Heating of the Midshelf and Inner Shelf by Warm Internal Tidal Bores

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ABSTRACT

Cross-shore heat flux (CHF) spatiotemporal variability in the subtidal (ST), diurnal (DU), and semidiurnal (SD) bands is described for 35 days (summer 2015) from collocated vertical measures of temperature and currents obtained by moorings deployed from 50- to 7-m water depths near Pt. Sal, California. The CHF is largest in the ST and SD bands, with nearly zero contribution in the DU band. The sum of CHF and surface heat flux (SHF) account for 31% and 17% of the total change in heat storage on the midshelf and inner shelf, respectively. The ST CHF for the midshelf and inner shelf is mostly negative and is correlated with upwelling-favorable winds. A mostly positive SD CHF on the midshelf and inner shelf decreases linearly in the shoreward direction, is correlated with wind relaxations, and is attributed to warm-water internal tidal bores (WITBs) that are observed to propagate to the edge of the surf zone. A negative SD CHF is correlated with upwelling-favorable winds on the midshelf at 15–25-h time lags, and is believed to be associated with cold-water internal tidal bores. The WITBs have characteristics of progressive waves on the midshelf and transition to partially standing waves on the inner shelf potentially reducing the SD CHF contribution on the inner shelf. Heat accumulation over the midshelf and inner shelf is primarily driven by WITBs and SHF, which is largely balanced by cumulative cooling by ST processes over the midshelf and cumulative cooling by alongshore heat flux (AHF) over the inner shelf.

1. Introduction

The importance of onshore transport caused by shoaling internal tidal bores (ITBs) over the continental shelf is well documented (Pineda 1994, 1999; Lamb 2002, 2003; Lamb 2014; Woodson 2018; among others). Internal tidal waves are generated by the interaction of stratified tidal flow with the continental shelf break and propagate onshore as an internal wave of depression (e.g., Lamb 1994). These internal waves of depression shoal, become more bore-like than wave-like, and can evolve into ITBs. ITBs can reverse polarity and transition into waves of elevation when the thickness

of the bottom and top layers of two-layer stratification becomes equal (Shroyer et al. 2009; Lamb 2014). ITBs, in the form of internal waves of depression, typically arrive as a sharp warm front that extends downward from the surface mixed layer (Pineda 1999; Helfrich and Melville 2006; Colosi et al. 2018) and are herein referred to as warm-water internal tidal bores (WITBs). ITBs, in the form of internal waves of elevation, typically arrive as a sharp cold front that extends upward into the surface mixed layer (Walter et al. 2012; Woodson 2018; Colosi et al. 2018; Sinnett et al. 2018) and are herein referred to as cold-water internal tidal bores (CITBs).

Recent work has highlighted the onshore transport of cold nutrient rich water owing to shoaling CITBs over the inner shelf (e.g., Nam and Send 2011; Walter et al. 2012; Smith et al. 2016; Sinnett et al. 2018; Woodson 2018) and into the surf zone (Sinnett et al. 2018). Cross-shore transport by shoaling inner shelf WITBs has been

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demonstrated in numerical simulations (Lamb 2002, 2003) and has also been found to be important in observational studies of salinity, heat, and nitrate fluxes (Lucas et al. 2011), and near-surface larvae (Pineda 1994, 1999). WITBs have been observed in water depths greater than 100 m (e.g., Holloway 1987; Colosi et al. 2001; Helfrich and Melville 2006) although they are less commonly observed in water depths less than 40 m (Lucas et al. 2011; Pritchard and Weller 2005; Pineda 1999; Colosi et al. 2018), which could be attributed to polarity reversals of shoaling WITBs into CITBs. Recently, Colosi et al. (2018) reported on WITB evolution, dissipation, and statistics for water depths of 50–20 m during the Point Sal Inner Shelf Experiment (PSIEX). However, unlike the case of CITBs (Sinnott et al. 2018) the evolution, fate, and impact of observed WITBs connecting the inner shelf to the edge of the surf zone is poorly understood.

A primary objective of this work is to quantify the cross-shore transport of warm water by WITBs as they traverse the midshelf and inner shelf (section 2c). An effective method for quantifying cross-shore exchange is through the computation of heat fluxes determined from collocated vertical profiles of temperature and current velocity (section 3b). Here, the spatiotemporal variability of the cross-shore heat flux (CHF) is separated into the subtidal (ST; $f < 33^{-1}$ cph), diurnal (DU; $33^{-1} < f < 16^{-1}$ cph), and semidiurnal and higher (SD; $16^{-1} < f < 1$ cph) frequency bands for 50–7-m water depths (section 4a). The CHF in the SD band is presumed to be associated with ITBs. Note that the SD frequency band is extended to a higher-frequency limit than traditionally associated with SD (e.g., $16^{-1} < f < 10^{-1}$ cph) in order to incorporate all resolvable frequencies associated with ITBs. A heat budget (section 4b) and accumulation of heat (section 4d) is estimated over the midshelf and inner shelf to determine the relative importance of heating by the CHF in their frequency bands, the surface heat flux, and residual heating/cooling by the alongshore heat flux. The influence of wind forcing on CHF is quantified through cross-correlation analyses (section 4c). The ITBs are determined to be progressive, standing, or partially standing from cross-spectral analysis on temperature and cross-shore velocity (section 5).

2. Experiment and observations

a. Experiment

Vertical profiles of temperature and velocity were obtained within the 50–7-m water depths directly offshore of Pt. Sal, California, from a 6-km cross-shore array consisting of six collocated thermistor-strings (T-strings) and ADCPs from 10 June to 22 July 2015 (Fig. 1) as part of the Pt. Sal Inner Shelf Experiment

FIG. 1. (a) Map of the experiment site where black triangles indicate collocated T-strings and ADCPs. (b) Instrument layout in the cross-shore array, where black dots indicate thermistors, black triangles indicate ADCPs, and vertical dashed line demarks the boundary between the mean midshelf and inner shelf. Mooring names are labeled along the top of (b).

(PSIEX). The field site is marked by three prominent features: 1) the Pt. Sal headland, 2) a smaller headland, Mussel Pt., and 3) a submerged rocky outcrop that shoals to a water depth of 16 m, ~2 km from the coastline. The moorings are labeled from nearshore (X02) to offshore (X12). Hereafter, the moorings in the text will include water depth in parentheses [e.g., mooring X06(15) is in 15-m water depth]. The ADCPs at X02(7) and X06(15) are Nortek 2-MHz Aquadopps, and the ADCP at X08(20) is Nortek 1-MHz Aquadopp. The ADCPs sampled at 2 Hz and measured velocities with a vertical resolution of either 0.5 m or 1 m. The thermistors at X02(7), X06(15), and X08(20) are RBR soloTs that sampled at 1 Hz. The mean vertical spacing of thermistors for X02(7), X06(15), and X08(20) is 1.0, 1.7, and 2.6 m, respectively. Velocities obtained one bin below surface wave troughs and above are removed due to significant wave height biases, which are calculated from collocated pressure measurements using linear wave theory (Dean and Dalrymple 1991). ADCPs at

FIG. 2. (a) Wind stress in the cross-shore τ_{sx} (red line) and alongshore τ_{sy} (blue line) at NDBC buoy 46011. Positive values indicate northward and eastward directions. (b) Example of hourly averaged temperature over the vertical plotted against time at X08(20). (c) Example of baroclinic cross-shore currents u' at X08(20). The trends in the temperature and current are similar across the X array from $h = 7$ to 50 m.

X10(30), X11(40), and X12(50) are 300-kHz RDI systems that sampled at 12 pings min^{-1} and obtained velocities at 2-m vertical resolution. For these ADCPs, the top 8 m from the surface are removed from the velocity profile owing to side-lobe contamination. The thermistors at X10(30), X11(40), and X12(50) are Sea Bird Electronics SBE9 instruments that sampled every 30 s. The mean vertical spacing of thermistors for X10(30), X11(40), and X12(50) is 5.0, 7.5, and 10.0 m, respectively. All thermistor and velocity data were averaged over 2.5-min intervals. A local coordinate system was defined at each ADCP mooring based on the principal axis direction of the hourly-averaged velocity. The principal axes were typically aligned with the local topography where positive x and y is defined as onshore and poleward, respectively. The cross-shore currents u , alongshore currents v , and temperature T are decomposed into depth-averaged and baroclinic quantities [e.g., $u'(z, t) = u(z, t) - \bar{u}(t)$, where $u'(z, t)$ is the baroclinic cross-shore velocity and $\bar{u}(t)$ is the depth-averaged cross-shore velocity].

Hourly wind speeds at 5 m above sea level were obtained from the National Data Buoy Center (NDBC) station 46011 located approximately 30 km offshore of Pt. Sal. After applying a log-layer correction factor to adjust the wind speed to 10 m above sea level, wind stress is computed using $\tau_s = \rho C_d w^2$, where ρ is the density of air, w is the wind speed at 10 m, and $C_d = 1.15 \times 10^{-3}$ for $w \leq 11 \text{ m s}^{-1}$ ($C_d = 4.9 \times 10^{-4} + w 6.5 \times 10^{-5}$ for $w > 11 \text{ m s}^{-1}$ (Large and Pond 1981).

The wind stress is subsequently decomposed into an east–west (τ_{sx}) component considered the cross-shore wind stress and north–south (τ_{sy}) component considered the alongshore wind stress.

b. Overview of observations

The general wind regime patterns in the vicinity of Pt. Sal during summertime conditions exhibit persistent upwelling-favorable winds from the northwest that are interrupted by periods of wind relaxations that occur every 10–14 days and last 2–5 days (Fewings et al. 2015; Melton et al. 2009). Consistent with these findings, τ_s during PSIEX exhibited upwelling-favorable and relaxation wind regimes (Fig. 2a). The first 9 days (year-days 167–176) are dominated by upwelling-favorable winds that are interrupted by brief periods of relaxed winds lasting 1 day or less. The remaining 26 days exhibit persistent relaxed winds that are interrupted by upwelling-favorable wind pulses on year-days 180, 188, and 194–196.

Observations from X08(20) are shown as an example of the temperature and current trends during PSIEX (Figs. 2b,c). At this location temperature ranged from 10° to 18°C . Periods of relatively cold water occur on year-days 171–176, 180–184, and 195–196 (Fig. 2b) and tend to occur during times of increased alongshore wind stress (blue line in Fig. 2a). Temperature fluctuations occurred at DU (e.g., year-days 167–170) and SD (e.g., year-days 185–199) time scales. There is a near-surface heating trend that occurs between year-days 185–195 in

FIG. 3. Temperature plotted as a function of time and elevation for two example WITBs propagating (a)–(f) from X12(50) to X02(7) from yearday 192–193.3. (h)–(m) Baroclinic, cross-shore currents u' for the same bores as in (a)–(f). The black arrows illustrate the onshore propagation of the first WITB.

the upper 5 m of the water column that is concomitant with the SD variability (Fig. 2b). Baroclinic cross-shore velocities exhibit a two-layer, mode-1 like structure throughout PSIEX with velocities as large as 0.25 m s^{-1} directed onshore and offshore (Fig. 2c). Consistent with periods of SD temperature variability (yeardays 185–195), $u'(z, t)$ cross-shore velocities also exhibit semidiurnal variability.

c. Warm-water internal tidal bore observations

The evolution of two shoaling WITBs are demonstrated with observations of T and u' variability over the vertical in Fig. 3. The two WITBs exemplify the 17 WITBs observed during PSIEX. The WITBs are identified by the arrival of sharp increases in T and u' . Averaged over all WITBs, the sharp increases in T averaged $1.88^\circ \pm 0.77^\circ\text{C}$, and the WITBs arrived every $12.5 \pm 3.14 \text{ h}$ (where $\pm$ represents the standard deviation). These sharp increases in onshore near-surface u' are as large as 0.13 m s^{-1} and are compensated by offshore directed near-bottom currents. The arrival times of the rapid changes in T and u' at each of the moorings is tracked to determine the onshore propagation speeds, which are estimated to range between $8.6 \pm 1.3 \text{ cm s}^{-1}$ at X08(20) and $6 \pm 2 \text{ cm s}^{-1}$ at X02(7). At water depth $h = 50 \text{ m}$, the WITB amplitude is as large as $\sim 30 \text{ m}$ (Fig. 3a). As the WITBs propagate into shallower water, they eventually occupy the entire water column and u' associated with the WITBs become weaker

and less defined. Although CITBs are occasionally observed, the majority of the waves are WITBs as documented by Colosi et al. (2018).

The normalized depth of maximum vertical temperature gradients at each mooring is estimated from neighboring instruments over the vertical. Subsequently, a probability of occurrence of maximum vertical temperature gradients is plotted as a function of normalized depth (Fig. 4). At all mooring locations, approximately 70% of the identified maxima occurred in the upper half of the water column. The vertical temperature gradients, which are representative of the background stratification in this region (Colosi et al. 2018), are favorable for sustaining internal waves of depression since they occur in the upper half of the water column (Shroyer et al. 2009; Lamb 2014).

3. Methods

a. Inner shelf width

The inner shelf is identified when the combined thickness of the surface δ_s and bottom δ_b boundary layers are greater than the water depth h . The thickness of the bottom boundary is computed as

$$\delta_b = \sqrt{\frac{\tau_b}{\rho_0}} \frac{1.3}{f_i \left(1 + \frac{N^2}{f_i^2}\right)^{1/4}}, \quad (1)$$

FIG. 4. The normalized depth of maximum vertical temperature gradients as a function of probability at moorings (a)–(f) from X12(50) to X02(7). Middepth is indicated by the horizontal black dashed line.

where $\tau_b = \rho_0 \varepsilon u_{da}$ and $\varepsilon = 5 \times 10^{-4} \text{ m s}^{-1}$ is a linear bottom friction coefficient (e.g., [Lentz and Winant 1986](#); [Fewings and Lentz 2010](#)), u_{da} is the depth-averaged velocity, $\rho_0 = 1025 \text{ kg m}^{-3}$ is the density of seawater, $f_i = 21^{-1} \text{ cph}$ is the local inertial frequency for a latitude of 34.9°N , and $N = [-\alpha_T g (\Delta T / \Delta z)]^{1/2}$ is the buoyancy frequency (s^{-1}), where $\alpha_T = 2.6 \times 10^{-4} \text{ }^\circ\text{C}^{-1}$ is the coefficient of thermal expansion, g is the acceleration due to gravity, and ΔT is the difference in ST temperature over the distance Δz between the top and bottom thermistor at each array. Density fluctuations are assumed to be a result of temperature fluctuations ([Weatherly and Martin 1978](#); [Fewings et al. 2015](#)) based on CTD casts obtained during PSIEX ([Colosi et al. 2018](#)). Similarly, δ_s is computed by replacing τ_b with τ_s in (1). The 2.5-min sampled boundary layer thicknesses are ST filtered, and if $h < \delta_s + \delta_b$ then the circulation at the mooring is considered governed by inner shelf dynamics ([Fewings et al. 2008, 2015](#)). From the above computations the mean inner shelf width is estimated as 1.85 km during PSIEX.

b. Cross-shore heat flux computations

For the CHF computations, the velocity profiles were hourly-averaged and depth-normalized to account for 2-m surface tidal modulation ([Hendrickson and MacMahan 2009](#); [Suanda et al. 2011](#)). The normalized depth scale was set to $z/h = -1.0$ at the seabed to $z/h = 0$ at the sea surface with 0.05 vertical increments, where z is the elevation relative to mean sea level. To extend the profile throughout the full water column, the near-surface velocity is extended equally to the sea surface. At depth, the bottom ADCP velocity is linearly interpolated such that the velocity is zero at the sea floor, representative of a no-slip bottom boundary condition ([Suanda et al. 2011](#)).

The net air–sea heat flux Q_0 is estimated as a linear sum of the incident shortwave solar radiation Q_{sw} , sensible Q_{sen} , and latent heat Q_{Lv} , and longwave radiation Q_{lw} . Data for Q_0 , including incident Q_{sw} , were obtained approximately 30 km north of Pt. Sal at Port San Luis

and Morro Bay, California (data are available at <https://www.cencoos.org/data/access>; [Walter et al. 2017](#)). The fluxes Q_{sen} and Q_{Lv} are estimated from bulk flux algorithms ([Fairall et al. 2003](#)), and Q_{lw} is estimated according to [Dickey et al. \(1994\)](#) and [Connolly and Lentz \(2014\)](#).

A heat equation for a two-dimensional cross-shore slice that extends from the coast ($x = 0$) to offshore ($x = -L$), is bounded by the sea surface ($z = 0$) and sea floor ($z = -h$), and assumes zero cross-shore flux at $x = 0$ has been derived in previous studies (e.g., [Dever and Lentz 1994](#); [Austin 1999](#); [Suanda et al. 2011](#)). The equation can be written as

$$\begin{aligned} \rho_0 c_p \int_{-L}^0 dx \int_{-h}^0 \frac{\partial T}{\partial t} dz &= \rho_0 c_p \int_{-h}^0 uT \Big|_{x=-L} dz \\ &- \rho_0 c_p \int_{-L}^0 dx \int_{-h}^0 \left(T \frac{\partial v}{\partial y} + v \frac{\partial T}{\partial y} \right) dz + \int_{-L}^0 Q_0 dx, \end{aligned} \quad (2)$$

where the terms, from left to right, are the time rate of change of heat storage (HS), CHF, alongshore heat flux (AHF), and surface heat flux (SHF). Here, $c_p = 3850 \text{ J kg}^{-1} \text{ }^\circ\text{C}^{-1}$ is the specific heat of seawater. Following [Dever and Lentz \(1994\)](#), u , v , and T are decomposed into depth averaged and baroclinic quantities as described above in [section 2a](#). The AHF cannot be resolved in this study because the alongshore gradients in T and v are not known inshore of the 30-m water depth. The inability to resolve the AHF is not critical in this study as it does not detract from the primary goal of quantifying the CHF and determining the relative contribution to heating by the CHF in each frequency band. After applying the continuity equation, the heat balance used herein becomes

$$\rho_0 c_p \int_{-L}^0 dx \int_{-h}^0 \frac{\partial T}{\partial t} dz = \rho_0 c_p \int_{-h}^0 u'T' \Big|_{x=-L} dz + Q_0 L + \text{AHF}, \quad (3)$$

which represents $HS = CHF + SHF + AHF$. HS is estimated with trapezoidal integration where each T observation is weighted by the area defined as half the distance to an adjacent instrument or the sea surface, sea bed, or offshore boundary at $x = -L$ (Dever and Lentz 1994; Austin 1999; Suanda et al. 2011). A mean heat budget over the duration of the experiment is constructed using the area integrated HS, CHF, and SHF. The fractional contribution of CHF and SHF to HS are subsequently decomposed into the ST, DU, and SD frequency bands.

The depth-integrated CHF in each frequency band (f) is computed as

$$CHF^f(t) = \rho_0 c_p \int_{z/h=-1}^0 u'_f\left(\frac{z}{h}, t\right) T'_f\left(\frac{z}{h}, t\right) h(x) d(z/h), \quad (4)$$

where u'_f and T'_f represent the ST, DU, and SD filtered u' and T' , and $h(x)$ is the water depth at each mooring. The SD band includes observed ITBs that infrequently occur at higher frequencies and energy occurring at SD harmonics owing to the nonlinearity of the ITBs. Although internal solitary waves (ISWs) associated with the ITBs were found to occur at $f > 1$ cph at the deeper moorings during PSIEX (Colosi et al. 2018), the CHF analysis does not incorporate these higher frequencies owing to possible corruption by infragravity waves over the inner shelf that occur at these similar frequencies (e.g., Herbers et al. 1995). The decorrelation time scale of the CHF is determined from the first zero-crossing of the autocorrelation function of the hourly-averaged, depth-integrated $u'T'$. The decorrelation time at X12(50) and X08(20) is ~ 60 h. A moving average on CHF^{SD} , CHF^{DU} , and CHF^{ST} using a 60-h window allows for direct comparison of CHF across frequency bands, and their respective contribution to the total flux for longer (>60 h) time scales. Herein, all analyses use the 60-h averaged CHF, total cross-shore heat flux $CHF^{TOT} = CHF^{ST} + CHF^{DU} + CHF^{SD}$, HS, and SHF. The match filter method implemented by Colosi et al. (2018) to obtain IW statistics for determining energy flux and dissipation is difficult to apply to the shallower water observations as the clarity of the IW structure diminishes (e.g., Fig. 3). By using CHF, this difficulty is avoided and provides a standard technique for estimating fluxes at all water depths.

The time-varying accumulation of heat H is computed by cumulatively summing integrations of the CHF including SHF in each band to get H^{ST} , H^{DU} , H^{SD} , H^{SHF} , H^{AHF} , and H^{HS} . For example, the accumulation of heat by CHF^{ST} at a relative time t' , representing the start of the experiment, is computed as

$$H^{ST}(t) = \int_0^t CHF^{ST}(t') dt'. \quad (5)$$

c. Vertical baroclinic structure of DU and SD temperature and cross-shore velocity

Following Kumar et al. (2016), vertical empirical orthogonal function (EOF) analyses are performed on the DU and SD band u' and T' at each mooring to determine their respective vertical modal structures. Vertical EOF analysis decomposes the variability of value $F(z, t)$ into vertical $\phi_n(z)$ and temporal $A_n(t)$ modes such that

$$F(z, t) = \sum_{n=1}^K A_n(t) \phi_n(z), \quad (6)$$

where F represents u' or T' , K is the number measurements in the vertical, and n is the mode. Here we take $n = 1$ as the mode describing the most variance. The modal $u_n'^{SD}$ can be reconstructed as

$$u_n'^{SD}(z, t) = A_n'^{SD}(t) \phi_n'^{SD}(z) \quad (7)$$

and $T_n'^{SD}$ can be reconstructed in the same manner, and similarly for the DU band. The reconstructed $u_1'^{SD}$ and $T_1'^{SD}$ represent the mode-1 baroclinic response associated with the ITBs.

4. Results

a. Observations of cross-shore heat flux

The spatiotemporal variability for the midshelf and inner shelf CHF estimates along the cross-shore array is discussed next for the ST, DU, and SD frequency bands, as well as the total. The total cross-shore heat flux CHF^{TOT} exhibits periods of positive and negative values ranging between -0.9×10^7 and $0.5 \times 10^7 \text{ W m}^{-1}$ at ST time scales (Fig. 5a). CHF^{TOT} is generally a maximum at the offshore extent of the array and decreases shoreward in shallower water. The dashed black line in Figs. 5a–d demarks the mean offshore extent for the inner shelf. Note that inner shelf boundary is nearly collocated with the rocky outcrop (Fig. 1), demarked by a black line in Figs. 5a–d. Both warm and cool CHF^{TOT} episodically occur across the inner shelf boundary. Though CHF^{TOT} tends to decrease near the inner shelf boundary, it also extends farther shoreward when the CHF^{TOT} is positive. Since CHF^{TOT} represents a number of different processes, CHF is explored within the ST, DU and SD bands (Figs. 5b–d). The magnitude, temporal and spatial pattern of CHF^{ST} (Fig. 5b) is similar to the CHF^{TOT} (Fig. 5a), but it is important to note that CHF^{ST} supports both positive and negative contributions. For CHF^{DU} (Fig. 5c), the magnitude is

FIG. 5. (a) Total cross-shore heat flux (CHF^{TOT}), and cross-shore heat flux in the (b) ST band (CHF^{ST}), (c) DU band (CHF^{DU}), and (d) SD band (CHF^{SD}) plotted against time from the coast to $h = 50$ m. The spring–neap cycle is identified by the symbols S and N as identified by Colosi et al. (2018). The horizontal dashed black line indicates the mean inner shelf width, and the solid black line indicates the cross-shore location of the rocky outcrop.

nearly zero except for a few isolated events, and even these events are weaker than those estimated in the ST and SD bands (Fig. 5b and d). CHF^{DU} can be therefore neglected hereafter. CHF^{SD} is primarily positive, with some weaker negative occurrences, and ranges between -0.1×10^7 and $0.2 \times 10^7 \text{ W m}^{-1}$ (Fig. 5d). CHF^{SD} is also largest at the offshore, decreases shoreward, and extends across the inner shelf boundary during two main periods, year day 182–184 and 190–194. These periods are generally coincident with times of low τ_s (Fig. 2a), and are not coincident with a neap or spring tide (Fig. 5d). Previous studies found that the CHF^{SD} was attributed to ITBs (e.g., Boehm et al. 2002; Lucas et al. 2011; Kumar et al. 2016). Here, the ubiquitous WITBs observed during PSIEX (Fig. 2) are also presumably responsible for the prevalence of positive CHF^{SD} off of Pt. Sal.

b. Heat budget

The relative contribution of $\text{CHF}^{\text{TOT}} + \text{SHF}$ is determined as the slope of linear regression between the bin-averaged HS and bin-averaged $\text{CHF}^{\text{TOT}} + \text{SHF}$

(Fig. 6). This analysis is performed for two control volumes: one from the 50-m isobath to the coast to represent the combined mid and inner shelf, and one from the 20-m isobath to represent the inner shelf only. Bin widths for the 50- and 20-m control volumes are 1×10^6 and $0.15 \times 10^6 \text{ W m}^{-1}$, respectively, ensuring a minimum of 10 estimates per bin. The blue line in each subplot, which has a slope of 1 and y-intercept of 0, represents the entire heat budget as HS versus $\text{CHF} + \text{SHF} + \text{AHF}$ [Eq. (2)]. Regression slopes for the 50- and 20-m control volumes are 0.31 ($r^2 = 0.71$) and 0.19 ($r^2 = 0.86$) (Fig. 6), which indicate respective $\text{CHF}^{\text{TOT}} + \text{SHF}$ contributions of 31% and 19% to HS. The removal of SHF in the regression analysis resulted in slope decreases of 0.27 and 0.13 (not shown), implying that that SHF contributes 4% and 6% to HS. AHF accounts for the remainder of the contributions of the HS over the mid-shelf and inner shelf.

c. Correlation of cross-shore heat flux and wind stress

The cross (auto)-correlation function r as function of time lag ξ is defined as

FIG. 6. Heat budget, as represented by a linear regression analysis of HS vs $\text{CHF}^{\text{TOT}} + \text{SHF}$, for control volumes extending from the (a) 50-m isobath to the coast and from the (b) 20-m isobath to the coast. Black dots represent the binned-mean HS, and the gray dots are the unbinned data. Black vertical bars represent the 95% confidence interval and are smaller than the black dots at times. The dashed, black line is the linear fit to the data, and the solid blue line is the 1-to-1 line for reference. Slope of the linear fit is represented by m , and the coefficient of determination is represented by r^2 .

$$r(\xi) = \frac{\mathbb{E}[X(t)Y(t + \xi)]}{\sigma_X \sigma_Y}, \quad (8)$$

where $X(t)$ and $Y(t)$ are time signals, $\mathbb{E}$ is the expectation operator, and σ_X and σ_Y are the standard deviations of $X(t)$ and $Y(t)$ (Emery and Thomson 2001). When ξ is negative (positive), it indicates that $X(t)$ leads (lags) $Y(t)$. The autocorrelation function is for a single time signal, where $Y(t) = X(t)$ and $\sigma_Y = \sigma_X$ in Eq. (8). Decorrelation time scales for the autocorrelation function is determined from the zero crossing of $r(\xi)$.

Autocorrelation function of the ST north-south component of wind stress $\tau_{s,y}^{\text{ST}}$ indicates that upwelling-favorable winds during the experiment decorrelate at approximately 70 h (Fig. 7a). CHF^{ST} and CHF^{SD} are cross-correlated with $\tau_{s,y}^{\text{ST}}$ at all moorings where $r(\xi)$ is considered significantly different than zero at 95% confidence level when located outside the gray boxes in Fig. 7b,c. At ST time scales, CHF^{ST} is significantly and positively correlated with $\tau_{s,y}^{\text{ST}}$ at all moorings (Fig. 7b). Note $\tau_{s,y}^{\text{ST}}$ is negative in the equatorward direction during upwelling-favorable wind conditions and CHF^{ST} is negative resulting in the positive correlation between $\tau_{s,y}^{\text{ST}}$ and CHF^{ST} . The peaks in the correlation between CHF^{ST} and $\tau_{s,y}^{\text{ST}}$ occur at positive ξ indicating CHF^{ST} lags $\tau_{s,y}^{\text{ST}}$ at all moorings with the exception of X12(50) (Fig. 7b). The time lags ranged between 5 h at X11(40) and 20 h at X02(7). These results are consistent with onshore transport of cool water associated with upwelling dynamics.

A positive and significant (at 95%) cross-correlation exists between CHF^{SD} and $\tau_{s,y}^{\text{ST}}$ at approximately $\xi = 15\text{--}25$ h over the midshelf [moorings X12(50), X11(40), and X10(30)] (Fig. 7c). This positive correlation indicates that a negative CHF^{SD} occurs 15–25 h after the onset upwelling-favorable (ST) winds. There is also a significant correlation for the inner shelf mooring X02(7) at $\xi = 70$ h, but it should be noted that the CHF^{SD} is small at this location (Fig. 5d) and this correlation is considered not important. There are significant negative correlations between CHF^{SD} and $\tau_{s,y}^{\text{ST}}$ at most moorings [exception of X12(50)] from $\xi = -80$ to -70 h. These correlations indicate that over the inner shelf, and most of the midshelf, a positive CHF^{SD} leads upwelling favorable winds by 70–80 h. These lags occur at the decorrelation time scale of $\tau_{s,y}^{\text{ST}}$ (Fig. 7a) indicating that a positive CHF^{SD} occurs during wind relaxations.

d. Cumulative heating and cooling

Accumulation of heat is representative of temperature whereas heat fluxes are representative of the rate

FIG. 7. (a) Autocorrelation coefficient of ST alongshore wind stress $\tau_{s,y}^{ST}$ plotted as a function of lag. Cross-correlation coefficients between $\tau_{s,y}^{ST}$ and (b) CHF^{ST} and (c) CHF^{SD} plotted as a function of lag at each mooring. Gray regions indicate where the cross-correlation is not statistically significant at 95%.

at which temperature changes. Therefore, while the breakdown of the heat budget and CHF provide useful information on relative rates of heating and cooling, it is informative to demonstrate how heat is accumulated or lost by all identified contributors including SHF and AHF. A breakdown of the time-varying accumulation is presented for the 50- and 20-m control volumes to represent the midshelf and inner shelf (Fig. 8). The added information that heat accumulation analysis provides is exemplified by comparing the contribution of SHF to HS with the contribution of H^{SHF} to H^{HS} . For both the midshelf and inner shelf, H^{SHF} is the largest positive contributor to H^{HS} owing to persistent solar heating despite the small contribution of SHF to HS.

The midshelf H^{HS} is initially negative to yearday 180 and then accumulates heat (positive H^{HS}) over the second half of the experiment (Fig. 8a). The SD accumulation of heat H^{SD} is positive throughout and continually increases after yearday 182 when winds were mostly relaxed and there is increased SD temperature variability (section 2b). The net heat accumulation by H^{SD} ($1.5 \times 10^{12} \text{ J m}^{-1}$) is comparable to H^{HS} ($1.0 \times 10^{12} \text{ J m}^{-1}$). For the midshelf, H^{ST} oscillates on a synoptic scale associated with ST wind forcing though with a negative trend (Fig. 8a). The AHF accumulation of heat H^{AHF} inversely oscillates with H^{ST} with a near flat trend at zero such that its net contribution is nearly zero on the midshelf for the experiment. Thus, even though AHF, from a heat flux perspective accounts for a majority of the heat budget (section 4b), AHF both heats and cools the midshelf such that the temperature change due to AHF is minimal compared to other processes.

On the inner shelf, H^{HS} is also initially negative until yearday 180 and thereafter slightly accumulates heat

(positive H^{HS}) over the second half of the experiment (Fig. 8b). H^{SD} increases in a near linear fashion. For the inner shelf, unlike the midshelf, H^{AHF} and H^{ST} are not strongly related; H^{ST} is relatively constant, whereas H^{AHF} becomes exponentially negative and also becomes the largest contributor to cumulative cooling (Fig. 8b).

Cumulatively, the midshelf is primarily heated by WITBs (H^{SD}) and solar heating, and cooled solely by ST upwelling. The inner shelf is primarily heated by WITBs and solar heating and cooled solely by alongshore processes. WITB and solar heating are relatively consistent for the midshelf and inner shelf though at differing magnitudes.

5. Discussion

Since WITBs typically undergo a polarity reversal into CITBs as they shoal (Lamb 2014), most studies have reported on cooling of the inner shelf by CITBs. Shoaling CITBs transport near bottom cold water onshore (Boehm et al. 2002; Bourgault et al. 2007; Sinnett et al. 2018) and potentially cool the inner shelf through turbulent mixing (Masunaga et al. 2016) before returning offshore as a gravity current (Walter et al. 2012; Sinnett et al. 2018). The majority of WITBs observed during PSIEX, however, do not undergo a polarity reversal as they shoal (Fig. 3). This may be related to a shallow pycnocline internal waveguide owing to a shallow surface mixed layer during light winds. This is supported by the likelihood of intensified stratification in the upper half of the water column (Fig. 4) and the positive CHF^{SD} observed during light wind forcing associated with WITBs (Fig. 7b). It is therefore believed that the WITBs are transporting near surface

FIG. 8. The accumulation of heat terms H^{ST} (blue line), H^{SD} (red line), H^{SHF} (purple line), H^{HS} (black line), and H^{AHF} (gray line) plotted vs time over (a) the midshelf at mooring X12(50) and (b) the inner shelf at mooring X08(20).

warm water onshore which is responsible for the prevalent positive CHF^{SD} observed during PSIEX (Fig. 5d). Although there have been studies on heating of the inner shelf by WITBs at a single mooring (Lucas et al. 2011), and cross-shore transport to the inner shelf by WITBs (Pineda 1999), heating by WITBs over the midshelf and inner shelf in relation to other processes from a heat budget perspective has not been previously investigated.

The cross-shore structure of the CHF^{SD} associated with WITBs and CITBs is now examined by conditionally averaging the CHF^{SD} for periods of positive cross-shore heat

flux and negative cross-shore heat flux at each mooring in the cross-shore (Fig. 9a). Negative CHF^{SD} only contributes on the midshelf, with no negative CHF^{SD} found on the inner shelf. Walter et al. (2014) found that CITB activity decreased on the inner shelf during periods of upwelling owing to the thermocline shoaling offshore and the pooling of cold, offshore water on the inner shelf. The absence of negative CHF^{SD} over the inner shelf is consistent with their findings suggesting that the cross-shore structure of the negative CHF^{SD} is associated with CITBs.

Positive CHF^{SD} decreases nearly linearly from X12(50) to X02(7) (red line in Fig. 9a). The WITBs observed during PSIEX over the midshelf by Colosi et al. (2018) exhibited a cross-shore exponential decay of energy flux attributed to bore dissipation. It is not clear why an exponential decay would occur in energy flux and not in the positive CHF^{SD} . One possible mechanism could be related to the transitional properties of the WITBs as they shoal. Coherence and phase difference ϕ from cross-spectral analysis on u' and T' at a single mooring at specified levels of the water column can be used to determine whether ITBs are behaving as progressive or standing waves (e.g., Lerczak et al. 2003; Kumar et al. 2016). A small ϕ between u' and T' is covarying and implies that the ITBs are progressive and contribute to the CHF^{SD} . A $\phi = 90^\circ$ between u' and T' are not covarying and implies that the ITBs are standing and do not contribute to the CHF^{SD} . Phases between 0 and 90 result in partially standing and partial contributions to CHF^{SD} . The coherence between u' and T' determines the significance of ϕ . Here, cross-spectral analysis is performed on $u_1'^{\text{SD}}$ and $T_1'^{\text{SD}}$ at the second observation from the bottom at each mooring (Fig. 9b). Since the ϕ between $u_1'^{\text{SD}}$ and $T_1'^{\text{SD}}$ at the three midshelf moorings are nearly zero with high coherence, the WITBs over the midshelf are progressive and contribute to a CHF^{SD} . On inner shelf, WITBs are partially standing based on the phase relationship, though the coherence is high for X06(15) and X08(20) and low for X02(7). The transition from progressive WITBs over the midshelf to partially standing over the inner shelf may partially explain the observed cross-shore decrease in positive CHF^{SD} (Figs. 5d and 9a).

6. Conclusions

Collocated vertical measures of temperature and velocity were obtained by a cross-shore array that spanned the midshelf and inner shelf off Pt. Sal, California during the summer of 2015. This allows for the spatiotemporal variability of the cross-shore heat flux (CHF) to be computed and subsequently described in the subtidal (ST), diurnal (DU), and semidiurnal (SD) bands. The CHF, including surface heat flux, is found to account

FIG. 9. (a) Conditionally averaged CHF^{SD} (positive indicated by red line, and negative indicated by blue line) plotted against cross-shore distance from the coastline for each mooring). The dashed black vertical line indicates the mean location of the inner shelf. (b) Phase difference and coherence between u_1^{SD} and T_1^{SD} at the second measurement from the bottom for each mooring. The vertical dashed line demarks the boundary between the midshelf and inner shelf.

for 31% and 17% of the heat budget over the midshelf and inner shelf while the remainder is attributed to the alongshore heat flux (AHF). The subtidal cross-shore heat flux (ST CHF) is primarily negative, correlated to upwelling-favorable winds, and extends into the inner shelf. The contribution of diurnal cross-shore heat flux (DU CHF) is negligible. The semidiurnal cross-shore heat flux (SD CHF) is primarily positive for the midshelf and inner shelf during wind relaxations, and occasionally negative for the midshelf occurring shortly after upwelling-favorable winds. Therefore, the ST winds regulate the ST CHF and the SD CHF. The majority of the SD CHF is attributed to warm-water internal tidal bores (WITBs), which were found not to undergo a polarity reversal into cold-water internal tidal bores (CITBs) as they are shoaled across the midshelf and inner shelf. Background stratification was typically intensified over the upper half of the water column, consistent

with favorable conditions for WITBs. Since WITBs differ from CITBs, the respective cross-shore transport of marine biota and nutrients may also differ. The positive SD CHF decreases linearly from midshelf to the inner shelf. The partial standing wave pattern that develops near the coast may be contributing decrease in SD CHF, as it reduces the covariance (in-phase contributions) between baroclinic velocity and temperature. Cumulative heating on the midshelf and inner shelf is primarily driven by WITBs and solar heating (differing in relative magnitude). Cumulative cooling on the midshelf is driven by ST processes whereas cumulative cooling on the inner shelf is driven by processes associated with the AHF.

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