Deep-Sea Research II 114 (2015) 39–48

Contents lists available at ScienceDirect

Deep-Sea Research II

journal homepage: www.elsevier.com/locate/dsr2

Southern Ocean forcing of the North Atlantic at multi-centennial time scales in the Kiel Climate Model

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ARTICLE INFO

Available online 30 January 2014

Keywords:
Climate variability
Deep convection
Meridional ocean circulation
Bi-polar ocean seesaw

ABSTRACT

Internal multi-centennial variability of open ocean deep convection in the Atlantic sector of the Southern Ocean impacts the strength of the Atlantic Meridional Overturning Circulation (AMOC) in the Kiel Climate Model. The northward extent of Antarctic Bottom Water (AABW) strongly depends on the state of Weddell Sea deep convection. The retreat of AABW results in an enhanced meridional density gradient that drives an increase in the strength and vertical extent of the North Atlantic Deep Water (NADW) cell. This shows, for instance, as a peak in AMOC strength at 30°N about a century after Weddell Sea deep convection has ceased. The stronger southward flow of NADW is compensated by an expansion of the North Atlantic subpolar gyre and an acceleration of the North Atlantic Current, indicating greater deep water formation. Contractions of the North Atlantic subpolar gyre enable warm water anomalies, which evolved in response to deep convection events in the Southern Ocean, to penetrate farther to the north, eventually weakening the AMOC and closing a quasi-centennial cycle.

Gyre contractions are accompanied by increases in sea level of up to 20 cm/century in some areas of the North Atlantic. In the Southern Ocean itself, the heat loss during the convective regime results in a sea surface height decrease on the order of 10 cm/century, with a maximum of 30 cm/century in the Weddell Sea. Hence, the impact of the Southern Ocean Centennial Variability (SOCV) on regional as well as North Atlantic sea level is of the same order of magnitude as the rise of global average sea level during the 20th century, which amounts to about 15–20 cm. This suggests that internal variability on a centennial time scale cannot be neglected a priori in assessments of 20th and 21st century AMOC and regional sea level change.

1. Introduction

A teleconnection between the Southern Ocean and the North Atlantic referred to as the bi-polar ocean seesaw, involving asynchronous changes in the two regions, has been documented in many previous papers which dealt with climate fluctuations during the last glacial period and the transition to the current interglacial (e.g., Broecker, 1998; Blunier et al., 1998; Stocker, 1998; Seidov et al., 2001; Swingedouw et al., 2009). The bi-polar ocean seesaw is an oscillating meridional overturning regime driven by two deep water sources: the North Atlantic Deep Water (NADW) in the north, and Antarctic Bottom Water (AABW) in the south. A decrease (increase) in AABW production caused by surface salinity variations results in a retreating (advancing) bottom water mass in the deep Atlantic thereby increasing (decreasing) southward export of NADW, which consequently intensifies (reduces) NADW formation and northward surface currents in the Atlantic (Seidov et al., 2001). The AABW retreat results in an overall density decrease, first within a couple of decades in the South Atlantic, then also in the North Atlantic. The anomalous meridional density gradient caused by this delay is the driver of the enhanced NADW export (Swingedouw et al., 2009). Broecker (2001) hypothesized that such thermohaline circulation oscillations may be responsible for the 1500 year cycles in ice-rafted debris in the northern North Atlantic, which has been found by Bond et al. (1997).

The bi-polar ocean seesaw and related ocean circulation changes may be either internally driven through stochastic forcing by the atmosphere, or externally by e.g. low-frequency changes in solar radiation or volcanic activity (e.g., Otterå et al., 2010). In particular, surface freshening by meltwater input from the continental ice sheets lowering sea surface salinity is thought to have been one important driver of the bi-polar ocean seesaw. In contrast, the study by Toggweiler and Samuels (1980) and modeling results from Goosse and Fichefet (1999) stressed the

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0967-0645/$ - see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.dsr2.2014.01.018

importance of increasing sea surface salinity, e.g. by brine rejection during sea ice formation, for Atlantic Meridional Overturning Circulation (AMOC) variability. The AMOC is a key element of the bi-polar ocean seesaw connecting the Northern and Southern Hemispheres. Seidov et al. (2001) by conducting a systematic set of ocean general circulation model experiments highlighted the role of Southern Ocean salinity anomalies in forcing the AMOC and found them much more influential than North Atlantic salinity anomalies. Here we also focus on the Southern Ocean influence on the AMOC, but concentrate on internal variability and investigate the link at centennial time scales.

The concept of the bi-polar ocean seesaw was also applied to multidecadal variability in the Atlantic during the instrumental period. The North Atlantic depicts pronounced basin-wide multidecadal sea surface temperature (SST) variability that is connected to the Southern Ocean SST and referred to as the Atlantic Multidecadal Oscillation or Variability (AMO/AMV). Folland et al. (1986), by investigating historical SST observations, were the first to identify the multidecadal dipolar SST anomaly pattern which is characterized by opposite changes in the North Atlantic and Southern Ocean. Climate models suggest that this pattern is potentially predictable at decadal time scales (e.g., Boer and Lambert, 2008). The existence of a twentieth century “bi-polar seesaw” of the Arctic and Antarctic surface air temperatures (SATs) has been postulated from observations by Chylek et al. (2010), but this was recently challenged by Schneider and Noone (2012) who investigated additional Antarctic stations. They did not find a robust correlation between Antarctic SAT and AMO/AMV. In many climate models, the decadal to centennial variations of the AMOC drive asynchronous SST changes in the North and South Atlantic (e.g., Latif et al., 2004; Knight et al., 2005; Park and Latif, 2008; Delworth and Zeng, 2012), while there is no robust pattern simulated in the high latitudes.

A centennial mode of open ocean deep convection in the Weddell Sea has been documented in two control integrations of the Kiel Climate Model (Martin et al., 2013). The flip-flop behavior of deep convection in one of the two integrations, which is further analyzed here, is clearly seen in both the Weddell Sea mixed layer depth (Fig. 1A) and Weddell Sea SST (Fig. 1B). The Weddell Sea deep convection is the major source of AABW in the Kiel Climate Model (KCM). It is driven by heat accumulated at mid-depth in the Atlantic–Indian Ocean Basin of the Southern Ocean and ceases when a strong surface freshening in the convection region coincides with the heat reservoir being virtually depleted. The heat is provided by the lower branch of the AMOC and gets trapped in the Weddell Gyre. The freshening, which is stochastic in nature, is caused by both net precipitation and enhanced sea ice melt. The centennial time scale originates from the slow built-up of the heat reservoir, which extends beyond the Weddell Sea and is big enough to fuel deep convection for several decades once the water column in the Weddell Sea is destabilized. [See Martin et al. (2013) for a detailed analysis of the mechanism.] The heat exchange with the atmosphere drives global atmospheric teleconnections (Latif et al., 2013). This constitutes a fast communication path between the Southern Ocean and the Northern Hemisphere, which can be termed atmospheric bridge.

Here we describe a slow oceanic bridge between the Southern Ocean and the North Atlantic. In Section 2, we give a brief overview of the KCM and control simulation on which our study is based. The results are presented in Section 3, in which we demonstrate how the Southern Ocean deep convection flip-flop drives the bi-polar ocean seesaw and impacts the lower and upper branch of the AMOC on a centennial time scale. It is further shown that the redistribution of heat is well expressed by sea level variations in the Southern Ocean and North Atlantic. We also show that sea level is an excellent indicator of centennial shifts in the Antarctic Circumpolar Current (ACC) and North Atlantic subpolar gyre, and that these centennial shifts can be linked to the Southern Ocean Centennial Variability (SOCV). In Section 4 we discuss the main results and present the major conclusions.

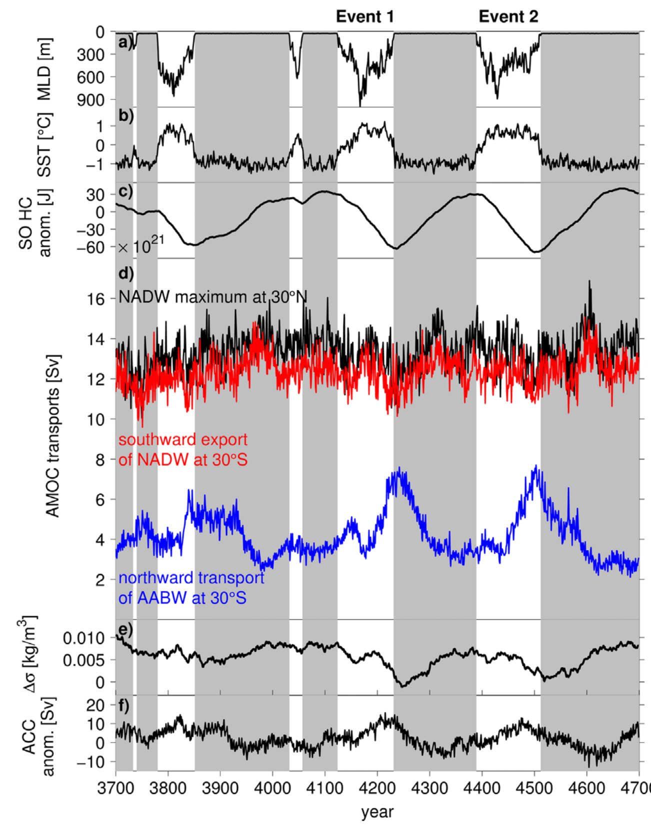

Fig. 1. Time series of annual mean (A) mixed layer depth [m] averaged over the Weddell Sea convection region (WSCR, 58°–68°S, 35°W–10°E), (B) SST [°C] averaged over the same area, (C) deep ocean heat content (HC) anomaly [10^{21} J] for the Atlantic–Indian sector of the Southern Ocean (SO, 70°W–80°E, south of 40°S) below 1600 m, (D) southward NADW transports [Sv] at 30°N (black) and 30°S (red) and northward AABW transport at 30°S (blue), (E) density difference [kg/m^3] in the Atlantic between 30°–40°S and 30°–40°N below 1200 m, and (F) transport anomaly [Sv] through Drake Passage as a measure of ACC strength variations. In all panels gray shaded areas mark time periods of the non-convective regime, i.e. without deep convection in the Weddell Sea. (See the web version of this article for color figures.)

2. Climate model

We analyze a 1300-yr long control integration of present-day climate conditions of the Kiel Climate Model (KCM). The KCM (Park et al., 2009) consists of the ECHAM5 atmosphere general circulation model (AGCM) on a T31 (3.75° × 3.75°) grid coupled to the NEMO ocean sea-ice GCM on a 2° Mercator mesh with 0.5° meridional resolution in the equatorial region. No form of flux correction or anomaly coupling is used. The model employs constant levels of greenhouse gas concentrations characteristic of the present climate with a CO_2 concentration of 348 ppmv. The KCM simulates a rich spectrum of internal variability. In particular, the model simulates multidecadal SST variability in the North Atlantic and North Pacific Oceans with realistic period and spatial structure (Park and Latif, 2010). Compared to the original model version used by Park and Latif (2008) and Park and Latif (2010) the version used here employs a slightly modified parameterization in the sea ice model yielding a thicker sea ice cover in the Southern Ocean (Martin et al., 2013, their Fig. 1), which agrees well with observations (Latif et al., 2013, their Fig. 5). Nevertheless, this