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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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Key words:

Cross-slope flow; gliders, exchange; drifters; nutrients; nitrate flux

Highlights:

- Slope water has been tracked on the European Shelf using drifters and gliders
- The deflection onto the shelf is not captured in models
- The slope water has a higher nitrate concentration that the shelf water, and supplies nutrients to the shelf
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 (Figure 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.
Figure 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.

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 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 $0.3 \text{ m}^2\text{s}^{-1}$ 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 m to 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 (Figure 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 (Figure 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.
During summer 2013, as part of the FASTNEt (Fluxes Across the Sloping Topography of the North East Atlantic) project, we conducted a multi-platform campaign to observe the Slope Current and the Atlantic Inflow Current, to assess their level of interaction as well as the Inflow Current’s magnitude, variability and structure. This work was primarily conducted during cruise JC88 on the RRS James Cook in July 2013. As part of the study 30 satellite tracked GPS drifters were released above the slope, upstream of the shallow canyon, while simultaneously three buoyancy driven gliders were conducting cross slope transects. The three gliders were subsequently replaced by two additional gliders which continued occupation into the winter. Throughout the cruise a vessel mounted Acoustic Doppler Current Profiler (VM-ADCP) operated continuously. Additional descriptive observations of sea surface temperature (SST) and surface chlorophyll were available from satellites. The relative

Figure 2:
False colour chlorophyll-a from the MODIS sensor on the Aqua satellite (NEODAAS, 2017) These images show a mean composite for June 2013. The inset shows an intrusion of water with a higher chlorophyll-a concentration on to the shelf.
timings of instrument deployments are summarised in Table 1, with the details provided in the following section.

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<th>Instrument</th>
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Table 1: The instruments used in this study and their dates of deployment (indicated by the black bars within the table)

2.1 VM-ADCP

The data collected by the 75 kHz VM-ADCP during JC88 give the velocity of the water down to depths of 800 m beneath the ship’s track. During JC88 three cross-slope transects were revisited multiple times, upstream of, downstream of and in the over the shallow slope canyon at 55.5°N (Jones, 2016). Time means of the velocity transects were computed in conjunction with time mean CTD transects, allowing us to establish whether salinity acts as an effective tracer of the slope current water, as has been seen previously (Porter et al., 2016b; Souza et al., 2001).

Due to the complex nature of the tidal velocities on and around the slope, with a significant internal component (Inall et al., 2001), the VM-ADCP data have not been detided. While it has been shown that the along-slope velocity on the Malin Slope can be partly driven or limited by the local tides (Jones, 2016; Stashchuk and Vlasenko, 2017) we have followed Jones (2016) and mitigated the effects of this by averaging co-located transects across a range of tidal phases.

2.2 Drifters

With the intention of tracking the currents implied by previous descriptive work and satellite images, 30 drifters were deployed on the Malin Shelf Slope above the 600 m contour at 55.2°N, on the 17 July 2013. Inspection of VM-ADCP transects made immediately prior to the release (Jones 2016) identified the 600 m isobath as the location for the local core of the Slope Current.
The drifters used were MetOcean SVP (Surface Velocity Program) drifting buoys, with a holey-sock drogue at 15m or 70m (Sybrandy et al., 2009). The drifters were split into two groups; the first 15 were drogued at 15 m, in the surface mixed layer, and the second group were drogued at 70 m, at the bottom of the seasonal pycnocline (deduced from the glider transects).

The drifter positions have been examined to determine drogue loss, grounding, or if the drifter was picked up by a passing vessel. Drogue loss can be determined through a strain gauge on the coupling between the drifter and the tether; a marked reduction in the strain indicates loss, while an increase indicates snagging. Snagging can also be identified using bathymetric charts. Removal of the drifter from the water is signified by changes in the strain gauge, a reduction in transmission frequency (due to the drifters being covered) and changes in the drift patterns reflecting vessel movement. The shelf regions of the Malin and Hebrides Shelves are busy fishing areas with relatively heavy boat traffic. In this high risk environment a total of 3227 drifter days were collected between 17 July 2013 and 6 January 2014.

Given the dominance of the M2 and K1 tides in the region (Rippeth and Inall, 2002) the data were filtered using a 10th order zero phase Butterworth low pass filter with a cut off at 2 cpd, this limits the effects of other high frequency motions, such as inertial oscillations. Any gaps in the position data have been linearly interpolated, with the largest gap being 21 hours.

Throughout this study, individual drifter trajectories have been described in components aligned with ($y$) and perpendicular to ($x$) the movement of the centre of mass of the drifter cluster as a whole (Figure 3 a), and consequently the direction of these components varies through time.
**Figure 3:** Panel a shows the pathway of the shallow drifters over the first 45 days after their release, in grey. The thick black trajectory shows the time mean line, from which the local across and along flow directions are derived. The local bathymetry is shown by thin black lines (higher detail is given in Figure 1) and Coriolis parameter/depth (f/h) contours by dashed lines. Location A is the point at which the shallow drifters stagnated and turned to cross f/h contours (a). Panel b shows the trajectories of all of the drifters throughout their active periods, shaded by the date. Location C in panel b shows the drifter release point, Location D shows where the deeper drifters crossed onto the shelf and Location B where the deeper drifters re-joined the slope.

Details of how the shear and turbulence develop within the current can be described by the dispersion ($D^2$) of the drifters from their centre of mass (LaCasce, 2008), defined in components as:

$$D_x^2 = \left[ (x_m(t) - x_i(t))^2 \right]; \quad D_y^2 = \left[ (y_m(t) - y_i(t))^2 \right]$$

where $x_m(t)$ and $y_m(t)$ give the location of the centre of mass of the drifter cluster at time $t$, $x_i(t)$ and $y_i(t)$ give the location of a given drifter, and the overbar indicates the average over all of the drifters at this time. The change in dispersion through time defines the diffusivity (Batchelor, 1954) in cross and along-flow directions:

$$K_x = \frac{1}{2} \frac{d}{dt} D_x^2; \quad K_y = \frac{1}{2} \frac{d}{dt} D_y^2$$

Additionally, the variance in the velocities of the drifters, relative to the mean current, is the eddy kinetic energy (EKE), defined as:
where \( u' = u - \bar{u} \), with \( u \) being the low pass filtered velocity component in the zonal direction and the overbar indicates the mean of a local 0.25°x0.25° spatial box (Richardson, 1983) \( (v') \) is defined similarly for the meridional component.

2.3 Gliders

A total of five gliders were used, during and after the drifter deployment. The glider missions focussed on cross-slope transects, documenting spatio-temporal changes in the hydrographic structure of the slope, up- and downstream of the shallow canyon at 55.5°N (Figure 1). An additional glider transect was conducted perpendicular to the anticipated trajectory of the drifters.

Concurrent with the drifter deployment, three Slocum gliders (Teledyne_Webb, 2010) fitted with Seabird CTD packages were active in the region. In November 2013, a further two Seagliders (Eriksen et al., 2001) were deployed on the slope. For each of the glider missions the data have been processed to account for errors arising from thermal lag in the CT cell (Garau et al., 2011). The data collected by the Slocum gliders were processed following the methods of Garau et al. (2011) and the Seagliders were processed using the Seaglider basestation v2.08 (Eriksen and UW, 2012), which accounts for the thermal lag using a thermal model of the CT cell.

The glider profiles were collected in a saw tooth pattern and then interpolated onto a telescopic grid, using a Barnes optimal analysis scheme (Barnes, 1994) with a search radius of 10 km, reflecting the local first baroclinic Rossby radius.

2.4 High resolution CTD profiles

On 21 July 2013, ten high-resolution, ship-deployed, temperature and salinity profiles were obtained along a transect between 55.8°N, 8.1°W on the Malin Shelf and near to the Scottish coast at 55.7°N, 7.3°W. This transect crossed the predicted track of the Atlantic inflow Current (AIC) on the shelf to the north of the North Channel.

2.5 Satellites

AVHRR images of SST and chlorophyll-a were collected throughout the drifter experiment (NEODAAS, 2017). Due to cloud cover during the early drifter deployment the coincident satellite data are limited.
3 Results and analysis

The repeat VM-ADCP transects collected during JC88 in July and August 2013 show a poleward along-slope flow with speeds of between 0.1 ms\(^{-1}\) and 0.2 ms\(^{-1}\), between 200 m and 400 m below the surface, extending a distance of up to 10 km oceanward from the shelf break over the slope (Jones 2016). This slope current appears to be consistent both upstream of the canyon (JC88-1), in it (JC88-2) and downstream of it (JC88-3).

3.1 Slope current structure

Slocum gliders occupied two transects (Figure 4), one upstream (south) and one downstream (north) of the drifter release. The two transects were occupied within three weeks of each other, with the downstream transect beginning before the drifter release, on 5 July 2013, and the upstream transect beginning after the drifter release, on 29 July 2013. In our analysis we assume these transects are synoptic.

Both transects show a surface mixed layer (SML) of approximately 40-50 m depth with a corresponding thermocline extending to ~70-80 m. The sub thermocline water is predominantly a mix of North Atlantic Water (absolute salinity = 35.39-35.7 g kg\(^{-1}\), conservative temperature = 8-10 °C (converted from Pollard et al., 1996)) and Eastern North Atlantic Water (absolute salinity = 35.52-35.62 g kg\(^{-1}\), conservative temperature = 9.5-10.5 °C (converted from Pollard et al., 1996)). The thermal stratification weakens with depth; however, the isotherms are observed to diverge close to the slope, in conjunction with a high salinity (S>35.6 g kg\(^{-1}\)) core feature (Figure 4). This salinity feature was present between 250 m and 600 m, extending out ~10 km from the shelf break onto the slope. Given the comparisons of VM-ADCP and salinity data, we interpret this high salinity feature as the European Slope Current. Notably, the downstream transect shows a warmer and more saline slope current core (upstream 35.62<S<35.64, downstream S>35.64). The implied increase in salinity further north supports the hypotheses of the exchange of water within the slope current as it travels poleward, with gains from the North Atlantic (Marsh et al., 2017) and loss to the east (the present study), although further analysis of this is beyond the scope of the present study.
Figure 4:
Glider transects of (a-b) practical salinity and (c-d) conservative temperature, with approximations of the local water masses highlighted. Panels e-f show the T-S scatter plots for each of the two transects. The scatter plots are coloured by sample depth. The background lines depict density. The solid lines on each plot depict the properties of Eastern North Atlantic and North Atlantic Water (converted from Pollard et al., 1996). Panels a, c and e are from a transect conducted in early July 2013 south of the shallow canyon at 55.5°N and panels b, d and f north of it, during late July 2013.
Subsequent glider transects, completed in December 2013 and March 2014, in similar locations to the upstream (July 2013) transect, reveal how the hydrographic structure varies through time (Figure 5). By December the SML had deepened to around 300 m, depressing the salinity signal of the slope current to this depth. Here the signal of the slope current is both more saline and warmer (Figure 5a & c). By March the SML has deepened further to 700-800 m. Accordingly, this spring transect lacked the high salinity signal associated with the slope current. However, this lack of salinity signal is not thought to represent a weaker current because we would expect the maximum along slope flow of the slope current to occur in winter (Pingree et al., 1999).
Figure 5:
Glider transects south of the canyon at 55.5°N, of (a-b) practical salinity and (c-d) conservative temperature. Panels e-f show the T-S scatter plots for each of the two transects. The scatter plots are coloured by sample depth. The background lines depict density. The solid lines on each plot depict the properties of Eastern North Atlantic and North Atlantic Water. Panels a, c and e are from a transect conducted in the December 2013 of the corner at 55.5°N and panels b, d and f in March 2014.

The pathways taken by this Atlantic Water from the slope current onto the shelf are shown by the trajectories of the drifters after they were released into the core of the slope current.
Immediately after release at 55.2°N the drifters were advected poleward along the slope (Figure 3). With an average speed of 0.07 ms\(^{-1}\) the deep (70 m) drogued drifters continued along the slope for three days before reaching an apparent stagnation point at approximately 55.4°N (Location A on Figure 3 a). By day five the shallow drifters had mostly reached this same point, after being advected along the slope at approximately 0.05 ms\(^{-1}\). The shallow drifters remained in this location for up to three days before turning sharply to the east and onto the shelf. Seven of the deeper drifters showed a similar behaviour, but crossed the slope further north, between 55.75°N and 60°N (Location D on Figure 3 b). The remainder of the deep drifters showed more varied behaviour; one travelled west into the Rockall Trough eddy field, five travelled south-west, later returning to the slope and crossing it at more varied and equatorward locations, and finally two drifters continued along the slope from Location A to cross the slope at 56.5°N and 57°N.

After leaving Location A on the slope and crossing onto the shelf, the shallow drifters were advected eastward in a narrow current, to the north of Ireland, towards the North Channel and Islay Front, consistent with the flows identified in modelling studies (Lynch et al., 2004; Xing and Davies, 2001). Dispersion in this current was dominated by along-flow processes, with little dispersion across the primary axis of flow (Figure 6 a, c). The drifters remained in an apparently narrow, jet-like structure in the region to the north of Ireland. This jet-like flow is also consistent with the highly anisotropic EKE (Figure 6 e) with the anisotropy enhanced in the along flow direction in the region north of Ireland. The deeper drifters show similar anisotropy (not shown), but with more extreme along-flow dominance in dispersion and diffusivity. Here, along-flow dispersion was two orders of magnitude greater than in the cross-flow direction. The cross-flow diffusivity saw little overall trend until after day 30, when over the following 10 days there was a rapid increase from 26 m\(^2\)s\(^{-1}\) to over 300 m\(^2\)s\(^{-1}\); this occurred in concert with the drifters reaching the Islay Tidal Mixing Front and associated near surface baroclinic jet (Hill and Simpson, 1989; Simpson et al., 1979). As the drifters were advected northwards their EKE became more isotropic which, combined with the high diffusivities, suggests a region of increased spatial complexity and mixing.
Figure 6:
The mean along- and across-flow dispersion (panels a and c) and diffusivity (panels b and d) over the first 45 days of release for the 15 drifters drogued at 15 m. Panel e shows the local drifter speed and EKE derived from the same drifter trajectories. The sum of the major and minor axis of the red ellipses represents the EKE, while the coloured dots depict the speed.

Of the thirty drifters released over the 600 m contour on the slope, all but eight followed the AIC onto the shelf. Two drifters continued north along the slope before crossing onto the shelf independently. A further six turned westward, leaving the slope and entering the eddy field of the Rockall Trough (Booth, 1988), before returning to the slope. Through this recirculation we are able to see some of the temporal variability in the initial ingress of the AIC onto the Malin Shelf. Of the five drifters that recirculated to the slope through the Rockall Trough, four returned to the slope during August 2013 within a month of their original release date. The final drifter returned to the area in December 2013 before crossing onto the shelf on a similar pathway to that previously seen, indicating some persistence of the onshelf current. These drifters re-joined the slope south (red circle in Figure 3b) of the release location, with the southernmost two crossing onto the shelf soon after returning to the slope.
One of these two drifters crossed the slope in late August, and continued toward the Irish coast (Figure 3 b), joining the Irish Coastal Current, identified by Fernand et al. (2006). The other crossed in December and tracked northward to ultimately join the AIC. The three more northern tracks followed the slope before turning to cross onto the shelf in the AIC (green circle in Figure 3 b), at least one month after the original observations of such behaviour. Drifter occupations of the slope region and their entrainment into the AIC indicate that this current was persistent throughout at least the summer and early winter.

After crossing the slope and following a pathway along the northern coast of Ireland the drifter trajectories became more dispersed as they turned to travel northwards. The presence of the Islay front (Jones, 2016; Simpson et al., 1979) is likely to have limited the eastern extent of this extension of the AIC. During times when this front and the fronts between Coll/Tiree and the Minch were weak, such that their geostrophic control on the current was weak the drifters were able to track towards the Isles of Coll and Tiree or through the Minch and then further into the Hebrides. Otherwise, when the front was strong and present across the mouth of the Minch, the drifters were deflected around the western edge of the Outer Hebrides. Drifters from each of these two pathways are observed to continue through into the North Sea. The CTD transect (conducted with the Microstructure Shear profiler – MSS90) across this northward limb of the AIC shows that the core of Atlantic Water, identified in the glider transect, has mixed with the local shelf waters, however the drifters indicate that the AIC is continuous.

These two sets of drifter tracks indicate the location of a localised AIC. The inflow of Atlantic water onto the Malin Shelf at 55.4°N ultimately acts as a source of Atlantic Water to the North Sea, providing a newly described pathway for this water, in addition to the routes identified by Marsh et al. (2017). The structure of this current is investigated in more detail using glider and CTD transects collected in conjunction with the drifter release.

3.3 The cross flow structure of the Atlantic Inflow Current

3.3.1 Upstream Atlantic Inflow Current transect

Through the analysis of the trajectories of drifters drogued at both 15 m and 70 m, we have shown the presence of an AIC on the Malin Shelf. In order to investigate the hydrographic structure of this current as it travels across the shelf we conducted a glider transect perpendicular to it, north of Ireland (approximately at a longitude of 8.5°W) in September 2013 (Figure 1).
As the drifters advected eastward on the Malin Shelf (in the AIC) they clustered into three distinct groups. The shallow drifters were focused in a narrow band, tracking the edge of the Irish Shelf Front (Huang et al., 1991) (Figure 7), which isolated the inflow current from the warmer and fresher coastal water. The deeper drifters formed two distinct groups, one in a narrow band between 55.75°N and 56°N, which appears to follow the topography, and one more diffuse band to the south.

Figure 7:
Sea surface temperature fronts, derived from AVHRR satellite data between 17 and 23 September 2013 (Panel a) and 23 and 29 September 2013 (Panel b). The blue/red lines show the locations and directions of SST fronts. The Islay front is weak in Panel a, but is stronger and blocks the passage of the drifters in Panel b. The shallow drifter trajectories are shown in grey and the deep in black.

The glider transect (Figure 8 a-c), conducted in September, 30 days after the average day of local drifter presence, shows that deep drifters between 55.75°N and 60°N tracked a warm (10-10.5°C), high salinity (>35.6 g/kg) core of East North Atlantic Water (Figure 8). Assuming that the speed of the drifters as they passed through this region (0.25 ms⁻¹ (Figure 6 e)) is representative of the local velocity, we estimate that this core transports approximately 2.8 TW of heat (referenced to 7°C – the winter minimum identified in Jones et al 2018) in 0.2 Sv of North Atlantic Water (Sal > 35.6) from the slope onto the shelf. This heat flux is likely a major component of the heat flux into the Malin Shelf which loses an average of 2.4 TW of heat into the atmosphere each year (Kalnay et al., 1996). The flux of water increases the
estimate of total cross shelf flow in this region to 1.2 Sv (net 0.7 Sv) from 1 Sv (Huthnance et al., 2009). This is likely an underestimation of the total net water transport as we see a deep saline core, suggesting that the core of the current is in the lower water column but the drifters, throughout the upper water column also largely show evidence of the current, indicating a full depth current.

Through visual inspection of satellite images (Figure 7) and the cross-current glider transect we can see that the shallow drifters approximately track the Irish Shelf Front (Gowen et al., 1998) which separates warm and fresh surface coastal water in the Irish Coastal Current from cooler and more saline surface shelf water. The location of this front appears to persist between July, when the drifters crossed the location of the glider transect, and September, when the glider transect was conducted. The glider transect shows the presence of the Irish Front to a depth of approximately 50 m (Figure 8 a- b), below which a pool of cold water can be seen to spread beyond the limits of the front. This cold pool represents a distinct water mass (Figure 8 c), which Fernand et al. (2006) identified as a signal of the Irish Coastal Current, sourced in the Celtic Sea (Hill et al., 2008).

Figure 8: Panels a and b show the salinity (a) and temperature (b) along the CTD transect, with panels e and f showing the same along the glider transect. Within these the locations of the shallow drifters are shown by the green stars and the deep ones by the pink squares. Panel
c shows the T-S scatter for the glider transect and panel d for the CTD with the heavy black lines indicating the North Atlantic Water and the black square in d highlighting Irish Sea Water.

3.3.2 Downstream Atlantic Inflow Current transect

At the Islay Front the drifters within the AIC turned to flow poleward, remaining as a coherent group, bounded to the east by the front (Simpson et al., 1979). In July, prior to the passage of the drifters (September), this poleward flowing Scottish Coastal Current (SCC) was sampled by a transect of 7 high resolution CTD profiles at ~ 55.75°N between 7.5°W and 8.6°W (Figure 8 d - f). It is clear that across this transect, while the Atlantic Water is largely apparent below 50 m depth, the core of high salinity Atlantic Water is no longer present and the drifters were more dispersed than in the upstream glider section across the AIC. In addition to this, and in contrast to the glider transect across this current, we can see fresher water (S <= 35.2 g/kg) in the surface water toward the east of the transect, likely signal of the outflow from the Irish Sea (Jones, 2016).

The Lagrangian statistics from the drifters combined with the hydrographic profiles from the CTD transect provide evidence that as the AIC progresses poleward along the Malin Shelf it is mixed with the surrounding shelf water and as it flows along the Scottish coast the core of saline Atlantic Water is no longer evident. In conjunction with this, we observed increases in the dispersion from the drifter’s centre of mass, the diffusivity and the EKE, as well as a change in the direction of the EKE isotropy (Figure 6 e). Consequently we interpret this to be a region of high shear, turbulence and therefore mixing. The upper water in the CTD transect is largely warmer and fresher than the glider transect upstream of these profiles, further suggesting significant mixing between the various local water masses (Figure 8). While these two sections are two months apart the structure identified by the CTD transect is consistent with the synoptic structure shown in Jones et al (2017). We see little hydrographic evidence of the core of the AIC in the vicinity of the SCC.

The impact of this current on nutrient fluxes and its continuation through the Hebrides Shelf and onward are discussed further in the following section.

4. Discussion
In the textbook discussion of shelf seas, the advective input of heat is assumed (or demonstrated) to be small in relation to the (seasonal) time rate of change of total heat content (see, for example Simpson and Sharples (2012) Section 2.2.4). Here, however, the advective input of heat from the ocean is non-negligible, and indeed is the same order as the total annual heat loss due to surface processes. For the Malin shelf as a whole, we quantify only an advective input and not any potential advective heat loss to the north, nevertheless significant heat advection does invalidate commonly adopted models of annual temperature cycle in shelf seas (Prandle and Lane, 1995). The effects of heat advection on the Malin shelf (and beyond) are not within our scope; we note though that the effect likely has a significant impact on the annual temperature cycle of this sea region. Here we will discuss the potential physical drivers of this important inflow current and its effect on the local nutrient availability.

4.1 The initialisation of the Atlantic Inflow Current

The stagnation point of the drifter trajectories at 55.54°N (Location A on Figure 3 a) is followed by a sharp change in the direction of the drifters, suggesting the initialisation of the AIC. Neither of these features, nor the current, have been reproduced in hydrodynamic models. The Xing and Davies model and the Lynch model do not reproduce a clear pathway linking the Slope Current to currents north of Ireland. The more recent, high resolution Atlantic Margin 7km Model (AMM7) (CMEMS, 2017) shows that at the time of the drifter observations the streamlines of the model horizontal velocity field do not cross f/h contours (Figure 9) and therefore do not show a pathway that links the slope and shelf. While all of these models show the Slope Current and eastward advection with the Irish Coastal Current they do not explain this observed “jump” between two stable geostrophically balanced currents. As these models are unable to reproduce the observations we look to higher resolution topographic features on the slope and ultimately the local wind field in an attempt to explain the presence of the newly-named Atlantic Inflow Current (AIC).
Figure 9:
The velocity field from the AMM 7 model at (a) 15m and (b) 70m depth. The coloured background on each plot represents the water speed and the arrows, the velocity. The green lines show the drifter trajectories at each depth and the white lines the streamlines of particles released from the drifter release location and in the 10 grid cells east of that.

Whilst there is a clear difference between the behaviour of the drifters drogued at different depths, their pathways prior to points C and D (Figure 3 b) appear to be constrained by the local bathymetry. The consistency of these crossing points when they are revisited by drifters later in the season suggests that they may be the product of a process or feature that is either not unique to the first crossing event or further than it is persistent within the system, although a full analysis is beyond the limits of this dataset.

Contrary to the results of Hill (1995) the flow across the shelf break does not appear to be related to the steepness of the slope (Figure 10), nor does it appear to be linked to the local radius of curvature (derived from GSI (2018)). Instead, Locations A and D are immediately up-stream and downstream respectively of a region of particularly steep and irregular slope geometry (Figure 3 and Figure 10). Upstream of, and directly at, Location A the shallow drifters moved in a cluster, crossing the shelf break, largely together. Noting this clustering behaviour and using a linear least squares approximation and SVD decomposition of the drifter displacements (Okubo and Ebbesmeyer, 1976; Righi and Strub, 2001) we estimate the relative vorticity of the cluster (Figure 11, $\xi/f$, non-dimensionalised by the local Coriolis parameter).

Relative vorticity oscillates periodically with amplitude of approximately ±0.1f, approximately 35 km upstream of Location A (Figure 11). This observation is consistent with the presence of coastal trapped waves (CTWs) propagating northward, with phase speed differing from the mean flow (e.g. Inall et al, 2015). Close to Location A, the vorticity oscillations increase in magnitude, and then cease around the stagnation point (x~30km) (Figure 11), implying either disruption of these possible CTWs by changing topography, or that their phase speed is much less than the mean flow experienced south of x = 30km (Figure 11). Immediately after the eastward turn of the cluster (at Location A), which notably has no relative vorticity signal, the cluster experiences a large and rapid decrease and then increase in relative vorticity (from −0.15f to +0.35f). This behaviour is very curious and
remains unexplained. Thereafter (40km < x < 65km) relative vorticity oscillations return, with reduced amplitude (±0.05f) and longer apparent wavelength (possibly a Doppler effect). After the cluster has left the slope and entered the flat shelf area (x > 65km) relative vorticity oscillations all but disappear. The above discussion suggests that, at the cluster scale (1 to 3 km) variations in flow relative vorticity are consistent with the presence of CTWs, and that the marked right turn of the cluster at Location A is not accompanied by a change in relative vorticity. Although within the scope of this work it is not possible to further probe this. What is apparent, though, are rapid inputs of relative vorticity immediately after the turn.

These km-scale relative vorticity variations effectively offer a high-pass filtered view on the vorticity dynamics of the slope current flow, apparently offering little insight to the larger-scale behaviour. For example, the slope current crossing from 500 m into 600 m would induce a relative vorticity of ~-0.3f, and at Location A, following a drift slightly off slope into deeper water over a distance scale much larger than the cluster scale, the centre of mass of the cluster turns anti-cyclonically. Overall, we suggest that the slope current is destabilised by the complicated topography as it approaches Location A and thus it enters deeper water, inducing negative relative vorticity, potentially initiating the cross slope flow. It is likely that this cross-slope flow is assisted by the prevailing south-westerly wind direction. However, the isolated nature of the slope crossing location suggests that the wind cannot be the primary cause of this behaviour.

Overall, we suggest that the slope current is disrupted by the complicated topography and adjacent coastline as it approaches Location A. To slow the northward passage of the drifters to stagnation, as observed, necessarily implies a pressure gradient adverse to the flow, or greatly enhanced bed friction, or both. Satellite derived sea surface height (SSH) products frequently show higher SSH values on the southern flanks of the Anton Dhorn seamount. In July 2013 there was a meridional SSH difference of approximately 35 cm over 110 km (CMEMS, 2018), south of the Anton Dhorn. However the coarse temporal and spatial resolution of these products does not allow for precise comparison with drifter trajectories. Nonetheless, a pressure gradient towards the south, combined with a reduction in the westward SSH gradient (expected as the distance to the coastal boundary greatly increases to the north of island of Ireland) would result in both a deceleration of the northward flow, and an acceleration of eastward flow (due to loss of geostrophic balance in the u-momentum equation.)
Figure 10: The maximum slope gradient across the 500 m contour (grey) and the curvature (the reciprocal radius of the locally fitting circle) of this same contour (black). The dashed line at 55.4°N and the shaded area between 55.75 °N and 56 °N shows the locations of the main crossing points of the drifters C and D, respectively (Figure 3). The bathymetry used is from the GSI (2018) multibeam survey.

Figure 11: The vorticity of the cluster of shallow drifters as it progressed along the slope, from a linear least squares approximation the dashed black line corresponds to a latitude of 55.45°N, highlighted in Figure 3 (a).

4.2 Nutrient fluxes
Satellite imagery shows bands of high chlorophyll on the shelf, associated with the AIC (Figure 2), suggesting locally high productivity, either advected from the slope as phytoplankton or as a response to increased nutrient levels. These features are often observed
suggesting that this current and its impact on the shelf seas are persistent. On the shelf the primary source of nutrients is the open ocean (Proctor et al., 2003) and productivity is limited by the availability of nitrate and nitrite (hereafter the combination of these is referred to as nitrate) as well as phosphate (Smith et al., 2014). Locally, nitrate and phosphate are correlated to temperature in both horizontal and vertical senses (Siemering et al., 2016).

Using the temperature – nitrate/phosphate relationships identified by Siemering et al. (2016) on the Malin Shelf during 2014 we can infer the flux of nitrate/phosphate onto the shelf in the AIC. In Figure 8 we see that the temperature signal of the AIC is between 10 and 10.5°C, which on the slope coincides with nitrate concentrations of 11-12 mmol/m³. Assuming a continuous AIC transport of 0.2 Sv this input of nitrate onto the shelf represents a flux of 1.2 kmol/s (74.4 kg/s) with respect to a background concentration of 2-5 mmol/m³, on the southern shelf. Similarly we can infer a phosphate flux of 80 mol/s (7.6 kg/s), with respect to a background concentration of 0.26-0.36 mmol/m³.

These estimated fluxes are particularly large when compared to previous estimates of fluxes of 0.14 -1.5 MT/yr of nitrate onto the Malin Shelf and 0.02 – 0.21 MT/yr of phosphate (Proctor et al., 2003), not including AIC transport. If fluxes within the AIC were multiplied up to represent the full year the estimated flux would be approximately 2.3 MT/yr of nitrate and 0.24 MT/yr of phosphate, however this is unrealistic as we do not know the annual stability of this current. Although, assuming that the current is persistent over a month the total flux of the AIC (0.18 MT of nitrate and 0.018 MT of phosphate in 28 days) is comparable to the previous annual estimate.

Mixing of the AIC and its continuation around the Hebrides into the Malin Shelf waters is clearly an important pathway for limiting nutrients in this region and may contribute to the local carbon pump. In addition to potential enhanced growth from influx of nutrients, phytoplankton seed populations might be directly transported from Atlantic waters onto the shelf. This is important for understanding transport of harmful phytoplankton that can be responsible for contamination with biotoxins or mass mortalities of farmed fish and shellfish (Jones et al., 1982; Silke et al., 2005; Whyte et al., 2014). It was previously hypothesised that some species might develop offshore or near the shelf break (Davidson et al., 2009; Gillibrand et al., 2016). Influx of Atlantic water could play a major role in transporting such populations towards coastal regions and aquaculture sites (Gillibrand et al., 2016). Current management of harmful phytoplankton relies on frequent monitoring, with output from hydrodynamic models being recently used in addition to provide information about potential
transport of cells (Silva et al., 2016) www.habreports.org). As mentioned above, the feature observed here is not captured by current generation hydrodynamic models, though may be by the next generation (Guihou et al., 2018). Further work should therefore establish the role of this observed feature in transport of harmful phytoplankton.

5. Summary

In this paper we have used lagrangian data from drifters, and hydrographic data from VM-ADCP, high resolution CTD casts and glider surveys to identify an inflow of Atlantic water onto the Malin Shelf at 55.5°N. The loss of this water from the slope does not appear to reduce the strength or size of the slope current, which increases in transport downstream of this intrusion. Drifter tracks showing on-shelf advection of water suggest potential pathways of local and a persistent supply of slope water onto the shelf.

Using drifter derived velocities we have used a glider transect to estimate a volume transport of Atlantic Water (S > 35.5) in the AIC of 0.2 Sv, with a corresponding heat transport of 8.3 TW (referenced to 0°C) below 70 m. This corresponds to an increase in the total regional cross-shelf transport estimate to 1.2 Sv (net 0.7 Sv). Assuming that this current is largely persistent throughout the year, as is suggested by the drifters, we estimate that it may be responsible for the flux of 74 kg N/s onto the shelf.

We see evidence that water within the AIC mixes, at depth, with waters of the Irish Coastal Current. This mixing then extends to the surface as this current starts to flow poleward, north of the North Channel. The current, comprised of these two water masses then continues through the Hebrides, passing numerous important fishing grounds en-route to the North Sea.

These observations are undoubtedly important for local biological processes, such as fish larvae recruitment, enhanced primary production and potential transport of harmful phytoplankton. Further work should therefore include studies to investigate the direct effect of the observed Atlantic influx on these biological processes. To better assess this it would be desirable to establish the seasonal and inter-annual variation in Atlantic influx as this is likely to affect the biological response of the system. The exact nature of the dynamical processes behind the stagnation and steering of waters from the slope, across the isobaths and onto the shelf remains unclear from analyses possible using the present data sets. Higher resolution hydrodynamic models, such as the AMM60 model (Guihou et al., 2018) soon to replace AMM7 as the operational forecast model for the region, may be able to provide those answers.
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