Shortcomings of the isolated abyssal reservoir model for deglacial radiocarbon changes in the mid-depth Indo-Pacific Ocean

Mathis P. Hain,[1,2] Daniel M. Sigman,[1] and Gerald H. Haug[2,3]

Received 11 November 2010; revised 17 December 2010; accepted 3 January 2011; published 17 February 2011.

[1] Severely negative $\Delta^{14}C$ anomalies from the mid-depth Pacific and the Arabian Sea have been taken as support for the hypothesized deglacial release of a previously isolated, extremely ^{14}C-deplete deep ocean carbon reservoir. We report box model simulations that cast doubt on both the existence of the hypothesized deep reservoir and its ability to explain the mid-depth $\Delta^{14}C$ anomalies. First, the degree of ice age isolation needed to substantially reduce the deep $\Delta^{14}C$ of the deep reservoir causes anoxia and the trapping of alkalinity from $CaCO_3$ dissolution, the latter increasing atmospheric CO_2. Second, even with a completely ^{14}C-free deep reservoir, achieving the mid-depth $\Delta^{14}C$ anomalies of observed duration requires *ad hoc* stifling of aspects of deep circulation to prevent rapid dissipation of the anomalous ^{14}C-free carbon to the rest of the ocean and the atmosphere. We suggest that the mid-depth anomalies do not record basin-scale $\Delta^{14}C$ changes but are instead local phenomena. **Citation:** Hain, M. P., D. M. Sigman, and G. H. Haug (2011), Shortcomings of the isolated abyssal reservoir model for deglacial radiocarbon changes in the mid-depth Indo-Pacific Ocean, *Geophys. Res. Lett.*, *38*, L04604, doi:10.1029/2010GL046158.

1. Introduction

[2] At the termination of the last ice age, climate and ocean circulation changed, atmospheric CO_2 increased rapidly, and atmospheric $\Delta^{14}C$ ($\Delta^{14}C_{atm}$) declined by about 190‰ [e.g., *Reimer et al.*, 2009], leading to the term "Mystery Interval" for the period between 17.5 and 14.5 ka [*Denton et al.*, 2006]. No important changes in cosmogenic ^{14}C-production have been reconstructed for the Mystery Interval [e.g., *Muscheler et al.*, 2004; *Laj et al.*, 2002]. The decline of $\Delta^{14}C_{atm}$ has been hypothesized to result from the deglacial release of dissolved inorganic carbon from an ice age abyssal water mass that had lost most of its initial ^{14}C due to isolation for 4.5 kyr or longer [e.g., *Broecker and Barker*, 2007]. Below, we refer to this hypothesized abyssal water as the "Mystery Reservoir".

[3] In apparent support of this hypothesis, severely negative $\Delta^{14}C$ deglacial excursions have been observed at two mid-depth eastern Pacific sites [*Marchitto et al.*, 2007; *Stott et al.*, 2009] and in the mid-depth Arabian Sea [*Bryan et al.*, 2010]. It was proposed that shifting Southern hemisphere westerly winds upwelled the Mystery Reservoir in the Southern Ocean and subducted its isotopic signature into mid-depth Pacific waters via Antarctic Intermediate Water (AAIW) [*Marchitto et al.*, 2007; *Skinner et al.*, 2010; *Bryan et al.*, 2010]. However, objections have been raised based on the absence of such ^{14}C anomalies in the South Pacific along this AAIW pathway [*De Pol-Holz et al.*, 2010; *Rose et al.*, 2010].

[4] The Mystery Reservoir itself has never been identified [e.g., *Broecker and Clark*, 2010] and even the ~3800 year old deep Southern Ocean water reconstructed by *Skinner et al.* [2010] had a $\Delta^{14}C$ of about −120‰; this is less negative than any of the mid-depth anomalies. Moreover, the implications of the hypothesized Mystery Reservoir, for ^{14}C and other ocean properties, have not yet been explicitly simulated.

[5] Herein, we evaluate (a) the feasibility of a ^{14}C-deplete reservoir with regard to ice age observations and (b) its capacity to explain the mid-depth $\Delta^{14}C$ minima after 17.5 ka. We argue that the existence of an extremely isolated water mass in the ice age ocean, as required by the "Mystery Reservoir" hypothesis, conflicts with important constraints such as deep ocean oxygen status, $CaCO_3$ lysocline depth and atmospheric CO_2. Importantly, the prevailing assumption equating the Mystery Reservoir with the ocean's sequestration of CO_2 during glacial times is likely contradicted by the sequestration of alkalinity from $CaCO_3$ raining into the abyss. With regard to the deglacial mid-depth observations, within centuries, ocean overturning, mixing, and gas exchange dissipate the anomalous ^{14}C-deplete carbon throughout the ocean and atmosphere, reducing both the amplitude and the duration of simulated $\Delta^{14}C$ anomalies. Thus, it seems unlikely that the observed anomalies [*Marchitto et al.*, 2007; *Stott et al.*, 2009; *Bryan et al.*, 2010] reflect basin-scale $\Delta^{14}C$ changes.

2. Methods

[6] We employ a modified version of CYCLOPS [*Keir*, 1988], an 18-box geochemical ocean/atmosphere model coupled to a 1900 Pg terrestrial carbon reservoir. To initialize the new experiments presented here, we use a Last Glacial Maximum (LGM) scenario from *Hain et al.* [2010] including intermediate water (i.e., GNAIW), rather then deep water (i.e., NADW), formation in the North Atlantic. This scenario amounts to the simulation of a hypothesis for reaching ice age CO_2 levels [e.g., *Sigman et al.*, 2010]. Pertinent model information and details on the isolation experiments (Figures 1 and S1a) and the idealized deglacial experiments (Ex1 to Ex6 in Figures 2 and S1b) are provided in the auxiliary material.[1]

[1]Department of Geosciences, Princeton University, Princeton, New Jersey, USA.
[2]DFG-Leibniz Center for Surface Process and Climate Studies, Potsdam University, Potsdam, Germany.
[3]Geological Institute, Department of Earth Sciences, ETH Zürich, Zürich, Switzerland.

0094-8276/11/2010GL046158

[1]Auxiliary materials are available in the HTML. doi:10.1029/2010GL046158.

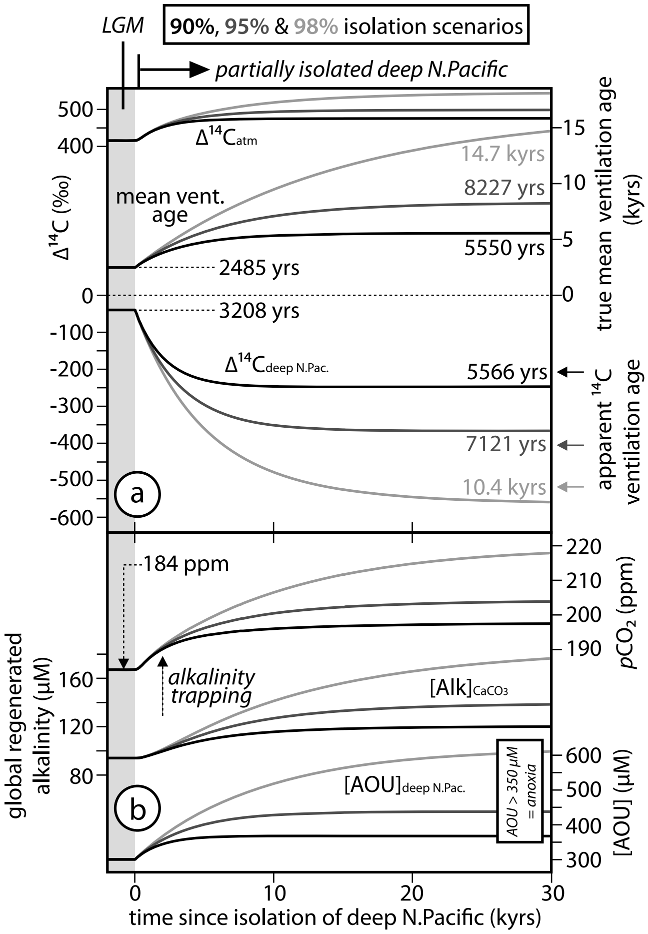

Figure 1. North Pacific isolation experiments. The model is initialized with LGM conditions [*Hain et al.*, 2010], then deep/intermediate mixing in the North Pacific is turned off and exchange between deep North and South Pacific is reduced by 90, 95 and 98% from the initial 24 Sv. (a) $\Delta^{14}C$ of the atmosphere and the deep North Pacific, which is used to calculate apparent ^{14}C ventilation ages after 30 kyrs. These apparent ^{14}C ventilation ages are compared with an ideal ventilation age tracer. (b) Atmospheric pCO_2 rise in the simulations is dominated by trapping of regenerated alkalinity from $CaCO_3$ dissolution. Trapping of respired carbon in the isolated North Pacific causes anoxia (shown at the bottom as apparent oxygen utilization, AOU).

[7] While a thin abyssal layer is the most plausible configuration for the proposed isolated reservoir, we instead isolate the deep North Pacific (Figure 1). This choice discourages but does not succeed in preventing anoxia because it minimizes the biogenic particle rain to volume ratio of the reservoir (and thus oxygen demand and alkalinity sequestration per volume).

[8] All experiments are conducted at 130% of modern ^{14}C production rates. The value of 130% production is close to reconstructions [*Muscheler et al.*, 2004; *Laj et al.*, 2002] and results in an absolute ^{14}C inventory roughly appropriate for the latest LGM (i.e., less negative deep ocean $\Delta^{14}C$ than in the Holocene [e.g., *Galbraith et al.*, 2007; *Skinner et al.*, 2010]).

[9] The calculation of $\Delta^{14}C$ is versus the pre-bomb atmosphere and includes the standard normalization for isotope fractionation. $\Delta\Delta^{14}C_x$ is the difference in $\Delta^{14}C$ between reservoir "x" and the atmosphere. The "true" mean ventilation age is derived from an ideal age. The "dye tracer", measuring water dissipation, is set to 100% in a given deep box (where we also impose the ^{14}C-free carbon) and 0% elsewhere and then circulated freely. We use this tracer to measure the dissipation of the imposed ^{14}C-free carbon by water transport alone (i.e., excluding gas exchange).

3. Results

3.1. Isolation Problems

[10] ^{14}C ventilation ages are a successful tool for studying modern ocean ventilation because overturning of the modern ocean is rapid relative to the ^{14}C half-life. This is not the case for the hypothesized Mystery Reservoir. In the three ice age deep North Pacific isolation experiments (Figure 1), the apparent ^{14}C age of the deep North Pacific increases from 3208 years to 5566, 7121 and 10400 years, respectively. The true mean ventilation age of the isolated box, however, increases from 2485 years to 5550, 8227 and >14700 years (Figure 1a). This systematic underestimation of true ventilation age is caused by non-conservative mixing of ^{14}C ventilation ages, which becomes most severe when the age differences among the mixing water parcels are large. The net result of this non-linear behavior is that, when hypothesizing a highly ^{14}C-deplete Mystery Reservoir, one is essentially invoking a water mass age much greater than suggested by the ^{14}C ventilation age.

[11] In our experiments, deep North Pacific isolation causes atmospheric CO_2 to rise, violating ice age observations. $CaCO_3$ rain into the isolated reservoir sequesters alkalinity in regenerated form (Figure 1b) and increases the carbonate ion concentration, promoting sea-floor burial of $CaCO_3$. These two processes, a strengthening of the carbonate pump and a whole ocean alkalinity decrease, deplete the ocean's inventory of preformed alkalinity and thus raise atmospheric CO_2 [*Hain et al.*, 2010]. The efficiency of the soft-tissue component of the biological pump [e.g., *Ito and Follows*, 2005] is approximately neutral in these experiments and does not contribute to simulated CO_2 change. The respiration of sinking organic matter rapidly consumes all oxygen in the isolated reservoir (Figure 1b; anoxia ensues at AOU > ~350 μM). For a given reservoir volume, the amplitude of these effects scales with the area of abyssal sea floor bathed in the isolated water mass, so that a thin but areally extensive stagnant bottom layer, as envisioned by *Broecker et al.* [2008], seems even less feasible than the isolation of the deep North Pacific that we simulate.

3.2. Dissipation Problems

[12] Negative $\Delta^{14}C$ anomalies have been observed in mid-depth sites near Baja California [*Marchitto et al.*, 2007], Galapagos [*Stott et al.*, 2009] and Oman [*Bryan et al.*, 2010]. We use these observations to define the "target" of our deglacial experiments as: (1) mid-depth $\Delta^{14}C$ more negative than −200‰, and (2) an anomalous ≥400‰ difference between atmospheric $\Delta^{14}C$ and mid-depth $\Delta^{14}C$ persisting for a ~2000 year period (grey bars in Figure 2).

[13] In the first deglacial experiment, Ex1 in Figure 2, we simply switch from full LGM to interglacial conditions to establish the model's baseline response, before we impose a

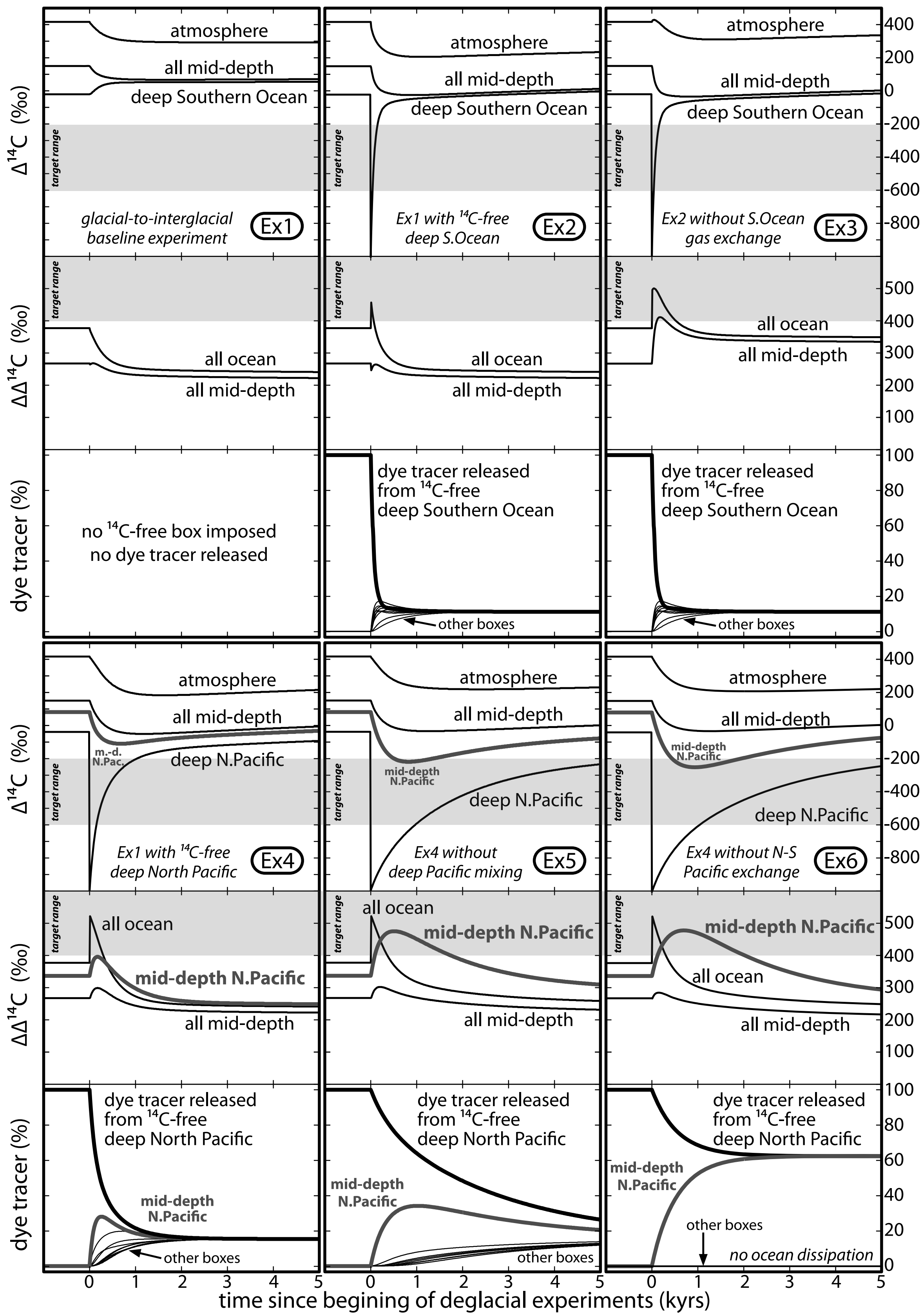

Figure 2. Idealized deglacial experiments, Ex1 to Ex6. Underlying all experiments is an instantaneous switch from LGM to interglacial conditions. Ex2 to Ex6 include an imposed ^{14}C-free deep Southern Ocean or deep North Pacific. For more details on the experiments see also the auxiliary material. (top) Δ^{14}C of selected reservoirs. (middle) Difference between atmospheric Δ^{14}C and the Δ^{14}C of selected reservoirs (i.e., $\Delta\Delta^{14}$C). (bottom) Distribution of passive dye tracer in all ocean interior boxes; pertinent boxes are identified.

^{14}C-free deep reservoir in the subsequent experiments. In Ex1, the destratification of the Antarctic and the resumption of NADW-formation accelerate the ventilation of the deep ocean, which leads to a repartitioning of ^{14}C from the atmosphere, surface ocean and mid-depth ocean (declining $\Delta^{14}C$) into the deep ocean (rising $\Delta^{14}C$). Furthermore, upon the switch to the interglacial circulation scheme, 21.5 Sv of deep Southern Ocean water is brought to the Southern Ocean surface and then advected into the mid-depth boxes of the adjacent basins (i.e., by Ekman overturning), which leads to a convergence of deep Southern Ocean and mid-depth $\Delta^{14}C$. This Southern Ocean pathway has been called upon to transfer the Mystery Reservoir carbon to the mid-depth Indo-Pacific [e.g., *Marchitto et al.*, 2007; *Bryan et al.*, 2010]. However, in Ex1, there is no such Mystery Reservoir: the deep Southern Ocean box LGM $\Delta^{14}C$ is −23‰, which is higher than some recent observations (e.g., −120‰ [*Skinner et al.*, 2010]), but only modestly. Without a Mystery Reservoir, neither the mid-depth $\Delta^{14}C$ deglacial decrease nor the mid-depth/atmosphere $\Delta^{14}C$ decoupling target can be achieved.

[14] In Ex2, we impose a ^{14}C-free deep Southern Ocean upon deglaciation (−1000‰; Figure 2). Even with the release of this imposed Mystery Reservoir, mid-depth $\Delta^{14}C$ still does not decline below −200‰, nor is mid-depth $\Delta^{14}C$ decoupled from the atmosphere. There are two main reasons for this model behavior. First, Southern Ocean upwelling allows the ^{14}C-free carbon to be transferred directly to the atmosphere, causing $\Delta^{14}C_{atm}$ to decline more steeply than in Ex1. Second, ocean circulation rapidly "mixes away" the ^{14}C-free carbon, dissipating its $\Delta^{14}C$ signature throughout the ocean within about 1000 years (see dye tracer in Figure 2).

[15] In Ex3, we repeat Ex2 but do not allow for air-sea gas-exchange in the Southern Ocean during deglaciation, so as to prevent direct transfer of the ^{14}C-free carbon to the atmosphere. The restricted gas-exchange reduces and retards the decline of $\Delta^{14}C_{atm}$, while the $\Delta^{14}C$ of the ocean interior boxes is not qualitatively affected, in disagreement with the expectation of *Rose et al.* [2010]. The slower and weaker decline in $\Delta^{14}C_{atm}$ causes a transient deglacial maximum in the atmosphere/mid-depth $\Delta^{14}C$ difference and leads to a large increase in the steady state difference ($\Delta\Delta^{14}C$ in Ex3, Figure 2). Nonetheless, neither of the two mid-depth targets (i.e., (1) $\Delta^{14}C_{mid\text{-}depth} <-200$‰; (2) $\Delta\Delta^{14}C_{mid\text{-}depth} >400$‰ for ~2000 years) is achieved because the anomalous ^{14}C-free carbon is mixed throughout the ocean within ~1000 years (dye tracer in Figure 2).

[16] Ex4 to Ex6 are radically biased so as to (a) prevent the rapid global dissipation of the Mystery Reservoir, and (b) focus the release of the anomalous ^{14}C-free carbon from the deep North Pacific to the mid-depth North Pacific so as to simulate the Baja, California observations [*Marchitto et al.*, 2007].

[17] In Ex4, the same idealized deglacial experiment as in Ex1 is coupled with an imposed ^{14}C-free deep North Pacific. Although the mid-depth North Pacific box is directly above the imposed ^{14}C-free reservoir, its $\Delta^{14}C$ does not decline into the observational target range. Further, the decoupling of mid-depth and atmosphere $\Delta^{14}C$ lasts for only a few centuries without reaching the observed magnitude. Again the ocean dissipation of the ^{14}C-free carbon is the culprit: within 1000 years, about two thirds of the dye tracer have already been "mixed away" into the global ocean, mainly through the exchange among deep ocean boxes.

[18] In Ex5, we repeat Ex4 but do not allow for any exchange between the deep North and South Pacific. In this extreme scenario, all ^{14}C-free carbon has to exit the deep North Pacific (15.3% of model ocean volume) through the mid-depth North Pacific (8% of model ocean volume) (Figure S1b). Under these conditions, the observations of *Marchitto et al.* [2007] are satisfied: mid-depth North Pacific $\Delta^{14}C$ rapidly declines to −200‰, and $\Delta\Delta^{14}C$ surpasses 400‰ for almost 2000 years (Ex5 in Figure 2). After 2000 years, about half of the dye tracer still resides in the North Pacific, illustrating the reason for the successful simulation of the anomaly observed off Baja California. However, for the same reason, the simulated ^{14}C anomaly is confined to the North Pacific, counter to observations [*Stott et al.*, 2009; *Bryan et al.*, 2010]. The much greater amplitude of the anomaly observed at Galapagos [*Stott et al.*, 2009] remains unexplained.

[19] In Ex6, we completely isolate the North Pacific from the rest of the ocean (no water exchange; Figure S1b). The exchange between the mid-depth and surface North Pacific is also doubled (to 6 Sv) to yield vertical ventilation of the mid-depth box on a centennial time-scale ($V_{mid\text{-}depth}$/6 Sv = 570 years versus a combined lateral and vertical renewal time of 428 years in the interglacial control) even in the absence of lateral ventilation from the isopycnal outcrop regions. In this case, the ^{14}C-free carbon is dissipated exclusively through the atmosphere rather than by ocean circulation (see the dye tracer). We find only minimal differences in $\Delta^{14}C$ and $\Delta\Delta^{14}C$ between Ex5 and Ex6. Thus, exchange with the atmosphere is also a potent pathway for the global dissipation of the hypothesized ^{14}C-deplete carbon. Upon escaping to the atmosphere, most of this carbon is reabsorbed in other regions and then circulated through the global ocean.

4. Discussion and Conclusion

[20] In this study, we critically assess the hypothesis that the deglacial release of a ^{14}C-deplete deep ocean reservoir caused severely negative deglacial $\Delta^{14}C$ anomalies in the shells of benthic foraminifera observed in parts of the mid-depth Pacific [*Marchitto et al.*, 2007; *Stott et al.*, 2009] and the Indian Ocean [*Bryan et al.*, 2010]. Our simulations render unlikely the existence of such a ^{14}C-deplete ice age "Mystery Reservoir". Even if such a reservoir did exist and was released upon deglaciation, the negative $\Delta^{14}C$ anomalies found in mid-depth Indo-Pacific are difficult to maintain over millennial time-scales in the face of ocean circulation and gas-exchange acting to disperse the "old" carbon signature.

[21] The difficulties of an extremely isolated deep reservoir during the ice age can be illustrated with a simple calculation. Taking the thickness of the previously envisioned stagnant ^{14}C-deplete bottom layer to be 1000 m, sinking fluxes of 100 and 150 mmol/m^2/a organic carbon and $CaCO_3$ [e.g., *Berelson*, 2001, and references therein; *Berelson et al.*, 2007; *Klaas and Archer*, 2002] would raise the carbonate ion concentration and decrease dissolved oxygen by ~0.03 μM and 0.15 μM per year, respectively, unless the reservoir is free floating and not in contact with the seafloor. Hence, a completely stagnant bottom layer

would turn anoxic and reach $CaCO_3$ saturation in less than 2500 years if all biogenic rain is respired or dissolved.

[22] Neither regional anoxia nor abyssal $CaCO_3$ preservation are observed in the ice age deep ocean [e.g., *Jaccard et al.*, 2009; *Catubig et al.*, 1998]. In addition, the sequestration of alkalinity in regenerated form and enhanced burial of $CaCO_3$ would tend to elevate atmospheric CO_2, interfering substantially with the goal of simulating an ice age atmospheric CO_2 concentration as low as ~180 ppm [*Hain et al.*, 2010]. This alkalinity argument can be alleviated if the reservoir was situated at the bottom of the low-$CaCO_3$ Southern Ocean, but the anoxia problem remains.

[23] In addition to the above problems with an ice age Mystery Reservoir, our deglacial experiments (Figure 2) highlight ocean and atmosphere dissipation as the principle dynamics that make it difficult to produce and maintain upper ocean $\Delta^{14}C$ anomalies even if a sizable ^{14}C-free reservoir is being released: anomalously ^{14}C-deplete carbon released upon deglaciation would simply be dissipated throughout the entire ocean on a timescale much shorter than the observed anomalies (Ex2, Ex3 and Ex4 in Figure 2). Southern Ocean gas-exchange can modulate the $\Delta^{14}C$ of the small atmosphere carbon inventory but does not significantly alter the $\Delta^{14}C$ of the ocean interior [cf. *Rose et al.*, 2010] (Ex2 and Ex3). The only experiments (Ex5 and Ex6) that achieve the duration of *Marchitto et al.*'s [2007] anomaly essentially isolate the anomalous carbon from the global overturning circulation, in this way slowing down its dissipation. Clearly, the drive toward dissipation is much greater in the case of the hypothesis that the low-^{14}C signal is communicated to the mid-depths through Southern Ocean Ekman overturning [e.g., *Marchitto et al.*, 2007; *Bryan et al.*, 2010]. Once upwelled to the Antarctic surface, the anomalous ^{14}C-deplete carbon is not solely funneled into newly formed AAIW; it is also mixed into Antarctic Bottom Water and Subantarctic Mode Water, and it escapes into the atmosphere. Even without these mechanisms for dissipation of the low $\Delta^{14}C$ signal during the transformation of deep Southern Ocean water into AAIW, the net new formation of AAIW in the Polar Frontal Zone of the Southern Ocean (>25 Sv = 7.9×10^{14} m^3/a [e.g., *Downes et al.*, 2009]) replaces the standing volume of AAIW (roughly 15% of the ocean volume = 2×10^{17} m^3) every ~250 years. Given that the entire ocean would have cycled through the mid-depth ocean over the course of the Mystery Interval, rapid dissipation of the ^{14}C-deplete carbon is unavoidable. This argument is only strengthened when one considers that the geostrophic circulation brings mid-depth waters into contact with the atmosphere on the time-scale of decades to centuries [e.g., *Fine et al.*, 2001].

[24] One aspect of our idealized deglacial simulations that we have not touched on so far is the surprisingly short response time of $\Delta^{14}C_{atm}$: even in the experiments where we have greatly impeded the dissipation of the anomalous ^{14}C-free carbon, $\Delta^{14}C_{atm}$ fully adjusts to perturbations within 1000 years. We argue that the $\Delta^{14}C$ of the small carbon reservoir of the atmosphere plus terrestrial biosphere (~3000 Pg C) is tightly locked to the carbon inventory of the upper ocean by rapid ventilation (i.e., within decades) and a gross annual air-sea carbon flux of >70 Pg C. Due to the short residence time of carbon in the atmosphere (3000 Pg C / 70 Pg C a^{-1} ~43 years), the isotopic signature of anomalously ^{14}C-deplete carbon entrained into the mid-depth ocean must rapidly propagate into the atmosphere. In contrast, the observations indicate a relatively gradual decline in $\Delta^{14}C_{atm}$ through the Mystery Interval [e.g., *Reimer et al.*, 2009], which our model suggests is yet another point of inconsistency with the hypothesis of deglacial release of a ^{14}C-deplete Mystery Reservoir.

[25] **Acknowledgments.** The authors thank J. Adkins, T. Marchitto, P. Köhler and E. Bard for discussions. Two anonymous reviewers improved the manuscript. Support was provided by the US NSF, the German DFG, the Humboldt and MacArthur Foundations, the Siebel Energy Grand Challenge at Princeton, and O. Happel.

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M. P. Hain and D. M. Sigman, Department of Geosciences, Princeton University, Guyot Hall, Princeton, NJ 08544, USA. (mhain@princeton.edu)

G. H. Haug, Geological Institute, Department of Earth Sciences, ETH Zürich, CH-8092 Zürich, Switzerland.