

The response of the circulation in the Faroe-Shetland Channel to the North Atlantic Oscillation

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ABSTRACT

This study, based on satellite-derived sea-surface heights and temperatures as well as hydrographic data, attempts to shed some light on the role of the extreme phases of the North Atlantic Oscillation (NAO) for the local dynamics of the Faroe-Shetland Channel (FSC). During the low-NAO event 2009–10 the Shetland-slope current showed a significant deflection from its usual path above the maximal gradient of the bathymetry, ultimately resulting in an anticyclone. This led to an accumulation of North Atlantic Water (NAW) over the deeper parts of the channel, manifested as a pronounced deepening of the halocline. Leading this deflection of the slope current by around 2 weeks, a cyclonic eddy associated with a doming of the halocline and originating from north of the Faroes (and hence constituted by Modified North Atlantic Waters) had moved southwards in the channel, coming to rest at its southern entrance. Assessing the influence of the NAO on these regional dynamics using 1992–2010 altimetric data, it was found that for positive phases of the NAO, the surface circulation tended to be strongly bathymetrically constrained and thus resembles the mean regional circulation. The negative phases of the NAO are associated with a regional weakening of the wind-stress curl, which leads to a contraction of the Norwegian-Sea gyre and a linked northward migration of the FSC recirculation involving a deflected path of the Shetland-slope current. This change in the circulation under negative NAO conditions may have an impact on the regional ocean climate through the accumulation of saline NAW in the channel.

Keywords: satellite altimetry, slope current, North Atlantic Oscillation, mesoscale dynamics, Norwegian-Sea gyre, topographic control

1. Introduction

The Faroe-Shetland Channel (FSC), shown in Fig. 1, is delimited to the east by the Shetland shelf and to the west by the Faroe plateau. It is an important choke-point for the global thermohaline circulation since this is a region of significant inflow of warm Atlantic surface waters to the Norwegian Sea and towards the Arctic as well as of the return outflow of cold deep waters. The FSC is one of the best surveyed areas in the world, regular hydrographic work here having commenced as far back as the 1880s. Helland-Hansen and Nansen (1909) noted that this passage is an area of intense dynamic activity, a feature that later has been confirmed by, for example, Tait (1957) and Poulain et al. (1996). This is ultimately due to the North Atlantic current and its two-branch extension in

the Faroe region. One of these branches, composed of North Atlantic Water (NAW; $T > 9.5$ °C, $S > 35.3$ psu), crosses the Wyville-Thomson ridge (WTR) and continues along the eastern slope of the FSC. The other enters the Norwegian Sea via the Iceland-Faroe gap and partially merges with the Norwegian-Sea gyre and hence moves eastwards before discharging Modified North Atlantic Waters (MNAW; $7 < T < 9$ °C, $35.1 < S < 35.3$ psu) southwards along the Faroe Plateau. These waters recirculate in the FSC and join the Shetland-slope current.

Most recently, the internal dynamics of the FSC recirculation have been investigated by Sherwin and co-workers in two important papers primarily focused on mesoscale eddies within the passage (Sherwin et al., 1999, 2006). A key point in the first of these studies was the identification of an eddy-induced 70 km deflection offshore of the Shetland-slope current. In the subsequent paper, this mesoscale variability was explained in terms of baroclinic instability, although it should be noted that this mechanism cannot explain the specific locations of the highly energetic eddies.

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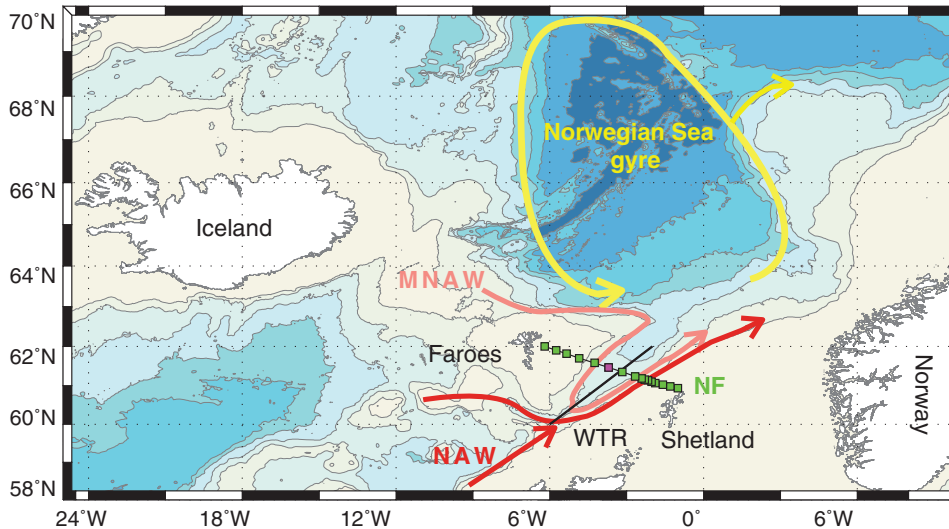


Fig. 1. Map of the Faroe-Shetland Channel (FSC) region including bathymetry and a schematic representation of the large-scale surface currents. South of the Norwegian-Sea gyre, the inflow from the Atlantic is seen to have two main branches: one, constituted by Modified North Atlantic Waters (MNAW), which crosses the Iceland-Farøe Ridge west of the Farøes, and an eastern branch traversing the Wyville-Thomson Ridge (WTR) which transports North Atlantic Waters (NAW). Green squares show the hydrographic stations of the Nølsøy-Flugga (NF) section; temperature–salinity diagrams are based on the station in magenta. The black line in the middle of the channel is used for time-latitude diagram analysis.

Otto and Van Aken (1996) noted that a drifter that had crossed the Iceland-Farøe Ridge and moved eastwards north of the Farøes hereafter was trapped for 2 months by a cyclonic eddy in the northern deep part of the FSC. In a model study of the FSC, Oey (1998) confirmed the energetics of the eddies in the passage and that these induced the Shetland-slope current to assume a wave-like structure, a feature that was attributed to ageostrophic dynamics, consonant with previous results of Spall (1997).

A deeper understanding of the internal dynamics of the FSC requires an analysis of its response to atmospheric forcing. In this context, it is, as will be recognised, useful to let the perspective encompass the entire North Atlantic. Westerly winds are of particular interest, their strength frequently measured in terms of the meridional sea-level pressure difference between the Icelandic low and the Azores high, an approach pioneered by Walker (1924). This pressure dipole is regarded as one of the large-scale modes of climate variability and is, in one or another of the forms whereby it can be quantified as an index, commonly referred to as the North Atlantic Oscillation (NAO). When it is in its positive or negative phase, westerly winds over the North Atlantic are stronger or weaker, respectively, than normally is the case. This evidently affects the dynamics of the FSC, not least via the European continental-shelf slope current extending from well south of Ireland into the Norwegian Sea towards the Arctic (Skagseth, 2004).

Consequently, the present study will deal with the following question: How do the local dynamics in the FSC respond to the atmospheric forcing as mirrored by the NAO? This has, to the best of our knowledge, not yet been investigated, but, as to be demonstrated here, taking into account this putative linkage may cast new light on the physical regime characterising the passage. Since it was found that the most striking changes from the well-known mean circulation in the Farøe region (see Fig. 1) take place during periods of negative NAO indices, the study is initiated by examining the autumn–winter event in 2009–10 (DJF) which occurred for a record-low NAO index of -5.1 (see e.g. <http://www.cgd.ucar.edu/cas/jhurrell/indices.html>). The study is commenced by examining observational data and hereafter takes a broader approach in order to assess the influence of the two different NAO regimes on conditions in the FSC. The present investigation could serve as a guideline for the FSC dynamic activity to be expected during extreme NAO periods, which should be seen in the light of previous NAO-related investigations primarily limited to how the magnitude of the Atlantic-water inflow in the FSC is affected by the NAO (see Nilsen et al., 2003).

2. Data and methodology

The global satellite-altimetric sea-surface height (SSH) data in weekly form utilised in this study are merged from a

number of satellite missions (Ducet et al., 2000), a method that significantly improves the estimates of mesoscale signals (Pascual et al., 2006). This $1/3^\circ$ Mercator-projected gridded data set, denoted SSALTO/DUACS (multimission ground Segment for ALTimetry, Orbitography and precise localisation/Developing Use of Altimetry for Climate Studies), was obtained courtesy of the French archive AVISO (Archiving, Validation and Interpretation of Satellite Oceanographic Data, <http://www.aviso.oceanobs.com>). Geophysical corrections pertaining to tidal, inverse barometric and dry/wet tropospheric effects have been applied to the data set. The period under investigation stretches from 14 October 1992 to 29 December 2010. Gridded ($1/3^\circ \times 1/3^\circ$) maps of the absolute dynamic topography (ADT), determined as the sum of the of sea-level anomalies (SLA) and the mean dynamic topography, viz the SSHs with respect to the marine geoid (Rio and Hernandez, 2004), are used to determine geostrophic velocities based on finite-difference approximations:

$$u_g = -\frac{g}{f} \frac{\partial ADT}{\partial y}, \quad (1)$$

$$v_g = \frac{g}{f} \frac{\partial ADT}{\partial x}. \quad (2)$$

Here u_g and v_g are the zonal and meridional absolute geostrophic velocities, g the gravitational acceleration and f the Coriolis parameter. Additionally, geostrophic velocity anomalies calculated from the SLAs are used to determine the eddy kinetic energy (EKE):

$$EKE = \frac{1}{2} (u_g'^2 + v_g'^2), \quad (3)$$

where

$$u_g' = -\frac{g}{f} \frac{\partial SLA}{\partial y}, \quad (4)$$

$$v_g' = \frac{g}{f} \frac{\partial SLA}{\partial x}. \quad (5)$$

To investigate the response of conditions in the FSC to the NAO, composites of the ADT-, EKE-, and flow fields have been assembled for situations with extremely positive (≥ 3) and negative (≤ -3) NAO indices (henceforth referred to as high/low NAO). Based on weekly averages of daily NAO indices (Li and Wang, 2003), 33 and 32 altimetric-data weeks from the years 1992–2010 were found to fall within these extreme categories. Note that this NAO index encompasses the entire North Atlantic sector, 80°W to 30°E and between 35°N and 65°N , and hence does justice to the large-scale features of the NAO.

The hydrographic data to be analysed originate from the Nólsoy-Flugga section extending from the Shetland shelf to the Faroe plateau (green squares in Fig. 1). This transect is

jointly monitored by the Scottish Fisheries Services and the Faroese Marine Laboratory. The salinity distributions across the entire section on two different occasions are shown. Temperature–salinity (T–S) diagrams are calculated from a single, centrally located station, see the magenta square in Fig. 1. The conductivity-temperature-depth (CTD) data, obtained by courtesy of Barbara Berx at the Fisheries Research Services, have been manually despiked and subsequently low-pass filtered before being averaged into 1 m depth bins. The altimetric and hydrographic data are complemented by satellite-derived composites of NEODAAS sea-surface temperatures (SSTs) from the last months of 2009.

3. Observational results

In this section, results based on altimetric observations and hydrographic surveys of the 2009–10 winter event are presented as well as some illustrations of the NAO-dependence of the physical regime characterising the channel.

3.1. The spatial and temporal evolution of the 2009–10 event

Figure 2 shows the evolution of the SSH and the associated geostrophic velocities in the FSC region during autumn and winter of 2009–10. North of the Faroes, the interior of the Norwegian Sea is characterised by the large-scale depressed ADT, whereas to the south polewards-moving warm Atlantic water is constantly present. Their resulting interaction is one of the dominating features giving rise to the complex dynamics of the FSC. On 14 October, an isolated cyclonic eddy moved southwards into the channel and is visible east of the Faroes. This vortex is characterised by a depressed sea-surface in contrast to the higher levels surrounding it. Around 1 month later, 25 November, the cyclonic eddy moved slightly southwards, while enveloped by slope water of Atlantic origin that intrudes over the central parts of the passage. On 30 December, the slope current is seen to have made an excursion over the deeper parts of the FSC. Subsequently, an anticyclonic eddy is formed, and distinct ADT gradients between the counter-rotating eddies dominate the interior of the channel. This dipole structure persists until 17 February, see Fig. 2d which shows that the cyclonic vortex has deepened and become more elongated in the along-channel direction, a shape that appears to have adapted to the channel morphology. This cyclonic eddy is located over a topographic rise (note the break of the 1000 m isobaths), a feature which appears to be essential for the stabilisation of the eddy. The ADT levels of the anticyclonic eddy have

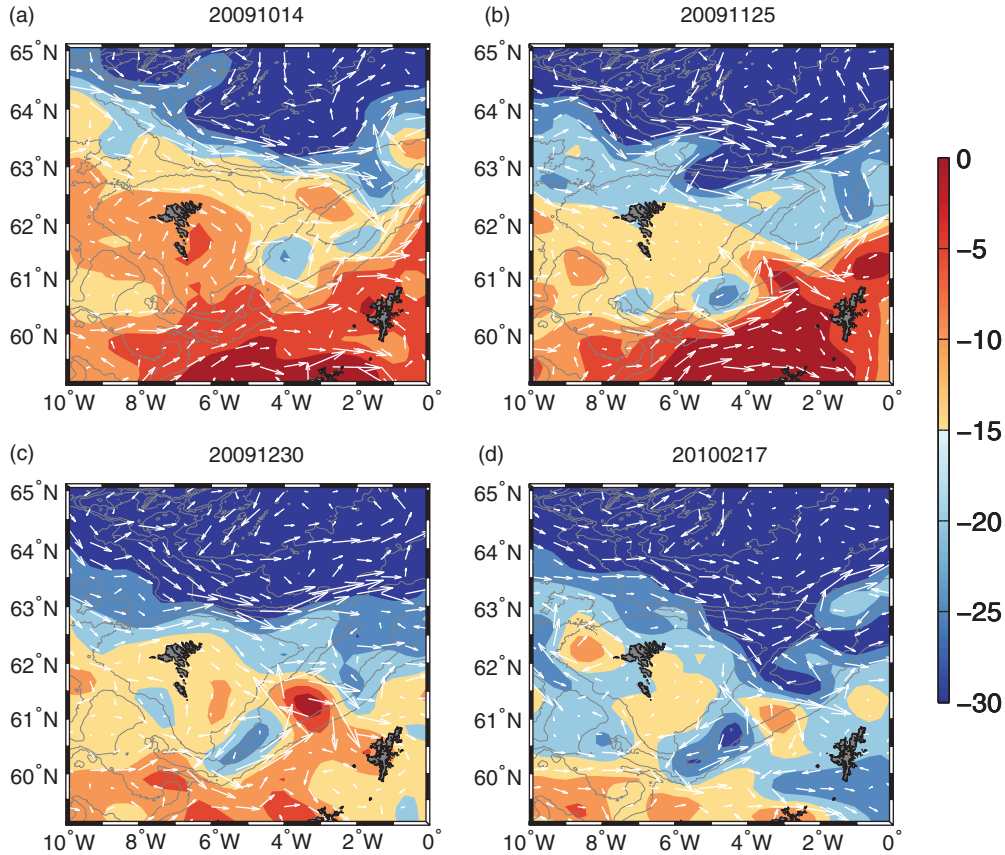


Fig. 2. Suite of absolute dynamic topographies (cm) and associated geostrophic-velocity vectors from November 2009 to February 2010. Black lines represent isobaths with 500 m spacing down to 1500 m. The diagram illustrates the sequence of events associated with the deflection of the Shetland-slope current.

now decreased, indicating its diminishing strength associated with the damping stage, but it should be noted that its high ADT level is still visible. These counteracting eddies undergo different stages, in the case under consideration here having a life cycle of around 5 months, but once having reached a pronounced dipole pattern, their existence is prolonged.

From Fig. 3 it is recognised that the largest geostrophic velocities are found along the edge of the deflected slope current. During the early phase of the deflection, the overall speeds are low compared to those during the later stages. On 25 November, a significant increase of the velocities is clearly seen, and the greatest speeds (around 40 cm s^{-1}) are found on the eastern side of the southern entrance to the FSC. It appears likely that these high speeds are caused by the cyclonic-eddy ADT gradients reinforced by the confluence of the isobaths, which appears to locally enhance the inflow of Atlantic water into the FSC, see Skagseth et al. (2004). It should be noted that even though the path of the slope current is deformed in the channel, a continuation to the Norwegian Sea is discernible.

This large-scale feature is interrupted when the counteracting eddies have organised themselves during December and the current instead follows a highly convoluted track within the channel. Even though the overall evolution seems to comprise different stages, some common traits can be distinguished. Thus the November and December situations show the Faroe and Shetland-slope currents as not interacting, whereas during October and February they are linked to one another, viz. a return to the classical picture of the FSC recirculation given in Fig. 1.

The time-latitude (Hovmöller) diagram in Fig. 4 shows the along-channel gradient of the ADT from the beginning of September 2009 until the end of March 2010. The section used to construct this graph runs down the middle of the passage; hence, the diagram does not show the initial stages of the cyclonic vortex on the Faroe slope. From the Hovmöller diagram, it can, however, be inferred that a negative ADT gradient has moved south-westwards down the passage. In particular, two features are worthy of highlighting: First, it is clearly visible that the occurrence of the minima and maxima of the eddy-associated ADT

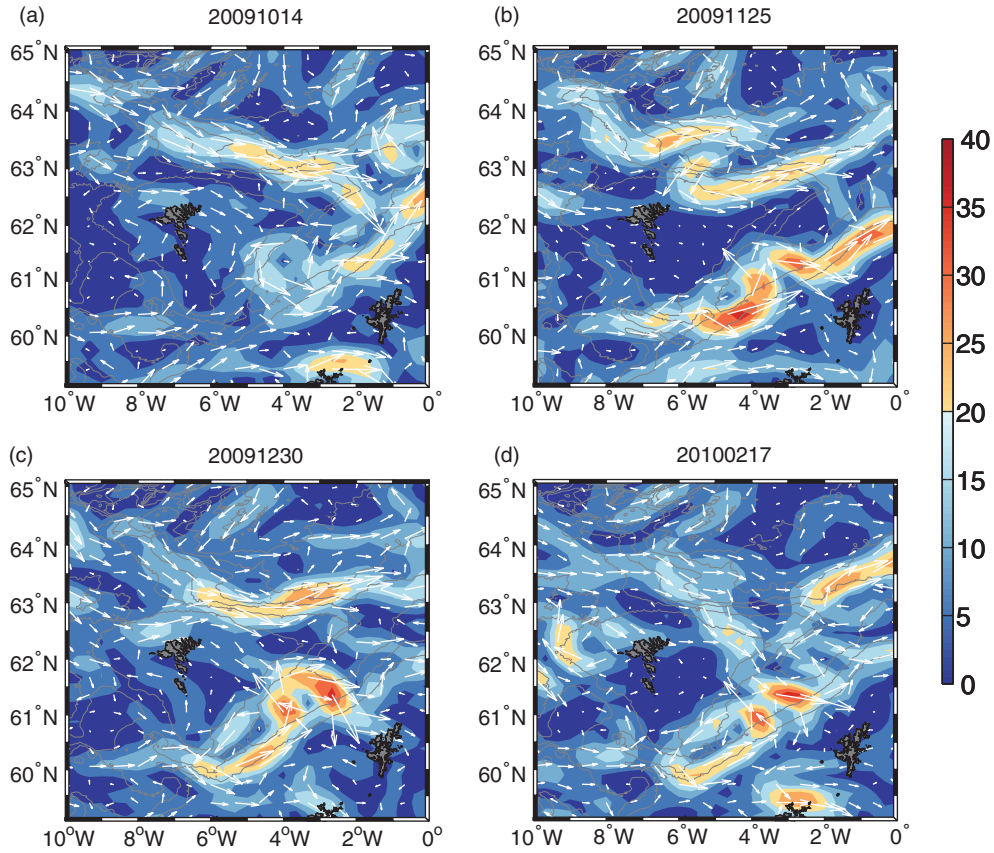


Fig. 3. Sequence of the velocity magnitudes (speeds) in centimetre per second overlaid by the associated geostrophic-velocity vectors for the same periods as in Fig. 2.

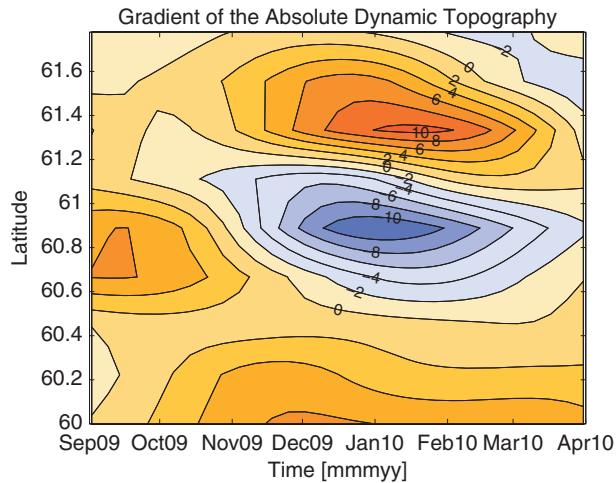


Fig. 4. September 2009–March 2010 time-latitude (Hovmöller) diagram of the weekly along-channel absolute dynamic topography gradient (low-passed using a fourth-order Butterworth filter with an 8-week cut-off). A lag of around 2 weeks between the cyclonic and anticyclonic eddy is clearly discernible.

gradients, respectively, is lagged in time. This shows that the cyclone deepening leads the intensification of the anticyclone; the delay was found to be around 2 weeks. Second, the life times are comparatively long, leading to a quasi-stationary situation reminiscent of a standing wave. This provides a hint of another factor, viz. the large-scale wind-field, which possibly contributed to the persistence of the eddy activity and the resulting deformation of the Shetland-slope current. As next will be shown, this regime change, inducing warm waters to extend all the way to the Faroe slope, also manifests itself in the hydrographic structure characterising the channel.

3.2. Hydrographic evidence

Before examining the hydrographic structure associated with the eddies, a highly informative sequence of satellite-derived SST fields taken during three periods (see Fig. 5) is discussed. In Fig. 5a, the SST composite from 6 to 12 October 2009 is related to the first stage of the ADT evolution in the FSC as shown in Fig. 2, and it is seen that an isolated region of cold surface water is present in the

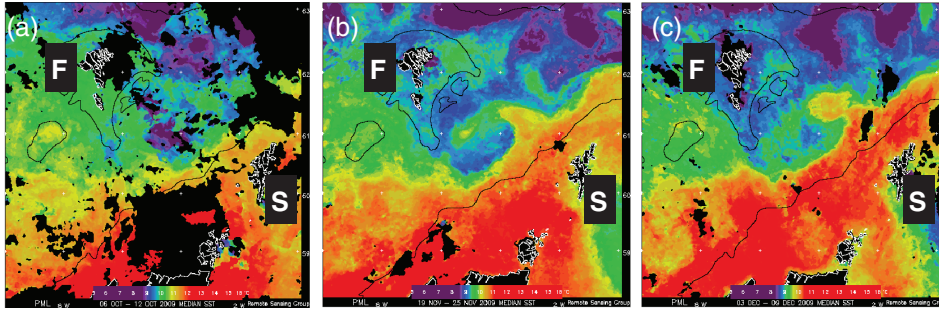


Fig. 5. Composites of satellite-derived sea surface temperatures around the Faroe-Shetland Channel (F = Faroes; S = Shetland) from 6 to 12 October, 19 to 25 November, and 3 to 9 December 2009 showing the evolution of the cold-core eddy and the deflection of the warm Shetland-slope current. (Courtesy of NEODAAS.)

passage. Since water of this type is also found North and Northwest of the Faroes (Hansen and Østerhus, 2000), this similarity indicates that the cyclonic eddy has been cut off from the main body of Norwegian-Sea water and has moved southwards in the FSC, that is, the cold-core vortex was not generated locally. In Fig. 5b, the composite from 19 to 25 November (second stage) shows a major deformation of the Shetland-slope current. Consonant with the ADT results reported in Fig. 2, it also seen how the warm filaments of the slope current gradually envelop the cyclonic vortex in a counter-clockwise direction, and in

Fig. 5c a fully developed SST dipole pattern is in clear evidence.

This eddy activity exerts a pronounced influence on the hydrography in the FSC, as evidenced by substantial changes in its vertical structure. In Fig. 6a, a pronounced doming of the isohalines is seen to characterise the Faroe slope, with low salinities extending upwards and affecting the entire water column. Note that this doming is associated with the initial stage of the cyclonic vortex seen in Fig. 2a. This linkage is even more visible from the minimum of the cross-channel SLA distribution, which is

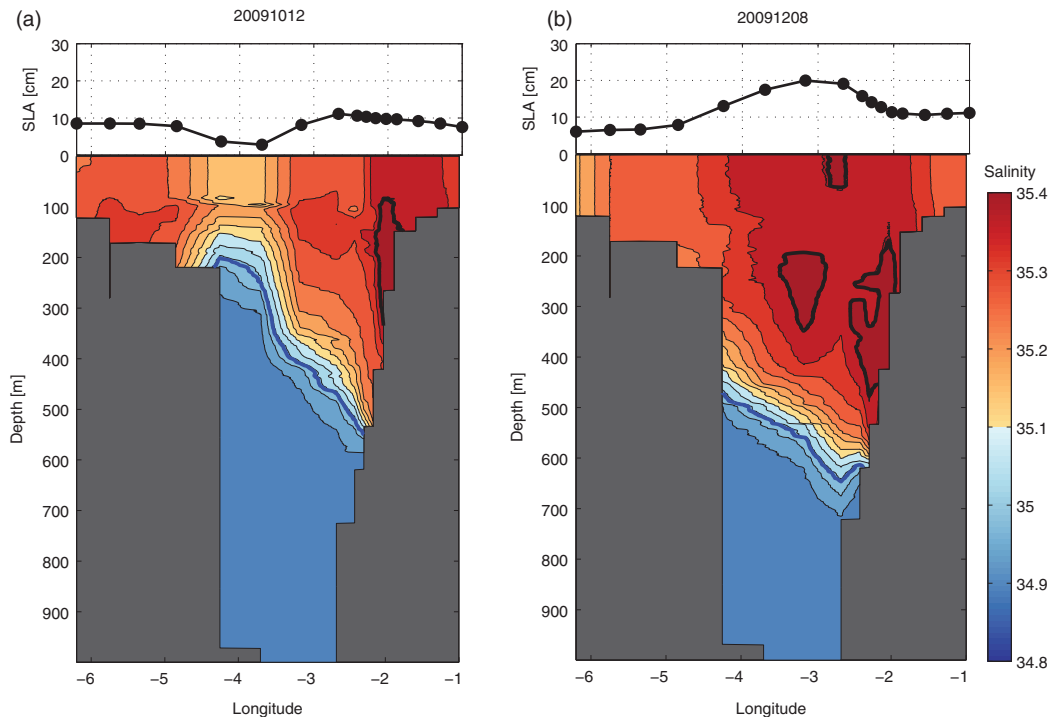


Fig. 6. Salinity distribution across the Nólsoy-Flugga section on 12 October and 8 December 2009. These surveys are chosen to show the effects of cyclonic and anticyclonic surface-water motion, respectively. The blue 35 psu contours highlight the shoaling and deepening of the halocline. Black 35.4 psu contours delimit the warm cores of the northward-directed slope current. The cross-channel SLA distributions from the same days as the hydrography are also included on top of the diagrams.

seen to be located squarely above the dome. These altimetric results are also included in Fig. 6 and were obtained on the same days as the hydrography. Fig. 6b analogously demonstrates the impact of the surface anticyclone (note the location of the SLA maximum), and how it effectively deepens the halocline. The blue 35 psu contours superimposed on these two hydrographic sections serve as an indication of major shoaling/deepening of the halocline, in this case comprising a few hundred meters during a period of 2 months. The black 35.4 psu contours are intended to highlight the inflow core of the NAW, where a pronounced difference between the two situations is evident. In Fig. 6a, the area of the maximum salinity is generally smaller and shallower than in Fig. 6b, where several maxima can be identified. Moreover, it should be noted that this hydrographic structure associated with the anticyclonic eddy is characterised by an accumulation of NAW, which has spread all over the section. This feature signifies a deviation of the slope current from its natural path above the maximal gradient of the bathymetry and its strong impact over the deeper parts of the channel.

Figure 7 shows T–S relationships pertaining to the two different situations exemplified in Fig. 6. That in blue

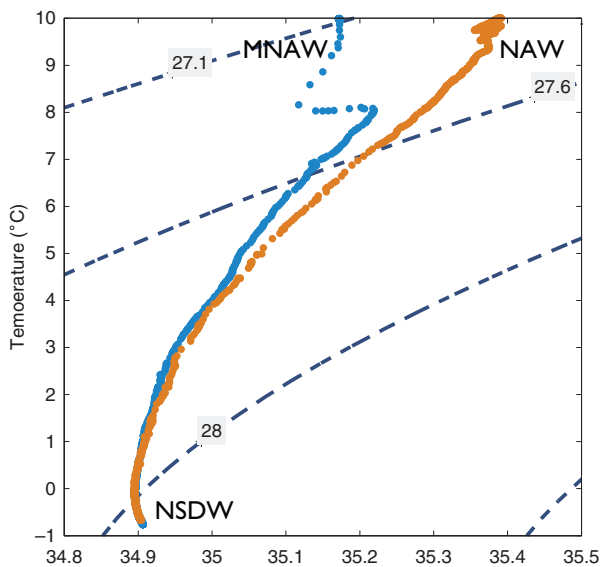


Fig. 7. Temperature–salinity profiles from a centrally located station on the Nólsoy-Flugga section (magenta in Fig. 1) from the same surveys as represented in Fig. 6. The blue profile (12 October) shows the presence of low-saline Modified North Atlantic water (MNAW) related to the cyclonic circulation; the red profile (8 December) comprises North Atlantic water (NAW) of higher salinity due to the deflection of the Shetland-slope current and the resulting anticyclonic circulation. The cold Norwegian-Sea deep water (NSDW) is also shown.

shows a profile associated with the cyclonic eddy and hence the doming; it is evident that the eddy originates from north of the Faroes since it is constituted by MNAW. The T–S results in red from December show a signature clearly dominated by NAW. The separation between the two T–S profiles is related to the shoaling and deepening of the halocline.

3.3. Influence of the NAO

The quasi-persistent eddy-related structure illustrated by Fig. 2 coincided with the period in 2009–10 of an extremely low NAO regime, which is suggested as a possible driving agent for the long-lasting eddy behaviour. This presumed linkage has been investigated by generating composites of the ADT and its associated geostrophic velocities for high and low NAO weeks (Fig. 8).

During a high phase of the NAO, the area of depressed SSH dominating the interior of the Norwegian Sea (which can be perceived as a large-scale gyre, see Fig. 1) expands and reaches the southern parts of the FSC. Furthermore, the Ekman transports associated with more active south-westerly winds lead to an increased level of the sea surface over the Shetland shelf, thus further strengthening the SSH gradient across the FSC. This reinforces the tendency of the Shetland-slope current (with its associated NAW properties) to adhere to its natural route along the bathymetric contours. Consequently, the conditions in the FSC during high NAO phases resemble the mean circulation presented in Fig. 1.

However, periods of low NAO causes the Norwegian-Sea gyre to contract, cf. Fig. 8. This not only leads to a northward migration of the FSC recirculation but also results in a sharpened front north of the Faroes, which in turn could create instabilities that potentially pinch off and advect southwards along the eastern Faroe slope with the mean flow. During this phase of the NAO, the large-scale atmospheric conditions over the region are furthermore dominated by northerly winds; hence, the Ekman transports under these circumstances tend to weaken the cross-channel SSH gradient. In conjunction with the abovementioned northward retreat of the FSC recirculation, this coincides with the observed deflection of the Shetland-slope current, which ultimately leads to the overall situation seen in Figs. 2 and 5.

In order to provide further support for the considerations above, the altimetric data have also been used to construct ensembles of weekly observed -30 and -10 cm SSH isolines originating from the Norwegian Sea and the North Atlantic, respectively. (These isolines are intimately related to the geostrophic streamlines.) This has been done for the previously specified conditions of high and low NAO, see Fig. 9. The general picture that emerges is that

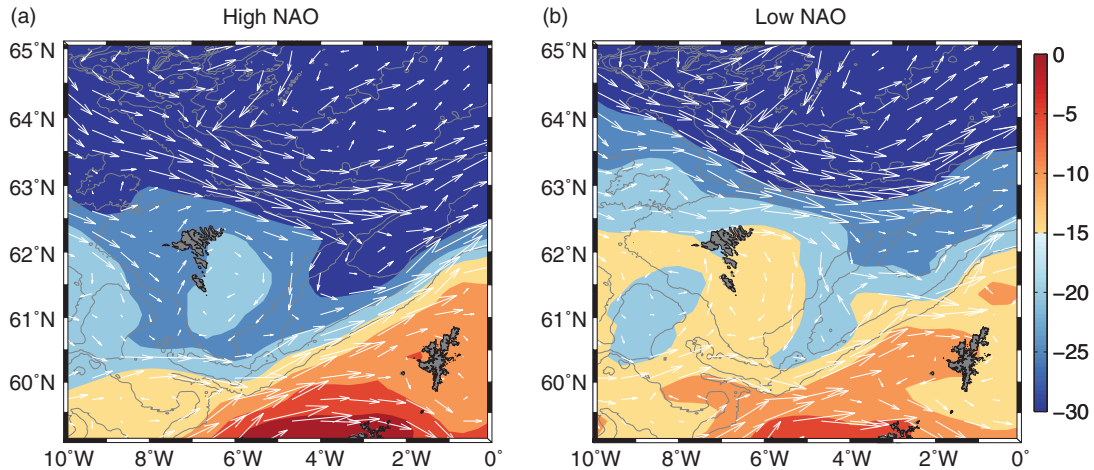


Fig. 8. Composites of observed ADT distributions and their associated velocity vectors for extremely high (≥ 3) and low (≤ -3) NAO-index weeks. During conditions of high NAO the sea-surface height (SSH) field is depressed and the associated flow pattern resembles the ‘standard’ circulation illustrated in Fig. 1. For low NAO, the depressed SSH has retreated northwards and a prominent bulge intrudes over the deeper parts of the Faroe-Shetland Channel.

during periods of high NAO, both ensembles are relatively coherent. The isolines show a tendency to be bathymetrically constrained, viz. those originating in the Norwegian Sea adhere to the Faroe slope, cross the FSC and hereafter are orientated north-eastwards along the Shetland slope, where also the isolines of Atlantic origin are concentrated. These well-organised clusters indicate that the flow during periods of high NAO is topographically steered in the Faroe region. During periods of low NAO, however, the SSH isolines originating from the Norwegian Sea have shifted northwards and no longer form a distinct part of a FSC recirculation extending to the southern reaches of the passage. Instead, closed contours of the -30 cm isolines are seen to dominate the interior of the passage under low-NAO conditions. Concurrently, the geostrophic contours originating in the Atlantic generally deviate from the topographically constrained location of the Shetland-slope current as recognised from their disordered pattern.

In direct analogy with the mode of presentation utilised for Fig. 8, the composite EKE fields during the two phases of the NAO have also been calculated, see Fig. 10. A significant difference between the two sets of results is that for a high NAO, the overall magnitude of the EKE is in general smaller than that during low-NAO conditions (149 vs. 199 $\text{cm}^2 \text{s}^{-2}$). In the former case, local EKE maxima are found at the southern entrance of the FSC and on the eastern side of its northern exit, possibly due to the large bathymetric gradients in these areas. In the low-NAO case, the direct effect of the bathymetry appears less evident as the highest EKE values occur above the deeper parts of the channel.

4. Discussion

As shown in Fig. 2, a quasi-persistent, coherent eddy structure was detected in the FSC on the basis of satellite-altimetric observations. Although bearing a superficial resemblance to features previously observed in the passage by Sherwin et al. (2006), it differs from the meandering mesoscale (~ 65 km) eddies analysed by these authors. These short-lived structures (with growth times of days) were ascribed to baroclinic instability and furthermore linked to the ‘backward breaking wave’ phenomenon as investigated by Griffiths and Linden (1981) – these two researchers simulated an unstable boundary current by continuously releasing a buoyant fluid into an anticyclonically rotating tank. Closed cyclonic eddies developed behind the clockwise meandering boundary current; hence, a suite of asymmetric dipoles arose. Figures 2 and 5 show, however, that the evolution of the slope-current meander examined here differs from the scenario given by Sherwin et al. (2006) in that the deflection is not initiated by instabilities of the buoyant Shetland-slope current. Instead, it is preceded by the propagation southwards along the Faroe-slope of a cold-core eddy of Norwegian-Sea origin. Once this has reached the southern part of the passage, a deflection of the slope current takes place, ultimately resulting in the flow pattern most clearly visible in Figs. 2c and 5c, respectively. The Hovmöller diagram (Fig. 4) based on the along-channel gradient of the SSH demonstrates a 2-week lag between the arrival of the cold-core eddy and the deflection of the slope current. It is consequently suggested that well-organised leakage of MNAW into the FSC in the form of a cold-core eddy may play a role for the onset of the slope-current deflection. It should, however, be

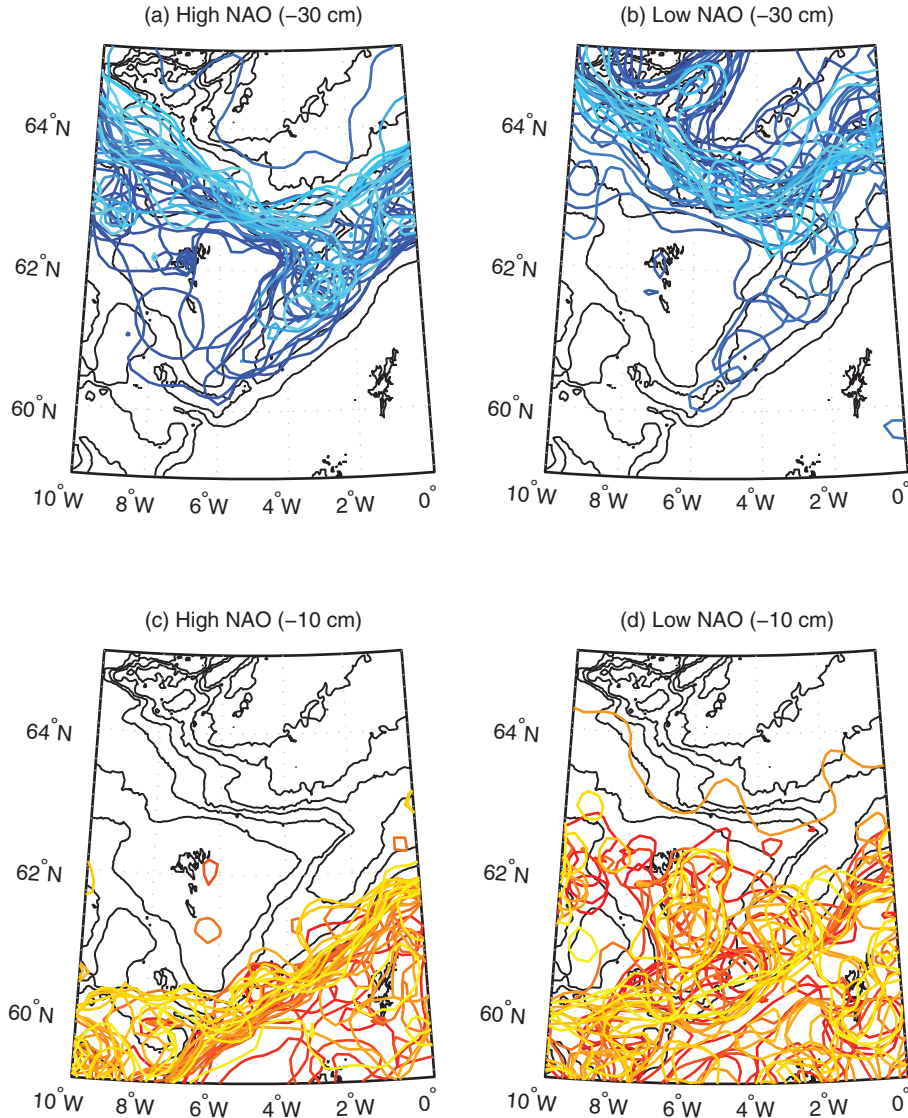


Fig. 9. Absolute dynamic topography isolines originating from the Nordic Seas (-30 cm) and from the North Atlantic (-10 cm) for the same high- and low-NAO-index weeks used when constructing the composites shown in Fig. 8. Black lines with a spacing of 500 m pertain to the bathymetry. The diagrams are aimed at clarifying the degree of topographic control exerted on the flow during high and low phases of the NAO.

emphasised that this progression of events does not provide a ready answer to the intriguing question of what causes the comparative longevity of the flow pattern seen in Fig. 2. A rigorous investigation of this matter is beyond the scope of the present study, but, as outlined below, the pace of the evolution of the NAO index with its attendant consequences for the Norwegian-Sea gyre may underlie the persistence of the observed eddy structure. A large-scale mechanism of this type could be further reinforced by the local small-scale processes leading to the ultimate breakdown of the slope-current deflection acting in so slow manner that the life-time of the eddy system is prolonged.

The behaviour of the SSH isolines for high- and low-NAO conditions shown in Fig. 9 clearly underlines the importance of the large-scale wind-field for the degree of topographic control exerted on the flow in the Faroe region. For a high NAO, the isolines originating from the Norwegian Sea extend far southwards in the FSC before recirculating and joining those of Atlantic origin. This stronger topographical steering in phases of high NAO is consistent with the anticipated increase of the wind-driven barotropic flow along the closed f/H contours (H being the depth) in the Nordic Seas (Isachsen et al., 2003; Nøst and Isachsen, 2003).

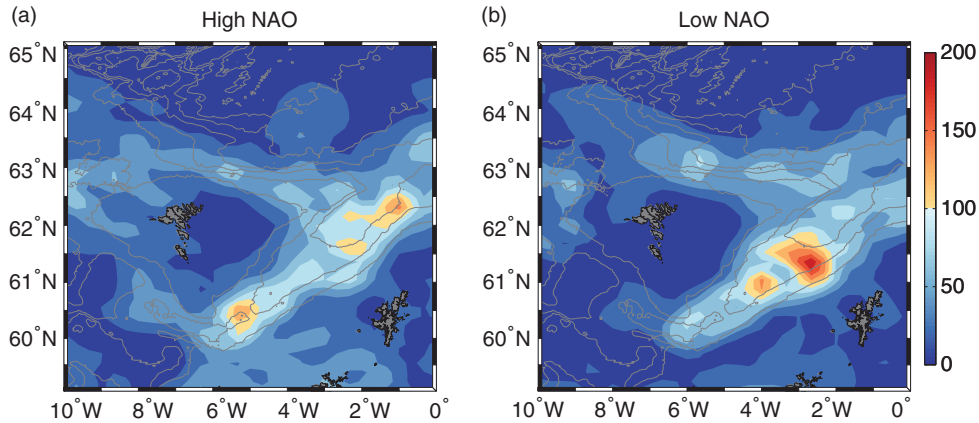


Fig. 10. Composites of the eddy kinetic energy (EKE) distributions for high (≥ 3) and low (≤ -3) NAO-index weeks, see Fig. 8. The overall EKE values in the high-NAO case are smaller than for a low NAO. Furthermore, the locations of the maxima do not correspond, indicating qualitatively different flow fields.

For a low NAO, however, it is seen how the -30 cm isolines from the Norwegian Sea shift northwards and link more-or-less directly with the Norwegian slope current instead of partaking in the FSC recirculation. Most likely, this behaviour is due to the weakened wind-stress curl inducing a contraction of the Norwegian-Sea gyre with attendant consequences for the geostrophic streamlines. An analogous low-NAO relaxation of the bathymetrical constraints on the flow manifests itself in the behaviour of the geostrophic streamlines originating from the Atlantic proper, which in Fig. 9d are seen to pursue deformed paths through the FSC consonant with the observed bulge of the slope current. This irregular behaviour led to the increased level of eddy activity in the passage visible in Fig. 10b.

The disruption of the slope current visible in the cluster of isolines originating from the North Atlantic (Fig. 9d) occurred during extreme negative states of the NAO. This raises the question of to which extent the large-scale low-NAO conditions in the Eastern North Atlantic contribute to the anomalous flow and hydrographic patterns in the FSC. Häkkinen et al. (2011) most recently pointed out that a negative NAO phase with its associated decrease of the wind-stress curl leads to weakening of the subpolar gyre, which in turn permits more saline subtropical waters to penetrate northwards. Sarafanov (2009) had previously presented the schematic picture that when the NAO is in its positive/negative mode, the subpolar gyre tends to expand/contract, in turn leading to a retreat/advance of the subtropical waters. It thus appears likely that the physical regime as well as the water-mass properties in the FSC also is influenced by this variability of the North-Atlantic wind-driven gyres governed by the NAO-associated wind shifts. Elucidating the precise

details of the underlying mechanisms is, however, beyond the scope of the present study.

5. Summary and conclusions

It has been found that the dominant North-Atlantic atmospheric regime, especially when in its low-NAO mode, has a large impact on the local dynamics of the FSC. In Fig. 11, the major effects related to this NAO state are summarised. An analysis, based on satellite-derived SSH and SST data, of the spatial and temporal evolution of conditions in this passage during the autumn and winter 2009–10 (characterised by extreme negative values of the NAO index) showed a cyclonic eddy propagating southwards in the passage from north of the Faroes. This preceded a distortion of the Shetland-slope current, leading, around 2 weeks later, to the emergence of an anticyclonic circulation concomitant with a striking increase of the slope-current speeds in the channel. The cross-passage hydrography was strongly influenced by this eddy activity, as seen from the pronounced shoaling and deepening of the halocline associated with the cyclonic and anticyclonic eddies, respectively, which were also clearly visible in the cross-channel SLA transects from the same days as the hydrographic surveys. T–S diagrams from a centrally located station (Fig. 7) further underlined that flow-pattern changes of the type represented by Fig. 11 affect the FSC water-mass characteristics by transporting and hence accumulating comparatively warm shelf–slope-current NAW over the deeper parts of the passage.

The ADT composites (Fig. 8) as well as the immediate response of the geostrophic streamlines to extreme phases of the atmospheric forcing (Fig. 9) showed that during

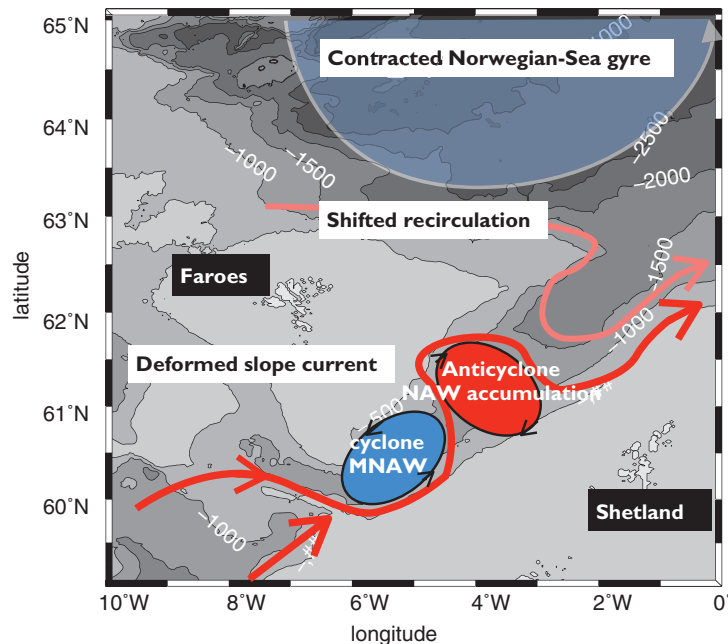


Fig. 11. Schematic diagram summarising the main results related to the low-NAO regime. The large-scale flow pattern and its associated eddies clearly differ from the ‘standard’ surface circulation shown in Fig. 1. Note the accumulation of North Atlantic Water in the Faroe-Shetland Channel (FSC) related to the deflection of the Shetland-slope current accompanied by an anticyclonic circulation. The northward migration of the recirculation in the FSC associated with the contraction of the Norwegian-Sea gyre is also in clear evidence.

high-NAO conditions the flow is bathymetrically constrained to follow constant f/H contours and more or less reflects the mean circulation in the passage as sketched in Fig. 1. For a low NAO, however, these isolines present an unruly pattern consonant with the perturbed flow structure illustrated in Fig. 11, a situation which contributed to the high EKE levels visible in Fig. 10b. Concurrently, the FSC recirculation has shifted northwards as a result of the decreased wind stress having led to a weakening and contraction of the Norwegian-Sea gyre to which it is linked. This most likely played a role for the deflection of the Shetland shelf-slope current. Furthermore, as pointed out in the previous section, negative phases of the NAO also has consequences for the interplay between the wind-driven subpolar and subtropical gyres, which, mediated via the slope current, can be expected to affect the internal dynamics of the FSC.

The main focus of the present study has been directed towards the effects of extreme NAO conditions on the dynamics of the FSC. It has been shown here that the Shetland-slope current is sensitive to the large-scale atmospheric forcing and tends to be either firmly confined to the continental slope or, under low-NAO conditions, deflected from its ‘natural’ bathymetrically constrained path, hereby spreading comparatively warm NAWs across the passage. Note that the atmospheric coupling outlined here provides a response to the unanswered question posed by Sherwin

et al. (1999) about the cause of the pronounced SST-observed slope-current deflection by these researchers in May 1980. Consonant with the results of the present study, this striking feature in fact took place during a low-NAO month with an index of -2.1 .

Facing the challenges of global climate change, and hence the possibility of more frequent extreme events (Field et al., 2012), it is hoped that the investigative approach taken in the present study may provide insights of how changing forcing is likely to project in the Faroe region. It should finally be underlined that satellite altimetry yielded valuable information on the dynamical response of the Faroe-region circulation to the NAO. These results were entirely consistent with standard hydrographic measurements across the FSC as well as with satellite-derived SST observations. It has thus been concluded that satellite altimetry is highly suitable for studying the eddy activity in this passage and its links to the spatio-temporal variability of the poleward-heat-conveying Shetland-slope current.

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