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Increased Ventilation of the Northern Indian Ocean during the Last Deglaciation

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ABSTRACT

This paper gives an overview of the deep-water ventilation studies carried out over the world oceans using radiocarbon. There is a consensus that aged water mass existing in the abyssal ocean during the last glacial, dissipated during the Heinrich Stadial 1 (HS1; 17.5-14.7 ka) and the Younger Dryas (YD; 12.9-11.7 Ka, cold event) and hence ventilation increased. The data from the Arabian Sea is in agreement with global records and shows a significant aging of intermediate waters during HS1 and to a lesser extent during the YD and also shows an outgassing of CO_2 centered on the early Bølling Allerød (B-A). Though several studies have been carried out in the Atlantic and Pacific, the Indian Ocean remains scantily studied. Hence it is extremely important to have sufficient data on the ventilation aspect from specific locations in the Indian Ocean chosen to be in the pathway of the deep water circulation branch directing southern sourced waters up north.

INTRODUCTION

Atmospheric CO_2 concentrations are known to be regulated by the oceans, as the ocean can act as a source or sink for CO_2 through its physical and biological pump (Sundquist and Broecker, 1985). The oceans soak up almost one third of CO_2 released into the atmosphere as a result of human activities (Sabine et al., 2004). The present day atmospheric CO_2 concentrations have risen to > 400 ppm as a result of anthropogenic activities since the industrial era. This rise has been steep, from 280 ppm before the beginning of the industrial era to the present, over a short span of 200 years and has led to an ocean storage of ~120 Pg C (Sabine and Tanhuat, 2010). As is well documented, high CO_2 levels in the atmosphere leads to 'global warming' along with changes in ocean water temperature, ocean acidification and deoxygenation.

For the last 800,000 years, the glacial-interglacial CO_2 variations have been within bounds of 180 to 280 ppm (Lüthi et al., 2008). There was an increase in atmospheric CO_2 from glacial to interglacial, but was not gradual throughout. Especially, during the last deglaciation (~ 17.5 – 10 ka) there was a two-step jump in atmospheric CO_2 (Fig. 1a). This has been thought to be facilitated by a large release of CO_2 stored deep in the ocean during glacial times (Broecker and Barker, 2007). This process of CO_2 release is supposed to have mainly occurred through enhanced upwelling of deep waters in the Southern Ocean and subsequent incorporation of these ^{14}C-depleted waters into the thermocline and intermediate water masses (especially the Antarctic Intermediate Water; AAIW) which spread northward into the Pacific, Indian and Atlantic Ocean basins (Skinner et al., 2010). Skinner et al. (2010) showed that deep waters of the Southern Atlantic which were thought to be ^{14}C depleted during the glacial, upwelled into intermediate waters, thus decreasing the ^{14}C of intermediate waters (Fig. 1a and 2). Similar results were reported at many locations throughout the world oceans and therefore this mechanism has come to be widely accepted.

Many studies have shown that during the last glacial there was an aged water mass that existed in the abyssal ocean which dissipated during the Heinrich Stadial 1 (HS1; 17.5-14.7 ka) and the Younger Dryas (YD; 12.9-11.7 ka, cold event) (eg. Marchitto et al., 2007; Skinner et al., 2010). During the HS1/YD, the Southern Ocean warmed as a result of the 'bipolar seesaw'. This led the Antarctic sea ice to reduce significantly from its large extent during the glacial times and deep water masses (Antarctic Bottom Water; AABW) were drawn upward and mixed into the Circumpolar Deep Water (CDW) through which the ^{14}C depleted CO_2 was eventually released to the atmosphere at the sea surface (Skinner et al., 2010). Hence it is observed that lower ^{14}C (Fig. 1b), greater ventilation ages (Fig. 1a) and larger B-P (Benthic – Planktic) offsets in many sediment cores at intermediate water depths (see Table 1). During the Bølling Allerød (B-A; 14.7-13 ka, a warm climatic stage in the North Atlantic, coinciding with the Antarctic Cold Reversal; ACR, a cold stage) the Southern Ocean cooled as a result of the bipolar seesaw and the sea ice extent increased (Skinner et al., 2010). Mixing of AABW into the CDW ceased, which is seen in higher ^{14}C of intermediate waters, decrease in ventilation age and smaller B-P offsets (Skinner et al., 2010). Thus, ocean

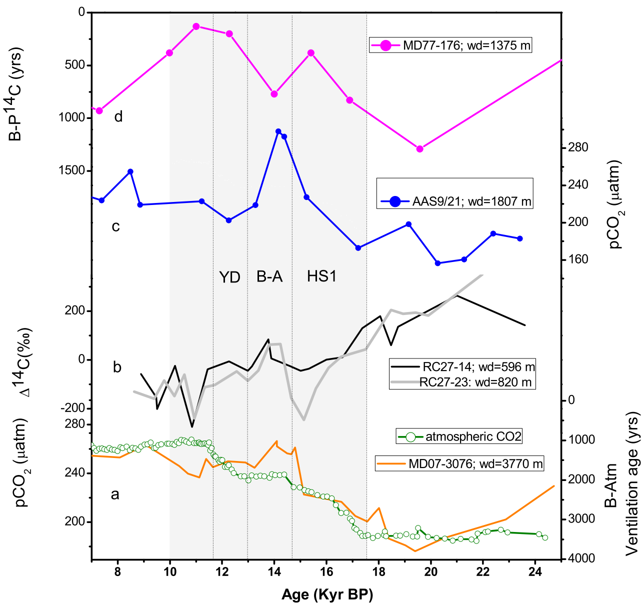

Fig.1. (a) B-Atmosphere ventilation age from the Southern Ocean (Skinner et al., 2010) plotted along with atmospheric CO_2 concentrations (Monnin et al., 2001, Lemieux-Dudon et al., 2010, Schmitt et al., 2012), **(b)** $\Delta^{14}C$ from sediment cores of the western Arabian Sea (Bryan et al., 2010), **(c)** pCO_2 from the eastern Arabian Sea (Naik et al., 2015) and **(d)** Benthic-Planktic ^{14}C age from the Bay of Bengal (Ma et al., 2019). The grey shaded area marks the entire deglacial period. The dotted lines mark the Heinrich Stadial 1, HS1; Bølling Allerød, B-A and the Younger Dryas, YD.

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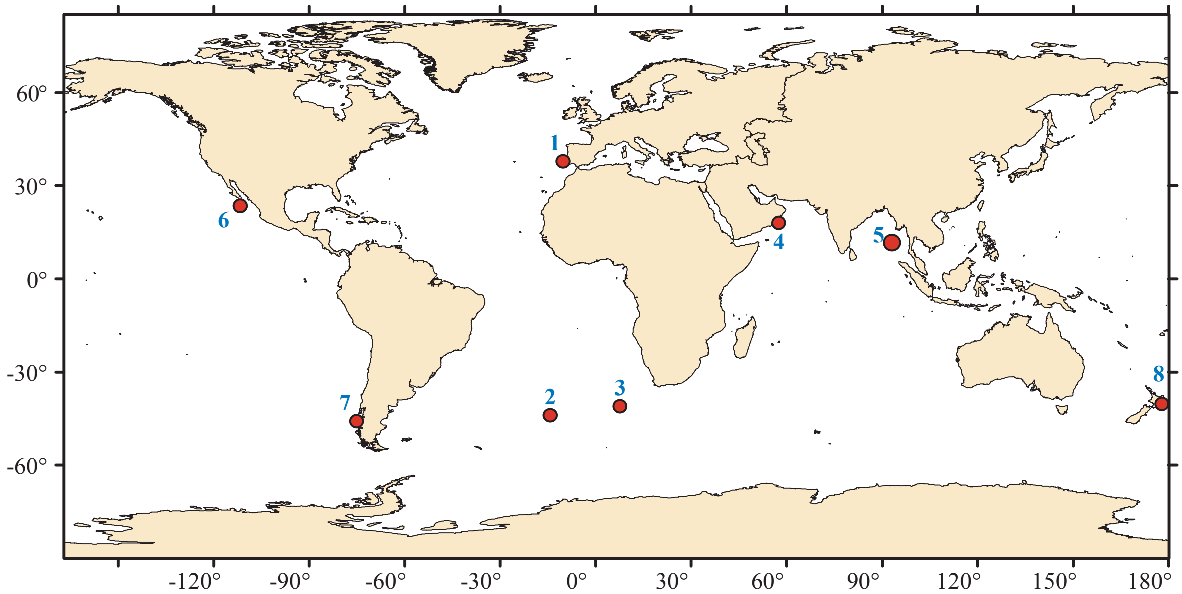

Fig. 2. Map showing the location of sediment cores in all the major oceans used in understanding ventilation changes and discussed in the text. (1) Skinner and Shackleton, 2004, (2) Skinner et al., 2010, (3) Barker et al., 2010, (4) Bryan et al., 2010, (5) Ma et al., 2019, (6) Marchitto et al., 2007, (7) Siani et al., 2013, and (8) Skinner et al., 2015.

circulation can be seen to drive climate variability at timescales ranging from seasonal to glacial–interglacial.

Against the above background, in this paper we have attempted a comparative study of the ventilation history of the deep water masses in two segments of the northern Indian Ocean, the Arabian Sea constituting the western segment and the Bay of Bengal forming the eastern arm. The choice of the study area was dictated by three factors: (a) the northern Indian Ocean is in the pathway of the deep water circulation branch of the global circulation system which directs the southern-sourced waters northwards; (b) the paucity of observations on the deglacial ventilation history of the Indian Ocean compared to such studies in the Atlantic and the Pacific Oceans; and (c) the availability of radiocarbon data from the sediment cores in the Arabian Sea and the Bay of Bengal.

Datasets

Existing data from sediment cores from the two basins of the northern Indian Oceans, viz, $\Delta^{14}C$ data from the Arabian Sea (RC27-14 and RC27-23 from a water depth of 596 and 820 m respectively; Bryan et al., 2010) and benthic-planktic ^{14}C from the Bay of Bengal (MD77-176 from a water depth of 1375 m; Ma et al., 2019) both covering the last 25 kyr is used. Both the data sets from the Indian Ocean sectors will give an idea on the changes in ventilation of the respective water masses through time. For comparison, published results of similar studies carried out elsewhere in the Atlantic and the Pacific is used (Fig.2 and Table 1).

DISCUSSION

As mentioned earlier, several studies have been carried out on unravelling the last deglacial ventilation history of deep waters of the Atlantic and Pacific oceans (Fig.1, Murayama, 1992; Skinner and Shackelton, 2004; Marchitto et al., 2007; Barker et al., 2010; Basak et al., 2010; Skinner et al., 2010; Siani et al., 2013; Skinner et al., 2015). In contrast, similar studies in the Indian Ocean have been non-existent till a decade or so back, when Bryan et al., (2010) showed a significant aging of intermediate waters in the Arabian Sea during HS1 and, to a lesser extent, during the YD (Fig. 1b). The timing and magnitude of ^{14}C depletion in the Arabian Sea during HS1 is very similar to that previously observed in the eastern North Pacific near Baja California (Marchitto et al.,2007), indicating that similar mechanisms were involved in controlling $\Delta^{14}C$ (radiocarbon activity) at these two sites. The low $\Delta^{14}C$ intervals are coincident with increased atmospheric pCO_2 and decreased atmospheric $\Delta^{14}C$ suggesting the release of ^{14}C-depleted carbon from the deep ocean. Subsequently, there have been two more studies in the Arabian Sea which show outgassing of CO_2 during the deglaciation; both studies use boron isotopes from planktic foraminifera. Palmer et al. (2010) showed that p_{CO_2} of surface waters was highest during the 11-17 kyr period and linked it to the Asian monsoon. Naik et al. (2015) found an outgassing of CO_2 during the last deglaciation centered on the early B-A and thought it was related to increased monsoon upwelling of high CO_2 waters which were advected from elsewhere (Fig. 1c). These two studies point to the northern Indian Ocean as a location for CO_2 outgassing along with many other locations in the Atlantic and the Pacific. For example, the surface waters at sub-Antarctic Atlantic and the eastern equatorial Pacific, both, which partly derive from deep water upwelled in the

Table 1. Details of all cores shown in Fig.2 and discussed in text.

Sr. No.	Core	Location	Latitude	Longitude	Water Depth (m)	Reference
1	MD99-2334K	North Atlantic	37.80°N	10.17°W	3146	Skinner and Shackleton (2004)
2	MD07-3076 CQ	South Atlantic	44.07° S	14.21°W	3770	Skinner et al. (2010)
3	TNO57 -21	South Atlantic	41.1° S	7.8° E	4981	Barker et al. (2010)
4	RC27-23 RC27-14	Arabian Sea	18°N 18.3°N	57.6°E 57.6°E	820 596	Bryan et al. (2010)
5	MD77 176	Bay of Bengal	4.50°N	93.12°E	1375	Ma et al. (2019)
6	MV99-MC19/ GC31/ PC08	North Pacific	23.5°N	111.6°W	705	Marchitto et al. (2007)
7	MD07-3088	South Pacific	46° S	75° W	1536	Siani et al. (2013)
8	MD97-2121	South Pacific	40.38°S	177.99°E	2314	Skinner et al. (2015)

Southern Ocean became a significant source of carbon to the atmosphere during the last deglaciation (Martinez-Boti et al., 2015). A point to make here is that the timing of CO_2 degassing and the ventilation of deep oceans from different regions of the world oceans were nearly synchronous and happened during the last deglaciation. However the mechanism of how the outgassing occurred at the same time over distant locations is still a matter of debate.

In contrast to the Arabian Sea, the Bay of Bengal sediment core record shows decreased ventilation during the B-A relative to HS1 and the YD (Fig. 1d, Ma et al., 2019). This is an intriguing finding as the AS and BoB cores are from intermediate water depths and we could expect the same mechanism to operate in both these regions on either side of the Indian landmass, and more so since the AAIW (source of low ^{14}C) has been documented to penetrate into both these regions (Böning and Bard, 2009; Yu et al., 2018). Such a contrast has also been observed between the eastern and western Pacific (De Pol-Holz et al., 2010). A point to note here is that the study location of Ma et al. (2019), in the BoB is further to the north of the study location by Bryan et al. (2010) in the AS. With regard to the study location of Ma et al. (2019) in the northern BoB, it is possible that there was an increase in stratification which started during the Bølling-Allerød, consequent on a freshening of the BoB due to a strengthening phase of SW monsoon and resultant increased freshwater discharge from the Ganges-Brahmaputra river system (Govil and Naidu, 2011).

This increased stratification may not have allowed the sub-surface radiocarbon depleted/aged waters, derived from the Southern Ocean waters, to upwell to the surface, thus leading to a decrease in B-P ^{14}C yrs. This hypothesis is however, based on the interpretation from a one-off data point from a single sediment core and needs supporting evidence from more studies in the future.

CONCLUSIONS

In agreement with the global records of deep-water ventilation from radiocarbon studies, the lone Arabian Sea record shows aging of intermediate waters during HS1 and the YD. There is a paucity of well-constrained data from the pathway of the deep-water circulation branch which directs the southern-sourced waters northwards in the northern Indian Ocean. The focus should be on unravelling the mechanisms responsible for ventilation changes and whether these ventilation changes are timed and linked globally.

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