The role of the alongshore wind stress in the heat budget of the North Carolina inner shelf

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Abstract. The heat budget of a cross-shelf section extending 16 km offshore of the outer banks of North Carolina is studied during two time periods: August 1994 and October 1994, using data collected as part of the Coastal Ocean Processes (CoOP) Inner Shelf Study. Heat budgets are computed on two different timescales: monthly averages over August and October, which reflect seasonal variations, and a fluctuation budget, which reflects variation on daily to weekly timescales. During August, a period of strong stratification, the increase in the area-averaged water temperature (approximately 3.2°C) was due primarily to the surface heat flux. Fluctuations in temperature during August were caused primarily by the cross-shelf heat flux, due to wind-driven upwelling and downwelling circulation. In October, the area-averaged shelf temperature dropped by approximately 3.5°C due to both surface heat loss and the alongshore transport of heat. Weak vertical stratification in October led to small cross-shelf heat fluxes, and temperature fluctuations in October were due primarily to fluctuations in the surface and alongshore heat fluxes. In both August and October, variation on daily to weekly timescales of the area-averaged temperature of the shelf was strongly correlated with the alongshore component of the wind stress. In August, alongshore poleward winds caused upwelling and the area-averaged temperature decreased; conversely, equatorward winds caused downwelling and warming. In October, although the variations in temperature were smaller, alongshore winds were positively correlated with alongshore currents and the surface heat flux (for reasons discussed by Austin and Lentz [this issue]), so that poleward winds resulted in warming; conversely, equatorward winds resulted in cooling. Therefore the dependence of the change in heat content on the alongshore wind stress changed sign between August and October. A simple dynamical model was constructed to relate changes in heat content to the alongshore wind stress. The model results were compared to 12 years of meteorological records from the Coastal Engineering Research Center’s Field Research Facility, directly onshore of the experimental site. The results suggest a seasonal cycle in the dominant fluctuating heat balance, consistent with the field results found for August and October 1994. In May through August, cross-shelf flux dominates variation in the heat content. In October through March, the surface heat flux and alongshore heat flux dominate the variation.

1. Introduction

Shelf regions are susceptible to surface forcing such as wind stress and surface heat flux due to the shallowness of the water, and they display circulation patterns (such as coastal upwelling and downwelling) unique to the coastal ocean. Aspects of the shelf circulation off North Carolina create a situation in which there are several different potentially significant sources of temperature variability. Understanding these sources and quantifying their relative importance are vital to a more general understanding of observed mean hydrographic conditions and variability. This paper addresses the relationship between various sources of heat and the variability in the heat content of a two-dimensional cross-shelf section of the North Carolina inner shelf and presents a simple model linking the alongshore wind stress to potential sources of variability.

The influence of the alongshore wind stress on the heat budgets of other regions has been considered in
previous studies. Atkinson et al. [1989] looked at the heat budget of a region of the South Atlantic Bight on an episodic basis, considering both a one-dimensional balance between the surface heat flux and local heating and a three-dimensional balance, taking cross-shelf advection and advection of Gulf Stream water into account. They concluded that heat content variability was due primarily to cross-shelf heat transport, which was balanced by alongshore heat transport generated by alongshore transport divergence. Both Lentz [1987] and Lentz and Chapman [1989] studied the relationship between variability in the heat content of the northern California shelf and the alongshore wind stress during the Coastal Ocean Dynamics Experiment (CODE), in which the balance was primarily two-dimensional (cross-shelf heat flux and surface flux dominated). In contrast to the results presented here, they noted very little seasonal variability in the relationship between the change in heat content and wind stress, as the wind-driven cross-shelf heat flux dominated variability in all seasons. Dever and Lentz [1994] considered seasonal fluctuations in the primary sources of heat and fluctuations in heat content on the northern California shelf during the Surface Mixed Layer Experiment (SMILE). During winter, they observed a mean balance between cross-shelf heat flux and alongshore heat flux divergence, and during spring they saw a balance between cross-shelf flux and the surface heat flux. In both seasons, fluctuations in the heat content were balanced primarily by the cross-shelf heat transport (as by Lentz and Chapman [1989]), which was consistent in magnitude with the alongshore wind stress.

As part of the Coastal Ocean Processes (CoOP) Inner Shelf Study [Butman, 1994], an array of instruments was deployed on the North Carolina Shelf north of Cape Hatteras from August 1994 through November 1994. During this time period, the region was characterized by highly variable meteorological forcing [Austin and Lentz, this issue] (hereinafter referred to as AL), and the observed circulation reflects this [Lentz et al., this issue]. During the field program, the character of the shelf changed from strongly vertically thermally stratified to weakly stratified. By comparing mean and fluctuation budgets between these two distinct time periods, the role of thermal stratification in determining the primary sources of heat content and its variation can be assessed. In addition, by developing relationships between each of the sources of heat and the alongshore wind component, a simple model of thermal variability can be constructed and applied to historical data from the region. Additionally, the robustness of the seasonal variation in the strength of the source terms can be studied.

The rest of the paper is organized as follows. In section 2, the field site and instrumentation are described and the heat budget method is presented. Section 3 is an outline of the data collected, section 4 presents the heat budgets themselves, and section 5 consists of a discussion of the link between the alongshore wind stress and the heat budget, along with the application of a simple model to historical data. Section 6 is a short summary.

2. Field Site, Instrumentation and Methods

2.1. Field Site

The CoOP Inner Shelf Study field site (Figure 1) is located off the coast of the Outer Banks of North Carolina between Cape Henry (at the mouth of the Chesapeake Bay) and Cape Hatteras. The coastline in the region is relatively straight, extending 80 km north and south of the central observational region. The shelf is shallow, deepening to approximately 26 m at the site of the deepest mooring (16.4 km offshore). The shelf break is located approximately 80 km offshore, at which the depth is approximately 60 m. The coastline is unbroken except at Oregon Inlet, 50 km south of the central observational region. The Chesapeake Bay represents a significant source of fresh water to the region, but as the estuarine water is similar in temperature to the ambient shelf water, it does not appear to be a significant source or sink of heat. Cape Hatteras is located approximately 80 km south of the observational region. The Gulf Stream separates from the coast at Cape Hatteras and is responsible for occasional intrusions of warm, salty water onto the shelf in this region [Gawarkiewicz et al., 1992; Churchill and Cornilion, 1991].

2.2. Instrumentation

This study focuses on moored instrument data [Alessi et al., 1996], which were collected from August 1994 to December 1994 as part of the CoOP Inner Shelf Study. The moored instrumentation was centered around a cross-shelf array that consisted of three surface/subsurface mooring pairs located 1.4, 5.4, and 16.4 km offshore in 13, 21, and 26 m of water and are referred to as d1, d2, and d3, respectively (Figure 1). These three mooring sites were instrumented with a total of 16 vector-measuring current meters (VMCMs), 30 thermistors, and 11 conductivity cells (Figure 2). The surface mooring at d2 carried a vector-averaging wind recorder (VAWR) meteorological package that measured air and near-surface water temperature, downward long-wave and shortwave radiation, wind speed and direction, barometric pressure, and relative humidity to make estimates of the heat and momentum fluxes from the atmosphere to the ocean. In addition to the central cross-shelf array, instruments placed off the central array axis provided information about alongshore gradients of temperature and salinity. Surface/subsurface mooring pairs with temperature and conductivity sensors near the surface and bottom were placed on the 20-m isobath approximately 30 km north (north Seacat, (NSC)) and 30 km south (south Seacat, (SSC)) of...
the central array. Temperature and conductivity measurements were made at five sites along the 6-m isobath (j0-j4), spaced approximately 15 km apart in the along-shore direction. Data were recorded every 4 min (except for the meteorological data, which were recorded every 7.5 min) and binned into hourly averages.

Other data were used to situate the moored data in a regional and seasonal context. Shipboard conductivity-temperature-depth (CTD) sections were made along the central line (Figure 1) 16 times in August and 20 times in October by the R/V Cape Hatteras, as well as multiple sections to the north and south of the central line [Waldorf et al., 1995, 1996]. The Army Corps of Engineers’ Field Research Facility (FRF) (Figure 1) has archived various meteorological data since 1982 [Birkemeier et al., 1985], including wind velocity measured at the end of the pier at a height of 19.4 m (the bulk formulation of Fairall et al. [1996] was used to estimate surface stress) and sea surface temperature from the end of the pier, measured daily (at approximately 0700 LT) using a bucket thermometer. CTD sections from the National Marine Fisheries Service Marine Resources Monitoring, Assessment, and Prediction (MARMAP) [Manning and Holzwarth, 1990] project were used to assess seasonal variability in thermal stratification.

2.3. Heat Budget Equation

The basic method for defining and estimating the values of the heat budget terms is taken from Dever and Lentz [1994]. The heat budget is applied to a two-
Figure 2. A schematic side view of the central and alongshore moored array showing distribution and coverage of measurements, and cartoon definitions of the heat balance terms.

The interpretation of the individual terms of (1) are as follows. CHF represents the net exchange of heat across the offshore boundary in the presence of vertical temperature gradients due to depth-dependent cross-shelf flow. An important implication of the form of this term is that if the water column is well mixed, $T = 0$, the cross-shelf heat flux is zero. AHF represents the advection of alongshore temperature gradients into the region. SHF is the surface heat flux over the domain. The estimation of each of these terms and the sources of uncertainties in these estimates are discussed in appendix B. The net heat flux (HF) into the region is defined as:

$$HF = CHF + AHF + SHF,$$

which can be compared directly to the observed change in heat content. The heat budget closes if $HF = \frac{\partial H}{\partial t} (STO)$.

3. Data

This study focuses on two time periods: from 2200 UTC on August 10 to 0000 UTC on September 4, 1994 referred to as the “August time period”, and from 1500 UTC on October 4 to 0000 UTC on November 2, referred to as the “October time period.” The August time period was chosen to coincide with the greatest availability of meteorological and oceanic data, as described in AL. The October time period was chosen to avoid the effects of a slope water intrusion, which commenced on November 2 (Figure 4e), as the focus of this paper is on more local influences to the heat content of the shelf.

3.1. Atmospheric Forcing

The surface heat flux (Figures 3a and 4a) and wind stress (Figures 3b and 4b) are discussed in AL. The principal axis of the wind forcing was oriented approximately 45° to the coast, with poleward and offshore winds being correlated (0.78 in August and 0.66 in October) and of approximately the same magnitude. The magnitude of the mean wind stress increased between August and October, 0.052 N m$^{-2}$ to 0.10 N m$^{-2}$. The surface heat flux changed from a mean value of 147 W m$^{-2}$ (positive into the ocean) in August to -39 W m$^{-2}$ in October. The subtidal variance of the surface heat flux in each of the 2 months was around 135 W m$^{-2}$ (when diurnal variation is included, the variance is much higher). Subtidal variation in the heat and momentum fluxes in both months was due primarily to the passage of atmospheric cold fronts, which cause the surface heat flux to decrease significantly and the wind direction to change from poleward and offshore to equatorward and onshore as they pass. The prevalence of cold fronts causes the heat flux to be highly correlated with the alongshore component of wind stress (correlation 0.73 in August, 0.68 in October), so that positive heat flux into the ocean is associated with pole-
Figure 3. Time series of atmospheric forcing and temperature during the August time period, with arrows indicating timing of CTD sections in figure 5: (a) surface heat flux (solid line), and low-pass filtered surface heat flux (dashed line); (b) wind stress; (c) temperature, mooring d1, seven thermistors; (d) temperature, mooring d2, 12 thermistors; (e) temperature, mooring d3, 10 thermistors.
Figure 4. Time series of atmospheric forcing and temperature during the October time period. (a) Surface heat flux (solid line), and low-pass filtered surface heat flux (dashed line); (b) wind stress; (c) temperature, mooring d1, three thermistors (these data are not used in the heat balance, for reasons discussed in Appendix B); (d) temperature, mooring d2, 12 thermistors; (e) temperature, mooring d3, 10 thermistors.
ward offshore winds and negative heat flux is associated with equatorward onshore winds. This correlation is not causal, but simply a consequence of the structure and orientation of cold fronts and their dominance as a source of subinertial meteorological variability, as discussed in AL.

3.2. Temperature Data

The primary difference in the character of the water column between August and October was the change in vertical thermal stratification, from a highly stratified, layered water column in August (Figures 3c-e) to a weakly stratified water column in October (Figures 4c-e). The change in stratification from August to October was due primarily to a storm event starting September 4 with sustained wind stress of more than 0.4 N m$^{-2}$. Thermal stratification in August was strong, with temperature differences across the thermocline of up to 8°C, with the strongest vertical thermal gradients at d3. The d3 site was characterized by a very sharp thermocline for the duration of August, with a temperature difference of 7°C over 3 m depth and well-mixed surface and bottom layers. Before August 24, the d2 site was characterized by a well-mixed bottom layer and a stratified surface layer. After the relaxation of a downwelling event on August 25, the surface layer was also well mixed. Periodic upwelling and downwelling events resulted in local homogeneity of the water column during August at d1 and d2. When the thermocline was advected offshore, the water inshore of the thermocline became uniformly warm (during downwelling) or cold (during upwelling). CTD sections from representative events on August 21 and August 25 (Figure 5, timing indicated on Figure 3) show the upwelling and downwelling of the thermocline relative to the positions of the moorings.

Because the distance the thermocline is advected offshore is a function of the strength and duration of the forcing event, they were most often observed closest to shore at d1, where weak wind events advected the ther-

![Figure 5](image_url). CTD sections from (a) August 21 and (b) August 25, taken from the R/V Cape Hatteras. Location of CTD stations is indicated by triangles, and the locations of the three mooring sites are indicated by dashed lines.
mocline past the mooring, and occasionally at d2, where a stronger (or longer) wind event was required to advect the thermocline past the mooring. Homogenization was not observed at d3 until a large downwelling-favorable wind event at the beginning of September, which homogenized the water at the d3 site through both advection and mixing. These upwelling and downwelling events will be shown to have caused the largest fluctuations in the total heat content of the shelf during August. The offshore displacement of the thermocline during upwelling and downwelling is considered in the discussion and in a subsequent paper.

In October, the average temperature dropped from about 21°C to 17°C (Figures 4c-e). The water column was well mixed in temperature except during small surface thermal restratification events, which generated differences of up to 1°C between the surface and the bottom water and lasted up to 7 days. Fluctuations in the vertically averaged temperature are correlated at the three sites and are linked to fluctuations in the surface heat flux and alongshore heat flux in section 4.

The mean alongshore temperature gradient in the region, determined using data from NSC and SSC (Figure 1), was of order $-10^{-5}$ °C m$^{-1}$ (colder to the north) in both months. This corresponds to a temperature difference over the alongshore extent of the array (60 km) of around 0.6°C. This is consistent with estimates of the alongshore gradients from historical data [Walford and Wicklund, 1968].

4. The Heat Budget

The heat budget is considered on two timescales: first, the mean heat budget averaged over the August and October time periods, and second, the fluctuation heat budget for variation on daily to weekly timescales.

4.1. Mean Heat Budget

The mean heat budgets for August and October (Table 1) reflect variation in the heat budget on seasonal time scales. The most dramatic difference is the change in the mean value of the surface heat flux. In August, the surface heat flux dominates the mean balance, and in October, the surface heat flux and alongshore heat flux are approximately equally important. The cross-shelf heat flux is relatively unimportant in both months.

The predominant mean balance in August is between the surface heat flux and the increase in heat content of the region (Table 1). The estimated mean surface heat flux averaged over the month is approximately $2.2 \times 10^6$ W m$^{-1}$ (equivalent to a temperature increase of 4°C averaged over the area). The increase in heat content is $1.7 \times 10^6$ W m$^{-1}$, equivalent to an average temperature increase of approximately 3.2°C. Neglecting the downwelling event that commences on September 1, the upper and lower layer at the 25 m site both increase in temperature by approximately 2°C, while the thermocline deepens from approximately 10 to 15 m. Solar radiation cannot be directly responsible for the increase in the heat content of the lower layer, as shortwave extinction lengths were of the order of 2 m, based on transmissometer data from the R/V Cape Hatteras cruises. Presumably, the bottom layer is heated during wind-driven mixing events. Although the alongshore and cross-shelf fluxes contributed to the mean, their contributions were much smaller than the standard error and hence suggest that the actual mean is not resolved with the time series.

During the October time period, the observed change of the heat content was $-1.9 \times 10^6$ W m$^{-1}$ (equivalent to an area-averaged decrease in temperature of $-3.6$°C). The primary mean sources of loss were the surface heat flux ($-0.55 \times 10^6$ W m$^{-1}$, equivalent to an area-averaged decrease of 1.0°C), and the alongshore heat flux ($-0.75 \times 10^6$ W m$^{-1}$, equivalent to an area-averaged decrease of 1.4°C). The mean alongshore heat flux is due primarily (80%) to the advection of a mean alongshore temperature gradient. The mean changes are larger than the standard error, suggesting that the mean changes observed in October are properly resolved with the time series.

<table>
<thead>
<tr>
<th>Period</th>
<th>SHF</th>
<th>CHF</th>
<th>AHF</th>
<th>HF</th>
<th>$\theta_t$(STO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>August</td>
<td>2.22</td>
<td>2.2</td>
<td>0.55</td>
<td>0.15</td>
<td>2.1</td>
</tr>
<tr>
<td>October</td>
<td>-0.55</td>
<td>2.2</td>
<td>0.5</td>
<td>-0.14</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Units are $10^6$ W m$^{-1}$. Abbreviations are SHF, surface heat flux; CHF, cross-shelf heat flux; AHF, alongshore heat flux; HF, net heat flux; $\theta_t$(STO), change in heat content. Both time series had 17 degrees of freedom, assuming a decorrelation timescale of 40 hours.

- \*Mean of the data, $\bar{x} = N^{-1} \sum x$.
- Standard deviation, $\sigma_x = \left[ \frac{\sum(x - \bar{x})^2}{N-1} \right]^{1/2}$.
- Standard error, $\sigma_{\bar{x}} = \sigma_x / \sqrt{d.f.}$.
4.2. Fluctuating Heat Budget

The fluctuating budget indicates the primary source of variation in the heat content of the region on synoptic timescales. High-frequency variation such as the diurnal shortwave radiation cycle and tides have been removed by low-pass filtering, so most of the remaining variation is due to fluctuations in atmospheric forcing associated with synoptic weather systems.

Variation in the heat content in August is due largely to the cross-shelf heat flux (Table 1 and Figure 6). The cross-shelf heat flux reflects changes in temperature due to cross-shelf advection in the upper layer and a compensating flow in the lower layer. The difference in temperature between the two layers causes these flows to drive a large net cross-shelf heat transport, which is highly negatively correlated (-0.81) with the alongshore wind stress (Table 2). The consistency of the transport with Ekman theory is considered in section 5.1. Upwelling events occurred on August 15, 17, and 20, resulting in significant losses of heat, and downwelling events occurred on August 24 and September 2, resulting in significant gains of heat. The change in heat on the shelf in these cases was due not to local heating or cooling but to a change in position of the thermocline during wind stress events (Figure 5). The dominance of the cross-shelf heat flux in determining temperature fluctuation on the shelf during August led to a correlation between the alongshore wind stress and the change in the measured storage term of -0.73 (Table 2). The measured net heat flux (HF) and the change in storage $\delta H/(STO)$ were highly correlated (correlation 0.74).

For the October time period, variation in the heat content was due primarily to fluctuations in the surface wind stress (Table 2). The consistency of the transport with Ekman theory is considered in section 5.1. Upwelling events occurred on August 15, 17, and 20, resulting in significant losses of heat, and downwelling events occurred on August 24 and September 2, resulting in significant gains of heat. The change in heat on the shelf in these cases was due not to local heating or cooling but to a change in position of the thermocline during wind stress events (Figure 5). The dominance of the cross-shelf heat flux in determining temperature fluctuation on the shelf during August led to a correlation between the alongshore wind stress and the change in the measured storage term of -0.73 (Table 2). The measured net heat flux (HF) and the change in storage $\delta H/(STO)$ were highly correlated (correlation 0.74).

For the October time period, variation in the heat content was due primarily to fluctuations in the surface

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**Figure 6.** The low-pass filtered heat budget terms for the August balance. (a) surface heat flux; (b) cross-shelf heat flux; (d) alongshore heat flux; (e) change in heat content, solid line, net heat flux, dashed line.
**Table 2. Regression Statistics Between Alongshore Wind Stress and Heat Budget Terms**

<table>
<thead>
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</thead>
<tbody>
<tr>
<td>SHF</td>
<td>cold fronts</td>
<td>$\kappa L$</td>
<td>$5.4 \pm 1.4, [0.73]$</td>
<td>$2.1 \pm 0.6, [0.68]$</td>
<td>$5.4^a$</td>
<td>$2.1^a$</td>
</tr>
<tr>
<td>CHF</td>
<td>ekman dynamics</td>
<td>$-\frac{\rho \beta \Delta T}{\sigma r}$</td>
<td>$-23 \pm 4.7, [-0.81]$</td>
<td>$(-0.07 \pm 0.1), [-0.18]$</td>
<td>$-25$</td>
<td>$0.6$</td>
</tr>
<tr>
<td>AHF</td>
<td>alongshore flow</td>
<td>$-\frac{\rho \beta \Delta T}{\sigma r}$</td>
<td>$(3.0 \pm 1.2), [0.56]$</td>
<td>$1.5 \pm 0.4, [0.68]$</td>
<td>$2.1$</td>
<td>$3.0$</td>
</tr>
<tr>
<td>HF</td>
<td>net flux</td>
<td>$\hat{\Gamma}<em>{SHF} + \hat{\Gamma}</em>{CHF} + \hat{\Gamma}_{AHF}$</td>
<td>$-14 \pm 4.3, [-0.69]$</td>
<td>$3.5 \pm 0.8, [0.73]$</td>
<td>$-18.3$</td>
<td>$5.1$</td>
</tr>
<tr>
<td>$\partial_t (STO)$</td>
<td>balance closure</td>
<td>$\hat{\Gamma}_{HF}$</td>
<td>$-17 \pm 4.4, [-0.73]$</td>
<td>$4.5 \pm 1.2, [0.69]$</td>
<td>$-18.3$</td>
<td>$5.1$</td>
</tr>
</tbody>
</table>

$\Gamma$ is regression coefficient; $\hat{\Gamma}$ is dependence on alongshore wind stress. Units are $10^7$ Wm$^{-1}$. Numbers in brackets denote correlation coefficient of fit. Numbers in parentheses indicate regression coefficient not significant at the 95% level.

*Here $\kappa$ is determined empirically from the observations.*

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**Figure 7.** Same as Figure 6, but for the October balance.
heat flux and, to a lesser extent, the alongshore heat flux (Figure 7 and Table 1). Although the variance of the surface heat flux was approximately the same in August and October, it played a dominant role in October, since the weak vertical temperature gradient effectively shut down the cross-shelf heat flux. This led to smaller net changes in heat content in October. Variations in surface heat flux are positively correlated with the alongshore wind stress (correlation 0.68), owing to the passage of cold fronts in the atmosphere. The alongshore flux was due to the weak \([O(-10^{-5} \ ^\circ C m^{-1})]\) negative alongshore temperature gradient (colder to the north) advected by the alongshore current and was correlated with the alongshore wind (correlation 0.68). These positive correlations resulted in a positive correlation of 0.69 between the alongshore wind and the storage term and a correlation between the net heat flux and the storage term of 0.88.

5. Role of the Alongshore Wind

The alongshore wind plays a central role in determining coastal circulation, and has been studied in many contexts [Csany, 1977; Allen, 1973; Winant and Beardsley, 1979]. In this section, it will be shown that on the North Carolina inner shelf, the relationships between the wind stress and the heat flux terms are dependent on season, resulting in seasonal changes in the primary fluctuating budget. Variation in the different sources and sinks of heat can be explained in terms of simple, dynamically based models. In the following section, this simple relationship between the alongshore wind stress and heat fluxes based on the CoOP data set is developed, and this model is used to interpret historical data collected at the FRF between 1984 and 1995.

5.1. Simple Wind-Driven Models and the CoOP Data

In this section, the regression between the heat flux terms and the alongshore wind stress is estimated using a simple model and compared to the best fit, in the least squares sense, between the measured heat flux terms and the alongshore wind stress. The regression coefficients from the observations are denoted by \(\Gamma\), which represents the strength of the influence of the alongshore wind stress on a given term in the heat budget. The dependence on the alongshore wind stress in the simple dynamical models is denoted by \(\hat{\Gamma}\).

The cross-shelf heat flux is presumably due to Ekman transport in the upper, warm layer balanced by a reciprocating flow in the lower, cold layer. The balance in the upper (lower) layer of the water column is between the surface (bottom) stress and the Coriolis force. For a two-dimensional flow (that is, the alongshore flux divergence is zero), the transport in the upper layer offshore of the pycnocline front is \((u_1)_1 = \tau^S \rho_0 f^{-1}\), where \(\tau^S\) is the alongshore surface stress. If the flow is two-dimensional, the transports in the upper and lower layer must be opposite in sign but equal in magnitude. Assuming the difference between the temperature in the upper and lower layers is \(\Delta T\), the cross-shelf heat flux due to the Ekman circulation can be approximated [Lentz, 1987] by

\[
\text{CHF}_{\text{MODEL}} = \hat{\Gamma}_\text{CHF} \tau^S, \tag{3}
\]

where

\[
\hat{\Gamma}_\text{CHF} = \frac{\rho_0 c_p \Delta T}{\rho_0 f}, \tag{4}
\]

where \(f = 0.95 \times 10^{-4} \text{s}^{-1}\) is the local Coriolis parameter. An estimate of the cross-shelf heat flux can be computed for the month of August using the average difference in temperature between the top and the bottom thermistors at \(d3\) for \(\Delta T\) (6° in August and 0.15° in October) and the wind stress time series from \(d2\). A comparison of the Ekman model cross-shelf heat flux and the actual estimated cross-shelf heat flux in August (Table 2) shows reasonable agreement between the magnitude of the signals, as \(\text{CHF} = (-23 \pm 4.7) \times 10^7 \text{W m}^{-1}\) and \(\text{CHF} = -25 \times 10^7 \text{W m}^{-1}\). Therefore, to first order, the size of the regression coefficient \(\Gamma_{\text{CHF}}\) is consistent with this simple model. In October, both \(\Gamma_{\text{CHF}}\) and \(\hat{\Gamma}_{\text{CHF}}\) are small, as the stratification is weak. In addition, the correlation of the CHF with the alongshore wind stress is not significant in October.

Alongshore currents in the same direction as the wind stress occur during both upwelling and downwelling events. These currents can advect the mean alongshore temperature gradient, causing local fluctuations in temperature. During the CoOP Inner Shelf Study, a weak alongshore temperature gradient existed with cooler water to the north. Data of Walford and Wicklund, [1968] suggest that this alongshore temperature gradient is a year-round feature of this region. Positive (poleward) wind stress drove alongshore poleward currents, resulting in a net increase in heat content, and equatorward alongshore wind stress resulted in a net decrease in heat content. By assuming an approximate balance between the surface and bottom stress [Lentz et al., this issue], a simple model for the alongshore velocity can be derived. Variations in the alongshore heat flux in the CoOP Inner Shelf Study data were primarily due to variations in the alongshore velocity, so the alongshore heat flux can be approximated by:

\[
\text{AHF}_{\text{MODEL}} = \hat{\Gamma}_\text{AHF} \tau^S, \tag{5}
\]

where

\[
\hat{\Gamma}_\text{AHF} = - \frac{\rho_0 c_p}{\rho_0 r} \frac{dT}{dy} \Delta A, \tag{6}
\]

and \(r = 5 \times 10^{-4} \text{m s}^{-1}\) is a reasonable value for linear bottom drag and \(\Delta A = 3.1 \times 10^{16} \text{m}^2\) is the cross-sectional area of the budget region. Values of \(dT/\text{dy}\), based on mean temperatures measured at NSC and SSC, of \(0.8 \times 10^{-5} \ ^\circ C \text{m}^{-1}\) and \(1.2 \times 10^{-5} \ ^\circ C \text{m}^{-1}\) are
used for August and October, respectively. In the data, the alongshore heat flux is not significantly correlated with the alongshore wind stress in August, but well correlated in October. The lack of correlation in August may be due to the fact that the largest apparent alongshore differences in temperature are due to alongshore variation in the cross-shelf shoaling of the thermocline, and do not accurately represent the local alongshore gradient, suggesting that the local alongshore temperature gradient is not well resolved. In October, the observed variation in the alongshore heat flux is less heavily dependent on the wind stress than expected.

The surface heat flux is correlated with the alongshore wind stress such that positive wind stress is associated with heating (of the ocean) and negative wind stress with cooling, as discussed in AL, and is attributed to the spatial structure of the meteorological fields associated with cold fronts.

The surface heat flux can be modeled as a function of the alongshore wind stress as

$$SHF_{MODEL} = \Gamma_{SHF} \tau^S$$

(7)

where

$$\Gamma_{SHF} = \kappa L,$$

(8)

and $\kappa$ is a transfer coefficient between the alongshore wind stress and the surface heat flux. Since no dynamical model exists to determine the value of $\kappa$, it must be determined empirically from field observations, so that

$$\kappa = \Gamma_{SHF} L^{-1}.$$  

(9)

It follows that $\Gamma_{SHF} = \Gamma_{SHF}$. Here $\kappa$ is determined separately for each month, with $\kappa = 3500 \text{ W m}^{-1} \text{ N}^{-1}$ in August and $\kappa = 1300 \text{ W m}^{-1} \text{ N}^{-1}$ in October.

All of the heat source terms can be related to the alongshore wind stress, so the net heat content should also be a function of the alongshore wind stress. The directly measured change in heat content, $\delta_t(\text{STO})$, is related to the alongshore wind stress by

$$\delta_t(\text{STO}) = \Gamma_{\delta_t(\text{STO})}\tau^S.$$  

(10)

The total heat flux into the region is given by (2). Similarly, the total heat flux into the region is modeled as

$$HF_{MODEL} = SHF_{MODEL} + AHF_{MODEL} + CHF_{MODEL}$$

(11)

so that

$$\Gamma_{HF} = \Gamma_{CHF} + \Gamma_{SHF} + \Gamma_{AHF}.$$  

(12)

The model for the change in temperature is

$$\Gamma_{\delta_t(\text{STO})} = \Gamma_{HF},$$  

(13)

since the modeled heat balance assumes closure.

Three different comparisons can be made here. Comparing $\Gamma_{HF}$ and $\Gamma_{\delta_t(\text{STO})}$ reflects an imbalance in the observations, due either to measurement error or a breakdown of the assumptions about heat balance closure. Comparing $\Gamma_{HF}$ and $\Gamma_{HF}$ reflects the adequacy or inadequacy of the simple models to explain variation in net heat content and is simply the sum of the errors in the individual source terms. Finally, comparing $\Gamma_{\delta_t(\text{STO})}$ and $\Gamma_{\delta_t(\text{STO})}$ reflects the combined error of the measurements and the appropriateness of the simple models. All of these values are summarized in Table 2.

In August, the measured dependence of the net flux was $\Gamma_{HF} = (-14 \pm 4.3) \times 10^7 \text{ W m}^{-1}$, which is consistent with the model, where $\Gamma_{HF} = -18 \times 10^7 \text{ W m}^{-1}$. In addition, the observed change in temperature was consistent with both of these estimates, with $\Gamma_{\delta_t(\text{STO})} = (-17 \pm 4.4) \times 10^7 \text{ W m}^{-1}$. In October, the dependence of the net heat flux on the alongshore wind stress, $\Gamma_{HF} = (3.5 \pm 0.8) \times 10^7 \text{ W m}^{-1}$, fell slightly short of the modeled dependence, $\Gamma_{HF} = 5.1 \times 10^7 \text{ W m}^{-1}$. This discrepancy is due primarily to a poor estimation of the alongshore heat flux dependence. The dependence of the measured change in the temperature, $\Gamma_{\delta_t(\text{STO})} = (-4.5 \pm 1.2) \times 10^7 \text{ W m}^{-1}$, was consistent with the model prediction. The October $\Gamma_{HF}$ and $\Gamma_{\delta_t(\text{STO})}$ are smaller in magnitude and opposite in sign from August, due primarily to the predominance of the cross-shelf heat flux in August and its relative lack of importance in October. This suggests that when the shelf is stratified, variations in the heat content of the shelf are strongly dependent on and negatively correlated with the alongshore wind stress. In the absence of stratification, the heat content is positively correlated with the alongshore wind stress but the dependence is not as strong.

5.2. Seasonal Cycle

Historical archives of several meteorological variables, including wind velocity and water temperature from January 1984 to December 1995 were acquired from the Coastal Engineering Research Center's Field Research Facility, located inshore of the main array of moorings (Figure 1). These two time series can be used to estimate a time series of the monthly $\Gamma_{HF}^{\text{FRF}}$. The seasonal cycle in the dominance of the individual terms of the heat budget should be reflected by this analysis. In addition, monthly values of the expected size of $\Gamma_{HF}$ can be estimated from independent sources of data to serve as a means of comparison and verification.

The daily water temperature measurements, taken with a bucket thermometer at the end of the pier (560 m offshore) were differenced to approximate the time derivative of the temperature. This time series of temperature change was assumed to be representative of the temperature change of the inner shelf out to a distance of 6 km, the region commonly affected by the displacement of the thermocline during upwelling and downwelling episodes during the stratified season. The wind velocities were binned into 1-day averages that co-
incided with the temperature differences. A time series of the regression between the alongshore component of the wind stress and the temperature change \( \Gamma^\text{FRF} \) was computed for month long time periods and is shown plotted as a function of month for the years 1984-1995 (Figure 8a). The correlations for the monthly fits are shown in Figure 8b. The time series shows a clear seasonal signal, varying between small positive values from October through March to large negative values from May through August.

It is desirable to check to see if the values of \( \Gamma^\text{FRF} \) shown in Figure 8a are consistent, in order of magnitude, with the interpretations offered in the previous section. To do this, values of \( \Gamma^\text{HF} \) are computed on a monthly basis using independent data. CTD measurements made as part of the Marine Resources Monitoring, Assessment, and Prediction (MARMAP) program include 25 surveys of a section extending offshore from Cape Henry, 80 km north of the CoOP Inner Shelf Study site, made between 1977 and 1985 [Manning and Holzwarth, 1990]. The surface-bottom temperature difference at station 13 (approximately 20 km offshore of the mouth of the Chesapeake Bay, in approximately 20 m of water) was used to determine a monthly mean \( \Delta T \) (Figure 9a) to compute \( \Gamma^\text{CHF} \).

Climatic summaries of water temperature data from the National Data Buoy Center CHLV2 buoy and from the FRF were differenced and suggest that, for the pur-

Figure 8. (a) Heat flux regression coefficient \( \Gamma^\text{HF} \) as a function of month. Crosses are monthly values of \( \Gamma^\text{FRF} \), 1984-1995. Simple regression model \( \Gamma^\text{HF} \) is indicated by solid line. (b) Correlation of the alongshore wind component with the time-differenced temperature from the Field Research Facility, as a function of month.
poses of this model, $dT/dy$ is approximately constant on seasonal scales, and a value of $-1.2 \times 10^{-5}$ °C m$^{-1}$ (colder to the north) is used to compute $\Gamma_{AHF}$. This is consistent in both sign and magnitude with historical values of the alongshore temperature gradient [Wallord and Wicklund, 1968]. Annual variation in $\kappa$, necessary for understanding the seasonal cycle of the surface heat flux contribution, cannot be estimated without more heat flux data, so it is assumed to be constant, with a value of $\kappa=2500$ W m N$^{-1}$, to estimate $\Gamma_{SHF}$. The conclusions of this section are not heavily dependent on seasonal variation in $\Gamma_{SHF}$, as this term is small compared to variations in the corresponding cross-shelf heat flux values (Figure 9b).

The resulting monthly $\Gamma_{SHF}$, $\Gamma_{AHF}$, and $\Gamma_{CHF}$ (Figure 9b) can be summed to create $\Gamma_{HF}$ (Figure 8a, solid line), and compared to the data from the FRF. They are consistent in magnitude with the direct measurements made at the FRF and suggest a strong seasonal cycle in the dominant term of the fluctuating heat budget. Between May and August, wind-driven cross-shelf heat flux dominates the heat content variability in very shallow water. The budget in October through March is dominated by the surface heat flux and, to a lesser extent, the alongshore flux. In March, April, and September, the coefficients and the model prediction are indistinguishable from zero, suggesting that neither process is dominant during these times or that the timing of the

Figure 9. (a) Surface-bottom temperature difference at MARMAP station 13, as a function of month from the Marine Resources Monitoring, Assessment, and Prediction data set (stars) and monthly temperature difference used in model (solid line). (b) $\Gamma_{SHF}$, $\Gamma_{AHF}$, and $\Gamma_{CHF}$ as a function of month.
seasonal cycle drifts to the extent that variation in any given March, April, or September can be dominated by one or the other. This is due to the fact that thermal stratification tends to be initially established in March or April and destroyed in September, a trend consistent with the CTD sections presented by Manning and Holzwarth [1990].

The model prediction for the months May-August is notably larger than the measured values. This may be due to the discrete nature of the measurement of the heat content of the inner shelf. Instead of reflecting a continuous change of heat on the inner shelf, a time series of change of heat content estimated from the single FRF temperature measurement would have “spikes” as the thermocline passed through the measurement site, causing the correlations and regression parameters to be smaller than expected.

The strength and regularity of the seasonal cycle in the fit and correlation can be addressed by comparing the relative sizes of the modeled surface and alongshore heat flux and the cross-shelf heat flux. Forming the ratio of surface and alongshore to cross-shelf heat flux, from (4), (6), and (8):

$$\frac{\hat{\text{AHF}} + \hat{\text{SHF}}}{\hat{\text{CHF}}} = \frac{c_p \rho H \frac{\partial}{\partial t} \int_T dA + \int_{H}^{0} (u_T)_{x=L} dz}{c_p \rho H \frac{\partial}{\partial y} \int_T dA}. \quad (14)$$

If the alongshore plus surface heat flux and the cross-shelf heat flux were to be equally important to the heat budget, this ratio would be about 1. This constraint requires the temperature difference across the thermocline to be of the order of 0.5°C. This corresponds to a bulk Richardson number of the order of 0.1. If ΔT is small, it is more easily mixed away by a small amount of wind or surface cooling, causing the cross-shelf heat flux to be negligible and making the ratio large. In summary, if this ratio is large, the alongshore and surface heat flux dominate the budget; if it is O(1), it may rapidly become large owing to the influence of mixing; if it is small, the cross-shelf heat flux dominates the budget. Essentially, the cross-shelf heat flux either dominates the budget or is zero.

6. Summary

Variation in the heat content of the North Carolina inner shelf is dynamically linked to the alongshore wind stress. If there is vertical thermal stratification, the cross-shelf heat flux dominates through Ekman dynamics, and if there is no vertical thermal stratification, the surface heat flux and the alongshore heat flux dominate. The dominant source of variation in the heat content varies on an annual cycle, owing to the seasonal nature of the vertical thermal stratification. This hypothesis is supported by the CoOP Inner Shelf Study data, in which variation during the August time period was dominated by the cross-shelf flux and variation in the October time period by the surface and alongshore heat fluxes. Analysis of wind and water temperature data from the FRF allowed a more basic test of this hypothesis over a 12-year time period. This analysis showed that between May and August, a time period characterized by strong thermal stratification, the cross-shelf heat flux dominates variation in heat content, and between October and February, the surface heat flux and alongshore flux dominate variation. These results differ from those of Dever and Lentz [1994], Lentz and Chapman [1989], and Lentz [1987], who all found variation in the heat balance off the California coast to be dominated by cross-shelf heat flux, independent of season. This difference is presumably due to the much weaker seasonal cycle of stratification on the west coast.

Appendix A: Derivation of the Heat Budget Equation

The heat budget equation can be derived by combining equations for the conservation of heat and mass of a fixed control volume. If it is assumed that there is no heat flux through the bottom of the domain, the statement of heat conservation can be written

$$\frac{\partial}{\partial t} \int_T dA + \int_{H}^{0} (u_T)_{x=L} dz + \frac{\partial}{\partial y} \int_T dA = \int_{0}^{L} \frac{Q}{\rho c_p} dz, \quad (A1)$$

where dA is the area bounded by the surface, bottom, and offshore extent L and H(x) is the bottom depth. Decomposing u and T into their instantaneous vertical average and an anomaly [u = < u > (x, t) + \tilde{u}(x, z, t), T = < T > (x, t) + \tilde{T}(x, z, t), where \(u > H^{-1} \int_{-H}^{0} u dz \) and \(< T > = H^{-1} \int_{-H}^{0} T dz\)] yields, for the second term:

$$\int_{-H}^{0} uT dz = < u > < T > + H^{2} \int_{-H}^{0} \tilde{u}\tilde{T}dz. \quad (A2)$$

The third term in (A1) can also be expanded, this time by breaking T into its area average and anomaly (\(T = \tilde{T} + T'\), where \(\tilde{T} = A^{-1} \int_T dA\). The third term becomes

$$\int_T \frac{\partial[v(T + T')]}{\partial y} dA = \int_T v \frac{\partial T}{\partial y} dA + \int_T \tilde{T} \frac{\partial v}{\partial y} dA + \int_T T' \frac{\partial v}{\partial y} dA. \quad (A3)$$

The third term on the right-hand side of (A3 cannot be evaluated with the data collected in this experiment and is disregarded; any real contribution from this term is reflected in the error. By mass conservation, the first term on the right-hand side of (A2) and the second term on the right-hand side of (A3) combine to form \(< u > H(T - < T >)\). This term represents heat deposited in the region owing to transport divergence and appears to be small for observed values of \(< u > \) in the CoOP ISS data set, as \(\tilde{T} \approx < T >\). Therefore the
two divergence terms are dropped. The heat budget equation now becomes
\[
\frac{\partial}{\partial t} \int_0^L \int_{-H(z)}^0 T \, dz \, dx = - \int_{-H(L)}^0 \bar{w} \tilde{T} \, dz - \int_0^L \frac{\partial T}{\partial y} \, dy \, dx + \int_0^L \frac{Q}{\rho c_p} \, dx, \tag{A4}
\]
where the term on the left hand side represents \( \partial_t (STO) \), and the first, second, and third terms on the right-hand side denote CHF, AHF, and SHF, respectively.

Appendix B: Discretization of the Heat Budget Terms

The storage term can be approximated as
\[
\partial_t (STO) \approx \Delta \sum_{i=1}^3 \sum_{j=1}^{n(i)} T_{ij} \alpha_{ij} / \Delta t, \tag{B1}
\]
where \( n(1) = 7, n(2) = 12, \) and \( n(3) = 10 \). Here \( \alpha_{ij} \) represents the weight given to each measurement, equal to the area of the region each instrument represents. The area of influence of each instrument extended to the horizontal and vertical midpoints of the distance to the next adjacent instrument. The top and bottom instruments were extrapolated to the surface and bottom, respectively. The sum of the weights is equal to the total cross-sectional area of the region inshore of \( d3 \). The \( \Delta t \) is the time interval between measurements, in this case 3600 s. In October, the mooring at the \( d1 \) site was not present for most of the time series, and the \( d2 \) data were accordingly weighted to compensate. As the nearshore cross-shelf temperature gradients during October were observed to be small from other data sources (such as the CTD surveys), this should make very little difference.

Error in the storage term is due primarily to low spatial resolution of the temperature measurements. This may be significant when there are strong horizontal density gradients, such as during upwelling and downwelling events.

The cross-shelf flux at \( d3 \) is approximated using
\[
\text{CHF} \approx - \sum_{j=1}^6 (\bar{u}_{3j})(\tilde{T}_{3j}) \beta_j, \tag{B2}
\]
where \( \beta_j \) represent vertical weightings. This term represents the exchange of heat across the offshore boundary at \( x = L \), in this case, 16.4 km offshore at the \( d3 \) site. For a given cross-shelf velocity profile, this term is smaller when the vertical temperature gradient is weak, as \( \tilde{T}_{3j} \approx 0 \). Essentially, if there is no vertical temperature gradient, water moving onshore and water moving offshore have the same heat content and no net heat transport occurs.

Error in computing the cross-shelf heat flux has two primary sources: not properly choosing the cross-shelf direction and the finite vertical resolution of the velocity and the temperature. The extrapolation of the top VMCM velocity to the surface is another potential source of error, but a comparison of the VMCM data with ocean surface current radar data [Shay et al., 1998] suggests that the surface shear is not large, and hence the extrapolation made here is not a large source of error. Temperature data taken closer to the surface suggested that the extrapolation of temperature data to the surface is a reasonable approximation.

The surface heat flux was approximated using
\[
\text{SHF} = Q \times L, \tag{B3}
\]
where \( Q \) is the estimated total surface heat flux measured at \( d2 \) and \( L \) is the width of the shelf; \( d2 \) is the only location where reliable surface heat flux measurements were made (see AL).

There are two sources of error in determining the surface heat input to the region. First, reliable meteorological measurements were made at only one site (\( d2 \)) and it is known that meteorological fields varied considerably across the shelf (as discussed in AL). However, \( d2 \) was in the center of the domain, and cross-shelf variations in the estimated surface heat flux were large only during upwelling-favorable winds in August. In the absence of reliable measurement of the surface heat flux at different cross-shelf locations, the other source of error is due to the fact that the estimates of surface heat flux at \( d2 \) contain error (see AL for a more thorough discussion of error associated with determining \( Q \)).

The alongshore heat flux was approximated using
\[
\text{AHF} = - \frac{1}{\Delta y} \sum_{i=1}^m \sum_{j=1}^{n(i)} \Delta T_{ij} v_{ij} \gamma_{ij}. \tag{B4}
\]

The alongshore heat flux was the poorest resolved of the components of the heat flux, owing to the poor alongshore resolution of temperature, which was measured only on the 6- and 20-m isobath. The difference in temperature between \( j3 \) and \( j1 \) was used to estimate the temperature gradient at \( d1 \). The difference between the surface temperature at NSC and SSC was used for the top half of the water column at \( d2 \) and \( d3 \), and the difference between the bottom of NSC and SSC was used for the bottom half of the water column at \( d2 \) and \( d3 \). Along the 6-m isobath, \( \Delta y = 34 \) km, and along the 20-m isobath, \( \Delta y = 58 \) km. This term represents the advection of alongshore temperature gradients. The other component of the alongshore heat flux, the flux divergence term \( (\int \frac{\partial T}{\partial y} \, dA) \) is ignored in this formulation.

Inaccuracy in the alongshore heat flux is due primarily to poor resolution of the alongshore gradient. In addition to the fact that the differences were made over a long alongshore distance (60 km), there were only three alongshore temperature gradient measurements used.
Finally, the term representing alongshore heat flux due to alongshore mass divergence could not be estimated, further degrading the measurement.

Acknowledgements. The moored meteorological and oceanographic measurements used in this paper were funded by National Science Foundation grant OCE-92-21615 and were provided by S. Lentz. Other data were kindly provided by the Field Research Facility in Duck, North Carolina. Support for the analysis of the data was provided by National Science Foundation grant OCE-96-33025. J.A.A. was supported by an ONR AASERT grant, N00014-93-1-1154. Conversations held with S. Lentz helped tremendously in the production of this paper. This is WHOI contribution 9559.

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