Continental Shelf Research 66 (2013) 92–104

Contents lists available at ScienceDirect

Continental Shelf Research

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

Research papers

The genesis of sea level variability in the Barents Sea

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ARTICLE INFO

Article history:
Received 11 March 2013
Received in revised form
4 July 2013
Accepted 16 July 2013
Available online 27 July 2013

Keywords:
Barents Sea
Sea level variability
Satellite altimetry
GRACE
ECCO2
Arctic seas

ABSTRACT

The regional variability of sea level is an integral indicator of changing oceanographic conditions due to different processes of oceanic, atmospheric, and terrestrial origin. The present study explores the nature of sea level variability in the Barents Sea—a marginal shelf sea of the Arctic Ocean. A characteristic feature that distinguishes this sea from other Arctic shelf seas is that it is largely ice free throughout the year. This allows continuous monitoring of sea level by space-borne altimeters. In this work we combine satellite altimetry, ocean gravity measurements by GRACE satellites, available hydrography data, and a high-resolution ocean data synthesis product to estimate the steric and mass-related components of sea level in the Barents Sea. We present one of the first observational evidence of the local importance of the mass-related sea level changes. The observed 1–3 month phase lag between the annual cycles of sea level in the Barents Sea and in the Nordic seas (Norwegian, Iceland, Greenland seas) is explained by the annual mass-related changes. The analysis of the barotropic vorticity budget shows that the mass-related sea level variability in the central part of the Barents Sea is determined by the combined effect of wind stress, flow over the varying bottom topography, and dissipation, while the impact of vorticity fluxes is negligible. Overall, the steric sea level has smaller amplitudes and mainly varies on the seasonal time scale. The thermosteric sea level is the main contributor to the steric sea level along the pathways of the Atlantic inflow into the Barents Sea. The relative contribution of the halosteric sea level is dominant in the southeastern, eastern, and northern parts of the Barents Sea, modulated by the seasonal sea ice formation/melt as well as by continental runoff. The variability of the thermosteric sea level in the Barents Sea is mostly driven by variations in the net surface heat flux, whereas the contribution of heat advection becomes as important as the ocean-atmosphere heat exchange at interannual time scales.

1. Introduction

The Barents Sea (BS) is a marginal sea of the Arctic Ocean located on the continental shelf between the northern European coast and three archipelagoes—Spitsbergen, Franz Josef Land, and Novaya Zemlya (Fig. 1a). It is a rather deep shelf sea with an average depth of 222 m and a maximum depth of about 600 m. The river runoff is small (163 km^3/year) compared to other marginal seas of the Arctic Ocean; the Pechora River contributes most of the runoff (130 km^3/year) [Lebedev et al., 2011]. The atmospheric circulation over the BS is dominated by cyclones coming from the North Atlantic. The strongest atmospheric pressure gradients are observed in winter months, when southwesterly and westerly winds prevail in the southern part of the sea and southeasterly and easterly winds dominate in the north (Terziev et al., 1990).

The BS is one of the gateways between the Atlantic and the Arctic oceans (Fig. 1a). Approaching the southwestern boundary of the BS the Norwegian Atlantic Current (NwAC) splits into the West Spitsbergen Current that flows north towards the Fram Strait, and into the North Cape Current that veers eastward and enters the BS between the continent and Bear Island. The NwAC transports warm and salty Atlantic Water (AW), about half of which enters the BS (Skagseth et al., 2008). The Norwegian Coastal Current enters the BS along the coastline and also carries some AW. While transiting the BS, the AW undergoes transformation due to heat loss to the atmosphere, mixing with ambient water masses, net precipitation, river runoff, and ice freezing and melting. Substantially modified water then exits the BS primarily to the north of Novaya Zemlya (Loeng et al., 1993). Changes in the volume and properties of the AW inflow as well as changes in atmospheric circulation and buoyancy fluxes greatly impact the variability of

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http://dx.doi.org/10.1016/j.csr.2013.07.007

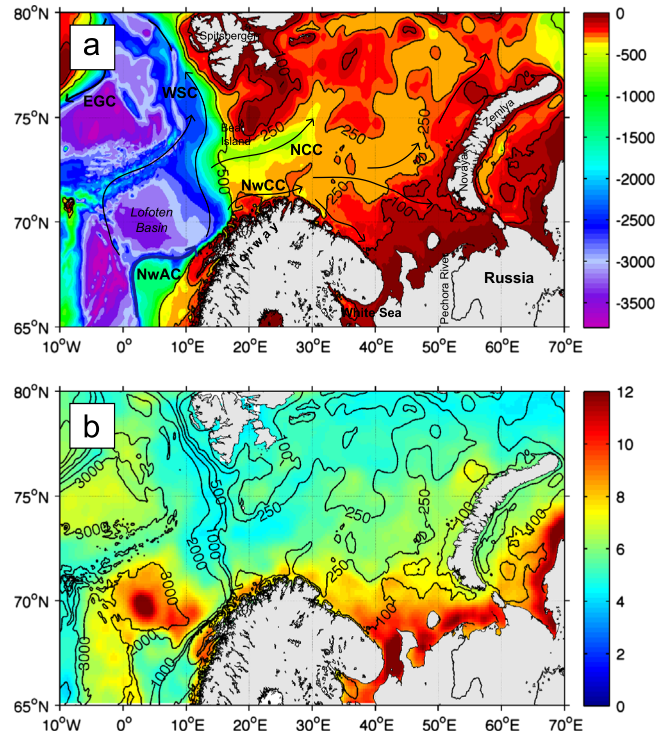

Fig. 1. (a) Bottom topography of the study domain (color) and major currents (arrows). (b) Standard deviation (cm) of SLA_T, measured with satellite altimetry. Contours show the bottom topography. Abbreviations: NwAC—Norwegian Atlantic Current, NCC—North Cape Current, NwCC—Norwegian Coastal Current, WSC—West Spitsbergen Current, EGC—East Greenland Current. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

oceanographic conditions in the BS (Furevik, 2001). Because of the AW inflow, the BS is never completely covered with sea ice, but the sea ice cover is subject to significant seasonal and interannual variability.

This paper aims to explore the causes of sea level variability in the BS. Sea level is an integral quantity that reflects (i) changes in the thermohaline properties of water masses, driven by the variations in buoyancy fluxes and advection by ocean currents, and (ii) changes in the mass of the water column, caused by the variations in wind forcing as well as the redistribution of water between the ocean, atmosphere, and land. Thus, the total sea level variability can be decomposed into the steric (expansion or contraction of water column due to the density variations) and mass-related sea level variability. The steric sea level variability can be further decomposed into the thermosteric and halosteric components.

Although the BS has been extensively surveyed over decades, the nature of the local sea level variability has not been adequately addressed. There have been a number of studies dedicated to the sea level variability in the Nordic seas (Mork and Skagseth, 2005; Steele and Ermold, 2007; Li et al., 2011; Richter et al., 2012), but only a few partially considered the BS (Proshutinsky et al., 2004, 2007; Volkov and Pujol, 2012; Henry et al., 2012; Calafat et al., 2013). Historically, sea level has been measured by tide gauges, the majority of which is located in the southern part of the BS along the Norwegian and Russian coasts. The BS tide gauges have been combined with other tide gauges along the Russian Arctic coast by Proshutinsky et al. (2004, 2007) to study the variability of sea level in the entire Arctic Ocean. Henry et al. (2012) analyzed the linear trends in tide gauge data along the Norwegian and Russian coasts and found an important contribution of the mass related change. Calafat et al. (2013) also analyzed the tide gauge records and explained the observed near-shore sea level variability by wind forcing and poleward propagation of sea level anomalies.

The advent of satellite altimetry has greatly advanced sea level studies by providing nearly global sea level measurements (Fu and Cazenave, 2001). From 1991 to 2012 the European Space Agency's satellites ERS-1, ERS-2, and Envisat were measuring sea level between 82°S and 82°N, thus completely covering the BS. Because of the ongoing long-term decrease of sea ice cover in the Arctic Ocean (Comiso et al., 2008), the sea ice edge in the BS is also retreating northeastward (Lebedev et al., 2011), which has made most of the BS area available for altimetry measurements. Lebedev et al. (2011) performed calibration and validation of satellite altimetry measurements in the BS and demonstrated its usefulness for local environmental monitoring. Volkov and Pujol (2012) showed that the quality of the recent global satellite altimetry product, distributed by AVISO (www.aviso.oceanobs.com), is adequate to study the synoptic and large-scale variability of sea level in the Nordic and Barents seas. The authors also estimated the amplitudes and phases of the annual cycle in the area and noted that the annual maximum sea level in the BS occurs 1–3 months later than in the Nordic seas. The launch of GRACE twin satellites in 2002 brought new perspectives of studying the variability of ocean mass (Chambers, 2006a, 2006b).

In this study, we aim to fill remaining gaps in the understanding of the mechanisms of local sea level changes. In particular, we want to (i) investigate the relative contribution of steric and mass effects to the regional sea level variability, (ii) explain the phase lag between the annual cycle in the BS and the neighboring Norwegian and Greenland seas, and (iii) study the role of wind forcing, net surface heat flux, and heat advection as drivers of the BS sea level variability. Hereafter, we use the following nomenclature for sea level anomaly (SLA) components: the total sea level anomaly (SLA_T), the mass-related sea level anomaly (SLA_M), the steric sea level anomaly (SLA_S), the thermosteric sea level anomaly (SLA_{TS}), and the halosteric sea level anomaly (SLA_{HS}).

2. Observational and modeled data

2.1. Satellite altimetry measurements

We use the AVISO maps of SLA_T from October 1992 to April 2012, generated by merging multi-satellite altimetry data. The high-latitude (above 66°) data are based on either ERS-1/2 or Envisat measurements. The data are corrected for instrumental errors, geophysical effects, tidal influence, and atmospheric wind and pressure effects, and objectively interpolated to a 1/3° Mercator projection grid (Le Traon et al., 1998). A dynamic atmospheric correction is applied to reduce the aliasing of the high-frequency sea level variability, especially in coastal regions (Carrere and Lyard, 2003; Volkov et al., 2007). Although the separation between the satellite's ground tracks and the ERS-1/2 and Envisat 35-day repeat period limits the resolution of eddy variability, the convergence of the ground tracks at high latitudes provides sufficient spatial and temporal coverage to adequately resolve the synoptic-scale variability in the Nordic and Barents seas (Volkov and Pujol, 2012).

Displayed in Fig. 1b is the standard deviation of SLA_T in the BS and in the neighboring areas. The maximum variability of SLA_T reaching about 15 cm is observed in the Lofoten Basin of the Norwegian Sea. It has been shown that among other factors this variability is largely due to the cyclonic propagation of topographic Rossby waves (Volkov et al., 2013). In the BS, the maximum SLA_T variability of 8–12 cm is observed in the south, over the shallow