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Seasonality and interannual variability of the European Slope Current from 20 years of altimeter data compared with in situ measurements

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ABSTRACT

The European Slope Current (SC) is a major section of the warm poleward flow from the Atlantic to the Arctic, which also moderates the exchange of heat, salt, nutrients and carbon between the deep ocean and the European shelf seas. The mean structure of the geostrophic flow, seasonality, interannual variability and long-term trend of SC are appraised with an unprecedented continuous 20-year satellite altimeter dataset. Comparisons with long term in situ data showed a maximum correlation of $r^2 = 0.51$ between altimeter and Acoustic Doppler Current Profilers (ADCP), with similar results for drogued buoy data. Mean geostrophic currents were appraised more comprehensively than previous attempts, and the paths of 4 branches of the North Atlantic Current (NAC) and positions of 5 eddies in the region were derived quantitatively. A consistent seasonal cycle in the flow of the SC was found at all 8 sections along the European shelf slope, with maximum poleward flow in the winter and minimum in the summer. The seasonal difference in the altimetry current speed amounted to ~8–10 cm s^{-1} at the northern sections, but only ~5 cm s^{-1} on the Bay of Biscay slopes. This extended altimeter dataset indicates significant regional and seasonal variations, and has revealed new insights into the interannual variability of the SC. It is shown that there is a peak poleward flow at most positions along a ~2000 km stretch of the continental slope from Portugal to Scotland during 1995–1997, but this did not clearly relate to the extreme negative North Atlantic Oscillation (NAO) in the winter of 1995–1996. The speed of the SC exhibited a long term decreasing trend of ~1% per year. By contrast the NAC showed no significant trend over the 20-year period. Major changes in the NAC occurred three times, and these changes followed decreases in the NAO index.

1. Introduction

1.1. Study area

The western edge of the European continental shelf, indicated by the rapid depth change from 200 m to over 2000 m, extends from the coast of the Iberian Peninsula, via the Bay of Biscay to the western edge of Ireland and thence north of Scotland (Fig. 1). Such sharp bathymetric changes limit across-shelf flow, and thus direct bottom or deep-reaching currents along the isobaths. A particular aspect of this is the extension of the North Atlantic Current (NAC) together with the poleward flowing Slope Current (SC) and Eastern Boundary Flow, which provide the main sources of saline and relatively warm Atlantic waters to the Arctic (Fig. 2). The heat imported with this flow keeps northern areas much warmer than would otherwise be the case, and thereby creates favourable conditions for phytoplankton and fish stocks, which bring great economic benefit to the European area (Hansen & Osterhus, 2000; Lehodey et al., 2006). Furthermore, the heat transported is critical for moderating the climate over western Scandinavia, the UK and Western Europe (Moron, Vautard, & Ghil, 1998).

Our study region is the Northeast Atlantic and western edge of the European continental shelf (Fig. 1). The Slope Current is a distinctive feature in the European shelf seas (Hackett & Roed, 1998), driven by a combination of oceanic density gradient and wind stress. The SC is centred on the 500 m isobath with mean speeds of 10 cm s^{-1} increasing to 20 cm s^{-1} over the Shetland Slope (Burrows & Thorpe, 1999; Huthnance, 1986). Fig. 2a shows the paths of the 4 NAC branches in this area, which are also marked by the frequent occurrence of Sea Surface Temperature (SST) fronts in the winter (Miller, Read, & Dale, 2013). The shelf break signature of the SC is also evident from the Celtic Shelf to the Shetland Shelf. The product used for that analysis was based on passive microwave data to provide year-round coverage. Fig. 2b provides a 1 km resolution infrared-based SST composite for January 1996; this shows the path of the SC from Portugal to Scotland along the European shelf slopes. The SC transports an estimated 2 Sv on the Celtic Slope (Pingree & Le Cann, 1989), but 5–8 Sv further north in the Faroe–Shetland Channel (Gould, Loynes, & Backhaus, 1985; Hackett & Roed, 1998; Huthnance, 1986; Pingree & Le Cann, 1989). Numerous studies have suggested that the SC flowing through the Faroe–Shetland channel carries most of the heat that enters the Nordic Seas (Sherwin, Turrell, Jeans, & Dye, 1999).

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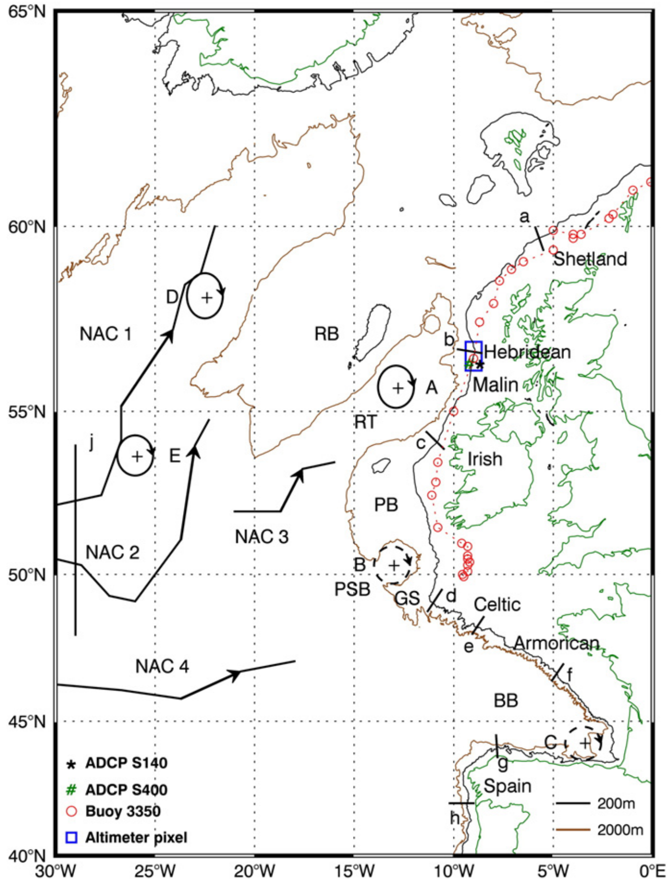

Fig. 1. Map of study area and the locations of SES ADCPs and tracks of drogued ARGOS buoy 3350. The study area covers the European continental shelf in the North East Atlantic Ocean from 40 to 65°N and 30–0°W. Marks A, B, C, D, and E show five geostrophic eddies: in the Rockall Trough, in the Porcupine Sea Bight, in the southeast corner of the Bay of Biscay, in the Maury channel and near the Eriador Seamount with + at the centre of each eddy and an arrow showing sense of rotation. A solid line shows a persistent eddy and a dashed line shows seasonal circulation. Black continuous lines with an arrow show four branches of NAC: 1. through the Iceland Basin; 2. to the west flank of Rockall Bank and Hatton Rockall Basin; 3 through Rockall Trough, 4. west of the Bay of Biscay. Place name abbreviations: PSB, Porcupine Sea Bight; PB, Porcupine Bank; GS, Goban Spur; BB, Bay of Biscay. Seasonality and interannual variability derived at normal sections a–h (see text for details). NAC mean annual current climate series derived at section j.

The SC has been widely studied by analysis of both drogued buoy trajectories and Acoustic Doppler Current Profiler (ADCP) data, enabling some investigation of the seasonal cycle from the Shetland Shelf to the Bay of Biscay. Based on one year's current meter data on the Shetland Shelf, Gould et al. (1985) reported a 7.8 Sv northeast mean transport with maximum (12.6 Sv) in the winter. Burrows and Thorpe (1999) confirmed a 25 to 50 km wide jet-like flow along the slope from the Hebridean Shelf to the Shetland Shelf with 42 drifters, with the suggestion that the flow was faster in the winter and slower in the summer. Using ADCP and current meter data, Souza, Simpson, Harikrishnan, and Malarkey (2001) reported a flow of 20 cm s^{-1} for the SC at a section of the Hebridean Shelf with a seasonal maximum in the winter and weak flow in the summer; whilst an 8-month record of current meters confirmed a SC flow of 10 to 20 cm s^{-1} off Ireland (White & Bowyer, 1997). Further south at the Goban Spur, a ~17 month current meter record also showed maximal northward poleward flow in winter throughout the water column (~1 km) with equatorward flow starting in March/April for two consecutive years (Pingree, Sinha, & Griffiths, 1999). A study of temporary circulatory features was performed by Shoosmith, Richardson, Bower, and Rossby (2005) who identified 96 different eddy features using the trajectories of RAFOS floats near the 27.5 density level. However, due to the limited duration and spatial extent of hydrographic observations and in situ data, full knowledge of the slope current seasonality, especially its interannual, regional variability and long-term trends are still not complete. Therefore, it is essential to make the best use of available satellite altimeter and in situ data to conduct such a long-term analysis.

1.2. Geostrophic currents from altimetry

Satellite altimetry has proved to be a powerful tool for studying open ocean surface geostrophic currents due to its global coverage and the ability to work regardless of weather conditions. Space-borne altimeters have provided an unprecedented continuous 20-year record of sea level, which has been sufficient to reveal interannual signals. Using both altimetry and in situ data, Pingree (2002) studied the structure and climate of the eastern Atlantic Ocean, and showed that the response of the North Atlantic Current lagged the wind stress by ~7 months. He also derived the westward phase speed, period and wavelength for geostrophic eddies as a function of latitude between 20° and 50°N.

More recently, altimetry has been used to characterise the flow and eddies in the Bay of Biscay. Caballero, Pascual, Dibarboure, and Espino (2008) analysed the current system in the southern Bay of Biscay with altimetry data, and found that the maximum sea level occurs in October while the minimum is in April. Le Henaff, Roblou, and Bouffard (2011) characterised the interannual variability of the SC flows along the northern coast of Spain in the winter and Herbert, Ayoub, Marsaleix, and Lyard (2011) also showed that the signature of the SC in the southeast corner of the Bay of Biscay can be depicted with altimeter data. Dussurget, Birol, Morrow, and De Mey (2011) studied eddy properties in the Bay of Biscay using fine resolution altimetry data from wavelet analysis. Caballero et al. (2014) investigated a quasi-stationary eddy in the Bay of Biscay with altimeter, in situ and modelling data, and showed that, for the period 2003–2010, the anticyclonic eddy was present every year from spring to autumn.

To the north, analysis of altimeter data by Richter, Segtnan, and Furevik (2012) revealed that the northeast Atlantic had a pronounced maximum of sea surface height anomaly around 1995 and two strong minima in 1997 and 2003. Berx et al. (2013) used ADCP data to link altimetry records to the flux through the Faroe–Shetland Channel and generated a flux budget time series back to 1992; however, this showed no significant change over that period across the whole channel. Further west, over the region of the Mid Atlantic Ridge, Miller et al. (2013) used oceanic fronts and altimeter data to study the variability of the NAC as it enters the region, and clarified the influence of bathymetric features on surface flow.

However, no study of the whole European slope current area has previously been performed using 20 years of altimeter data together with long-term ADCP and buoy measurements. Therefore, the aim of this paper is to characterise the seasonality and interannual variability of the SC in the region of 40°–65°N, 30°–0°W with this extensive dataset. The regional variability and long-term trends are also presented. A 16-month time series of ADCP measurements and data from a Lagrangian float are used to compare the satellite-derived currents in situations where the flow is expected to be geostrophic (Pingree et al., 1999; Souza et al., 2001).

The rest of the paper is organised as follows: Section 2 gives the details of the data and then Section 3 depicts and discusses the seasonal and interannual variability of the SC and also the NAC centred near 52°N, 30°W. Finally, Section 4 distils the main conclusions.

2. Data

2.1. Satellite altimetry

Satellite altimeters provide measurements of sea surface height only along their sub-satellite tracks, with different instruments occupying different patterns of tracks and having different repeat cycles. Altimeter