Progress in Oceanography 155 (2017) 54–73

Contents lists available at ScienceDirect

Progress in Oceanography

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

Variations in freshwater pathways from the Arctic Ocean into the North Atlantic Ocean

Zeliang Wang [a,*], James Hamilton [a], Jie Su [b]

[a] Ocean and Ecosystem Sciences Division, Bedford Institute of Oceanography, 1 Challenger Drive, Dartmouth, Nova Scotia B2Y 4A2, Canada

[b] Physical Oceanography Laboratory/CIMST, Ocean University of China and Qingdao National Laboratory for Marine Science and Technology, 238 Songling Road, Qingdao 266100, China

ARTICLE INFO

Article history:
Received 31 January 2017
Received in revised form 21 April 2017
Accepted 17 May 2017
Available online 21 May 2017

Keywords:
Freshwater pathways
Canadian Arctic Archipelago
Fram Strait
GRACE
Arctic Oscillation
Arctic Dipole

ABSTRACT

Understanding the mechanisms that drive exchanges between the Arctic Ocean and adjacent oceans is critical to building our knowledge of how the Arctic is reacting to a warming climate, and how potential changes in Arctic Ocean freshwater export may impact the AMOC (Atlantic Meridional Overturning Circulation). Here, freshwater pathways from the Arctic Ocean to the North Atlantic are investigated using a 1 degree global model. An EOF analysis of modeled sea surface height (SSH) demonstrates that while the second mode accounts for only 15% of the variability, the associated geostrophic currents are strongly correlated with freshwater exports through CAA (Canadian Arctic Archipelago; $r = 0.75$), Nares Strait ($r = 0.77$) and Fram Strait ($r = -0.60$). Separation of sea level into contributing parts allows us to show that the EOF1 is primarily a barotropic mode reflecting variability in bottom pressure equivalent sea level, while the EOF2 mode reflects changes in steric height in the Arctic Basin. This second mode is linked to momentum wind driven surface current, and dominates the Arctic Ocean freshwater exports. Both the Arctic Oscillation and Arctic Dipole atmospheric indices are shown to be linked to Arctic Ocean freshwater exports, with the forcing associated with the Arctic Dipole reflecting the out-of-phase relationship between transports through the CAA and those through Fram Strait. Finally, observed freshwater transport variation through the CAA is found to be strongly correlated with tide gauge data from the Beaufort Sea coast ($r = 0.81$), and with the EOF2 mode of GRACE bottom pressure data ($r = 0.85$) on inter-annual timescales.

1. Introduction

As part of its role in the global climate system, the Arctic Ocean serves as a hub between the North Atlantic Ocean and the Pacific Ocean (Fig. 1). Observations have revealed persistent flows of relatively low salinity water from the Pacific to the Arctic through Bering Strait, and from the Arctic to the North Atlantic through Fram Strait and the passages through the CAA (e.g., Melling, 2000; McGeehan and Maslowski, 2012; Woodgate, 2012; Peterson et al., 2012; Rabe et al., 2011; Wang et al., 2012; Lu et al., 2014; Hu et al., 2015; Rudels, 2015). The freshwater outflow from the Arctic Ocean may interact with the large-scale Atlantic Meridional Overturning Circulation (AMOC), e.g., Aagaard and Carmack (1989), Steele et al. (1996), Häkkinen (1999), Proshutinsky et al. (2002), Curry and Mauritzen (2005), Seidov et al. (2015).

Previous studies indicate that the role of freshwater flowing through the CAA and the role of that through Fram Strait on dense water formation in the northern North Atlantic Ocean may be different. Houssais and Herbaut (2011) suggested that the freshwater water export through the CAA contributes to surface salinity variability on the Labrador shelf, while the freshwater through Fram Strait contributes to the interior Labrador Sea surface salinity variability. Dodd et al. (2009) found that liquid freshwater mainly stays in the East Greenland Current and transits the Nordic Seas to the subpolar North Atlantic undisturbed. Våge et al. (2009) reported that increased freshwater transport through Davis Strait (dominantly coming from the CAA) enhanced sea ice formation in parts of the Labrador Sea, allowing cold air to progress farther into the interior of the Labrador Sea leading to deep convection in the winter of 2007–2008. It is widely acknowledged that deep convection there is linked to the AMOC. Understanding the variability of the two freshwater pathways can enhance our knowledge of climate related changes in the North Atlantic Ocean. There are a few studies suggesting a possible existence of an out-of-phase relationship

* Corresponding author.
E-mail addresses: Zeliang.Wang@dfo-mpo.gc.ca (Z. Wang), JamesHamilton@eastlink.ca (J. Hamilton), sujie@ouc.edu.cn (J. Su).

http://dx.doi.org/10.1016/j.pocean.2017.05.012

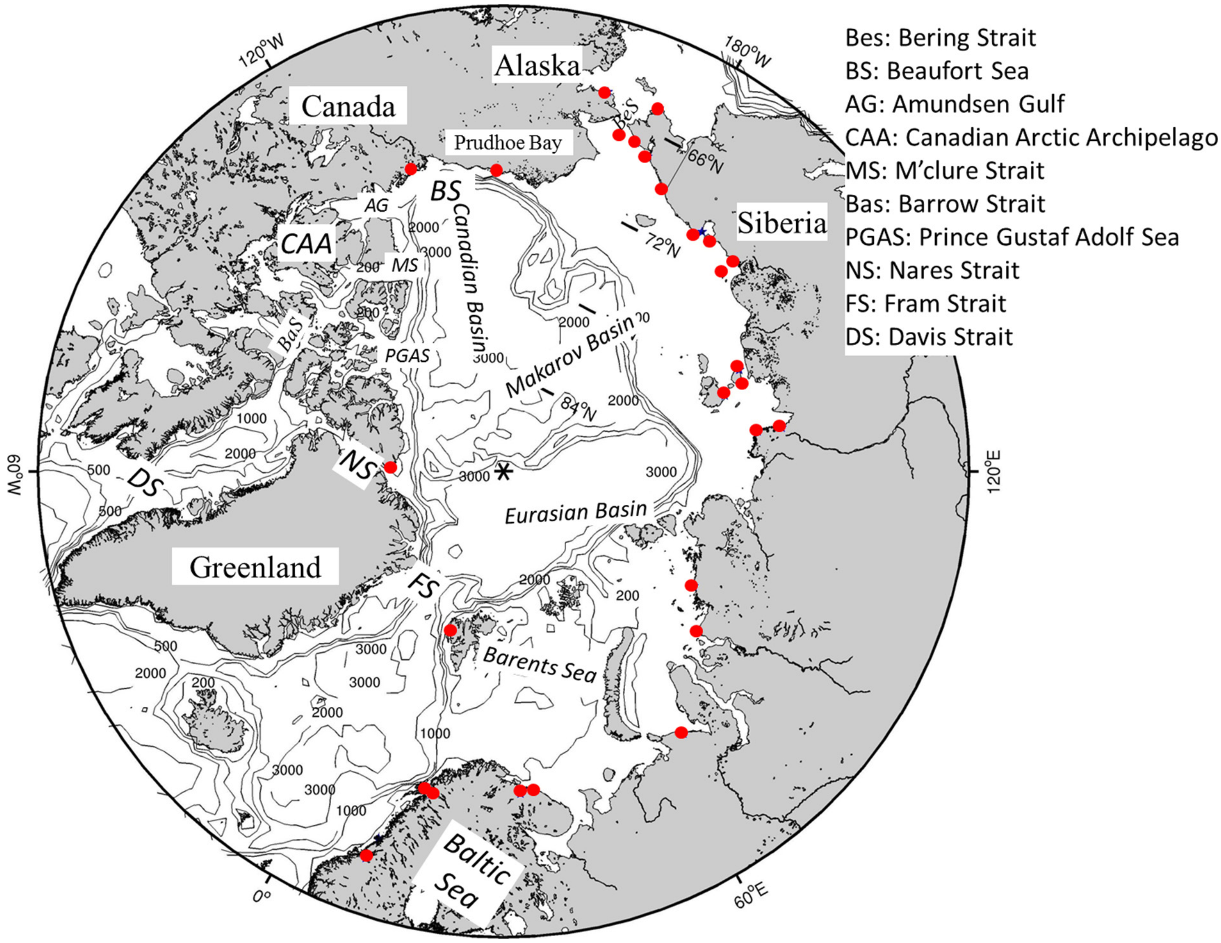

Fig. 1. Locations of tide gauge stations (red dots) used in the model validation and of geographic names mentioned in this paper. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

between these two pathways. Lique et al. (2009) reported volume transports through Davis and Fram Straits are strongly negatively correlated based on model results. Steele et al. (1996) reported freshwater outflow through the CAA tends to compensate for the ocean freshwater outflow through Fram Strait with a one year lag. Results presented in Haine et al. (2015) (their Fig. 4) also show a negative correlation between Fram and Davis Strait freshwater fluxes for the 2005–2011 period. A more recent study by Zhang et al. (2016) also reported this out-of-phase relationship. But the mechanism for this out-of-phase relationship remains unclear. Considering the different rolesthe freshwater from the two major routes may play on stratification in the North Atlantic, and hence mixing and ice formation there, investigating the freshwater pathway variations remains an important and intriguing issue.

A pioneering study by Proshutinsky and Johnson (1997) demonstrated the existence of two regimes of wind-forced circulation (the Arctic Ocean Oscillation – AOO) in the Arctic using a barotropic model. Recently, Proshutinsky et al. (2015) demonstrated that the first principal component (PC1) of the annual mean sea surface height can objectively represent this AOO index, which provides a convenient measure for the Arctic circulation. Proshutinsky et al. (2002) proposed and demonstrated that the Beaufort Gyre accumulates a significant amount of fresh water during one climate regime (anticyclonic/positive AOO) and releases this water to the North Atlantic during another climate regime (cyclonic/negative AOO). However, Lique et al. (2009) reported that the correlation between the Beaufort Gyre SSH variability (a measure of the strength of Beaufort Gyre) and the time series of the freshwater transports across Fram Strait and Davis Strait is insignificant. What circulation changes drive the freshwater out of the Arctic Ocean needs further investigation.

The Arctic Oscillation (AO) and Arctic Dipole (AD) are two leading atmospheric modes of variability over the Arctic Ocean. Previous studies have reported on the importance of the AO in the storing or releasing of freshwater in the Arctic Ocean, e.g., Proshutinsky et al. (2002), Polyakov et al. (2008), Häkkinen and Proshutinsky (2004), Morison et al. (2012). The AD has been demonstrated to have a role in the freshwater content variability, e.g., Rabe et al. (2014). Rabe et al. (2014) also mentioned that a positive AD would strengthen the freshwater exports through Fram Strait. How the atmospheric change over the Arctic Ocean may impact the freshwater exports through the two pathways is still an open question.

Sea surface height is a parameter that often has long-time records at tide gauge stations. Previous studies on relating variability of freshwater transport to sea level changes indicate a possibility of representing freshwater transport variability with sea level variation. Prinsenberg and Bennett (1987) found that moored measurements of transports through Barrow Strait in the central part of the Northwest Passage (part of CAA) were correlated with the sea level difference along the passage on seasonal scales. More recently, with a much longer time series of moored instrument data, Peterson et al. (2012) showed that volume and freshwater transport variability through Barrow Strait were significantly correlated with the sea level buildup at Arctic coast. The modeling work of Wekerle et al. (2013) identified variability in sea level dif-