



Delft University of Technology

Document Version

Final published version

Licence

CC BY

Citation (APA)

Enge, A., Pietrzak, J. D., Mienis, F., & van Prooijen, B. C. (2026). One-Year Long ADCP Data Reveal the Influence of Tides, Winds, and Coastal-Trapped Waves on the Deep Cross-Slope Transport in a Submarine Trench. *Journal of Geophysical Research: Oceans*, 131(8), Article e2026JC024009. <https://doi.org/10.1029/2026JC024009>

Important note

To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright

In case the licence states "Dutch Copyright Act (Article 25fa)", this publication was made available Green Open Access via the TU Delft Institutional Repository pursuant to Dutch Copyright Act (Article 25fa, the Taverne amendment). This provision does not affect copyright ownership.
Unless copyright is transferred by contract or statute, it remains with the copyright holder.

Sharing and reuse

Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy

Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.

This work is downloaded from Delft University of Technology.

Key Points:

- Two high-resolution ADCPs reveal energetic variability in the deep flows at 300–400 m depth in the Norwegian Trench over 1 year
- Remotely forced winds and coastal-trapped waves (CTWs) cause upwelling of cold Arctic water and intensified inflow of warm Atlantic water
- Matter transport is event-driven, influenced by diurnal tides and CTWs, but strongest during positive winter North Atlantic Oscillation conditions

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

A. Enge,
a.enge@tudelft.nl

Citation:

Enge, A., Pietrzak, J. D., Mienis, F., & van Prooijen, B. C. (2026). One-year long ADCP data reveal the influence of tides, winds, and coastal-trapped waves on the deep cross-slope transport in a submarine trench. *Journal of Geophysical Research: Oceans*, 131, e2026JC024009. <https://doi.org/10.1029/2026JC024009>

Received 11 JAN 2026

Accepted 21 JUL 2026

Author Contributions:

Conceptualization: A. Enge

Formal analysis: A. Enge

Investigation: A. Enge

Methodology: A. Enge, J. D. Pietrzak,
B. C. van Prooijen

Project administration: F. Mienis

Supervision: J. D. Pietrzak,
B. C. van Prooijen

Visualization: A. Enge

Writing – original draft: A. Enge

Writing – review & editing: A. Enge,
J. D. Pietrzak, F. Mienis,
B. C. van Prooijen

© 2026 The Author(s). Journal of Geophysical Research: Oceans published by Wiley Periodicals LLC on behalf of American Geophysical Union. This is an open access article under the terms of the [Creative Commons Attribution License](#), which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

One-Year Long ADCP Data Reveal the Influence of Tides, Winds, and Coastal-Trapped Waves on the Deep Cross-Slope Transport in a Submarine Trench

A. Enge¹ , J. D. Pietrzak¹ , F. Mienis² , and B. C. van Prooijen¹ 

¹Department of Hydraulic Engineering, Delft University of Technology, Delft, The Netherlands, ²Department of Ocean Systems, NIOZ, Den Burg, The Netherlands

Abstract Submarine canyons and trenches are the main pathways for transport of water, sediments, and nutrients across the continental slope. In the North Sea, transport across the slope and into the Norwegian Sea is confined to the Norwegian Trench (NT). From June 2023 to May 2024, we recorded time series data in the middle of the NT (272 m) and close to the Atlantic continental slope (363 m) using moored ADCPs to investigate the hydrodynamic variability. We identified semi-diurnal and diurnal tidal influence explaining 19% of the variance in the flow in the middle of the NT, and 10% of the variance at the continental slope, respectively. The deep currents respond to local winds and to coastal-trapped waves (CTWs) on time scales of 1–10 days. Significant correlations between increased water temperature and along-slope winds from the Southwest show that CTWs enable strong inflows of Atlantic Water, whereas winds from the Northeast favor upwelling of Arctic waters. In the central trench, seasonal signals in velocity, backscatter, and temperature are related to the North Atlantic Oscillation, highlighting the connectivity of the NT to the North Sea. The interactions of remotely forced CTWs and the up-and downwelling of water masses are typically observed in submarine canyons. With this study we add to a new understanding of the hydrodynamics in the NT, which are comparable to the dynamics observed in canyons around the world.

Plain Language Summary Underwater trenches are deep channels that serve as the main transport routes for water and the particles suspended within it in the ocean. They often function as a link between shallow and deep areas of the ocean. In the North Sea, transport into the Norwegian Sea is restricted to the Norwegian Trench (NT). To measure the transport, we monitored water velocities at two points for a year. The data show that water movement is driven partly by the tides and partly by wind and slow-moving waves propagating along the continental slope. The interaction between the wind and these waves causes warm Atlantic Water to flow into the NT during winds from the West, whilst cold Arctic water flows into the trench under opposite wind conditions. These events last for a few days. Over longer timescales, the data show that mass transport is associated with the North Atlantic Oscillation and is thus linked to the large-scale North Sea Circulation. These results contribute to a new understanding of the flows in the NT, which are comparable to the dynamics observed in similar systems around the world.

1. Introduction

Submarine canyons and trenches are important features connecting the shallow shelf and the deep ocean by cutting into the shelf (Allen & Durrieu de Madron, 2009; Allen et al., 2001; Harris & Whiteway, 2011; Huang et al., 2023; J. M. Huthnance et al., 2009; Sobarzo et al., 2016). They form major transport pathways and traps for waters, nutrients and sediments (Diesing et al., 2021; Ramos-Musalem & Allen, 2020; Sobarzo et al., 2016). Globally, more than 6,000 submarine canyons have been identified (Harris & Whiteway, 2011), yet the environmental impacts of canyon-induced cross-shelf exchanges are still a major unknown, for example, Allen and Durrieu de Madron (2009), Saldías et al. (2021). It is known that submarine canyons enable the upwelling (Allen & Hickey, 2010; Li et al., 2022; Ramos-Musalem & Allen, 2020; Saldías et al., 2021; Sobarzo et al., 2016) and downwelling (Figueroa et al., 2025) of water across the slope under favorable wind and flow directions, resulting in either deep water supply on the shelf, or the cascading of shelf water into the ocean, respectively. These vertical water mass displacements have non-negligible effects on nutrient supply and mixing (Brun et al., 2025; Sobarzo et al., 2016). Enhanced tidal energy dissipation (Nazarian et al., 2021) and large deep eddies (Allen et al., 2001; Huang et al., 2023) are the results of the steep bathymetry of the canyon and lead to interaction between the flows

in and outside the canyon. These properties have been found in numerous canyons, but even in systems with slightly different geometries than in the idealized canyon definition given in Allen and Hickey (2010), for example, in the Barrow Canyon, where the canyon head is not enclosed by land (Huang et al., 2023) or in the Gulf of California (Gutiérrez et al., 2014). This suggests that the processes mentioned above occur in systems which have canyon-like shapes but do not follow the classic definition of a submarine canyon.

The canyon-like system we are focusing on in this study is the Norwegian Trench (NT), a large underwater trench, formed by glacial erosion along the Norwegian coast (Figures 1a and 1b). The NT is the primary conduit for sea water (Hordoir et al., 2013; O. M. Johannessen, 1986; Sætre et al., 1988; Winther & Johannessen, 2006), suspended particulate matter (SPM) (Eisma & Kalf, 1987), and carbon and nutrients (J. M. Huthnance et al., 2009; van der Molen & Paetsch, 2022) from the North Sea across the slope and into the Norwegian Sea. It is also the most efficient region for carbon export from the North Sea toward the Atlantic (Holt et al., 2009) and long-term carbon burial in seabed sediment in the North Sea (Bockelmann et al., 2018; de Haas et al., 1996; Diesing et al., 2021; Eisma & Kalf, 1987). Net outflows through the NT into the Norwegian Sea are estimated with 2–3 Sv (1 Sv = 10⁶ m³/s) (Enge et al., 2025; J. M. Huthnance et al., 2009; Skagseth et al., 2011; Winther & Johannessen, 2006). The flow in the NT is complex due to the various barotropic and baroclinic processes interacting with the complex topography of the submarine trench (Furnes et al., 1986; J. A. Johannessen et al., 1989; M. Mork, 1981; Mysak & Schott, 1977; Winther & Johannessen, 2006). Surface and deep currents vary spatially and temporally, as they are primarily driven by local and remote wind forcing (Akpınar et al., 2022; Skagseth & Orvik, 2002; Winther & Johannessen, 2006) and topography (Furnes et al., 1986; Svendsen et al., 1991). Within the NT, surface currents have been more extensively studied, particularly the exchange of the North Sea and the Atlantic Ocean (J. M. Huthnance et al., 2009; Skagseth et al., 2011; Sætre et al., 1988) and the emergence of energetic mesoscale eddies (Ikeda et al., 1989; J. A. Johannessen et al., 1989) but deeper flows remain largely understudied, especially by observational data.

There are several mechanisms which have been identified that largely explain the variability in the flow field in canyon-like systems worldwide, for example, in the Barrow Canyon (Huang et al., 2023), in the Gulf of California (Gutiérrez et al., 2014), and in the Biobio River Canyon (Sobarzo et al., 2016). We introduce the three mechanisms, namely coastal-trapped waves (CTWs), local winds, and large scale wind forcing. The first mechanism is related to wave propagation in the slope current along the continental shelf break. Waves of sub-inertial frequencies ($\omega > f$) (ω = inertial frequency in Hz with $1/\omega$ = 13.82 hr at 60°N and 13.55 hr at 62°N, f = frequency in Hz) can be coastally trapped by the sloping topography (CTWs), and propagate with the coast on their right (left) in the northern (southern) hemisphere, hence eastward along the NW European shelf in the slope current (Gordon & Huthnance, 1987; Hughes et al., 2019; J. Huthnance et al., 2022; Skagseth & Orvik, 2002; Wise et al., 2024). CTWs were first identified by Adams and Buchwald (1969) off the coast of Australia and have since then been observed along shelves worldwide (Camayo & Campos, 2006; Gelderloos et al., 2021; Gordon & Huthnance, 1987; Gutiérrez et al., 2014; Inall et al., 2015; Koerner et al., 2024), usually triggered by along slope wind forcing. CTWs are known to cause fluctuations of several days, with the wave's periods being sensitive to the shelf width (Adams & Buchwald, 1969; Gordon & Huthnance, 1987; Mysak & Schott, 1977; Woodham et al., 2013). On the Scottish shelf, Gordon and Huthnance (1987) related an oscillatory response with period of $T \approx 23$ hr and a quasi-steady response in the flow to the propagation of shelf waves during persistent along slope wind forcing. Skagseth and Orvik (2002) found that the leading mode in the Norwegian Atlantic Current (NwAC) is a quasi-stationary response to an along slope wind forcing with a lag of $\Delta T \approx 12$ hr. They identified topographic wave modes with $T = 20$ –70 hr (second mode) and $T = 80$ –110 hr (third mode). Studies suggest that CTWs properties can be modified when interacting with trenches and submarine canyons, for example, due to reflection (Gordon & Huthnance, 1987) and CTWs splitting (Gutiérrez et al., 2014; Saldías et al., 2021). Allen and Durrieu de Madron (2009) state that flows opposite (aligned) to the direction of propagation of CTWs strengthen (weaken) cross-isobath flows in submarine canyons and thus favor upwelling (downwelling). Yet, Saldías et al. (2021) found upwelling for flow aligned with CTWs propagation, suggesting that the response might vary across different canyons. By enabling upwelling of denser, often oxygen rich water, CTWs are key drivers for the generation of biologically rich areas in the vicinity of submarine trenches (Allen et al., 2001; Inall et al., 2015; Koerner et al., 2024; Saldías et al., 2021; Sobarzo et al., 2016). Second, local wind is often identified as the primary forcing of currents near the surface. On short timescales, Inertial Oscillations with frequencies slightly smaller than the inertial frequency ($\omega > f$) are expected to have a short duration of $T < 23$ hr and weaken with increasing depth (Kundu, 1976; Mied et al., 2010). In the NT, surface flows are known to respond to the local

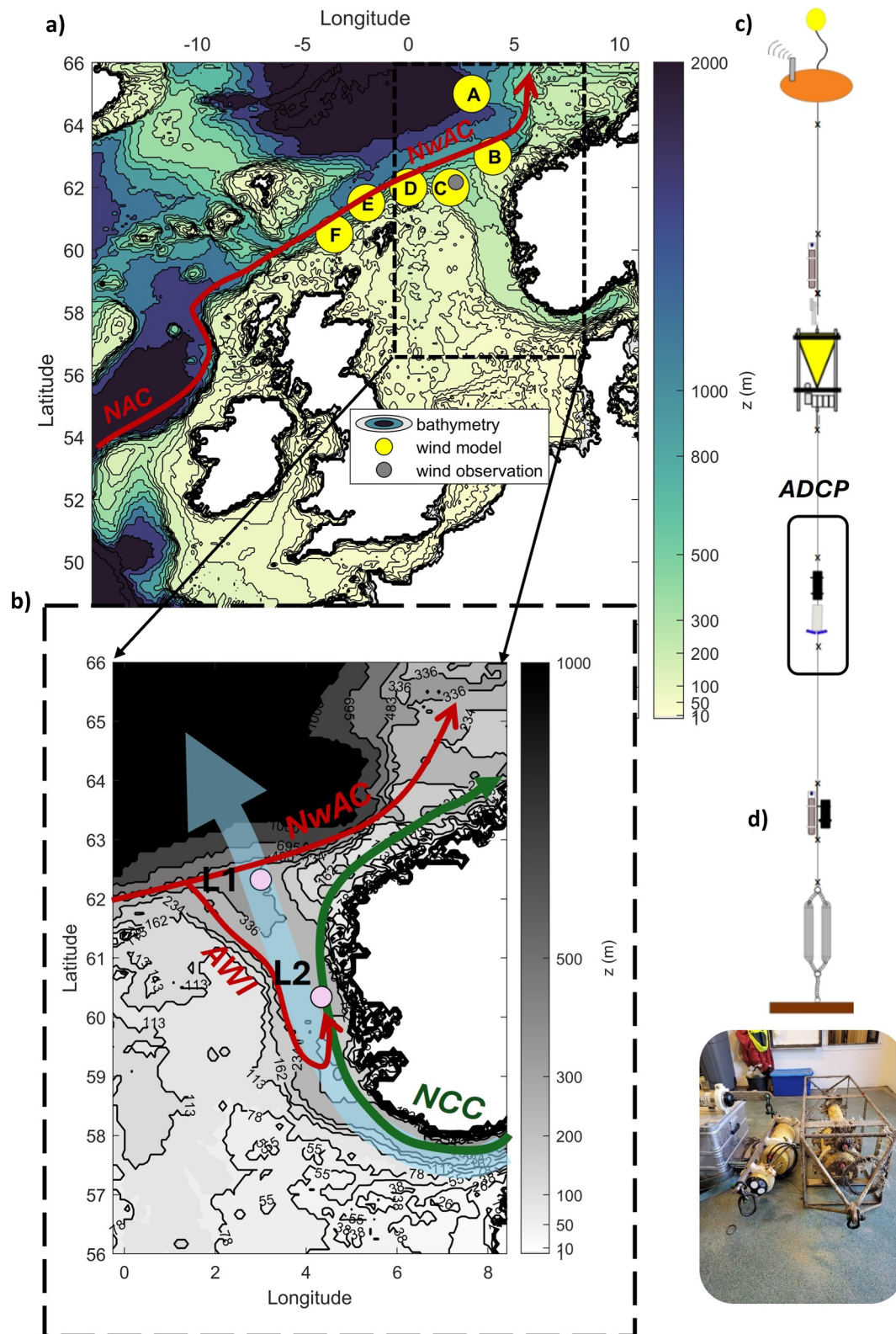


Figure 1.

wind forcing (Akpınar et al., 2022; Winther & Johannessen, 2006), but the influence of local wind on the deep flows has not been studied so far. Third, large scale meteorological forcings, like the North Atlantic Oscillation (NAO) and El Niño (Camayo & Campos, 2006; Gutiérrez et al., 2014), influence the flows. Seasonality in storm events in northern Europe is often related to the phasing and strength of the NAO (Akpınar et al., 2022; Hurrell & Deser, 2010; Skagseth et al., 2004; Winther & Johannessen, 2006). Positive NAO conditions result in strong winds from the West (W). Negative NAO conditions are related to weaker winds or winds from the East (E). Hydrodynamic simulations reveal that increased inflows into the NT correlate with winds from the Northwest (NW) and the Northeast (NE) in winter (J. M. Huthnance et al., 2009; Skagseth et al., 2004; Winther & Johannessen, 2006) and subsequently correlate with positive NAO phasing. Winther and Johannessen (2006) found that under persistent winds from the NE, Atlantic Water Inflows (AWIs) into the NT intensify as upwelling along the coastline allows new water to fill the deep parts of the NT. In summer, NAO phasing is often negative, resulting in weaker winds and flows (Skagseth et al., 2011; Winther & Johannessen, 2006).

As introduced above, the variability in the NT is expected to be large due to various forcing mechanisms, yet observational data are missing. Here, we present the results from two 1-year long time series of high-resolution ADCP measurements in the lower 20 m of the water column at two different sites in the NT (Figure 1). This study shows the spatial and temporal variability observed over 1 year, discussing the results in relation to dynamics observed in submarine canyons. By comparing the hydrodynamic processes in the NT with the dynamics inherent to submarine canyons, we aim to establish whether trenches behave similarly worldwide. This study leads to a new understanding of the deep flows in submarine channels globally, explaining their role in water and matter transport.

2. Materials and Methods

2.1. Study Area

In the study area of the NT, here defined as the region from 58°N to 8°E to 62.5°N and 2°E, three main currents have been identified (Figure 1b). The Norwegian Coastal Current (NCC) is a wind-driven current which flows northwards along the coast of Norway (Hordoir et al., 2013; J. A. Johannessen et al., 1989; Skagseth et al., 2011; Winther & Johannessen, 2006). The NCC is characterized by its low salinities (S in PSU) of 32–34 PSU and thereby only occupies the upper 50–100 m of the water column (Furnes et al., 1986). The strength of the NCC is regulated by zonal winds in the Skagerrak (Christensen et al., 2018; Skagseth et al., 2011). On the western side of the NT, Atlantic Water (AW) from the NwAC with $S \geq 35$ PSU and temperatures (θ in °C) $> 2^\circ\text{C}$ flows southward between 200 and 500 m (J. M. Huthnance et al., 2009; K. A. Mork et al., 2025; Skagseth & Orvik, 2002; Winther & Johannessen, 2006). A major part of the AWI recirculates cyclonically (“retroreflects”) between 58°N and 59°N and flows out in the alongshore direction underneath the NCC (Furnes et al., 1986), indicated with the red line in Figure 1b. Winther and Johannessen (2006) estimated that more than half of the AWI is mixed and retroflected before reaching 59°N. The rest of the water column in the trench is composed of a colder and denser mixture of North Sea water and AW which have been cooled over the previous winter (Enge et al., 2025; Svendsen et al., 1991). Off the slope toward the Norwegian Sea, Arctic water masses are found (K. A. Mork et al., 2025). In previous studies Mysak and Schott (1977) and Johannessen (1986) characterized the adjacent water mass to the NT as Norwegian Sea Deep Water (NSDW), with $\theta < 0^\circ\text{C}$ and $S < 34.95$ PSU. K. A. Mork et al. (2025) present an updated overview of the water masses. They classified the NSDW with $\theta < -0.5^\circ\text{C}$ and $S \sim 34.91$ PSU. Based on K. A. Mork et al. (2025) the NSDW is not the only water mass that might be found across the slope or in the NT, but also the Norwegian Sea Arctic Intermediate Water (NSAIW), sitting on top of the NSDW. The NSAIW is characterized by $\theta = -0.5$ – -1°C and $S = 34.87$ – 34.91 PSU. In this study, we choose to use NSAIW as it sits at shallower depths and is more likely to enter the NT. The occurrence of NSAIW events is indexed by the condition

Figure 1. (a) Bathymetric map of the North Sea using GEBCO (2024) data. Depth (z in m) is displayed on a logarithmic scale. We indicate selected wind stations of CMEMS (2024) data as yellow dots with letters A–F, the station of wind observations as gray dot, and the along slope North Atlantic Current turning into the Norwegian Atlantic Current (NwAC). (b) Zoomed-in bathymetric map of the Norwegian Trench with the locations of the ADCPs (L1 and L2) indicated as purple shaded dots. Mean flows of the Norwegian Coastal Current, the Atlantic Water Inflow and the NwAC are indicated. The blue arrow indicates the net northward discharge of North Sea waters across the continental slope at depth greater 100 m. (c) A sketch of the mooring setup at L2 and (d) a picture of the ADCP (left) after the successful recovery in 2024.

Table 1
Information About ADCP and CT Sensor Data

Mooring	Latitude, longitude	Date	Bottom depth (m)		Level (bin size) (m)	Variable	Recording information
L1	62.33°N, 3.03°E	8 June 2023–5 May 2024	384	ADCP	384–363 (0.7)	u, v (m/s)	$F_s = 2$ Hz
						θ (°C)	$B_{\text{int}} = 10$ min
				CT	349	bs (dB)	$D_B = 0.1$ m
						θ (°C)	$B_{\text{int}} = 15$ min
						S (PSU)	
L2	60.38°N, 4.30°E	12 June 2023–2 May 2024	293	ADCP	293–272 (0.7)	u, v (m/s)	$F_s = 2$ Hz
						θ (°C)	$B_{\text{int}} = 10$ min
				CT	258	bs (dB)	$D_B = 0.1$ m
						T (°C)	$B_{\text{int}} = 15$ min
						S (PSU)	
						P (bar)	

Note. We write bs = backscatter (dB), u = zonal velocity (m/s), v = meridional velocity (m/s), P = pressure (bar), F_s = sampling frequency (Hz), B_{int} = burst interval (min), D_B = blanking distance (m).

of $\theta \leq 5^\circ\text{C}$ in the temperature time series at L1 and the occurrence of warmer AWI events by $\theta \geq 9^\circ\text{C}$ at L2 throughout this study.

2.2. Observation Data

We present two mooring data sets, L1 and L2. The northern mooring (L1) was placed close to the shelf-edge of the NT toward the Norwegian Sea to capture the cross-shelf exchange flows. The southern mooring (L2) was placed in the middle of the NT, at approximately 35 km distance from the Norwegian coastline, to capture the outflowing waters of the North Sea. L1 recorded data from 8 June 2023–5 May 2024, and L2 from 12 June 2023–2 May 2024. The mooring lines cover the lower 100 m of the water column (Figure 1c). Each mooring was equipped with a downward looking ADCP (Figure 1d) attached at 20 m above the bed (Enge et al., 2026) and a Seabird MicroCAT (CT) at 35 m above the bed (Mienis, 2026). The ADCPs are 1,000 kHz instruments (Signature 1,000) from Nortek. Information about the instrument settings and parameters are presented in Table 1. Information about post-processing and data quality checks are added in Text S1 and Figures S1 and S2 in Supporting Information S1.

2.3. Meteorological and Bathymetric Data

In this study, large scale wind forcing is represented by the NAO index. We use weekly and monthly index data from June 2023 to May 2024 from the Climate Prediction Center (NOAA, 2025). To study the local winds, we use both, model and observational data. The observational wind data are measured at the station Gullfaks C (ID: SN76923, 61.2114°N, 2.2721°E) provided by Norsk klimaservicesenter (Meteorologisk institutt, 2026). Data of wind speed (m/s) and direction (°) are recorded at 80 m above sea level every 3 hr. Modeled wind velocity data (u_w, v_w in m/s) are used from simulation outputs of the Copernicus product *Global Ocean Hourly Reprocessed Sea Surface Wind and Stress from Scatterometer and Model* (CMEMS, 2024). Local wind forcing is investigated at two stations with the same coordinates as the mooring locations, L1 and L2 (see Table 1). We use the observational data to study the effect of local winds and to compare it to the model results at L1 and L2. Six other wind stations are selected from the CMEMS model in proximity to the shelf break, where up-and downwelling conditions and along-slope propagation of CTWs would be forced (see Figure 1a). The coordinates are the following: A (65°N 3°E), B (63°N 4°E), C (62°N 2°E), D (62°N 0°E), E (61.5°N–2°E), and F (60.5°N–3.5°E). All wind data time series cover the full length of the ADCP time series, that is, from 8 June 2023, to 5 May 2024. Stations A–C are selected primarily to capture cross-slope upwelling (Aagaard, 1970), and stations D–F to study the effect of along-slope propagating CTWs. As presented in previous studies, for example, Skagseth and Orvik (2002) and Gordon and Huthnance (1987), we expect flow responses to local wind forcing at L1 and L2 to have periods <24 hr, and flow responses to remote wind forcing and CTWs to range between 1 and 5 days. The bathymetric data are provided by the General Bathymetric Chart of the Oceans (GEBCO, 2024).

2.4. Data Analysis

2.4.1. ADCP Data Processing

For all ADCP data analysis we use burst-averaged and vertically averaged meridional (v) and zonal (u) current velocities (m/s) and four-beams averaged backscatter (bs) (dB). Averages are calculated over all cells, which is approximately 21 m. Temperatures are only measured at one point and are therefore only burst-averaged. Flow speed (m/s) is calculated as $U = \sqrt{u^2 + v^2}$. In this study, we use deviations of backscatter from the average because sensors may have different sensitivities. Haalboom et al. (2021) and Merckelbach (2006) showed that high-resolution ADCP backscatter measurements correlate to absolute particle volumes, such that we understand increases in backscatter as increases in particle concentrations.

2.4.2. Frequency Analysis

The MATLAB package UTide from Codiga (2026) is used to identify the tidal contribution in the velocity data. The depth-averaged velocity components are used for tidal analysis. We present the tidal amplitude of the velocity (m/s) along the semi-major axis (L_{smaj}) which is positive in the same direction as u and v by definition (Codiga, 2011). The orientation angle (φ in $^\circ$) is positive in counterclockwise direction from east. We calculate the variance (R^2) in the flow velocities which is explained by tides using the reconstructed astronomical tidal signal for both velocity vectors (u_{rec}, v_{rec}). The explained variance is calculated as

$$R^2 = 1 - \frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{\sum_{i=1}^n (y_i - \bar{y}_i)^2}, \quad (1)$$

where y are the flow velocities in u and v , $\hat{y}$ the tidally reconstructed velocities u_{rec} and v_{rec} , $\bar{y}$ the averaged velocities and n is the length of the time series. R^2 is multiplied by 100 and presented as rounded percentage. The constituents identified and used in the tidal analysis are presented in Tables S1 and S2 in Supporting Information S1. In addition, we use Equation 1 for the regression calculation between our time series and the NAO index, where we display R^2 for monthly and weekly averages (R_M, R_W).

To study the ADCP time series in the frequency and time domain, we use continuous wavelet transform (CWT). We choose the Morlet wavelet (*amor*) which has been shown to be a good choice to study the frequency content in real world periodicities over time (Camayo & Campos, 2006; Grinsted et al., 2004; Torrence & Compo, 1998). The Morlet wavelet is described by an exponential function modulated by a Gaussian. Localized changes in frequency can be detected in time by taking the inverse Fourier transform and applying a convolution with the time domain wavelet. CWT is a common approach to identify CTWs in time series data (Gelderloos et al., 2021; Inall et al., 2015). In addition, we calculate the time-averaged wavelet power spectrum of the signal using the CWT filter bank function in MATLAB. By definition, the power spectrum $S(f)$ is obtained by time-averaging the magnitude-squared scalogram over time.

2.4.3. Flow and Wind Coherence

The relation between wind and flow velocities is investigated by analyzing coherence correlation between the wind and velocity time series (Gutiérrez et al., 2014; Inall et al., 2015; Kundu, 1976; Mied et al., 2010; Skagseth & Orvik, 2002). We write the complex form of the flow and wind velocities (u_w, v_w) as

$$U = u + iv; \quad U_w = u_w + iv_w \quad (2)$$

The function `complex_corr.m` (Twedt, 2014) written for MATLAB correlates the complex velocity time series, taking into account the amplitude and phase relationship and returning a correlation coefficient (`corr`) and the phase (φ in $^\circ$). We adjusted the function to account for lags. Magnitude-squared coherence (C_{fw}) between flow and wind time series is calculated based on the power spectral densities of each time series ($P_{ff}(f), P_{ww}(f)$) and the cross power spectral density of flow and wind time series ($P_{fw}(f)$) as

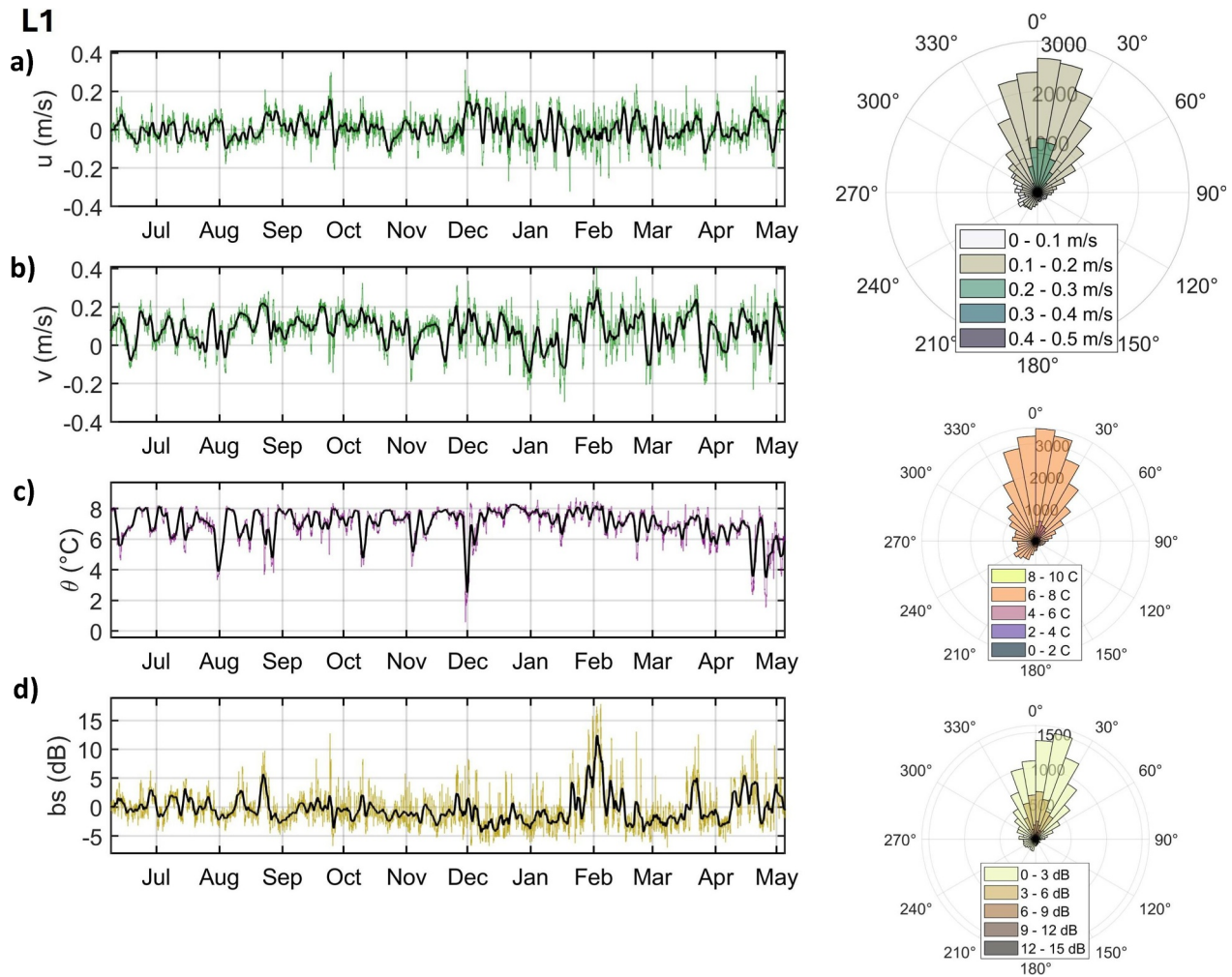


Figure 2. The time series of (a) u (m/s), (b) v (m/s), (c) θ ($^{\circ}\text{C}$), and (d) bs deviations from the mean (dB) from the ADCP at L1 are displayed as hourly averages (colored line) and as smoothed by a 2-day moving average (black line). The current directions of 10-min recordings are presented in current roses for U , θ , and bs .

$$C_{fw}(f) = \frac{|P_{fw}(f)|^2}{P_{ff}(f)P_{ww}(f)} \quad (3)$$

Coherence explains the similarity between the time series for each frequency (f).

3. Results

3.1. Temporal and Spatial Variability at L1 and L2

3.1.1. Variability Close to the Continental Slope

At L1 (the Northern location), hourly and daily averaged fluctuations in u and v are ± 0.1 m/s throughout the year and up to ± 0.2 m/s in winter, especially in v (Figure 2). The u fluctuations are similar throughout the year with maximum magnitude of 0.3 m/s in westward and eastward direction. v is largest in winter in the northward and southward direction with maximum magnitudes of 0.4 and 0.3 m/s, respectively. Resulting current speeds are on average of 0.11 m/s with a maximum of 0.45 m/s in early February. Besides larger variability and higher velocities in December and February, there is no indication of seasonality in the time series. The direction of the flow is oriented parallel to the coastline in north/north-eastward direction.

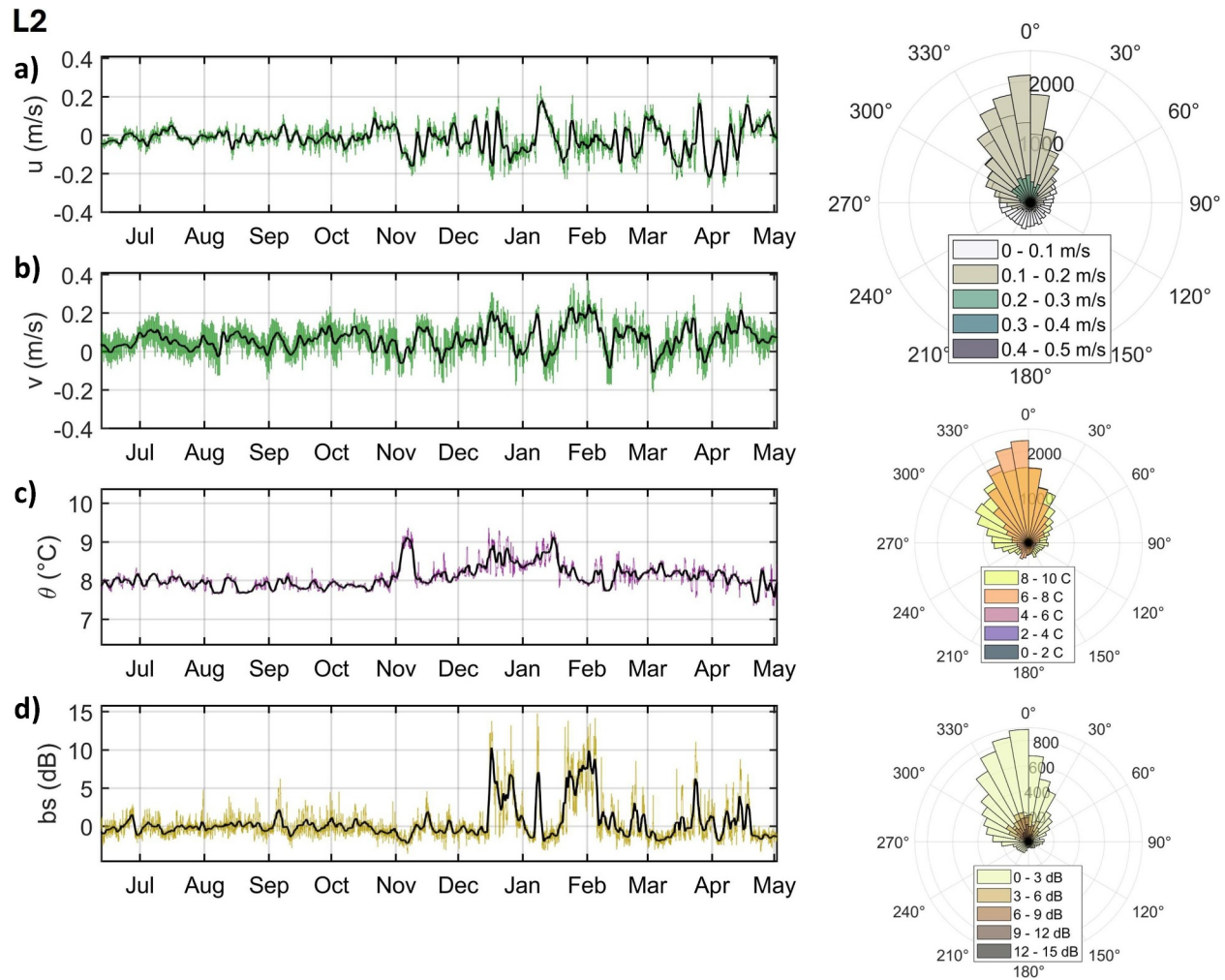


Figure 3. The time series of (a) u (m/s), (b) v (m/s), (c) θ ($^{\circ}\text{C}$), and (d) bs deviations from the mean (dB) from the ADCP at L2 are displayed as hourly averages (colored line) and as smoothed by a 2-day moving average (black line). The current directions of 10-min recordings are presented in current roses for U , θ , and bs .

At L1, temperatures range from 0.5°C to 8°C . Hourly variations can be as large as $\pm 6^{\circ}\text{C}$, but smaller variations of $\pm 2^{\circ}\text{C}$ – 3°C are more common throughout the year. Sudden drops to below 5°C indicate the occurrences of NSAIW, for example, in August and December 2023, as well as in May 2024. Hourly and daily fluctuations in backscatter are large throughout the year. Especially hourly variations can be as large as ± 5 dB, that is, September–January, even when the 2-days moving averages are small. The largest deviations are observed in February 2024, where increases up to 10 dB are recorded. This increase aligns with a northward directed flow indicated by the positive maximum in v .

3.1.2. Variability in the Center of the Trench

At L2 (the Southern location), the hourly variations in v are more than double as large (± 0.2 m/s) than the 2-days moving averages (Figure 3). Hourly variations in u are small, but become comparable to v in winter. u is small in summer, but up to 0.2 m/s in both, eastward and westward direction in winter. In v , a clear northward direction is observed, which dominates throughout the year and reaches maximum magnitudes of 0.4 m/s in February 2024. Calculated current speeds are on average of 0.11 m/s. Velocities show a strong seasonality, with higher velocities in winter than in summer. The orientation of the flow is parallel to the coastline in north/north-westward direction. At L2, temperatures range from 7 to 9.5°C . Hourly and daily variations in θ are in general $\pm 0.5^{\circ}\text{C}$. From December–April hourly variations increase but stay below 1°C . Increases of temperature over winter (November 2023 and over December 2023 to February 2024) show the seasonal trend. The direction of waters with $\theta > 7^{\circ}\text{C}$ is

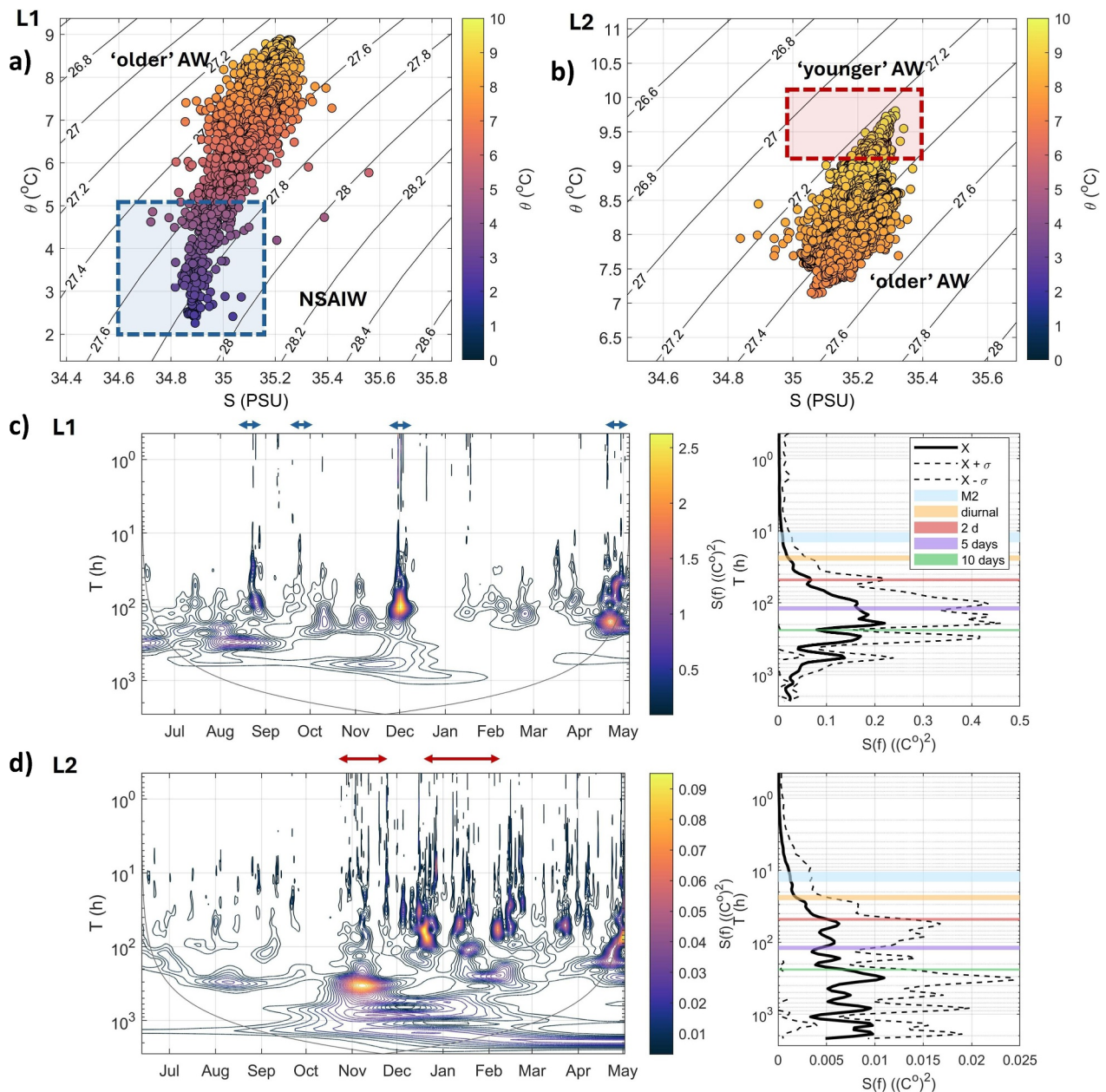


Figure 4. θ -S diagrams are calculated with the TEOS-10 Gibbs-SeaWater software package (McDougall & Barker, 2011) from the hourly averaged CT sensor data at L1 (a) and at L2 (b). We name the dominant water masses (AW = Atlantic Water, NSAIW = Norwegian Sea Arctic Intermediate Water). The wavelet plots on the left show the continuous wavelet transform of the 10-min averaged temperature time series at L1 (c) and at L2 (d). The cone of influence by the gray line. On the right, the time-averaged power spectra of the 10-min averaged temperature time series are shown as black lines and the $\pm$ standard deviation (σ) bounds as dashed lines. We indicate periods with bars of ± 2 hr for M2 (=12.42 hr), diurnal tides (=24 hr) and 2 days, and bars of ± 8 hr for 5 and 10 d for better readability. In blue we indicate cold water upwelling events and in red Atlantic Water Inflow events.

north-westwards, while warmer waters ($\theta = 8^{\circ}\text{C}$ – 10°C) have a stronger westward tendency. L2 shows a typical seasonal trend of low speeds and low backscatter in summer (June–November 2023) and high speeds and high backscatter in winter (December 2023 to May 2024). Hourly variations in backscatter increase to up to ± 15 dB in winter, showing an event-driven response of SPM transport.

3.2. Water Masses and Their Forcings

In Figure 4, we present temperature and salinity data from the CT sensor in the θ - S space for L1 and L2 (a, b) and the results of the CWT on the temperature time series of the ADCPs (c, d). We identify three water masses: the NSAIW with $\theta = -0.5^{\circ}\text{C}$ – 1°C and $S < 35$ PSU, the “older” AW with $S \geq 35$ PSU and $\theta = 5^{\circ}\text{C}$ – 9°C , and the “younger” AW with $\theta > 9^{\circ}\text{C}$. The warmer and saltier “younger” AW still carries the heat from the NwAC whereas residual and “older” AW is generally colder due to a lack of surface exchange and mixing. NSAIW and “older” AW are measured at L1, whereas at L2, the “younger” and “older” AW are measured.

The wavelets at L1 and L2 show no, or only very little power in the tidal frequencies, indicating that tides do not impact the movement of water masses. At both locations, most power is accumulated in the period bands of $T > 2$ days but the fluctuations have a very different timing. At L1, power increases with longer periods, with a peak at $T = 4$ – 8 days. Power decreases for $T = 9$ – 11 days but increases again for 13 day periods. At L1, the NSAIW upwelling events in August, October, December 2023, and May 2024 (blue arrows) are captured and carry the largest amount of power in the time series, especially the December inflow event (Figure 4c). At L2, power is accumulated in winter in fluctuations with $T = 2$ – 4 and 7 days. In November 2023 and February 2024, fluctuations with periods of 13 days show a large power contribution too. Fluctuations of $T = 2$ – 4 days are related to the inflow events of “younger” and warmer AW in November and January–February (red arrows) (Figure 4d). Over summertime (June–November 2023) the wavelets show low power accumulation, underlining that the water mass inflows are highly event-driven.

3.3. Tides

The results of the tidal analysis, as well as the power spectra $S(f)$, are presented in Figure 5. The full tidal analysis results from UTide are presented in Tables S1 and S2 in Supporting Information S1. The major tidal axis of the dominant constituents is in the northward direction ($\varphi = 90^{\circ}$) at both locations, and thus oriented in the same direction as the mean currents at L1 and L2 (see Figures 2 and 3). The explained variance (R^2) calculated with Equation 1 is 10% at L1 and 19% at L2. The tidal spectrum at L1 shows the largest amplitudes of low-frequency tides, for example the SSA and the MSF (14.7 days, 8%, $\varphi = 87.6^{\circ}$). The third strongest constituent is the semi-diurnal M2 ($\varphi = 70.6^{\circ}$) explaining 7% of the variance, followed by the diurnal O1 tide explaining 2%. The diurnal constituents are oriented toward the northeast ($\varphi = 45^{\circ}$) at L1 and northwest ($\varphi = 110^{\circ}$) at L2. In contrast at L2, the semi-diurnal tides, that is, M2 (12.4 hr, 37%, $\varphi = 90.8^{\circ}$) and S2 (12 hr, 4%, $\varphi = 91.8^{\circ}$) dominate the spectrum. The contribution of the semi-diurnal constituents at L2 is more than twice as large as at L1, and is the main reason why the explained tidal variance is larger at L2 than at L1 (see $S(f)$). Low-frequency and diurnal tides have slightly smaller amplitudes at L2. We observe very low contributions of non-principal constituents and overtides, for example, M4 at L2. The spectra on the right hand side show the different contributions of the M2 and M4 tidal constituents at L1 and L2, which contain more power at L2 than at L1.

3.4. Fluctuations in Speed and Backscatter

In Figure 6 we present the wavelets of current speed in (a) and (c) and of backscatter in (b) and (d), respectively for L1 and L2. At L1, semi-diurnal tides dominate in the current speed wavelet, whereas in backscatter, we observe that the diurnal tides are more powerful. This indicates that more SPM is moved by diurnal tides than by semi-diurnal tides, even if the speed fluctuations are stronger for the latter ones. This process is indicated as “Diurnal matter movement” in Figure 6b. A similar discrepancy is observed for the spring-neap tidal cycle, which is captured in the current speed wavelet but not in the backscatter wavelet. The majority of power is found at periods of $T = 2$ – 3 , 5, and 9–11 days in both spectra. The timing of the fluctuations of $T = 2$ – 3 and 5 days roughly coincide in both wavelets but are not the same. The fluctuations occur predominantly in winter but there are still a few weak events in summer. The deviations in timing of the intensified power show that increases in SPM volume are not necessarily coupled to increases in speed.

At L2, we observe a large peak in power from the M2 tide in the current speed wavelet, which however is absent in backscatter. As found at L1, there is no influence of the semi-diurnal tides on SPM concentrations or movement. It is even more significant at L2 as the power of the M2 is much larger than at L1. In the backscatter wavelet of L2 the tidal contribution is weak, especially compared to L1. In speed and backscatter, we observe that sub-inertial frequency events are most abundant in winter and cause accumulation of power in the periods of $T = 2$ – 3 , 7 and $T = 12$ – 13 days in the time-averaged power spectra at L2. Therefore, the dominant periods of the fluctuations are

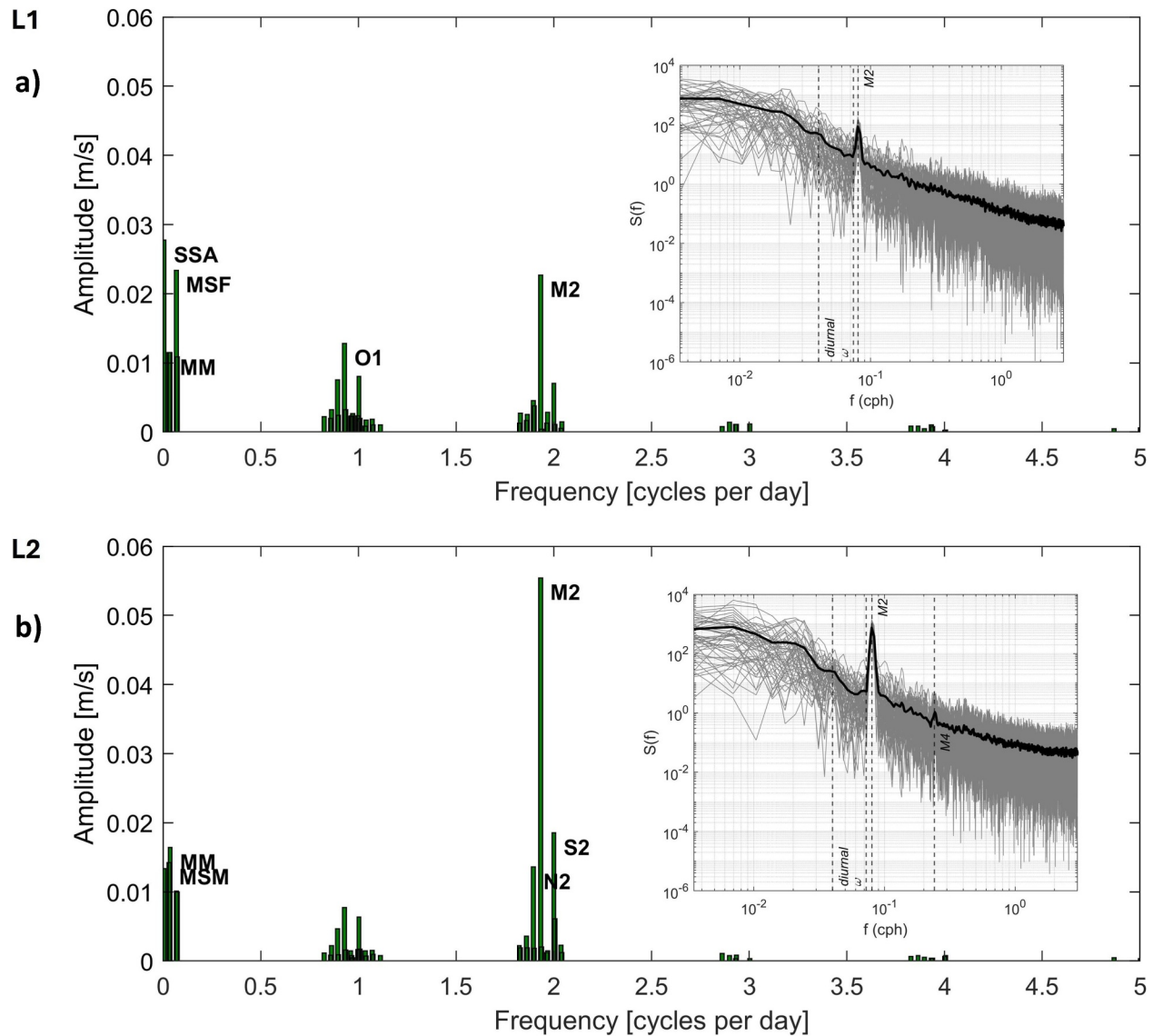


Figure 5. Tidal analysis results at L1 (a) and at L2 (b). We display the frequency of the tidal constituents on the x-axis in cycles per day and L_{smaj} in m/s on the y-axis. We indicate the names of the constituents with the five greatest percentages of explained variance. On the right, we show the power spectra calculated over windows of 12 days as gray lines and the overall average as black line. We indicate tidal constituents and the inertial frequency ω_i .

slightly longer compared to L1. The powerful events in backscatter and velocity at L2 do coincide in timing, yet the frequencies of the same signal differ. To highlight the episodic nature of the backscatter fluctuations we highlight the process “Storm induced matter transport” in Figure 6d. Both stations show that the transport of SPM is event-driven even though diurnal tides play a significant role in transport at L1. Some of the strong events captured at L2 can also reach L1, for example, in February 2024.

3.5. Meteorological Forcing

3.5.1. NAO

In Figure 7 we show the influence of the large-scale wind forcing on the deep flows in the NT. Over the time of the measurements, the NAO index is negative from July–November 2023, positive from November 2023–March 2024 and negative again from March–May 2024. This trend shows the typical seasonality in the pressure and wind systems over the North Sea, with weaker winds in summer and intensified winds from the West in winter.

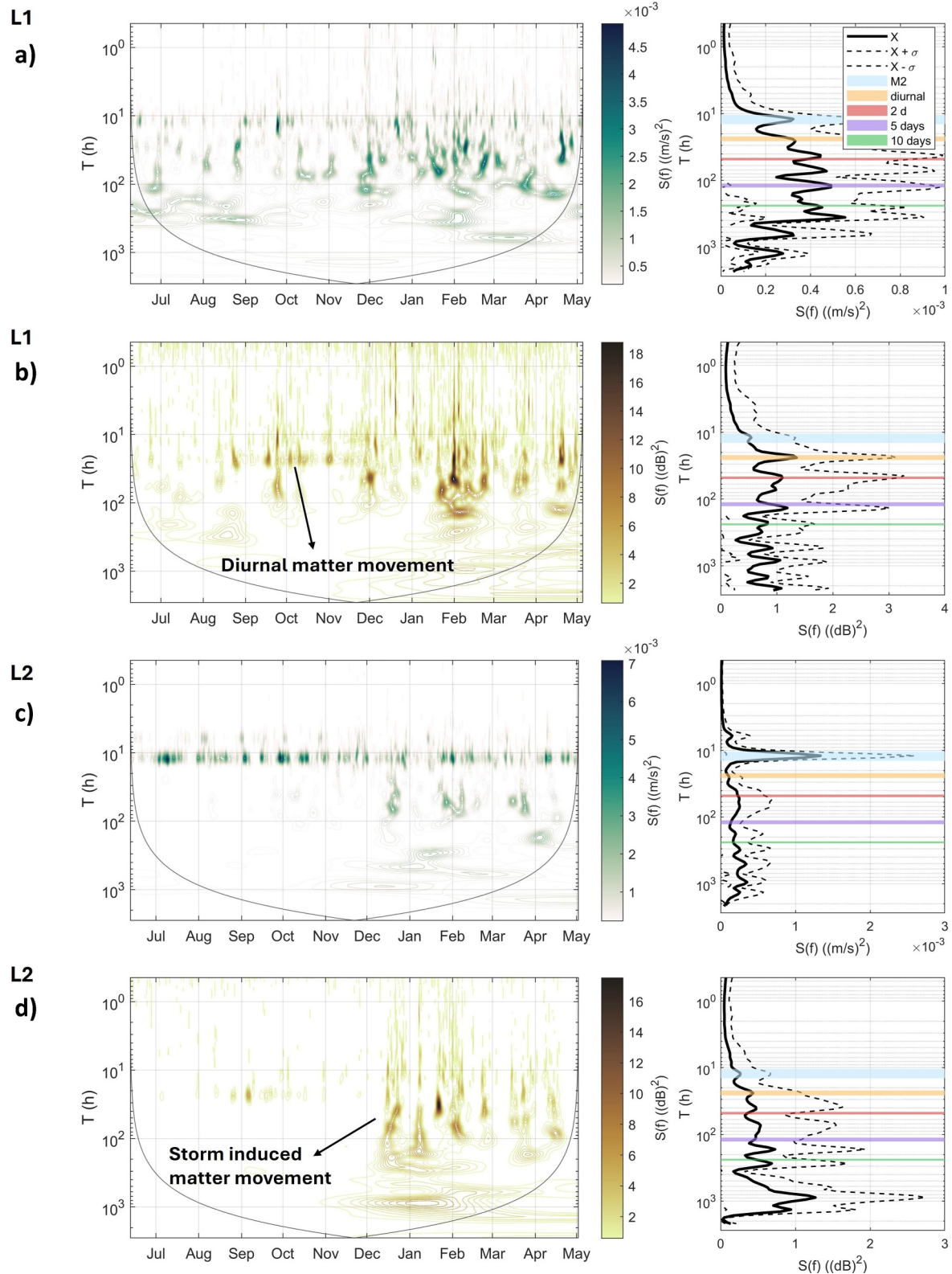


Figure 6. The wavelet plots on the left show the continuous wavelet transform of the 10-min averaged current speed time series at L1 (a) and at L2 (c) and of the 10-min averaged backscatter time series at L1 (b) and at L2 (d). The cone of influence is indicated by the gray line. On the right, the time-averaged power spectra of the 10-min averaged velocity and backscatter time series are shown as black lines and the $\pm$ standard deviation (σ) bounds as dashed lines. We indicate periods with bars of ± 2 hr for M2 (=12.42 hr), diurnal tides (=24 hr) and 2 days, and bars of ± 8 hr for 5 and 10 d for better readability.

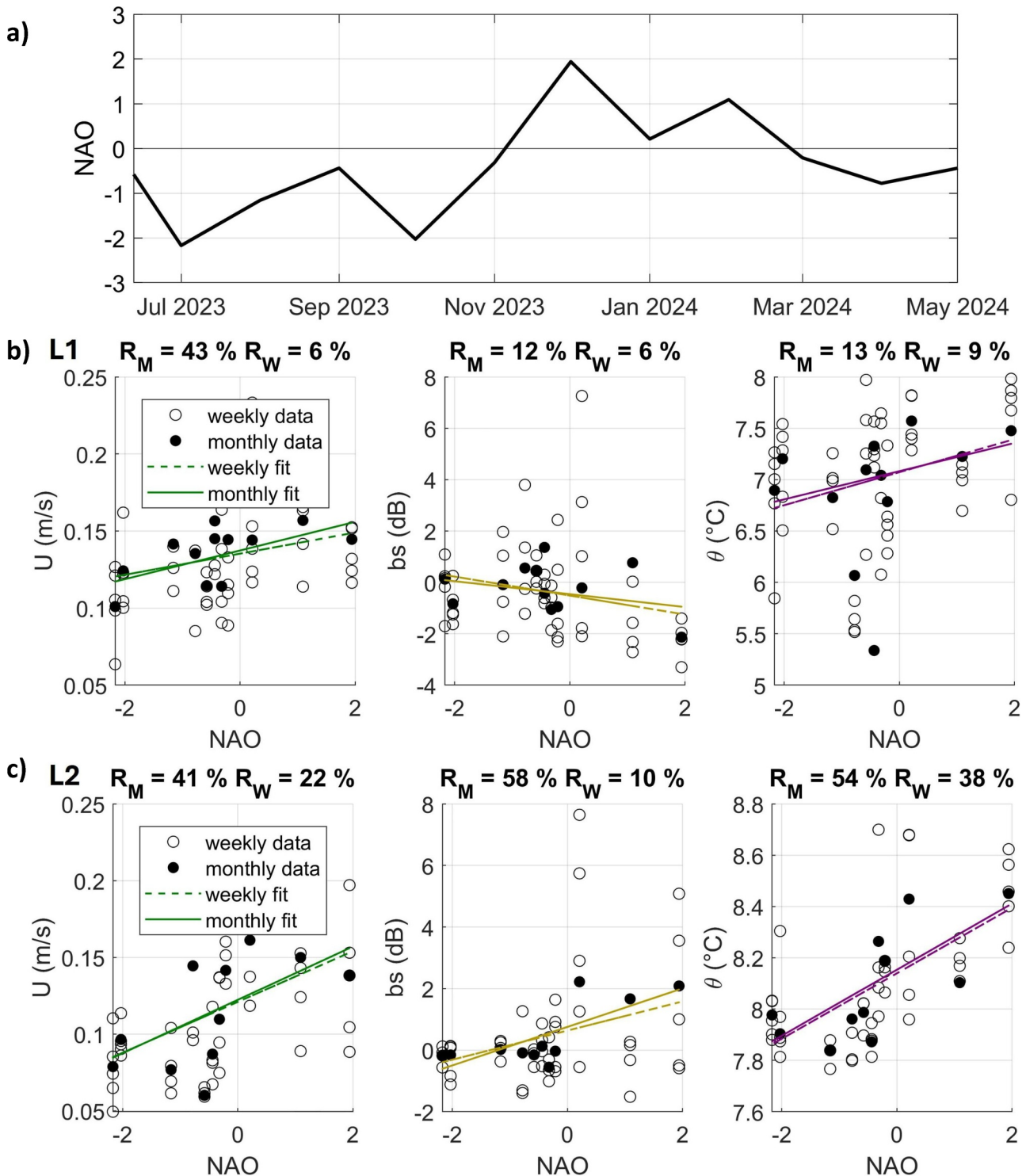


Figure 7. (a) Monthly North Atlantic Oscillation (NAO) indices and a zero-line for better readability. We show the results of the linear regression between NAO and current speed, backscatter, and temperature at L1 (b) and at L2 (c). The explained variance is given in % for monthly averages (R_M) and weekly averages (R_W) (Equation 1).

NAO indices range between ± 3 , where an index of two is already considered a very strong NAO (NOAA, 2025). The positive indices in December 2023 and February 2024 are related to strong storms, namely Zoltan on 22–23 December 2023 (Purkiani et al., 2024) and Ingunn on 30 January–2 February 2024 (Fagerlid et al., 2024).

We observe that the explained variances from monthly averaged data at L2 are generally larger than at L1, indicating that the stations are not influenced to the same extent by meteorological conditions, but that L2 is more and L1 less meteorologically driven. At L2, all parameters show increasing magnitudes during positive NAO conditions for monthly averages, indicating that large current speeds, high backscatter and increased temperatures due to AWIs are related to intensified westerly winds. R_M is 41% for current speeds, 58% for backscatter, and 54% for temperature at L2. At L1 the relation of the NAO and current speed is very similar to L2 ($R_M = 43\%$). Backscatter shows a negative relation to the NAO and a low explained variance of only 12%. The weak linear relation in backscatter at L1 can partly be explained by the strong diurnal tidal influence, which causes backscatter fluctuations on much shorter timescales throughout the year. At L2, backscatter is primarily influenced by winter storms (Figure 6c). Temperature at L1 does not show much response to the NAO with only 13% explained variance, which indicates that the inflows of NSAIW are not meteorologically forced by the NAO. Overall, the explained variance for weekly averages is significantly lower compared to the explained variance for monthly values. Only at L2, do the explained variances for weekly temperatures (38%) and current speeds (22%) remain relatively large.

3.5.2. Local Wind Forcing

We show the results of local wind forcing at L1 and L2 using hourly averaged simulation wind data from CMEMS (2024) at the mooring locations (see Figure 1a), hourly observation wind data, and hourly current velocities from the ADCPs. Both wind time series agree very well. Largest wind speeds occur in October 2023, end of November and February 2024. Over summer the wind speeds are smaller. There is no dominant wind direction. The winds are either coming from the North (N), NW, or NE or from the South (S), Southwest (SW), or SE. In June–October winds are variable and weak, compared to October–January, where winds from the NE and NW dominate, until turning to winds from the SW in February–April. In the correlation results, the local wind response at both locations is restricted to timescales smaller than 2 days and rotated slightly in agreement with Ekman transport to the right ($\varphi = 0^\circ$ – 50°). The lagged correlation spectra are very similar for the modeled and observed wind time series. Specifically, we find maximum correlations of up to 0.2 ($\varphi = 20^\circ$ – 50°) at positive lags of $T = 3$ and 18 hr at L1 and maximum correlations of 0.23 ($\varphi = \sim 50^\circ$) at positive lags of $T = 6$ and 48 hr at L2. Positive lags indicate that wind leads the velocity, which suggests wind-driven forcing of the obtained correlation. The coherence calculations at L1 show largest coherence of wind and flow velocity for periods of $T = 1/\omega = 13.55$ hr, 40 hr and 3.7 days. At L2 largest coherence is found for periods of $T = 26$ and 40 hr. The coherence at the inertial frequency is not significant. Wind and flow velocity oscillations with periods of 40 hr show the highest coherence with 0.2 at both locations. The coherences calculated from the model and from the observations are very similar, but at L2 the magnitude of coherence derived from the observation is lower than for the model.

3.5.3. Remote Wind Forcing on Water Masses

Remote wind forcing on the upwelling of NSAIW and AWI is investigated using six wind locations (see Figure 1a) at which we retrieved wind time series from CMEMS (2024) (Figure 9). At L1, we observe that winds from NE favor NSAIW upwelling. We find maximum correlations at C where $\text{corr} = 0.45$ and at B where $\text{corr} = 0.42$. Even though the wind data are scattered and the correlation coefficients show little variations among the stations, winds are from the NE during 10 out of the 14 upwelling events. During the other four events, winds are from the SW at the stations A–C. During upwelling favorable winds from the NE at A–C, velocities are north-eastwards, and thus in line with the mean flow direction at L1. At L2, we captured three events (6 days) of which all show large scatter in wind direction. Yet, from the correlation, winds at E, F, and A have the largest influence on the AWIs, that is, F: $\text{corr} = 0.85$, E: $\text{corr} = 0.69$ and A: $\text{corr} = 0.56$. Winds from SW favor AWIs at the stations E and F, for example, in December 2023. At station A, AWIs are favored during winds from the N. During the events the current velocities are weak and westwards. In December and January strong along slope winds from the W and SW are captured at D–F. These wind conditions favor downwelling flows by theory, as they align with the direction of CTWs propagation along the shelf (Allen & Durrieu de Madron, 2009). Downwelling of AW into the NT can therefore be related to CTWs propagation and is investigated by correlations with winds at the westernmost stations in (e).

We compute lagged correlations for the velocity time series at L1 and L2 and wind time series at D, E, and F during the full year to identify dominant lags and relate these to remotely forced CTWs and their propagation into the NT. The results of the correlation at all three stations are very similar. The largest correlations at L1 are

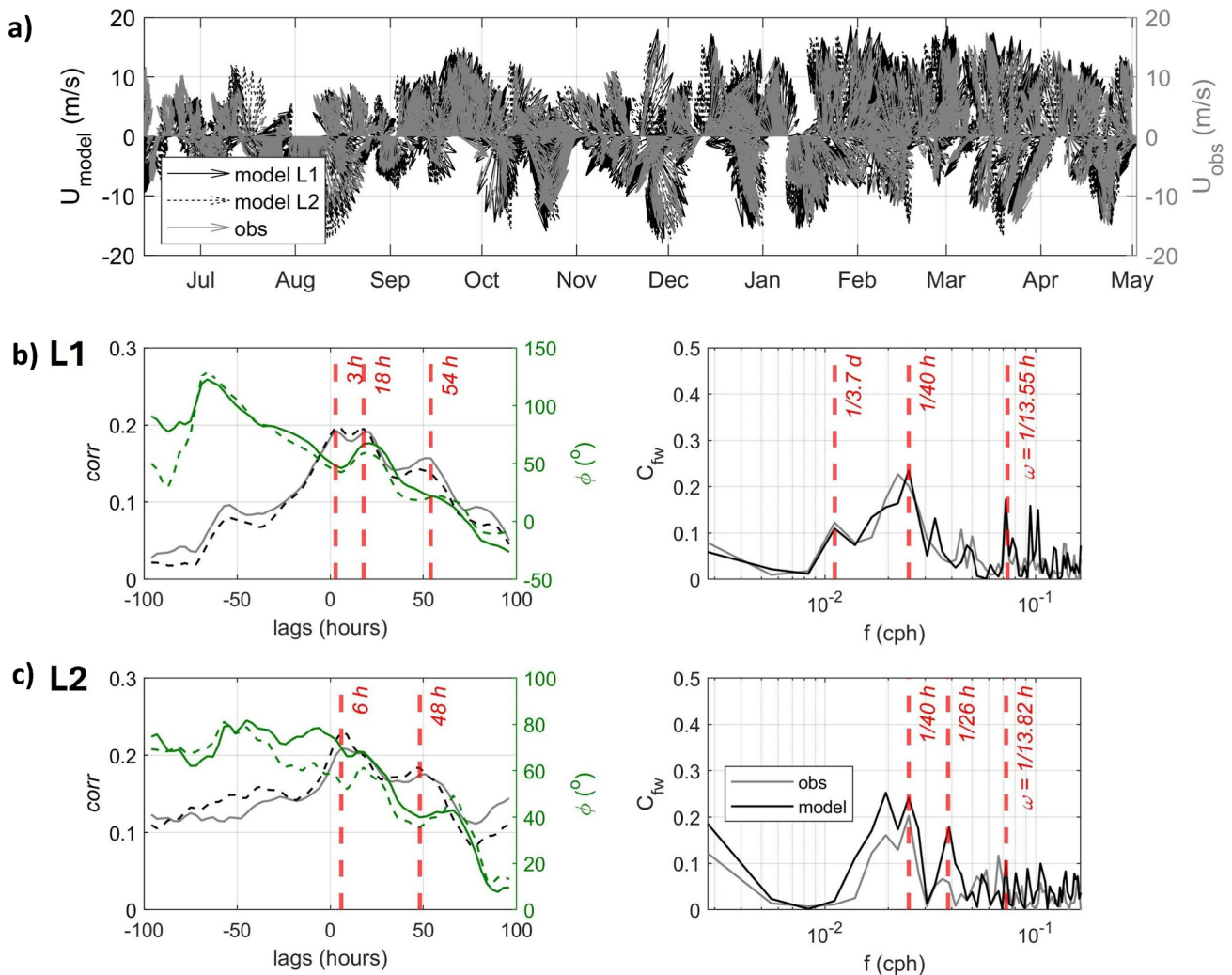


Figure 8. (a) Wind time series from model data at L1 and L2 (black lines) and from observation data at Gullfaks (gray line). The direction of the arrows corresponds to the direction in which the wind is blowing. We have smoothed the time series slightly using a 12-hr moving average. (b) Results for L1: (left) Results of the complex correlation between modeled wind and the flow velocity time series (black/---), as well as between measured wind and the flow velocity time series (gray/---), (right) Results of the averaged coherence (C_{fw}) between the complex modeled wind and complex flow velocity time series, shown as the average of several 15-days windows. (c) Results for L2 have the same description as for L1 in (b). Equations 2 and 3 are used for the calculations of correlation and coherence. The red lines highlight periods with the highest correlations (left) and frequencies with the highest coherence (right).

identified for $T = 20$ hr and $T = 2, 7-8$, and 15 days. At L2 the lags with highest correlations are slightly longer than at L1, peaking at $T = 20$ hr, and $T = 4, 10$, and 15 days. With the distance indicated in Figure 9a, CTWs with periods of $T \sim 2$ days travel with $100-200 \text{ km d}^{-1}$, whereas CTWs with $T = 7-10$ days are much slower ($20-60 \text{ km d}^{-1}$). Larger lags at L2 can be related to the longer travel times of CTWs to reach L2 or modifications of the waves.

4. Discussion

In this study we show observational data collected in a deep submarine trench. These data add to a new understanding of the deep flows in that specific environment, and to the general body of literature on trenches and features that incise the shelf such as submarine canyons. As introduced, the NT is not a classic submarine canyon, as described in Allen and Hickey (2010) and Harris and Whiteway (2011). Yet, we find that the NT does show characteristic processes observed in other canyons worldwide. Here, we discuss the newly observed dynamics in the NT in the context of submarine canyons. Furthermore, we discuss the use of the data, in terms of research outlooks.

4.1. Large Scale Flows and Forcings

Monthly flow speed is linearly correlated with the seasonal shift in the North European wind system (NAO) (Figure 7). The dependence of the currents on the NAO is an indication that our measurements in the NT, especially in the central trench, capture the larger scale response of the North Sea to winds. Our results are in good agreement with Skagseth et al. (2004) and Winther and Johannessen (2006), who found that the flows in the NT show low correlation to weekly NAO indices, but strong correlation to monthly NAO indices, especially over winter (Orvik, 2022). Furthermore, Skagseth et al. (2004) could conclude that the annual variability is explained by the monthly NAO mode, and that monthly variability is much larger than the interannual variability in the flows between 1995 and 2002. This suggests that the results we present in this study are representative for the general annual fluctuations and applicable to other years as well.

The mean deep flows recorded at L1 and L2 are north-eastward and north-westward respectively and thus follow the local bathymetry (Figures 2 and 3). Throughout the year there is only little variability in flow direction, but southward currents occur more frequently close to the continental slope toward the Norwegian Sea, than in the central trench. However, in the West of the NT, flows are expected to be southward (Furnes et al., 1986; Winther & Johannessen, 2006), which, at the location of our instruments, we simply did not capture. As discussed in previous studies, AWIs are expected to turn eastward and join the northward directed outflow in the East of the trench (e.g., Furnes et al., 1986). J. A. Johannessen et al. (1989) explained this rotational flow as a cyclonic eddy, being generated by topographic steering of inflowing AW and the conservation of potential vorticity. This large cyclonic eddy is also captured in model outputs during large AWIs (Enge et al., 2025). These deep eddies are expected to have a significant influence on the canyon outflow (Huang et al., 2023), on the local current speed (Enge et al., 2025) and on the trapping of water and matter (Ramos-Musaleem & Allen, 2020). Allen and Hickey (2010) relate the likelihood of eddies forming in submarine canyons to the geometry of the canyon itself.

4.2. Tidal Mixing and Transport

The tidal analysis reveals different tidal forcing in the center of the NT and close to the slope (Figures 5 and 6). As observed by J. M. Huthnance et al. (2009) diurnal tides dominate close to the slope, whereas the M2 signal is weak ($R^2 = 10\%$). In the central NT, we observe a significant M2 contribution, with $R^2 = 19\%$ and amplitudes of 0.05 m/s, which agree with McClimans et al. (2009) recordings of tidal amplitudes. In the North Sea, Stanev and Ricker (2020) found that tides affect energy cascades where mesoscale eddies are present. As the NT is an active area of mesoscale eddy activity (Ikeda et al., 1989; J. A. Johannessen et al., 1989), increased tidal energy cascades can be expected. In addition, Nazarian et al. (2021) show that submarine canyons are important sinks of tidal energy, dissipating from 3.2% to 7.8% of the global M2 tidal energy, as the dissipation can be intensified by reflection in the canyon. How the NT influences tidal dissipation is not fully clear from this study, yet should be considered when studying water mass mixing in the NT. Interestingly, the M2 tide, even though having a large effect on the current velocity, is not detected in backscatter. On the other hand, diurnal influence is observed in backscatter close to the slope. This indicates that diurnal SPM transport and frequent resuspension could enhance cross-shelf transport of SPM and carbon into the Atlantic Ocean, adding to the net outflowing carbon flux calculated by Holt et al. (2009).

4.3. Up-and Downwelling by Winds and CTWs

The flows at both locations are responding to wind forcing on multiple time scales. Even though the instruments are at 300–400 m water depth we observe that local winds influence the deep flows (Figure 8). Yet, the response is small with maximum correlations of 0.2 at short lags of periods of $T = 3\text{--}6$ hr and $T = 18\text{--}19$ hr. These lags agree with Skagseth and Orvik (2002), who found that flows lag local winds with $T = 12$ hr. Our relatively low correlation coefficients agree with theory, as wind influence is known to weaken with increasing depth, often not even being considered for larger depths (Gordon & Huthnance, 1987; Mied et al., 2010). However, we also find a large lag with period of $T > 48$ hr which might be related to CTWs forcing, as indicated in Figure 9e. From the coherence, we find that wind and flows oscillate with periods of 40 hr, which based on the period's length, are more likely related to wind forced CTWs as well. CTWs are sensitive to wind forcing (Gordon & Huthnance, 1987) but also to the local shelf depth and width (Adams & Buchwald, 1969; Woodham et al., 2013). The pathway of CTWs toward L2 is longer and the bathymetry shallows, whereas L1 is closer to the shelf. The CTWs which we identify in the wavelets (Figures 4 and 6) have periods of $T = 2\text{--}3$ days, $T = 5\text{--}7$ days, and

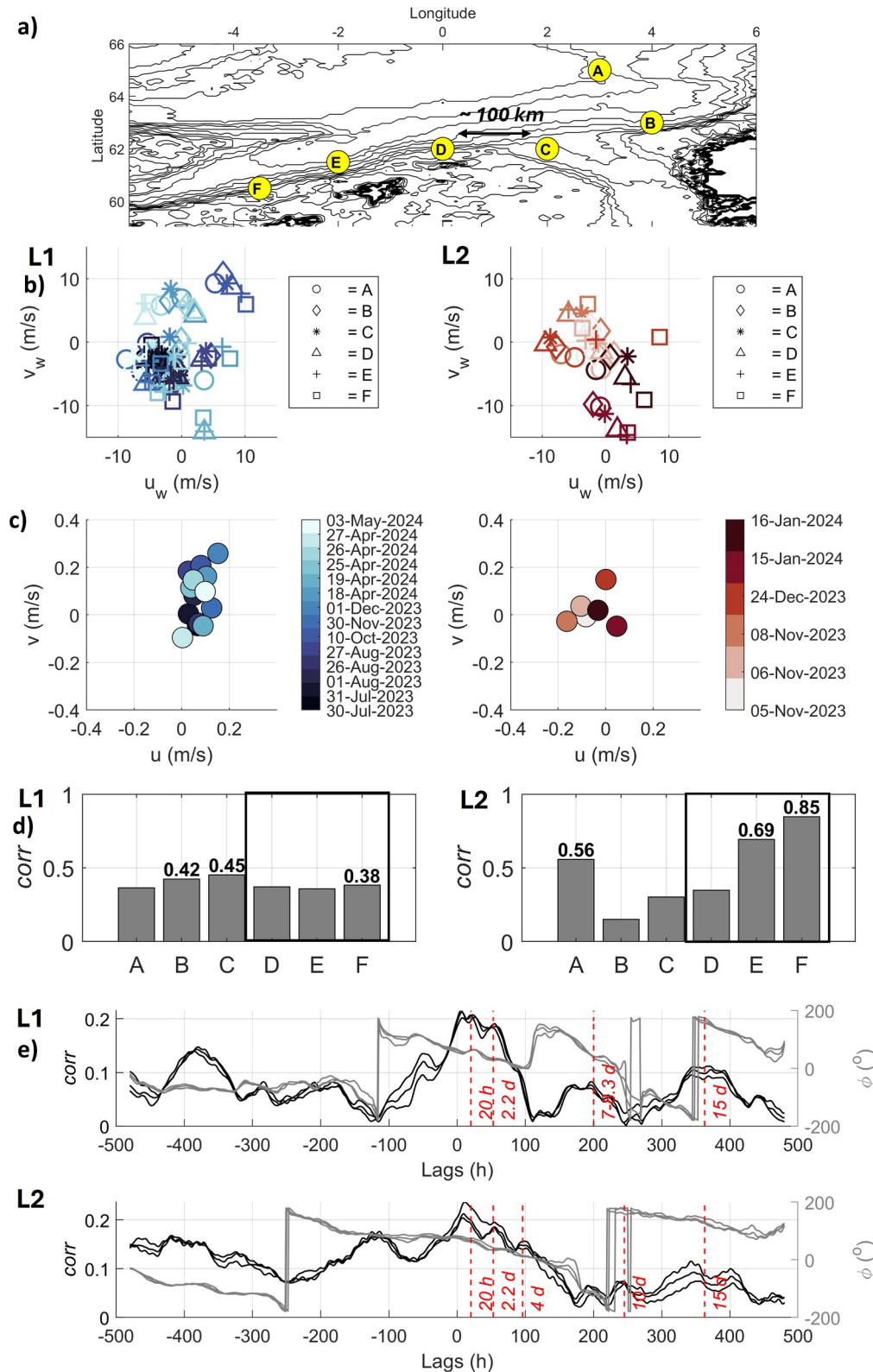


Figure 9.

$T = 9\text{--}12$ days, with the longer periods occurring at L2 and the shorter periods at L1. The periodicities identified agree with previous findings of Gordon and Huthnance (1987) and Skagseth and Orvik (2002). In agreement with our results, Saldías et al. (2021) also found slower CTWs further downstream in the canyon. A mechanism explaining this could be the splitting of CTWs modes when interacting with the canyon (Gutiérrez et al., 2014), resulting in slightly faster waves at L1 and slower waves at L2. For the NT, Gordon and Huthnance (1987) calculated that the properties would not change significantly, which agrees with the similarities in the periods of the CTWs observed at both locations and only slightly slower waves at L2.

As shown in numerous studies, for example, Allen et al. (2001), Gutiérrez et al. (2014), Saldías et al. (2021), and Sobarzo et al. (2016), CTWs can favor cross-isobath flows in submarine canyons and consequently favor up- and downwelling of water masses. Both, upwelling and downwelling events are also identified in the NT (Figures 4 and 9). AWIs into the trench would, according to theory, be called “downwelling” as the directions of the propagation of CTWs and the mean flow of the NwAC are in the same direction (eastwards) (Allen & Durrieu de Madron, 2009). The correlations between the wind at the westernmost stations (D–F) and the occurrence of AWI events at L2 are as large as $\text{corr} = 0.69\text{--}0.85$ (Figure 9d). Further indication of the contribution of CTWs to downwelling of AW are the periods of the lags in the correlations at L1 and L2, which are consistent travel times for CTWs (Figure 9e). The dominant lags agree well with the periods identified in the wavelets in Figure 4. Beside CTWs forcing, we find AWIs during winds from the N and the NE at the northernmost station. Winther and Johannessen (2006) explained that persistent winds from the NE can cause upwelling along the Norwegian coastline, which by continuity causes AW flowing into the NT.

In contrast to the downwelling of AWIs, NSAIW occurrences are related to upwelling conditions. During winds from the NE, the wind-driven flow opposes the direction of CTWs propagation, which by theory would intensify upwelling (Allen & Durrieu de Madron, 2009). In 10 out of 14 events winds are from the NE over the northern part of the NT (stations A–C), indicating that upwelling of NSAIW into the NT follows canyon upwelling theory. Saldías et al. (2021) highlight that the joint effect of upwelling-favorable winds and CTWs could enable extremely dense water upwelling. This agrees with what we observe in the temperature wavelet at L1, where NSAIW upwelling events show an oscillatory character with CTWs periodicities. Aagaard (1970) observed that the inflow of NSDW, which we referred to as NSAIW based on the modification by K. A. Mork et al. (2025), is related to the local wind forcing at higher latitudes, that is, the intensity of the wind systems over the Norwegian Sea, which agrees with our observations at the northernmost wind station.

4.4. Outlook

Our observations, high frequency and long term, show the variety of timescales that is needed to identify the dominant dynamics. However, spatially, our data are limited to two locations only. More observations along the continental shelf would help to quantify the complex dynamics in the NT, such as upwelling and downwelling of NSAIW and AW, SPM transport, and CTWs pathway in further spatial detail.

Building upon literature discussing the environmental impacts of cross-shelf flows (e.g., Holt et al., 2009), both upwelling and downwelling could significantly influence the waters in the NT and on the shelf, affecting primary productivity patterns and the vertical draw down of organic matter. Based on the findings of J. M. Huthnance et al. (2009), who showed that the AW is the main nutrient supply for the North Sea, intensified AWIs would significantly impact the environmental condition in the Norwegian waters. Increased AWIs might also change the salt and heat budget in the NT and even in the North Sea. Impacts of NSAIW upwelling are not known, yet deep water upwelling is expected to have strong effects on oxygen and nutrient fluxes.

Finally, the transport of SPM can be directly linked to the potential of carbon burial in seabed sediment (Diesing et al., 2021). Knowledge about the frequency of resuspension and transport improves the understanding of carbon storage in the seabed sediment and the role of the NT as carbon sink of the North Sea (Diesing et al., 2021). From

Figure 9. (a) Bathymetric maps with six wind locations A–F from CMEMS (2024), (b) wind velocities at A–F during cold water events ($\theta < 5^\circ\text{C}$) at L1 (left) and during warm water events ($\theta > 9^\circ\text{C}$) at L2 (right), (c) current velocities at A–F during corresponding events at L1 (left) and L2 (right), (d) correlation coefficients of complex correlation between wind and velocity during the events for L1 (left) and L2 (right), (e) Lagged complex correlation of the velocity time series with wind time series of D–F at L1 and at L2. In the lagged correlation analysis, positive lags indicate that changes in wind precede changes in the flow, while negative lags indicate that changes in the flow precede changes in the wind.

our data, we cannot conclude whether increases in backscatter are due to resuspension or advection of SPM. We suggest that during the extreme winter NAO, which we captured in December 2023 and February 2024 (Fagerlid et al., 2024; Purkiani et al., 2024), it is likely that sediments in the North Sea are eroded and transported northward through the NT into the Atlantic Ocean (Eisma & Kalf, 1987; van der Molen & Paetsch, 2022).

5. Conclusions

We show that the NT is a complex system but that the variability in the deep flows can be explained by three dominant forcings, namely tides, winds, and CTWs. Even though the NT is not a classic submarine canyon, we observe characteristic dynamics, namely upwelling and downwelling of water masses, deep rotational flows at the canyon mouth, and the interaction of CTWs with the local bathymetry, which show that the deep flows exhibit similar dynamics as observed in submarine canyons. Here, for the first time, we discuss the hydrodynamics in the NT with a focus on submarine canyon dynamics, due to a similar morphology, which might explain the deep flows in deep channels much better than without considering canyon dynamics. We show that semi-diurnal and diurnal tides vary spatially, but are important for mixing and SPM transport in the central trench and at the slope, respectively. Wind and CTWs cause oscillations with periods of 1–10 days. When CTWs interact with the NT, they keep their characteristics and only become a little slower toward the shallower central trench. During winds from the NE, cold NSAIW upwells into the NT. CTWs propagating eastwards along the slope can contribute to these dense upwelling events. During winds from the SW, AWI is intensified and propagates in the same direction as the CTWs into the central NT. Over 1 year of measurements, strong seasonality linked to the NAO is observed in the central trench, whereas close to the slope, local hydrodynamics are more important. The relation of the NAO to the flows in the central trench indicates that the deep flows are interconnected to the North Sea circulation. In summary, we find that tides, remote wind forcing, and CTWs are key mechanisms for the cross-shelf transports through the NT, making it a complex and highly interesting study area to investigate cross-shelf exchange dynamics. With this study, we present the first 1-year long time series of deep currents recorded in the NT and a detailed analysis of forcing mechanisms, for the first time, discussed in the context of submarine canyon dynamics, allowing a comparison to similar systems worldwide.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

The raw and post-processed ADCP data used for the analysis in this study are available via Enge et al. (2026). The raw CT sensor data used for the analysis in this study are available via Mienis (2026). The observed and modeled wind data used to analyze the influence of local and remote winds are available via Meteorologisk institutt (2026) and CMEMS (2024), respectively. The GEBCO data used for the bathymetry visualizations are available via GEBCO Bathymetric Compilation Group (2024). The NAO index data used in this study are available via NOAA (2025). Version 2017 of UTide, which was used for the tidal analysis, is available via Codiga (2026). The TEOS-10 Gibbs-SeaWater (GSW) software package used for the T-S diagrams is available via McDougall and Barker (2011). The Nortek codes used to process the ADCP data are available via Thomson (2022). Version 2014 of the MATLAB function “complex_corr.m,” which was used for the complex correlation of velocity and wind time series, is available via Twedt (2014).

Acknowledgments

This publication is part of the program “The role of the North Sea in the Atlantic Ocean biogeochemical system: North Sea-Atlantic Exchange (NoSE)” with file number OCENW.XL21.XL21.075, which is financed by the Dutch Research Council (NWO). The expeditions were part of the NoSE research project. We thank the technicians at TU Delft and NIOZ for helping with the mooring deployment, the recovery and with the preparation of the instruments. In addition, we want to thank T. Wegman for the exchange on the post-processing of the ADCP data, R. Gelderloos and P. de Bruijn for insightful discussions on CTWs and the project members of the NoSE project for valuable discussions about the NT. Last, we want to thank the editor and the reviewers for the constructive and valuable feedback.

References

- Aagaard, K. (1970). Wind-driven transports in the Greenland and Norwegian seas. *Deep-Sea Research and Oceanographic Abstracts*, 17(2), 281–291. [https://doi.org/10.1016/0011-7471\(70\)90021-5](https://doi.org/10.1016/0011-7471(70)90021-5)
- Adams, J. K., & Buchwald, V. T. (1969). The generation of continental shelf waves. *Journal of Fluid Mechanics*, 35(4), 815–826. <https://doi.org/10.1017/S0022112069001455>
- Akpinar, A., Palmer, M. R., Inall, M., Bex, B., & Polton, J. (2022). Locally modified winds regulate circulation in a semi-enclosed shelf sea. *Journal of Geophysical Research: Oceans*, 127(3), e2021JC018248. <https://doi.org/10.1029/2021JC018248>
- Allen, S. E., & Durrieu de Madron, X. (2009). A review of the role of submarine canyons in deep-ocean exchange with the shelf. *Ocean Science*, 5(4), 607–620. <https://doi.org/10.5194/os-5-607-2009>
- Allen, S. E., & Hickey, B. M. (2010). Dynamics of advection-driven upwelling over a shelf break submarine canyon. *Journal of Geophysical Research*, 115(C8), C08018. <https://doi.org/10.1029/2009JC005731>
- Allen, S. E., Vindeirinho, C., Thomson, R. E., Foreman, M. G. G., & Mackas, D. L. (2001). Physical and biological processes over a submarine canyon during an upwelling event. *Canadian Journal of Fisheries and Aquatic Sciences*, 58(4), 671–684. <https://doi.org/10.1139/cjfas-58-4-671>

- Bockelmann, F.-D., Puls, W., Kleeberg, U., Mueller, D., & Emeris, K.-C. (2018). Mapping mud content and median grain-size of North Sea sediments—A geostatistical approach. *Marine Geology*, 397, 60–71. <https://doi.org/10.1016/j.margeo.2017.11.003>
- Brun, L., Garreau, P., Pairaud, I., & Jacinto, R. S. (2025). Deep canyon-upwellings in the northwestern Mediterranean Sea in contrast with open oceans. *Journal of Geophysical Research: Oceans*, 130(11), e2024JC022008. <https://doi.org/10.1029/2024JC022008>
- Camayo, R., & Campos, E. J. D. (2006). Application of wavelet transform in the study of coastal trapped waves off the west coast of South America. *Geophysical Research Letters*, 33(22), 1–5. <https://doi.org/10.1029/2006GL026395>
- Christensen, K. H., Sperrevik, A. K., & Brostroem, G. (2018). On the variability in the onset of the Norwegian coastal Current. *Journal of Physical Oceanography*, 48(3), 723–738. <https://doi.org/10.1175/JPO-D-17-0117.1>
- CMEEMS. (2024). WIND_GLO_PHY_L4_MY_012_006 [Dataset]. *E.U. Copernicus Marine Service Information (CMEMS). Marine Data Store (MDS)*. <https://doi.org/10.48670/moi-00185>
- Codiga, D. L. (2011). Unified tidal analysis and prediction using the UTide matlab functions. In *Technical report 2011-01* (p. 59). Graduate School of Oceanography, University of Rhode Island. <https://doi.org/10.13140/RG.2.1.3761.2008>
- Codiga, D. L. (2026). UTide unified tidal analysis and prediction functions [Software]. <https://www.mathworks.com/matlabcentral/fileexchange/46523-utide-unified-tidal-analysis-and-prediction-functions>
- de Haas, H., Okkels, E., & van Weering, T. C. E. (1996). Recent sediment accumulation in the Norwegian Channel, North Sea. *Norwegian Geological Bulletin*, 430, 57–65.
- Diesing, M., Thorsnes, T., & Bjarnadóttir, L. R. (2021). Organic carbon densities and accumulation rates in surface sediments of the North Sea and Skagerrak. *Biogeosciences*, 18(6), 2139–2160. <https://doi.org/10.5194/bg-18-2139-2021>
- Eisma, D., & Kalf, J. (1987). Distribution, organic content and particle size of suspended matter in the North Sea. *Netherlands Journal of Sea Research*, 21(4), 265–285. [https://doi.org/10.1016/0077-7579\(87\)90002-0](https://doi.org/10.1016/0077-7579(87)90002-0)
- Enge, A., Pietrzak, J. D., & van Prooijen, B. C. (2025). The variability of wind-driven currents in the Norwegian Trench. *Frontiers in Marine Science*, 12, 1600994. <https://doi.org/10.3389/fmars.2025.1600994>
- Enge, A., Pietrzak, J. D., & van Prooijen, B. C. (2026). Acoustic Doppler Current Profiler data 2023–2024 NoSE—Norwegian Trench [Dataset]. *Version 1. 4TU. ResearchData*. <https://doi.org/10.4121/f3d666f6-4a60-4fb3-b866-9f6656d34da4.v1>
- Fagerlid, G. O., Soldal, I. H., Mamen, J., Ristesund, E. W., & Velle, M. (2024). Henderlserrapport—Ekstremvaeret “Inguun”; ekstremt kraftige vindkast i Trondelag og Nordland 31.
- Figuerola, P. A., Saldías, G. S., & Allen, S. E. (2025). The influence of a submarine canyon on the wind-driven downwelling circulation over the continental shelf. *Ocean Science*, 21(2), 643–659. <https://doi.org/10.5194/os-21-643-2025>
- Furnes, G. K., Hackett, B., & Sætre, R. (1986). Retroflection of Atlantic water in the Norwegian trench. *Deep-Sea Research, Part A: Oceanographic Research Papers*, 33(2), 247–265. [https://doi.org/10.1016/0198-0149\(86\)90121-4](https://doi.org/10.1016/0198-0149(86)90121-4)
- GEBCO Bathymetric Compilation Group. (2024). The GEBCO_2024 Grid—A continuous terrain model of the global oceans and land [Dataset]. *NERC EDS British Oceanographic Data Centre NOC*. <https://doi.org/10.5285/1c44ce99-0a0d-5f4f-e063-7086abc0ea0f>
- Gelderloos, R., Haine, T. W. N., & Almansí, M. (2021). Coastal trapped waves and other subinertial variability along the Southeast Greenland Coast in a realistic numerical simulation. *Journal of Physical Oceanography*, 51(3), 861–877. <https://doi.org/10.1175/JPO-D-20-0239.1>
- Gordon, R. L., & Huthnance, J. M. (1987). Storm-driven continental shelf waves over the Scottish continental shelf. *Continental Shelf Research*, 7(9), 1015–1048. [https://doi.org/10.1016/0278-4343\(87\)90097-5](https://doi.org/10.1016/0278-4343(87)90097-5)
- Grinsted, A., Moore, J. C., & Jevrejeva, S. (2004). Application of the cross wavelet transform and wavelet coherence to geophysical time series. *Nonlinear Processes in Geophysics*, 11(5/6), 561–566. <https://doi.org/10.5194/npg-11-561-2004>
- Gutiérrez, M. O., López, M., Candela, J., Castro, R., Mascarenhas, A., & Collins, C. A. (2014). Effect of coastal trapped waves and wind on currents and transport in the Gulf of California. *Journal of Geophysical Research: Oceans*, 119(8), 5123–5139. <https://doi.org/10.1002/2013JC009538>
- Haalboom, S., de Stigter, H., Duineveld, G., van Haren, H., Reichert, G.-J., & Mienis, F. (2021). Suspended particulate matter in a submarine canyon (Whittard Canyon, Bay of Biscay, NE Atlantic Ocean): Assessment of commonly used instruments to record turbidity. *Marine Geology*, 434, 106439. <https://doi.org/10.1016/j.margeo.2021.106439>
- Harris, P. T., & Whiteway, T. (2011). Global distribution of large submarine canyons: Geomorphic differences between active and passive continental margins. *Marine Geology*, 285(1–4), 69–86. <https://doi.org/10.1016/j.margeo.2011.05.008>
- Holt, J., Wakelin, S., & Huthnance, J. M. (2009). Down-welling circulation of the northwest European continental shelf: A driving mechanism for the continental shelf carbon pump. *Geophysical Research Letters*, 36(14). <https://doi.org/10.1029/2009GL038997>
- Hordoir, R., Dietrich, C., Basu, C., Dietze, H., & Meier, H. E. M. (2013). Freshwater outflow of the Baltic Sea and transport in the Norwegian current: A statistical correlation analysis based on a numerical experiment. *Continental Shelf Research*, 64, 1–9. <https://doi.org/10.1016/j.csr.2013.05.006>
- Huang, J., Pickart, R. S., Foukal, N., Spall, M. A., & Lin, P. (2023). Structure and variability of the Barrow Canyon outflow from two high-resolution shipboard surveys in 2018. *Journal of Geophysical Research: Oceans*, 128(6), e2023JC019640. <https://doi.org/10.1029/2023JC019640>
- Hughes, C. W., Fukumori, I., Griffies, S. M., Huthnance, J. M., Minobe, S., Spence, P., et al. (2019). Sea level and the role of coastal trapped waves in mediating the influence of the open ocean on the coast. *Surveys in Geophysics*, 40(6), 1467–1492. <https://doi.org/10.1007/s10712-019-09535-x>
- Hurrell, J. W., & Deser, C. (2010). North Atlantic climate variability: The role of the North Atlantic Oscillation. *Journal of Marine Systems*, 78(3–4), 231–244. <https://doi.org/10.1016/j.jmarsys.2009.11.002>
- Huthnance, J., Hopkins, J., Berx, B., Dale, A., Holt, J., Hosegood, P., et al. (2022). Ocean shelf exchange, NW European shelf seas: Measurements, estimates and comparisons. *Progress in Oceanography*, 202, 102760. <https://doi.org/10.1016/j.pocean.2022.102760>
- Huthnance, J. M., Holt, J. T., & Wakelin, S. L. (2009). Deep ocean exchange with west-European shelf seas. *Ocean Science*, 5(4), 621–634. <https://doi.org/10.5194/os-5-621-2009>
- Ikeda, M., Johannessen, J. A., Lygre, K., & Sandven, S. (1989). A process Study of mesoscale meanders and eddies in the Norwegian Coastal Current. *Journal of Physical Oceanography*, 19(1), 20–35. [https://doi.org/10.1175/1520-0485\(1989\)019<0020:apsomm>2.0.co;2](https://doi.org/10.1175/1520-0485(1989)019<0020:apsomm>2.0.co;2)
- Inall, M. E., Nilsen, F., Cottier, F. R., & Daae, R. (2015). Shelf/fjord exchange driven by coastal trapped waves in the Arctic. *Journal of Geophysical Research: Oceans*, 120(12), 8283–8303. <https://doi.org/10.1002/2015JC011277>
- Johannessen, J. A., Svendsen, E., Sandven, S., Johannessen, O. M., & Lygre, K. (1989). Three-dimensional structure of mesoscale eddies in the Norwegian Coastal Current. *Journal of Physical Oceanography*, 19(1), 3–19. [https://doi.org/10.1175/1520-0485\(1989\)019<0003:tdsome>2.0.co;2](https://doi.org/10.1175/1520-0485(1989)019<0003:tdsome>2.0.co;2)
- Johannessen, O. M. (1986). Brief overview of the physical oceanography. In B. G. Hurdle (Ed.), *The Nordic Seas, chapter 4*. Springer-Verlag New York Inc.

- Koerner, M., Brandt, P., Illig, S., Dengler, M., Subramaniam, A., Bachèlery, M.-L., & Krahmann, G. (2024). Coastal trapped waves and tidal mixing control primary production in the tropical Angolan upwelling system. *Science Advances*, 10(4), ead6686. <https://doi.org/10.1126/sciadv.ad6686>
- Kundu, P. K. (1976). An analysis of inertial oscillations observed near Oregon Coast. *Journal of Physical Oceanography*, 6(6), 879–893. [https://doi.org/10.1175/1520-0485\(1976\)006<0879:aoio>2.0.co;2](https://doi.org/10.1175/1520-0485(1976)006<0879:aoio>2.0.co;2)
- Li, S., Lin, P., Dou, T., Xiao, C., Itoh, M., Kikuchi, T., & Qin, D. (2022). Upwelling of Atlantic water in barrow canyon, Chukchi Sea. *Journal of Geophysical Research: Oceans*, 127(3), e2021JC017839. <https://doi.org/10.1029/2021JC017839>
- McClimans, T. A., Eidnes, G., & Moshagen, H. (2009). Extreme bottom currents along a deep fjord pipeline route. In *Proceedings of the nineteenth (2009) international offshore and polar engineering conference*.
- McDougall, T. J., & Barker, P. M. (2011). Getting started with TEOS-10 and the Gibbs seawater (GSW) oceanographic toolbox [Software]. <http://www.teos-10.org/>
- Merckelbach, L. M. (2006). A model for high-frequency acoustic Doppler current profiler backscatter from suspended sediment in strong currents. *Continental Shelf Research*, 26(11), 1316–1335. <https://doi.org/10.1016/j.csr.2006.04.009>
- Meteorologisk institutt (MET). (2026). Gullfaks C (SN76923) [Dataset]. *Norsk KlimaService Senter Seklima*. Retrieved from <https://seklima.met.no/stations/>
- Mied, R. P., Schulz, W. J., Handler, R. A., Snow, C. M., Fusina, R. A., & Porter, J. H. (2010). Remote and local forcing of a coastal lagoon: The Virginia Coast Reserve. *Continental Shelf Research*, 30(20), 2057–2066. <https://doi.org/10.1016/j.csr.2010.10.005>
- Mienis, F. (2026). CT data 2023-2024 NoSE—Norwegian Trench [Dataset]. *DAS NIOZ, NIOZ, V1*. <https://doi.org/10.25850/nioz/7b.b.dk>
- Mork, K. A., Skagseth, Ø., & Sjøland, H. (2025). Hydrographic changes and water mass distribution in the Norwegian Sea, 1995–2023. *Journal of Geophysical Research: Oceans*, 130(9), e2025JC022397. <https://doi.org/10.1029/2025JC022397>
- Mork, M. (1981). Circulation phenomena and frontal dynamics of the Norwegian coastal current. *Philosophical Transactions of the Royal Society of London Series A*, 302(1472), 635–647. <https://doi.org/10.1098/rsta.1981.0188>
- Mysak, L. A., & Schott, F. (1977). Evidence for baroclinic instability of the Norwegian Coastal Current. *Journal of Geophysical Research*, 82(15), 2087–2095. <https://doi.org/10.1029/JC082i015p02087>
- Nazarian, R. H., Burns, C. M., Legg, S., Buijsman, M. C., Kaur, H., & Arbic, B. K. (2021). On the magnitude of canyon-induced mixing. *Journal of Geophysical Research: Oceans*, 126(11), e2021JC017671. <https://doi.org/10.1029/2021jc017671>
- NOAA. (2025). Climate prediction Center—Teleconnections: North Atlantic oscillation [Dataset]. *Monthly mean NAO indexes since 1950*. Retrieved from <https://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/norm.nao.monthly.b5001.current.ascii.table>
- Orvik, K. A. (2022). Long-term moored current and temperature measurements of the Atlantic inflow into the Nordic Seas in the Norwegian Atlantic Current; 1995–2020. *Geophysical Research Letters*, 49(3), e2021GL096427. <https://doi.org/10.1029/2021GL096427>
- Purkiani, K., Jochumsen, K., & Fischer, J.-G. (2024). Observation of a moderate major Baltic Sea inflow in December 2023. *Scientific Reports*, 14(1), 16577. <https://doi.org/10.1038/s41598-024-67328-8>
- Ramos-Musale, K., & Allen, S. E. (2020). The impact of initial tracer profile on the exchange and on-shelf distribution of tracers induced by a submarine canyon. *Journal of Geophysical Research: Oceans*, 125(3), e2019JC015785. <https://doi.org/10.1029/2019JC015785>
- Saldías, G. S., Ramos-Musale, K., & Allen, S. E. (2021). Circulation and upwelling induced by coastal trapped waves over a submarine canyon in an idealized eastern boundary margin. *Geophysical Research Letters*, 48(11), e2021GL093548. <https://doi.org/10.1029/2021GL093548>
- Sætre, R., Aure, J., & Ljøen, R. (1988). Wind effects on the lateral extension of the Norwegian Coastal Water. *Continental Shelf Research*, 8(3), 239–253. [https://doi.org/10.1016/0278-4343\(88\)90031-3](https://doi.org/10.1016/0278-4343(88)90031-3)
- Skagseth, Ø., Drinkwater, K. F., & Terrile, E. (2011). Wind- and buoyancy-induced transport of the Norwegian Coastal Current in the Barents Sea. *Journal of Geophysical Research*, 116(C8), C08007. <https://doi.org/10.1029/2011JC006996>
- Skagseth, Ø., & Orvik, K. A. (2002). Identifying fluctuations in the Norwegian Atlantic Slope Current by means of empirical orthogonal functions. *Continental Shelf Research*, 22(4), 547–563. [https://doi.org/10.1016/S0278-4343\(01\)00086-3](https://doi.org/10.1016/S0278-4343(01)00086-3)
- Skagseth, Ø., Orvik, K. A., & Furevik, T. (2004). Coherent variability of the Norwegian Atlantic Slope Current derived from TOPEX/ERS altimeter data. *Geophysical Research Letters*, 31(14), L14304. <https://doi.org/10.1029/2004GL020057>
- Sobarzo, M., Saldías, G. S., Tapia, F. J., Bravo, L., Moffat, C., & Largier, J. L. (2016). On subsurface cooling associated with the Biobio River Canyon (Chile). *Journal of Geophysical Research: Oceans*, 121(7), 4568–4584. <https://doi.org/10.1002/2016JC011796>
- Stanev, E. V., & Ricker, M. (2020). Interaction between barotropic tides and mesoscale processes in deep ocean and shelf regions. *Ocean Dynamics*, 70(5), 713–728. <https://doi.org/10.1007/s10236-020-01348-6>
- Svendsen, E., Sætre, R., & Mork, M. (1991). Features of the northern North Sea circulation. *Continental Shelf Research*, 11(5), 493–508. [https://doi.org/10.1016/0278-4343\(91\)90055-B](https://doi.org/10.1016/0278-4343(91)90055-B)
- Thomson, J. (2022). Nortek Codes repository [Software]. *GitHub, SASlabgroup*. <https://github.com/SASlabgroup/NortekCodes>
- Torrence, C., & Compo, G. (1998). A practical guide to wavelet analysis. *Bulletin of the American Meteorological Society*, 79(1), 61–78. [https://doi.org/10.1175/1520-0477\(1998\)079<0061:apgtwa>2.0.co;2](https://doi.org/10.1175/1520-0477(1998)079<0061:apgtwa>2.0.co;2)
- Twedt, J. (2014). *Complex_corr.m* [Software]. https://github.com/jtwedt/matlab/blob/master/complex_corr.m
- van der Molen, J., & Paetsch, J. (2022). An overview of Atlantic forcing of the North Sea with focus on oceanography and biogeochemistry. *Journal of Sea Research*, 189, 102281. <https://doi.org/10.1016/j.seares.2022.102281>
- Winther, N. G., & Johannessen, J. A. (2006). North Sea circulation: Atlantic inflow and its destination. *Journal of Geophysical Research*, 111(C12), 1–12. <https://doi.org/10.1029/2005JC003310>
- Wise, A., Calafat, F. M., Hughes, C. W., Jevrejeva, S., Katsman, C. A., Oelsmann, J., et al. (2024). Using shelf-edge transport composition and sensitivity experiments to understand processes driving sea level on the Northwest European shelf. *Journal of Geophysical Research: Oceans*, 129(5), e2023JC020587. <https://doi.org/10.1029/2023JC020587>
- Woodham, R., Brassington, G. B., Robertson, R., & Alves, O. (2013). Propagation characteristics of coastally trapped waves on the Australian Continental Shelf. *Journal of Geophysical Research: Oceans*, 118(9), 4461–4473. <https://doi.org/10.1002/jgrc.20317>

References From the Supporting Information

- Guerra, M., & Thomson, J. (2017). Turbulence measurements from five-beam acoustic Doppler current profilers. *Journal of Atmospheric and Oceanic Technology*, 34(6), 1267–1283. <https://doi.org/10.1175/JTECH-D-16-0148.1>