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Seasonal diversity & behaviour of internal tidal bores revealed by year-long direct monitoring within a submarine canyon: Implications for particulate transport

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ABSTRACT

Submarine canyons are the primary conduits for particulate transport from the continents to the deep sea, including sediments, organic carbon, and pollutants. Previously, focus has primarily been on transport due to downslope gravity currents. There is increasing recognition of the role internal tides may play, however, a lack of long-term seabed monitoring limits understanding of their significance. Here, we present novel near-seafloor monitoring data of breaking internal tides ('bores'), spanning one year within Whittard Canyon, a land-detached submarine canyon on the NE Atlantic margin. Throughout the year, these bores are energetic, with flow speeds regularly exceeding 0.5 m/s, and capable of resuspending seafloor sediments. Bores were observed for ~80 % of tidal cycles during the deployment. The shape and structure of bores varies throughout the year, in relation to spring-neap tidal cycles and longer-term seasonal changes. During the period of November-March, these bores generally attain higher speeds, show more abrupt changes in flow speed, and hold the greatest potential for up-canyon sediment transport. While fine-grained material may be moved throughout the year, this stronger winter activity has the greatest capacity to mobilize larger grains up-canyon. We show that bores, driven by internal tides, are an important, but previously poorly-observed agent for particulate transport. Bores occur frequently, yet exhibit variability at both seasonal and shorter time scales that may shape particulate transport within submarine canyons. These findings change our view of the general significance of internal tides in submarine canyons, with wide implications for hazards, tempo and fluxes of particulate transport.

1. Introduction

1.1. Submarine canyons: Globally-important conduits to the deep sea

Submarine canyons occur on submerged continental slopes worldwide, acting as conduits exchanging particulates, organic carbon, pollutants, and nutrients between continental shelves and the deep ocean, and creating important biodiversity hotspots (De Leo et al., 2010; Harris and Whiteway, 2011). These incised features are shaped by a variety of processes, including sediment-laden gravity flows (such as turbidity currents), slope failures, river floods, and wave action (e.g., Fildani 2017; Harris and Whiteway 2011; Harris et al., 2014; Karageorgis et al., 2018; Puig et al., 2014; Smith et al., 2018; Talling et al., 2022, 2024). However, the background hydrodynamic processes can be complex, and it is increasingly apparent that the resultant particulate transport regimes in submarine canyons may be equally complex (Bailey et al., 2024; Lee et al., 2009; Li et al., 2019; Liao et al., 2017; Maier et al., 2019; Soutter et al., 2024).

1.2. Internal tides: A contributor to particulate transport

Where the water column is suitably stratified, perturbations to that stratification (i.e., displacement of isopycnal surfaces) can propagate in the form of internal gravity waves. These displacements may be caused

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by wind, tsunamis, or interactions between surface (barotropic) tides and topography, among other phenomena (Pomar et al., 2012). The resultant internal waves are not only apparent as currents within the water column, but also as oscillating vertical displacements of temperature, salinity and density layers (analogous to sea surface displacement for surface waves). When these internal waves are caused by tides and/or have tidal frequencies, they are called internal tides. They have long been studied in physical oceanography for the roles they play in energy transfer and turbulent mixing within the ocean (e.g. Bell, 1975).

Internal tides may occur anywhere tidal currents, impinging seafloor topography, and stratification coincide, and thus are commonly generated and observed at continental shelf breaks (Jackson et al., 2015; Masunaga et al., 2019), abyssal hills, and seamounts (de Lavergne et al., 2019; Tuerena et al., 2019). Internal tides provide a mechanism for tidal energy to be transported away from the sea surface and help drive turbulent mixing in the interior of the ocean (Bell, 1975; de Lavergne et al., 2019). Additionally, they can be a key contributor to cross-shelf exchange of nutrients, sediment, and organic matter (de Lavergne et al., 2019; Martini et al., 2013; Pineda 1991; Tuerena et al., 2019).

Like other internal waves, internal tides can be heavily influenced by seafloor topography (Cacchione and Wunsch, 1974; Cacchione et al., 2002; Jackson et al., 2015; Lamb 2014). The ratio between topographic slope and the angle of the propagation of the internal wave group (dependent on wave frequency, stratification and latitude) determines whether internal waves (including internal tides) will be reflected away from (supercritical, >1), break upon (critical, ~1), or transmit further up a slope (subcritical, <1). Steep-walled features like submarine canyons can generate, trap and conduct internal waves along their axis (Gordon and Marshall 1976; Shepard, 1976), and submarine canyons generally serve as significant focal points for internal tides (Aslam et al., 2018; de Lavergne et al., 2019; Gordon and Marshall 1976; Hall and Carter, 2011; Puig et al., 2014; Vlasenko et al., 2016).

Under critical slope conditions, internal waves will begin to break on the slope, which can lead to the formation of particularly vigorous near-seafloor currents in the form of bores (Aslam et al., 2018; Cacchione et al., 2002; Hall and Carter, 2011; Lamb 2014; van Haren et al., 2022). This shoaling and breaking of internal tides can locally and episodically exceed thresholds to remobilize and transport particles (Maier et al., 2019; Pomar et al., 2012; Puig et al., 2013; Shepard and Marshall, 1969). However, most field studies of internal tides in submarine canyons have focused on the water column (Hall and Carter, 2011; Martini et al., 2013; Walter et al., 2012; Walter and Phelan, 2016), and our knowledge of the near-bed behaviour of breaking internal tides in these settings remains poor (Hall et al., 2017;, Lamb, 2014; van Haren et al., 2022). This paucity of data limits our understanding of the temporal variability and role of internal tides in particulate transport. Our study addresses this issue, presenting novel, long-term monitoring data that captures dramatic variation in seafloor hydrodynamics driven by short-lived, fast-moving surges associated with breaking internal tides, known as internal tidal bores.

1.3. Internal tidal bores

Bores are among a family of related physical phenomena, and terminology differs based upon the context and fields of study involved (Martini et al., 2013). Most generally, bores share similarities with waves breaking upon a beach; however, internal bores result from internal waves breaking upon submerged slopes (Jackson et al., 2015; Martini et al., 2013; Pineda, 1994; Venayagamoorthy and Fringer, 2007). Tidal bores may be loosely classified as a propagating non-linear wave-front of tidal origin, moving against the prevailing current regime (typically towards land on a beach or against the present tidal direction in the case of submarine canyons) (Jackson et al., 2015; Martini et al., 2013; Pineda, 1994; Venayagamoorthy and Fringer, 2007; Walter et al., 2012). In the context of internal tidal bores, the most common pattern of behaviour (termed "canonical" bores) includes a sharply-defined front of cold water moving up-shelf, often followed by a period of turbulence that follows the front. This turbulent mixing tends to result in a gradual warming as formerly stratified water masses equilibrate (Arthur and Fringer, 2014; Jackson et al., 2015; Martini et al., 2013; Masunaga et al., 2019; Walter et al., 2012; Walter and Phelan, 2016). The inverse, termed a "non-canonical" bore, has also been observed to occur, wherein a shock front does not form during the bore run-up – instead, a front of warm water rushes down-canyon during the "relaxation" phase as the bore collapses (Masunaga et al., 2019; Walter et al., 2012). The primary bore front may sometimes be followed by smaller undulations or solitary waves ('wave trains') (Walter et al., 2012).

While bores are comparatively well-studied in oceanographic contexts and on open slopes (Bourgault et al., 2007; Johnson et al., 2001; Lamb et al., 2014; McSweeney et al., 2020; Miramontes et al., 2020), they have received far less attention in submarine canyons (van Haren et al., 2022). It is increasingly apparent that internal tides can play a role in particulate transport across many settings worldwide, both within and outside submarine canyons (Bailey et al., 2024; Bogucki et al., 1997; Maier et al., 2019; Martini et al., 2013; Miramontes et al., 2020; Puig et al., 2013; Tuerena et al., 2019). As often the most vigorous state of internal tides, bores have been noted to likely be particularly important, but their behaviour remains relatively poorly constrained due to a paucity of long-term detailed in-situ measurements close to the seafloor (Bailey et al., 2024; Bogucki et al., 1997; Lamb, 2014; van Haren et al., 2022). Monitoring near-seafloor conditions in submarine canyons is challenging, due to their remote nature, deep water, and energetic hydrodynamics; however, as technology has continued to develop, measurements using instruments such as high frequency Acoustic Doppler Current Profilers (ADCPs) – recording the speed, direction and acoustic backscatter (commonly used as a proxy for suspended material in the water column) – have become increasingly widespread (e.g., Hage et al., 2024; Heijnen et al., 2022; Li et al., 2019; Simmons et al., 2020; Talling et al., 2022). Despite these advances, until recently the monitoring of near-seafloor hydrodynamics in submarine canyons has not focused on internal bores, and/or has not acquired timeseries across the durations necessary to examine seasonal variability in internal tides nor the characterisation of bores over such timescales (van Haren et al., 2022). Such studies have largely been limited to low frequency ADCPs or single point current meters (located away from the seafloor), and/or are of short duration (e.g. days to weeks) which does not permit investigation of long-term changes in near-seabed regime (Martini et al., 2013). While long-term (1+ year) studies examining internal tides have been performed in some canyons (e.g. Bailey et al. (2024); Maier et al. (2019)), bores were not a primary focus. Indeed, while many prior studies that focused on internal bores have done so by tracking the changes in temperature representative of moving density gradients, the lack of complementary information on current speed and direction means that the implications of those studies for particulate transport cannot be easily assessed.

1.4. Aims and study site

Here, we analyse a year-long, detailed (1 m vertical resolution, 1.5 min temporal resolution) ADCP record of near-seafloor current velocity, temperature, and suspended particulates, to document the near-seafloor behaviour of internal tides in a submarine canyon, recording numerous internal bores. The overarching aim is to assess and characterize the nature and frequency of internal bores in a submarine canyon, demonstrating novel methods for their identification, in order to understand the broader implications for particulate transport.

This study focuses on Whittard Canyon, a dendritic submarine canyon located on the North-West European continental margin, in the Celtic Sea (Fig. 1). We choose Whittard Canyon as an exemplar study site, as it is known to be an important hotspot for benthic biodiversity, and is broadly representative of many other submarine canyons worldwide whose heads lie far from shore – having been disconnected from

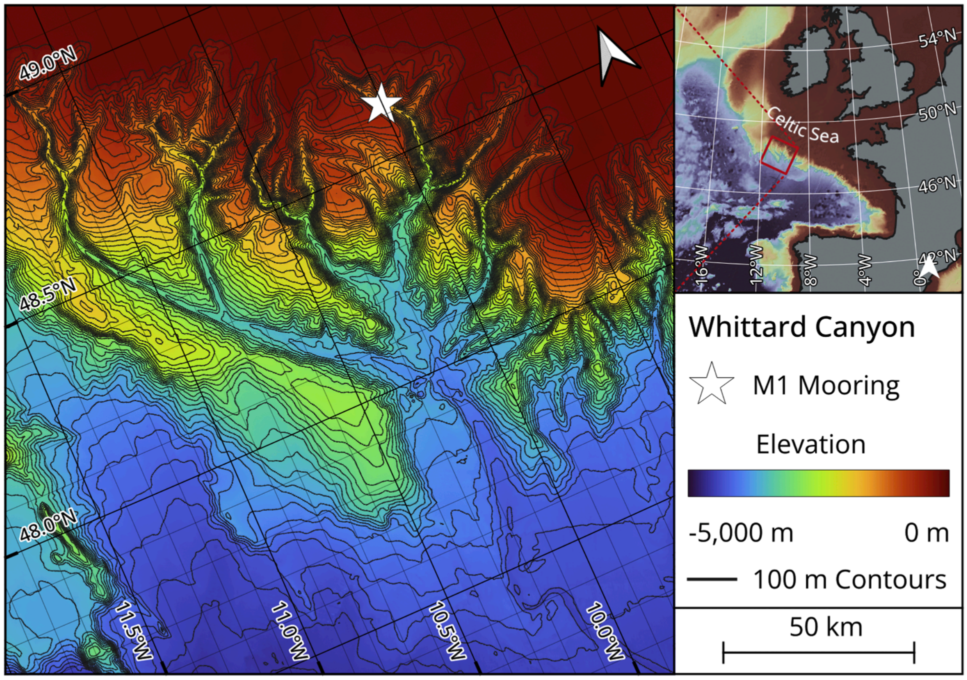

Fig. 1. Map displaying the location of the M1 mooring within Whittard Canyon. Also shown is the location of Whittard Canyon within a larger context in the Celtic Sea.

continental rivers by rising seas following the last ice age (Amaro et al., 2016; Heijnen et al., 2022; Zaragosi et al., 2000). Specifically, we analyse data from a mooring deployed at 1500 m water depth in the upper eastern branch of Whittard Canyon. The novel duration and resolution of our dataset enables new insights into the longer-term implications of short-lived features such as internal bores. We address our overarching aim by answering the following specific questions. First, how frequently do bores occur in Whittard Canyon, and does that frequency remain constant throughout the period studied? Second, what is the variability in bore behaviour and appearance throughout the year? Finally, what are the implications of frequent and vigorous bores for sediment transport in submarine canyons? We relate our findings in Whittard Canyon to other submarine canyon systems to discuss implications for sediment, carbon and pollutant transport, and canyon ecosystems.

2. Methods

2.1. Acquisition of ADCP data

We analyse data from a moored Acoustic Doppler Current Profiler (ADCP) deployed on 29/03/2021 during research expedition DY130 and recovered on 02/05/2022 during expedition JC231. The mooring was deployed in the upper eastern branch of Whittard Canyon at 1500 m water depth and included a downward-facing, 600 kHz Teledyne Workhorse II ADCP housed in a syntactic buoy roughly 30 m above the seabed (Fig. 1). The ADCP recorded a vertical profile of current velocity (speed and direction) and acoustic backscatter in depth bins of 1 m, extending from the instrument to the seabed, and recorded a data ensemble (averaging together 23 individual measurements) every 90 s (1.5 min). In addition to the acoustically measured water column variables above, the ADCP also records information about conditions experienced by the instrument housing, specifically including rotation (heading, pitch, roll) of the casing, its temperature, and depth (as a function of pressure).

2.2. Processing of ADCP data

Velocity data was converted from North–South and East–West components to along- and cross-canyon components, relative to the canyon axis. The along-canyon component is oriented so down-canyon motion (in the direction of gravitationally-driven sediment transport) is positive, and upslope movement is negative. As the ADCP was not calibrated against known concentrations of sediment, the Receiver Signal Strength Indicator ('echo intensity') as recorded by the ADCP was used as a qualitative estimate for overall acoustic backscatter in the water column and thereby an indicator to infer changing levels of particulate suspension over time (Heijnen et al., 2022; Soutter et al., 2024).

The rate of change of the measured temperature and velocity with respect to time was then calculated. Within the year-long time series, four exemplar case study months were chosen to highlight the variability in internal tides observed: June, August, November, and February.

2.3. Bore characterization: Complementary approaches

2.3.1. Bore identification through gradient thresholds

We used two contrasting approaches to objectively identify and locate bores. The first method is based upon the two rapid property changes indicative of the bore's wavefront: cooling, and upslope acceleration of the water. For the purposes of this paper, we defined a bore as any instance where the change in down-canyon velocity falls below -0.003 m s^{-2} or the change in temperature falls below -0.5 mK s^{-1}. These thresholds were chosen as they represent the approximate upper bound on background tidal variability in the absence of bores, as seen in Fig. 2.

2.3.2. Geometric curve-fitting & parameterization

The second method used to characterize bores makes use of a novel curve-fitting algorithm to describe the asymmetry of the velocity signal through time. Individual segments of this fitted curve are defined by the function (eq. 1) presented by Mustafa et al. (2024) as a 'skew-permitting waveform',

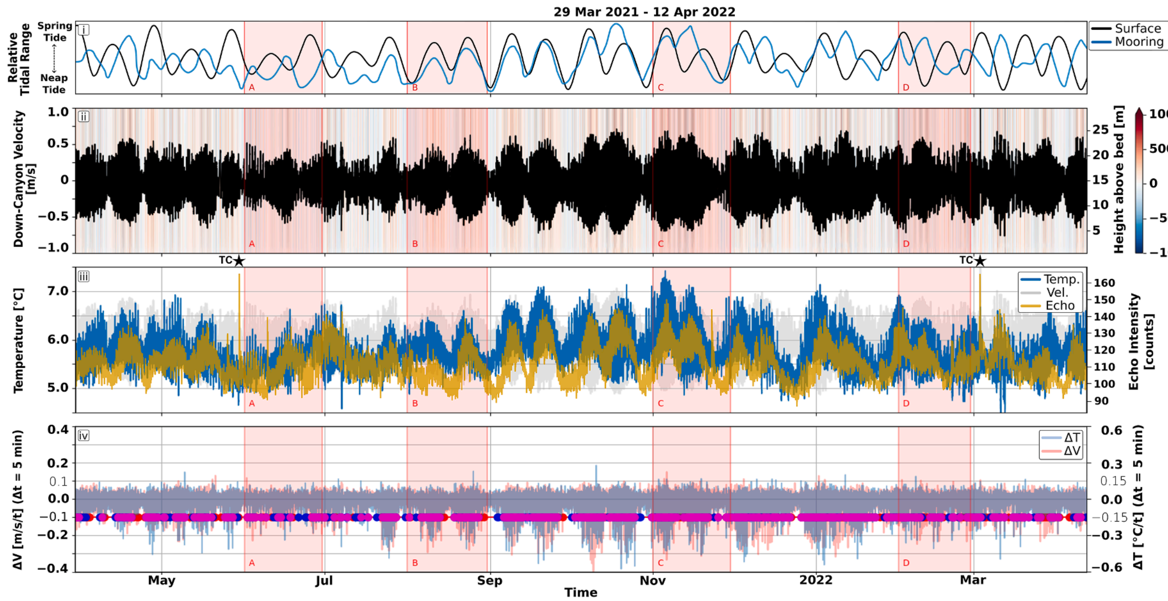

Fig. 2. General characteristics and context of the near-bed water column for the duration of the mooring deployment, including parameters used to identify internal tidal bores. The light red rectangles indicate the selected months chosen for closer analysis. **i.** The surface (black) and near-bed (blue) spring-neap tidal cycles; **ii.** Contour plot showing near-bed (0–30masb) down-canyon flow velocities, overlaid by a line plot displaying the depth-averaged down-canyon velocity; **iii.** temperature as recorded by the ADCP housing, overlaid by depth-averaged echo intensity (backscatter) in yellow; **iv.** Velocity and temperature derivatives calculated over 5-minute intervals. Circles mark bore detections where the rate of change exceeds the threshold criteria. Colour indicates which criteria is met: Blue = temperature criteria, red = velocity, magenta = both.

$$f(t) = \frac{A}{\arctan\left(\frac{\alpha_0}{\sqrt{1-\alpha_0^2}}\right)} \times \arctan\left(\frac{\alpha_0 \sin\left(\frac{2\pi}{T}(t-\phi) + \arccos(\alpha_0)\right)}{1-\alpha_0\cos\left(\frac{2\pi}{T}(t-\phi)+\arccos(\alpha_0)\right)}\right) + c$$

where A is the amplitude, T is the wave period, ϕ is the phase, and c is a vertical offset. α_0 is a parameter varying between −1 and 1 describing the 'skewness' of a waveform, referred to in this paper as asymmetry. (See note in Supplementary material regarding terminology of asymmetry vs skewness in waves.)

The function was fit to the time series of down canyon-velocity in a rolling 13-hour window with a 12-hour overlap. The final curve parameters for any individual timestep are a weighted mean of the 13 windows that the timestep is within. We consider a signal to be 'bore-like' if the magnitude of its asymmetry value exceeds 0.4. Negative asymmetry (< -0.4) is representative of conventional bores, with an upcanyon-propagating wavefront, while positive asymmetry indicates the reverse.

2.4. Calculating sediment mobility

Prior studies have shown that the seafloor sediments within this region of Whittard Canyon are primarily silts and very fine sands (Amaro et al., 2016; Haalboom et al., 2021), however, turbidity current deposits are defined by much coarser sand (Heijnen et al., 2022). We selected a broad range of grain sizes in order to capture fine background sediments, consider the potential for reworking of coarser-grained turbidity current deposits, and facilitate comparisons to other canyons. We infer that transport is possible for a particular grain size if the observed flow velocity at 5 m above the seabed exceeds the critical threshold velocity (at 5 m above bed) for that grain size.

3. Results

3.1. Internal bores occur frequently throughout the year

The near-seafloor ADCP data reveal numerous episodes of a rapid transition to up-canyon flow, followed by a slower return to down-canyon flow that are diagnostic of bore-like behaviour. During the year-long monitoring period, a total of 602 instances of rapidly-reversing canyon flow were found to exceed the thresholds of temperature or velocity change that we set as the criteria for detecting a bore (Fig. 2). Of those, 411 exceeded both velocity and temperature thresholds, 102 for temperature alone, and 89 for velocity alone (Table 1, Fig. 2). Averaged across the 379-day dataset, this equates to approximately 1.59 detected bores each day at this location. These bores have measured flow speeds ranging from 0.1 to 0.7 m/s, and are typically accompanied by a positive spike in echo intensity (Figs. 2, 3) that subsequently decays. These bores exhibit a surprisingly wide diversity in form and behaviour, predominantly aligning with descriptions of "canonical" bores, but not universally.

Table 1
This table displays the counts of bores detected based upon the chosen gradient thresholds. Detections are shown for the selected focus months, as well as for the full deployment. Detections are categorized based on whether they satisfied both temperature and velocity thresholds, or only one. Total detections and the number of tidal cycles within the time period can be used to determine the relative prevalence of bores.

	Bore Detections						Tidal Cycles
	ΔT	(excl)	ΔV	(excl)	Both	Total	
June	19	(6)	18	(5)	13	**24**	60
August	23	(0)	35	(12)	23	**35**	62
November	39	(0)	44	(15)	39	**44**	60
February	31	(5)	37	(11)	26	**42**	56
Full Deployment	513	(102)	500	(89)	411	**602**	758

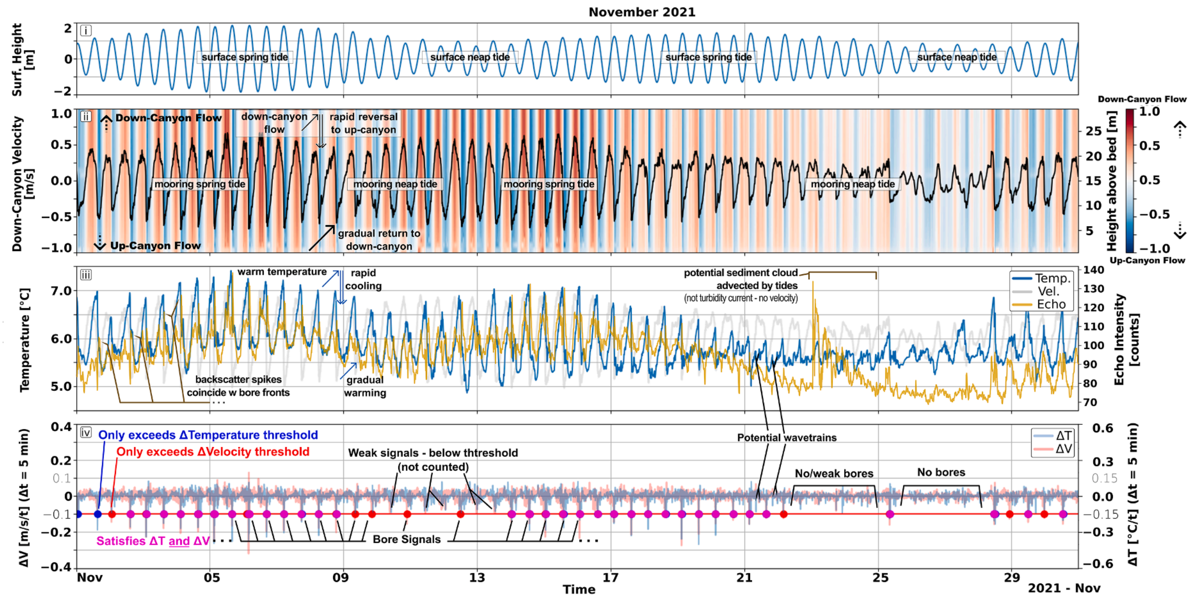

Fig. 3. General characteristics and context of the near-bed water column for the month of November, including parameters used to identify internal tidal bores. **i.** Sea surface height above the location of the ADCP mooring; **ii.** Contour plot showing near-bed (0–30masb) down-canyon flow velocities, overlaid by a line plot displaying the depth-averaged down-canyon velocity; **iii.** temperature as recorded by the ADCP housing, overlaid by depth-averaged echo intensity (backscatter) in yellow; **iv.** Velocity and temperature derivatives calculated over 5-minute intervals. Points in time where the rate of change exceeds the threshold criteria are marked with a circle depending on which criteria is met. Blue = temperature criteria, red = velocity, magenta = both.

3.2. *Highly variable behaviour of internal bores*

Most of the internal waves have negative velocity asymmetry, consistent with conventional bores with a wavefront that flows up-canyon. While these bores are frequent, their behaviour is highly variable. Under the gradient thresholds approach, multiple instances occur where bores can be clearly defined based on their change in velocity, but not temperature, and vice versa (Figs. 2, 3). Through our moving window curve-fitting approach (Fig. 4), we observe that bore properties vary significantly while still maintaining an identifiable non-linear (non-sinusoidal) shape. The degree of asymmetry varies, ranging from sinusoidal waves with negligible asymmetry ($|\alpha_0| \leq 0.1$) to strongly asymmetric waves with near-instantaneous reversals of flow direction ($\alpha_0 < -0.8$). Down-canyon tidal current speeds preceding bores ranged from

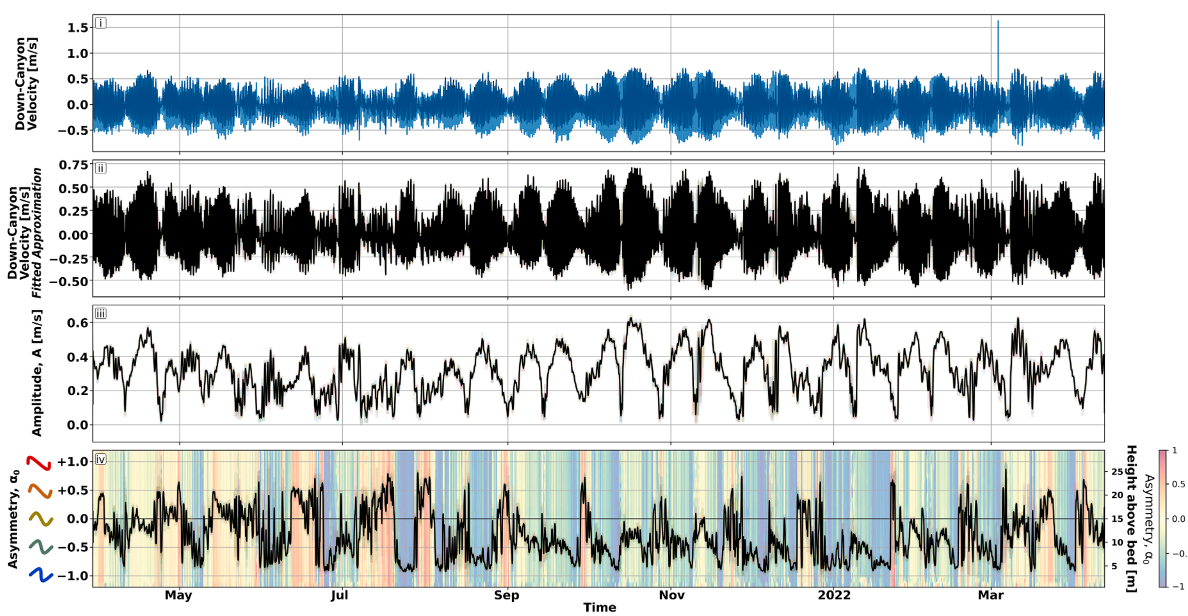

Fig. 4. Overview of the relevant parameters obtained from the curve fitting algorithm; **i.** shows the raw data used for the fit, as well as the average fitted result (background black line) for comparison; **ii.** shows the average fitted curve (black line) overlaid on the fits from each trial (faint lines). Areas where trials diverge indicate where the fitting is less stable; **iii.** shows the amplitude (black), A, of the fitted curve. Amplitude represents the distance from the peak/trough to the estimated midline of the wave; **iv.** displays a contour plot and depth-average of the asymmetry parameter, α_0, of the fitted curve. Asymmetry is a property of non-linear waves, and describes how a wave "leans" forwards or backwards. An asymmetry of +1.00 (red) describes a wave with a fully vertical rear face and a gently sloping front face, whereas an asymmetry of −1.00 (blue) describes the inverse, with a shallow rear face and vertical front. A wave with 0 asymmetry (yellow) is perfectly symmetric about the y-axis. Internal tidal bores typically have negative asymmetry. Examples of individual trials (faint lines) diverging may be seen more clearly in Fig. 5.

over 0.7 m/s to under 0.25 m/s. Associated temperature changes vary from nearly 2 °C to less than 0.5 °C (Fig. 2). Changes in wave asymmetry coincide with these other variations, with broad shifts visible over seasonal timescales. Other non-linear effects, such as the appearance of smaller wave trains following the initial bore front are also occasionally present (Fig. 3), however smaller-amplitude features like these have not been categorized or treated independently from the primary bore.

3.3. Bore behaviour varies across seasonal timeframes

While bores are observed frequently, they are not evenly distributed through the year-long deployment. We find that bores are strongly coupled to the spring-neap tidal cycle (Figs. 2, 3). This is expected, as stronger surface tides may generate larger internal tides and thus stronger internal tidal bores; however, we also observe that tidal bores can occur close to some neap tides, albeit rarely.

Both methods of evaluating bores indicate that they consistently reach higher flow speeds (> 0.6 m/s) and are more prevalent during the winter months (Nov–Feb), while during the summer, bores are comparatively weaker and less frequent (Table 1, Figs. 2, 4). In addition to the overall higher number of bore detections during the winter months, temperature and velocity criteria agreed most frequently in November and least frequently in June, suggesting that bores may be weaker or less defined during the summer. This appearance of winter bore strengthening coincides with overall increased magnitudes of tidal velocities during the winter, as spring tides are at their strongest. Observed temperatures are most variable and also attain their highest peak during the November–February period (Fig. 2). Acoustic backscatter is also elevated during this time (indicating higher levels of suspended particles), likely due to bore activity. Wave asymmetry values determined by the curve fitting algorithm are also more consistently negative in winter than summer (Fig. 4), with negative asymmetry indicating the sudden, abrupt transitions from down-canyon to up-canyon flow and slow, gradual transitions from up- to down-canyon flow that are characteristic of canonical bores. The observed internal spring-neap cycle does not consistently align with modelled surface tides at this location. Surface tides and internal tides align best from August through to November, and become increasingly out of phase from December through spring to early summer (Fig. 2).

Scattered occurrences of positively asymmetric velocities, with sharp transitions from up-canyon to down-canyon are found throughout the year, however only during the summer are waves consistently so for any length of time. In general, asymmetry tends to be mostly neutral ($\alpha_0 \sim 0$) during the summer, suggesting conditions for tidal bores are less favourable overall (Fig. 4). However, short periods of strongly negative asymmetry are found during spring tides in June (Figs. 4, 5), July and August, suggesting that while winter conditions may be more broadly favourable for bore generation, summer conditions do retain some capability to sporadically generate up-canyon bores, with velocities comparable to those seen in winter.

3.4. Influence of internal bores on sediment mobility and transport

Internal tidal currents (both bore and non-bore-related) during the year-long monitoring window regularly reach and exceed the seafloor velocities required to mobilise silt and fine-grained sand up to 380 μm in both up- and down-canyon directions (Fig. 6). Speeds capable of moving grain sizes up to 980 μm are attained mainly during the winter. When these coarser grains (approaching 1 mm and greater) are considered, velocities exceeding the critical threshold of motion consistently favour up-canyon motion (Fig. 6). Up-canyon flow accounts for approximately 55 % of measurements approaching the critical threshold for grains 120–480 μm in diameter (Fig. 7). This proportion rises to account for roughly 80 % of measurements exceeding the threshold by 0.2 m/s (Fig. 7). These higher velocities are most frequently reached when measured velocity asymmetry is strongly negative (Fig. 6), supporting the involvement of tidal bores at those times. However, the highest observed velocities (> 1 m/s) flow exclusively down-canyon, and are attributed to two turbidity currents that were observed in the dataset (Figs. 6, 7) – these represent a small fraction of overall data points.

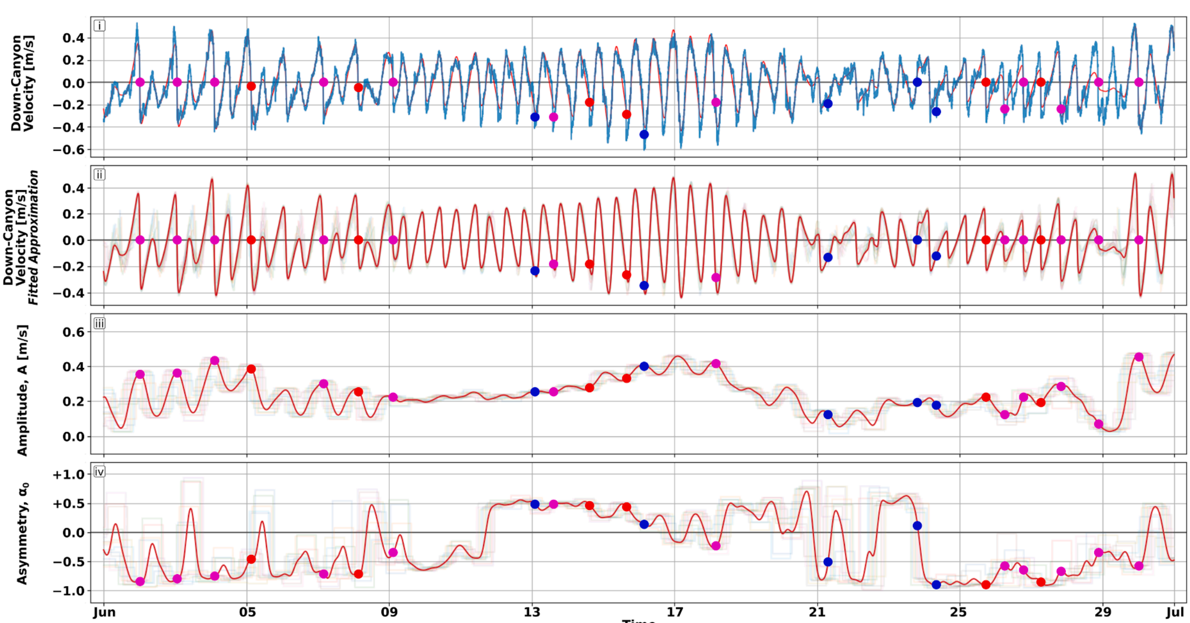

Fig. 5. Parameters from the fitting algorithm for the month of June in 2021; **i.** shows the raw data used for the fit, as well as the average fitted result (thin red line) for comparison; **ii.** shows the average fitted curve (red line) overlaid on the fits from each offset (faint lines). Areas where offsets diverge indicate where the fitting is unstable; **iii.** shows the amplitude, A, of the fitted curve. Amplitude represents the distance from the peak/trough to the estimated midline of the wave; **iv.** displays the depth-average of the asymmetry parameter, α_0, of the fitted curve. Circles mark bore detections based upon change thresholds for temperature and velocity, and are colourized similarly to Figs. 2 and 3.

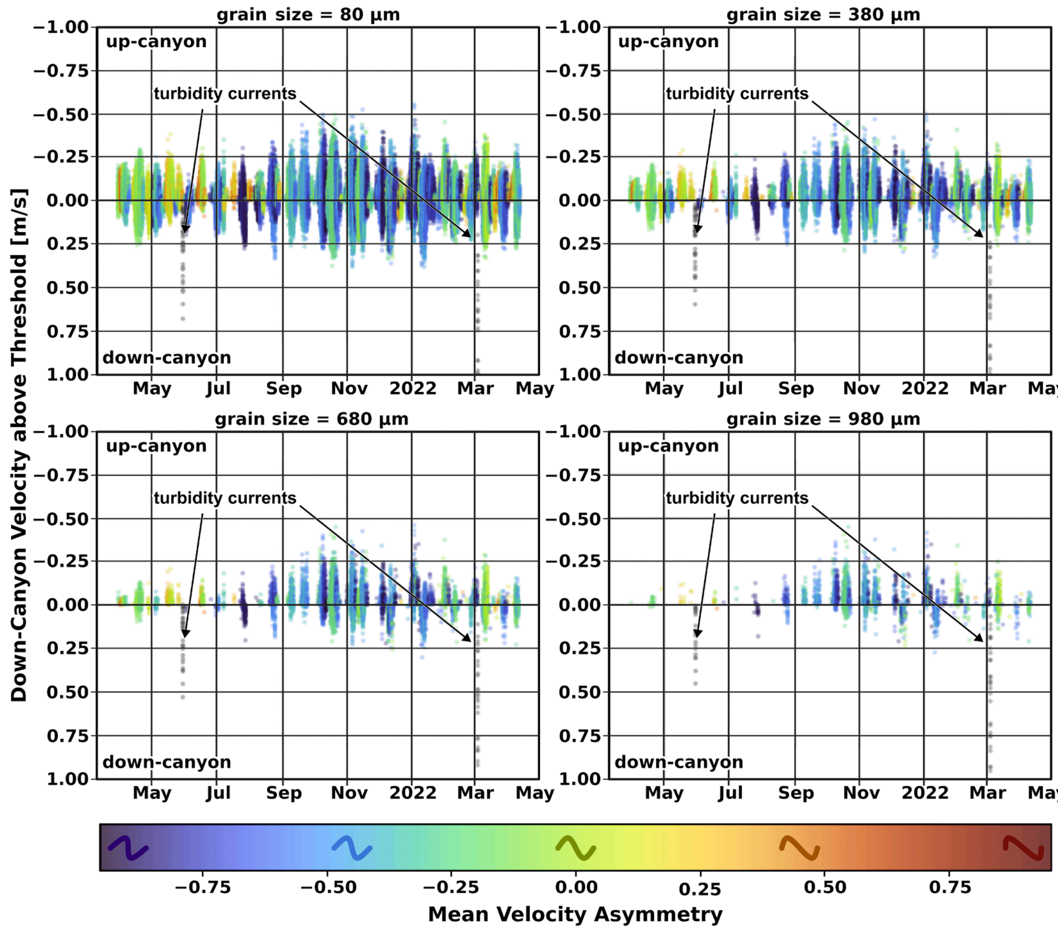

Fig. 6. Timeseries spanning the deployment, displaying datapoints where water velocity exceeds the threshold for moving sediment of various grain sizes. Points are positioned so that zero on the vertical axis is the critical threshold for the given grain size. Speeds that do not reach the threshold are not shown – positive and negative values indicate down-canyon and up-canyon mobilization, respectively. Note that this plot is oriented such that positive values (down-canyon) are down. Points are coloured according to the mean velocity asymmetry, such that blue indicates negative asymmetry (canonical bores). Note that for coarse grain sizes, velocities sufficient for motion are predominantly up-canyon, and occur when asymmetry is negative, during the winter.

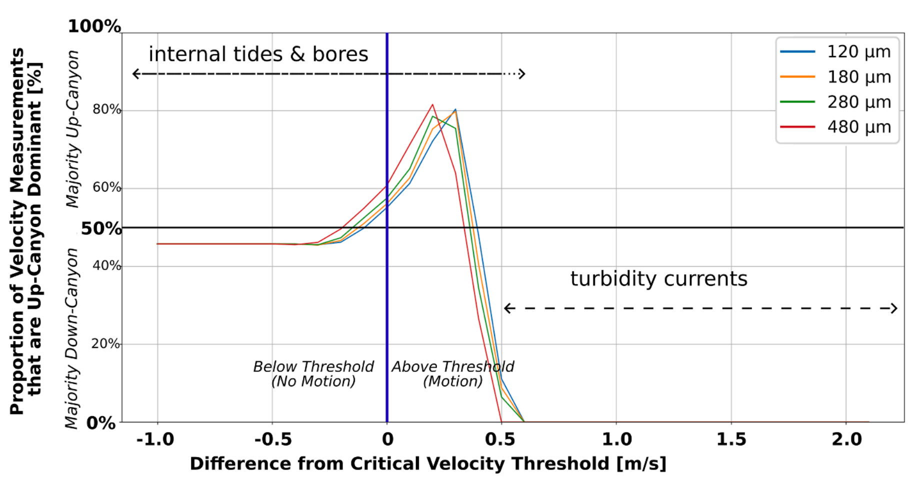

Fig. 7. The relative proportion of velocity measurements within the dataset exceeding critical motion thresholds for various grainsizes. The horizontal axis indicates the difference above/below the threshold for each grainsize, such that positive values indicate mobilization may be achieved. The vertical axis represents the fraction of measurements that are net up-canyon, for a given overall speed. Velocities up to roughly 0.5 m/s above thresholds are mainly due to internal tides and bores, though higher velocities were reached by two turbidity currents that passed by the mooring.

4. Discussion

4.1. Frequent and powerful internal tidal bores in Whittard Canyon and their implications for particulate transport

We show that internal bores occur frequently within Whittard Canyon, and with a high degree of regularity. Most tidal cycles resulted in a bore, even when close to a neap tide. While not every tide forms a bore at this location, nearly 80 % of tidal cycles do. These bores can be easily identified based on criteria targeting their shock-like fronts (through their associated abrupt changes in conditions), but we show that they are not uniform in potential source and impact, instead exhibiting a range of behaviours. We observed these bores to occur within a range of tidal flow speeds and temperatures, suggesting potential variations in the local vertical density structure. Changes in the asymmetry of the velocity signal coincide with these other variations, with broad shifts visible over seasonal timescales. Previous studies (e.g., Aslam et al., 2018; van Haren et al., 2022; Vlasenko et al., 2014) have not enabled these insights due to a lack of high-resolution near-bed measurements over year-long timescales.

Bores regularly exceed flow speeds that are required to move sediment within Whittard Canyon, with a bias towards up-canyon transport (Figs. 6, 7). It is likely that the remobilization capability of these bores is even stronger than indicated here, as factors below the resolution of the ADCP (such as rapid velocity fluctuations and fine-scale turbulence) may mobilize and resuspend deep-sea sediment even when time-averaged velocity thresholds are unmet (Hu et al., 2025; Salim et al., 2018). The sudden increases in echo intensity coincident with each bore front further indicate that particulate mobilization and suspension is occurring (Figs. 2, 3).

The seasonally changing nature of bores additionally results in seasonal changes to the sediment transport regime in this area of Whittard Canyon. The weakening and strengthening of bores enables transport of sediment with differing grain sizes. During winter months, tidal bores appear to be the primary force capable of mobilizing coarse sediment grains, however, as bores weaken during summer, their influence wanes as well (Fig. 6). Seafloor currents capable of shifting coarse material are rare during the summer, suggesting that coarse sands may remain immobile for parts of the year.

As shown in Fig. 8, while net up-canyon flow is most common across the year, bores and non-bore tides are not limited to a singular heading and can vary by up to 20° within a month. Additionally, flow directions are variable between months and change with different bore velocities. Currents with higher velocities (those able to move sand-sized grains)

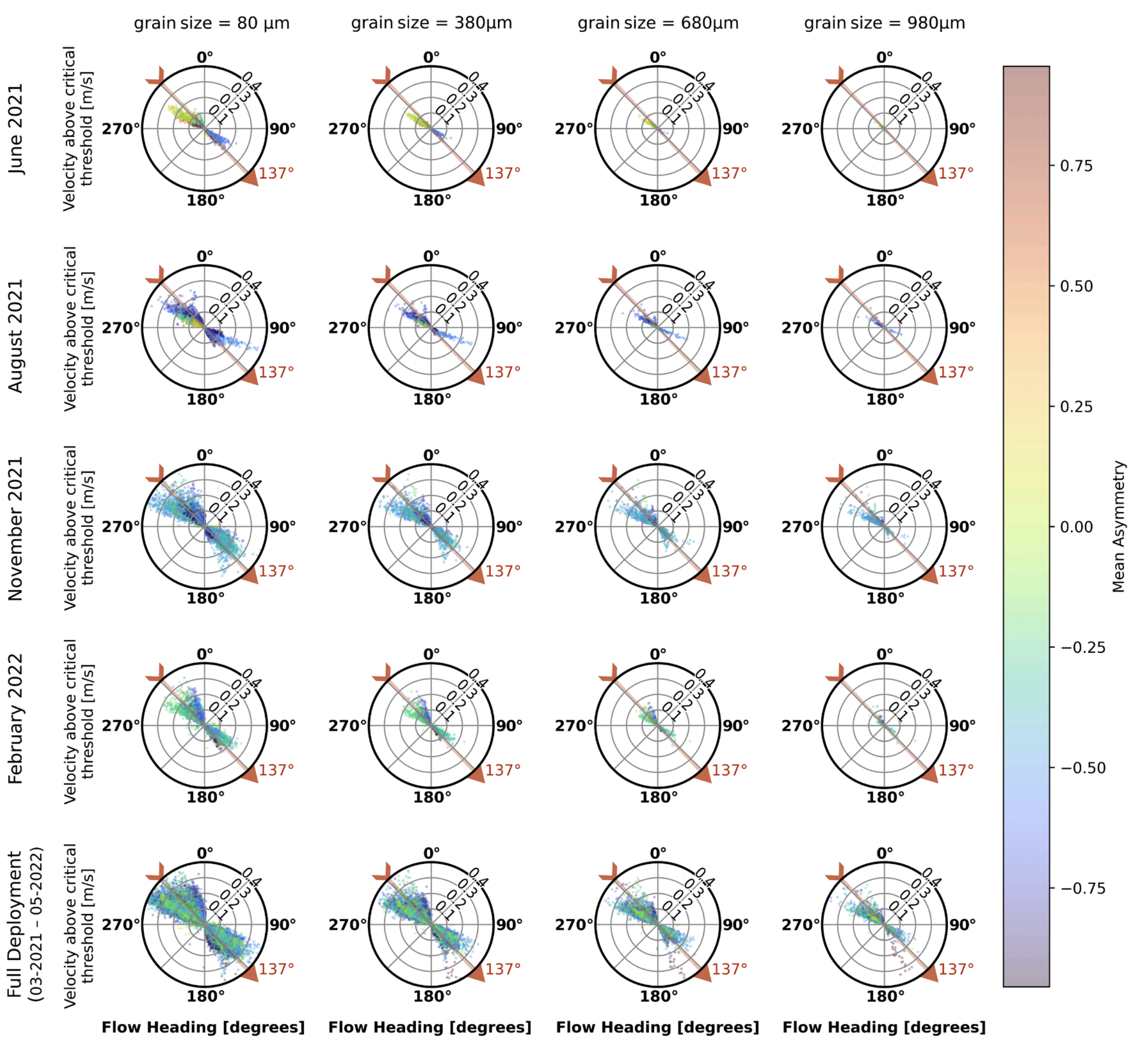

Fig. 8. Polar scatter plots displaying all occurrences (bores and non-bores) within the data where near-seafloor current velocity exceeds the threshold for initiation of sediment motion, calculated for multiple grain sizes. The first four rows show the data for the stated month, while row five contains points from the full deployment. Point position displays the flow direction and velocity. Points are coloured by the mean asymmetry evaluated at that time. An asymmetry of 0 (pale yellow-green) indicates a normal sinusoidal tide, while an asymmetry <-0.4 (teal-dark blue) is more indicative of typical up-canyon bores. Positive asymmetry >0.4 (orange-red) indicates down-canyon ("non-canonical") bores. The heading of the canyon thalweg at the position of the mooring (137°E of N) is also shown.

tend to be more variable in heading than currents that fall below the -threshold to transport sand (Fig. 8). This presents the possibility of bore-driven sorting of material, as the most powerful bores traverse the canyon with different headings relative to currents that are weaker but more numerous. Highly mobile material, such as fine sands, would be shifted generally in the direction of the most common tides; whereas particles only capable of being moved by the strongest bores would experience different net movement directions and may be concentrated towards different areas of the canyon floor. It is additionally worth noting however, that any potential sorting could be disrupted by infrequent, but powerful turbidity currents (Heijnen et al., 2022; Normandeau et al., 2024; Soutter et al., 2024).

At an even larger scale, the work of Lo Iacono et al. (2020) proposes that shelf-canyon sediment transport is not uniformly up- or down-canyon across multiple tributary branches of the dendritic Whittard Canyon. Bedforms indicative of dominant up-canyon flow are found above some tributary heads (at approximately 200 m depth), while indications of down-canyon flow are present in others. Tidal bores were suggested to be potential drivers for this differential sediment movement. Numerical modelling studies show that the topographic complexity of Whittard Canyon results in equally complex hydrodynamics – with some branches generating and others dissipating internal tides (Aslam et al., 2018; Hall et al., 2017). Branches that effectively concentrate and dissipate internal tide energy via wave breaking and bore formation might be those with apparent transport away from the head. Our findings provide further evidence of bores as an agent for sediment transport.

The frequent recurrence of bores and strong tidal currents shown in the time-series presented in this study suggests that long term preservation of tidal bedforms or signatures within deposits (i.e., as internal tidalites) might be unlikely within this section of Whittard Canyon and potentially much of the upper canyon. The prevalence of bores capable of mobilizing the majority of sediment grains, combined with sporadic inputs of coarser (less mobile) material by turbidity currents, may favour continuous reworking and transport of sediment, with limited potential for prolonged aggradation when these episodic large sediment inputs are absent. Sedimentary structures identified as internal tidal reworking of turbidity current deposits have been noted in sediment cores taken from Whittard Canyon (Soutter et al., 2024). However, such signatures are dependent upon the presence of turbidite deposits to be reworked, and can easily be erased by subsequent sediment flows, thus rarely surviving in the stratigraphic record (Normandeau et al., 2024; Soutter et al., 2024). However, due to the high spatial complexity of tidal dynamics within Whittard Canyon (Amaro et al., 2016; Aslam et al., 2018; Hall et al., 2017), it remains possible that long-term deposition or temporary accumulation is favoured elsewhere within the larger Whittard Canyon system. Additionally, accumulation may occur on canyon terraces and interfluves above the thalweg, where sediments attributed to turbidity current spillover have been found previously (Amaro et al., 2016).

4.2. *Seasonal variations due to changing stratification or changing tides*

Multiple factors may ultimately be responsible for the seasonal variability seen in bore occurrence and strength. The shelf and slope currents in the region surrounding Whittard Canyon experience seasonal variations in both current strength and direction, with velocities peaking in winter (Pingree et al., 1999). Resultant changes in the strength of the internal tide would likewise impact the formation and size of bores. Changing stratification within the water column can also impact the development and observed appearance of bores in the data. Oceanographic measurements and numerical modelling studies have found that stratification in the Celtic Sea and adjacent Bay of Biscay varies seasonally (New, 1988; Ruiz-Castillo et al., 2019). The internal (tidal) waves that become bores propagate along density gradients, and movement of the seasonal thermocline has been previously linked to changing bore strength in submarine canyons, such as within Monterey submarine canyon (Walter and Phelan, 2016). Numerical models also show that differing stratification and internal wave amplitude strongly impact bore development (Dauhajre et al., 2021). Here we present different scenarios in which simplified potential 'end members' for the varying modes of actions behind the drivers of the seasonal variations are summarised, alongside speculated causes (Fig. 9).

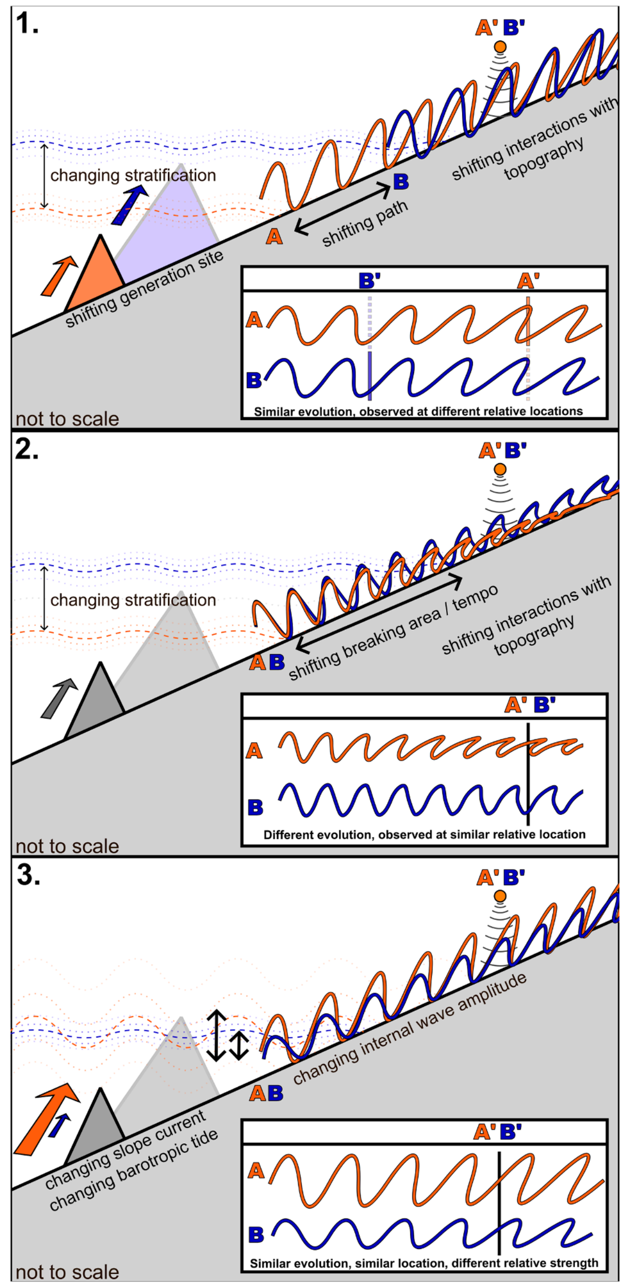

Fig. 9. Theorized end members for factors contributing to the seasonality of internal tidal bores. In all three scenarios, [A] and [B] represent the initial point of interaction between the internal tide and the canyon slope. [A′] and [B′] represent the bore's point of observation by the ADCP mooring. **1.** Changing stratification and/or movement of the tide generation site causes offset of the internal waves/bores relative to the mooring site, while wave evolution with time is not impacted. **2.** Differing stratification causes internal waves to shoal and break more quickly/slowly, resulting in observations of "older" or "younger" bores, despite no change to generation site. **3.** Changes in strength of internal tide generation (i.e. slope currents), results in smaller or larger amplitude waves, resulting in differing energetics.

1. Changing local/non-local conditions can shift internal tides and bores in space, relative to the mooring position. For example, changing stratification and/or height of pycnocline relative to canyon slope, or capturing of non-local internal tides. Shifting generation sites or changing paths cause internal tides to interact with topography at different points along the canyon. Thus, bore evolution with time remains the same, but our measurements are viewing the bore in a different relative position.
2. Changing local conditions such as changing stratification strength, or temperature/density contrasts between layers, may change bore development, though bore initiation is not shifted relative to the mooring. The initial interactions between tides and topography might remain generally consistent at a location, however, the breaking area, manner, speed, as well as subsequent topographic interactions change. Thus, bore evolution with time is changed, when viewed at a similar position/time.
3. Changes in strength of slope/bottom currents and/or barotropic tides modulates internal tides directly; weaker internal tides lead to weaker bores.

While simplistic, these contrasting modes may represent relative importance of locally or non-locally generated internal tides, as well as sensitivity to local and/or regional conditions. Given the complex morphology of Whittard Canyon, the proportional role of each scenario cannot be conclusively determined from a single point mooring alone. Variations in wave/bore heading could point to variations in tidal generation site, but also be the result of complex interactions with canyon topography.

4.3. Bores as a key driver of particulate transport in other submarine canyons

Submarine canyons and continental margins more generally are key areas for the focusing and dissipation of internal tides globally, and thus internal tidal bores are expected to be a common feature in those locations. Bores have been directly observed both within various submarine canyons and on continental slopes (Li et al., 2019; Martini et al., 2013; Pineda 1994; van Haren et al., 2022; Walter et al., 2012; 2016). However, the observed behaviour of a bore is dependent upon a multitude of variables whose relative impact can vary depending on observation site within the canyon, the canyon's location, and time (Aslam et al., 2018; Hall et al., 2017; Jackson et al., 2015; Pingree and Le Cann, 1990; Pingree and Mardell, 1985). Internal tides can propagate for long distances depending on latitude (de Lavergne et al., 2019; Jackson et al., 2015), meaning that even if a canyon experiences minimal internal tide generation locally, it may still receive and dissipate non-local tides – potentially forming bores. Potential interactions between locally and non-locally generated tides additionally complicate attempts to identify any singular generation mechanism (Jackson et al., 2015).

The relative significance of internal tides/bores for particulate transport within submarine canyons will necessarily depend on both the energy of the tide, and the amount and type of sediment available to be moved. The presence of other strong sediment transport processes such as turbidity currents also determines the relative significance of bores within the sedimentary regime of any particular canyon system. Although differing morphologies and dynamics make every submarine canyon a unique environment to some degree, the range of dynamic sediment processes within these systems is similar. For submarine canyons lacking external, high-volume sediment inputs, the presence or absence of energetic internal tides and bores may be a controlling factor for a canyon to be considered as "active" or "inactive" in terms of overall sediment mobility through the system.

Despite the multitude of factors at play, observations of breaking internal waves in other canyons share some similarities to those from Whittard Canyon, suggesting that internal tides can similarly influence particulate transport across a diverse range of canyons. Internal tidal bores observed in Logan Canyon (Scotian Shelf, Canada) were highly asymmetric in the up-canyon direction (Li et al., 2019). However, both up- and down-canyon moving bores were observed, and net sediment transport was down-canyon (Li et al., 2019). Meanwhile, Puig et al. (2013) recorded up-canyon propagating bores in Halibut Canyon (SE Canadian Margin) associated with rapid cooling of approx. 1 °C. These bores were accompanied by sudden spikes in suspended sediments which rapidly decay following the passage of the bore front (Puig et al., 2013), as in our observations via ADCP backscatter. Seasonal shifts in bore strength have been observed in the shallow water (30 m depth) head of Monterey Canyon, and were attributed to a combination of changing stratification strength and movement of the offshore seasonal thermocline (Walter and Phelan, 2016). However, these bores are noted as being stronger in summer and weaker in winter, as the thermocline shoals and deepens, respectively (Walter and Phelan, 2016). This strong summer/weak winter bore regime is contrary to the observed pattern noted in Whittard Canyon at ~1500 m. Interestingly, it should be noted that the Celtic Sea experiences a similar pattern of seasonal stratification (Ruiz-Castillo et al., 2019).

Within Monterey Canyon, repeat high-resolution mapping revealed scours caused by internal tides within recent turbidity current deposits (~1800 m) (Wolfson-Schwehr et al., 2023). These scours were observed in May (following a turbidity current in January) and March (after turbidity current in March), but notably absent in October (after turbidity current in September) (Wolfson-Schwehr et al., 2023). Locations where scours were found lacked any obvious topographic trigger for their formation, and no potential cause was suggested for their absence in October. Seasonally-varying internal tidal bores may provide an answer, as the presence of scours seemingly agrees with the seasonal regime observed in shallower water by Walter and Phelan (2016).

Sedimentary structures observed in canyon sands (or sandstones) have commonly been used to understand the record of sediment-gravity currents and natural hazards, for example rhythmic mud-sand 'bundles' have been attributed to earthquakes and their aftershocks, or pulses in river floods (e.g. Mulder et al., 2003; Wils et al., 2021). However, we show that seasonal variations in bed shear stress attributed to internal tides and bores are potentially capable of creating such a depositional signature, implying that caution should be taken in interpretation where direct constraint in hydrodynamic conditions is absent.

Bailey et al. (2021), described how steady accumulation of material within the canyon head might precondition a slope to fail, allowing for turbidity currents even in the absence of notable triggers. Two turbidity currents were observed within the dataset, and both occurred during the period where bores are seemingly weaker (Fig. 6). However, net up-canyon transport of sediments due to breaking tidal bores may facilitate accumulation of mobile sediments along the canyon head rims. In addition to the focusing of material towards locations favourable to turbidity current generation via slope failure, continuous resuspension of material could make it easier for turbidity currents to initiate by maintaining clouds of suspended sediment. Hage et al. (2019) observed turbidity current generation from extremely dilute river plumes, raising the potential for suspended sediment concentrations previously considered sub-threshold elsewhere to potentially spawn turbidity currents, given the right conditions.

4.4. Implications for other particulates

Though our calculations focus on transport of sedimentary material specifically, non-lithogenic particulates with ecological significance will also be influenced by breaking internal tides. Large volumes of marine 'litter' can be transferred through river-connected submarine canyons (Pierdomenico et al., 2023), but even in land-detached canyons marine litter can be delivered to canyon heads, and subsequently transported and deposited by turbidity currents (Zhong and Peng, 2021). In Whittard Canyon, microplastics are found on the seabed and in shallow sediments, and were present in sediment trap samples capturing the passage of a large turbidity current, demonstrating their active transfer to the deeper sea (Chen et al., 2025). Internal tidal bores may continually resuspend low-density microplastic particles at the seabed, leaving a relatively enriched seafloor accumulation. In addition, a range of harmful pollutants can sorb to mineral grains (Higgins and Luthy 2006; Karickhoff et al., 1979; Sanches-Vidal et al., 2015), and are thus prone to delivery by sediment transport pathways. These include dichloro-diphenyl-trichloroethane (DDT, an insecticide), which has been found in the Monterey Canyon at thousands of metres water depth, associated with clay grains transported by turbidity currents (Hartwell, 2004), and perfluoroalkyl substances (PFASs) used in surface coatings, which are transported with fine particulate matter by dense water cascades into the Cap de Creus Canyon, offshore Spain (Sanchez-Vidal et al., 2015). In both cases, these pollutants associated with fine-grained material that breaking internal tides and bores may also be capable of transporting. The predicted increase in volume and variety of pollutants being carried by sediment gravity flows means that understanding the transport processes and pathways are critical to quantify in terms of the global budgets and the way these relate to delicate benthic ecosystems (Kane and Fildani, 2021).

Beyond pollutants, internal tides and bores also play a significant role in distributing nutrients, organic carbon, and living organisms throughout the water column, both within submarine canyons and elsewhere (Leichter et al., 1996; Maier et al., 2019; Pineda 1991, 1994; Sharples et al., 2007; Tuerena et al., 2019; Washburn and McPhee-Shaw 2013). Breaking internal tides contribute to vertical mixing and facilitate the upwards transport of nitrate from colder deep water and into shallower near-surface waters (Leichter et al., 1996; Sharples et al., 2007; Tuerena et al., 2019). Observations by Sharples et al. (2007) on the Celtic shelf edge found significantly enhanced nitrate fluxes into the subsurface chlorophyll maximum, due to internal tide dissipation during spring tides. Average nitrate fluxes were measured to be almost 3 times larger during springs than neaps, and much of this difference was attributed to strong turbulent dissipation due to breaking internal tides (Sharples et al., 2007). Internal tidal bores have been linked to shoreward transport of phytoplankton and planktonic larvae (Pineda 1991), and high nutrient and food concentrations may then attract further organisms (Martini et al., 2013).

The direct interactions between tidal bores and larger-scale benthic ecology are likewise highly complex. While the very rapid, large shifts in temperature (1–2 °C in a few hours), might initially be expected to be detrimental to sessile organisms such as cold-water corals, prior studies have documented that Whittard Canyon hosts diverse populations of fauna, including cold-water corals (Amaro et al., 2016; Huvenne et al., 2011). These species must also contend with high current velocities, both due to tides as well as episodic turbidity currents. Within Gaoping Submarine Canyon, the action of internal tides appears to negatively impact benthic fauna, because of seabed disturbances and degraded food supply (Liao et al., 2017). Conversely, internal tides and bores can also have a beneficial influence on benthic ecology, dependent on the range of velocities involved (Pearman et al., 2020). Internal waves contribute to the generation of nepheloid layers, both near the seabed and higher in the water column (Amaro et al., 2016; Johnson et al., 2001; Mienis et al., 2007; Wilson et al., 2015). It is likely that internal bores specifically enhance this formation, due to their capacity for sediment remobilization (Masunaga et al., 2019). Internal tides appear to be favourable to corals in the NE Atlantic Shelf (Rockall Trough margin) (Mienis et al., 2007), and indeed Whittard Canyon is home to notable coral walls and overhangs (Amaro et al., 2016; Carter et al., 2018; Huvenne et al., 2011). The spatial heterogeneity of internal tides and bores may make habitat mapping more complex by causing unexpected changes in current regime and sediment transport patterns (Morris et al., 2013). However, once properly accounted for, species distribution models and habitat mapping are improved by the inclusion of physical oceanographic parameters (Pearman et al., 2020).

5. Conclusions

Through analysis of novel temporally-extensive and high resolution ADCP data, we observe frequent occurrence of internal tidal bores within the eastern limb of Whittard Submarine Canyon. These bores over a year-long timescale appear to be very frequent, but vary in intensity, likely as a result of seasonal drivers. These bores regularly achieved up-canyon flow speeds exceeding those required to mobilize sediment grain sizes found in Whittard Canyon. The impact of these tidal bores is most apparent for larger grains raising the potential for preferential movement of coarse material up-canyon and additionally facilitating generation of nepheloid layers through resuspension of fines. Their continuous activity may simultaneously obscure any traces left in the sedimentological record, in the absence of episodic large sediment inputs. We conclude that these seasonally varying bores play significant roles in sediment and particulate transport, impacting submarine canyon environments.

CRediT authorship contribution statement

Morgan T. Wolfe: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Michael A. Clare:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Data curation, Conceptualization. **Esther J. Sumner:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Conceptualization. **Veerle A.I. Huvenne:** Funding acquisition, Writing – review & editing, Validation, Supervision, Project administration, Methodology, Conceptualization. **Rob A. Hall:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Conceptualization. **Ian A. Kane:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Morgan T. Wolfe reports financial support was provided by UK Research and Innovation Natural Environment Research Council. Michael A. Clare reports financial support was provided by UK Research and Innovation Natural Environment Research Council. Veerle A.I. Huvenne reports financial support was provided by UK Research and Innovation Natural Environment Research Council. Rob A. Hall reports financial support was provided by UK Research and Innovation Natural Environment Research Council. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2026.119835.

Data availability

Data will be made available on request.

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