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Key Points:

- Local modification of winds provides an important control on North Sea circulation.
- Orography and ocean-atmosphere generates wind stress curl extrema that have both local and far-field effects on shelf sea dynamics.
- Local winds are shown to be more important than previously documented and may be more susceptible to change that prevailing winds.

Abstract

Wind driven circulation in the North Sea is revisited with a specific focus on locally modified winds and their impacts. We show for the first time that local extrema of the wind stress curl (WSC), generated by orography and ocean-atmosphere interactions, help regulate circulation in the northern North Sea. Calculated transports are strongly coupled with wind stress, whereas transports through the Norwegian Trench are more strongly correlated with the WSC field due to local extrema. Such WSC extrema regulates the sub-mesoscale eddy activity around the Norwegian Trench. We conclude that local modification of the WSC is a result of both orography and ocean-atmosphere interaction along the frontal Norwegian coastline. Our results show that local winds are more important than previously documented, with important implications for regional circulation likely to result from future changes to local surface gradients, such as may arise from changing meteorological or hydro-climatic forcing.

Plain Language Summary

North Sea circulation is investigated with a specific focus on the local winds and their impacts. We show for the first time that the local extrema of the wind field, generated by the coastline and oceanic contributions, helps regulate circulation in the northern North Sea. Wind is driven by large-scale forcing mechanisms, and is closely related with volume transports. Volume transports through the Norwegian Trench are better related to the wind field, due to local extrema of wind. Local extrema of wind, and their direction, stimulates rotation in the region, controlling the eddy activity around the Norwegian Trench. We conclude that the local extrema of wind are a result of interaction with the land and an ocean-atmosphere feedback mechanism along the Norwegian coastline. Our results show that local winds are more important than previously known and have important implications for regional circulation. Therefore, future changes to local density differences from changing meteorological conditions may have further impacts on North Sea circulation.

1 Introduction

The North Sea is surrounded by approximately 184 Million inhabitants that inevitably rely on its blue economy, placing it amongst the most human influenced marine ecosystems (Halpern et al., 2008; Moullec et al., 2021). Additionally, the North Sea is a hotspot for climate change having large seasonal shifts and climate change velocity (Burrows et al., 2011; Holt et al., 2012; Degraer et al., 2019), and so provides an indicator for change for the wider North West European continental shelf.

The North West European continental shelf plays an important role as a sink for atmospheric carbon dioxide (Frankignoulle and Borges, 2001). The North Sea has been shown to be a particularly efficient component of this system, exporting most of the regional oceanic CO_2 extracted from the atmosphere during summer months off the continental shelf to the deeper waters of the Atlantic Ocean (Thomas et al., 2005) via down-welling circulation (Holt et al., 2009). North Sea circulation is therefore a critical component of the biological carbon pump. In return, Atlantic inflow has a conditioning influence on the physical structure (Marsh et al., 2017; Sheehan et al., 2017) and biogeochemistry of the North Sea (Mathis et al., 2019). Recent studies however, have indicated potential blocking of Atlantic inflows (Holt et al., 2018) in future climate scenarios with subsequently dramatic implications for the health and productivity of the North Sea (Wakelin et al, 2020). Wind stress is an important forcing mechanism to consider for North Sea exchange with the Atlantic, as it is identified as the major driver of regional circulation (Huthnance, 1991). Changes in the strength and direction of prevailing wind can induce a reversal in circulation (Stanev et al., 2019), and even blocking (Christensen et al., 2018). Additionally, wind has implications for the biogeochemistry: driving inter-annual to decadal variability in nutrient concentrations in the northern North Sea (Pätsch et al., 2020). Changing winds also have an impact on carbon (Kühn et al., 2010) and nutrient (Pätsch and Kühn, 2008) budgets. Thorough understanding of regional wind variability is therefore essential to understand North Sea circulation, regional biogeochemistry and future impacts from changing hydro-climatic forcing.

Previous North Sea studies have shown the importance of large-scale winds (Winther and Johannessen, 2006), as well as the topographic modification of wind-driven circulation around the Norwegian Trench (Davies and Heaps, 1980) but local wind forcing and its impacts on regional circulation remain poorly documented. The Norwegian Trench is a frontal area maintained by freshwater influence from the Baltic outflow and numerous riverine inputs, with instabilities leading to meanders and eddy generation (Johannessen et al., 1989). This area is subsequently a prime candidate for ocean-atmosphere interaction since mesoscale ocean-atmosphere interactions are well documented in the vicinity of fronts both over the open-ocean (e.g. O'Neill et al., 2010; Chelton and Xie, 2010) and global coastal ocean (e.g. Wang and Castelao, 2016). Blowing down a sea surface temperature (SST) front, wind accelerates (decelerates) over warm (cold) water, resulting in wind stress curl and divergence anomalies (O'Neill et al., 2010), which are related to crosswind and downwind components of the SST gradient (Chelton et al., 2007).

In this study we investigate local extrema of wind stress curl observed around the Norwegian coast and consider its implications for local and regional (i.e. northern North Sea) circulation. First, we investigate the impact on both large-scale and sub-mesoscale circulation. Second, we investigate causes of the local WSC extrema, considering orography and ocean-atmosphere interaction as potential drivers.

2 Materials and Methods

Data used in this study are provided by the ~7km reanalysis product (Atlantic Margin Model, AMM7: North-West Shelf Monitoring and Forecasting Center (NWS-MFC, 2021) and the ~1.5 km forecast product (AMM15: Tonani et al., 2019; Lewis et al., 2019; Crocker et al., 2020, NWS-MFC, 2020) for the North-West European Shelf Seas, distributed freely by CMEMS (Copernicus Marine Environment Monitoring Service). Both products are configurations of the NEMO (Nucleus for European Modelling of the Ocean; Madec and the NEMO Team, 2016) model. Atmospheric forcing is ECMWF (European Centre for Medium-Range Weather Forecasts) ERA5 fields for AMM7 (NWS-MFC, 2021) and ECMWF Integrated Forecasting System (IFS)-Atmospheric Model High Resolution (HRES) operational Numerical Weather Prediction forecast fields for AMM15 (NWS-MFC, 2020). In section 3.1 we use AMM7 to demonstrate the large-scale circulation and in section 3.2 we use AMM15 to investigate the (sub)mesoscale circulation in the North Sea.

In section 3.1, monthly mean fields of the AMM7 model were used for 1993-2019. The AMM15 model was available as daily mean fields for 2017-2019. In section 3.2, daily AMM15 fields were averaged into monthly means for coherence with the AMM7 analysis. Volume transports were calculated using the following formula:

$$\mathrm{VT}_{positive/negative} = U_n * dx * h$$

$$\mathrm{VT}_{\mathrm{net}} = \mathrm{VT}_{\mathrm{positive}} + \mathrm{VT}_{\mathrm{negative}}$$

Where VT stands for volume transport, $\mathrm{U_n}$ is the normal velocity component, dx is the grid spacing and h is the layer thickness at position of normal velocity. Positive (negative) volume transport denotes transports in the same (opposite) direction as the arrows shown in Figure 1. Net transport is the sum of positive and negative transports. All "transports" presented in this study refer to the net volume transport. Transects were chosen from those already prescribed by the North West Shelf Operational Oceanographic System (NOOS; O'Dea et al., 2017, NOOS Team, 2013) (Figure 1) and relate to Transect 1 (T1-Shetland North), Transect 2 (T2-Sognesjoen), Transect 4 (T4-Orkney), Transect 5 (T5-Utsira), Transect 7 (T7-Aberdeen), Transect 8 (T8-Hanstholm west). Direction of positive net transport for Transect 1, Transect 4 and Transect 7 (Figure 1) are counter to the definition of NOOS (NOOS Team, 2013). Transition between the shallow and deep transects corresponds to the 200m depth contour. Coordinates of the NOOS transects have been provided in supplementary material for reference (Table S1). Northern North Sea transports account for the majority of exchanges with the Atlantic Ocean (Winther and Johannessen, 2006). Transports through other transects north and south of T4 and T5 showed similar temporal variability and so only the results from these two transects are presented to represent the link between transports and wind forcing in the northern North Sea.

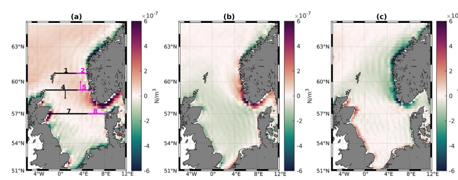

Figure 1 (a) First EOF mode of WSC (Variance explained: 48%) with NOOS transects overlaid. (b) Second EOF mode of WSC (Variance explained: 21%) (c) Third EOF mode of WSC (Variance explained: 16%).

Monthly mean SST and wind (10 m eastward and northward components) data were obtained from ERA5 reanalysis (Copernicus Climate Change Service (C3S), 2017). Zonal and meridional wind stress were computed in addition to the wind stress curl (hereon WSC).

The WSC field was inherently noisy, so was decomposed into its major components using EOF (Empirical Orthogonal Functions) analysis. The first principal component was most significant, explaining 48% of the total variability, and was therefore used for calculating the WSC correlations with transport. Statistical significance of correlations presented in this study is calculated following a random phase test (Ebisuzaki, 1997). All presented correlation coefficients are statistically significant at the 95% confidence level, unless specified otherwise.

Following previous studies (Chelton et al., 2007; Desbiolles et al., 2014; Wang and Castelao, 2016) cross-wind SST gradients were calculated by decomposing the SST gradient vector:

$$\nabla SST \times \hat{k} = \nabla SST * \sin\theta$$

where $\hat{k}$ is the unit vector in the direction of the wind stress and θ is the counter clockwise angle from the SST gradient vector to $\hat{k}$. Monthly North Atlantic Oscillation (NAO) Index was obtained from Hurrell et al (2020).

3 Results

3.1 Wind regulated volume transport

The 27-year monthly net volume transport across the selected NOOS transects (Figure 2) present a clear seasonal cycle with maxima in winter. The period mean (1993-2019) transport was 0.82 Sv (1 Sv = 10^6 m^3 s^{-1}) across T4 and 1.00 Sv across T5. The volume transport across northern transects are well correlated with the zonal wind stress, with a correlation coefficient r=0.84 and r=0.85 for T4 and T5 respectively. These results demonstrate how westerly wind stress regulates much of the seasonal circulation in the northern North Sea, including the inflow of Atlantic water. The WSC likely provides a better representation of local wind forcing as it represents both the zonal and meridional wind stress. Meridional wind stress becomes enhanced around the Norwegian coast. The WSC (1^{st} principal component) consequently displays a dipole extremum around the Norwegian coast, with a positive (cyclonic) maximum around southern Norway and negative (anti-cyclonic) maximum around the northwest (north of ~61°N) Norwegian coast, with ~60°N being an apparent focal point (Figure 1a).

Figure2a shows the transport through T4 and T5 alongside the 1^{st} principal component amplitude of WSC. Correlation between the WSC principal component amplitude and transport is r=0.78 for T4 and r=0.88 for T5.

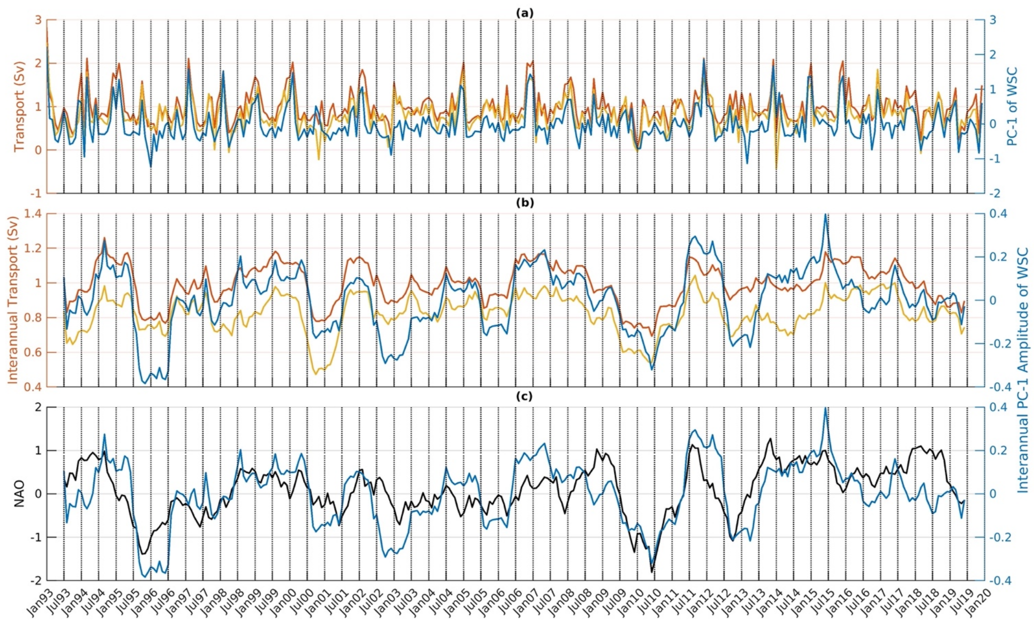

Figure 2 (a) Volume Transport through T4 (yellow line) and T5 (red line) vs First principal component (PC-1) of WSC (blue line). (b) Interannual Volume Transport through T4 (yellow line) and T5 (red line) vs PC-1 of WSC (blue line). (c) NAO (black line) vs PC-1 of WSC (blue line). For (b) and (c), all time-series are low-pass filtered with a 1 year moving window.

Transport is enhanced during winter periods when the regional wind field is intensified. The maximum transport for both transects was observed in winter 1993, which corresponds to the maximum observed value of positive WSC amplitude. However, it is not possible to explain every peak in the transport time-series solely from wind. For example, minimum transport values for T4 in November 2000 do not correspond to a WSC minimum. Interestingly, this date corresponds to a reversal in the direction of net transport (negative values). Nevertheless, these time series and their high correlations demonstrate how the wind generally provides a primary control on regulating regional seasonal circulation. Positive WSC amplitudes correspond to enhanced positive transport, which represents flow into the North Sea (through T4) and outflows to the northern Atlantic through T5, which describes much of the seasonal cyclonic circulation in the northern North Sea.

To identify interannual variability, the seasonal signal was removed using a low-pass filter (1-year moving average) for both transports and WSC. The strongest correlation in all NOOS transects (Transects 1 to 8) between transport and WSC was observed at T5 in the Norwegian Trench, denoting the significance of the local WSC extrema interannually. Figure 2c clearly shows the negative NAO periods in 1996 and 2010 and 2012, causing negative WSC amplitude and reduced transport, whereas 2007 and 2011 showed an opposite signal. Transports were well correlated (r=0.61 for T4 and r=0.82 for T5) with the interannual component of WSC proving a close match with the wind regulated circulation. The WSC was well correlated with the NAO (r=0.66), indicating its role as the large-scale driver of regional and local wind fields.

3.2 Wind driven eddy activity

Data from the eddy resolving model (AMM15) reveal WSC extrema around the Norwegian Trench to impact eddy activity in the region, with strong coupling between the WSC strength and relative vorticity (Figure 3). Positive WSC amplitudes correspond well with positive relative vorticity, which indicate periods of enhanced cyclonic circulation. Correlations between WSC and relative vorticity are presented for two areas (squares in Figure 3c): the Norwegian Trench (Figure 3a) and central North Sea (Figure 3b). In both cases, the calculated relative vorticity demonstrates some agreement with WSC; r=0.43 for Central North Sea (Figure 3c, cyan square) and r=0.58 for Norwegian Trench (Figure 3c, magenta square), which undergoes significant variability over time (not shown, but highest in 2018). Area-mean representation of relative vorticity is prone to errors as positive and negative features negate each other's signal. For a better representation of the (sub)mesoscale activity, here we use the EOF decomposition of normalized relative vorticity. Figure 3c represents the spatial distribution of the first principal component, which represents 44% of the total variability and shows strong (sub)mesoscale activity around the Norwegian coastline. Temporally (Figure 3d), it is well correlated with WSC (r=0.76). The second mode of relative vorticity (Supplementary Figure 1a) has statistically insignificant correlation (r=0.10). The third mode of relative vorticity (Supplementary Figure1b) also has good correlation (r=0.45). By its nature, spatial patterns of relative vorticity are highly turbulent but regardless of the spatial pattern of relative vorticity, high correlation coefficients confirm that WSC promotes rotatory motion in the region.

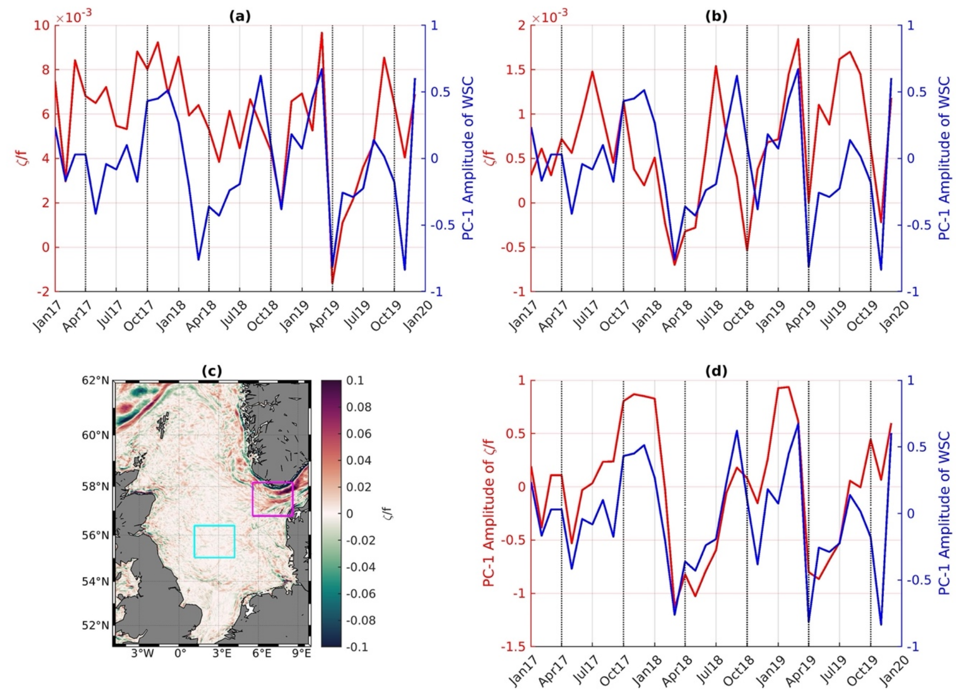

Figure 3 (a) Normalized relative vorticity in Norwegian Trench vs PC-1 Amplitude of WSC. (b) Normalized relative vorticity in Central North Sea vs PC-1 Amplitude of WSC. (c) First EOF mode of normalized relative vorticity. (d) PC-1 Amplitude of normalized relative vorticity vs PC-1 Amplitude of WSC.

3.3 Regional wind stress curl variability and its drivers

Regionally, the majority of WSC variability is shown to arise from the zonal wind stress, with the 1st EOF amplitudes of each being tightly coupled (r=0.93), whereas meridional wind stress has a weaker coupling (r=0.43). Locally around the Norwegian coastal area however, correlation between zonal wind stress and WSC is considerably reduced (r=0.57) and correlation between meridional wind stress and WSC increases (r=0.85). WSC was found to provide a better representative of the local wind forcing than either component of wind stress alone, particularly in the eastern region in proximity to the Norwegian Trench and coast.

In total, the first three EOF modes represent ~85% of the total WSC variability. All three modes show a local WSC pattern around Norway. The 1st EOF mode of WSC explains 48% of the total variability and shows well organised dipole extremum around the Norway coast (Figure 1). The magnitude of both the spatial mode (Figure 1a) and amplitude (Figure 2a) of the 1st EOF mode are larger than the those of 2nd and 3rd EOF modes (Figure S2). The temporal variability of modal amplitude (Figure 2) however, displays interannual oscillation between positive and negative values that are well correlated to the NAO. Positive values of amplitude result in enhanced extrema of the dipole WSC pattern, whereas negative values of amplitude create a weaker dipole pattern. The first EOF mode (Figure 1a) is mostly positive in the northern North Sea (with the exception of coastal features) which leads to enhanced (reduced) cyclonic circulation when its amplitude is positive (negative).

Second and third EOF modes of the WSC explain 21% and 16% of the total variability respectively. Similar to the first mode, the second EOF mode displays a dipole pattern around Norway, with a change of sign at ~62^{o}N, around 2^{o} latitude difference from that of the 1st mode. The second mode (Figure 1b) displays a generally negative pattern for the majority of the North Sea with positive values most evident in Norwegian coastal waters (south of ~62^{o}N) and extending through much of the Norwegian Trench. The amplitude of the 2nd EOF mode (Figure S2a) displays positive (negative) values which correspond to enhanced cyclonic (anticyclonic) WSC around the Norwegian Trench. The western boundary of the positive WSC field in the 2nd mode corresponds to the western boundary of the Norwegian Trench, however, no direct relationship was identified with transports across the NOOS transects.

The 3rd EOF mode (Figure 1c) demonstrated a different distribution to the first two modes but was not found to have any direct relationship with the transports across the NOOS transects. The amplitude of the 3rd mode (Figure S2b) has both negative and positive values, with the positive (negative) values resulting in an enhanced anticyclonic (cyclonic) WSC around Norway.

These results clearly demonstrate the local modification of the WSC around Norway. Potential mechanisms for this regional wind pattern are small-scale regional winds, orographic steering and ocean-atmosphere interaction. The resolution of our data (0.25^{o}) restricts this study to consider only the last two mechanisms; orography and ocean-atmosphere interaction.

Statistically significant correlations between SST and WSC (Figure S3b), and between crosswind SST gradients (CWSST) and WSC (Figure S3a) suggest a potential feedback mechanism between these variables. SST-WSC correlations (Figure S3b) reach a maximum around the Norwegian coast ($r>0.35$). Correlations (Figure S3a) between CWSST and WSC were slightly higher ($r>0.4$). Positive (negative) correlations suggest that increased surface temperature gradients will lead to enhanced positive (negative) WSC anomalies. Regardless of the sign convention, these correlations document ocean-atmosphere interaction in the region, with the potential for influencing regional scale circulation.

Seasonally, highest CWSST-WSC correlations were found in winter, corresponding to intense temperature gradients that formed around the Norwegian Trench. Further assessment of seasonality was achieved via sequential filtering of coupling coefficients (following Legaard and Thomas, 2007; Wang and Castelao, 2016); calculated as the slope of linear regressions between CWSST and WSC (following Chelton et al., 2007). Intra-seasonal (< 6 months) variability was the dominant signal in the coupling coefficients time series.

4 Discussion

4.1 Wind regulated volume transport

Transport estimates have the same order of magnitude with previous studies (O'Dea et al., 2017) and zonal wind stress was confirmed as the dominant forcing mechanism of transport and subsequently circulation in the northern North Sea, a re-affirmation of previously known studies (Otto et al.,1990; Huthnance, 1991). WSC was used as a proxy for the combined zonal and meridional wind stress, the latter being shown to be locally important around the Norwegian trench and coast. Correlations between transports and WSC were found to be higher than with zonal wind in the north-eastern part of the North Sea, implying the local importance of meridional wind stress as a driving mechanism for transport in the northeast and subsequently in regional circulation. Our approach; using space-time decompositions to wind forcing instead of mean fields, is not limited to large-scale wind but also includes local wind fields that have been shown here to be important, as proposed in previous studies (Winther and Johannessen, 2006). We have found that local WSC anomalies around the Norwegian coast introduce vorticity into the broader North Sea, and thus have rotatory implications (Section 3.2), whereas large-scale wind forcing controls basin wide cyclonic circulation. Westerly and northerly (easterly and southerly) winds enhance cyclonic (anticyclonic) circulation (Furnes, 1980). Correlation coefficients between transports and WSC were highest over seasonal periods (Section 3.1), but correlation was also high (minimum r=0.61, at T4) interannually. Interannual variability of wind forcing was in good agreement (r=0.66) with the NAO, which provides a good indicator for the westerly winds (Iversen and Burningham, 2015). Shifts in the NAO index correspond to changes in the wind regime, such as the one observed in 1996, where negative NAO resulted in reduced transport (Figure 2c) with further implications for the nitrogen and carbon budgets of the North Sea (Pätsch and Kühn, 2008; Kühn et al., 2010).

4.2 Eddy activity

AMM7 transport estimates indicate cyclonic circulation of the North Sea corresponds well to enhanced positive WSC (section 3.1). The AMM7 configuration is not however sufficient to resolve mesoscale activity unlike AMM15, which was able to resolve some small-scale processes (Graham et al., 2018). AMM15 outputs reveal rich sub-mesoscale activity, particularly in the Norwegian Trench, corresponding to both highest mean and eddy kinetic energy (supporting Røed and Fossum, 2004). Sub-mesoscale activity is present at higher frequencies, and some eddies live shorter than 1 month but for this study, we only considered monthly means for compatibility with AMM7 temporal resolution. A general indicator of rotatory motion (relative vorticity normalized by Coriolis) showed good correlation with WSC in the central North Sea (r=0.43) and in the Norwegian Trench (r=0.58). Similarly, PC-1 of relative vorticity was in good correlation with WSC (r=0.76). PC-2 of relative vorticity (Figure S1a) has very low correlations with WSC (r=0.1, statistically insignificant). These results show that mesoscale and sub-mesoscale activity is highly coupled with WSC. The generation of an anticyclonic eddy around Skaggerak was recently documented (Christensen et al., 2018), which is spatially coherent with the WSC anomaly presented here. Previously, eddy activity at the southern tip of Norway was linked with offshore veering of the Norwegian coastal current due to barotropic instability (Røed and Fossum, 2004). Considering the aforementioned good correlation between WSC and relative vorticity (Section 3.2), we suggest that the WSC provides a regulating control on eddy activity in the region surrounding the Norwegian Trench. Topography also plays a crucial role through conservation of potential vorticity, leading to re-distribution of the eddy field, although the exact role of topographic steering has been beyond the scope of this study and would require assessment through a series of controlled simulations.

4.3 Origins of Wind stress curl extrema

Potential mechanisms for the regional WSC extrema are: orography, small scale regional winds and ocean-atmosphere interactions. Synthetic Aperture Radar (SAR) data have revealed channelling winds through Norwegian fjords (Karagali et al., 2013), resulting in coastal wind variability around the Norwegian coast. We investigated the mesoscale winds (0.25° data resolution), hence such small-scale winds are beyond our discussion and their exact contribution to regional WSC extrema remain an outstanding question, but mesoscale orographic modification of winds around the Norwegian coastline does remain a potential mechanism for the observed WSC extrema and warrant further investigation. Modelling studies (Barstad et al., 2005) have confirmed regional modification of winds due to complex orography.

Ocean-atmosphere interaction, is the third possible reason for the observed regional extrema of WSC. Ocean-atmosphere (i.e. SST – Wind) interaction has previously been investigated for the global coastal ocean (Wang and Castelao, 2016). North-western European shelf ocean-atmosphere coupling has only been investigated for summer, and was found to have intra-seasonal variability (Wang and Castelao, 2016). Our results are similar; intra-seasonal variability is the dominant signal in the time-series. However, seasonally, we've found highest ocean-atmosphere coupling in winter, corresponding to enhanced frontal gradients around Norwegian Trench. Winter also happens to be the season to show highest instability in southern Norway, corresponding to outbreaks of low-salinity waters (Fossum, 2005).

If WSC derives upwelling, it is expected to be correlated with SST (as in Figure S3b), whereas if WSC is a result of ocean-atmosphere interactions, it is expected to be correlated with crosswind SST gradients (Castelao, 2012). Results here

(Figure S3) show that WSC is, at times, well correlated with both SST and crosswind SST gradients, with the latter showing the strongest correlations and so indicating a predominance of ocean-atmosphere interaction in the region. In other words, the predominant regional mechanism for driving WSC is CWSST gradients (Figure S3b), with wind driven upwelling (Figure S3a) of secondary importance.

While the correlation is moderately high (r>0.4), coupling coefficients between WSC and CWSST gradients are erratic, with considerable intra-seasonal variability. Previous studies have used ERA products (Yu et al., 2020) and satellite products (Chelton et al., 2007, Wang and Castelao, 2016, among others) to quantify the ocean-atmosphere interaction. Yet, modelling (Jin et al., 2009; Boe et al., 2011) is required to quantify how much of the WSC variability is due to CWSST gradients (Castelao, 2012). Wind variability arising from orographic effects can be more important than that of wind variations associated with SST anomalies (Boe et al., 2011). This seems to be the case here, with the highest correlations (Figure S3) corresponding to regions of complex topography (mountains and fjords) around the western Norwegian coast (north of 62°N).

5 Conclusions

Local WSC extrema exist around the Norwegian coast, which are evident in the total WSC variability (represented by EOF modes). These local extrema are an important component of the WSC field in the North Sea, and are important for regional circulation as these are well correlated with the overall cyclonic circulation in the North Sea. Our results suggest transports are highly coupled with wind forcing on monthly timescales. Correlation coefficients between transports and WSC are higher around the Norwegian Trench, indicating the importance of local wind forcing. We conclude therefore that local wind forcing is critical for a complete understanding North Sea circulation. Using WSC (notably its EOF decompositions) as a representation of the wind forcing is advantageous over wind stress (i.e. NAO driven westerly wind stress), as it also represents local wind forcing. WSC is particularly important around the Norwegian Trench where it is a consequence of ocean-atmosphere coupling, and a local cause of upwelling (Section 3.3 and 4.3) and rotatory motion (Sections 3.2 and 4.2).

Simulations with high spatial resolution show ubiquitous sub-mesoscale activity around the Norwegian Trench. Relative vorticity is correlated with WSC in the central North Sea, but higher correlations are present around the Norwegian Trench. A relative vorticity response to WSC indicates a regional influence on vorticity from WSC, however, the redistribution of the vorticity field is controlled by topography. Our results suggest that regional WSC extrema might therefore be the forcing mechanism for the regional eddy activity investigated by previous studies (Røed and Fossum, 2004; Christensen et al., 2018). WSC induces rotatory motion and therefore has potential implications for the carbon budget through vertical motions related to Ekman dynamics (Holt et al.,2009) and likely ageostrophic secondary circulations arising from frontogenesis (Røed and Fossum, 2004).

We conclude that WSC extrema around the Norwegian coast are a result of orography and ocean-atmosphere interaction. While the exact contribution from either requires further investigation, this local wind forcing plays an important role in North Sea circulation and should be accounted for in future studies, particularly when considering exchanges with the Baltic (Christensen et al., 2018) and the Atlantic Ocean (Holt et al., 2018) and suggests exchange estimates should only be derived from eddy resolving models. This is particularly important for future projections, where changing wind fields are predicted (Pryor et al., 2006) that may have significant impacts on local WSC effects and therefore on regional circulation and exchange.

Acknowledgments

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Open Research

The model data used in this paper are available at E.U. Copernicus Marine Service Information (https://resources.marine.copernicus.eu/products) , via the following links for AMM7 (https://resources.marine.copernicus.eu/?option=com_csw&view=details&product_id=NWSHELF_MULTIYEAR_PHY_004_009) and AMM15 (https://resources.marine.copernicus.eu/?option=com_csw&view=details&product_id=NORTHWESTSHELF_ANALYSIS_FORECAST_PHY_004_013). Hurrell North Atlantic Oscillation Index is available via (https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based). ERA5 data were downloaded from Copernicus Climate Change Service ((C3S), 2017) and is available via (https://doi.org/10.24381/cds.f17050d7).

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