, S., and Ding, Z., 2014, A 249 kyr stack of eight loess grain size records from northern China documenting millennial-scale climate variability: Geochemistry, Geophysics, Geosystems, v. 15, p. 798–814, doi:10.1002/2013GC005113.

Zhang, J., Liu, S.M., Ren, J.L., Wu, Y., and Zhang, G.L., 2007, Nutrient gradients from the eutrophic Changjiang (Yangtze River) Estuary to the oligotrophic Kuroshio waters and re-evaluation of budgets for the East China Sea Shelf: Progress in Oceanography, v. 74, p. 449–478, doi:10.1016/j.pocean.2007.04.019.

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