Subtidal to Supertidal Variability of Reynolds Stresses in a Midlatitude Stratified Inner Shelf

ANDRÉ PALÓCZY,* JENNIFER A. MACKINNON,* and AMY F. WATERHOUSE*

*Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California

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ABSTRACT: We describe the spatiotemporal variability and vertical structure of turbulent Reynolds stresses (RSs) in a stratified inner shelf with an energetic internal wave climate. The RSs are estimated from direct measurements of velocity variance derived from bottom-mounted acoustic Doppler current profilers. We link the RSs to different physical processes, namely, internal bores, midwater shear instabilities within vertical shear events related to wind-driven subtidal along-shelf currents, and nonturbulent stresses related to incoming nonlinear internal wave (NLIW) trains. The typical RS magnitudes are $O(0.01)$ Pa for background conditions, with diurnal pulses of $O(0.1–1)$ Pa, and $O(1)$ Pa for the NLIW stresses. A NLIW train is observed to produce a depth-averaged vertical stress divergence sufficient to accelerate water $20$ cm s$^{-1}$ in $1$ h, suggesting NLIWs may also be important contributors to the depth-averaged momentum budget. The subtidal stresses show significant periodic variability and are $O(0.1)$ Pa. Conditionally averaged velocity and RS profiles for northward/southward flow provide evidence for downgradient turbulent momentum fluxes, but also indicate departures from this expected regime. Estimates of the terms in the depth-averaged momentum equation suggest that the vertical divergence of the RSs are important terms in both the cross-shelf and along-shelf directions, with geostrophy also present at leading-order in the cross-shelf momentum balance. Among other conclusions, the results highlight that internal bores and shoaling NLIWs may also be important dynamical players in other inner shelves with energetic internal waves.

KEYWORDS: Continental shelf/slope; Coastal flows; Internal waves; Turbulence; Mixing; In situ oceanic observations

1. Introduction

Turbulent processes in the coastal ocean are important players in the transport and mixing of chemical tracers, plankton and other biological material, heat, salt, and momentum (e.g., Burchard et al. 2008). Turbulence is particularly important in the shallow region of the continental shelf where surface and bottom boundary layers overlap, usually defined as the inner shelf. Here, the momentum balance is complicated, with important contributions from surface gravity waves, bottom stress, wind stress both in the along-shelf and cross-shelf directions, and pressure gradients. This situation contrasts with the midshelf, where boundary layers are separated by a geostrophic interior, and the momentum imparted by the wind stress is not directly transported to the bottom (e.g., Lentz et al. 1999; Lentz and Fewings 2012).

Dynamically, turbulent processes enter the momentum balance in the Reynolds-averaged equations via divergences of time-averaged covariances between velocity components (e.g., Cushman-Roisin and Beckers 2011; Kirincich 2013), often called Reynolds stresses (RSs). Turbulence also mixes temperature and salinity, modifying the density stratification and indirectly feeding back into the momentum equation by producing or modifying pressure gradients. RSs can be directly measured in the field using high-frequency acoustic Doppler velocimeters (ADVs; e.g., Feddersen and Williams 2007; Guerra and Thomson 2017; Trowbridge et al. 2018); however, each ADV measures only a single point in the water column. Alternatively, a vertical profile of RS can be derived from raw acoustic Doppler current profiler (ADCP) velocity measurements logged in beam coordinates using the variance technique (e.g., Lohrmann et al. 1990; Stacey et al. 1999), described in section 2b.

Turbulence can be generated by a number of processes, for example, surface stress due to the wind, bottom stress due to currents, and surface gravity waves interacting with the bottom. Other turbulent processes include internal and surface gravity wave breaking and shear instabilities associated with the ambient shear produced by subtidal along-shelf flow, internal tides or near-inertial internal waves (e.g., MacKinnon and Gregg 2003, 2005; Rippeth 2005; Burchard et al. 2008; Walter et al. 2012; Lamb 2014). In particular, turbulence caused by internal tides can take a variety of forms, such as internal tidal bores, solitary wave packets or hybrids between the two (e.g., Lamb 2014). These processes might be associated with substantial RSs. Still, most observational studies of RSs in the ocean using ADCPs have concentrated on tidally dominated flows (e.g., Lu and Lueck 1999; Stacey et al. 1999; Rippeth et al. 2003; Williams and Simpson 2004; Guerra and Thomson 2017) or in the bottom boundary layer in deeper regions (Lohrmann et al. 1990; van Haren et al. 1994), where contamination by surface gravity waves is not a concern. However, on the continental shelf, shoaling surface gravity waves complicate the picture by adding spurious contributions to the observed stresses, and different techniques to remove these contributions have been developed (Whipple et al. 2006; Rosman et al. 2008; Kirincich et al. 2010; Kirincich and Rosman 2011).

In terms of the subtidal circulation, the observed RS profile at the 12-m isobath off Martha’s Vineyard (Massachusetts) has been shown to be well correlated with the local wind stress near the surface and to be consistent with simplified theoretical models of inner-shelf dynamics, when conditionally averaged over different wind, wave and stratification settings (Kirincich 2013). At 30-m depth, poor correlations between the local wind...
stress and the near-surface RSs in the Outer Cape Coastal Current have been observed (Kirincich and Gawarkiewicz 2016). At both locations, the RS profiles showed significant vertical divergence, suggesting a departure from a purely frictional momentum balance where the bottom stress balances the wind stress directly (Kirincich 2013; Kirincich and Gawarkiewicz 2016). This contrasts with the constant-stress profile observed just offshore of the surfzone (Feddersen and Williams 2007).

Other studies concentrating on linking observations of RSs to different inner-shelf physical processes appear to be lacking, especially in the superinertial band. The current understanding of inner-shelf dynamics is that the subinertial circulation (particularly in the along-shelf direction) is sensitive to the vertical structure of the eddy viscosity calculation (particularly in the along-shelf direction) is sensitive to the vertical structure of the eddy viscosity $A_w = \frac{\bar{v}w}{\nu}$, where $\bar{v}w$ is the along-shelf stress and $\nu$ is the vertical shear of the along-shelf velocity (Lentz 1995; Lentz et al. 2008). Direct observations of turbulent stresses are therefore pointed out as an important knowledge gap (Lentz and Frewings 2012; Kirincich 2013). The sensitivity of the inner shelf’s subtidal circulation to the vertical structure and magnitude of the RSs implies that transports driven by along-shelf winds, cross-shelf winds and along-shelf pressure gradients have different stress signatures (Kirincich 2013, his Fig. 2). Therefore, understanding the observed variability of subtidal RSs is relevant for processes involved in cross-shelf exchange and in the way turbulence is represented in Reynolds-averaged coastal regional models.

This approach of linking $\bar{v}w$ to $\nu$ through an eddy viscosity assumes a local flux gradient relationship, i.e., that the vertical flux of mean momentum is downgradient. While this aspect of subtidal dynamics is a knowledge gap in its own right, it is also unclear whether the use of an eddy viscosity hypothesis is valid at supertidal frequencies. As discussed above, RSs can also be generated by high-frequency turbulent processes, most of which are highly nonlinear and have complex shear and stress signatures, transporting momentum with them often independently from the background sheared flow. We will show that processes such as internal bores and nonlinear internal wave packets often have shear and stress signals that depart from such a simplified eddy viscosity relationship.

The central aim of this study is to describe the vertical structure, temporal and spatial variability of observed Reynolds stresses in a stratified, midlatitude (35°N) continental shelf (25–40 m), linking this variability to some of the turbulent processes mentioned above and to the momentum balance in the inner/midshelf. We first describe the dataset and the techniques used to derive turbulent stresses corrected for the bias introduced by surface gravity waves (section 2). We then describe the oceanographic setting, the variability of the observed stresses and their role in the momentum balance in section 3. Finally, we summarize the results and present our conclusions in section 4.

## 2. Data and methods

In this section, we first describe the datasets used in the analyses and the preprocessing steps. Next, we explain the method used for estimating Reynolds stresses with reduced influence from the surface gravity waves’ orbital velocity. All times in the manuscript are in UTC.

### a. Dataset

We analyze a subset of the moored data from the Inner Shelf Dynamics Experiment’s (ISDE; Lerczak et al. 2019; Kumar et al. 2021) primary field component, which was carried out in September–October 2017 in the vicinities of Pt. Sal, off central California (Fig. 1a). The ISDE was funded by the Office of Naval Research (ONR) and had the overarching objective of advancing the understanding of the dynamics of the region of the coastal ocean inshore of the 50 m isobath, including phenomena such as surface and internal gravity waves, wind-driven currents, headland eddies, and rip currents. Our focus is on part of the Oceano Array (Fig. 1b), wherein a group of five upward-looking, five-beam ADCPs were deployed. The moored ADCPs were all Teledyne-RD Instruments (TRDI) Sentinel V’s logging at 1 Hz (OC40S, OC40N, OC25SA, and OC25SB), with the exception of OC25M, which was a Nortek Signature1000 logging at 8 Hz (Fig. 1b). The vertical resolution of the instruments at the 25- and 40-m isobaths was 0.45 and 0.90 m, respectively, and the near-surface blanking distance due to sidelobe contamination was 2.3 and 3.8 m, respectively. All ADCPs had associated thermistor chains nearby (see McSweeney et al. 2020a,b for details).

All velocity data were quality controlled and rotated to an across-shelf/along-shelf coordinate system based on the local along-isobath direction (approximately −6° at 40 m and −17° at 25 m). OC25M’s vertical beam was set to high-resolution mode, which decreased its range to about 5 m above the bottom, while the Janus beams retained their near-full-depth range. OC40N failed after 6 October 2017 and OC25SB data are usable only for the final 10 days of the deployment (20–31 October 2017). The wind stress and RS profiles were rotated to the same across-shelf/along-shelf coordinate system.

Wind stress data are derived from anemometers installed on a land-based meteorological tower in Oceano Beach [Applied Physics Laboratory (APL) meteorological station, magenta square in Fig. 1] and in a meteorological buoy deployed south of Pt. Sal [ Scripps Institution of Oceanography (SIO) meteorological station, magenta diamond in Fig. 1a]. Wind velocity was converted to wind stress using the Large and Pond (1982) bulk formula modified for light winds as in Trenberth et al. (1990), and rotated to the same across-shelf/along-shelf coordinate system as the 25-m moorings. Wave data are derived from a Sofar Spotter wave buoy located on the 20-m isobath off of Oceano Beach (magenta cross in Fig. 1). Sea level data are taken from the adjacent NOAA station (ID 9412110) located in San Luis Obispo Bay.

### b. Estimation of Reynolds stresses and wave bias removal

We estimate the $\bar{u}w$ (hereafter the cross-shelf stress) and $\bar{v}w$ (hereafter the along-shelf stress) components of the Reynolds stress tensor using the variance technique, which consists of using the velocity variances measured by opposing ADCP beams and assuming horizontal homogeneity of the stress tensor components across the beam separation (e.g., Lohmann et al. 1990; Stacey et al. 1999; Lu and Lueck 1999;
Whipple et al. 2006). We employ the five-beam expressions for $u_0w_0$ and $w_0y_0$ with full tilt corrections (Dewey and Stringer 2020):

$$u_0w_0 = \frac{-1}{4S^3C} \left[ S^2C(b_2^2 - b_3^2) + 2S^4C^2 \phi_2 (b_2^2 + b_3^2) \right. - \left. 4S^4C^2 \phi_2 b_3^2 - 4S^6 C^2 \phi_2 u'v' \right], \tag{1}$$

and

$$w_0y_0 = \frac{-1}{4S^3C} \left[ S^2C(b_1^2 - b_3^2) - 2S^4C^2 \phi_3 (b_1^2 + b_3^2) \right. + \left. 4S^4C^2 \phi_3 b_1^2 + 4S^6 C^2 \phi_3 u'v' \right], \tag{2}$$

where $b_n^2$ is the $n$th beam’s variance; $\theta = 25^\circ$ is the Janus beams’ angle with the vertical axis; $S = \sin\theta$; $C = \cos\theta$; and $\phi_2$, $\phi_3$, $u'$, and $v'$ are the pitch and roll angles and the instrument-coordinate horizontal velocity anomalies, respectively. Overbars indicate ensemble time averages. Biases in Eqs. (1) and (2) introduced by instrument noise are corrected (appendix A). We use RS estimates from all valid ensembles for calculating mean RS profiles and spectral estimates. However, for interpretation of the stress signature of individual events, we mask out RSs that are smaller than the noise threshold, $RS_{\text{min}}$, based on a conservative single-ping standard deviation of $\sigma_{\text{sp}} = 0.07 \text{ m s}^{-1}$, i.e., (Williams and Simpson 2004),

$$RS_{\text{min}} = \frac{\sigma_{\text{sp}}}{\sqrt{M \sin 2\theta}}, \tag{3}$$

where $M$ is the number of pings in the ensemble.

There are several challenges in calculating accurate turbulent RSs. Removing the effect of surface wave orbital velocities is the main difficulty in the coastal ocean, and a number of wave bias correction methods exist in the literature. The applicability of these methods depends, among other factors, on the characteristics of the surface wave field. The surface wave climate during the experiment was characterized by long waves (peak periods of up to 20s, section 3a and Figs. 3b,c). Additionally, the ratio between the root-mean-square velocities and the ensemble-averaged velocity ($u_{\text{rms}}/U$) had medians of 2.2 or higher for the 25-m moorings (OC25SA, OC25SB, and OC25M), indicating that less than 50% of the ensembles are possible candidates for the cospectra-fit method (Kirincich et al. 2010), one of the wave bias removal methods. We therefore apply corrections for the bias introduced by the surface gravity waves’ orbital velocities using the adaptive filtering method as described by Rosman et al. (2008). Briefly, the adaptive filtering method uses windowed segments of the velocity record at one of the ADCP’s bins to fit a linear function to the velocity record at an overlying bin separated by a specified number of bins. The result is then subtracted from the first bin. By assuming that this vertically coherent part of the
velocity is dominated by the orbital velocities of surface gravity waves, this technique enables turbulent RS estimates with reduced surface gravity wave bias. We also estimate the RS from the low-pass-filtered (cutoff period at 100 s) along-beam velocities. This eliminates the high-frequency signal both due to surface waves and stress-carrying turbulent eddies, leaving only lower-frequency, larger-scale stresses which we interpret as being due to internal wave velocities (see van Haren et al. 1994).

Figure 2 exemplifies the effect of the adaptive filtering method on the along-beam velocities. A 5-min record from one of OC25M’s beams reveals the clearly resolved signal of surface gravity wave orbital velocities, with periods around 10 s (Fig. 2a). After application of the adaptive filtering method, the orbital velocity signal has been mostly removed, presumably leaving the velocity due to turbulent eddies and instrumental noise (Fig. 2b). We point out that the method also decreases the spectral levels of lower-frequency motions, such as nonlinear internal wave trains and along-shelf subtidal flows, as a side effect (Fig. 2d).

The smallest vertical scales resolved are ≈1 m for the 25-m moorings and ≈2 m for the 40-m moorings. The 25%, 50%, and 75% percentiles of the near-bottom Ozmidov scale estimated from the nearby thermistor chain and OC25M’s vertical beam (in high-resolution, low-noise pulse-coherent mode) from turbulent kinetic energy dissipation rates independently derived from a modified structure function method (not shown; Scannell et al. 2017) are 2.2, 4.0, and 6.4 m, respectively, compatible with the vertical scale of the velocity structure in Fig. 2b. The vertical scale of the adaptive filter is set to 2 m, as a compromise between the competing error-minimizing issues explained by Rosman et al. (2008). We find, however, that results are relatively insensitive to the vertical separation chosen for the adaptive filter in our dataset (not shown). As a result, we choose this relatively small vertical separation to maximize the vertical extent of the estimated Reynolds stress profiles (the larger the separation, the larger the near-surface gap in the stress estimates). We therefore expect to underestimate the real Reynolds stresses, due to the fact that the Ozmidov scale near the bottom at the 25-m isobath is smaller than 2 m about 25% of the time. It is difficult to assess how well the stresses are resolved higher up in the water column because a reliable estimate of the vertical structure of the Ozmidov scale is not available.

The squared correlation coefficient between the depth-averaged cross-shelf Reynolds stress and the significant wave height decreases from 19% to 4% (average for the five moorings), suggesting that the adaptive filtering method substantially reduces contamination by surface gravity waves. The effect of the filtering on the RS can be seen by comparing time series of filtered and unfiltered \( \overline{\rho \vec{u} \vec{w}} \) (where \( \rho \) is the water density, Fig. 2c). The raw (wave-contaminated) stress is systematically larger than its de-wave counterpart. The associated depth-averaged frequency spectra show a substantial reduction in the variance contained in the surface gravity wave band after filtering (Fig. 2d). The noise floor is seen to be at \( \approx 1 \times 10^{-5} \) (m s\(^{-1}\))\(^2\) (cpmin\(^{-1}\)), which translates into a single- ping standard deviation of \( \approx 4.9 \) cm s\(^{-1}\). By conservatively assuming \( \sigma_w = 7 \) cm s\(^{-1}\) in Eq. (3), we obtain a minimum detectable RS of 0.07 Pa for OC25M (8-Hz sampling) and 0.20 Pa for the other four moorings (1-Hz sampling) if an ensemble-averaging period of 20 min is used, as in Figs. 6–8.

3. Results

We begin this section by setting the stage for our detailed examination of the observed RS variability using the five mooring records (Fig. 1). We first describe the general characteristics of the winds, waves, and the vertical stratification throughout the experimental period (section 3a). Next, we examine typical flow patterns and the cross-shelf/along-shelf partitioning of horizontal kinetic energy and vertical shear (section 3b). Having identified the primary physical processes associated with these signals and their potential for generating turbulence, we then describe the temporal variability of the RS across different time scales (from subtidal to supertidal) and associate them with various physical processes (section 3c). We then examine the vertical structure of the time-averaged RSs at each mooring (section 3d) and the uncertainties involved (section 3e). Finally, we perform a dynamical analysis of the data in the cross-shelf and along-shelf momentum budgets (section 3f).

a. Wind, waves, and stratification

The wind, wave, and vertical stratification conditions during the experiment are shown in Fig. 3. The low-frequency wind stress was mostly onshore with a typical magnitude of up to 0.05 Pa, with both the cross-shelf and the along-shelf components having similar magnitudes. Significant wave heights \( H_s \) fluctuated between 1 and 3 m, and peak periods were between 5 and 25 s. The incoming wave direction remained fairly constant in the northwest quadrant, approximately between 270° and 300°. The time-mean stratification was linear and similar at all moorings (Fig. 3d). Temperature is used here as a proxy for density because it dominated the density variability throughout the experiment (McSweeney et al. 2020b). The time-mean buoyancy frequency, estimated as \( N = \sqrt{\frac{g \alpha T_z}{a}} \), where \( g \), \( \alpha \), and \( T_z \) are the gravitational acceleration, the thermal expansion coefficient of seawater, and the vertical temperature gradient (estimated from a linear fit to the \( T \) profiles), respectively, was \( 1.44 \times 10^{-2} \) s\(^{-1}\) at the 25-m isobath (from OC25M, OC25SA, and OC25SB) and \( 1.23 \times 10^{-2} \) s\(^{-1}\) at the 40-m isobath (from OC40S and OC40N). From shipboard data measured in the area of our moorings, the fractional difference between \( N \) calculated from temperature only and \( N \) calculated from both temperature and salinity was 2%. The stratification was stronger in the beginning of the experiment, and gradually eroded throughout September (Fig. 3e).

b. Flow patterns, kinetic energy, and shear variance

In preparation for our discussion of the temporal variability of RSs and the associated physical processes, we first examine an example of typical flow patterns in this region, and the associated temporal variability and spectral content of the horizontal kinetic energy and vertical shear variance (Fig. 4). The baroclinic velocities exhibit a two-layer structure in the
along-shelf direction and a relatively more complicated vertical structure in the cross-shelf direction, although both components have similar magnitudes ($\sim 15 \text{ cm s}^{-1}$, Figs. 4a,b). The barotropic (i.e., vertically averaged) velocities are stronger in the along-shelf direction, and have typical magnitudes of $10$–$30 \text{ cm s}^{-1}$, with episodic jets that last for a few days (Fig. 4c). These jets are associated with pulses of elevated along-shelf depth-averaged kinetic energy with duration of about a day, while the cross-shelf velocity is associated with comparatively weaker pulses of cross-shelf kinetic energy, such that the total kinetic energy is often dominated by the along-shelf component (Fig. 4d). Shear variance, on the other hand, has a more complicated partitioning, with both cross-shelf and along-shelf components being comparable in magnitude (Fig. 4e). Kinetic

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**Fig. 2.** Example of the vertical adaptive filtering method for removal of surface gravity wave bias in ADCP along-beam velocities. (a) Raw velocities from OC25M’s beam 1 (positive toward instrument) over a 5-min period starting at 0000 UTC 12 Sep 2017. (b) As in (a), but after application of the adaptive filtering method with vertical separation of four bins (about 2 m) and a 1-s-long window. (c) Middepth along-shelf Reynolds stress derived from 10 min ensembles of raw and de-waved along-beam velocities over a 4-day period starting at 0000 UTC 15 Sep 2017. (d) Depth-averaged frequency spectra (calculated for a 24-h period centered at 0400 UTC 22 Oct) of along-beam velocities prior to and after application of the adaptive filtering method, with shadings indicating the 95% confidence intervals about each spectrum. The color scale is the same for (a) and (b).
energy is slightly higher in the cross-shelf direction at high frequencies and in the along-shelf component at low frequencies (Fig. 4f), consistent with the superposition of supertidal motions such as internal waves projecting preferentially on the cross-shelf velocity and subtidal wind-driven flows projecting on the along-shelf velocity. In contrast, cross-shelf and along-shelf shear variances are indistinguishable within error bounds (Fig. 4g). The diurnal and semidiurnal tidal peaks, as well as their higher-order harmonics, are visible in both the kinetic energy and in the shear. These results show that physical processes at all frequency bands (supertidal, tidal, and subtidal) are energetic and produce shear that may lead to turbulence and therefore contribute to the RS variability.

c. Temporal variability of Reynolds stresses

In this subsection, we describe the temporal variability of the observed RSs at different frequency bands, discussing its link with several physical processes. We begin with a qualitative overview and a description of the spectral content of the RSs at all moorings and then focus on different physical processes, namely, internal bores, wind-driven along-shelf currents, nonlinear internal wave trains, and subtidal currents.

1) SPECTRAL CONTENT AND QUALITATIVE OVERVIEW

The depth-averaged frequency spectra of the cross-shelf $\tau_{x}$ and along-shelf $\tau_{y}$ stresses reveal peaks at the diurnal and semidiurnal tidal frequencies, as well as higher harmonics (Fig. 5). All moorings exhibit similar variance levels for the RSs in both directions, especially at supertidal frequencies, and their discrepancies at tidal and subtidal frequencies are largely indistinguishable to within error bounds.

General features present in all mooring records can be identified in Fig. 6, a representative example from OC40S’s second deployment (October 2017). Wind reversals occur...
multiple times throughout the record, and the spring–neap cycle is clearly seen in the barotropic tide. Stratification weakens toward the fall, in agreement with Fig. 3e. The tidal signal is most visible in $u$ and $T$, which also track the sharp-edged internal bores described by McSweeney et al. (2020b), especially in $T$. The vertical shear in $u$ has a consistent two-layer structure, which appears to erode with the stratification. One striking feature of all events is the rich vertical structure in the shear that tracks the tidal signal (Figs. 6b,e,h). The along-shelf shear is partly associated with the internal tide and with longer-lasting, possibly wind-driven and geostrophically balanced, along-shelf flows, specifically the northward and southward jets around 17 and 22 October, respectively (Fig. 6h). Background RSs are $O(0.01)$ Pa, often indistinguishable from instrumental noise [Eq. (3)] and similar in magnitude to the wind stress (Figs. 3a and 6a,f,i).

![Figure 4](image.png)

**Fig. 4.** Example of baroclinic and barotropic velocities, horizontal kinetic energy, and shear variance during a subset of OC25SA’s deployment. Baroclinic (total minus vertical average) (a) cross-shelf ($u_{bc}$) and (b) along-shelf ($u_{a}$) velocities. (c) Time series of barotropic (vertically averaged) cross-shelf ($u_{bt}$) and along-shelf ($u_{bt}$) velocities. (d) Time series of depth-averaged cross-shelf, along-shelf, and total kinetic energies. (e) Time series of depth-averaged cross-shelf, along-shelf, and total shear variance. (f) Depth-averaged frequency spectra of cross-shelf and along-shelf kinetic energies. (g) Depth-averaged frequency spectra of cross-shelf and along-shelf shear variances. The shaded areas in (f) and (g) indicate the 95% confidence intervals about each spectrum.
pulses of $O(0.1–1)$ Pa in the RS are conspicuous (vertical stripes on Figs. 6f,i).

### 2) INTERNAL BORES AND ALONG-SHELF JETS

Examples of the semiregular elevated RS events are seen in 15–18 October around 0600 UTC (Figs. 7f,i). These events are likely associated with the arrival of internal bores (Fig. 7c), which share similarities with the bores observed in Monterey Bay by Walter et al. (2012). In this type of bore, there is an initial “surging” period where the near-bottom temperature drops over several hours, followed by the arrival of an abrupt warm front, which partially restores the stratification to its prior state before the next bore arrives and the cycle repeats. Interestingly, however, the other bores (i.e., those occurring between the stress-laden bores) hardly display any measurable stress signature. At OC40S, McSweeney et al. (2020b) identify a total of 149 bores during the experimental period (an average of 2.91 bores per day), which arrive on average every 7.93 h, with a standard deviation of 3.60 h (their Table 1). McSweeney et al. (2020b) also observe that the bore type alternates between sharp-edged bores (which cause more mixing) and more rarefied bores that trail the sharp-edged ones, affected by the change in the stratification waveguide caused by the prior sharp-edged bore. Figures 7c,f,i suggests that, out of all the bores observed in this time period, only one per day (approximately from 0000 to 1200 UTC daily, vertical dashed lines on Figs. 7f,i) contains a substantial stress signature, both in $\overline{u^0 w^0}$ and in $\overline{v^0 w^0}$. This bore-to-bore cyclic variability may be able to explain the semiregular, approximately diurnal elevated midwater stress events seen in Figs. 6f,i and 7f,i. Our measurements do not resolve all turbulent scales or the lower bottom boundary layer, and therefore likely underestimate the Reynolds stresses there. Becherer et al. (2020) have shown that during this field experiment, bursts of elevated turbulent kinetic energy dissipation occur within the bottom boundary layer as a result of the velocities associated with the internal bores, and that this response is asymmetric between onshore and offshore pulses (the onshore pulses are more turbulent).

Do the prolonged along-shelf flows seen in Fig. 6 have important RS signatures? The internal bore events described in the previous paragraph are superimposed on a period of persistent northward flow potentially associated with a downwelling-favorable wind event centered around 17 October (Figs. 7a,g). Onshore velocity and its vertical shear display a semidiurnal pattern, with vertically propagating signals in the shear (Figs. 7d,e). The RS structure seems to lack a persistent surface-to-bottom negative signal associated with the northward jet (i.e., evidence

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**FIG. 5.** Depth-averaged frequency spectra of (a) across-shelf ($\overline{u^0 w^0}$) and (b) along-shelf ($\overline{v^0 w^0}$) stresses at each mooring. Each curve is the depth average of the spectra of $\overline{u^0 w^0}$ or $\overline{v^0 w^0}$ at each depth. The shaded areas indicate the 95% confidence intervals about each spectrum.
of downgradient momentum flux), with the elevated stress signature of the stress-laden daily bore events described above being the dominant feature in the RS (Figs. 7f,i). In contrast, a sustained southward jet potentially associated with a mild upwelling event (Figs. 8a,c) displays intense downgradient momentum flux in both the cross-shelf and along-shelf directions (opposite signs in the shear and the associated stress, Figs. 8e, 8f, 8h, 8i, around 0300 UTC 22 October). In both cases, turbulence linked to processes that project their shear mostly in one direction (i.e., bores in the cross-shelf direction and along-shelf sheared flows in the along-shelf direction) tends to produce elevated patches of both $r_u^0 w^0$ and $r_y^0 w^0$, vertically mixing both cross-shelf momentum and along-shelf momentum.

A question that naturally arises from this analysis is whether these elevated RS events linked to different physical phenomena have a net effect on driving the circulation, i.e., do they contribute to the local force balance in a time-mean sense?
Figure 9 shows the mean $\rho u'w'$ and $\rho v'w'$ RS profiles averaged during different time periods. The solid curves are the average profiles during the entire northward (red) and southward (blue) flow periods depicted in Figs. 7 and 8, respectively. Their minimum significant RS [Eq. (3)] are 0.012 and 0.019 Pa, respectively. The associated dashed curves are weighted averages over the subset of those time periods when there is elevated RS due to bores (for the northward flow case, red dashed curves) and elevated RS due to along-shelf sheared flow (for the southward flow case, blue dashed curves). The northward along-shelf current case is clearly dominated by the internal bore events, both in $\rho u'w'$ and $\rho v'w'$. Quantitatively, the conditionally averaged profiles for the bore arrivals contain 99% and 95% of the total variance in the $\rho u'w'$ and $\rho v'w'$ profiles, respectively. This is evidence that the bulk of the stress during this northward along-shelf flow period is found during these semiregular daily bore arrival events, but curiously, not during all bore events. It also appears that the “sharpness” of the bores is not clearly related to the presence or absence of stress (e.g., the very sharp bore-like feature seen at around 0600 UTC 16 October has a weaker RS signature than the other three less-sharp bores; Figs. 7c, 7f, 7i). The southward...
along-shelf current case, on the other hand, is not dominated by internal bore arrivals. The main RS signal in this period is right after the peak of southward velocity (Figs. 8f,g,i). The average $r_{uw}$ and $r_{uw}$ profiles for this period depart significantly from the profiles averaged only within the elevated stress period. In particular, the positive $r_{uw}$ maximum at ~15 m above the bottom (Fig. 9b, blue dashed line), is the mean signature of the red patch in $r_{uw}$ and $r_{uw}$ at around 0300 UTC 22 October (Figs. 8f,i), and the conditionally averaged profiles for the elevated southward shear period contain only 61% and 17% of the total variance in the $r_{uw}$ and $r_{uw}$ profiles, respectively.

3) NONLINEAR INTERNAL WAVE TRAINS

While internal bores are one of a host of internal tide-related processes, another typically observed form of internal tidal signal in the mooring records are nonlinear internal wave (NLIW) packets such as the one depicted in Fig. 10. The along-beam velocities have been corrected for the phase differences of the NLIWs across the ADCP beam separation following a simplified form of the Scotti et al. (2005) method. We note that this correction has been performed only for Fig. 10, and therefore the RS results discussed in the rest of the manuscript may have contamination from this ADCP beam phase lag.
effect during NLIW events. The signature of a NLIW train is seen in the cross-shelf velocity $u_x$, the instantaneous low-pass-filtered (cutoff period of 100 s) cross-shelf stress (i.e., the unaveraged $\rho u'_w'$ quantity derived from along-beam velocities) and the instantaneous vertical transport of cross-shelf momentum, i.e., the unaveraged $\rho u'_w w_e'$ product derived from Earth-coordinate velocities, where $w_e$ is the vertical velocity (similar to van Haren et al. 1994). The arrival of the NLIW packet produces a similar banded signal with alternating negative and positive values in both the turbulent stress $\rho u'_w w_e'$ and the advective transport $\rho u'_w w_e'$, but the amplitude of the latter is a factor of $\sim 2$ larger than the former. Importantly, both $\rho u'_w w_e'$ and the covariances independently derived from the low-pass-filtered (cutoff period of 100 s) along-beam velocities are in good agreement. This suggests that there is also a substantial covariance of cross-shelf and vertical velocities at scales larger than the turbulent eddies and the ADCP’s beam separation. We interpret these stresses as due to the orbital velocities of the NLIWs, whose covariance produces a net vertical transport of cross-shelf momentum in a manner analogous to the radiation stresses associated with surface gravity waves (Longuet-Higgins and Stewart 1964). This momentum transport might be part of the manifestation of the radiation stress due to internal wave shoaling and breaking (Hogg 1971; Thorpe 1999; Zikanov and Slinn 2001), in an analogous way to the processes undergone by surface gravity waves as they propagate onshore.

Figure 10e shows that the time integral of the depth-averaged vertical convergence of $\rho u'_w w_e'$ does not cancel out after the passage of the NLIW train, showing a net accumulation of onshore momentum in the water column (the net onshore force is sufficient to accelerate the depth-averaged flow 20 cm s$^{-1}$ in less than an hour, solid green line in Fig. 10e). This momentum deposition is likely balanced by other forces, as an acceleration of such magnitude is not observed (Fig. 10a). This suggests that incoming NLIW trains in the inner shelf might be an important source of momentum in the depth-averaged equations of motion. This is a significant result, since NLIWs have not typically been considered important players in inner-shelf dynamics. In contrast to the putative internal radiation stresses ($\rho u'_w w_e'$), the vertical divergence of the turbulent RS ($\rho u'_w'$) is associated with a much smaller net momentum deposition (dashed lines in Fig. 10e).
Examination of the time-averaged vertical profiles of $r_{ue}$ and $r_{u0w0}$ shows that deposition of cross-shelf momentum by this NLIW train takes place mainly via vertical divergence of the nonturbulent momentum transport (the potential internal radiation stress discussed in the previous paragraph), and not via vertical divergence of the turbulent RS (Fig. 11), consistent with Fig. 10e. The time-mean vertical structure of $r_{ue}$ shows barely significant values of RS in the lower 10 m of the water column and a positive slope in the upper water column, indicating vertical divergence of onshore momentum (or convergence of offshore momentum) and an offshore-directed force. Conversely, the time-mean $r_{ue}$ vertical profile shows a two-layer structure, with an offshore force at depth and an onshore force in the upper water column, with the net depth-averaged force being onshore. The fact that the net cross-shelf acceleration due to this NLIW event is onshore means that the combined effect of NLIW trains and tidal bores (also associated with net onshore acceleration, negative-sloping red lines in Fig. 9a) may lead to a substantial time-averaged deposition of onshore momentum at tidal frequencies. This might have important implications for the cross-shelf momentum balance.

**FIG. 10.** Example of the stress signature of an incoming NLIW train, from a subset of OC25SA’s deployment. (a) Cross-shelf velocity $u_e$. (b) Low-passed (cutoff period of 100 s) instantaneous (unaveraged) cross-shelf stress $\rho u'w'$. (c) Instantaneous vertical transport of cross-shelf momentum $\rho u_e w_e$, derived from Earth-referenced velocities. (d) Instantaneous depth-averaged $\rho u_e w_e$ and its beam-coordinate equivalent $\rho u_b w_b$, derived from low-passed (cutoff period of 100 s) along-beam velocities. (e) Time series of depth-averaged vertical convergence of $u_e w_e$ and its time integral (solid lines) and time series of depth-averaged vertical convergence of the turbulent stress, $u'w'$ (dashed lines), showing a net accumulation of onshore cross-shelf momentum in the water column after the passage of the NLIW train. The magenta contours overlain in (a)–(c) are the 16°C isotherm derived from the adjacent thermistor chain, offset by 2.5 min to account for the distance (∼100 m) between the ADCP and the thermistor chain. The vertical dashed lines indicate the time of arrival of the NLIW train.
in this region (as we will discuss in section 3f), and perhaps also in other shelves with energetic internal tides.

Finally, we note that NLIWs have been observed to cause substantial cross-shelf mass transports (e.g., Shroyer et al. 2010), and that may be related to the advective (i.e., nonturbulent) transport of horizontal momentum. Due to the bottom slope, an onshore depth-averaged mass transport is associated with an upward velocity, and, consequently, with a positive \( u_e w_e \) product. The vertical structure of this product would then lead to a nonzero vertical divergence of \( u_e \) transport, and therefore to a net deposition or removal of onshore momentum in the water column. Other motions, such as internal bores and the time-mean cross-shelf circulation, may similarly be associated with momentum deposition via nonzero vertical gradients of \( u_e w_e \).

4) SUBTIDAL FLOW

At this point, both tidal and supertidal processes have been shown to contribute to RS variability. Similarly, how do subtidal flows influence the RS variability on the inner shelf? The cross-shelf and along-shelf velocities and stresses measured at the 40-m isobath (OC40S, Fig. 12) show significant subtidal variability, consistent with the spectra in Figs. 4f and 5. The subtidal cross-shelf velocity exhibits significant fluctuations with a mode-1 shape, while the along-shelf velocity has a more equivalent-barotropic character. The cross-shelf and along-shelf stresses are comparable in magnitude.

A striking feature of Fig. 12 is the persistence of the cross-shelf stress (\( \rho u'w' \)) structure. Considering our previous finding that the \( \rho u'w' \) profile at tidal/supertidal time scales is mainly shaped by incoming internal bores (Figs. 7f.i and 9a), this may be interpreted as a rectified subtidal signal linked to the semiregular bore arrivals. We will return to this point in section 3f and show that a baroclinic cross-shelf pressure gradient may be able to balance the momentum input from this subtidal vertical divergence of \( \rho u'w' \). In the along-shelf direction, evidence for sustained periods of downgradient momentum flux can be seen in the stress during the northward and southward along-shelf jets around 17–25 October (see discussion in the second paragraph of section 2).

Correlations between the subtidal near-surface (averaged over the top few meters) stresses and the subtidal wind stress components are weakly significant. No mooring presented significant correlations beyond the 72% confidence level. This suggests a physical situation similar to that found by Kirincich and Gawarkiewicz (2016), where a local along-shelf pressure gradient unrelated to the wind stress is found to be an important and perhaps dominant driver of the observed RSs. The near-surface gap jointly caused by the sidelobe contamination cap and the adaptive filtering method’s constraints can partly explain this discrepancy, since the bulk of the stress that can be expected to correlate with the wind stress might have been missed. However, we will also show in section 3f that pressure gradient forces are indeed important in both the cross-shelf and along-shelf directions.

d. Spatial structure of time-averaged Reynolds stresses

Having described the temporal variability of the RSs across different frequency bands and the associated physical processes, we are now in a better position to discuss the time-averaged vertical structure of the RSs and whether any insight on the spatial variability of the RS can be gained from them. We focus on the total conditionally averaged profiles of \( u, v, \rho u'w', \) and \( \rho w'u' \) (qualitatively similar to the subtidally filtered velocities and stresses, not shown) for all five moorings (OC25SA, OC25SB, OC25M, OC40S, and OC40N, Fig. 1) during periods of northward along-shelf flow (\( v \approx 1 \text{ cm s}^{-1} \)) and southward along-shelf flow (\( v \approx -1 \text{ cm s}^{-1} \)). The conditional averages are performed to better isolate the effects of high shears, instead of averaging the entire record of mutually cancelling signals. The mean northward and southward \( v \) profiles have positive and negative vertical shears, respectively, while the \( u \) profiles have a two- and sometimes three-layer structure (Figs. 13a–e,k–o). The cross-shelf velocity is consistently offshore in the bottom 5–10 m, and has an onshore maximum at middepth (both for northward and southward currents), with a third offshore-flowing near-surface layer for the southward-flowing mean at the 40-m moorings (Figs. 13n,o). This cross-shelf velocity profile resembles that observed in the late upwelling relaxation season off the Washington coast as a result of the combination of wind-driven cross-shelf transport, coastally trapped waves and the large-scale along-shelf pressure gradient (McCabe et al. 2015).

Some aspects of the RS vertical structure are relatively consistent across moorings (especially in the cross-shelf direction). Conditionally averaged RS profiles are remarkably persistent in
time at any given mooring, being very similar between periods of northward and southward currents (Figs. 13f–j,p–t). This suggests that the bulk of the RS is not associated with the time-mean along-shelf flow, and that only some events of elevated vertical shear [such as the one in Figs. 8 and 9 (blue lines)] cause an expected RS signature. The cross-shelf RS has a negative slope (except for OC25SB), tends to be more positive near the bottom and more negative near the surface (in agreement with Fig. 12b). The along-shelf RS is more variable across moorings, often being single-signed throughout the water column (with the exception of OC40N, Figs. 13j,t). The differences in the vertical RS profiles across moorings contrast with their persistence in time at individual moorings, which might suggest that the lateral decorrelation scales are smaller than the mooring separations. This vertically sloping structure of the RSs across most moorings clearly indicates a departure from a classical inner-shelf frictional regime (e.g., Lentz and Fewings 2012) at the 25-m isobath and also (unsurprisingly) at the 40-m isobath. Interestingly, there is no consistent evidence for down-gradient momentum flux in the along-shelf direction across all moorings, but rather only at OC25SA, OC25SB, OC40S, and OC40N for northward flow (Figs. 13a,f,b,g,d,e,j) and OC25M for southward flow (Figs. 13m,r). The correlation coefficients between the time series (smoothed with a 1-day-wide running mean) of the depth-averaged magnitude of the Reynolds stress, i.e.,

$$R_{\text{mag}} = \left[ (u'w')^2 + (v'w')^2 \right]^{1/2},$$

between OC25SA and the other four moorings (OC25SB, OC25M, OC40S, and OC40N) range between 0.30 and 0.47, indicating that the elevated Reynolds stress events are moderately spatially coherent between the 25- and 40-m isobaths across different moorings.

e. Reynolds stress uncertainty

Before proceeding with the dynamical analysis of the RSs, we note the main implications of the RS uncertainties for the results in the previous subsections. The minimum significant RS for the subtidal and time-averaged RSs is much smaller than the amplitude of the variability seen in Figs. 12 and 13. For example, for a 30-day average (like most of the profiles in Fig. 13), Eq. (3) gives a minimum detectable RS of 0.004 Pa. For the 30-h low-pass-filtered data (Fig. 12), integrating the noise floor in Fig. 2d up to 30 h gives a noise standard deviation of 0.01 cm s$^{-1}$, which translates into 0.004 Pa through Eq. (3). We note that this assumes that the RS uncertainties are unbiased. This is true when the noise variance in opposing beams is the same (e.g., Stacey et al. 1999), which is the case for all instruments in our dataset (not shown).

f. Reynolds stress variability and the momentum balance

In this section, we seek to put some of the conclusions of the previous subsections into a broader context for inner-shelf dynamics, in terms of the momentum balance. Are the vertical divergences of the RSs potential leading-order forcings? The surface wave-free, depth-averaged, cross-shelf momentum equation can be written as

$$\partial_t \langle u \rangle + \langle \partial_x u^2 \rangle + \langle \partial_y uu \rangle - f \langle v \rangle - \rho_0^{-1} \langle \partial_z p \rangle - \langle \partial_z w'w' \rangle,$$

and the analogous along-shelf momentum equation can be written as

$$\partial_t \langle v \rangle + \langle \partial_y v^2 \rangle + \langle \partial_y vv \rangle + f \langle u \rangle - \rho_0^{-1} \langle \partial_z p \rangle - \langle \partial_z u'w' \rangle.$$
FIG. 13. (a)–(e),(k)–(o) Cross-shelf and along-shelf velocities $u$ and $v$ and (f)–(j),(p)–(t) associated stresses $\bar{\rho}u'w'$ and $\bar{\rho}v'w'$ conditionally averaged over periods of northward flow ($v \geq 1$ cm s$^{-1}$; red) in (a)–(j) and southward flow ($v \leq -1$ cm s$^{-1}$; blue) in (k)–(t). Each row corresponds to one mooring record. The shaded envelopes indicate the 95% confidence intervals (twice the standard errors).
where \( \mathbf{u} = \mathbf{u} + \mathbf{v} + \mathbf{w} \) is the velocity vector, \( f \) is the Coriolis parameter, \( \rho_0 \) is the Boussinesq reference density (1024 kg m\(^{-3}\)), \( p \) is the pressure and \( \langle \cdot \rangle = \int_0^h \langle \cdot \rangle \, dz \) indicates a vertical average, where \( h \) is the water depth. All terms are derived from 10-min ensemble averages (see appendix B for details).

Time series of the terms in Eqs. (5) and (6) estimated for the OC25SA location during the September deployment are plotted in Fig. 14. The vertical divergence of cross-shelf stress \( \partial_z (\mathbf{u} \cdot \mathbf{w}) \) is the same magnitude as the Coriolis term and the baroclinic pressure gradient force (Fig. 14a). The Coriolis term and the baroclinic pressure gradient force balance each other to some degree (correlation coefficient \( r = 0.34 \), significant at the 99% confidence level), consistent with geostrophic balance (only the baroclinic component of the cross-shelf pressure gradient force could be accurately estimated, see appendix B). In the along-shelf direction, the frictional term \( \partial_z (\mathbf{v} \cdot \mathbf{w}) \) is generally weaker than its cross-shelf counterpart (Fig. 14b).

It must be noted that these terms have very low correlations with each other, with the highest correlation being that between \( -fv \) and the cross-shelf pressure gradient, indicating geostrophic balance in the cross-shelf direction. Although this measurement-derived momentum budget does not close, the analysis does suggest that the vertical divergence of the cross-shelf stress is generally higher in the cross-shelf direction [consistent with the larger slope of \( \rho \mathbf{u} \cdot \mathbf{w} \) compared to \( \rho \mathbf{v} \cdot \mathbf{w} \), Figs. 13f-j,p-t (except at OC40S, Figs. 13i,s)] and that the divergence of \( \rho \mathbf{v} \cdot \mathbf{w} \) plays a more second-order role compared to the divergence of \( \rho \mathbf{u} \cdot \mathbf{w} \). At subtidal frequencies, the momentum balance in the along-shelf direction appears to be more complex than in the cross-shelf direction. Although the vertical RS divergences do seem to be order-one terms in the momentum balance (Fig. 14a), we are unable to draw firm conclusions on the mechanisms involved in cross-shelf exchange (for example) from this analysis alone, since it is unclear which term or terms balance the \( f \mathbf{u} \) term, hence driving the cross-shelf circulation. It might be the case that the term that balances the vertical divergences of the Reynolds stresses cannot be captured by the present analysis and other unmeasured gradients of covariances are important, as evidenced by the lack of correlations between \( -\partial_z (\mathbf{u} \cdot \mathbf{w}) \), \( -\partial_z (\mathbf{v} \cdot \mathbf{w}) \) and other terms in Eqs. (5) and (6).

4. Summary and conclusions

In this study, we described the observed variability of Reynolds stresses (RSs) across different frequency bands in a midlatitude inner/midshelf system (25–40-m depth) with an energetic internal wave climate, using acoustic Doppler current profiler (ADCP) measurements of along-beam velocity variances. Emphasis is given to the RS signature of supertidal processes (nonlinear internal waves and internal bores), and subtidal along-shelf jets and the potential importance of some of these physical processes for inner-shelf dynamics through vertical mixing of horizontal (cross-shelf and along-shelf) momentum.

We have presented evidence showing that cross-shelf momentum deposition by internal bores and nonlinear internal wave (NLIW) trains are important in the inner shelf (Figs. 9a}
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and 11). For bores, this deposition seems to be turbulent, occurring via vertical divergence of the cross-shelf RS. On the other hand, NLIWs seem to cause accumulation of cross-shelf momentum via their orbital velocities (Figs. 10 and 11), which we hypothesize to be the expression of radiation stress-like forces linked to the shoaling process of the NLIW trains (Hogg 1971; Thorpe 1999; Zikanov and Slinn 2001). Future observational work could be designed with a focus on better understanding the interplay between the RS divergences and the other order-one terms in the momentum balance in internal wave-rich inner shelves.

In the along-shelf direction, the vertical divergence of momentum transport is also chiefly associated with turbulent bores (Fig. 9b) and NLIW trains (not shown), but is modified (likely by shear instabilities) by along-shelf subtidal flows (Figs. 8i and 9b). Bores account for more than 95% of the vertical structure of the $\overline{\mu'w'}$ and $\overline{w'w'}$ profiles in a 4-day period (Fig. 9). These RS features project onto the total time-averaged RS profiles (Fig. 13), which also show some lateral coherence of the RS across the mooring array, specifically with respect to the existence of a vertical slope in the $\overline{w'w'}$ profiles. There is evidence for downgradient flow of momentum (e.g., Figs. 12c,d and 13a,f,g,d,i,e,j,m,r), but in some cases the signs of the shear and RS suggest upgradient momentum flux (e.g., Fig. 13). We hypothesize that part of this upgradient momentum flux is due to the inherently complex nature of the turbulence carried by the internal bores, which may not conform to a simple flux–gradient relationship typically employed in the Reynolds-averaged formalism.

An estimate of the momentum balance terms in the cross-shelf direction [Eq. (5), Fig. 14] reveals a persistent vertical convergence of onshore momentum, which we interpret as the rectification of the turbulent deposition mostly caused by internal bore arrivals. This imparts a leading-order onshore force to the water column, which coexists with the vertical divergence of nonturbulent vertical transport of cross-shelf momentum (either by NLIWs or by the mean cross-shelf circulation) and geostrophic balance. In the along-shelf direction [Eq. (6)], turbulent deposition of along-shelf momentum is a comparatively smaller term, and often changes sign with the along-shelf flow, likely modulated by elevated along-shelf shear events such as that seen in Figs. 8g–i. However, this relationship is not sufficiently persistent in time to project onto the experiment-averaged vertical profiles of along-shelf velocity and RS (Fig. 13).

In both the across-shelf and along-shelf directions, the emerging picture implies a novel (to our knowledge) paradigm where internal waves can be leading-order drivers of inner-shelf circulation, in addition to their known roles in mixing of scalar properties and energy dissipation. Most inner-shelf studies to date have focused on wind-driven and surface gravity wave–driven subtidal dynamics (e.g., Mitchum and Clarke 1986; Lentz 1995; Lentz et al. 1999, 2008; Austin and Lentz 2002; Pringle and Riser 2003; Fewings et al. 2008, 2015; Lentz and Fewings 2012; Kirincich 2013; Horwitz and Lentz 2014, 2016; Kirincich and Gawarkiewicz 2016). While some of our conclusions involve subtidal processes, we believe that the most important implications of our study are that the system we examine may represent a different class of inner shelf, where the dynamics departs from a canonical wind-driven frictional regime (e.g., Lentz and Fewings 2012). To summarize, the main specific conclusions of this study are as follows:

- Several inner-shelf physical processes, namely, internal bores, nonlinear internal wave trains, and subtidal along-shelf wind-driven currents, all have measurable turbulent Reynolds stress signatures.
- Internal bores and high-frequency nonlinear internal waves induce a substantial vertical divergence of vertical transport (either turbulent or advective) of cross-shelf and along-shelf momentum, hence being potentially important players in inner-shelf dynamics.
- During the experimental period, the conditionally averaged Reynolds stresses displayed significant vertical divergence in both the cross-shelf and along-shelf directions, indicating a clear departure from a purely frictional regime where the wind stress balances the bottom stress directly.
- The vertical divergences of the cross-shelf and along-shelf Reynolds stresses are leading-order terms in the momentum balance.

We also highlight the limitations of our analyses. As discussed in section 3e, the fact that the top few meters of the water column are not observed due to a combination of limitations of the adaptive filtering method (two vertically separated bins are needed) and the range cap applied to eliminate sidelobe contamination can be a source of bias. Additionally, being based on point measurements, lateral gradients such as the horizontal advection terms in the momentum equations only represent gradients at the scale of the mooring separation. Finally, the low correlations in the momentum balance analysis leave a knowledge gap regarding what force or forces might balance the vertical divergence of the Reynolds stresses, which may be a good avenue for further research.

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Data availability statement. Codes and reduced datasets required to reproduce the results are available at https://github.com/apaloczy/InnerShelfReynoldsStresses, archived under https://doi.org/10.5281/zenodo.4601716. The full inner-shelf dataset with the raw mooring data required to derive the reduced datasets is archived under https://doi.org/10.6075/J0WD3Z3Q.
APPENDIX A

Instrument Noise Biases in Five-Beam Reynolds Stress Estimates

The five-beam expressions for $\bar{\nu}'\bar{\nu}'$ and $\bar{\nu}'\bar{\nu}'$ with full tilt corrections [Eqs. (1) and (2)] show that the terms proportional to the tilts are time-averaged covariances between tilts and along-beam velocity variances. The measured beam-coordinate variances $\tilde{B}_i^2$ are related to the true variances $\bar{B}_i^2$ by (Stacey et al. 1999)

$$\tilde{B}_i^2 = \bar{B}_i^2 + \text{var}(N_j),$$

(A1)

where $N_j$ is the instrument velocity noise (single-ping standard deviation), assumed to be the same for the Janus beams ($N_j$) but different for the vertical beam ($N_y$). For each instrument, $N_j$ is set to the average of the noise levels of the four Janus beams. The measured pitch ($\phi_y$) and roll ($\phi_i$) angles are related to the true pitch ($\Phi_y$) and true roll ($\Phi_i$) angles by

$$\Phi_{y,3} = \Phi_{y,3} + N_y.$$

(A2)

Using Eqs. (A1) and (A2) in Eq. (1) and assuming that the signals are uncorrelated with the noises gives

$$\bar{\nu}'\bar{\nu}' = -\frac{1}{4S^iC^i} \left[ S_i^i C_i^i (\bar{B}_i^2 - \tilde{B}_i^2) + 2S_i^i C_i^i \Phi_i^i (\bar{B}_i^2 + \tilde{B}_i^2) \right.$$

$$
- 4S_i^i C_i^i \Phi_i^i \bar{B}_i^2 - 4S_i^i C_i^i \bar{\nu}' \bar{\nu}' \right] \ldots + \frac{\Phi_i}{S_i} \left[ \text{var}(N_j) - \text{var}(N_i) \right].$$

(A5)

which simplifies to

$$\bar{\nu}'\bar{\nu}' = -\frac{1}{4S^iC^i} \left[ S_i^i C_i^i (\bar{B}_i^2 - \tilde{B}_i^2) + 2S_i^i C_i^i \Phi_i^i (\bar{B}_i^2 + \tilde{B}_i^2) \right.$$

$$
- 4S_i^i C_i^i \Phi_i^i \bar{B}_i^2 - 4S_i^i C_i^i \bar{\nu}' \bar{\nu}' \right] \ldots + \frac{\Phi_i}{S_i} \left[ \text{var}(N_j) - \text{var}(N_i) \right].$$

(A6)

Analogously, using Eqs. (A1) and (A2) in Eq. (2) gives

$$\bar{\nu}'\bar{\nu}' = -\frac{1}{4S^iC^i} \left[ S_i^i C_i^i (\bar{B}_i^2 - \tilde{B}_i^2) - 2S_i^i C_i^i \Phi_i^i (\bar{B}_i^2 + \tilde{B}_i^2) \right.$$

$$
+ 4S_i^i C_i^i \Phi_i^i \bar{B}_i^2 + 4S_i^i C_i^i \bar{\nu}' \bar{\nu}' \right] \ldots + \frac{\Phi_i}{S_i} \left[ \text{var}(N_j) - C^i \text{var}(N_i) \right]$$

(A7)

which simplifies to

$$\bar{\nu}'\bar{\nu}' = -\frac{1}{4S^iC^i} \left[ S_i^i C_i^i (\bar{B}_i^2 - \tilde{B}_i^2) - 2S_i^i C_i^i \Phi_i^i (\bar{B}_i^2 + \tilde{B}_i^2) \right.$$

$$
+ 4S_i^i C_i^i \Phi_i^i \bar{B}_i^2 + 4S_i^i C_i^i \bar{\nu}' \bar{\nu}' \right] \ldots + \frac{\Phi_i}{S_i} \left[ \text{var}(N_j) - C^i \text{var}(N_i) \right] - \bar{\nu}' \bar{\nu}' \text{var}(N_i).$$

(A8)

Equations (A5) and (A8) show that the biases [last two terms on the right-hand side of (A5) and last three terms on the right-hand side of (A8)] are proportional to the pitch and roll angles averaged within each ensemble, and are therefore time dependent.

APPENDIX B

Estimation of the Momentum Balance Terms

The linear terms (except for the vertical stress divergence) in Eqs. (5) and (6) are estimated for mooring OC25SA (Fig. 1) following Lentz et al. (1999). The depth-averaged pressure gradient force is estimated with the density $\rho$ derived from the adjacent thermistor chains, and using an expression obtained from vertically integrating the hydrostatic equation, taking its lateral derivative and depth-averaging the result. In the cross-shelf direction, the depth-averaged pressure gradient force is

$$-\frac{\partial (\rho g)}{\partial z} = -\frac{\partial \rho g}{\partial z} \int_{-h(s)}^{0} \rho dz' - \rho g \int_{-h(s)}^{0} \frac{\partial}{\partial z'} \rho dz'$$

$$-\frac{\rho g}{h(s)} \frac{\partial}{\partial z'} \rho dz',$$

(B1)

where $g = 9.81 \text{ m s}^{-2}$ is gravity, $\rho = \rho_0[1 + \alpha(T - T_0)]$, $T_0 = 21^\circ\text{C}$ is the reference temperature, $\alpha = 2.65 \times 10^{-4} \text{K}^{-1}$ is the thermal expansion coefficient and $T$ is the temperature measured by the thermistors. The barotropic part of the pressure
gradient force [first term on the right-hand side of Eq. (B1)] is not estimated due to the fact that the near-bottom pressure $p_b$ measured by the ADCPs is not sufficiently accurate.

The vertical advection term is estimated using the vertical velocity measured by the ADCP’s vertical beam. Gradients in the cross-shelf ($\delta$) direction are calculated as finite differences between OC2SSA and OC40S (Fig. 1).

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