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Bipolar Seesaw of Atmospheric CO_2 Between North Pacific and Southern Ocean at Millennial Timescales

Yi Zhong[1,2], Yanguang Liu[3,4], Jimin Yu[5,6], Chijun Sun[7], Qin Wen[8], Sev Kender[9], Keiji Horikawa[10], Xu Zhang[11], Michael E. Weber[12], Siqi Li[13], Hu Yang[14], Stefanie Kaboth-Bahr[15], André Bahr[16], Zhaoyang Song[17], George E. A. Swann[18], Wei Cao[2], Sheng Yang[1,2], Yuxing Liu[2], Jingyu Zhang[2], Hai Li[19], Wenyue Xia[2], and Qingsong Liu[2,20]

[1]Advanced Institute of Ocean Research, Southern University of Science and Technology, Shenzhen, PR China, [2]Department of Ocean Science and Engineering, Centre for Marine Magnetism, Southern University of Science and Technology, Shenzhen, PR China, [3]Key Laboratory of Marine Geology and Metallogeny, Shandong Key Laboratory of Deep-Sea Mineral Resources Development, First Institute of Oceanography, Ministry of Natural Resources (MNR), Qingdao, China, [4]College of Ocean Science and Engineering, Shandong University of Science and Technology, Qingdao, China, [5]Laoshan Laboratory, Qingdao, China, [6]Research School of Earth Sciences, The Australian National University, Canberra, ACT, Australia, [7]Department of Earth and Planetary Sciences, University of California, Davis, Davis, CA, USA, [8]School of Geography, Nanjing Normal University, Nanjing, China, [9]Department of Earth and Environmental Sciences University of Exeter, Camborne School of Mines, Cornwall, UK, [10]Faculty of Science, Academic Assembly, University of Toyama, Toyama, Japan, [11]British Antarctic Survey, Cambridge, UK, [12]Department of Geochemistry and Petrology, Institute for Geosciences, University of Bonn, Bonn, Germany, [13]State Key Laboratory of Tibetan Plateau Earth System, Resources and Environment (TPESRE), Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing, China, [14]Southern Marine Science and Engineering Guangdong Laboratory, Zhuhai, China, [15]Institute of Geological Sciences, Freie Universität Berlin, Berlin, Germany, [16]Institute of Earth Sciences, Heidelberg University, Heidelberg, Germany, [17]School of Atmospheric Sciences, Key Laboratory of Tropical Atmosphere–Ocean System, Sun Yat-sen University, Ministry of Education, Zhuhai, China, [18]School of Geography, University of Nottingham, Nottingham, UK, [19]Southern Marine Science and Engineering Guangdong Laboratory (Guangzhou), Guangzhou, China, [20]Shanghai Sheshan National Geophysical Observatory, Shanghai, China

Yi Zhong and Yanguang Liu contributed equally to this work.

Key Points:

- We present the variability of biological productivity, and deep water circulation for North Pacific Ocean spanning 20–60 kyr
- Surface nutrient utilization was modulating deep Pacific carbon storage and atmospheric CO_2 variations over the glacial-interglacial cycle
- Our study emphasizes the deep subarctic Pacific Ocean as being a potential location for absorbing atmospheric CO_2

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

Y. Zhong and Q. Liu,
zhongy@sustech.edu.cn;
qsliu@sustech.edu.cn

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Author Contributions:

Data curation: Qin Wen, Zhaoyang Song, Wei Cao
Formal analysis: Siqi Li, Sheng Yang
Funding acquisition: Yi Zhong, Yanguang Liu, Qingsong Liu
Investigation: Sev Kender, George E. A. Swann, Sheng Yang, Yuxing Liu
Project administration: Yi Zhong, Yanguang Liu, Qingsong Liu
Resources: Sev Kender, Zhaoyang Song
Software: Qin Wen
Supervision: Hu Yang, Qingsong Liu

Abstract The interhemispheric relation of deep-water ventilation and surface-ocean productivity may have played a prominent role in past atmospheric CO_2 regulation. However, how these processes vary on orbital-millennial timescales remains poorly understood. Here, we present high-resolution proxy data and model simulations on the variability of biological productivity and deep water circulation for the abyssal northwestern Pacific Ocean spanning 20–60 kyr. We found that enhanced surface productivity increased during Heinrich Stadials (HS) and long term, caused by intensified westerly winds and associated dust fertilization, implying CO_2 extraction from the atmosphere and increased nutrient supply to the euphotic zone. A similar increase in productivity for the Southern Ocean during Heinrich events implies enhanced upwelling and exhalation of CO_2 to the atmosphere, indicative for an interhemispheric carbon cycle seesaw on millennial time scales. However, the longer-term global cooling demonstrates that deep ocean carbon storage and degassing was predominantly modulated by the North Pacific Ocean.

Plain Language Summary The ocean's ability to store and release carbon via bio- and physiochemical processes makes it a prime candidate for driving changes in atmospheric carbon dioxide concentration and hence global climate on millennial-to orbital time-scales. Our records and model simulations suggest that surface nutrient utilization was a critical factor into draw down atmospheric CO_2 into deep Pacific Ocean for carbon storage on those time scales. Our study emphasizes the importance of the deep subarctic Pacific Ocean as being a potential region for absorbing more atmospheric CO_2, while the Antarctic Southern Ocean tends to release CO_2 to the atmospheric.

1. Introduction

The ocean's ability to store and release carbon via bio- and physiochemical processes makes it a prime candidate for driving changes in atmospheric carbon dioxide (CO_2) on millennial-to-orbital time-scales, thereby impacting the global climate system (Sigman et al., 2021; Toggweiler, Russell, & Carson, 2006). Numerous studies have suggested that the Southern Ocean plays a key role in influencing the glacial-interglacial variability of atmospheric pCO_2 (Sigman et al., 2010). Moreover, the stratification and convection in the water masses of the

Writing – original draft: Jimin Yu, Chijun Sun, Keiji Horikawa, Xu Zhang, Michael E. Weber, Hu Yang, Stefanie Kaboth-Bahr, André Bahr, George E. A. Swann, Wei Cao, Jingyu Zhang, Hai Li, Wenyue Xia
Writing – review & editing: Jimin Yu, Chijun Sun, Keiji Horikawa, Xu Zhang, Michael E. Weber, Stefanie Kaboth-Bahr, André Bahr, Jingyu Zhang

Southern Ocean have a vital impact on the global heat uptake and carbon budget (Le Quere et al., 2007), which are associated with oscillations in the Atlantic Meridional Overturning Circulation (AMOC), which can occur during Heinrich Stadials (HS) (Weber et al., 2022) and Dansgaard-Oeschger (D-O) events (Walczak et al., 2020). However, despite being the largest oceanic carbon reservoir (X. Zhang et al., 2021; Zhou & McManus, 2024), the role of the Pacific Ocean's role during past millennial-scale climate variability is much less well constrained.

It has been previously suggested that the North Pacific Ocean was important for regulating the exchange of carbon between the atmosphere and ocean interior on millennial timescale, as evidenced by neodymium and boron isotope studies during the last deglaciation (Gray et al., 2018; Walczak et al., 2020). However, bio-physical responses in the North Pacific to D-O cycles remain still poorly understood due to uncertainties on deep and intermediate water formation, as well as upwelling intensity that regulates nutrient cycles and oceanic outgassing of CO_2 (Gray et al., 2018; Praetorius et al., 2020), along with changes in iron-limited primary productivity (Du et al., 2022; Lam et al., 2013). Although a recent study suggests that the Northeastern Pacific is influenced by iron fertilization from volcanic ash, triggered by regional ice unloading (Du et al., 2022; Zhong et al., 2022), enhanced deep water ventilation in the North Pacific may be another oceanic process that fuels marine productivity, ultimately driving air-sea carbon partitioning (Okazaki et al., 2010, 2012). Potential factors put forward to explain changes in the oceanic CO_2 ventilation on millennial timescales include sea ice volume (Detlef et al., 2020; Weber et al., 2022; Worne et al., 2019), Glacial North Pacific Intermediate Water (GNPIW) (Gong et al., 2019; Gray et al., 2018; Rae et al., 2014), and flushing of Antarctic Bottom Water (Du et al., 2018). In this study, we present high-resolution proxy data of export productivity, bottom water current variability, and upwelling rate changes during the last glacial period (20–60 kyr) from a high-sedimentation rate (average 12 cm/kyr) core NP02 collected on the northwestern Pacific Ocean abyssal plain at ~5,000 m water depth (Figure 1 and Figure S1 in Supporting Information S1). By comparing our new North Pacific data with published Southern Ocean records from the Antarctic Zone and climate modeling results, our proxy data-model comparison supports bipolar forcing and seesaw of atmospheric CO_2 at millennial time-scales.

2. Materials and Methods

Oceanographic currents in the North Pacific are dominated by two large-scale gyres, the subpolar gyre and the subtropical gyre, separated by the Subarctic Front, which is marked by the pronounced latitudinal sea surface temperature (SST) gradient (Figure 1a). This gradient is also seen within salinity, whilst the subtropical gyre is comparatively saltier and nutrient poor (Locarnini et al., 2013). The study area encompasses the region from the Kuroshi-Oyashio transition area to the Western subarctic gyre. Under present-day conditions, deep water is not produced in the North Pacific by higher precipitation relative to evaporation (Warren, 1983), and this region is the terminus of global deep-water circulation. The studied gravity core NP02 (40.47583°N, 150.1022°E, 5,177 m water depth) in the ocean basin of the northwestern Pacific is bathed in Lower Circumpolar Deep Water (LCDW), which is sourced from the Southern Ocean water mass (Figure S1a in Supporting Information S1). However, NPIW is defined by the salinity minimum at depths of 300–800 m with a density range centered at 2.67–26.9 σ_θ under the North Pacific subtropical gyre (Yasuda, 1997) (Figure 1b).

As carbonate preservation is poor and, at best, sporadic, chronological control of sediment core NP02 is based on ^{14}C measurements and relative paleointensity combined with visible-tephra-based tephrochronology (Gai et al., 2021, 2023) (Table S1 in Supporting Information S1). In general, linear sedimentation rates vary between 2.57 and 18.7 cm/kg (average of 12.2 cm/ka), which translates into a sub-millennial time resolution for our reconstructions. Therefore, this core with a high depositional rate is expected to capture deep water changes in response to abrupt climate transitions over the time period ~21–57 kyr. For this study, sediment samples for geochemical and mineral analysis, grain size analysis were taken at 1–3 cm (80–250 kyr on average) spacing throughout the core. Full details of analytical methods are provided in Text S2 in Supporting Information S1.

The iTRACE simulation is used to unravel the potential mechanism for bipolar coherence at millennial timescales. The iTRACE is an isotope-enabled transient climate experiment covering 20–11 ka, performed in the state-of-the-art isotope-enabled Community Earth System Model (iCESM1.3) (Brady et al., 2019; He et al., 2021; J. Zhang et al., 2017). It follows a similar strategy as in the previous transient TraCE-21ka simulation (Z. Liu et al., 2009). The horizontal resolution of the atmosphere and land model is 1.9° × 2.5°, with 30 vertical hybrid coordinate levels in the atmosphere; the horizontal resolution of the ocean and sea ice model is nominal 1°, with 60 vertical levels in the ocean (He et al., 2021).

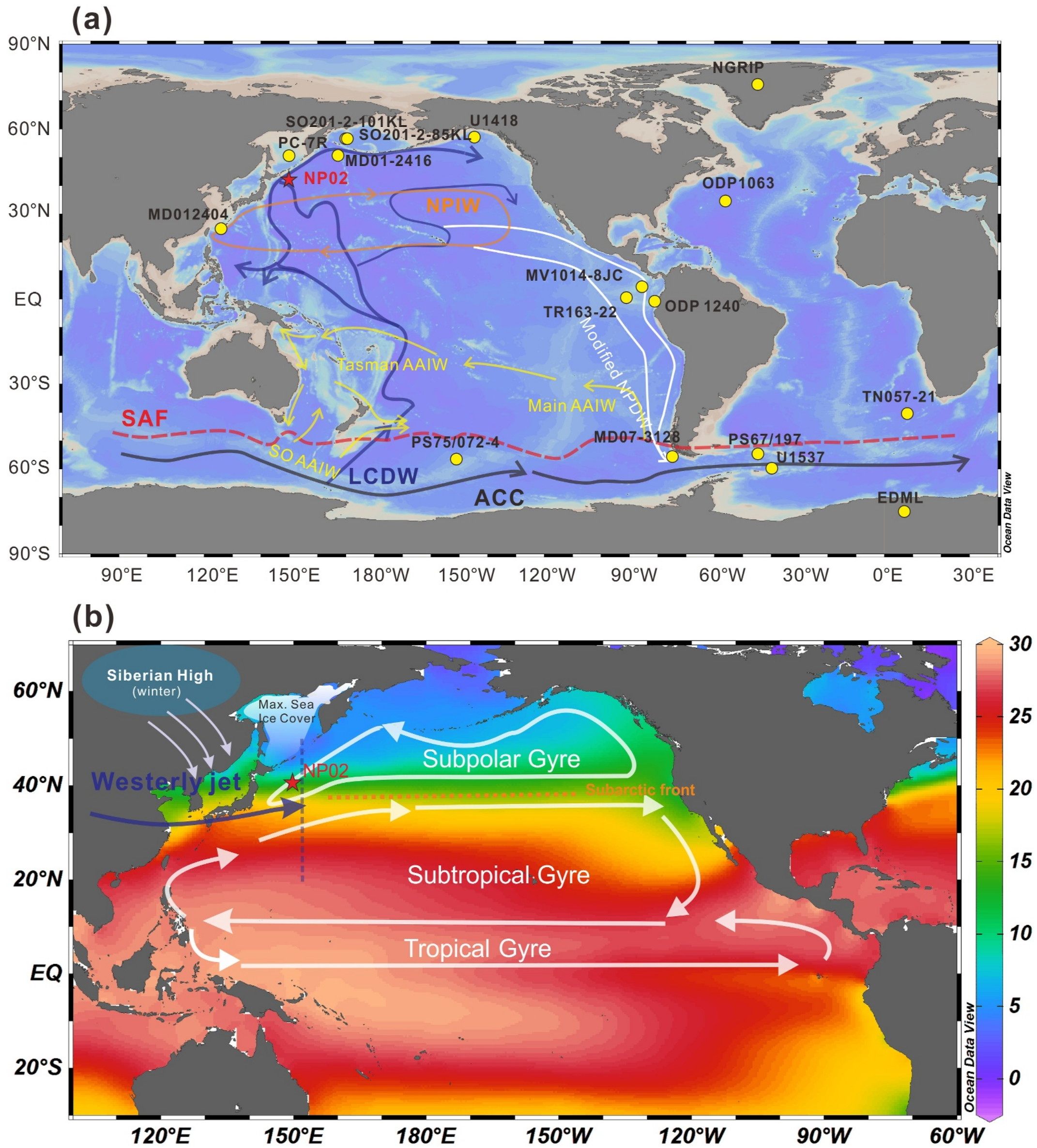

Figure 1. Map of the studied area. (a) Core NP02 (study site, red star) is located in the North Pacific Ocean, and sites studied in the literature (yellow dots) are discussed in this study; (b) Ocean and atmospheric circulation in the North Pacific Ocean. Major ocean currents are based on Brown et al. (2001). The position of the Westerly Jet is based on Y. Zhang and Huang (2011). Other atmospheric systems are shown schematically. Ocean temperatures (scale to right) are from the World Ocean Atlas 2013, drawn with Ocean Data View software (Schlitzer, 2015).

The iTRACE simulation is forced by four forcing factors that are applied additively from the Last Glacial Maximum (LGM; 20 ka). The first experiment was integrated with changing ice sheets and ocean bathymetry (ICE). The continental ice sheets were modified at the beginning of each 1,000-year interval (e.g., 19, 18, 17, 16 ka…) based on the ICE-6G reconstruction (Peltier et al., 2014). The next adds insolation forcing (ICE + ORB), followed by greenhouse gas concentrations (ICE + ORB + GHG) (Laskar, Robutel, Joutel, Gastineau, Correia, et al., 2004). At last, the iTRACE simulation (ICE + ORB + GHG + MWF) was branched from the ICE + ORB + GHG run by adding meltwater forcing. The meltwater fluxes, which largely emulated the scheme used in the TraCE-21ka simulation (Z. Liu et al., 2009), were designed to broadly align with the reconstructed sea level changes rather than to simulate the exact timing and routing of each meltwater event. Previous studies have shown a good performance of iTRACE in modeling the deglacial climate (Z. Liu et al., 2023; Zhu et al., 2022). We investigate the difference between HS1 and LGM in the model to infer climate responses during HSs. One caveat of using iTRACE is that the boundary conditions (e.g., greenhouse gasses and orbital parameters) and external forcings (e.g., freshwater fluxes) during HS 1-5 are not all the same. However, previous studies applying freshwater forcings under different boundary conditions show consistent hemispheric scale responses despite minor regional differences (Kageyama et al., 2013; Okumura et al., 2009; R. Zhang & Delworth, 2005), which is not unexpected due to the predominant impact of AMOC weakening in these experiments. The repeated responses registered in proxy records further support the similarities between different HSs.

3. Long-Term Dust Fertilization Enhanced Biological Pump in the North Pacific

The sedimentary opal content serves as a reliable and widely utilized qualitative method for reconstructing historical fluctuations in export production within the subarctic North Pacific (Y. Liu et al., 2022; Rae et al., 2020) and oceanic upwelling in the Southern Ocean (Kaiser et al., 2021; Weber et al., 2022). Our findings (Figure 2d and Figure S3d in Supporting Information S1) show high peaks during intervals corresponding to HSs identified in Greenland ice cores (Andersen et al., 2004) particularly the prominent stadials HS4, HS5, and HS5a, with the exception of HS3, which marks the coldest period of the past 60,000 years in the northern high latitudes, as discussed later (Figure 2a). This stadial increase in productivity in the Subarctic North Pacific is consistent with higher productivity in the Antarctic Zone of the Southern Ocean (Figure 2e; Figure S2f in Supporting Information S1) thereby reinforcing the bipolar coherence observed over millennial timescales (Ai et al., 2020; Lu et al., 2022; Studer et al., 2015). There is also strong consistency with redox-sensitive elemental concentrations (Figure S2h in Supporting Information S1) at core NP02. High productivity occurs under oxic conditions, which correspond to Antarctic Isotope Maximum events (Barbante et al., 2006) that themselves coincide with HSs (i.e., HS2, 4, 5, and 5a) (Figure 2a and Figure S3a in Supporting Information S1).

We observe prominent high-amplitude, millennial-scale variability in export productivity in the North Pacific (Figure 2d), overlaying the prolonged decline in CO_2 due to global cooling (Figure 2g, Köhler et al., 2017). This reduction of CO_2 suggests a gradual sequestration of CO_2 and thus accumulation of Si in the deep Pacific, which explains the improved preservation of exported biogenic opal (Rafter et al., 2022). Enhanced nutrient accumulation supports the "nutrient deepening" hypothesis (Boyle, 1988), which suggests that nutrients are transferred from upper and mid-depth waters to the abyssal layers during glacial periods. The North Pacific data indicate that the extent of change in preformed nutrients likely explained most of the decrease in glacial atmospheric pCO_2 (Jaccard et al., 2009).

The increased nutrient utilization at NP02 would suggest a more efficient biological pump in the North Pacific during HSs (Figure 2d). Iron is a crucial micronutrient that restricts primary production in the modern subarctic Pacific, equatorial Pacific, and Southern Ocean (Kim et al., 2021). In the context of global cooling, strong links between dust supply (Figure 2c) (Ruth et al., 2007; Xiao et al., 2021) and opal content in the North Pacific (Figure 2d) present evidence that iron has played a significant role in influencing productivity in the North Pacific.

This is also supported by the eolian dust fertilization in glacial periods across the Japan Sea and mid-latitude Pacific, accompanying increased export productivity variability (Hovan et al., 1991; Kawahata et al., 2000). This mechanism is clearly shown in our model simulation. In the northern China desert–source region for dust transported to the North Pacific (Figure 3a), extensive drying during HSs enhances dust production (Figure 3b). Transport of eolian dust to the northwestern Pacific is further enhanced by strengthened westerly winds (Figure 3b), which is a response to high-latitude cooling and a steepened meridional temperature gradient during HS1 (Nagashima et al., 2011).

Both enhanced deposition of opal and eolian dust in Greenland ice core records (Ruth et al., 2007) (Figure 2d) occurred during HS 2, 4, 5, but not during HS3. This also corresponds to the Heinrich event, which discharged ice from the Laurentide or Greenland Ice sheet. Given that HS3 was the coldest period of the past 60,000 years in the northern high latitudes (Andersen et al., 2004) (Figure 2a), the intensified cooling in the Northern Hemisphere due to reduced insolation appears to have played a crucial role as a negative feedback mechanism in the collapse of the marine-based Greenland Ice Sheet. This phenomenon influenced the dynamic atmospheric interaction between

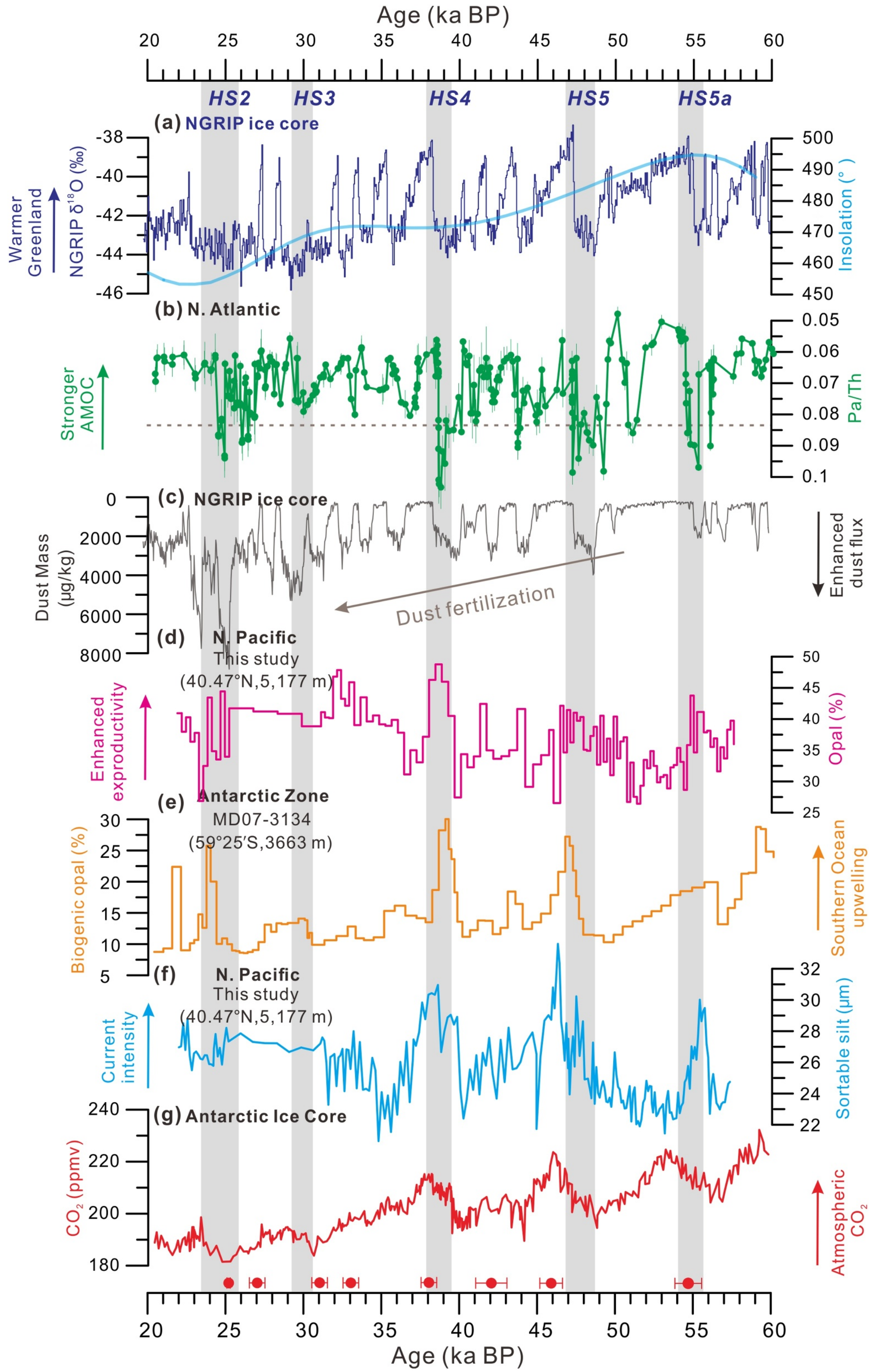
Age (ka BP)
20
25
30
35
40
45
50
55
60
HS2
HS3
HS4
HS5
HS5a
(a) NGRIP ice core
Warmer Greenland
NGRIP δ18O (‰)
Insolation (°)
(b) N. Atlantic
Stronger AMOC
Pa/Th
(c) NGRIP ice core
Dust Mass (μg/kg)
Enhanced dust flux
Dust fertilization
(d) N. Pacific
This study
(40.47°N,5,177 m)
Enhanced exproductivity
Opal (%)
(e) Antarctic Zone
MD07-3134
(59°25′S,3663 m)
Biogenic opal (%)
Southern Ocean upwelling
(f) N. Pacific
This study
(40.47°N,5,177 m)
Current intensity
Sortable silt (μm)
(g) Antarctic Ice Core
CO2 (ppmv)
Atmospheric CO2
Age (ka BP)

Figure 2.

the North Atlantic and the Northern Hemisphere westerlies during HSs. In general, from the long-term pCO_2 decline (Köhler et al., 2017) (Figure 2g), the increased nutrient utilization would cause enhanced pCO_2 sequestration in the North Pacific during HSs.

4. Potential Mechanism for Bipolar Coherence at Millennial Timescales

Our core NP02 is located along the flow path of Lower Circumpolar Deep Water (LCDW), sourced from the Southern Ocean (Kawabe & Fujio, 2010). On this basis, periods of vigorous abyssal circulation (i.e., higher current speeds of the LCDW) detected at core NP02 (Figure 2f) are consistent with periods of destratification in the Antarctic Zone of the Southern Ocean (Figure 2e), thought to be driven by coupled atmosphere-ocean (Watson et al., 2015; Wu et al., 2021) and sea-ice processes (Weber et al., 2022). Previous studies showed that a southward shift of the westerlies in the Southern Hemisphere enhanced wind stress at the latitude of Drake Passage during HSs (Toggweiler, Russell, Carson, et al., 2006), which resulted in strengthened air-sea coupling with the Antarctic Circumpolar Current and enhanced upwelling via Ekman transport (Anderson et al., 2009).

Our model simulations support that a southward shift of the southern westerlies induces strengthened upwelling in the Southern Ocean (red shadings in Figures 4b and 4d between 60° and 80°S), which would be responsible for transmitting CO_2 into the atmosphere. We find that the concentrations of trace elements sensitive to bottom water oxygen concentrations at core NP02, such as uranium (U), vanadium (V), and gallium (Ga) (Jin et al., 2006), reveal abyssal North Pacific oxygenation changes over the past 60 ka (Figures S3g and S3h in Supporting Information S1). Over the North Pacific Ocean, strengthened downwelling agrees with our trace element records showing more oxic conditions (Figure S3h in Supporting Information S1). This increased North Pacific downwelling (blue shadings in Figures 4b and 4d near 40°N) is closely related to decreased surface water buoyancy driven by cooling and drying (Figure 3b).

A deeper penetration of glacial NPIW during Northern Hemisphere cold events, nutrient supply to the euphotic zone may have been reduced over extensive regions of the North Pacific (Rafter et al., 2022). This is because nutrient supply from subsurface waters possibly decreased during HSs, which is expected to form NPIW with low nutrients due to downwelling (Li et al., 2017) (Figure S3c in Supporting Information S1). This is further evidenced by basin-wide decline in export productivity during HSs, as noted from studies in the Bering Sea (Riethdorf et al., 2013) (SO201-2-85KL), and the Okhotsk Sea (PC-7R) (Gorbarenko et al., 2012) (Figure S1a in Supporting Information S1). Conversely, our sortable silt data (Figure 2f) and redox sensitive elements (Figure S3h in Supporting Information S1) support that the Southern Ocean leakage is increased with wind stress due to heat flux changes, Antarctic warming, and southward-intensified Southern Hemisphere westerlies (Anderson et al., 2009; Skinner et al., 2020) (Figure 2g), influencing atmospheric CO_2 and climate change at millennial timescales. In general, both opal records show enhanced productivity during Heinrich events. In the Southern Ocean, this means enhanced upwelling and more CO_2 exhalation to the atmosphere; in the North Pacific, opal increase extracts CO_2 from the atmosphere and sequesters it in the deeper ocean. Accordingly, our work supports a bipolar CO_2 cycle seesaw, which is similar to that discovered in the North Atlantic (Yu et al., 2023).

5. A Search for Mechanisms and Future Implications

The enhancement of upwelling at millennial timescales allows us to infer the coupling relationship between the dynamics of the Southern Ocean south of the Polar Front and climate change (Y. Liu et al., 2022). Although the Southern Ocean is vital for regulating Pleistocene pCO_2 variability, similar processes may have taken place in the subarctic Pacific, as evidence suggests that around 30 ppm of pCO_2 was released into the atmosphere due to

Figure 2. Millennium variabilities in productivity, bottom water current and the associated paleoclimate during 20–60 ka. (a) Oxygen isotope record of the North Greenland Ice Core Project (NGRIP) (Andersen et al., 2004) and Northern Hemisphere summer insolation (65°N, July–September) (Laskar, Robutel, Joutel, Gastineau, Correia, & Levrard, 2004); (b) Complication of North Atlantic $^{231}Pa/^{230}Th$, reflecting the strength of the Atlantic Meridional Overturning Circulation (Böhm et al., 2015; Henry et al., 2016; McManus et al., 2004); (c) Dust flux of NGRIP; dust flux was calculated using the published dust concentration data (Ruth et al., 2007); (d) productivity recorded by opal content at core NP02 (this study); (e) opal content in Site MD07-3134 from Scotia's Sea Iceberg Alley; (f) Sortable silt mean grain size reflecting deep water current speed at core NP02 (this study); (g) Atmospheric pCO_2 (Köhler et al., 2017); Gray bars indicate Heinrich Stadials (HS2-5a).

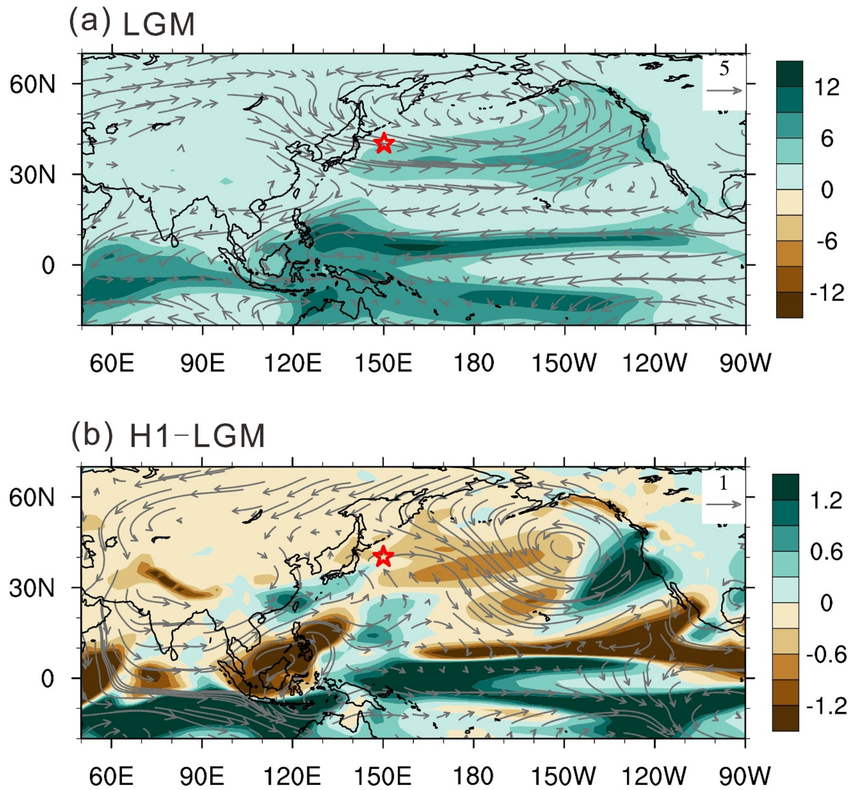

Figure 3. Simulated annual precipitation (mm/day) and 850 hPa wind (m/s) in iTRACE. (a) Annual mean in LGM; (b) Changes in HS1 compared with LGM.

increased overturning during the last deglaciation (Gray et al., 2018). In comparison to the deep-water CO_3^{2-} levels in the North Atlantic, Southern Ocean ventilation was also a key factor in modulating millennial deep Atlantic carbon storage and atmospheric CO_2 variations over the last glacial cycle (Yu et al., 2023). Our records and model simulations suggest, alongside published data, that surface nutrient utilization was a critical factor in modulating deep Pacific carbon storage and atmospheric CO_2 variations over the long-term cycle. Importantly, our data underscore a previously underappreciated role of North Pacific biological pump efficiency in regulating deep-sea carbon sequestration and atmospheric CO_2 (Rafter et al., 2022). Moreover, it does not currently appear feasible to quantify the relative decrease of atmospheric CO_2 in the Northern Hemisphere to the relative increase in the Southern Hemisphere based on our proxies given the very complex interactions of the interhemispheric atmospheric-ocean-ice system. Future, successive model simulations of the marine carbon cycle should be considered to address this question.

During HSs, thermal wind balance, associated with the meridional temperature gradient at Northern Hemisphere high latitudes, was coupled with the expansion and strengthening of the North Pacific Ocean Gyre, which arises in our model as both effects are driven by concurrent changes in wind stress curl (Gray et al., 2018, 2020; Rae et al., 2014). As demonstrated by model simulations, our results support that Southern Ocean upwelling was causally linked to pulses of atmospheric CO_2 during the last glacial and deglacial periods, which coincided with dynamics in the North Pacific deep water (Menviel et al., 2014, 2018) (Figure 4).

In light of the ongoing and possible future weakening of the AMOC (Biló et al., 2024; van Westen et al., 2024), it is crucial to comprehensively understand how processes in polar oceans, particularly in the Antarctic zone of the Southern Ocean and the subarctic North Pacific, influence atmospheric CO_2 levels and related ocean acidification (Gray et al., 2023). Overall, our study emphasizes the importance of the deep subarctic Pacific Ocean as a potential location to absorb more atmospheric CO_2 on the long timescales, while the Southern Ocean tends to release more atmospheric CO_2 during abrupt climatic changes.

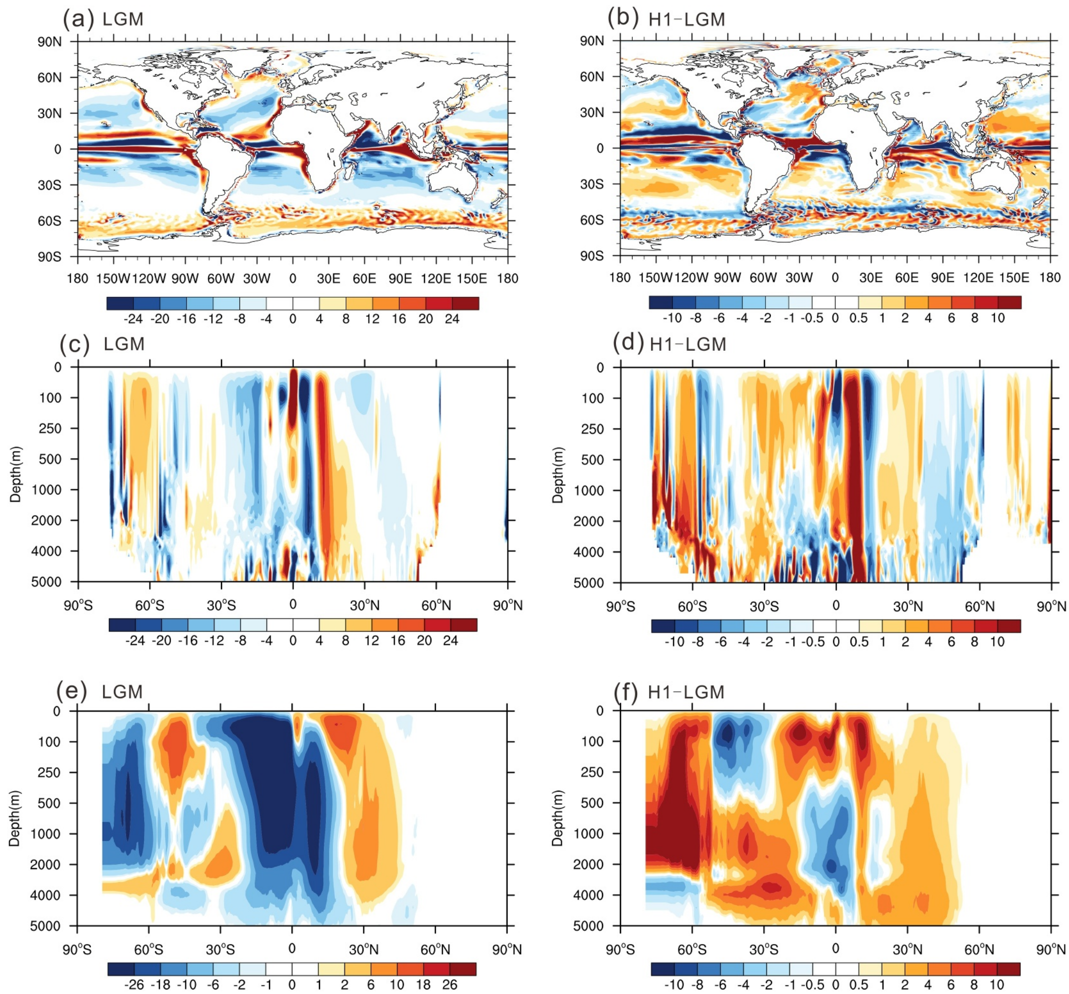

Figure 4. Simulated vertical velocity and streamfunction in iTRACE. (a) Climatology of vertical velocity (cm/day) averaged over the 0–100 m during the LGM. (c) Climatology of vertical velocity across the Pacific basin during HS1. (e) Climatology of streamfunction (Sv) across the Pacific basin during HS1. (b–f) are for corresponding changes in HS1 compared with LGM.

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Data Availability Statement

All model data supporting our findings are available at Zhong (2024). The information for the TraCE21ka experiments can be found in https://trace-21k.nelson.wisc.edu/portal.html. Figures were plotted with the NCAR Command Language (version NCL 6.4.0; NCAR Command Language, 2019), and codes for figures plotted in this study are available when required.

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