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Understanding carbon-climate feedbacks

Evaluating the Glacial-Deglacial Carbon Respiration and Ventilation Change Hypothesis as a Mechanism for Changing Atmospheric CO_2

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Key Points:

- Highly resolved proxy records of surface to deep water $\delta^{13}C$ and $\Delta^{14}C$ gradients from the Pacific are similar in the late Holocene and last glacial maximum
- Model simulations of the prevailing hypothesis for enhanced respired carbon accumulation do not match observations of $\delta^{13}C$, $\Delta^{14}C$, and $\varepsilon^{14}C$ in the deep Pacific
- Processes other than carbon respiration and ocean stratification must also be involved in explaining lower $[O_2]$ in the deep sea and lower pCO_2 during the last glacial

Supporting Information:

- Supporting Information S1
- Figure S1
- Figure S2

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Abstract The prevailing hypothesis to explain pCO_2 rise at the last glacial termination calls upon enhanced ventilation of excess respired carbon that accumulated in the deep sea during the glacial. Recent studies argue lower $[O_2]$ in the glacial ocean is indicative of increased carbon respiration. The magnitude of $[O_2]$ depletion was 100–140 μ mol/kg at the glacial maximum. Because respiration is coupled to $\delta^{13}C$ of dissolved inorganic carbon (DIC), $[O_2]$ depletion of 100–140 μ mol/kg from carbon respiration would lower deep water $\delta^{13}C_{DIC}$ by ~1‰ relative to surface water. Prolonged sequestration of respired carbon would also lower the amount of ^{14}C in the deep sea. We show that Pacific Deep Water $\delta^{13}C_{DIC}$ did not decrease relative to the surface ocean and $\Delta^{14}C$ was only ~50‰ lower during the late glacial. Model simulations of the hypothesized ventilation change during deglaciation lead to large increases in $\delta^{13}C_{DIC}$, $\Delta^{14}C$, and $\varepsilon^{14}C$ that are not recorded in observations.

Plain Language Summary The prevailing hypothesis to explain atmospheric CO_2 variability during glacial/interglacial cycles assumes atmospheric CO_2 was sequestered into the deep sea as respired metabolic carbon. Recent studies argue in support of this by suggesting lower oxygen concentrations in the deep Pacific during the glacial reflects increased oxidation of marine organic matter that promoted a larger accumulation of respired carbon. We show this interpretation is not validated by independent tests, including records of deep water $\delta^{13}C$ and $\Delta^{14}C$.

1. Introduction

For over 3 decades, efforts have been underway to identify the Earth system processes that modulate the concentration of atmospheric CO_2 on glacial/interglacial time scales. The prevailing hypothesis to explain the glacial/interglacial pCO_2 variability calls upon ocean-stratification and reduced ventilation of deep waters during glaciations. In this scenario, atmospheric CO_2 is drawn down by the marine biological pump and respired metabolic carbon accumulates in a deep ocean reservoir that remains isolated from the atmosphere. Much of the research to test this hypothesis has focused on the last glacial termination where detailed records from ocean and ice cores have documented the sequence of events surrounding the last glacial termination and the rise in atmospheric pCO_2 from 18.5 to 15 ka (P. U. Clark et al., 2012). These events include the Heinrich 1 ice and meltwater advance across the North Atlantic that disrupted deep water convection and the distribution of heat (Boyle, 2000; Hodell et al., 2017; McManus et al., 2004; Seidov & Maslin, 2001) In the Southern Ocean, sea ice retreat and enhanced wind forcing during the Heinrich 1 interval may have increased Ekman upwelling and altered air-sea gas exchange (Anderson et al., 2009; Eggleston & Galbraith, 2018; Khatiwala et al., 2019; Menviel et al., 2018). The increased upwelling is thought to have enhanced deep water ventilation and release of excess respired carbon from the ocean to the atmosphere (Anderson et al., 2009; Menviel et al., 2017; Sigman & Boyle, 2000) At the same time, the strength and position of the southern Westerlies remains a difficult variable to robustly assess from proxy records (Kohfeld et al., 2013; Sime et al., 2013).

The respired carbon hypothesis calls upon increased accumulation and isolation of respired metabolic carbon in the deep sea due to greater ocean stratification and reduced ventilation rates relative to today (Adkins, 2013; Menviel et al., 2012, 2017; L. Skinner et al., 2015). The hypothesis has recently been expanded to include accumulation of "old" respired carbon throughout the deep Pacific (below 1,500 m) including the equatorial Pacific (Anderson et al., 2019; Jacobel et al., 2020). The evidence in support of an expanded

respired-carbon reservoir comes from observations of lower dissolved oxygen concentrations in the Pacific during the glacial. The lower oxygen levels during the glacial are attributed to the oxidation of organic carbon (Anderson et al., 2019; Jaccard & Galbraith, 2012; Jacobel et al., 2020) which would enhance the concentration of dissolved carbon. Previous studies have found no evidence of enhanced productivity and organic carbon export in either the Eastern or Western Equatorial Pacific (Costa et al., 2016; Winckler et al., 2016) implying that if the respired carbon inventory increased, it must have sourced from elsewhere. Such a scenario would require that additional respired carbon C_{org} and lower $[O_2]$ be transported to the deep Pacific via a conduit from higher latitudes, specifically the Southern Ocean because productivity appears to have been reduced in the North Pacific (Jaccard et al., 2010). Early box-models (Knox & McElroy, 1984) simulated depleted $[O_2]$ in the Southern Ocean and have been validated by proxy data (Jaccard et al., 2016; Lu et al., 2016).

An issue that complicates the inference of enhanced respired carbon from proxies of $[O_2]$ is the potential influence of air-sea disequilibrium on preformed $[O_2]$ in the deep water source region (Eggleston & Galbraith, 2018). Previously, Khatiwala et al. (2019) also challenged the carbon oxidation hypothesis by invoking enhanced air-sea disequilibrium through changes in temperature and iron fertilization, which could account for most glacial-interglacial CO_2 variability independent of circulation and enhanced C_{resp}. By extension, air-sea disequilibrium may also account for reduced deep-sea oxygen during the last glacial maximum (LGM). Although expanded sea ice may have had limited influence on air-sea exchange of CO_2, large differences in air-sea processes and equilibration times may imply a significant effect on O_2. Large uncertainties exist, especially since the equilibration time for O_2 is a magnitude smaller than that of CO_2. Modern studies suggest a diminishing and proportional relationship between air-sea exchange and the fraction of sea ice up to ~90%, with seasonal and annual variability in Southern Ocean preformed O_2 at least partly attributable to sea ice and its indirect effects on biology (Bushinsky et al., 2017). Because zones of the South Ocean exhibit $[O_2]$ undersaturation during austral winter, expanded sea ice and shorter summer melting seasons are likely to have reduced air-sea exchange and lowered preformed $[O_2]$ in the glacial deep Pacific. For this reason, lower $[O_2]$ values in the deep Pacific during the last glacial cannot be directly converted to estimates of carbon respiration without an independent form of validation. Here we use a separate proxy to assess how much of the oxygen concentration change in Pacific deep water can be attributed to metabolic carbon oxidation.

If oxygen depletion in the deep Pacific was solely the result of carbon respiration, there would have been an accompanying shift in deep water $^{13}C/^{12}C$ (referred to as $\delta^{13}C$ in ‰ relative to the Vienna Pee Dee Beleminite [VPDB] standard). This is because photosynthetic carbon is depleted in ^{13}C by approximately 20‰ relative to dissolved carbon in surface waters. As photosynthetic carbon is oxidized in the subsurface, ^{12}C is added back to the pool of dissolved inorganic carbon (DIC), lowering its $\delta^{13}C$. This relationship is illustrated in Figure 1 where the $\delta^{13}C$ of DIC is plotted versus dissolved $[O_2]$ in the deep Pacific. In the modern ocean a decrease in $[O_2]$ of ~100–140 μ mol/kg is accompanied by a lowering of $\delta^{13}C$ by nearly 1‰ (Figure 1).

If the waters in the deep Pacific lost 100–140 μ mol/kg of $[O_2]$ during the last glacial maximum due entirely to metabolic carbon oxidation, it would be reflected in the $\delta^{13}C$ of calcitic benthic foraminifera relative to surface water $\delta^{13}C$ as recorded by planktic foraminifera. The calcite of the surface-dwelling planktic foraminifera *Globigerinoides ruber s.s.* records changes in the $\delta^{13}C$ of western equatorial surface waters in contact with the atmosphere (Kawahata, 2005; Lin et al., 2004; Numberger et al., 2009) a species-specific offset of 0.9‰ for specimens between 250 and 350 μm (Spero et al., 2003). Preindustrial $\delta^{13}C_{DIC}$ values of the western equatorial tropical surface waters would have been between 1.9‰ and 2.3‰ (Eide et al., 2017) values that are simulated well in current climate models (Menviel et al., 2015; Schmittner et al., 2013). The average $\delta^{13}C$ of late Holocene *G. ruber* in the western equatorial Pacific is 1.3‰ ($1\sigma = 0.3$‰; Figure 2). With a species-specific offset of 0.9, the late Holocene *G. ruber* are recording an average late Holocene $\delta^{13}C_{DIC}$ value of 2.1‰ ± 0.3‰, very close to the modern, preindustrial value. The epibenthic foraminifer *Cibicidoides mundulus* records the $\delta^{13}C$ of dissolved inorganic carbon of Pacific Deep Water, with minor influences from $CO_3^{=}$ and pressure (Schmittner et al., 2013). The $\delta^{13}C$ offset between late Holocene *G. ruber* and *C. mundulus* is ~1.3‰ and therefore is very close to the modern (pre-Industrial) surface to deep water $\delta^{13}C$ gradient. We use the $\delta^{13}C$ of fossil *G. ruber* and *C. mundulus* from a sediment core collected at 2,114 m in the western equatorial Pacific to reconstruct how the surface to Pacific Deep Water $\delta^{13}C$ gradient has

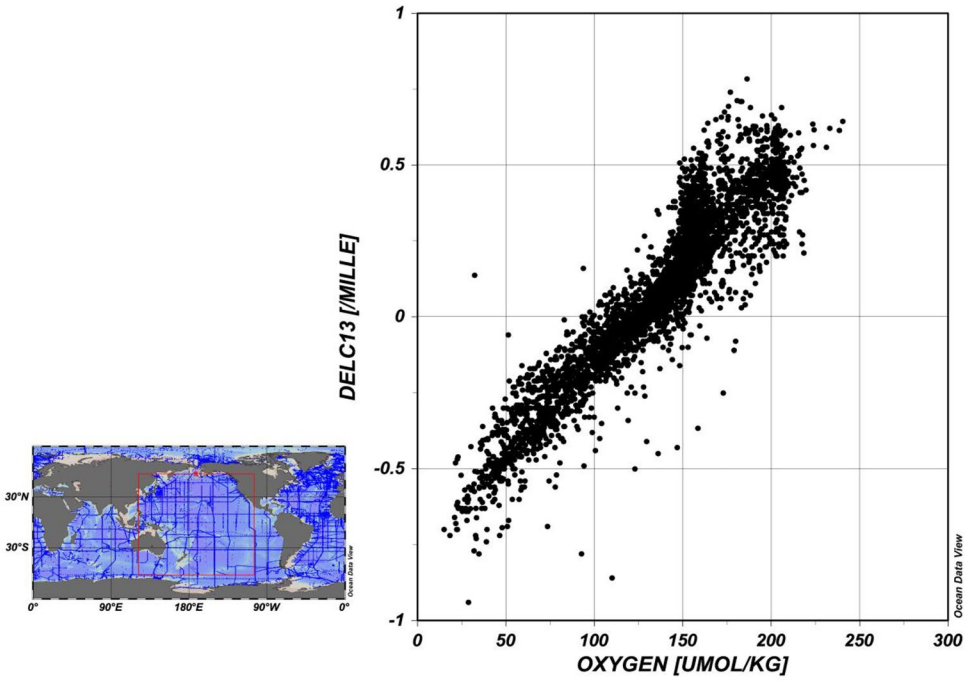

Figure 1. Plot of $\delta^{13}C_{DIC}$ versus dissolved [O_2] from the GLODAP (https://www.pmel.noaa.gov/co2/story/GLODAP) database of sites below 1,500 m in the Pacific. Over time deep waters lose [O_2] and acquire lower $\delta^{13}C_{DIC}$ values as oxidized organic carbon is added. DIC, dissolved inorganic carbon; GLODAP, Global Data Analysis Project.

varied in time and evaluate whether the gradient was larger during the late glacial relative to the Holocene as the carbon respiration hypothesis predicts. The magnitude of the thermodynamic effect (Broecker & Maier-Reimer, 1992; Lynch-Stieglitz et al., 1995) on the isotope composition of both western tropical Pacific surface water (where there is no upwelling) and Pacific Deep Water, whose temperature is formed at high southern latitudes, would have been of equivalent magnitude and direction during the LGM because both water masses were 2–3°C colder (Broecker & Maier-Reimer, 1992; Lynch-Stieglitz et al., 1995; L. Stott et al., 2007). Sediment core MD98-2181 was collected within the core of Pacific Deep Water, which is the oldest and among the most oxygen depleted waters in the deep North Pacific today. This water mass would have carried the oldest, most oxygen deficient and most carbon-rich waters southward toward the Southern Ocean during the deglaciation.

The prevailing hypothesis also predicts that as excess respired carbon accumulated in a more stratified and less ventilated glacial ocean the $^{14}C/^{12}C$ ($\Delta^{14}C_{DIC}$) would have decreased relative to the surface ocean. Then, during the deglaciation both $\Delta^{14}C_{DIC}$ and $\delta^{13}C_{DIC}$ would have increased as older, O_2-poor deep waters were replaced by younger, better ventilated waters with higher $\delta^{13}C_{DIC}$ (Menviel et al., 2018). We test this prevailing hypothesis by comparing new and existing data from the deep Pacific with the predictions and with an Earth System Model (LOVECLIM) simulation that depicts the timing and magnitude of $\delta^{13}C$ and $\Delta^{14}C$ response to the hypothesized changes in deep water ventilation.

2. Materials and Methods

2.1. $\delta^{13}C$ and $\Delta^{14}C$ Proxies

The MD98-2181 core was collected from the margin of Mindanao where the flux of terrigenous sediments to the sea floor is high and consequently the temporal resolution of individual samples from this core is also very high. Typical sediment accumulation rates are between 60 and 80 cm/ky (L. Stott et al., 2004, 2007). The planktic foraminifera $\delta^{13}C$ values (*G. ruber s.s.*) are not affected by upwelling of subsurface waters and thus reflect the $\delta^{13}C$ of surface water DIC. The $\delta^{13}C$ of the benthic foraminifera (*C. mundulus*) record the

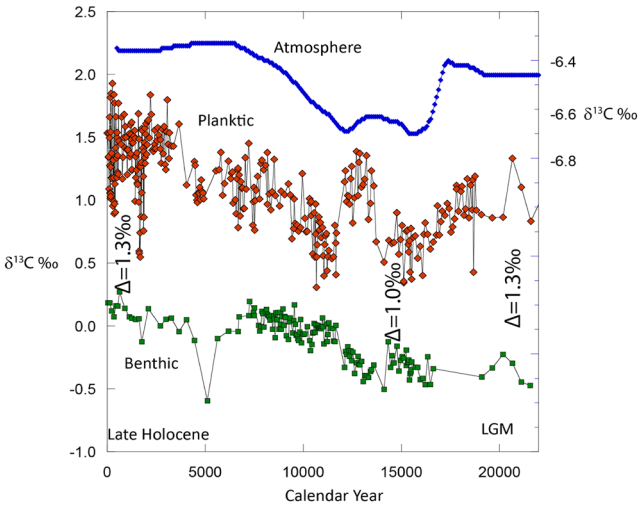

Figure 2. The record of atmospheric $\delta^{13}C$ (CO_2; Schmitt et al., 2012), planktic (*G. ruber*) $\delta^{13}C$ and benthic (*C. mundulus*) $\delta^{13}C$ from core MD98-2181 from the western tropical Pacific. There is an interval between 17 and 19 ka where *C. mundulus* does not occur in the core. All values are plotted relative to the Vienna Pee Dee Beleminite (VPDB) standard. Located at 2,114 m water depth, the core is bathed today by Pacific Deep Water.

history of Pacific Deep Water $\delta^{13}C_{DIC}$. Culturing studies have shown that this benthic foraminifer may migrate from the sediment water interface into the shallow most sediments briefly if disturbed but rapidly (within 24 h) returns to the sediment water interface (Wollenburg et al., 2018). It appears therefore this species spends most of its life at the sediment water interface. After the MD98-2181 core was split, discrete samples were extracted at 1 to 2-cm intervals. The samples were dried at 40°C and then disaggregated in a buffered solution of water and sodium hexametaphosphate. The disaggregated sediment was then washed over at >63 mm screen to remove the finer material and then dried again. Planktic and benthic foraminifera from each sample were picked under a microscope. For stable isotope measurements the planktic species *G. ruber* (white) was picked from the greater than 250 μm fraction. The benthic species *C. mundulus* (s.l.) was picked from the >180 μm size fraction. The picked specimens were gently cracked open between glass slides, transferred to small centrifuge tubes and sonicated in buffered DI water for several seconds to remove fine debris (via syringe) from the calcite. After drying, the calcite was loaded into vials for stable isotope analysis on a Micromass Instruments Isoprime isotope ratio mass spectrometer located at the University of Southern California following standard procedures in which a sample of CO_2 from the calcite is compared to a reference gas calibrated to the National Bureau of Standards carbonate standards for both $\delta^{13}C$ and $\delta^{18}O$. Average precision of the USC inhouse calcite standard (Ultiss) averaged <0.1‰ for $\delta^{13}C$. Note, the $\delta^{13}C$ data from core MD98-2181 have not been published previously. Only the oxygen isotope data from this core have been published previously (L. Stott et al., 2007).

For radiocarbon measurements, different species of planktic and benthic foraminifera were picked, depending on the interval and the abundances of species. Specimens were cleaned in the same fashion as those for stable isotope measurements. The analyses were conducted at the Woods Hole Oceanographic Institution Accelerator Mass Spectrometry (AMS) Laboratory and at the Keck Carbon Cycle AMS Laboratory at the University of California, Irvine. In samples with enough *C. mundulus* (s.l.), *C. wuellerstorfii*, and *C. Uvigerina* for single species measurements, we analyzed more than one species to assess reproducibility. Typical reproducibility of both benthic and planktic samples were within 300–500 years. There were intervals of the core where abundances were too low to obtain a measurement from a single species. In these cases, mixed species were used. Estimates of $\Delta^{14}C$ are based on the following equation:

$$\Delta^{14}C = (Fm * e^{\lambda/(\text{calendar age})} - 1) * 1{,}000\%$$

where Fm is the faction of modern, $\lambda = 1/8{,}267$ is the decay constant for ^{14}C, and a 5,730 years half-life (Stuiver & Polach, 1977). The uncertainties include the compounded analytical uncertainty of Fm and calendar ages. Calendar ages for the MD98-2181 samples were obtained by converting planktic ^{14}C ages to a calendar age using BchronCalibrate ages (Haslett & Parnell, 2008) with the Marine 20 calibration curve and a constant reservoir age. The surface reservoir age offset (ΔR) in the western tropical Pacific today is 0–50 years (G. Clark et al., 2006; Southon et al., 2002). There is no indication that the reservoir age of surface waters in the western tropical Pacific varied significantly during the past 22,000 years. Thus, we applied a reservoir age correction ($\Delta R = 0$) to each planktic ^{14}C age from the MD98-2181 core. There are two discrete intervals of this core at 941–961 and 1,011 cm that are disturbed and not included (L. D. Stott, 2007). To infer ocean ventilation state from radiocarbon data, it is more useful to compare benthic foraminifera $\Delta^{14}C$ values to the contemporaneous atmosphere. Here, instead of using the more traditional $\Delta\Delta^{14}C$ notation ($\Delta\ ^{14}C_{benthic} - \Delta\ ^{14}C_{atm}$), we adopt the epsilon metric ($\varepsilon^{14}C = [(\Delta\ ^{14}C_{benthic}/1{,}000 + 1)/(\Delta\ ^{14}C_{atm}/1{,}000 + 1) - 1]*1{,}000$). The advantage of the epsilon metric is that as long as ocean circulation stays the same, $\varepsilon^{14}C$ does not change at different atmospheric $\Delta^{14}C$ levels, while this is not true for $\Delta\Delta^{14}C$ (Soulet et al., 2016).

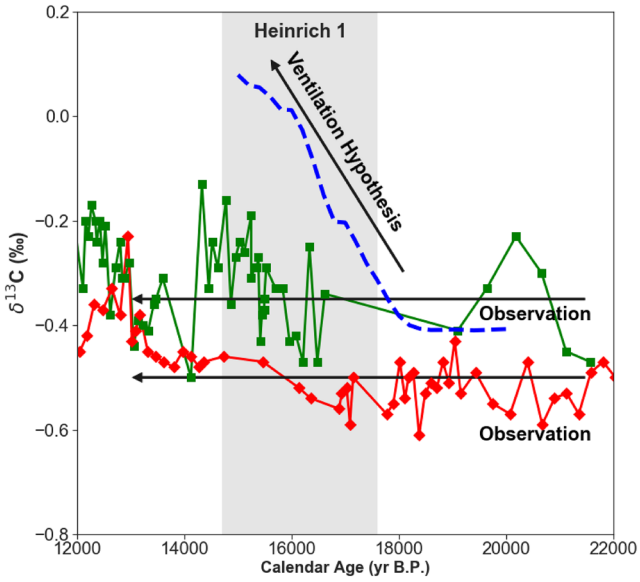

Figure 3. Benthic $\delta^{13}C$ (Obs) from deep Pacific cores MD98-2181 (green, this study), W8709A-13PC (red; Lund & Mix, 1998; Lund et al., 2011), and the LOVECLIM simulated Deep Pacific $\delta^{13}C_{DIC}$ response to enhanced ventilation (blue; Menviel et al., 2018).

The 1σ uncertainties of $\Delta^{14}C$ and $\varepsilon^{14}C$ are derived through a Monte-Carlo approach that fully propagates the uncertainties of ^{14}C measurements, calibrated calendar ages, atmospheric $\Delta^{14}C$ values from the IntCal20 curve. These data are archived on National Oceanic and Atmospheric Administration's Data Server.

3. Results and Discussion

The deep Pacific $[O_2]$ is estimated to have been ~100–140 μ mol/kg lower during the glacial (Anderson et al., 2019). If that lowering of O_2 was due entirely to metabolic carbon oxidation (Anderson et al., 2019), it would have lowered deep Pacific $\delta^{13}C_{DIC}$ by 1.0‰ beyond the global mean ocean $\delta^{13}C$ shift that is recorded by planktic foraminifera that inhabited the surface ocean where carbon respiration would not influence the $\delta^{13}C$ of DIC (Figure 1).

3.1. The Carbon Oxidation Hypothesis Versus Pacific $\delta^{13}C$ Records During the Glacial

In Figure 2, we illustrate the $\delta^{13}C$ values of surface-dwelling planktic and bottom-dwelling benthic foraminifera from core MD98-2181. We find that the $\delta^{13}C$ offset between the surface ocean (planktic values) and Pacific Deep Water (benthic values) was ~1.3‰ in the late Holocene as it is in the modern ocean and was also 1.3‰ in the late glacial. Both the Holocene and the late glacial offsets between the tropical surface ocean and deep Pacific were therefore very close to the modern ocean offset. There is no evidence that Pacific Deep Water $\delta^{13}C$ values were 2.3‰ lower than planktic values during the late glacial (the modern offset of 1.3‰ plus the 1‰ shift due to the oxidation of additional marine organic carbon) as required by the carbon oxidation hypothesis (Anderson et al., 2019).

3.2. Deep Pacific $\delta^{13}C$ and $\Delta^{14}C$ Data Do Not Support a Significant Increase in Ventilation Rate at the Glacial Termination

There are relatively few high-resolution benthic $\delta^{13}C$ records from the deep Pacific that span the last glacial termination. The results from MD98-2181 are shown in Figure 3 together with another well-resolved record from the deep North Pacific (Lund & Mix, 1998; Lund et al., 2011). In neither of these records is there evidence that deep Pacific $\delta^{13}C$ values increased during the Heinrich 1 interval as predicted by the ocean ventilation hypothesis (Menviel et al., 2018; Figure 2). It is possible that the LOVECLIM simulation overestimates the amount of ventilation in the deep Pacific and therefore overpredicts the magnitude of $\delta^{13}C$ increase during the early deglaciation. However, the fact that both sites do not record anomalously low glacial $\delta^{13}C$ values and do not record an increase in $\delta^{13}C$ during the early deglacial is not consistent with the prevailing hypothesis that calls for enhanced carbon oxidation to explain the lower glacial $[O_2]$ and increased $[O_2]$ during the deglaciation.

Similar to $\delta^{13}C_{DIC}$, the $\Delta^{14}C_{DIC}$ value of Pacific Deep Water starts as a preformed value acquired in the Southern Ocean source region where Antarctic Bottom Water and Upper Circumpolar Deep Water waters are subducted to abyssal depths. Pacific Deep Water is the product of aging of these waters as they flow toward the North Pacific and gradually upwell (Talley, 2013). The $\Delta^{14}C_{DIC}$ values decrease as waters age during northward transit through the ocean and are transformed into Pacific Deep Water that then returns to the Southern Ocean (Key et al., 2004). Today, Antarctic surface water $\Delta^{14}C$ values are close to −100‰. Circumpolar deep waters are approximately −150‰. Pacific Deep Water has the lowest $\Delta^{14}C$ in the ocean of approximately −200‰ (Figure S1), reflecting the roughly 1,400 years residence time of deep water in the Pacific (Khatiwala et al., 2012; Primeau & Holzer, 2006). The western topical Pacific surface water $\Delta^{14}C$ values are 0‰–50‰, being partially influenced by anthropogenic carbon. The offset between tropical surface water and Pacific Deep Water today is therefore, ~200‰–250‰ (Figure S1). The whole ocean $\Delta^{14}C$ was

higher during the last glacial (L. C. Skinner et al., 2017). Preformed values in the Southern Ocean would therefore have been higher during the last glacial. The extent to which air-sea disequilibrium influenced the preformed values is a matter of ongoing investigations. In a recent study, Khatiwala et al. (2019) found that preformed gases are strongly affected by greater air-sea disequilibrium during the LGM. But whole ocean $\Delta^{14}C$ values had begun to decrease at ~30 ka and continued to decrease throughout the LGM and deglaciation. Hence, the sustained decline in whole ocean $\Delta^{14}C$ must involve other factors in addition to changing temperatures and sea ice extent.

The radiocarbon content of deep and surface water is recorded in the calcite tests of bottom and surface-dwelling foraminifera. Using the radiocarbon decay constant and calendar ages for each interval of a sediment core the ^{14}C age of planktic and benthic foraminifers are converted to radiocarbon activity ($\Delta^{14}C$; Methods). The surface (planktic) to deep water (benthic) $\Delta^{14}C$ offset in the late Holocene and in the late glacial was 150‰, very close to the modern offset (Figures S1 and S2). Therefore, there is no evidence that there was a much larger offset in the late glacial period that would be indicative of a longer residence time of Pacific Deep Water. These findings are supported by other, lower resolution results from the deep Pacific that do not document lower ^{14}C content during the last glacial maxima (W. Broecker et al., 2004, 2008). Importantly, we show that high resolution $\Delta^{14}C$ values at MD98-2181 in the deep Pacific does not record a large increase during the early deglaciation as the prevailing hypothesis predicts (Menviel et al., 2018). The offset remains the same for 5,000 years after the beginning of deglaciation as atmospheric pCO_2 rose by 35–40 ppm.

For the purpose of using benthic $\Delta^{14}C$ and atmospheric $\Delta^{14}C$ offset to trace ventilation, $\varepsilon^{14}C$ is perhaps a more accurate metric, where more negative values reflect a larger gradient between the deep and surface (Methods). $\varepsilon^{14}C$ at the MD98-2181 site is ~250‰ during the LGM and ~200‰ during Holocene (Figure S2, lower panel). The 50‰ glacial-interglacial offset is consistent with changes in benthic-atmospheric $\Delta^{14}C$ (Figure S2, upper panel). There are small increases that occur during the Heinrich 1 and Younger Dryas time intervals (Figure S2). These shorter term features are also seen in other high resolution records from the North Pacific (Lund, 2013).

In Figure 4, the benthic $\Delta^{14}C$ record for MD98-2181 is plotted together with four previously published benthic $\Delta^{14}C$ records from deep water sites in both the north and south Pacific. These records are plotted with the simulated values from the Earth System Model (LOVECLIM) for the deep Pacific $\Delta^{14}C$ in response to increased deep water ventilation at the onset of deglaciation (Menviel et al., 2018). In each of the observational records, spanning water depths between ~1,500 and 2,800 m, there is a ~100‰ decrease in $\Delta^{14}C$ between 17.5 and 14.5 ka whereas the model simulates a 100‰ increase over this time interval. The observational records of deep water $\Delta^{14}C$ document a decline in both the North and South Pacific as atmospheric pCO_2 was rising. This is in direct conflict with results from the LOVECLIM experiment that simulates the deep Pacific response to enhanced ventilation. Considering that the absolute values of atmospheric $\Delta^{14}C$ during the last glacial termination (i.e., from IntCal20) are different from the simulated atmospheric $\Delta^{14}C$ in LOVECLIM, $\varepsilon^{14}C$ from observations and model data are also calculated to make a direct comparison of the ^{14}C-based ventilation state from the data and from the model simulation (Figure S2). The simulated deep Pacific $\varepsilon^{14}C$ shows a rapid 150‰ increase, while the observations only record a 50‰ increase. This contrast in $\varepsilon^{14}C$ clearly indicates the model overestimates the degree of enhanced ventilation during the early deglaciation.

4. Conclusions

The observational data now available from the deep Pacific Ocean spanning the last 25kys do not support the prevailing hypothesis that calls upon significantly reduced deep water ventilation rate and enhanced accumulation of respired carbon during the last glacial. The small (50‰) decrease in $\varepsilon^{14}C$ may reflect some reduction in ventilation rate during the LGM but not to the extent that it affected the amount of respired carbon that accumulated as there is no indication that the $\delta^{13}C$ of Pacific Deep Water was lower as would have occurred if the reduced $[O_2]$ was due entirely to carbon respiration. We suggest a more likely explanation for lower deep-water oxygen concentrations during the glacial was reduced O_2 ocean-atmosphere equilibration in the source regions where deep waters formed, warranting further investigation into past variability of preformed O_2 of deep source waters and also proxies used to reconstruct the history of deep water O_2.

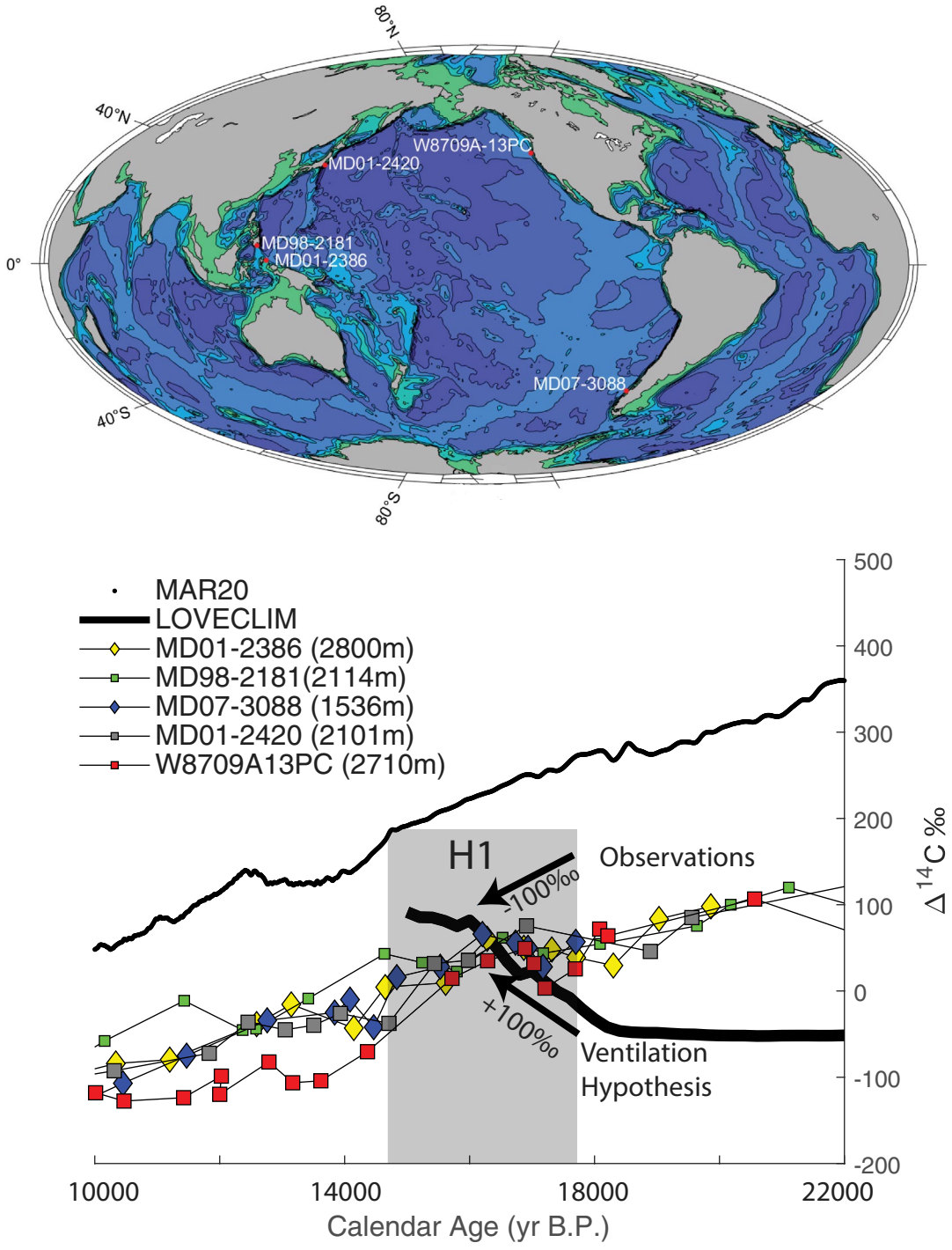

Figure 4. Upper Panel, Deep Pacific core locations. Lower Panel Benthic $\Delta^{14}C$ from the deep Pacific cores. Lower Panel, MARINE20 (global surface ocean) $\Delta^{14}C$ (Heaton et al., 2020). The solid black line is the simulated deep Pacific (130 E–130 W, 0–50 N, and 2,000–3,000 m) $\Delta^{14}C$ response to enhanced ventilation during the deglaciation using LOVCLIM (Menviel et al., 2018). Core MD98-2181 data is from this study. Raw 14°C ages from Core MD01-2386 (W. Broecker et al., 2008); MD07-3088 (Siani et al., 2013); MD01-2420 (Okazaki et al., 2012); and W8709A-13PC (Lund, 2013).

Data Availability Statement

The archiving of stable isotope and ^{14}C age data from MD98-2181 is underway and will be uploaded to the NOAA National Centers for Environmental Research (https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets). Previously published ^{14}C ages are available for Core MD01-2386 (W. Broecker et al., 2008); MD07-3088 (Siani et al., 2013); MD01-2420 (Okazaki et al., 2012); W8709A-13PC (Lund, 2013).

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