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Anomalous circulation in the Pacific sector of the Arctic Ocean in July–December 2008

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ABSTRACT

Variability of the mean summer-fall ocean state in the Pacific Sector of the Arctic Ocean (PSAO) is studied using a dynamically constrained synthesis (4Dvar) of historical in situ observations collected during 1972 to 2008. Specifically, the oceanic response to the cyclonic (1989–1996) and anticyclonic (1972–1978, 1997–2006) phases of the Arctic Ocean Oscillation (AOO) is assessed for the purpose of quantitatively comparing the 2008 circulation pattern that followed the 2007 ice cover minimum.

It is shown that the PSAO circulation during July-December of 2008 was characterized by a pronounced negative Sea Surface Height (SSH) anomaly along the Eurasian shelf break, which caused a significant decline of the transport in the Atlantic Water (AW) inflow region into the PSAO and increased the sea level difference between the Bering and Chukchi Seas. This anomaly could be one of the reasons for the observed amplification of the Bering Strait transport carrying fresh Pacific Waters into the PSAO. Largrangian analysis of the optimized solution suggests that the freshwater (FW) accumulation in the Beaufort Gyre has a negligible contribution from the East Siberian Sea and is likely caused by the enhanced FW export from the region north of the Canadian Archipelago/Greenland.

The inverse modeling results are confirmed by validation against independent altimetry observations and in situ velocity data from NABOS moorings. It is also shown that presented results are in significantly better agreement with the data than the output of the PIOMAS model run utilized as a first guess solution for the 4dVar analysis.

1. Introduction

In recent years, studies of the Arctic Ocean circulation and the freshwater (FW) budget have gained considerable attention due to its influence on the global climate system. Ice conditions and the circulation in the Arctic Ocean have undergone a particularly pronounced change, including a persistent decrease in ice cover at an average rate of 15% per decade (IPCC, 2013) accompanied by the tremendous ice retreats of 2007 and 2012, when most of the Pacific Sector of the Arctic Ocean (PSAO) became almost completely ice-free in the summer (Zhang et al., 2013). These processes are well correlated with other observed phenomena such as: enhanced wind-driven vertical mixing during the ice free periods (e.g. Yang et al., 2004; Kawagachi, 2015), a tendency for intensification of the flow through the Bering Strait during 2007–2009 (Woodgate et al., 2010), and an increase in significant wave height (Francis et al., 2011). During the summer, increased storm activity may cause an additional reduction of the ice cover due to storm-generated mixing in the upper ocean (Zhang et al., 2013; Long and Perrie, 2012). The enhanced wave-ice interaction in the marginal ice zones and wave induced mixing also contributes towards the decrease of ice (Williams et al., 2013a; 2013b; Qiao et al., 2004). These processes may significantly accelerate the observed changes in the ice conditions and affect accumulation and redistribution of the freshwater in the Arctic Ocean (e.g. Woodgate et al., 2012).

The outflow of low-salinity Arctic Water into the North Atlantic, one of the most important advective sources of liquid freshwater

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in the World Ocean, is crucial for maintaining the global conveyer belt forced by the Atlantic Meridional Overturning Circulation (e.g. Jones and Anderson, 2008).

Alternatively, redistribution of the salty Atlantic, relatively fresh Pacific water, and riverine water within the Arctic Ocean are the key factors controlling thermohaline circulation and FW distribution within the Arctic Ocean (e.g., Jones et al., 1998). Importantly, the FW deficit in the surface layers may cause fast erosion of the pycnocline and enhanced vertical mixing. This may bring relatively warm Atlantic water (AW) to the surface and accelerate the observed trend of the diminishing ice cover in the Arctic Ocean (e.g. Carmack et al., 2015). Because of the importance of the FW budget, monitoring the FW balance and redistribution has become one of the primary objectives of several large observational programs (e.g. Beaufort Gyre Exploration Program (BGEP www.whoi.edu/beaufortgyre), Nansen Amundsen Basins Observing System (NABOS http://research.iarc.uaf.edu/NABOS/), Canadian Basin Observational System (CABOS)).

In the Arctic, the FW is mostly stored within the Beaufort Gyre (BG) (Aagaard and Carmack, 1989). According to Proshutinsky et al. (2002), wind is the major forcing responsible for the accumulation of FW in the Beaufort Sea through the convergence in the Ekman layer and subsequent FW downwelling in the central part of the Gyre. Intensification of this process is correlated with the Arctic Ocean Oscillation (AOO) index quantifying the Sea Surface Height (SSH) anomaly associated with the BG (Proshutinsky and Johnson, 1997). Thus, being closely connected to the regional changes in the atmospheric circulation, this relationship potentially allows large scale analysis of the FW accumulation and its export from the Arctic Ocean.

Analysis of the long-term SSH variability in the Arctic Ocean has shown that this process of FW accumulation and release is usually governed by a 5–7 year cycle (Proshutinsky et al., 2009). During cyclonic epochs (1953–1958, 1963–1970, 1980–1986, 1990–1996), the Arctic atmosphere was relatively warm and humid, while the FW outflow into the Atlantic was intensified (Proshutinsky et al., 2002; 2015). In contrast, the anticyclonic periods were characterized by the clockwise shifts in the PSAO circulation accompanied by a significant reduction in the FW export. According to this concept, the period of the positive AOO which started in 1997 should have changed sign around 2004–2006. However, the positive AOO values still persists through the years of 2005–2017. One of the hypotheses, explaining such anomalous behavior, is related to the additional FW export from Greenland which may significantly increase the periods of the positive AOO index due to the intensification of the FW advection from Greenland into the Arctic Ocean (Proshutinsky et al., 2015). It is noteworthy to mention that recent observations of FW anomalies in the Lincoln Sea (De Steur et al., 2013) appear to support this hypothesis.

Persistence of the positive AOO phase after 2007, associated with the FW accumulation and intensification of the BG was confirmed by McPhee et al. (2009) through analysis of in situ temperature and salinity observations and by Kwok and Morrison (2011) who analyzed ICEsat altimetry and diagnosed a distinct SSH dome of approximately 40 cm over the Beaufort Sea during 2004–2008. Recently, the BG intensification was also identified in a numerical study with simplified ice data assimilation by Zhang et al. (2016) who obtained a persistent amplification of the BG since 1992 and its stabilization after 2008. Analysis of a more advanced data assimilative solution (2002–2008) from the Global Ocean Reanalysis and Simulations (GLORYS1) run also revealed FW accumulation in the BG accompanied by salinization of the Eurasian Basin (Ligue et al., 2011). The authors linked these processes to specific atmospheric conditions during 2007 and 2008 and spatial re-distribution of the liquid freshwater in the Arctic Ocean. Lique et al. (2011) also diagnosed an enhanced inflow of the AW through the Fram Strait, which may lead to the observed salinization in the GLORYS1 solution. However, it is necessary to note that the above mentioned data assimilation solutions did not assimilate any oceanic and (in the case of GLORYS1) ice observations. In particular, salinization in the Eurasian Basin was not conclusively supported by McPhee et al. (2009) and Rabe et al. (2011) who analyzed the in situ observations in the Arctic Ocean.

In controversy to the above mentioned hypothesis, Morison et al. (2012) suggested that the observed BG freshening is caused by the increased sea ice melting and changes of the pathways of the Eurasian river runoff. According to this hypothesis, changes of the riverine water pathways are due to the strengthening of the eastward atmospheric circulation in the Northern Hemisphere, associated with the increased Arctic Oscillation index.

Due to a scarcity of hydrographic observations in the Arctic Ocean, most of the above mentioned in situ data analyses were performed via simple optimal interpolation by combining observations from different seasons (e.g. Proshutinsky et al., 2009; McPhee et al., 2009). To analyze interannual variability, it is also necessary to specify background fields in the regions where the observations were absent for a particular year (e.g. Proshutinsky et al., 2009). Taking the background from previous years may lead to significant errors in the derived temperature-salinity distributions due to the homogeneity of the correlation functions (MacIntosh, 1990) and time variations of the background information. These errors will inevitably impact the derived estimates of the circulation patterns which are usually obtained by estimating the geostrophic velocities relative to the level of no motion at 400–500 m (e.g. Morrison et al., 2012). In this regard, it is necessary to note that direct velocity observations in the Makarov and Amundsen Basins as well as along the Siberian continental slope demonstrate relatively strong (4–7 cm/s) currents at these depths (Pnyushkov et al., 2015).

Modeling studies (e.g., Maslowski et al., 2000; Zhang and Rothrock, 2003; Wang et al., 2014; Zhang et al., 2016; Wang et al., 2016) have the advantage of better dynamical consistency, but may suffer from uncertainties in the forcing fields and sub-grid parameterizations, resulting in a rather different and sometimes controversial representation of the water's properties and in estimating circulation in Arctic Ocean models (e.g. Stainer et al., 2004; Holloway et al., 2007; Aksenov et al., 2016).

In the present study, we make an attempt to combine observations with the dynamical constraints of a numerical model in the framework of the four-dimensional variational data assimilation approach (4dVar). The method (e.g., Le Dimet and Talagrand, 1986) provides a way of interpolating observations in space and time using the dynamical constraints of a numerical model. In particular, this approach allows a reasonably accurate reconstruction of the data-driven circulation on the shelves, where geostrophic currents cannot be estimated from temperature/salinity observation alone.

We reconstruct summer-fall PSAO circulations during four different periods, focusing on the comparison of the 2008 July-December circulation with the respective conditions reconstructed in the previous decades (1972–1978, 1989–1996, 1997–2006) which correspond to the periods of positive and negative AOO phases (Proshutinsky et al., 2015). The year 2008 was chosen due to the largest volume of observations collected, after the anomalous ice retreat of 2007. To assess interannual variations of the FW content, we also reconstructed July-December circulations for 2003, 2004, 2005 and 2006. A significant effort has also been made to validate the performance of the Pan-Arctic Ice-Ocean Modeling and Assimilation System (PIOMAS), whose solutions were used to initialize the 4dVar assimilation.

The paper is organized as follows. In the next section we describe the methodology and the data set that have been used. In Section 3, the PSAO circulations for two anticyclonic (1972–1978,