Earth’s climate underwent a major transition from the warmth of the late Pliocene, when global surface temperatures were ~2° to 3°C higher than today, to extensive Northern Hemisphere glaciation (NHG) ~2.73 million years ago (Ma). We show that North Pacific deep waters were substantially colder (4°C) and probably fresher than the North Atlantic Deep Water before the intensification of NHG. At ~2.73 Ma, the Atlantic-Pacific temperature gradient was reduced to <1°C, suggesting the initiation of stronger heat transfer from the North Atlantic to the deep Pacific. We posit that increased glaciation of Antarctica, deduced from the 21 ± 10-meter sea-level fall from 3.15 to 2.75 Ma, and the development of a strong polar halocline fundamentally altered deep ocean circulation, which enhanced interhemispheric heat and salt transport, thereby contributing to NHG.

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PALEOCEANOGRAPHY

Antarctic role in Northern Hemisphere glaciation

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Benthic foraminiferal oxygen isotope (δ18O) records trend toward higher values throughout the late Pliocene warm period (1), culminating in higher amplitude of glacial-interglacial (G-IG) δ18O variability (Fig. 1) associated with a dramatic increase of ice-rafted debris in sediments around the Arctic ~2.73 million years ago (Ma) (marine isotope stage (MIS) 6), and signaling a major intensification of Northern Hemisphere glaciation (NHG) (2-4). During the same period, proxy records indicate a long-term sea surface temperature (SST) cooling in most regions (5-8), which is mimicked in bottom water temperature (BWT) records from the deep North Atlantic (9-11). Here, we reconstruct the BWT history of the deep Pacific at 2 to 5-thousand-year (ky) resolution from Ocean Drilling Program (ODP) site 1208 (36.19°N, 158.20°W, 3350 m water depth) (fig. S1) on Shatsky Rise in the northwest Pacific Ocean (12), and we determine ice volume changes during the 400-ky interval preceding the NHG intensification (3.15 to 2.75 Ma, henceforth “pre-NHG”).

The Pliocene δ18O record at site 1208 is consistent with the global δ18O stack (LR04) (3) (Fig. 1). Beginning at glacial MIS G6, the amplitude of G-IG δ18O variability increases from ~0.5 to >0.8 per mil (%e) with more extreme glacial maxima and interglacial minima (fig. S2). The BWT record at site 1208 was reconstructed from Mg/Ca measurements of the infaunal foraminifer, Uvigerina spp. We determined a Mg/Ca temperature sensitivity (0.28 ± 0.16 mmol mol−1 °C−1) for this species by calibrating the Holocene–Last Glacial Maximum (LGM) δMg/Ca to the δ18O record at site 1208 (22, 23). Note that unlike the epifaunal species Cibicidoides wuellerstorfi, which was used to generate a North Atlantic BWT record (9), Uvigerina is apparently not affected by seawater carbonate ion saturation, which can alter Mg/Ca independently of temperature (12, 14). Pacific BWTs exhibit an average Pliocene G-I G range of ~2.1 ± 0.8°C (1 SD), similar to the average Holocene-LGM range of 2.6°C (22) and in contrast with oscillations of δ18O (Fig. 1), suggesting that the orbital-scale temperature variability of the Pliocene Pacific was somewhat decoupled from the ice volume. A notable change occurred ~2.75 Ma, when, following ~4°C deglacial warming, average Pacific BWT became ~1.5°C warmer and G-I G temperature changes exhibited slightly lower amplitude (Fig. 1 and fig. S3). Spectral analysis shows that pre-NHG our δ18O record is dominated by 41-ky pacing, consistent
with a strong response to obliquity variations, which is attributed to ice sheet dynamics (3). In contrast, Pacific BWT and benthic δ¹³C exhibit strong 100-ky periodicity during that interval (fig. S4), suggesting that BWT and circulation responded differently to orbital forcing than ice. The appearance of a secondary 100-ky beat in the latter part of our δ¹⁸Obf record provides evidence for stronger synchronization in the response of these climate-system components to orbital forcing as NHG intensified (12).

Site 1208 BWTs show no significant long-term trend over the 400-ky pre-NHG interval (Fig. 2). Therefore, we interpret the significant δ¹⁸Obf increase [0.21 ± 0.04‰ (1 SE)] at site 1208 over this interval (Fig. 2) to primarily reflect an increase in the extent of continental ice (12), assuming an average 0.1 ± 0.02‰ δ¹⁸O per 10 m of sea level (15), we estimate a 21 ± 10–m (2 SE) sea-level equivalent of “permanent” ice growth (12) pre-NHG. Because seawater Mg/Ca was probably ~20 ± 10% lower than modern levels during the Pliocene [e.g., (16), BWT at site 1208 might have been higher than present temperatures by ~1°C (17)]. However, this uncertainty has a negligible effect on our estimates of sea-level change and the G-IG variability of BWT and δ¹⁸Osw during the late Pliocene interval leading to the NHG intensification (12) (fig. S5). Using the long-term trends also minimizes uncertainties due to inaccurate temperature corrections or differences in the primary orbital beats of the isotope and temperature records. Thus, our reconstruction of continental ice provides only information regarding mean sea-level position and does not reflect glacial lowstands or interglacial highstands, which presumably occurred at orbital frequencies over this 400-ky interval (12).

We compare the Pacific with North Atlantic Deep Sea Drilling Project (DSDP) site 607 (41°N, 32°W, 3427-m water depth) records (9) and find that pre-NHG Atlantic BWTs generated using C. wuellerstorfi are, on average, 4 ± 1.4°C warmer than at site 1208 (9) (Fig. 2). New discrete measurements of Uvigerina Mg/Ca from site 607 range from 1.1 to 1.6 mmol mol⁻¹, well above values recorded by Uvigerina in the Pacific at the same time (fig. S6), supporting the interpretation of warm North Atlantic BWTs during the Pliocene (12). Over the pre-NHG interval, site 607 δ¹⁸Obf records a 0.48 ± 0.04‰ increase, more than double that observed at site 1208, and BWTs cool by ~1.3 ± 0.4°C (Fig. 2). After accounting for BWT cooling, we estimate a ~15 ± 14–m (1 SE) sea-level equivalent of “permanent” ice growth from the residual δ¹⁸Obf at site 607 (12), consistent with the estimate from site 1208. As the uncertainty in the Pacific sea-level record is less than the Atlantic estimate due to lack of temperature correction, we conclude that baseline sea-level fall very likely (>95% confidence) exceeded 11 m and possibly reached 31 m pre-NHG.

Fig. 1. Stable isotope and Mg/Ca data for the deep Pacific Ocean, site 1208. Records span the Holocene-LGM [0 to 25 thousand years ago (kya in figure), left] and the late Pliocene (3.3 to 2.5 Ma, right). Holocene-LGM data from V19-30 (eastern tropical Pacific) (38) and the Pacific δ¹⁸O benthic stack (39) are included for comparison. (A) Uvigerina spp. δ¹³C records from the Pacific Ocean. (B) Global benthic δ¹⁸O stack (LR04) (3). (C) Uvigerina spp. δ¹⁸Obf record from site 1208. (D) Uvigerina spp. Mg/Ca record from site 1208. The temperature scale is provided for reference. Raw data (points) were smoothed using a 15-ky low-pass filter (solid lines); gray shading indicates 1 SE of temperature estimate. The rectangle vertically spanning (A) to (D) identifies the pre-NHG interval, and the gray vertically shaded area highlights the period after NHG intensification. Important Pliocene MISs are labeled on the LR04 benthic δ¹⁸O stack. VPDB, Vienna Pee Dee belemnite.
The gradual increase in Pliocene δ18Osw records has previously been attributed to a prolonged onset of NHG (17, 18). Ice-rafted debris provides evidence of ice on Greenland since the Midocene and an augmented ice sheet extent ~3.3 Ma (19). Although tectonic uplift in high northern latitudes surrounding the Barents Sea likely promoted regional ice growth as early as 4 Ma (20), the alpine glaciers were not large enough to reach sea level until MIS G6 (20) and so probably account for negligible sea-level equivalent ice pre-NHG (12). In light of the little evidence for widespread glaciers in the Northern Hemisphere until ~2.75 Ma (4, 19, 20), we suggest that at least half of the 21:10-m sea-level fall pre-NHG was due to ice added to Antarctica. Furthermore, because the Greenland Ice Sheet and West Antarctic Ice Sheet can accommodate at most a ~12-m ice equivalent of sea level (21, 22), it is likely that the extent of the East Antarctic Ice Sheet was less than modern levels during the late Pliocene, consistent with records of a dynamic Antarctic margin (23–26).

The expansion of Antarctic ice sheets during the late Pliocene appears to surpass an important climatological threshold, which contributed to the intensification of NHG. The present deep Pacific δ18Osw value, ~0.15‰, reflects the mixture of North Atlantic Deep Water (NADW) (δ18Osw ~ 0.2‰) and Antarctic Bottom Water (AABW) (δ18Osw ~ 0.5 to ~0.3‰) forming Circumpolar Deep Water (CDW) (27). The pre-NHG deep Pacific δ18Osw was similar to modern AABW, averaging ~0.43‰ and fluctuating by as much as 0.4 to 0.8‰ on G-IG time scales (Fig. 3). During this interval, Pacific δ18Osw reached near-modern values only during glacial periods, with much lower values during interglacials. The δ18Osw reconstruction at site 607 shows no significant long-term change over the entire interval for which there is data overlapping with our Pacific record (9) (Fig. 9). Although the site 607 Pliocene G-IG amplitude of Δδ18Osw was similar to that of the Pacific, average δ18Osw was higher (0.28‰), with interglacial values not much different from those of the modern North Atlantic. Thus, the low Pacific δ18Osw value cannot be attributed to lower continental ice volume but must reflect a hydrographic difference.

The persistence of an average ~0.7‰ δ18Osw gradient between sites 607 and 1208 (Fig. 3B) suggests that the two sites were not ventilated by the same water mass pre-NHG. During the same interval, Pacific δ18Osw and BWTs were offset from the North Atlantic (Fig. 2). The relatively faster long-term change at site 607 compared with site 1208 indicates that site 607 was not ventilated by the same water mass pre-NHG. During the same interval, Pacific δ18Osw and BWTs were offset from the North Atlantic (Fig. 2). The relatively faster long-term change at site 607 compared with site 1208 indicates that site 607 was not ventilated by the same water mass pre-NHG. During the same interval, Pacific δ18Osw and BWTs were offset from the North Atlantic (Fig. 2). The relatively faster long-term change at site 607 compared with site 1208 indicates that site 607 was not ventilated by the same water mass pre-NHG. During the same interval, Pacific δ18Osw and BWTs were offset from the North Atlantic (Fig. 2).

Past studies, which attribute Pliocene warmth to increased oceanic heat transport via the thermohaline conveyor (30–32), cite weak meridional δ18C gradients (30, 31) and increased North Atlantic sediment drift accumulation (32) as evidence of enhanced NADW production. However, their interpretation of ocean circulation based on δ18C hinges upon the use of modern NADW...
Regardless, the absence of a long-term temperature trend in our Pacific BWT record over the period when NADW cooled by ~1.3°C attests to inefficient heat transport from the North Atlantic to the deep Pacific via the Southern Ocean before 2.73 Ma. We contend that NADW was not a major contributor to CDW and that deep water formed in the Southern Ocean was the primary source of deep water to the Pacific pre-NHG. This interpretation is also supported by a ~0.6‰ increase in site 1208 δ¹⁸Osw, which effectively eliminates the Pacific-Atlantic δ¹⁸Osw gradient by ~2.7 Ma (Fig. 3). The proposed change in deep ocean circulation was almost certainly tied to high-latitude processes that altered the temperature or salinity of either the northern or southern deep water mass, or both. Presumably, high-latitude cooling steepened equator-to-pole temperature gradients throughout the Pliocene (6, 7) and triggered the expansion of Antarctic glaciation in the Southern Hemisphere (26), as supported by our sea-level estimates from site 1208. Dust records suggest a northward shift in Southern Hemisphere wind belts about the time of NHG intensification (36), which would have allowed expansion of sea ice and promoted the development of a stronger halocline (34), reducing deep water upwelling around Antarctica (26, 35).

Stronger and more permanent stratification of Southern Ocean surface waters is indicated by decreased opal accumulation beginning around 2.73 Ma (33) (Fig. 3C). Such stratification probably reduced heat exchange between the atmosphere and upwelling Southern Ocean waters (e.g., (37)), trapping heat transported via NADW in the subsurface and causing the warming observed in our Pacific BWT record. A decreasing SST gradient between the North and South Atlantic (Fig. 3D) further signifies the transfer of heat from the high northern latitudes. Thus, we argue that the expanded glaciation of Antarctica during the late Pliocene culminated in a fundamental change in deep water circulation, contributing to the intensification of NHG by facilitating a major re-distribution of heat at Earth’s surface.

**REFERENCES AND NOTES**

12. Supplementary materials, analytical methods, supporting text, and supplementary figures are available on Science Online. Original data is archived as a paleoclimate data set with the National Oceanic and Atmospheric Administration’s National Climatic Data Center, available online at: www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets.
Projected increase in lightning strikes in the United States due to global warming

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Lightning plays an important role in atmospheric chemistry and in the initiation of wildfires, but the impact of global warming on lightning rates is poorly constrained. Here we propose that the lightning flash rate is proportional to the convective available potential energy (CAPE) times the precipitation rate. Using observations, the product of CAPE and precipitation explains 77% of the variance in the time series of total cloud-to-ground lightning flashes over the contiguous United States (CONUS). Storms convert CAPE times precipitated water mass to discharged lightning energy with an efficiency of 5% (6, 7) to over 100% (8) per degree Celsius (°C) of global mean temperature increase. Here we show that a simple proxy—the product of the convective instability and the precipitation rate—explains most of the variance in lightning flashes over the contiguous United States (CONUS). When applied to global climate models (GCMs), this proxy predicts a mean increase in flash rate of 12% per global-mean °C over the CONUS. This augurs significant changes in the future atmospheric chemistry and wildfire frequency of North America.

Fig. 1. Mean maps of CAPE, precipitation, CAPE times precipitation, and lightning flashes. For the year 2011, maps are shown of mean (top left) CAPE from the SPARC radiosonde data, (top right) precipitation from the National Weather Service River Forecast Center data, (bottom left) product of the top two maps, and (bottom right) CG lightning from the NLDN data. For CAPE, means are calculated by averaging all 00 and 12 GMT soundings; circles denote the locations of radiosonde releases. For precipitation and lightning, means are calculated by averaging over 22-02 and 10-14 GMT.

References (39–84)

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