Global and Planetary Change 79 (2011) 204–213

Contents lists available at ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

Quantifying rates of change in ocean conditions with implications for timing of sea level change

S.J.A. Jung *, D. Kroon

School of GeoSciences, Grant Institute, The King's Buildings, University of Edinburgh, West Mains Road, Edinburgh EH9 3JW, United Kingdom

ARTICLE INFO

Article history:
Received 1 May 2010
Accepted 15 November 2010
Available online 26 November 2010

Keywords:
millennial-scale
bi-polar seesaw
AAIW
rate of change
sea level change

ABSTRACT

The importance of southern hemisphere driven climate change is increasingly recognized in paleoclimate research. This is in particular relevant with regard to the rate of climate change initiated in the southern hemisphere and the phasing thereof compared to climate variability elsewhere. Here, we use previously published benthic oxygen isotope data from two deep sea sediment cores from the deep N-Atlantic and the intermediate depth Indian Ocean to quantify rates of oceanic change at the millennial-scale. The oxygen isotope data represent an integrated signal of temperature and global sea level changes. At both locations the sea surface ocean records strongly resemble Greenland climate change. When used to synchronize these surface ocean records with the GISP2 ice core chronology we show that the highest rates of change in the benthic oxygen isotope records, occur during late marine isotope stage 5 (MIS 5), MIS 3 and the last deglaciation, whilst generally modest rates of change prevail during the full glacial conditions of MIS 2. The synchronous variation of oceanic rates of change and Antarctic climate history suggests that the benthic oxygen isotope records from the glacial deep N-Atlantic and the intermediate Indian Ocean reflect variations in southern sourced Antarctic Bottom Water (AABW) and Glacial Antarctic Intermediate Water (GAAIW) respectively. Millennial-scale temperature variations in GAAIW are larger than in AABW. The repeated rapid heat storage in GAAIW during northern hemisphere cold phases points to an important role of GAAIW, potentially acting as an energy buffer, maintaining the pole-to-pole climate imbalance as part of the bi-polar seesaw. Combining the benthic oxygen isotope records with independent sea level records shows a pulsed sea level rise history during the deglaciation with conservative estimates of peak rates change of about ~2 m/100 yr. Similar rates of sea level change occurred during most Heinrich Events.

1. Introduction

On geologic time-scales Earth's climate has frequently changed between glacial and interglacial conditions. At these time-scales, orbitally driven climate change reflects the response of Earth's climate to variations in solar insolation due to cyclic shifts in planetary constellation (Hays et al., 1976). This has led to a regular waxing and waning of continental ice sheets and variations in atmospheric and oceanic flow patterns on Earth. Whilst the externally driven nature of long-term climate change is widely accepted, the causes of the superimposed millennial-scale variability are intensely debated. These rapid variations in Earth's climate during, for example, the last glacial period—the so-called Dansgaard-Oeschger (DO) events—were first described in Greenland ice cores (Dansgaard et al., 1993). Subsequently, studies using different types of continental and marine climate archives demonstrated the global nature of this millennial-scale climate change variability (e.g. Hendy and Kennett, 2000; Stott et al., 2002; Ivanochko et al., 2005)). The underlying controls of this short-term climate change pattern are poorly understood. Proposed mechanisms encompass a variety of hypotheses, ranging from being externally driven to being the result from internal feedback mechanisms in Earth's climate system (e.g. MacAyeal, 1993; Ganopolski and Rahmstof, 2001)).

Adding to the complexity was the discovery of the so-called bi-polar seesaw, i.e. out of phase climate change between the poles (Blunier et al., 1998). Using synchronized chronologies for ice cores from Greenland and Antarctica, respectively, millennial-scale climate change between the hemispheres appears asynchronous (Blunier et al., 1998; Blunier and Brook, 2001). Sedimentary evidence supporting the bi-polar seesaw was reported from the deep Atlantic Ocean off Portugal (Shackleton et al., 2000). In this region, the surface ocean change varies in tune with Greenland climate change, whereas the deepwater variability resembles Antarctic climate change. Similar observations have been published for the Indian Ocean (Jung et al., 2009).

The origin for this asynchronicity in climate change is intensely debated. One likely mechanism involves an inter-hemispheric imbalance in heat storage (Stocker and Johnsen, 2003; Knutti et al., 2004).

* Corresponding author.
E-mail address: Simon.Jung@ed.ac.uk (S.J.A. Jung).

0921-8181/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.gloplacha.2010.11.004

Evidence for this notion has been reported from the South Atlantic Ocean (Barker et al., 2009). This supports the view that asynchronous heat storage is instrumental in offsetting northern and southern hemisphere climate change at the millennial time-scale. Given the potentially crucial role of the deep ocean in this climate change pattern a profound knowledge of the deepwater history of the different parts of the world ocean is important. Compared to the wealth of information on short-term climate change in the N-Atlantic region, little is known about millennial-scale climate change in the southern hemisphere. In this regard, variations in southern hemisphere derived water masses such as Antarctic Intermediate Water (AAIW) and Antarctic Bottom Water (AABW) are increasingly recognized as key components involved in millennial-scale change around the globe (Pahnke and Zahn, 2005; Jung et al., 2009). We use previously published stable isotope data from two sediment cores retrieved from the deep N-Atlantic (core MD95-2042; (Shackleton et al., 2000)) and intermediate depth Indian Ocean (core NIOP 905; (Jung et al., 2009)) to assess the history of southern sourced water masses in these ocean basins. Synchronizing local surface water and Greenland climate change records (using the GISP2 ice core chronology) will allow us to focus on two central aspects: a) quantification of the rates of change in deep sea conditions at the millennial-scale with implications for origin of deep and intermediate water and timing of sea level change as well as b) an assessment of Indian Ocean glacial AAIW (GAAIW) temperature variability and its role in heat storage at the millennial time-scale.

2. Methodology

2.1. Sediment core locations, hydrography and stable benthic oxygen isotope data

Sediment cores NIOP 905 (water depth 1586 m; 10°46.01N; 51°57.04E) and MD 95-2042 (water depth 3146 m, 37°48′N; 10°10′ W) were retrieved from the intermediate depth northwestern Arabian Sea and the deep Atlantic Ocean off Portugal, respectively.

Site NIOP 905 is currently bathed by Circumpolar Deepwater, originating from the Southern Ocean (Emery and Meincke, 1986). At shallower depth, water masses formed in the Persian Gulf and the Red Sea prevail. To date, intermediate water masses formed in the southern hemisphere (such as AAIW) are not present in the northern Arabian Sea (McCarthy and Talley, 1999). AAIW-formation in the modern ocean primarily occurs in the southeastern Pacific and the southwestern Atlantic Ocean (Sloyan and Rintoul, 2001) where it involves mixing of cold and fresh Antarctic surface waters with warm and salty subtropical gyre waters. In the southwest Indian Ocean, AAIW has been recently documented to be an integral part of the circulation in the Mozambique Channel with temperatures of 4–7 °C (De Ruijter et al., 2002).

Whilst locally formed Red Sea and Persian Gulf water prevails in the modern Arabian Sea, the glacially lowered sea level eliminated these local intermediate water sources. Hence, in the absence of intermediate water formation locally in the glacial northern Indian Ocean (for full discussion see (Jung et al., 2009)) the most likely explanation for our data involves a change in intermediate water formation in the southern hemisphere, such as an expansion of Glacial AAIW (GAAIW).

At the site of core MD95-2042 off Portugal, modified Antarctic Bottom Water (AABW) prevails in the modern ocean (van Aken, 2000). AABW formed off Antarctica is the coldest water mass in the deep ocean with temperatures <1 °C. Modern AABW temperatures at site MD95-2042 are slightly above 2 °C (van Aken, 2000). Previous studies have shown that AABW was significantly enhanced in the glacial N-Atlantic at the water depth of core MD95-2042 (e.g. (Sarnthein et al., 1994; Jung, 1996; Vidal et al., 1997)). This supports the view that the benthic isotope data used in this study indeed reflect change in AABW. Consequently, although being located well north of the equator, glacial sections of *both* cores used in this study predominantly document climate change originating off Antarctica.

The benthic oxygen isotope records are based on stable isotope analysis of the epibenthic foraminifera species *C. kullenbergi* (core NIOP 905; see (Jung et al., 2009) for details) and mixed benthics in core MD 95-2042 (Shackleton et al., 2000). Stable oxygen isotope variation in shells of foraminifers through geologic time is mainly controlled by the global ice volume effect (i.e. the amount of ice stored on the continents) and the temperature of the ambient seawater in which the foraminifer lived. A full quantitative assessment with regard to the interpretation of the benthic oxygen isotope data would also include potential variations in the oxygen isotope values and pH of the ambient seawater, both factors probably of minor importance. Here, we qualitatively assess benthic oxygen isotope data and, hence, only focus on the two major contributing factors.

2.2. Age control

For both cores, age models have been published previously (Shackleton et al., 2000; Ivanochko et al., 2005), showing that the respective surface ocean records were aligned with the oxygen isotope record from the Greenland ice core GISP 2 (Fig. 1, see also further below), following previously recognized relationships of surface ocean change in the respective region and Greenland climate change (Schulz et al., 1998; Shackleton et al., 2000; Ivanochko et al., 2005).

In this work we will use the (Shackleton et al., 2000) age model for core MD 95-2042 where the authors closely tied the surface ocean changes off Portugal to the Greenland ice core record GISP2, although in a later paper (Shackleton et al., 2004) advocated a revision of Greenland ice core chronology by adjusting it to an updated chronology of core MD95-2042. We could have adopted the new Greenland ice core and MD95-2042 chronologies, but to our knowledge, the discussion on the Greenland ice core chronology is ongoing (Andersen et al., 2006; Svensson et al., 2006, 2008). The main aim of this paper, however, is to assess rates and phasing of climate change in different parts of the world ocean. In this regard internally consistent chronologies are of paramount importance, rather than using the very latest age model. Hence, we have opted for age models that place all time-series in the same overarching temporal framework as previously published, i.e. the age models for cores MD95-2042 (Shackleton et al., 2000) and NIOP 905 (Ivanochko et al., 2005) both of which are tied to the same GISP2 chronology rather than the revised chronology of (Shackleton et al., 2004).

2.3. Assessing rates of change in the oxygen isotope records at the millennial-scale

In order to emphasize the signal at the millennial time-scale, both stable isotope records were filtered using a boxcar filter with a window of 700 yr. We aimed at improving the signal to noise ratio in the millennial time-scale band by applying such a short time window. This choice suppressed influence of high-frequency change. The main results of this study would not have been altered using a slightly different filter size.

The estimates of the rates of change in the benthic oxygen isotope records are based on calculating differences in oxygen isotope values between neighbouring samples divided by difference in age of the same samples (Figs. 2 and 3). The resulting numbers are reported on a change per ka basis. Due to the high temporal resolution in both time-series, the combination of a small change in oxygen isotope value with a small age difference (i.e. age differences ~<100 yr; in the denominator) tends to amplify resulting rate of change values, leading to noise in the records. With larger age differences this problem diminishes. In order to keep the focus on the millennial-scale changes,