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Cross-slope flow in the Atlantic Inflow Current driven by the on-shelf deflection of a slope current

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ABSTRACT

We identify a newly described current, the Atlantic Inflow Current (AIC), a persistent pathway of Atlantic Water from the European Slope onto the Malin Shelf. Using drifters and gliders we examine the vertical and horizontal structure of the AIC and use Lagrangian statistics to quantify lateral mixing along its path. We estimate this current to have a transport of approximately 0.2 Sv, advecting 2.8 TW of heat onto the shelf (referenced to 7 °C) and 2.4 kT/day of the limiting nutrient, nitrate. This nutrient-rich AIC joins the Irish Coastal Current, continuing into the Minch and the outer Hebridean Shelf before ultimately entering the North Sea. The biological consequences of the influx of water masses and nutrients onto the shelf can range from altering primary production, and subsequent food web dynamics, to recruitment of fish larvae from oceanic water. A better understanding of the current dynamics described here is crucial for the assessment of shelf sea primary production and its impacts on carbon draw-down as well as recruitment for commercially important fisheries.

1. Introduction

In common with continental shelf seas worldwide, the Malin Shelf, west of Scotland and north of Ireland, is largely isolated from the deep ocean by a steep slope and the associated slope current at the shelf edge (Burrows and Thorpe, 1999; Souza et al., 2001). Crossing this boundary there is an estimated net on-shelf transport of 0.5 Sv (Huthnance et al., 2009). Evidence of Atlantic Water on the shelf has long been seen, indicating a persistent cross slope flow (Fig. 1) (Ellett, 1979; Inall et al., 2009; Jones et al., 2018). This nutrient-rich (Holt et al., 2012; Siemering et al., 2016), high salinity Atlantic Water continues on the shelf, and mixes with Irish Sea outflow to form the Scottish Coastal Current (SCC) (Hill et al., 1997). The SCC follows one of two paths, either passing inside the Outer Hebrides or recirculating in the Minch to flow west of the Hebrides (Hill et al., 1997) before entering the Nordic (Burrows and Thorpe, 1999) and North Seas (Marsh et al., 2017). The productive shelf regions are linked to the North Atlantic and its variability through the transport associated with these currents. Here we aim to quantify the transport of the North Atlantic sub-polar gyre from the slope current waters onto the Malin shelf.

The Malin Shelf slope is a section of the European continental slope, which is approximately 20–50 km wide (Huthnance and Gould, 1989) and drops from ~ 200 m at the shelf break to depths of up to 2500 m in the Rockall Trough. The combination of this steep topography and the mean meridional density gradient drives a poleward slope current, described in the JEBAR framework (Joint Effect of BAroclinicity and bottom Relief, (Huthnance, 1984)), which is constrained to preferentially track bathymetric contours following the Taylor-Proudman theorem (Simpson and Sharples, 2012). At the latitude of the Malin Shelf (56°N) the slope current has along-slope speeds of order 0.1–0.2 ms^{-1} and can be identified by a core of high salinity Eastern North Atlantic Water (ENAW), centred at approximately 300 m depth, above the 600 m contour (Hill and Mitchelson-Jacob, 1993). The volume transport of the current changes along its length, on average increasing poleward, fed by a zonal geostrophic flow from the west (Marsh et al., 2017).

Along the slope regions of cross-slope exchange and varying slope current stability (Huthnance et al., 2009) are driven by variability in the steepness and roughness of the continental slope. In the Bay of Biscay and the Celtic Sea, toward the southern end of the slope, the slope is steep, irregular and subject to strong internal tide generation, driving cross-slope exchange (e.g. Green et al., 2008; Hopkins et al., 2012). Irregular topography can also drive cross-slope flow through increased eddy activity (Huthnance et al., 2002; Porter et al., 2016a) and through along-canyon flow (Amaro et al., 2016; Porter et al., 2016b). Over these southern sectors of the slope, the slope current

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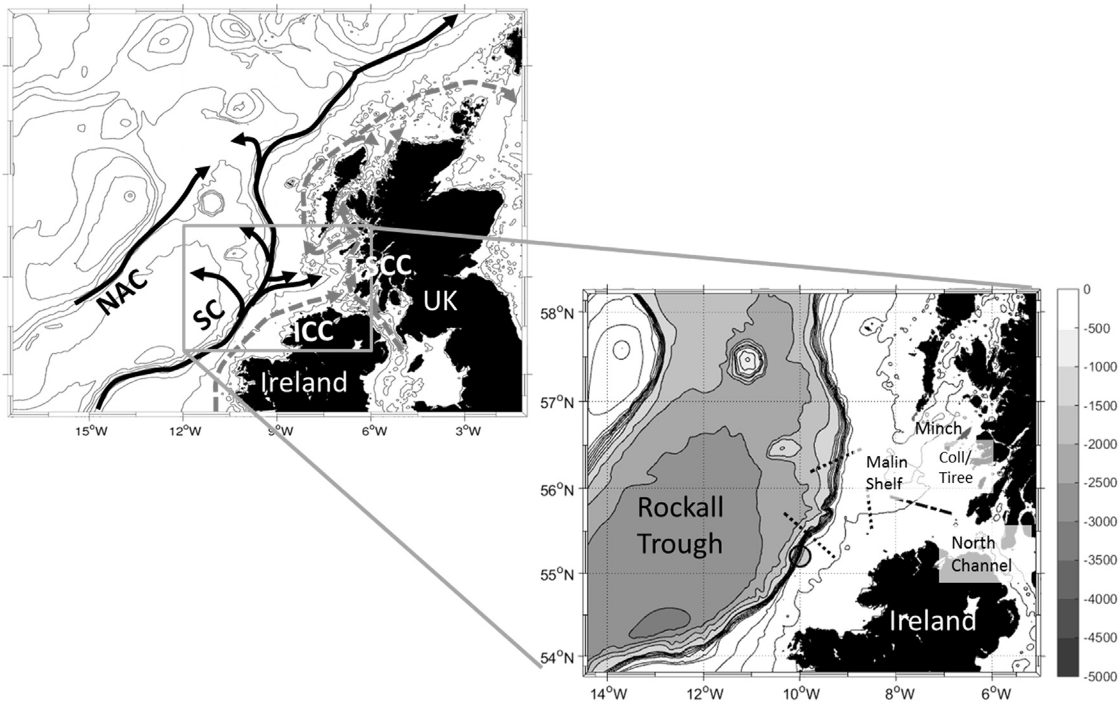

Fig. 1. Bathymetric map of the study regions. Topography is from the GEBCO dataset. Atlantic water pathways in the North Atlantic Current (NAC) and the Slope Current (SC) are shown in solid lines and continental shelf water pathways are shown by dashed lines in the Irish Coastal Current (ICC), the Scottish Coastal Current (SCC) and the Irish Sea outflow. In the inset the drifter release position is shown by the circle, the glider transects by the dotted lines and the high resolution CTD (conductivity, temperature and depth) transect by the dashed line.

reverses seasonally, with an equatorward mode apparent during the summer months (Pingree and Le Cann, 1989; Porter et al., 2016b; Xu et al., 2015). To the north, between the Celtic and Malin Seas, the reversals in the slope current become less significant and the slope topography becomes more regular, while remaining steep. At the Malin Shelf, despite its shallower topographic gradient, the slope generates internal tides which degenerate into non-linear internal waves. During the summer these can locally transport approximately $0.3\,m^2\,s^{-1}$ of water from the slope onto the shelf (Inall et al., 2001). At a shallow canyon at 55.5°N the major axis of the slope changes from southwest-northeast to south-north. To the north of this canyon the slope broadens and the shelf break deepens. This change in slope direction, gradient and the associated deepening of the shelf break are thought to destabilise the slope current (Hill, 1995; Xing and Davies, 2001). It has been speculated that such destabilisation of the slope current may be the source of the Atlantic Water identified on the shelf (Ellett, 1979; Jones, 2016).

In the region near to the canyon at 55.5°N hydrodynamic models show a subsurface poleward current on the outer shelf that turns eastward as the shelf deepens (for example Lynch et al., 2004; Xing and Davies, 2001). This modelled current then continues eastward, parallel to the north coast of Ireland and adjacent to the Irish Coastal Current. However, these models do not demonstrate that this current originates from the slope, rather it is from the outer shelf, and therefore it is unlikely to represent a source of Atlantic Water inflow. Hydrographic and drifter studies on the Malin Shelf, summarised by Ellett (1979), show an eastward flow of Atlantic Water on the shelf which, in agreement with the models, joins the cool Irish Coastal Current along the north coast of Ireland. Xing and Davies (2001) suggest that, depending on local wind forcing, this Atlantic Water then either enters the Irish Sea through the North Channel or, more likely, continues northward toward the Hebrides. Due to the persistent local baroclinic pressure gradient it is however unlikely that the water will flow into the Irish Sea (Brown and Gmitrowicz, 1995; Jones, 2016). In addition to this deeper saline current Lynch et al. (2004) show a shelf-located meandering surface current of $0.1–0.2\,ms^{-1}$ which, has a full depth presence over the 100–120 m contours. However, similarly to the deeper current discussed above, this surface current does not originate on the slope. In summary, whilst an on-shelf Atlantic current has been widely represented within schematics of the local circulation (for example, Ellett, 1979; Inall et al., 2009; Reid et al., 1997) it has not been reproduced in hydrodynamic models (for example, Lynch et al., 2004; Xing and Davies, 2001) and observations and analysis of its structure and variability are lacking.

North Atlantic slope current waters are nutrient-rich (Siemering et al., 2016), thus understanding the dynamics of Atlantic water flowing onto the shelf may provide information to help constrain the primary productivity of the shelf seas. The steep topography of the shelf edge induces mixing within the water column (via internal tide processes), which often creates areas of high productivity (Davidson et al., 2013; Holligan, 1981; Sharples et al., 2009). Areas of high chlorophyll over the slope are clearly visible from satellites (Fig. 2). Furthermore, satellite chlorophyll images reveal the presence of Atlantic inflow on the shelf, frequently visible as a high chlorophyll area that spreads from the slope onto the shelf (Fig. 2 – inset). Approximately 25% of global primary production is estimated to take place in shelf seas (Simpson and Sharples, 2012), thus factors governing shelf sea productivity (such as nutrient input) are important for estimating global primary production and the global biological carbon pump (Muller-Karger et al., 2005).

The dynamics of Atlantic water intrusion onto the shelf may also have a wider biological implication for higher trophic levels. The entrainment of eel larvae from the slope current onto the shelf in the inflow current is thought to sustain Scottish freshwater eel populations (Adams et al., 2013). Furthermore, the transport of various larvae and eggs northwards toward the North and Norwegian Seas in the Slope Current (Reid, 2001) may be disrupted by large scale flow onto the Malin Shelf having impacts on both local and wider fish stocks. The aim of this paper therefore is to further improve our understanding of the local slope-shelf exchange and estimate the impacts on biogeochemical processes on the shelf.