Progress in Oceanography 132 (2015) 262–272

Contents lists available at ScienceDirect

Progress in Oceanography

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

On the mechanisms behind decadal heat content changes in the eastern subpolar gyre

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ARTICLE INFO

Article history:
Available online 11 March 2014

ABSTRACT

Historical and modern hydrographic data show substantial decadal variability in the heat content (HC) of the eastern subpolar North Atlantic. Those changes are here investigated in an eddy-permitting simulation (ORCA025-G70) forced by reanalysis products for the period 1965–2004. The observed and simulated decadal signal is characterized by a strong cooling in the 1960s and 1970s, a period of minor changes in the 1980s, and a strong warming in the 1990s and 2000s. A heat budget calculation is performed within a box bounded by the Greenland–Scotland sills and the Cape Farewell (Greenland)–Portugal A25-Ovide section. The decadal variability of HC is mainly governed by the integrated effect of anomalous oceanic heat transport across A25-Ovide (HT_{A25}), with local air-sea heat fluxes playing a damping role. The impact of temperature changes acting upon the mean oceanic circulation is shown to dominate the long-term behavior of HT_{A25}. Through Lagrangian experiments, we show that temperature anomalies advected by the mean circulation across A25-Ovide are mostly created by the gyre circulation anomalies upstream of A25-Ovide and the associated changes in the relative proportion of cold subpolar and warm subtropical waters feeding the northern and southern branches of the North Atlantic Current. These temperature anomalies induce large-scale changes in the pycnocline slope east of Reykjanes Ridge along A25-Ovide: when the NAC is relatively cold (warm), the main pycnocline moves upward (downward) in the Iceland Basin and on top of Reykjanes Ridge, thereby increasing (decreasing) the pycnocline slope. The resulting velocity anomalies lead to heat transport changes that strongly oppose the thermally-driven heat transport anomalies.

1. Introduction

Understand the mechanisms governing oceanic temperature and associated heat content (HC) variability has become an essential issue for better climatic prediction. While observational evidences from a wide range of *in situ* measurements show a global warming of the world oceans since several decades (Levitus et al., 2009), the patterns of HC changes highlight significant regional disparities. Those inhomogeneities in the observed trends are particularly pronounced in the North Atlantic Ocean, where the subtropical and subpolar HC have evolved differently during the second half of the twentieth century: while the subtropical and tropical latitudes showed an overall heat gain, the subpolar region underwent an overall heat loss (Lozier et al., 2008; Zhai and Sheldon, 2012). Superimposed on this long-term trend stand decadal signals of significant amplitudes that presumably relate to changes in the large-scale oceanic circulation driven by the North Atlantic Oscillation (NAO), the dominant mode of atmospheric variability in the North Atlantic (Häkkinen, 1999; Curry and McCartney, 2001). In particular, the eastern subpolar gyre (SPG) encompasses regions where significant hydrographic changes were recently observed: the Irminger Sea, the Iceland basin and the Rockall Trough (Bersh, 2002; Holliday et al., 2008; Thierry et al., 2008). These are key regions for the buoyancy-driven formation of intermediate and deep water masses that feed the lower limb of the so-called Meridional Overturning Circulation (e.g. Brambilla and Talley, 2008), and any long-term modifications of the upper density field there may have significant climatic implications. Through the analysis of an Ocean General Circulation Model (OGCM) simulation, the present study concentrates on the decadal variability of HC in the eastern SPG for the period 1965–2004.

Following the relatively cold and fresh period of the 1980s and early 1990s, the hydrographic content of the eastern SPG underwent a sharp warming and increase in salinity that prevailed during the 2000s (e.g. Holliday et al., 2008). The direct influence of

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http://dx.doi.org/10.1016/j.pocean.2014.02.005
0079-6611/

local buoyancy fluxes at the air-sea interface was shown insufficient to explain the observed change, and the role played by the large-scale oceanic circulation consequently received much attention (e.g. Holliday, 2003; Thierry et al., 2008; Häkkinen and Rhines, 2009; de Boisséson et al., 2012). Thanks to the unprecedented spatio-temporal coverage of altimetry measurements, the post-1995 signal was shown to occur throughout a weakening of the SPG circulation, depicted in the so-called "gyre index" (Häkkinen and Rhines, 2004). Anomalous air-sea heat fluxes associated with a decreasing trend in the NAO index (Hurrell, 1995) was invoked as a dominant forcing mechanism (gray bars in Fig. 2). In hindcast numerical simulations, this surface weakening of the SPG after 1995 was shown to follow an intensification from the late 1960s (Hátún et al., 2005; Böning et al., 2006), which coincides with a positive trend in the NAO index and an observed cooling/freshening of the eastern SPG (e.g. Curry and McCartney, 2001).

A closer look into the mechanisms associated with decadal hydrographic changes in the eastern SPG was documented in the study of Hátún et al. (2005). The SPG dynamics was presumed to control the respective inflows of cold/fresh subpolar waters and warm/salty subtropical waters within the North Atlantic Current (NAC). Using salinity criteria to identify their respective signatures, the authors showed opposed transport variability of both source waters that closely mimic the gyre index fluctuations: when the SPG is strong, the cold/fresh (warm/salty) water transport is strong (weak), and vice versa for a weak SPG circulation. Using an OGCM forced by NAO-related atmospheric fields, Herbaut and Houssais (2009) excluded buoyancy-driven changes of the SPG circulation as a predominant mechanism behind hydrographic changes in the eastern SPG. Instead, the authors highlighted the role played by a wind-driven anomalous circulation located over the climatological position of the Gulf Stream/NAC, the so-called "intergyre gyre" (Marshall et al., 2001; Eden and Willebrand, 2001).

More recently, modeling studies by de Boisséson et al. (2012) and Desbruyères et al. (2013) showed the power of Lagrangian diagnostics for the study of hydrographic and volume transport changes in the eastern SPG. A Lagrangian decomposition of the NAC transport into a subtropical component from the Gulf Stream and a subpolar component from the Labrador Current showed that hydrographic criteria were not suitable to extract the signature of both gyres from the NAC variability (Desbruyères et al., 2013). Those authors showed that the decadal variability of the NAC in the eastern SPG was accompanied by opposed transport changes of its northern and southern branches, which respectively feeds the Iceland Basin and the Rockall Trough. Importantly, this horizontal reorganization of the NAC was shown to primarily reflect a signal of subtropical origin, rather than a spin-up/spin-down of the SPG circulation (Desbruyères et al., 2013). While this result complements the main conclusion of Herbaut and Houssais (2009), that is no causal relationship between the strength and shape of the SPG, the mechanisms involved in the observed hydrographic changes are still poorly documented.

The main objective of the present paper is to provide a link between the aforementioned regional circulation changes and the actual rate of change of HC in the eastern SPG. The numerical tools used are presented in Section 2 and the ability of the ORCA025-G70 simulation to reproduce the observed variability in the eastern SPG is evaluated. A heat budget calculation within a box bounded by the A25-Ovide section and the Greenland–Iceland–Scotland (GIS) sills (Fig. 1) is then performed (Section 3). Results from the heat budget study motivates a temporal decomposition of the full-depth heat transport across A25-Ovide (Section 4), and Lagrangian experiments are carried out to complement the Eulerian analysis (Section 5). A list of concluding remarks follows (Section 6).

2. Numerical tools

2.1. The ocean model

2.1.1. General configuration

The study utilizes the ORCA025-G70 simulation from the global configuration ORCA025 of the Nucleus for European Modeling of the Ocean (NEMO, (Madec, 2008)) coupled with the Louvain-la-Neuve Ice model version 2 (LIM2, (Fichefet and Maqueda, 1999)). The ORCA025 numerical characteristics are fully detailed in Barnier et al. (2006). The domain is global and is configured using a tripolar grid with 1442×1021 grid points and a horizontal resolution that increases with latitude (from 27.75 km at equator to 13.8 km at 60°N). The vertical grid consists of 46 z-levels with vertical spacing that increases with depth (6 m near the surface, 250 m at the bottom). The ORCA025 parameterizations comprise a Laplacian mixing of temperature and salinity along isopycnals, a horizontal biharmonic viscosity, and a turbulence closure scheme (TKE) for vertical mixing.

A complete description of the ORCA025-G70 simulation is provided by Molines et al. (2006) and Treguier et al. (2007). It was initialized with the Polar Science Center Hydrographic T/S Climatology (PHC 3.0, Steele et al. (2001)), which consists of the Levitus 1998 climatology (Levitus et al., 1998) everywhere except in the Arctic domain where a blend of the Arctic Ocean Atlas and additional data from the Bedford Institute of Oceanography was added to produce a more realistic Arctic hydrography. The simulation was run from 1958 to 2004 with no spin-up. The forcing dataset (referenced as DFS3 by Brodeau et al. (2009)) was built using data from various origins at different frequencies. Air temperature, wind and air humidity data originate from the European Centre for Medium-Range Weather Forecast (ECMWF) ERA40 reanalysis for the period 1958–2001 and from the ECMWF analysis for the period 2002–2004. Daily radiative flux and monthly precipitation fields came from the Coordinated Ocean-ice Experiment (CORE) (Griffies et al., 2009) database and turbulent fluxes (wind stress, latent and sensible heat fluxes) were calculated from the CORE bulk formulae (Large and Yeager, 2004). To minimize uncontrolled drift in salinity as a response to inaccurate precipitation (Griffies et al., 2009), a global sea surface salinity (SSS) restoring to the PHC climatology was incorporated. The SSS restoring term is converted into an equivalent freshwater flux through a relaxation coefficient that was set to 0.17 m per day. Considering the salinity evolution in the first vertical grid cell (6 m), the relaxation coefficient corresponded to a decay time of 36 days (Molines et al., 2006) and led to a freshwater flux of similar amplitude as the one calculated from the forcing fields. A SSS restoring under the ice cover was maintained with a 5-time enhanced coefficient. An additional restoring was also applied at the exit of the Red Sea and the Mediterranean Sea for a better representation of the overflows. The consistency of ORCA025-G70 in simulating the dynamics and hydrography of the subpolar gyre (de Boisséson et al., 2012; Desbruyères et al., 2013), strongly suggests that the following results are not significantly bias by such SSS restoring. Rattan et al. (2010) showed a strong drift in the freshwater content of the Labrador Sea during the first decade of integration in ORCA025-G70. The degree of equilibrium achieved by the late 1960s is however adequate with observations suggesting that the subsequent model variability relates to the prescribed interannual forcing (see next section). All the results presented in the present study are obtained with monthly model outputs and all time series presented thereafter are annual averages of the monthly time series.

2.1.2. Model evaluation: heat content variability in the eastern SPG

The consistency of the model temperature in the eastern SPG was recently documented by de Boisséson et al. (2010). Similar