Journal of Geophysical Research: Oceans

Supporting Information for

Observed variability of the North Atlantic Current in the Rockall Trough from four years of mooring measurements

L. Houpert[1], S. Cunningham[2], N. Fraser[2], C. Johnson[2], N. P. Holliday[1], S. Jones[2], B. Moat[1], D. Rayner[1]

[1]National Oceanography Centre, Southampton, UK

[2]Scottish Association for Marine Science, Oban, UK

Contents of this file

Text S1 to S2

Tables S1 to S2

Figures S1 to S8

Introduction

The files included in the supplementary materials are additional text, figures and tables supporting the analysis presented in the article.

Text S1: **Accuracy of the mooring transport**

The details of the errors associated with the calculation of the mid-basin, western wedge and eastern wedge transport are detailed below.

1 Mid-basin

In the mid-basin the principal sources of error are methodological (vertical and surface extrapolation) and instrumental.

1.1 Methodological: Vertical gridding (200m-1800m)

For the mid-basin geostrophic transport calculation, temperature and salinity data at the Eastern and Western boundaries are linearly interpolated onto a 20 dbar vertical grid from the shallowest (50-100 m) to deepest measurement (1760 m). We assess the gridding errors by subsampling lowered CTD profiles from 28 EEL hydrographic sections (1978-2018) at the location and depths of the moored instruments. These sub-sampled profiles are then vertically gridded as for the mooring data and used to compute the geostrophic transport. The latter is then compared to the geostrophic transport value computed from the full CTD profile. For a complete moored data return, such as in 2015-2016 and 2017-2018, the RMS error is ~0.30 Sv and the mean bias error ~0.10 Sv. Some data losses occurred in other periods resulting in higher RMS and bias errors (Table S1, Figure S5).

1.2 Methodological: Surface extrapolation (10-200m)

The mooring designs have the shallowest measurement at 50 m (100 m before 2017). Therefore, data have to be extrapolated to the surface so that transports can be calculated over the full water column. A number of approaches exist. At the RAPID array, a seasonally-varying climatology is used to determine the vertical gradients of temperature and salinity, with these being used to aid extrapolation of the shallowest temperature and salinity data to the surface (McCarthy et al., 2015). As winter convection in the Rockall Trough can reach 600 m (Holliday et al. 2000) and is spatially and temporally variable, monthly climatologies may not adequately constrain the surface extrapolation. Therefore, we take a simple approach of replicating the shallowest values of temperature and salinity to the surface maintaining a constant geostrophic shear.

The vast majority of the profiles have their shallowest measurements in the 50-200 m range (99.7% for WB1 and 100% for EB1). Strong currents occasionally knock down the moorings with the shallowest instrument being subducted. The deepest events are 233 m at WB1 (September 2015) and 197 m at EB1 (March 2015).

Because the time-varying upper ocean stratification combines with a time-varying shallowest measurement depth, the error in extrapolating the geostrophic shear to the surface also has a time-dependence. To quantify this, we use temperature and salinity profiles extracted at each mooring location from the Monthly Isopycnal / Mixed-layer Ocean Climatology, MIMOC (Schmidtko et al., 2013). These profiles were subsampled at the moored instrument depths and the shallowest temperatures and salinities copied to the surface. The RMS and bias errors over the upper 200 m were computed from the difference of the full and subsampled profiles. To simulate a broader range of variability from the climatology, we repeated this at each mooring data time step by interpolating the monthly climatological profiles on a time vector ranging from -14 to +14 days. Thus, at each mooring timestamp we have 29 samples of the climatology, using the depth of the shallowest instrument at that time, which are used to calculate the mean bias error and the RMS error.

The mean bias error associated with the surface extrapolation is typically less than 0.1 Sv (Table S1)., However, between July 2016 and December 2016, this increases to 0.22 Sv due to data loss at 250m. The RMS errors are generally small (< 0.03 Sv), but can increase up to 0.1 Sv during the period of data loss.

1.3 Instrumental: Measurement accuracy

The accuracy of the moored CTD data are estimated to be 1 dbar, 0.002°C and 0.003 in salinity over the duration of a two-year deployment (McCarthy et al., 2015; https://www.bodc.ac.uk/data/documents/nodb/pdf/37smbrochurejul08.pdf). Using a Monte Carlo approach, we found that both the pressure accuracy and the temperature accuracy lead to a RMS error on transport of 0.01 Sv, while salinity accuracy leads to a RMS error of 0.05 Sv. The combined effect of the pressure, temperature and salinity accuracies leads to a RMS error of 0.05 Sv. The method is detailed below.

For each moored CTD timeseries from the WB and EB moorings, we created an ensemble of 100 members with randomly perturbed pressure, temperature and salinity values. We added to the original timeseries a random error taken from a normal distribution. Because all the moored CTDs are calibrated against the ship-based CTD at the beginning and at the end of the deployment, we do not expect any mean bias between the moored CTDs and therefore the mean of the normal distribution is set to zero for all instruments. We use the assumption that 99.7% of the normally distributed error values lie within two times the moored CTD accuracy. Therefore, the standard deviation of our normal distribution is defined as the moored CTD accuracy divided by three. Then, the mid-basin geostrophic transport is calculated for every ensemble member and the RMS error is estimated as the standard deviation between the 100 ensemble members.

2 Western wedge

In the western wedge the principal sources of error are methodological (horizontal interpolation) and instrumental.

2.1 Methodological: Horizontal interpolation

Cross-section velocities at EEL station E (calculated from 12 LADCP profiles acquired between 1996 and 2018) show a remarkably similar mean and standard deviation compared to the four years of WB1 current-meter measurements (Figure S6). The errors of our method for the western wedge transport calculation were calculated by using data from the EEL LADCP cruises that sampled stations C to F in the Western Rockall Trough. For each cruise, we calculated the western wedge transport following two methods: using the full resolution LADCP velocity field from stations C to F, and using the LADCP profile obtained at station E but extrapolated to cover the entire western wedge area, following the method used to calculate the western wedge mooring transport (see section 3.3),

We found a mean difference between the two methods (mean bias error) of -0.30 Sv and a standard deviation of the difference (RMS error) of 0.62 Sv (Figure S7).

2.2 Instrumental: Measurement accuracy

The accuracy of the moored current meter is ± 1% of the measured value ± 0.5cm/s (https://www.bodc.ac.uk/data/documents/nodb/pdf/datasheet_aquadopp_6000m.pdf). Applying these values to our data results in a maximum transport error of ± 0.24 Sv. We consider this to be effectively 95% of the normally distributed values; thus to compare with our other RMS errors, we divide by 1.96 to obtain the 68% confidence interval giving an error of ± 0.12 Sv.

3 Eastern wedge

In the eastern wedge the principal source of error is due to the repeated losses of ADCP1 and the use of the GLORYS12v1 ocean reanalysis to create velocity time-series at the location ADCP1.

The eastern wedge transport errors are calculated using the data from the EEL LADCP cruises which sampled the eastern wedge. We calculated the error in the upper 750 m by comparing the "full" LADCP velocity field from the LADCP stations O, P, Q1 and Q to the velocity field reconstructed following the same method used for the calculation of the eastern wedge mooring transport (see section 3.4). The reconstruction of the velocity field from EEL data is achieved through three steps: 1) EEL-LADCP cruises are used to create a profile of meridional velocity at the location of EB1 by interpolating the LADCP velocity field; 2) GLORYS12 reanalysis is used to create a profile of meridional velocity at the location of ADCP1 adjusted by + 7.6cm/s so the 2014-2015 GLORYS mean velocity at ADCP1 is the same as the observed one from the recovered ADCP1; 3) The eastern wedge velocity field is created by linearly interpolating the velocity between 9.6°W and 9.3°W and by linearly decreasing them to zero at the edge of the continental shelf (9.2°W). We found a mean bias error in our method of -0.27 Sv and a RMS error of 0.58 Sv (Figure S8).

Transport errors below 750 m are calculated by comparing the "full" LADCP velocity field from the LADCP stations O and P with the reconstructed velocity field (calculated by copying over the velocity interpolated at EB1 into the eastern wedge). We found a mean bias error in our method of -0.06 Sv and a RMS error of 0.10 Sv.

Text S2: Comparison of near-surface current-meters and absolute surface geostrophic currents from altimetry

The surface absolute geostrophic currents from altimetry (mean and standard deviation) for the 2014-2018 period are indicated in Figure 3 (horizontal purple bars) and Table S2. Surface absolute currents have been extracted at WB1 and EB1 locations from the reprocessed global ocean gridded L4 COPERNICUS dataset. The mid-basin surface absolute geostrophic current is calculated from Absolute Dynamic Topography extracted at the locations of WB1 and EB1.

In the mid-basin, the mean and variability of the surface altimetry meridional current matches the near-surface geostrophic velocity (Figure 3). In the Western and Eastern part of the Rockall Trough, the mean absolute surface geostrophic currents from altimetry are lower than the near-surface current meter data. The differences are substantial: 4.6 cm/s at EB1 and -7.4 cm/s at WB1 (Table S2). In addition, the variability of the currents observed in situ is not well captured in the surface altimetry, indicated by the standard deviation of the surface altimetry data being only 52% of the standard deviation of the current observed in situ at WB1. Thus mismatch between in situ observation and satellite altimetry in the basin's boundary currents is consistent with the results of Pujol et al. (2016). They showed that nearly 60% of the energy observed in along-track measurements at wavelengths ranging from 200 to 65 km is missing in the Sea Level Anomaly gridded products.

Table S1: Summary of the errors for each component of the Rockall Trough transport. The bias error and RMS error estimated for the western wedge (WW) and eastern wedge (EW) transports are similar for all deployment periods. The western wedge transport errors are due to the horizontal extrapolation of the current meters and accuracy of the measurements. The eastern wedge errors are due to the horizontal extrapolation and the use of an ocean reanalysis profile at the location of the ADCP mooring. The mid-basin transport errors are due to the vertical gridding, the surface extrapolation and the accuracy of the measurements. The higher mean bias error and RMS error found in 2014-2015 are due to the failure of the the CTD deployed at 1000m on EB1. The loss of the CTD deployed at 250m on EB1 in March 2017 explains the higher errors found between July 2016 and May 2017. Two other events occurred during that third deployment which changed the array configuration: 1) in December 2016, the CTD deployed at 100m on EB1 slid the wire down to 240m but continued working correctly; 2) in March 2017, the top 400m of the EB1 mooring broke, certainly due to fishing activities. The upper CTD and current meter were recovered on the shore of St Kilda by a local boat and we were able to use the data prior to the breaking of the line. However, from March 2017 to May 2017, we reconstructed the temperature and salinity at 100m depth on EB1 using linear regressions with the temperature and salinity timeseries from the WB1 CTD located at 100m depth (correlation coefficients of 0.93 for temperature and 0.85 for salinity over the 2014-2016). The surface extrapolation error on the mid-basin transport calculation has a significant time-varying component (Figure S5) therefore we also indicate the minimum and maximum of the bias error for each deployment.

	Jul14 - Jul18	
	Bias (Sv)	RMS (Sv)
Total WW	**-0.30**	**0.63**
Total EW	**0.21**	**0.59**

		Jul 14 – Jun 15		Jun 15 – Jul 16		Jul 16- Dec 16		Dec 16–Mar17		Mar 17–May17		May 17 – Jul 18	
		bias (Sv)	RMS (Sv)	bias (Sv)	RMS (Sv)	bias (Sv)	RMS (Sv)	bias (Sv)	RMS (Sv)	bias (Sv)	RMS (Sv)	bias (Sv)	RMS (Sv)
mid-basin	Gridding	-0.25	0.65	0.10	0.27	0.19	0.28	-0.02	0.31	0.28	0.28	0.12	0.28
	Surface extrap. *[min; max]	-0.05 *[-0.09; 0.05]*	0.01 *[0.00; 0.03]*	0.02 *[-0.09; 0.17]*	0.01 *[0.00; 0.03]*	0.22 *[0.08; 0.35]*	0.03 *[0.00; 0.10]*	-0.01 *[-0.11; 0.06]*	0.02 *[0.00; 0.07]*	0.19 *[0.16; 0.22]*	0.01 *[-0.01; 0.01]*	-0.01 *[-0.07; 0.08]*	0.01 *[0.00; 0.03]*
	Instrument accuracy	0	0.05	0	0.05	0	0.05	0	0.05	0	0.05	0	0.05
	Tot. mid-basin *[min; max]	-0.30 *[-0.33; -0.19]*	0.68 *[0.68; 0.68]*	**0.11** *[0.02; 0.27]*	**0.34** *[0.33; 0.33]*	0.41 *[0.27; 0.55]*	0.34 *[0.33; 0.34]*	-0.03 *[-0.13; 0.04]*	0.36 *[0.36; 0.37]*	0.47 *[0.44; 0.50]*	0.34 *[0.34; 0.34]*	**0.11** *[0.05; 0.20]*	**0.33** *[0.33; 0.34]*
Total Rockall Trough *[min; max]*		-0.39 *[-0.43; -0.29]*	1.10	**0.03** *[-0.07; 0.19]*	**0.93**	0.32 *[0.18; 0.46]*	0.93	-0.12 *[-0.22; -0.05]*	0.94	0.38 *[0.34; 0.41]*	0.93	**0.03** *[-0.03; 0.11]*	**0.93**

Formatted: Numbering: Continuous

Table S2: Comparisons of the 4-year mean (standard deviation) of the surface absolute meridional geostrophic current from gridded altimetry with meridional velocity from the mooring array. Meridional currents from the mooring array are computed from the near-surface current meters (100 m depth) at WB1 and EB1, and from the mid-basin geostrophic current calculated at 100 m depth. Mooring and altimetry data are both low-pass filtered with a 25-day window. Units are cm/s.

	WB1	mid-basin	EB1
Mooring	-7.2 (14.5)	3.5 (1.8)	5.5 (10.7)
Altimetry	0.2 (7.6)	4.2 (1.7)	0.9 (8.0)
Difference	-7.4 (6.9)	-0.7 (0.1)	4.6 (2.7)

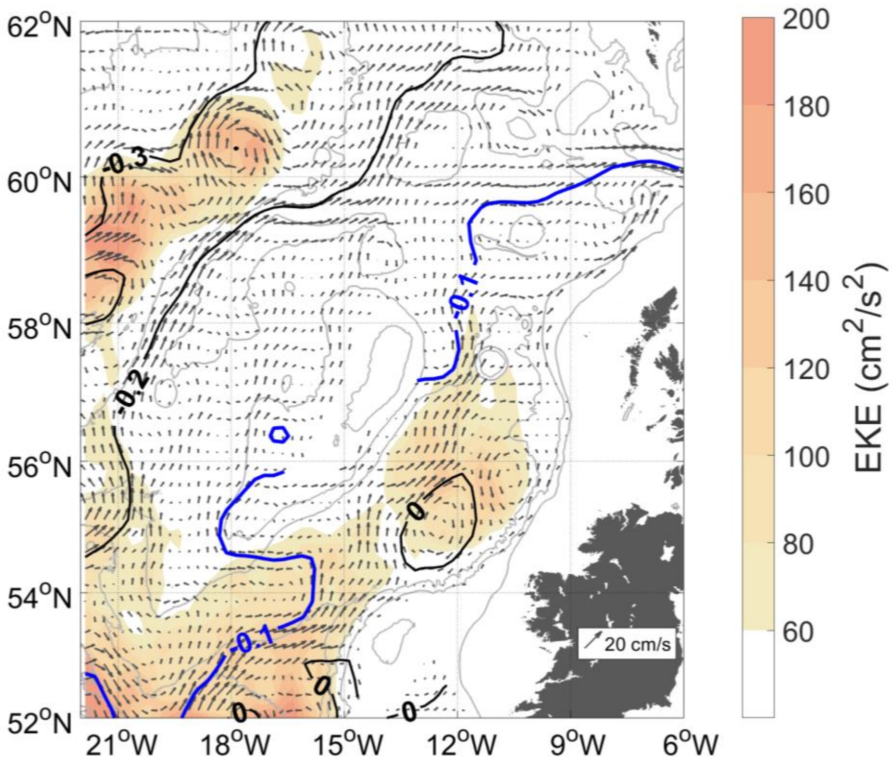

Figure S1: 4-year mean 90-day low-pass filtered EKE (red color scale) and surface absolute geostrophic current (black arrows) calculated during the Jul. 2014 – Jul. 2018 period. Data are plotted for water depth deeper than 400 m and velocity superior to 2.5 cm/s . The mean absolute dynamic topography contours are plotted as thick black lines with a contour interval of 0.1 m. Bathymetry contours from ETOPO are shown in grey for the 200, 1000, 2000, and 3000 m contours. Acronyms: eddy kinetic energy (EKE); Earth TOPOgraphic database (ETOPO).

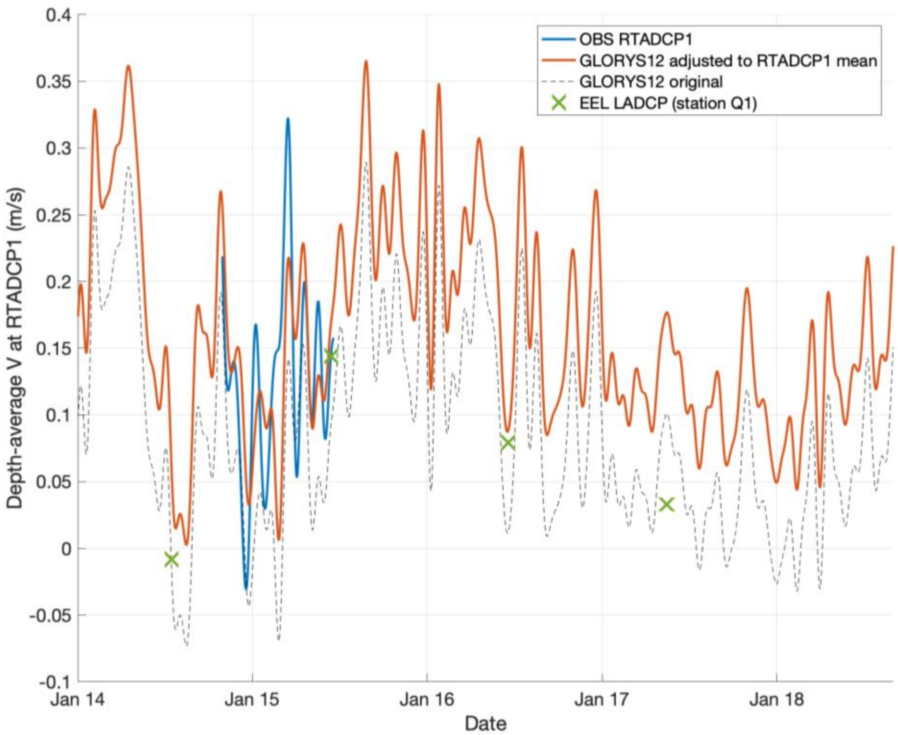

Figure S2: Depth-average meridional velocity V at the ADCP1 location (57.1°N, 9.3°W, water depth of 750m) from 8-months of ADCP observations (blue), from GLORYS12v1 reanalysis (black dashed line), from GLORYS12v1 adjusted to the 8-month mean of the ADCP observations (red line), and from LADCP profiles carried out during the Extended Ellett Line cruises (green crosses). The ADCP and GLORYS time-series are 25-day low-pass filtered so their variability reflects similar timescales. The LADCP are de-tided using barotropic tides at the time of each cast, obtained from the Oregon State University Tidal Inversion Software (Egbert & Erofeeva, 2002; https://www.tpxo.net/).

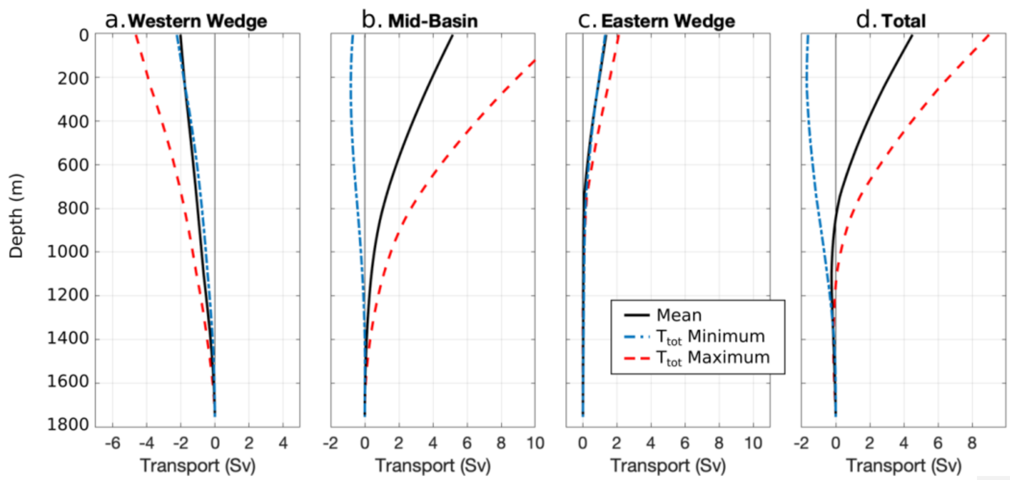

Figure S3: Cumulative transport integrated from 1760 m to the surface are shown for the western wedge (a), the mid-basin (b), the eastern wedge (c) and the whole section (d). The black solid line corresponds to the 4-year mean. The dashed lines correspond to cumulative transports at the time of the total Rockall Trough transport extrema (the minimum on July 2017 is in blue, the maximum on August 2016 is in red).

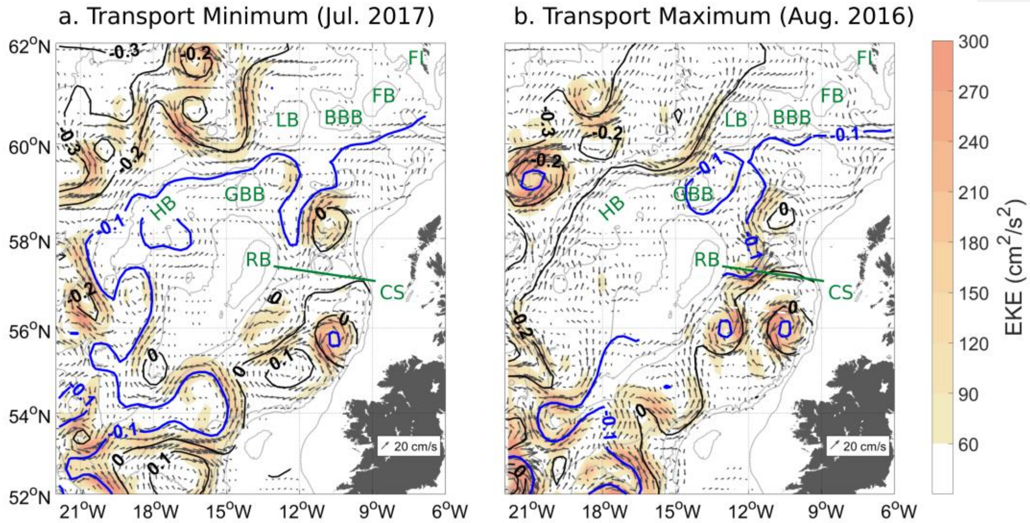

Figure S4: 90-day low-pass filtered EKE (red color scale) and surface absolute geostrophic current (black arrows) at the time when minimum transport (a) and maximum transport (b) are recorded in the Rockall Trough. The composite states for low and high transport periods are shown on Figure 7. Data are plotted for water depth deeper than 400 m and velocity superior to 2.5 cm/s . The green line along 57.5°N indicates the line along which our mooring array is deployed. The mean absolute dynamic topography contours are plotted as thick black lines with a contour interval of 0.1 m. Bathymetry contours from ETOPO are shown in grey for the 200, 1000, 2000, and 3000 m contours. Acronyms: eddy kinetic energy (EKE); Earth TOPOgraphic database (ETOPO); other acronyms are defined in Figure 1.

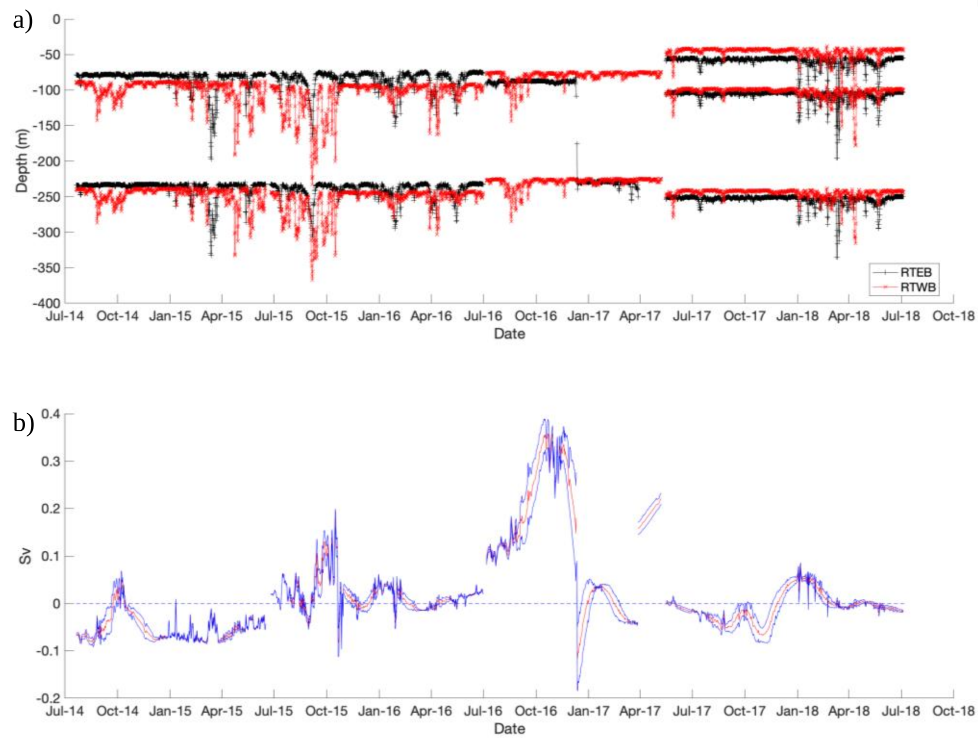

Figure S5: (a) Time-series of the near-surface pressure from the mooring instruments deployed on EB1 and WB1; (b) Mean bias error (red line) ± rms error (blue lines) of the transport calculated above 200 m due to the extrapolation of the geostrophic shear from the shallowest instrument depth to the surface.

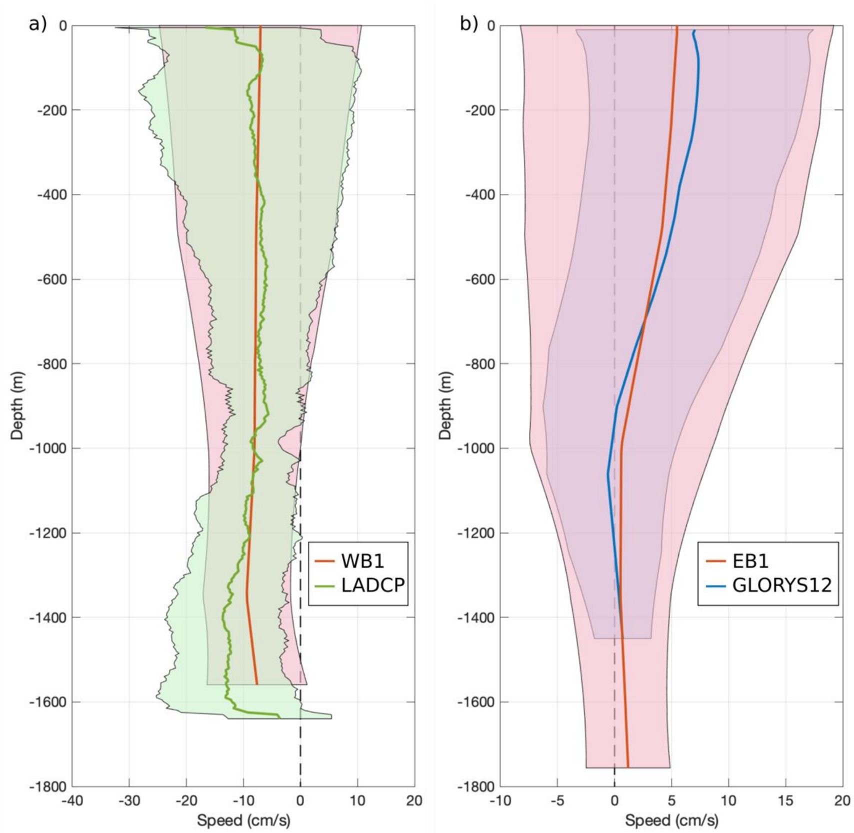

Figure S6: (a) Mean and standard deviation of the meridional velocity at the WB1 location from 4-years of OSNAP current meters (red line) and LADCP data from 12 EEL summer cruises which took place between 1996 and 2017 (green line); (b) 4-year mean meridional velocity profiles from mooring measurements at the EB1 location (red line) and GLORYS12v1 reanalysis at the same location (blue line). The shaded areas show the mean ± one standard deviation.

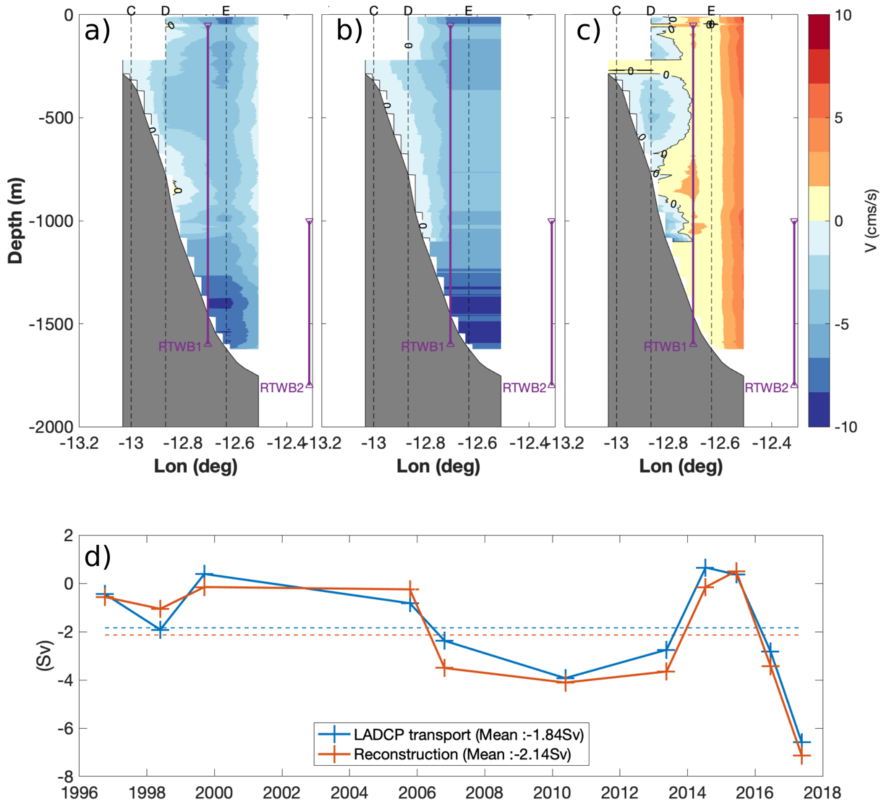

Figure S7: (a) Mean cross-section LADCP velocities over the Western Wedge area, calculated from the 11 EEL cruises which occupied all stations C, D, E and F; (b) cross-section velocity reconstructed from the LADCP profiles taken at station E and extrapolated to the western wedge area following the method indicated in this article: 1) EEL-LADCP cruises are used to create a profile of meridional velocity at WB1 location by interpolating the LADCP velocity field; 2) the western wedge velocity field is created by extending uniformly the WB1 velocities eastward to -12.5 °W, whilst west of WB1, velocities are linearly interpolated between those at WB1 to zero, either at the eastern boundary of the wedge (13.0 °W) or the seabed if this was intercepted; 3) the upper 250 m of the western wedge is filled by linearly interpolating velocities from WB1 to zero at

12.9 °W, instead of 13.0 °W in order to exclude from our calculation a northward flow recirculating around Rockall Bank (see the transport calculation section); (c) Mean difference between the LADCP velocities section and the reconstructed Western Wedge velocities; (d) Western Wedge transport calculated from the LADCP velocity profiles of every EEL cruise which occupied stations C, D, E and F (blue line) and from the reconstructed velocity field (red line); the mean (± one standard deviation) of the transport differences is 0.30 (± 0.62 Sv)

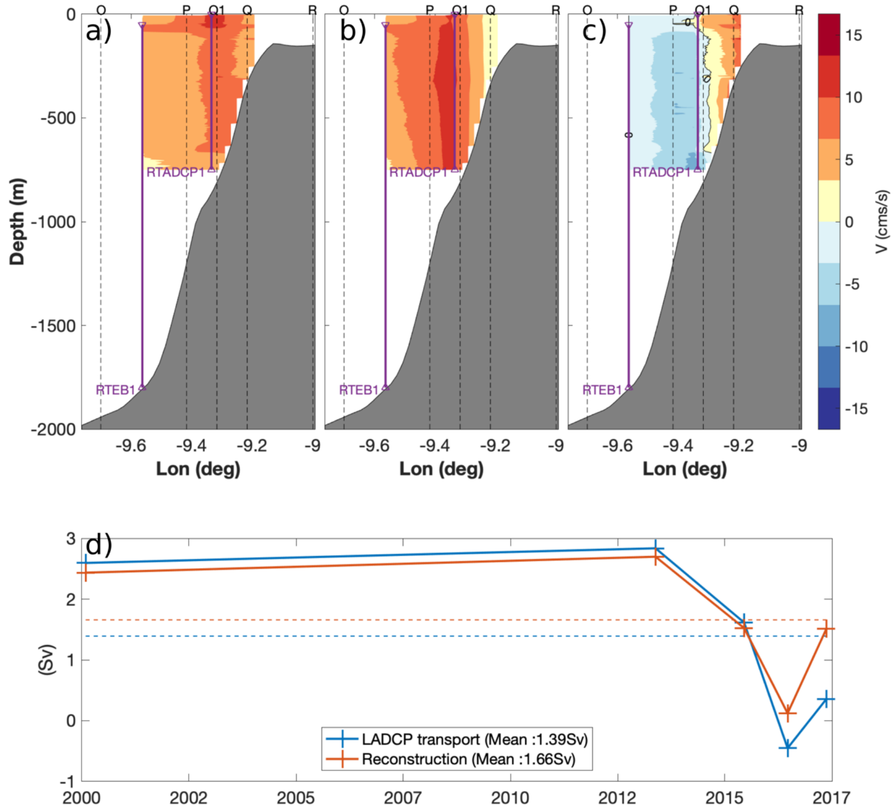

Figure S8: (a) Mean cross-section LADCP velocities over the upper Eastern Wedge area (<750m), calculated from the 5 EEL cruises which occupied all stations O, P, Q1 and Q; (b) cross-section velocity reconstructed following the method presented in this article: 1) EEL-LADCP cruises are used to create a profile of meridional velocity at EB1 location by interpolating the LADCP velocity field; 2) GLORYS12 reanalysis is used to create a profile of meridional velocity at RTADCP1 location adjusted by + 7.6 cm/s so the 2014-2015 GLORYS mean velocity at RTADCP1 is the same than the observed one from ADCP1 deployment; 3) The Eastern Wedge velocity field is created by linearly interpolated the velocity between 9.6W and 9.3W and by linearly decreasing them to zero at the edge of the continental shelf (9.2 °W); (c) Mean difference between the LADCP velocities section and the reconstructed upper 750 m Eastern Wedge velocities; (d) Eastern Wedge transport calculated from the LADCP velocity profiles of every EEL cruises which occupied station O, P, Q1 and Q (blue line) and from the reconstructed velocity field (red line); the mean (± one standard deviation) of the transport differences is -0.27 (± 0.58 Sv)