Coastal upwelling off Cape São Tomé (22°S, Brazil):
The supporting role of deep ocean processes

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Abstract

The regional ocean off Cape São Tomé (CST, 22°S, Brazil) is known to feature transient coastal upwelling and intense mesoscale activity associated with the Brazil Current (BC). Satellite and in situ observations are used to characterize the coastal upwelling and the oceanic pycnocline water intrusions onto the continental shelf. Coastal upwelling events around CST are found to be less intense than the ones around Cape Frio (23°S), confirming previous findings. It is shown that the quasi-standing growth of a BC cyclonic meander is an effective supporting mechanism to this primarily wind-driven coastal upwelling system. A typical propagating cyclonic meander event is described and compared with its quasi-standing counterpart. The propagating cyclones also appear to promote oceanic pycnocline water intrusions, but at a lesser extent than the quasi-standing features. The supporting effect of the BC cyclones was quantified via simplified numerical experiments carried out with a 2D, primitive-equation numerical model. It is shown that meanders enhance intrusions as they grow, and may decrease by \approx 50\% the momentum input needed from the wind to cause coastal upwelling. Also, the role of the sloping of the isolines linked to the mean baroclinic structure of the Brazil Current is examined in idealized numerical experiments. This structure is shown to be sufficient to explain the observed time scales of coastal upwelling. The kind of meander-driven intrusion investigated here appears to be a regional singularity of the CST region, and may provide insight into the cross-shelf dynamics of other Western Boundary Current regions where similar quasi-standing instabilities exist.

Keywords: Brazil Current, Coastal upwelling, Cape São Tomé, Intrusion, Cross-shelf exchange

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1. Introduction

Coastal upwelling and intrusions of waters from the oceanic pycnocline (the South Atlantic Central Water, SACW) onto the continental shelf off southeast Brazil are phenomena controlled by various physical processes, which operate at multiple space and time scales. It is widely accepted that the primary forcing to coastal upwelling in this region is the coastal divergence of the wind-induced Ekman transport. According to the review elaborated by Castro and Miranda (1998), when strong easterly-northeasterly winds reach the southern part of the Abrolhos–Campos region (22°S–23°S, Figure 1), the SACW penetrates deeply onto the shelf, bringing cold, nutrient-rich waters towards the coast, and into the euphotic zone.

1.1. The study region

Our study region is Cape São Tomé and its vicinities (Figure 1). As pointed out by Rodrigues and Lorenzzetti (2001), three major coastal upwelling centers off southeast Brazil can be readily identified (Vitória, around 20–21°S, Cape São Tomé, around 22°S and Cape Frio, around 23°S). The Cape Frio coastal upwelling region has received large scientific attention (e.g., Allard, 1955; Emilsson, 1961; Ikeda et al., 1976; Carbonel, 2003; Franchito et al., 2008). To our knowledge, however, no study dedicated specifically to coastal upwelling and SACW intrusions near Cape São Tomé has been conducted to date.

The continental margin encompassing these coastal upwelling centers has important along-shore variations in shelf width and shelfbreak depth. Off Vitória, the shelfbreak is located around the 35 m isobath. It deepens to 100–110 m at Cape São Tomé and 140–150 m at Cape Frio. The shelf is only 50 km wide off Vitória. It widens to 80–100 km off Cape São Tomé and narrows again to 50–80 km off Cape Frio (Zembruscki, 1979). As discussed by Rodrigues and Lorenzzetti (2001), such geomorphological features have important dynamical implications.

1.2. Deep ocean processes, South Atlantic Central Water intrusions and coastal upwelling

When instabilities (i.e., meanders/eddies) are concentrated at the outer shelf, it is reasonable to expect enhanced shelf-ocean exchange (Brink, 1998). When analyzing observations of slope water intrusions in the eastern coast of the United States, Lee and Pietrafesa (1987) concluded that such
intrusions could be explained by a combination of coastal and deep ocean forcings. They proposed three modes of intrusion, namely: (i) Proximity of the Gulf Stream to the shelfbreak, (ii) Presence of a cyclonic perturbation of the Gulf Stream and (iii) Upwelling-favorable wind stress. These authors also concluded that the oceanic modes (i and ii) are necessary to initiate an intrusion, but that the coastal mode (iii) is required for coastal upwelling to develop.

In a recent review on the East Australian Current (EAC), Suthers et al. (2011) point out some dynamical singularities of the central east coast of Australia (28–33°S). Slope water intrusions and coastal upwelling in this region may occur through four different mechanisms, three of which are driven by the EAC (Roughan and Middleton, 2002). Of particular interest to this study is the analogy between the production of divergence resulting from the separation of the EAC from the coast and the mechanism proposed in the numerical study of Calado et al. (2010). The offshore departure of the EAC may cause intrusion of slope water, and although it may not always account for coastal upwelling individually, it may cause the preconditioning of the water mass field on the shelf, thus enabling weak favorable winds to produce coastal upwelling (Gibbs et al., 1998; Roughan and Middleton, 2002). This effect is similar to the model suggested by Calado et al. (2010) for the coastal upwelling around Cape São Tomé (CST), in the sense that eddy-driven intrusions precondition the shelf waters to wind-induced coastal upwelling. These Brazil Current (BC) eddies are very common, but not permanent features. They appear as a conspicuous bend of the mean inshore thermal front of the BC (Lorenzzetti et al., 2009).

There are indications that near CST the BC occupies most of the shelf during the austral summer and may be detected even on the inner shelf, which causes the flow to be predominantly southward. During winter, however, the BC retreats to the shelfbreak, allowing inner- and mid-shelf currents to be mostly wind-driven (Castro and Miranda, 1998). The effects of the sharp coastline orientation changes and the complex bottom topography have been examined by Rodrigues and Lorenzzetti (2001). They showed that, around Cape Frio, the coastline geometry is the main driver of upwelling, while around Cape São Tomé, bottom topography prevails. It is possible that bottom fiction may induce onshore flow within the bottom boundary layer, through the mechanism proposed in the barotropic model of Hsueh and O’Brien (1971) and the two-layer model of Lorenzzetti et al. (1988), but this mechanism is yet to be investigated.

The overview presented above reveals unknowns regarding the coastal upwelling and the SACW
intrusions in the CST region. We point out that the experiment of Calado et al. (2010) had no wind forcing, and therefore did not include wind-driven Ekman dynamics. Also, a mechanism that has received little attention is the mean baroclinic signal of the BC. According to Castro et al. (2006), this sloping of the isolines may explain the year-round availability of SACW on the bottom of the outer shelf off southeast Brazil.

1.3. Questions addressed

This study aims to characterize the SACW intrusion and the coastal upwelling processes in the vicinities of Cape São Tomé. To this end, the following scientific questions are posed:

1. What are the general physical characteristics of the SACW intrusion and coastal upwelling processes near Cape São Tomé?
2. Is the quasi-standing growth of the Brazil Current cyclonic meanders a relevant supporting mechanism to the SACW intrusions and the coastal upwelling near Cape São Tomé?
3. How much of the SACW intrusions near Cape São Tomé can the mean baroclinic signal of the Brazil Current account for?

This paper is organized as follows. In Section 2, the dataset, the numerical model and the methods are described. Next, in Section 3, the results are presented and discussed. Section 4 concludes the paper, where results are summarized and conclusions are drawn.

2. Data and methods

2.1. Data analysis

The data used in this work comprise in situ and satellite observations. This provides a mutually complementary approach. On the one hand, in situ surveys using Conductivity, Temperature and Depth (CTD) sensors allow for the identification of the quasi-synoptic 3D signals of the relevant oceanographic features. Satellite data, on the other hand, provide synoptic 2D snapshots of surface signals. This dataset is used to characterize the intrusion and upwelling processes and to investigate the hypothetical coupling between such processes and the cyclones of the BC.
2.1.1. Quasi-synoptic hydrographic data

The in situ data analyzed in this work were collected in one winter and three summer oceanographic surveys (Figure 1). Those are: The summer cruise from the “Dynamics of the Western South Atlantic Shelf Ecosystem” (DEPROAS) project (transect from 23 through 24 January 2002), the summer (transect from 23 March through 10 April 2009) and winter (transect from 30 August through 15 September 2009) cruises from the “Environmental Heterogeneity Assessment of the Campos Basin” (HABITATS) project and the summer cruise from the “Ministry of Science and Technology 2” (MCT2) project (stations from 5 through 8 January 2011). For convenience, these surveys will be referred to as JAN02, MAR09, AUG09 and JAN11, respectively. The data processing was carried out following the standard procedures outlined in Emery and Thomson (2001). Temperature and salinity distributions were then prepared, and used to identify the signal of the eddies/meanders in the water column and to track the SACW intrusions. The objective interpolation technique described in Silveira et al. (2004) was used to smoothen the vertical sections, in order to facilitate their interpretation.

2.1.2. Satellite data

To obtain synoptic pictures of the upwelling events, Sea Surface Temperature (SST) data from the Geostationary Environmental Operational Satellites (GOES) was analyzed. The GOES data (6 km, 1 h resolution) was downloaded from ftp://podaac.jpl.nasa.gov/allData/goes/L3/goes_6km_nrt/americas/. Upwelling events at CST, from September 2003 through March 2012 were identified. As stressed by Walker et al. (2003), GOES SST composites provide several advantages over other SST products, particularly for the tracking of relatively fast-moving oceanographic features, such as upwelling plumes. These authors also show that the accuracy of this dataset is better than 0.5°C. Furthermore, the implementation of bayesian cloud detection algorithms (e.g., Uddstrom et al., 1999) allows for the efficient removal of cloudy pixels. In this study, pixels with cloud contamination probability greater than 2% were eliminated.

For the detection of the upwelling events, the 20°C isotherm was used as a tracer of the oceanic pycnocline. In some cases, the minimum SSTs were greater than 20°C (up to 21°C), but a plume-like feature was clearly visible. For this reason, the onset of an upwelling event was indicated either by the presence of pixels colder than 20°C or by the visual detection of a plume-like minimum in
the vicinities of CST. These criteria were deemed reasonable, since the average minimum SST associated with upwelling at CST was estimated to be 19.9°C by Castro et al. (2006), from a 10-year analysis of independent SST data. The time and date of each upwelling event was determined from the hourly GOES images. For the events where the hour of the day could not be determined due to cloud cover, the time considered was noon. Also, SST and Sea Surface Chlorophyll-a (SSC) data from the Moderate-resolution Imaging Spectroradiometers (MODIS) were used to identify upwelling plumes in cases where GOES data was unavailable or inconsistent. The L0 MODIS data (250 m resolution) was downloaded from [http://oceancolor.gsfc.nasa.gov](http://oceancolor.gsfc.nasa.gov), and kindly processed by the Aquarela-CEBIMar/USP group. One Advanced Very High Resolution Radiometer (AVHRR) image from the HABITATS project was kindly provided by Petróleo Brasileiro S/A (PETROBRAS).

After the detection of the coastal upwelling events between September/2003 and March/2012, events where the SST front (zone of maximum SST gradient) was located offshore of the mean thermal front presented by Silveira et al. (2008) were classified as events of simultaneous coastal upwelling and meandering. Only the cases where the meanders grew nearly without along-shore propagation were considered.

In order to isolate the effects of the wind forcing in the processes of intrusion and upwelling, a characterization of the wind regime was done. We resorted to eleven years (2000-2011) of wind data from a blended multi-satellite scatterometer product (Zhang et al., 2006), produced by the National Oceanic and Atmospheric Administration (NOAA). The scatterometer data (25 km, 6 h resolution) was downloaded from [http://nomads.ncdc.noaa.gov](http://nomads.ncdc.noaa.gov). The wind stress vector ($\vec{\tau}$) was parameterized via the bulk aerodynamic relation $\vec{\tau} = \rho_a C_D U u^{x,y}$, where $\rho_a$ is the air density (assumed to be 1.226 kg m$^{-3}$), $C_D$ is the drag coefficient, $u^x$ ($u^y$) is the zonal (meridional) component of the wind vector 10 m above the sea surface and $U$ is the wind vector magnitude. The drag coefficient $C_D$ was calculated as in Mellor (2004). This formulation is shown by the author to closely agree with others applied in the literature (Garratt, 1977; Large and Pond, 1981 and Smith et al., 1992), yielding values of $O(10^{-3})$. The same formulation of $C_D$ was applied both to the observations and to the simplified model experiments (to be described in the next section).

Once the prevailing wind pattern was determined, some quantification of the wind forcing in individual events was needed. To do this, we calculated the wind stress impulse ($I$). This
parameter was estimated for (i) The upwelling events detected in the SST image analysis, (ii) The hydrographic surveys and (iii) The simplified model experiments. This quantity is defined by Csanady (1982) as \( I = \int (\tau^y / \rho) dt \), where \( \rho \) is the density of seawater (assumed to be 1025 kg m\(^{-3}\)) and \( \tau^y \) is the along-shore component of the wind stress vector. The wind vector near CST was derived from the spatial average of the scatterometer vectors within the green area indicated in Figure 1. This procedure was done for each field from the six-hourly blended wind dataset. The series obtained was linearly interpolated to generate an hourly time series of \( \tau^y \) near CST. The along-shore direction was rotated 47° clockwise from the meridional direction, reflecting the average orientation of the coastline between Cape Frio and CST. Therefore, negative (positive) values of the quantities \( \tau^y \) and \( I \) are upwelling- (downwelling-) favorable.

Lastly, the estimates of the wind stress impulse for cases both with and without meanders were compared statistically. The confidence intervals of the samples were determined via the bootstrapping technique. The BCA method was employed, with \( 10^6 \) bootstrap samples. For an introduction to this technique, the reader is referred to Efron and Tibshirani (1994). The observed minimum SSTs in each event were compared in the same way.

2.2. Numerical modeling

The numerical model employed was a sectional version of the Princeton Ocean Model (hereinafter referred to as POMsec). For the governing equations of POMsec, the reader is referred to Allen et al. (1995). Details concerning the original tridimensional version of the model are found in Blumberg and Mellor (1987).

2.2.1. Model setup

The model grid consists of 329 horizontal grid points, with constant horizontal spacing of 1 km. The inshore boundary is closed at the 7 m isobath. The offshore boundary is open. To damp the reflection of internal waves in the offshore boundary, a buffer zone consisting of the repetition of the 329th temperature-salinity profiles over 164 additional grid points was added. Therefore, the total model section was 493 points (492 km) long. In the vertical direction, the grid consists of 101 sigma levels. The sigma levels are more closely spaced near the surface and the bottom. This was done to best simulate the boundary layers. Radiational boundary conditions were applied to
both barotropic and baroclinic velocities, and a no-gradient boundary condition was applied to the 
surface elevation. All surface fluxes were set to zero, except for the momentum flux (wind stress).

2.2.2. Simplified model experiments

The simplified 2D experiments were designed to analyze the subinertial cross-shelf motions as-
associated with the intrusion and upwelling processes. Hence, we assume that along-shore advection
is locally less important in driving coastal upwelling than cross-shore advection in a time scale of
4 inertial periods ($\approx 5$ days).

In the first experiment (E1), an idealized scenario was sought, in which the stratification
associated with the mean baroclinic structure of the BC was removed. Instead, a flat stratification
derived from climatological temperature-salinity profiles (WOA09, Locarnini et al., 2010; Antonov
et al., 2010), located 300 km ($\approx 10$ internal radii of deformation) away from the shelfbreak was
prescribed. In the second experiment (E2), the signal of the mean BC jet was imposed, derived
from the regional feature model elaborated by Calado et al. (2008). The part of the field over the
shelf was tuned with a climatological field, using a least-squares technique. This was done to adjust
the 20°C isotherm (the pycnocline tracer) to a climatologically-consistent position (roughly the 40
m isobath, according to the regional climatology elaborated by Cerda and Castro, 2013, this issue),
while preserving the vertical stratification associated with the BC jet. It must be acknowledged
that, in performing this “climatological tuning”, no distinction is made between the contribution
of the mean baroclinic signal of the BC (upward sloping of the isolines) and the contribution of
other mechanisms (e.g., current-driven upwelling).

The last set of experiments (E3) was dedicated to the quantification of the effects of the quasi-
standing growth of a cyclonic meander of the BC, in the presence of wind forcing. Different
growth stages of the meander simulated by Calado et al. (2010) were used as initial conditions
for five experiments (E3a through E3e). The simulations were carried out until the 20°C isotherm
outcropped, so that the wind stress impulse required for upwelling in each case could be quantified.
However, the simulation output fields were analyzed only until four inertial periods ($4T_f, \approx 5.2$
days). This “threshold” time scale was chosen based on the difference between the time scales
associated with the meander growth ($\approx 23T_f$, or 30 days) and those associated with the classic
wind-driven upwelling ($\approx 1–2T_f$, or 1.3–2.6 days). Due to this order-of-magnitude difference, we
consider reasonable to interpret each meander growth stage as a fixed scenario, in which the embedded, wind-driven coastal motions could develop independently.

All experiments were forced with a wind stress field derived from the wind data described in Section 2.1.2. This forcing represents the most frequent wind pattern, which was determined as follows. The full wind series (January 2000 through December 2011) was divided in ten direction classes. The vectors contained in the class with the highest frequency were averaged in time, and then interpolated onto the model grid.

The initialization of the numerical experiments was based on Ezer and Mellor (1994). The simulations consisted of four phases: (1) In the first $4T_f$, the mass field was held fixed, while the velocity field was allowed to adjust geostrophically to it (diagnostic mode), from its initial state of rest. This first phase was carried out to remove noise from the prescribed mass field, and to adjust it to the the bottom topography. (2) Then, the model was integrated for another $3T_f$ in the prognostic mode, where both the mass and velocity fields evolved in time. This was done to damp the signal of internal waves associated with residual noise, thereby facilitating the interpretation of the model results. (3) Next, the model was switched back to the diagnostic mode, and the wind forcing was ramped linearly over $1T_f$. (4) Finally, the model was switched to the prognostic mode. Only the model results from phase 4 were analyzed. This methodology is sketched in Figure 2.

3. Results and discussion

3.1. Local wind regime

Since the wind is known to be the primary forcing to coastal upwelling, a simple assessment of the wind regime was performed to confirm this locally. To this end, a wind time series was derived by taking the spatial average of the vectors over the green area indicated in Figure 1, for each 6-hour field from the Zhang et al. (2006) multi-satellite product. The eleven-year (2000-2011) wind time series revealed that the along-shore wind was upwelling-favorable 78% of the time. This result suggests that the wind is indeed the primary forcing of the upwelling and that the long-standing conclusions for the Cape Frio region (Section 1) hold for Cape São Tomé as well. The directional histogram (Figure 3) shows that over 50% of the time, winds with magnitudes up to 12 m s$^{-1}$ blew from the northeast quadrant. Winds with other directions are less frequent, such as those that blow from the southern quadrants (i.e., downwelling-favorable), mostly due to the
motion of atmospheric frontal systems. Indeed, according to Stech and Lorenzzetti (1992), part of these fronts are deflected offshore before reaching Cape Frio, and some that do reach Cape Frio are already weakened, bringing only mild southerly winds. For this reason, the response of the shelf circulation around CST to such downwelling-favorable wind events is expected to be less intense than the response of shelf waters to the south of the Abrolhos-Campos region (Figure 1).

3.2. Quasi-standing cyclones versus propagating cyclones

It will be shown in the next section that coastal upwelling events can occur simultaneously with Brazil Current (BC) frontal cyclones or not. These cyclones (meanders or eddies) either propagate southwestward or grow in-place. As remarked by Calado et al. (2010), this is a very important difference in terms of cross-shelf circulation.

The meanders that grow nearly without propagating (i.e., in a quasi-standing fashion, Figure 5a), cause divergence in the water column by drawing shelf waters offshore. This mechanism is thought to cause or enhance SACW intrusions (Calado et al., 2010).

The propagating meanders, on the other hand (Figure 5b), are similar to the ones observed and simulated by Campos et al. (2000) in the South Brazil Bight (south of Cape Frio). The results of Silveira et al. (2008), obtained from a linear instability analysis, show that both cases can be interpreted as low-Burger-number, baroclinic vorticity waves. According to these authors, the most unstable waves (i.e., the ones with highest growth rates) have the lowest phase speeds. That is, the meanders that propagate less throughout their life cycle are likely the ones that facilitate SACW intrusions the most.

A first approximation to the phase speed and wavelength of the propagating example yields values of 0.14 m s\(^{-1}\) to 0.20 m s\(^{-1}\) (southwestward propagation) and \(\approx 180\) km, respectively. The same crude estimate for the quasi-standing example yields values of -0.02 m s\(^{-1}\) to -0.04 m s\(^{-1}\) (very weak northeastward propagation) and \(\approx 250\) km, respectively. These estimates agree qualitatively with Silveira et al. (2008) (see their Figure 19). The associated growth rate of the quasi-standing example was estimated as 0.033 day\(^{-1}\), which is close to that simulated by Calado et al. (2010), but about half of that estimated from the instability analysis of Silveira et al. (2008).
### 3.3. Observations of coastal upwelling events

Both the upwelling plumes and the frontal meanders have conspicuous surface signals. Therefore, high-resolution MODIS images were used to describe the Sea Surface Temperature (SST) and Sea Surface Chlorophyll-a (SSC) fields in two representative upwelling events.

The first upwelling event (October 23, 2008) shows two distinct upwelling plumes in the SST image, one near Cape Frio, the other near CST. The Cape Frio plume has minimum temperatures under 16°C, while the CST plume is warmer, ≈19°C (Figure 4a). The BC front is evident both in the SST and SSC fields, and follows the shelfbreak position (roughly the 100 m isobath). A small cyclonic eddy can be identified in the SSC image, centered at ≈40.5°W, 22.5°S (Figure 4b). Cloud cover made it impossible to track this propagating cyclone closely. However, the SST image for October 26 (not shown) reveals that it displaced southward, following the shelfbreak.

The second upwelling event took place in the presence of a mature cyclonic meander (January 3, 2010). No upwelling is observed at Cape Frio, even though the CST plume is present, again with ≈19°C. A highly-developed BC meander is evident off CST, both in the SST and SSC fields (Figure 4c,d). The core-border SST difference within the meander is of ≈1°C. Also, an offshore-stretched SSC filament is visible in the northern edge of the meander, but not in its southern edge, which indicates a cyclonic circulation pattern. Therefore, it appears that the meander indeed draws surface water from the shelf, in agreement with the simulation of Calado et al. (2010). We note that, in both events, the daily-averaged wind stress was upwelling-favorable, as seen in the overlaid white vectors in Figure 4b,d.

Satellite observations of other concurrent coastal upwelling and highly-developed, quasi-standing cyclonic meanders exist in the literature. Although it was not the focus of their study, Schmid et al. (1995) present a good example (Their Figures 10-11). Their SST images show an event where all three major upwelling centers (Cape Frio, Cape São Tomé and Vitória) were active. The outcropping of waters colder than 19°C is observed in the vicinities of CST, and a filament of shelf water is entrained in the adjacent cyclonic meander, similarly to the event portrayed in Figure 4c.

### 3.4. Observations of South Atlantic Central Water intrusion events

To characterize the intrusion process, we resorted to the available *in situ* data. The analysis of the cross-shelf sections revealed different scenarios. The AUG09 transect captured a BC cyclonic
meander, evident from the doming of the isolines over the continental slope (Figure 6b,c). The simulation of Calado et al. (2010) shows a similar doming (their Figure 5). This doming extends over at least 300 m from the surface. The presence of the meander can also be seen in the corresponding SST image, as an offshore departure of the BC front (Figure 6a). SST images for the period following the survey (not shown) clearly depict the quasi-standing growth of the meander, until September 17 (18 days after the occupation of the stations located over the continental slope). These images also captured an upwelling event (September 2, not shown). The wind was highly variable. Before the occupation of the deep stations, an upwelling-favorable impulse of -64.0 m$^2$s$^{-1}$ (20–29 August) was observed. However, two opposing impulses followed (+12.8 m$^2$s$^{-1}$ from 29–30 August and -11.7 m$^2$s$^{-1}$ from 30 August through 1 September). Then, a weak downwelling-favorable impulse was in force during the upwelling event (+5.03 m$^2$s$^{-1}$, from 1–3 September). This curious scenario suggests that other forcings may have acted in triggering this particular intrusion event. Such forcings might be partly related with the local shelf topography, since this was shown by Rodrigues and Lorenzzetti (2001) to be important around CST.

The JAN02 sections show a deep intrusion, as the 20°C isotherm is uplifted to a depth of 20 m (Figure 6e). On the slope, the uplift is more intense as well. The 15°C isotherm touches the bottom at the shelfbreak (110 m), while on the other surveys it does so at the slope (200–250 m). Unfortunately, the cyclone was not sampled at its core (Figure 6d). This implies that the uplifting associated with this feature may be underestimated. Although it was not fully captured, there is a sharp dipping of the isolines on the offshore edge of the section (Figure 6e,f). Also, the position of the 12°C isotherm is the shallowest among the three sections (280 m). The SST image does not show evidence of upwelling (waters of 22°C near the coast, Figure 6d).

Inspection of the SST images of the period following the JAN02 survey reveals that the cyclone did not grow in-place, but rather propagated southwestward (Figure 5b). This raises the possibility of the influence of an uplift/intrusion mechanism similar to that present in the South Brazil Bight (Campos et al., 2000). Upwelling-favorable winds blew from days 11 through 20, resulting in an impulse of -63.2 m$^2$s$^{-1}$. However, the wind turned downwelling-favorable from days 21 through 24 (encompassing the transect occupation), producing an impulse of 24.7 m$^2$s$^{-1}$ that likely decreased the effects of the previous upwelling-favorable winds.

In summary, the wind data suggests that the scenario captured during the JAN02 survey was a
downwelling-favorable one. Then what was the mechanism that brought the SACW so close to the coast (Figure 6e)? It is most likely that the previous favorable wind impulse played a part. Still, it can be speculated whether the intrusion effects of the propagating cyclone had some influence in facilitating this. We suggest that this synoptic picture captured an intrusion event where the two oceanic modes proposed by Lee and Pietrafesa (1987) (proximity of the western boundary current to the shelfbreak and presence of a cyclonic perturbation) were active, but not the coastal mode (favorable wind stress).

The MAR09 transect did not capture a cyclone, as the slope of the isolines is gentle (Figure 6g,h). The surface stratification is much stronger than that which is observed in the AUG09 section (Figure 6b,c). Tracking of the cyclones during the MAR09 survey was not possible due to cloud cover. An SST image from 3 days before this survey (not shown) revealed that the transect captured the northern outer branch of a cyclone. The 20°C isotherm intersects the bottom roughly at the 40 m isobath in both surveys (Figure 6b,g). We will not discuss the AUG09 (MAR09) transect in more detail, since it was occupied in 19 (17) days (Section 2.1.1). For proper synoptic shelf-slope snapshots, we consider only the JAN02 and JAN11 surveys, which were occupied in 18 hours (23-24 January, 2002) and in less than 6 days (05-11 January, 2011), respectively.

Another point to be considered is the sharp temperature stratification over the shelf observed in the summer surveys (Figure 6e,g), in contrast to the relatively weaker stratification observed in the winter survey (Figure 6b). Intense vertical stratification is expected to counteract any subsurface onshore transport (as a result of the opposing buoyancy force).

To shed further light on the patterns of intrusion of SACW, we analyzed the near-bottom horizontal fields of the JAN11 survey. The composite SST image for the survey period shows a mild cyclonic perturbation of the BC front, identified as a small eddy (diameter of ≈30 km, Figure 7a). This eddy appears to have propagated southwestward across the survey area during its short life. Once again, cloud cover made it difficult to track. The near-bottom salinity (not shown) and temperature maps reveal an onshore inflexion of the isolines at transect C. This intrusion cannot be explained by local wind forcing, since the wind was downwelling-favorable during and prior to the occupation of transect C (Figure 7b). For this reason, we suggest that the propagating eddy may account for at least part of this SACW intrusion, as suggested by Campos et al. (2000). In the mechanism suggested by these authors, the leading edge of a cyclone promotes uplift as it
propagates along the shelfbreak, and due to interaction with the topography a net pumping of SACW to the shelf may occur.

After the occupation of transect C, the wind became increasingly upwelling-favorable (Figure 7b). This may account for the fact that the 17°C, 18°C and 19°C isotherms are closer to the coast in transect D than in transect C. However, the influence of the wind seems to decrease towards the shelfbreak, as the position of the isotherms in transect D lag behind relatively to transect C. This supports our interpretation of the onshore bend of the isolines at transect C as a local intrusion driven by the adjacent propagating BC eddy, and that its influence is more important near the shelfbreak. It is therefore reasonable to conclude that this synoptic picture was similar to that of the JAN02 survey (Figure 6e,f), in the sense that it captured the activity of the two oceanic modes of intrusion proposed by Lee and Pietrafesa (1987), but not the coastal mode.

3.5. Statistical analyses of coastal upwelling events

In the previous sections we compared propagating and non-propagating Brazil Current (BC) frontal cyclones, and characterized the upwelling and intrusion processes around Cape São Tomé (CST). But is there an actual observable interaction between the BC cyclones and the coastal upwelling? To answer this, the first step was to identify individual upwelling events. Nine years (September/2003 through March/2012) of SST data were analyzed, and a total of 62 upwelling events were detected. In 38 (61.3%) of them, a quasi-standing, cyclonic BC frontal meander was present. Does this result indicate a cause-effect relation between the meanders and the upwelling? Or does it simply reflect the fact that these features are very common near CST (e.g., Lorenzzetti et al., 2009)? Clearly, more substantial evidence is needed.

Next, we analyzed the cumulative effect of the wind forcing prior to each event, through estimates of the wind stress impulse (I). The minimum SST values observed in each event were also considered, as a measure of upwelling intensity. Since the position of our upwelling tracer (i.e., the 20°C isotherm) cannot be determined from satellite data, an objective criterion had to be chosen in order to make the impulse estimates comparable among each other. We chose to integrate the wind stress over four inertial periods prior to each event, consistent with the threshold time scale established for the wind-driven cross-shelf motions (Section 2.2.2).

We then compared all estimates of wind impulse and minimum SST, under the assumption that all events are statistically independent. The results are presented as histograms and boxplots (Fig-
ure 8). Generally, it can be seen from the sample medians that upwelling events with meandering received $\approx 25\%$ less wind contribution (smaller absolute impulse values) and tended to be slightly stronger (lower minimum SSTs). It is also pointed out that the most intense events took place in the presence of a meander (Figure 8b,d). The overall minimum SST was 16.9°C (Figure 8,d). This result agrees with Castro et al. (2006), who estimated 17°C to be the minimum SST of upwelling plumes at CST, from 10 years of independent data. Other than that, the minima and maxima both for the impulse and the SST are similar for cases with and without meanders. Since our samples are relatively small, we resorted to the bootstrapping technique to better estimate the confidence intervals around the sample medians (Section 2.1.2), at a 95% confidence level.

We conclude that the preconditioning effects of the shelf water mass field (as in Roughan and Middleton, 2002) by the meanders were captured by the statistical analyses. Thus, our earlier suggestion that such meanders facilitate coastal upwelling by decreasing the momentum input required from the wind stress is strengthened.

3.6. The effect of the mean baroclinic structure of the Brazil Current

The Brazil Current (BC) frontal cyclones appear to be an important supporting mechanism to the wind-driven coastal upwelling around CST. Now, we turn our attention to the sloping of the isotherms due to the mean baroclinic structure of the BC.

The results of the flat stratification experiment (E1) show that, in the absence of the mean BC structure, local intrusions would take much longer to develop, and would require a much greater momentum input from the wind (Figure 9, left panel). In this idealized scenario, the 20°C does not even reach the shelfbreak within the threshold time scale of $4 T_f (\approx 5.2 \text{ days})$. Consequently, coastal upwelling takes $19 T_f (24.7 \text{ days})$ to occur. The wind impulse needed is $-194 \text{ m}^2 \text{s}^{-1}$.

The results of the synoptic BC stratification experiment (E2) show a much more realistic picture (Figure 9, right panel). In this scenario, upwelling occurs after $2.2 T_f (\approx 2.9 \text{ days})$. The required impulse is $-22.5 \text{ m}^2 \text{s}^{-1}$, which is (in absolute value) one order of magnitude smaller than in the flat stratification case (E1). This result also agrees with the data-derived estimates (Figure 8a,c). We interpret this as evidence that the mean baroclinic structure of the BC is sufficient to explain the time scale of coastal upwelling as observed near CST. Once a mean BC is prescribed, the absolute value of the wind impulse for upwelling drops by $\approx 90\%$ (compared to a purely hydrostatic ocean, i.e., with no BC).
3.7. The effect of the quasi-standing meander growth

The results of the E3 experiment set (Figure 10) show that, when a cyclonic frontal BC meander is present, less time (and hence less wind impulse) is required to produce coastal upwelling. In these simplified model runs, this obviously occurs because the 20°C isotherm is already closer to the coast in the experiments where the meander is more developed, therefore reducing the remaining work the wind stress must do to bring the isotherm to the surface. The impulse values range from \(-36.8\) to \(-17.4\) m² s\(^{-1}\), which are also comparable to the observation-derived estimates (Figure 8a,c) and five-fold to one order of magnitude smaller (in absolute value) than the flat stratification case (E1). The associated time intervals range from 3.6 \(T_f\) to 1.7 \(T_f\) (4.7–2.2 days).

Again, we acknowledge that the model is 2D, is forced with a mean wind stress, has no surface heat fluxes and is initialized with 3D simulation results. Given these uncertainties, a comparison of the wind impulses required for upwelling between experiments E3a (least developed stage) and E3e (most developed stage) leads to the conclusion that the preconditioning of the shelf waters caused by the full growth of such a meander may be capable of decreasing the required wind impulse for coastal upwelling by \(\approx 50\%\).

It should be pointed out that, although the initial fields were derived from a quasi-standing cyclone (as simulated by Calado et al., 2010), the earlier growth stages may also be treated as slower-growing, smaller, southward-propagating cyclones, such as those observed in surveys JAN02 (Figure 6d,e,f) and JAN11 (Figure 7a).

This positive relation between the cyclonic meanders and the coastal upwelling regime is contrary to what seems to happen in the vicinities of Cape Frio. Castro et al. (2006) show that in this better-studied region, the BC cyclones often extend to the bottom near the shelfbreak. As a result, the flow in the bottom Ekman layer may be reversed by the interior flow of the inshore branch of the cyclone, thereby locally inhibiting SACW intrusions. To verify whether this inhibition occurs in CST, we examined the modeled velocity fields (not shown). It was found that upward and onshore velocities prevail at the shelfbreak, regardless of the initial conditions imposed. We therefore suggest that, relatively to the Cape Frio region, the cyclones near CST have a larger facilitating effect in SACW intrusions.

A point worth stressing is that the different intrusion scenarios represented in the initial fields of the E3 experiment set may very well be caused by mechanisms other than BC cyclones. We
take these results solely as evidence that the meander growth has incremental effects in facilitating the SACW intrusions.

3.8. Limitations underlying the use of a cross-sectional 2D model

The Princeton Ocean Model (POM) is clearly applicable for process studies where geometry and forcing are idealized (Federiuk and Allen, 1995). We acknowledge that the choice of a 2D model limits the extent to which model results can be interpreted, as the pathways of intrusion of oceanic pycnocline waters onto the shelf are unknown. It is possible that SACW upwelled at CST during any particular event has been advected from upstream, since the prevailing shelf flow is southward (Castro and Miranda, 1998). However, the inspection of the SST images during upwelling events (Figure 4) suggests otherwise, as the minimum SSTs are found in the cape vicinities. Thus, the experiments performed in this work were designed with the assumption that along-shore advection is locally less important than cross-shore advection of SACW onto the shelf. This hypothesis is clearly stated in Section 2.2.2.

A good example of a similar coastal process study using a 2D numerical model can be found in Allen et al. (1995) and Federiuk and Allen (1995) (Parts 1 and 2, respectively). Their main objective was to investigate the time-dependent evolution of both idealized (Part 1) and realistic (Part 2) cross-shelf velocity/density fields under upwelling-favorable wind forcing, on time scales greater than one inertial period. To this end, a 2D regional implementation of the POMsec was employed. An important point regarding the realistic experiments is that, even with the constraint of the two-dimensionality, their model succeeds in simulating several features of the observed flow field (Federiuk and Allen, 1995). Another example is the study of Gibbs et al. (1998), who used a similar model to investigate the role of the bottom boundary layer in intrusion scenarios driven by along-shore currents.

As in the process studies mentioned above, the simplified 2D experiments presented in Sections 3.6 and 3.7 are not intended to represent any particular feature of the time-dependent circulation. Rather, they are intended to quantify the cross-shelf response of idealized initial conditions to upwelling-favorable wind forcing. As stated in Section 2.2.2, only the cross-shelf motions are considered here. We also note that the most important numerical result is the order-of-magnitude difference in the wind impulse required to cause coastal upwelling when the mean baroclinic structure of the Brazil Current is removed (Section 3.6, Figure 9).
4. Summary and conclusions

The region around Cape São Tomé (CST, 22°S), off the southeastern coast of Brazil, is characterized by transient coastal upwelling (e.g., Castro and Miranda, 1998; Castro et al., 2006) and cyclonic vortical features (i.e., eddies/meanders) associated with instabilities of the Brazil Current (e.g., Silveira et al., 2004, 2008; Calado et al., 2008; Lorenzzetti et al., 2009; Calado et al., 2010). These cyclones often grow (i.e., there are unstable vorticity wave modes), and further, the most unstable waves (i.e., those with the highest growth rates) grow without significant along-shore displacement (i.e., they have very low phase speeds) (Silveira et al., 2008).

In this regional picture, there is little information on the characteristics of the CST upwelling, especially if compared to the adjacent Cape Frio (CF) upwelling. A preliminary analysis of satellite data showed that, as in CF, the wind is most likely the primary forcing of the CST upwelling. In all cases analyzed, the wind was upwelling-favorable. The minimum Sea Surface Temperature (SST) observed in an upwelling event at CST was $\approx 17^\circ$C, confirming the results of Castro et al. (2006) from 10 years of independent data. In contrast, the minimum SST at CF observed by these authors was $15^\circ$C. Also, the analysis of SST images showed evidence of frequent simultaneous occurrence of upwelling and quasi-standing frontal cyclones of the Brazil Current (BC), also consistent with previous findings (e.g., Schmid et al., 1995).

Additional satellite imagery was searched for further observational evidence of the quasi-standing BC meanders. However, the results also revealed the existence of southward-propagating cyclones, similar to those reported by Campos et al. (2000) in the South Brazil Bight (south of Cape Frio) and those predicted by the instability analysis of Silveira et al. (2008) near CST.

After characterizing the coastal upwelling surface patterns, we proceeded to gain insight in the SACW intrusions. Analysis of simultaneous satellite and in situ data (AUG09 survey) revealed a quasi-standing BC meander and its vertical structure. The sharp doming of the isolines supported the numerical findings of Calado et al. (2010), indicating possible meander-driven intrusion. The tracking of this cyclone confirmed its unstable (growing) nature, and also showed the onset of an upwelling event following the occupation of the transect.

Other simultaneous satellite/in situ datasets (JAN02, MAR09 and JAN11) revealed various SACW intrusion scenarios. In two of them (JAN02 and JAN11), southward-propagating cyclones were captured, and were associated with more gentle isoline slopes. Further, all of the propagating
cyclones appeared to have smaller amplitudes than their quasi-standing counterparts, supporting the findings of Silveira et al. (2008). In the JAN11 survey, a local intrusion of SACW is visible in the near-bottom temperature field, in spite of the downwelling-favorable winds. Hence, the uplift of SACW through the mechanism proposed by Campos et al. (2000) was suggested as a possible explanation for this SACW intrusion, which developed under unfavorable wind conditions.

Having described the CST coastal upwelling and SACW intrusion processes, we moved on to investigate the hypothetical coupling of the upwelling and the quasi-standing meanders. The inspection of nine years of SST imagery revealed that, in 61.3% of the 62 upwelling events detected, a quasi-standing cyclonic meander was present. To determine whether this was evidence of actual cause-effect relation, we performed additional statistical comparisons between the cases with/without meandering. It was found that, generally, the upwelling events with meanders tend to receive less impulse from the wind (≈25% less, on average), and tend to be more intense (lower minimum SSTs). We therefore concluded that the quasi-standing cyclones tend to precondition the shelf water mass field to coastal upwelling, thereby decreasing the momentum input needed from the wind to actually cause it. This conclusion is similar to that of Roughan and Middleton (2002) for the central east coast of Australia.

Next, we looked into the role of the upward sloping of the isolines due to the baroclinic structure of the mean BC jet. To achieve this, we employed a sectional version of the Princeton Ocean Model (a primitive-equation numerical model). Two idealized numerical experiments were carried out. In the first experiment, a stratification derived from the WOA09 climatology was used to represent a hypothetical case without the BC signal, i.e., a case in which the isopycnals are flat, and rest at their depth of hydrostatic equilibrium away from the western boundary. In the second experiment, a synoptic stratification derived from the Calado et al. (2008) feature model was used to represent a case containing the mean (i.e., steady-state) BC structure. The results showed that this mean structure suffices to explain the time scale within which coastal upwelling is typically observed near CST (i.e., ≈5 days).

Finally, additional simplified experiments were carried out to quantify the effect of the meander growth as a supporting mechanism to coastal upwelling. The results of a suite of five experiments representing different amplitudes of the meander showed that the more developed it is, the less impulse is required from the wind to produce coastal upwelling.
A point worth stressing is that the numerical experiments have shown that the quasi-standing growth of the BC frontal meanders seems to be a more efficient supporting mechanism to individual upwelling events than the mean baroclinic signal of the BC (compare Figures 9 and 10). This conclusion arises from the fact that the more developed the meander is, the more it facilitates the onshore movement of SACW. On the other hand, the mean baroclinic structure of the BC is a steady-state feature, and therefore can be used to explain the year-round availability of SACW in the outer shelf, but not an individual event of intrusion or coastal upwelling. To summarize the results of this study, we present in Table 1 its main quantitative findings.

As final points, it must be emphasized that the existence of transient baroclinic, quasi-standing unstable vorticity waves is a unique feature of this region (Silveira et al., 2008). Their supporting role in coastal upwelling and intrusion of oceanic pycnocline waters (South Atlantic Central Water, SACW) onto the shelf has been demonstrated by Calado et al. (2010) and the present study, both numerically and observationally. Nevertheless, its effects may have been underestimated, since the meander growth rate in the simulation of Calado et al. (2010) may be below observed values, and the in situ observations presented herein did not capture a meander at its maximum amplitude (as in e.g., the red line in Figure 5a). Certainly, faster-growing meanders will have a greater influence in the intrusion of SACW, and the possible effects of along-shelf advection of SACW from the Vitória upwelling region (upstream of Cape São Tomé, see Figure 1) have not been considered. Lastly, we acknowledge that no study aimed at other possibly relevant cross-shelf exchange mechanisms (e.g., onshore flow in the bottom boundary layer) in the vicinities of Cape São Tomé has been conducted to date. Therefore, further research is required to identify the full importance of the deep ocean forcings to this coastal upwelling system.

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data. The GOES Sea Surface Temperature data was obtained from the JPL Physical Oceanography Distributed Active Archive Center (PODAAC). The ETOPO2 topography data was obtained from the National Geophysical Data Center (NGDC). The suggestions of two anonymous reviewers greatly improved a previous version of this manuscript, and are gratefully acknowledged. We thank Ana Paula Falcão and Renato Parkinson Martins, from Petróleo Brasileiro S/A (PETROBRAS), for providing hydrographic data and the AVHRR image for 31/aug/2009 from the HABITATS project. Due to this collaboration, this work is proudly part of the HABITATS project.


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Table 1: Summary of the main quantitative results of the present study.

<table>
<thead>
<tr>
<th>Result</th>
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<tbody>
<tr>
<td>*Upwelling-favorable wind time</td>
<td>78 %</td>
</tr>
<tr>
<td>†Events with simultaneous coastal upwelling and quasi-standing meander</td>
<td>61 %</td>
</tr>
<tr>
<td>†Minimum SST observed during an upwelling event (with meander)</td>
<td>16.9°C</td>
</tr>
<tr>
<td>†Minimum SST observed during an upwelling event (without meander)</td>
<td>17.7°C</td>
</tr>
<tr>
<td>‡Modeled relative decrease in wind impulse required for upwelling (mean BC)</td>
<td>≈90 %</td>
</tr>
<tr>
<td>§Modeled relative decrease in wind impulse required for upwelling (meander)</td>
<td>≈50 %</td>
</tr>
</tbody>
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*Percentage of the total time interval between January/2000 and December/2011.
†Percentage of the 62 events detected between September/2003 and March/2012.
‡Mean Brazil Current case (E2) compared to the flat stratification case (E1).
§Fully-developed meander case (E3e) compared to the least-developed meander case (E3a).
Figure 1: Map of the study region, in the Mercator projection. The black contours are selected isobaths, derived from the ETOPO2 dataset. The green polygon marks the area where the wind stress time series was derived from. The filled (unfilled) red stars represent CTD stations from the MAR09/AUG09 surveys, HABITATS project (JAN02 survey, DEPROAS project). The blue dots represent CTD stations from the JAN11 survey (MCT2 project). The insert in the upper-left corner represents bottom topography (shading) and the location of the Abrolhos-Campos region in the south american coast. For interpretation of the references to color in this figure, the reader is referred to the online version of this article.
Figure 2: Initialization methodology used in the numerical experiments. The solid (dashed) line represents kinetic (potential) energy averaged over the model domain as functions of simulation time. The numbers 1–4 mark the phases of the simulation. The abbreviation diag. (prog.) stands for diagnostic (prognostic) mode.

Figure 3: Directional histogram of the 2000-2011 wind vector time series derived from the multi-satellite product (Zhang et al., 2006). The concentric circles represent relative frequency (in %), and the color shading palette represents the neutral wind magnitude 10 m above the sea surface.
Figure 4: Examples of upwelling events detected in the SST image analysis. (a,b): Coastal upwelling without a quasi-standing meander. (c,d): Coastal upwelling with a quasi-standing meander. The maps were derived from the MODIS/Aqua sensor, and are drawn in the Mercator projection. The white arrows overlaid in (b) and (d) represent the daily-averaged wind stress vectors, derived from the multi-satellite product (Zhang et al., 2006). The black contours represent the 100 m and 2000 m isobaths, derived from the ETOPO2 dataset. For interpretation of the references to color in this figure, the reader is referred to the online version of this article.
Figure 5: Examples of (a) Quasi-standing and (b) Propagating cyclonic meanders/eddies. The vector $\vec{c}$ represents the direction of propagation. The grey dashed contours represent the 100 m and 2000 m isobaths, derived from the ETOPO2 dataset. Each thick line represents a digitized SST front, showing the evolution of the cyclone. The maps are drawn in the Mercator projection.
Figure 6: Satellite and in situ observations during the AUG09 (a,b,c), JAN02 (d,e,f) and MAR09 (g,h) surveys. (a) SST map for survey AUG09, derived from AVHRR data kindly provided by PETROBRAS. (d) SST map for survey JAN02, derived from MODIS/Terra data. The black contours in the SST maps represent the 100 m and 2000 m isobaths, derived from the ETOPO2 dataset. The black lines (dots) in the SST maps represent the CTD transects (stations). The SST maps are drawn in the Mercator projection. Temperature (b,e,g) and salinity (c,f,g) sections derived from CTD data. The grey masks are drawn from the maximum depth of each CTD cast. The horizontal black line marks the depth of the shelfbreak (110 m), according to Zembruski (1979). The black triangles on the top of panels b,c,e,f,g and h mark the CTD stations. The contour interval for the temperature (salinity) sections is 1°C (0.2). The 20°C (36) isotherm (isohaline) is in bold. For interpretation of the references to color in this figure, the reader is referred to the online version of this article.
Figure 7: Satellite and *in situ* observations during the JAN11 survey (05–08/January/2011). (a) SST image for 10/Jan/2011, derived from MODIS data, and drawn in the Mercator projection. The overlayed black contours represent the near-bottom potential temperature ($\theta$) field. The 20°C isotherm is in bold. The thick grey line represents the digitized SST front for 10/January/2011. The grey dashed contours mark the 100 m and 2000 m isobaths, derived from the ETOPO2 dataset. The black dots mark the oceanographic stations occupied during transects A through D of the JAN11 survey. (b) Time series of along-shore wind stress ($\tau_y$) for the survey period. The occupation period of each transect is indicated by the vertical lines and the letters A, B, C and D. The numbers in the black squares represent the associated net wind stress impulse (in m$^2$/s$^{-1}$), computed from the multi-satellite product (Zhang et al., 2006). For interpretation of the references to color in this figure, the reader is referred to the online version of this article.
Figure 8: Statistical comparison of the observed upwelling events. (a,b) Histograms of the wind stress impulse ($I$, panel a) and minimum SST at the upwelling plume (panel b) for the events with (hatched) and without (grey) meander. The median for the events with (without) meander is indicated by the dashed (solid) vertical line. (c,d) Boxplots of the wind impulse (panel c) and minimum SST at the upwelling plume (panel d). The lines inside the boxes represent the medians of each statistical sample. The upper and lower limits of the boxes represent the bootstrapped errors of the sample medians, at a 95% confidence level. The data minima and maxima are indicated by the horizontal black lines outside the boxes. The wind impulse was estimated via integration over four inertial periods prior to each upwelling event. Only the negative (upwelling-favorable) values were considered.
Figure 9: Displacement of the 20°C isotherm for numerical experiments E1 (flat stratification, left panel) and E2 (synoptic Brazil Current stratification, right panel). $T_f$ is one local inertial period (1.3 days). $t_u$ is the time until the 20°C isotherm outcrops, for each simulation, and $I_u$ is the associated wind stress impulse. The horizontal black line marks the depth of the shelfbreak (110 m), according to Zembruski (1979).
Figure 10: Displacement of the 20°C isotherm for numerical experiments E3a (Meander at initial growth stage, upper left panel) through E3e (Meander at full growth stage, lower middle panel). Annotations are the same as in Figure 9.