Controls of subsurface temperature variability in a western boundary upwelling system

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[1] The mechanisms controlling subsurface temperature variability on the outer shelf in a western boundary upwelling system are quantified using observations from a mooring deployed off Cabo Frio, Brazil. Results from a multiple linear regression analysis reveal that, in addition to low-frequency variations associated with the seasonal evolution of temperature, the dominant mechanisms controlling temperature variability are wind stress curl–driven upwelling, cross-isobath transport, the proximity of the Brazil Current to the shelf break, and perhaps changes in the strength of tidal mixing associated with the spring-neap cycle. The influence of the proximity of the Brazil Current decreases strongly with depth, being restricted to the top 80 m. Regression coefficients indicate that the relative contributions from the different forcings are roughly similar and that no single process has a dominant role explaining temperature variability near the shelf break. These suggest that successful modeling efforts in the region must adequately represent each of those processes.
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1. Introduction

[2] Coastal upwelling regions have been intensively studied over the last four decades, in part because of their great importance to coastal ecosystems. Rising water brings nutrients to the euphotic zone, influencing the distribution of phytoplankton and sustaining a highly productive food web. Most upwelling studies, however, have been in eastern boundary currents [e.g., *Huyer*, 1983; *Barton*, 1998]. Studies of coastal upwelling in western boundary currents [e.g., East Australian Current: *Roughan and Middleton*, 2002; Florida Current: *Smith*, 1983] are much less frequent. One such region, the Cabo Frio Upwelling System off Brazil, has been the focus of renewed attention over the last decade. While the offshore region is dominated by warm and nutrient-poor Tropical Water flowing in the Brazil Current, the predominantly upwelling favorable (northeasterly) winds during spring and summer [e.g., *Castro and Miranda*, 1998] have long been shown to be correlated with surface cold water events near the cape [Figure 1; e.g., *Ikeda et al*., 1974], consistent with coastal upwelling dynamics. The upwelled water, mostly consisting of South Atlantic Central Water (SACW), enriches the water column with nutrients and supports regional fisheries productivity [*Matsuura*, 1996]. More recently, however, several other mechanisms in addition to coastal upwelling have been suggested to play an important role in bringing the cold water to the surface near the cape. Flow topography interactions [*Rodrigues and Lorenzzetti*, 2001], the passage of meanders and eddies produced by instabilities of the Brazil Current [*Campos et al*., 2000], and vertical transport driven by wind stress curl [*Castelao and Barth*, 2006; *Castelao*, 2012] have all been shown to potentially contribute to enhance upwelling near Cabo Frio. The region off the cape therefore exhibits a combination of the classic circulation of western boundary regions and multiple upwelling mechanisms that are more commonly observed in eastern boundary currents (coastal upwelling, wind stress curl–driven upwelling, etc.). Most previous studies of upwelling in the region have been based on numerical models, satellite observations, which are restricted to the surface of the ocean, or short-duration in situ observations. Here, we use 10.5 month long depth-resolving in situ observations from an oceanographic mooring to quantify the relative importance of different forcings in temperature variability at the outer shelf in a western boundary upwelling system.

2. Methods

[3] Observations were collected at the outer shelf off Cabo Frio (41.58°W, 23.61°S; Figure 1) from November 2010 to September 2011 (gaps from 2 February to 15 March and from 13 June to 20 July were due to instrument maintenance). A subsurface mooring was deployed at the 145 m isobath. The mooring was equipped with two 400 KHz Nortek Aquadopp Profilers installed at mid water (upward-looking and downward-looking) and 20 ONSET tidbits V2 temperature loggers spaced at approximately 5 m intervals between 120 and 30 m depth, the shallowest depth where operations could be conducted safely because of high fishing activity in the area. Temperature and velocity time series were block averaged in 1 h intervals and low-pass filtered (half-power point of 40 h).

[4] Surface winds were obtained from the Advanced Scatterometer (ASCAT) on board the Meteorological Operational (MetOp-A) polar satellites at 12.5 km sampling resolution. Surface stresses were calculated from equivalent neutral-stability 10 m winds using the modified Large-Pond drag coefficient for neutrally stable conditions [*Large et al*., 1994]. Coastal alongshore winds were determined as the dot product between wind measurements closest to the coast and a unit vector tangent to the local coastline around Cabo Frio.

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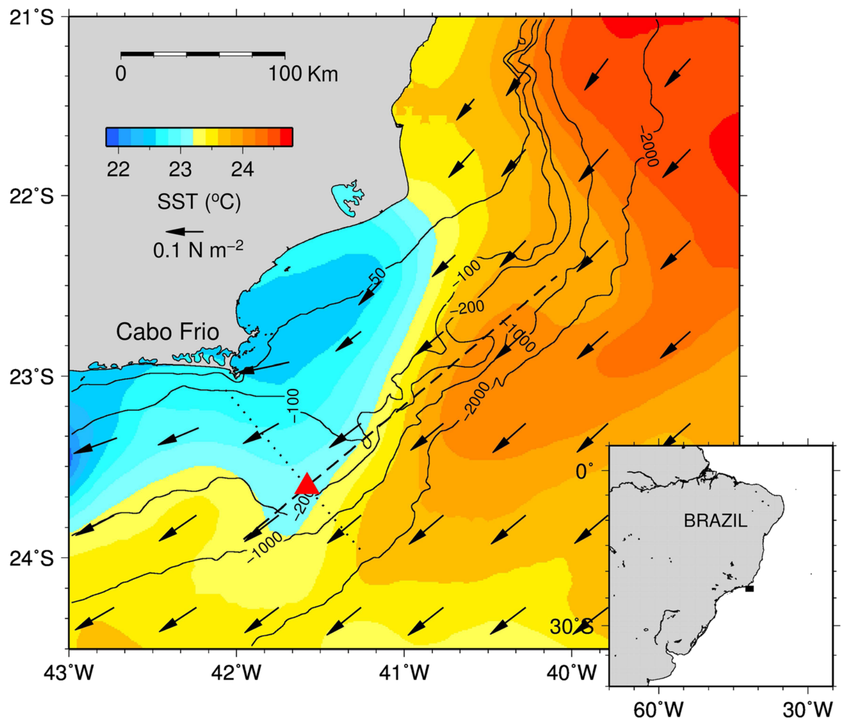

Figure 1. Average SST (°C) derived from GHRSST/OSTIA and vector average wind stress from ASCAT. The red triangle shows the mooring position, while black contours are isobaths. Cross-isobath and along-isobath directions (dotted and dashed lines, respectively) are defined with respect to the average direction of the 200 m isobath upstream of the mooring site.

This produces results comparable to those obtained using a unit vector tangent to the 200 m isobath, the approximate depth of the shelf break. The wind stress curl was computed within each ASCAT swath using centered differences. In the processing used here, wind stress cells closer than ~35 km from the coast were flagged to avoid land contamination.

[5] In order to determine the position of the Brazil Current and its internal front relative to the mooring site, sea surface temperature (SST) data were obtained from the Group for High-Resolution Sea Surface Temperature (GHRSST) Operational SST and Sea Ice Analysis (OSTIA). The Brazil Current core and internal front positions were defined as the distances between the mooring site and the location of maximum temperature (core) or maximum SST gradient (internal front) along a line orthogonal to the 200 m isobath passing through the mooring site (Figure 1). Sea surface height (SSH) observations constructed by SSALTO/DUACS using measurements from simultaneously operating altimeters (distributed by AVISO) were used to identify the presence of cyclonic and anticyclonic eddies using the eddy detection algorithm described by *Chelton et al.* [2011].

3. Results

[6] The temporal evolution of temperature at the mooring site throughout the water column is shown in Figure 2 (top panel). Low-frequency temperature variability is clearly superimposed by several short-term warming and cooling events. Most events span the entire water column, with temperature at the surface and that at depth varying in phase. The magnitude of the changes in temperature varies with depth, however. After averaging the in situ data to the same temporal resolution of satellite observations, temperature data were plotted against different forcings. The analysis reveals that temperature variability is correlated with several environmental conditions (Figure 3). Negative wind stress curl, which is up-

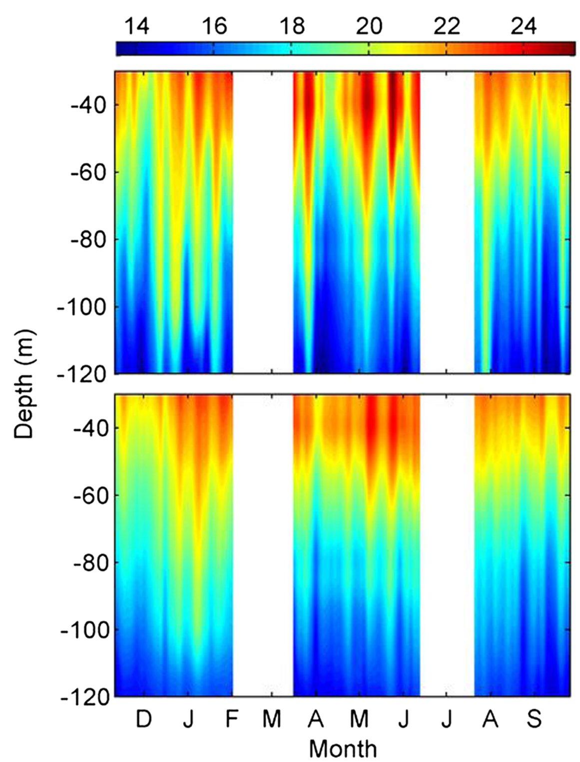

Figure 2. Observed (top) and reconstructed (bottom) temperature (°C) time series at the mooring site off Cabo Frio. Reconstructed temperatures are based on multiple linear regression analysis (see text for details).

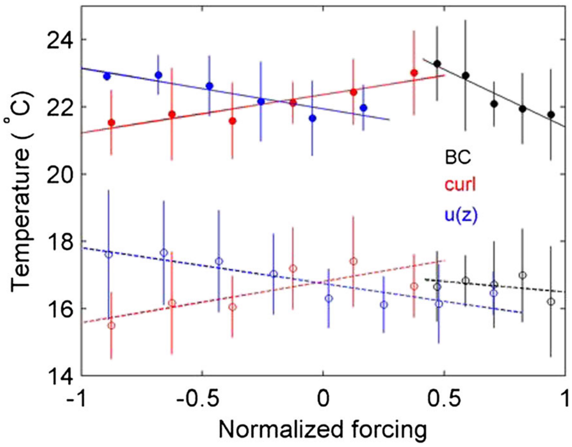

Figure 3. Color-coded binned scatterplot of temperature at 30 m (solid lines, solid symbols) and 100 m (dashed lines, open symbols) below the surface versus normalized forcing. Each forcing has been normalized by its maximum magnitude. The error bars represent the ±1 standard deviation within each bin. BC: distance from Brazil Current to mooring site; curl: wind stress curl; u(z): depth-dependent cross-isobath current.

welling favorable in the southern hemisphere, is associated with cooling, at both 30 and 100 m below the surface. Cross-isobath currents lead to temperature changes of similar magnitude, with onshore (negative) flow leading to warming and offshore (positive) flow leading to cooling. The effects of cross-isobath flow are roughly similar at 30 and 100 m below the surface. Changes in temperature are also related to changes in the position of the Brazil Current, although the effect seems to be restricted to the upper water column. The near-surface temperature is about 2°C higher at the mooring site when the warm Brazil Current is found closer to the coast compared to when it is located farther offshore. At 100 m below the surface, however, temperature variability does not seem to be correlated with changes in the position of the boundary current. Bin-averaged temperature data were also compared to the strength of coastal upwelling (i.e., Ekman transport at the coast estimated using alongshore coastal winds with several time lags) and the amplitude of cyclonic and anticyclonic eddies in the vicinity of the mooring site. In either case, temperature variability was not found to be correlated with the forcing.

[7] The temperature time series at the mooring site was reconstructed by multiple linear regression analysis as a function of annual and semiannual harmonics ($\omega_1 = 2\pi/365.25$ days; $\omega_2 = 4\pi/365.25$ days), wind stress curl, cross-isobath currents, and the distance from the core of the Brazil Current to the mooring site. Since spectral analysis of the temperature time series reveals a peak of energy with a period close to 14.75 days, we also used a third harmonic with frequency $\omega_3 = 2\pi/14.75$ days. The seasonal cycle was removed from the forcing before the regression analysis. It is important to point out that using a linear model is a simplification, since the relationship between the different forcings and temperature may be nonlinear. We also note that the time series are not long enough to confidently extract the seasonal cycle. The observations are fitted to annual and semiannual harmonics, however, so that the model can reproduce variability at scales much longer than the "event" time scale characteristic of the other forcings. Analysis of the variance of the regression model errors confirmed that the different inputs are statistically significant improvements to the model. Correlation coefficients (significant at the 95% confidence level) between the modeled data and the original data are slightly higher than 0.6 throughout most of the water column, increasing to 0.7 at 40 m below the surface (Figure 4). The correlation decreases substantially below 100 m depth, however. The model captures most warming and cooling events near the surface (Figure 2), although their magnitudes are somewhat underestimated. A few events, like the top-to-bottom warming observed in late July, are not well represented by the model.

[8] Vertical profiles of the regression coefficients for each forcing are shown in Figure 5. The time series of each forcing has been normalized to have unit standard deviation. Therefore, the coefficients are related to the relative contribution of the different environmental conditions to the total temperature variability. The annual harmonic is the largest term, dominating the low-frequency variability in the record. The other forcings contribute roughly equally to temperature variability. The regression coefficients for the wind stress curl term are positive, which is consistent with wind stress curl–driven upwelling in the southern hemisphere. Values are highest in the middle of the water column, decreasing slightly above 50 m but sharply below 100 m. The range in variations in the normalized wind stress curl time series (not shown) is ~4.5, indicating that curl-driven upwelling can lead to over 1°C temperature variations in the top 100 m of the water column. The regression coefficients due to cross-isobath currents are nearly depth independent and negative, indicating that onshore flow is associated with warming of the entire water column, while offshore flow is indicative of cooling. In contrast to these last two terms, the coefficients from the term related to the distance from the Brazil Current to the mooring site vary strongly with depth. They are high and negative near the surface, decreasing to approximately zero below 80 m depth. The negative coefficients at the surface indicate that warm waters are found when the Brazil Current is found closer to the shelf break. Finally, the regression coefficients for the harmonic with a period of 14.75 days are nearly constant above 100 m, decreasing to approximately zero at 120 m below the surface.

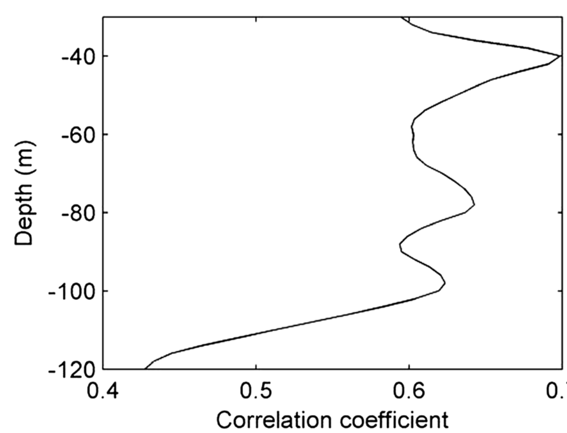

Figure 4. Correlation coefficients between temperature mooring data and results from a multiple linear regression analysis.

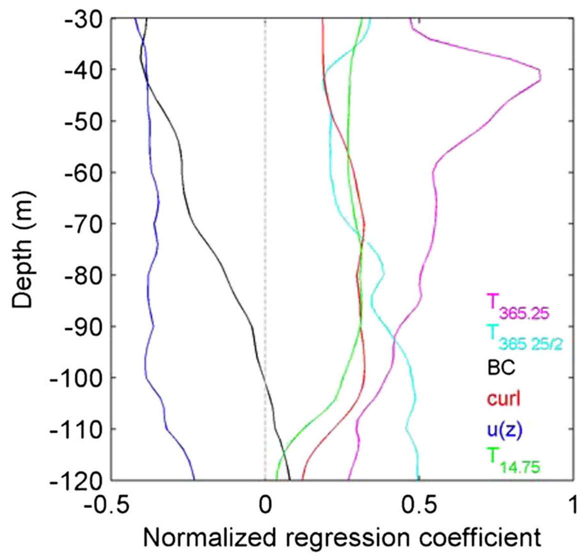

Figure 5. Color-coded normalized coefficients from a multiple linear regression analysis between temperature observations and harmonics with three different periods ($T_1 = 365.25$ days, $T_2 = 365.25/2$ days, $T_3 = 14.75$ days), wind stress curl (curl), the distance between the Brazil Current and the mooring site (BC), and depth-dependent cross-isobath current (u(z)). The time series of each forcing (not shown) has been divided by its standard deviation, while the regression coefficients have been multiplied by their respective standard deviations (calculated over the entire data period). Therefore, the time series of all forcings are nondimensional and have unit variance, while the normalized regression coefficients have units of degrees Celsius and are related to the contribution of the different forcings to the total temperature variability.

4. Discussion and Conclusions

[9] Observations from a 10.5 month long mooring deployment off Cabo Frio (Figure 1) are used to investigate the controls of subsurface temperature variability near the shelf break. Although the cape is located in a western boundary current system, the region is well known for frequent and persistent upwelling [e.g., *Castro and Miranda*, 1998]. Mooring observations reveal that several short-term warming and cooling events are superimposed on the seasonal evolution of temperature in the region (Figure 2). Many factors seem to contribute to temperature variability on scales of several days, including wind stress curl–driven upwelling, changes in the position of the Brazil Current, and advection of warm or cold water by cross-isobath currents (Figure 3). The relative importance of the different terms varies with depth (Figure 5), however, and the contribution from the position of the Brazil Current seems to be restricted to the upper water column. It is important to realize though that some of these processes may not be completely independent. For example, it is possible that cross-isobath flow is preferentially onshore during large episodic displacements of the Brazil Current toward the shelf break and preferentially offshore during large episodic offshore movements of the boundary current. Correlation coefficients between the different forcings are generally small and not statistically significant (Table 1) though. The only exception is the correlation between alongshore wind stress (not included in the model) and the position of the Brazil Current, which is marginally significant. Additionally, analysis of variance indicates that using the measures shown in Figure 5 as inputs in the regression leads to a statistically significant improvement of the model. We also found that the model is improved if harmonics with a period of 14.75 days are used. This may be related to variations in tidal mixing intensity due to the spring-neap cycle, which is substantial in the region [*Pereira and Castro*, 2007], although we cannot test this hypothesis with our current data sets.

[10] Surprisingly, temperature variability at the mooring is not correlated (at the 95% significance level) with alongshore winds near the coast. The mooring is located at approximately 80 km from the coast, so it is possible that much of the temperature variability associated with coastal upwelling is restricted to regions inshore of the mooring site. Off Cabo Frio, the Burger number $S = \alpha N/f$, where α is the bottom slope, N is the buoyancy frequency, and f is the Coriolis parameter, is generally much smaller than 1, implying that the return flow associated with the upwelling circulation occurs primarily in the bottom boundary layer instead of in the interior [*Lentz and Chapman*, 2004]. Therefore, an alternative explanation is that much of the temperature variability associated with coastal upwelling is restricted to surface and bottom boundary layers, which are not resolved by the mooring instrumentation.

[11] It is also surprising that temperature variability is correlated with neither the amplitude of cyclonic and anticyclonic eddies nor SSH itself, considering that several studies have shown that eddies and meanders of the Brazil Current can drive upwelling in the region [e.g., *Campos et al.*, 2000]. Unlike the other data sets used here, which are of relatively high temporal resolution, the global SSH gridded product is only available every 7 days, which is comparable to the time scale of the warming and cooling events observed in the temperature record (Figure 2). Additionally, eddies with e-folding scales smaller than 0.4° are filtered out by the objective analysis procedure implemented by SSALTO/DUACS, while those between 0.4° and 0.6° are

Table 1. Correlation Coefficients Between Several Forcings After Removing the Seasonal Cycle[a]

	Curl	BC	u (depth-averaged)	Coastal Ekman transport	SSH
Curl	1	--	--	--	--
BC	−0.20	1	--	--	--
u (depth-averaged)	0.14	−0.15	1	--	--
Coastal Ekman transport	−0.09	**0.33**	−0.22	1	--
SSH	0.04	−0.07	0.06	0.08	1

[a]The value in bold is significant at the 95% confidence level. Curl: wind stress curl; BC: distance from Brazil Current to mooring site; u: depth-averaged cross-isobath current; SSH: sea surface height.

attenuated [*Chelton et al.*, 2011]. Therefore, it is possible that eddies that contribute to temperature variability at the mooring site have been attenuated or even filtered out from the SSH fields, which would disrupt the correlation analysis.

[12] In summary, the analysis reveals that several processes act together to control subsurface temperature variability near the shelf break inshore of the western boundary current, with no single process playing a dominant role. Previous studies have shown that multiple upwelling mechanisms can also be important in other western boundaries (e.g., *Roughan and Middleton*, 2002). Numerical modeling efforts in those regions are therefore challenging since they must adequately represent wind stress curl–driven upwelling, changes in the position of a western boundary current, the relatively weak cross-isobath circulation, and possibly changes in the strength of tidal mixing. Modeling efforts should also represent coastal upwelling and the effect of eddies, even though they were not found to be correlated with temperature at the mooring site, because it is possible that the absence of correlation was due to limitations in the data sets rather than to a lack of a dynamic relationship. Lastly, additional long-term moorings distributed across the shelf are needed to quantify the spatial variability in the relative contribution of the different forcings to temperature variability in this western boundary upwelling system.

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