Mushroom-like eddy dipoles in the Brazil Current: genesis and dynamics diagnostics using a regional ocean model

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Abstract

The mesoscale dynamics of in the southeastern region of Brazil is dominated by Brazil Current (BC), which is permeated by features such as meanders and eddies. Some of these mesoscale features are recurring in time, and are often observed in pairs in the form of eddy dipoles that are sometimes referred as *Mushroom like eddies*. In this study we report the frequency at which these events occur, and investigate the main dynamic mechanisms driving the formation and evolution of these mesoscale features in the BC. To accomplish this, we combine the analysis of satellite data with numerical simulations targeting one event with average characteristics. The main finding from this study is that ... This is important because ...

Key words: Brazil Current, Mesoscale Features, Eddy Dipoles, Mushrooms-like Eddy Dipoles, Feature Models

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1 Introduction

The circulation around the Brazilian coast can be considered complex and highly variable, because water moves in distinct directions in different vertical layers and because it's mesoscale activity. Figure 1 shows state-of-the-art knowledge of the main oceanographic features in this domain, from which the Brazil Current (BC) can be considered one of the most important. This current, along with the North Brazil Current (NBC) originates from the Southern Equatorial Current (SEC) bifurcation around 15^{o}S [da Silveira et al., 2008; Soutelino et al., 2011].

The BC mesoscale activity is evident as a strong meandering south of the Vitoria Trindade Ridge (VTR) associated with described recurrent eddies, such as the Vitoria Eddy [Schmid et al., 1995], the Cabo de São Tomé Eddy (CSTE) and the Cabo Frio Eddy (CFE) [Calado et al., 2006] (Fig. 1). In the latter, the occurrence CFE is primarily linked with the abrupt change in the coastline orientation combined with the steepness bottom topography; south of Cabo Frio (CF) the BC detach the shelf break and flows inertially to deeper waters, developing potential vorticity and, thus, a cyclonic meander. The same dynamic reasoning also explains the meandering north of the Cabo de São Tomé (CST) [Silveira et al., 2000]. There, cyclonic and anticyclonic meanders alternate towards the Santos Basin, as a Rossby wave. As a consequence, the BC path shows strong variations in time [Garfield, 1990; Lorenzzetti et al., 2009; da Silveira et al., 2008].

The mesoscale variability of the BC can often develop as the recurring coupling cyclonic and antacyclonic eddies. These features, Eddy dipoles, are often observed to develop at the BC region approximately at 23N, where a cyclonic meander of the BC usually develops due to a sharp change in the topographic slope orientation. Sometimes, these eddy dipoles can evolve as a mushurrom-like eddy when the BC separates from the coast [Miranda 2013] (REFERENCIA??). These features are particularly of interest because they can steer the flow of the BC, which may have important consequences for offshore activities and various bio-physical processes, since western boundary currents and eddies can be key components in the dispersal of larvae from commercially important fish species [e.g Domingues et al., 2016].

Mushrooms like currents or eddies, are possibly one of the most common mesoscale features in the oceans [Fedorov and Ginsburg [1986] In fact, lagrangian analyis of altimeter data using the Lyapunov exponent technique revealed that, indeed, eddy dipole signals are indeed commonly observed in the global oceans [Beron-Vera et al. 2008]. Eddy dipoles may form on regions dominated by intense currents, such as within the Gulf Stream, and also under weaker regimes, suggesting that the formation of these features does not depend on the strength of the background flow [Hookers and Brown 1996]. In the BC region, idealized studies [Miranda, 2013] showed that that the formation of eddy dipoles along the BC seems to be linked with unstable wave trains that start when the BC detaches from the coast, suggesting the importance of barotropic instability mechanisms for the formation of the dipolar feature. Yet, a deeper understanding on the occurrence of eddy-dipoles in the BC, and on the processes driving their formation and evolution is still needed. This study aims to fulfill this gap.

In this study, we assess the occurrence of eddy dipoles events in the BC during 1993-2014, focusing on underlying dynamics of one event with mean characteristics. It is hoped that our results and analysis will provide additional insight into the understanding of mechanisms driving the mesoscale variability of the BC, and into the overall understanding of the interaction of western boundary currents with mesoscale eddies. This manuscript is organized as follows: in section 2, we estimate the occurrence and overall characteristics of eddy dipoles in the BC; in section 3, we describe the data and numerical approach employed to investigate the dynamics of one specific eddy dipole event that had average characteristics; in section 4 modeling results are verified against available satellite data; section 5 focus on assessing the dynamical mechanisms driving the formation and evolution of a eddy dipole event based on model simulations; and section 6 describes the main conclusions and final remarks from this study.

2 Eddy Dipoles in the BC during 1993-2014

Eddy dipoles correspond to recurring mesoscale features at the Brazil Current region, and may play an important role on the total variability of this western boundary current. Using AVISO's satellite altimetry record, dipole features may be identified as side-by-side eddy-like signals with positive and negative sea height anomaly values (SHA), which correspond to adjacent cyclonic and anticyclonic eddies, respectively. During 1993-2014, at least 62 events (Fig. 3) were identified using the search criteria described above. These events exhibited no evident seasonally and persisted for 42 28 days, with the shortest event lasting 21 days, and the longest lasting 140 days, over 4 months. The eddy-like features associated with these events had average diameters of 150 40 km, with values ranging between 90 km and 330 km.

This cyclonic meander eventually grows due to baroclinic instability mechanisms, originating the Cabo Frio Eddy (CFE) [Calado et al., 2006]. When the CFE, which integrates part of the coastal flank of the BC, encounters an anticyclonic feature originated in the ocean interior, an eddy dipole can form. A typical case developed in July 2006 (Fig. 3 a,b,c), when the CFE eddy encountered an anticyclonic feature of similar size on the offshore flank of the BC, forming a mushroom-like-eddy dipole. This type of eddy dipole constrains the flow of the BC between these two features, which then become symmetrically elongated as they are advected by the current to the south (Fig. 3 b,c). Figure 3 shows other examples of dipole features that are also observed at the BC region, such as dipoles with inversed polarity (Fig. 3 d,e,f) and dipoles with asymmetric eddies. In the latter, the BC and the unbalanced vorticity between the two eddies causes a translation-type movement of the smaller eddy around the bigger eddy (Fig. 3 e,f).

In this study, focus is given to the event from July 2006, which corresponded to an average typical case of mushroom-like eddy dipoles in the BC, with the dipole being formed by eddies with diameters of 140 km, and the event itself lasting 45 days. In addition, available meteorological conditions at that time permited satellites to capture enhanced quality high resolution satellite sea surface temperature (SST) imagery (Fig. 5). SST fields show how the interaction of the cyclonic feature with the anticyclonic causes the advection of warm waters from the BC, forming a mushroom-like eddy pattern. On the next few sections, our analysis focuses on assessing the existing ocean conditions during a period of one week, starting with the formation of the dipole from July 2006. To acomplish this, we employ a high resolution regional ocean model for the BC region. It is hoped that this analysis will provide additional knowledge about the formation and initial evolution of mushroom-like-eddy dipoles, and also about how these processes may affect the variability of the BC.

3 The July 2006 event: data & numerical simulations

3.1 Satellite SST data

In order to asses the synoptic scenario in the BC during the July 2006 event, SST data were derived from the GOES 10-12 satellite, calibrated at the infrared thermal band, for the period between July 23 and 28, 2006, which allowed a clear identification of the eddy dipole that developed into a mushroon-like eddy structure. The SST field from July 23 2006 was used to build the nowcast structure of the BC, while subsequent SST fields from July 24 to 28 were used to verify numerical simulations used to investigate the underlying dynamics driving this feature.

The SST field from July 23 2006 (Fig. 5) show the thermal signature of a meandering BC, and of proeminent eddy dipole near Cabo Frio. A dipole formation is evident, where the CFE is the cyclonic gire on the coastal side of the current, along with an anticyclonic gire on the oceanic side. This SST field shows how warm surface waters carried by the BC are entrained into both cyclonic and anticyclonic eddies that form the dipole. This mushroom-like feature also forms an SST front centered at approximately 25.5°S that can be used to trace the evolution of this feature. The configuration of this mushroon-like-eddy structure were our target features for the development of numerical simulations, which intend to represent: (i) the BC, with well developed CF meander (eddy) and (ii) the anticyclonic eddy on the offshore edge of the BC.

3.2 The Feature Model technique

In order to simulate the dynamics of the mushroom-like eddy dipole observed on July 2006, we develop numerical simulations based on a Feature Model technique. The Feature Model technique was first described by Robinson et al. [1988] and can be considered a realistic way to simulate the oceanic thermohaline structure in the lack of real oceanic data. Several studies employed this methodology in nowcasting, forecasting and data assimilation in the western North Atlantic [Fox et al., 1992; Gangopadhyay et al., 1997; Robinson and Glenn, 1999; Calado et al., 2008; Gangopadhyay et al., 2011]. It's philosophy is to build the three-dimensional structure of known oceanic features based on a parametric approach [Calado et al., 2008].

This study will follow the achievements of the methodology reported in Calado et al. [2008]. Below, we describe the steps of the Feature-oriented regional model system (FORMS) implementation, following the formulation presented on Gangopadhyay and Robinson [2002]. First, the in situ dataset used to develop the FORMS is presented, second the Feature Model conception is described, and third the description of modeling approach is presented to achieve the nowcast/forecast fields. Fig. 4 shows the steps within the FORMS methodology.

In order to prescribe the mesoscale features of interest, in this study it is employed data collected during several cruises from DEPROAS's ("Dinâmica do Ecossistema de Plataforma da Região Oeste do Atlntico Sul" - Ecosystem Dynamics of the Continental Shelf Region of the western South Atlantic) (for more information please refer to Silveira et al. [2004]; Calado et al. [2006, 2008]). It includes data from the winter 2001 campaign, the summer 2002 and winter and spring campaigns of 2003 . The main oceanographic features that are often observed in the southeastern Brazil coast were sampled during these cruises, such as the BC, the CFE and the Cabo Frio coastal upwelling. Following Calado et al. [2008], characteristic profiles from the BC inshore edge (TS-inshore), core (TS-core) and offshore edge (TS-offshore) were obtained from this dataset to support the feature model conception. These profiles Calado et al. [see Figure XX from 2008] shows that thermocline depths increase towards the ocean interior. At the inshore edge, thermocline depths varies between 20 and 70 meters, while at the offshore edge it ranges between 50 and 170 m. This the signature of the southward geostrophic transport from the BC, and it's the desirable structure for the feature model. This dataset contains the typical vertical structure of the features of interest, such as the BC, and the cyclonic and anticyclonic eddies.

Once identified the features of interest, the next step was to build a bi-dimensional grid to construct the Feature Models. The grid to construct the BC Feature Model was defined along the BC path and thickness identified from satellite SST imagery (Fig. 5). The grid is oriented in the cross-stream (X) and along stream (Y) direction, with Y varying according to the meandering of the current path. Similarly, the eddy Feature Model was built using a circular grid that matched the identified position and diameter. In the eddy grid, the X direction correspond to radial sections, while the Y direction indicates the section's angular position.

Once the bi-dimensional grid is ready, parametrics functions are used to build the Feature Model. First, the $\varphi(z)$ function (Equation 1), which represents the three non-dimensional profiles (TS-inshore, TS-core and TS-offshore), is used to construct the BC Feature Model. From these three profiles, the TS-offshore was filtered to match the surrounding July WOA'05 climatology profiles, which is used as a background dataset in the Objective Analysis mapping technique that is described next.

$$\varphi_i(z) = \frac{T_i(z) - T_{i_b}}{T_{i_s} - T_{i_b}} \tag{1}$$

Second, the standard temperature and salinity dimensionless sections are obtained by applying this non-dimensional profiles in the X direction. These sections have the characteristic horizontal gradient from a southward geostrophic transport. With this, the Feature Model enables one to build the three-dimensional structure of the current based on any surface tracer horizontal distribution using this relation:

$$T_i(z) = [T_{i_s} - T_{i_b}]\varphi_i(z) + T_{i_b} \tag{2}$$

where the index i indicates the X position along the Feature Model section, and subindices s and b refer to surface and bottom value of the hydrographic tracer. At this step the surface tracer distribution was based on the July WOA'05 climatology.

Third, to prescribe the cyclonic eddy, a similar technique based on dimensionless profiles ($\varphi(z)$) was employed using the equations proposed by Calado et al. [2006].

The forth step consisted in merging the three dimensionless fields using Equation 3. An Objective Analysis scheme was applied to merge our synoptic BC and anticyclonic eddy with the July WOA'05 1 degree background climatology. In this phase, the resulting tri-dimensional field contains background climatological conditions that were slightly modified to accomodate the synoptic structure of the Feature Models. We designate this field as Feature Oriented Models System (FORMS) (details available on Calado et al. [2008]).

$$\varphi_i^{'}(z) = [\varphi_{i=1,k}^{BC}(z); \varphi_{i-k+1,M}^{EDDY}(z); \varphi_{i=N+1,N}^{CLIM}(z)] \quad (3)$$

The fifth and last step consisted of transforming the dimensionless tri-dimensional field into dimensional temperature and salinity fields by applying satellite SST and WOA'05 surface salinity data at surface using Equation 4, respectively. The resulting field contained the synoptic BC structure and it's associated anticyclonic eddy Feature Models based on the July climatological distribution (Fig. 6). The final product is a three-dimensional initial conditions for temperature and Salinity field, that accurately assimilate the SST conditions attached to the FORMS structure (Fig. **??**).

$$T_i^{'}(z) = [T_{i_s} - T_{i_b}]\varphi_i^{'}(z) + T_{i_b} \quad (4)$$

3.3 The Numerical Model

Our numerical experiments were based on the Regional Ocean Modeling System (ROMS) v3.0 [Haidvogel et al., 2000; Shchepetkin and McWilliams, 2005]. ROMS is terrain following coordinate system model based on the hydrostatic balance and oceanic primitive equations. This model solves the Reynolds averaged form of the Navier Stokes equations and can be configured in several different ways.

The model domain comprises the southeastern area of the Brazilian coast, between 19°S, 30°S, 35°W and 49°W, and it is tilted approximately 45° to match the coastline orientation. Grid configurations were as follows: $172X172$ points evenly spaced every 1/12°, with forty vertical S (σ) layers. The bathymetry was derived from ETOPO-2, with gridded depths ranging between 10 and 4300 meters.

An open boundary condition scheme was also imposed on the northern, southern and western limits employing radiation condition was applied to solve the tracers and the baroclinic velocity component, a flather condition to the barotropic component and a gradient condition to the free-surface. Wind forcing was not applied to simulations developed here, since we were interested in understanding the role of geostrophic flows in driving the formation and evolution of the mushroom-like eddy dipole.

Simulations were based on two different approaches following the concept developed on Ezer and Mellor [1994]. For the nowcast experiment, ROMS was set to run in the diagnostic mode (flag TS_FIXED defined), which allows one to compute the free-surface and momentum fields based on a fixed/non-evolving density structure. The objective of this methodology is to spin-up the model maintaining it's initial temperature and salinity conditions. To perform the ocean forecast, the model was setup in the prognostic mode (flag TS_FIXED undefined). The prognostic run is based on the evolution of the mass field, and implies the prediction of the fluid state into the future. The prognostic run is initialized with the adjusted nowcast field, and a short-forecast of 5 days is performed (??)

4 Modeling Results

In this section, modeling outputs are assessed (i) to verify the model accuracy in reproducing the oceanographic features commonly observed along the brazilian coast (section 4.1), (ii) to evaluate the evolution of the eddy dipole event of July 2006 (section 4.2), and (iii) to investigate the mechnisms driving the formation and evolution of this mushroom-like eddy dipole in the BC (section 5).

4.1 The nowcast

- DESCREVER Figure 8

- DESCREVER Figure 9

Figure 7 shows the evolution of the averaged kinetic energy for the entire domain. It is visible that the model energy rapidly peaks around $1.6X10^{-2}\ J/m^2$ and then stabilizes at $10^{-2}\ J/m^2$ after the third day. Within the first day of simulation, it is evident the establishment of a balance between the density field (pressure gradients) and the momentum field (coriolis force), while the kinetic energy grows. Figure 8 shows steps of the diagnostic run,. After two hours, surface velocity vectors point in the direction of the pressure gradient force. As the Coriolis force begins to balance the pressure gradient force, the resulting velocity is deflected to the left (6 and 8 hours) until it reaches a stable position. Once the kinetic energy and the velocity field get stabilized, we have reached our Nowcast Field. When geostrophic balance is reached after three days of simulation, the nowcast field is obtained.

The Nowcast field is a thermohaline structure with satellite SST assimilated with fitted momentum structure for a synoptic behavior of the BC. The surface velocity field shows a meandering BC intimately associated to the SST. BC velocities range between $0.5\,m/s$ at the southernmost part of the domain and $1.7\,m/s$ at the eddy-dipole core, and the average value is around $0.9\,m/s$. These values agree with previously reported data from direct current measurements [Müller et al., 1998], from geostrophic calculations [Campos et al., 1995; Silveira et al., 2004] and from modeling experiments [Campos et al., 2000; Calado et al., 2008; Fernandes et al., 2009].

At the CFE secion a very interesting slice of the Nowcast field is seen (Fig. 9). On the coastal portion of the section a clear picture CFE is present. As observed, it's diameter reaches approximately 100 km and it's vertical structure is baroclinic-dominated. Silveira et al. [2004] described this baroclinic-eddy based on observations and highlighted it's distinct flow reversal with depths.

4.2 The forecast

- DESCREVER Figure 10

Figure 10 shows the comparison between the evolution of model-derived versus satellite-derived SST The comparation of the SST fileds (model and satellite) provides a qualitative assessment showing that the evolution of the dipole and the position of the CB were reproduced by the simulation.

- COMPARAR com o altimetro aqui (Nao consegui entender o que esta escrito no paragrafo abaixo) The evolution of scenario that started by FORMS, with the visual analysis of the figures is clean the development of a mushroom-like-eddy in comparison with the satellite SST data, as observed on AVISOs data (Fig. 3 j,k,l).

The development of the mushroom from July, 23 to July, 28 present a stable structure that grows stationary on offshore area between Cabo Frio (23^o) and São Paulo Basin (25^o). At surface, the structure grows in the order of $21\,/day$, with the maximum length between the two cores about $217\,km$ mesure at day 26.

4.3 Eddy dipole dynamics

- DESCREVER Figure 11

- DESCREVER Figure 12

- DESCREVER Figure 13

The Figure 11 shows the potential vorticity at surface and the relative vorticity surface fields. In the relative vorticity field is showed the section on mushroom, that is shown on Figure 12 for relative vorticity over velocity meridional component for days 23, 24 and 28 of july 2006. With these figures was possible to identify, that after one day of simulation (day 24) the mushroom-like-eddy is clear developed as a classic mushroom-like-eddy.

Figure 10 (c,d) and Figure 11 (c,d) show the cores of cyclonic and anticyclonic eddies and the head of mushroom, enveloping the frontal part of the dipoles. The Figure 12 for day 28 presents the configuration of 6 day evolution for the mushroom-like-eddy, thats is reveals symmetric behavior for this structure. The magenta lines is the zero relative vorticity values and the with lines a zero velocities values. For the days 23 and 24 the symmetry is not clear, but it can be confirmed as the dipole (mushroom) evolution as a dynamical coherent structure.

Based on the study of Mied et al. 1991, is calculated the Rossby number (Ro) and the ratio of the length scale to the internal deformation ratio $\lambda = 2b/Rd$, for the initial field on day 23. According the velocity field and the vorticity field was possible extract the parameters to calculate λ and Ro. According with the initial field the upper layer (H1) is 400m and the lower layer limits, $H2 = 5000\,m$. In this case was considered the dynamics of the BC as a two layers system (Fernandes et al, 2009). The $2b$ parameter, that measure the initial length of core flux between the two initial eddies (cyclonic and anticyclonic), for this case is $50\,km$. Therefore, was using these parameters is calculate the Internal Deformation Ratio (Rd) according:

$$Rd = \frac{1}{f}\left[\frac{g^{'}H1H2}{H1+H2}\right]^{\frac{1}{2}}; \qquad (5)$$

where, f is the coriolis parameter and g' is reduced gravity. With λ and $Ro = U/2bf$, where U is $1.7\,m/s$, is possible to find, according Mied et al. 1991, the zones that the initial field can develop the stable, unstable or no mushroom represent at Figure 13. The Figure 13, defines the region of formation evolution for a mushroom-like-eddy. The unrealistic regions for the BC mushrooms, corresponds a $\lambda > 2.55$ and $Ro < 1$, thats means the first density layer is lower than $100\,km$. On the other hand, for $\lambda < 1$ and $Ro > 1$, represents that the length of BC is lower than $50\,km$. These cases was considered unrealistic for the BC system.

For the experiment, conducted in this article, the initial field should develop a stable mushroom-like-eddies, according the $\lambda = 1.252\,m$ and $Ro = 3.9 \times 10^4\,m$ (Fig. 13 and Table 1). The symmetry evolution can be confirmed from the visual analysis of Figures 10, 11 and 12 . With the Ro, λ plane (Fig. 13), is easy to analysis the sensibility of the parameters $2b, U$, and Rd for the development of the mushrooms. For $H1$ parameter, increase or decrease the mushroom will still be in the region of stable development. On the other words, when the depth of first density layer vary (Tab. 1), the λ varies on the Ro, λ plane. However, when those variation happens, those do not change the condition of stable mushroom. On the other hand, if the initial speeds (U) increase, the mushroom development becomes asymmetric (Tab. 2). The comparison of the two tables can show that the case of $H1$ variation, the density layer changes the g', Rd and λ, However, when the U varies only Ro change. In this case the condition of asymmetric mushroom-like-eddy are satisfy.

For an other asymmetric development case, is when $2b$ parameter decreases significantly, therefore, that is unrealistic case, that means BC length is less than $50\,km$. Then is possible the development of a asymmetric mushroom if the core of Brasil current is greater than $2\,m/s$, and its path cross the isobaths. The first conclusion of this analysis shows that BC mushrooms, most of the time should develop a symmetric structures. The hypothesis for the BC mushroom develop a asymmetric structures, that the velocities can increase the horizontal shear and consequently the barotropic instabilities will increase, developing the unstables structures.

5 Discussion

- COMPARAR resultados quantitativos descritos na secao 5, com as informacoes especificas das referencias que estao nos paragrafos abaixo.

- OS paragrafos abaixo sao

According to the analysis, based on parameters Rossby number (Ro) and the ratio of the length scale to the internal deformation ratio λ, considering a two layer system, it was possible to confirm the evolution of a symmetrical mushroom-like-eddy, with a mean growth rate is $21\,km/day$, thats correspond a $0.048\,days^{-1}$. This growth rate corroborates with the values presents for the most untable wave growh rate decribe on Silveira et al. [2008], thats is about $0.045 - 0.06\,days^{-1}$. Also, the authors shows that this waves correspond a wavelengths are within the $260 - 350\,km$ range and are characterized by very low phase speeds compared to the surface BC velocity.

Mushrooms like currents or eddies, are possibly the most common structures in the ocean, according to an Fedorov and Ginsburg [1986]. In this article are discusses the various ways of forming these structures in the ocean. Essentially, the authors claims that horizontal shear, induced by current flows plays the principal role. However, these authors refer to these structures with vertical coherence of a few meters to a few tens of meters. In Fedorov et al. [1989], with studies in rotation tanks, it was discussed in more detail the formation of mushrooms like currents, based on the influence of Earth's rotation. In this study, the authors explore how the β-plan and f-plan plays a role in the evolution and formation of mushrooms. The conclusions was appointed as the β-plan does not have a key role on these structures. Moreover, this study pointed out how the stratification can stabilizes the mushrooms structures after its formation.

From these fundamental works, Meid et al. [1991], with idealized numerical experiments in f-Plan , discussed the formation of mushrooms-like-eddies based on geostrophic scenario. These authors explain a symmetrical mushroom occur when the Rossby number Ro is $\leqslant 1$ or the range of deformation radius in λ structure $\leqslant 0.5$. However, the formation of an asymmetric structure of mushrooms occurs when $Ro \geqslant 1$ and $\lambda \geqslant 1$, indicating that vorticity is dominated by the tikness water column. These authors, unlike Fedorov and Ginsburg [1986], tried to isolate numerically the formation conditions of these structures. It could reveal the importance of wind gradient swing the formation mechanism of mushrooms-like-eddies. Hookers and Brown [1996] discussed the formation of dipole vortices the possible evolution of mushrooms-like-eddies in the region of the confluence Brazil - Malvinas through remote sensing. These authors show that is evident how the interaction of boundary currents can form the bipolar structures. Therefore the dipoles are vortically more active than the isolated eddies. These authors also show that the dipoles can be formed by intense currents like the Gulf Stream and also by weak currents, such as the Brazil Current. This suggests that the formation of structures does not depend on the strength of the current.

Moreover, in the context of western boundarys Current, where often recurrent mushrooms-like-eddies are observed, it is necessary to deepen the discussion of geophysical instability. That is knowing [Silveira et al., 2008] the growth of primary meanders and eddies of western boundary Currents mechanisms. The study of Stern and Whitehead [1990], where coastline curvature along the path of western boundary Current jet passing an abrupt angle of coast break, similar that occour in Cabo Frio, it favors separation of the jet from the boundary and a mushroom-like-eddy form. The authors suggest the Barotropic instability is de mais mechanism for the formation of mushrooms as separation jet.

The work Beron-Vera et al. [2008] through altimeter data and calculation of Lyapunov exponent, across the ocean as well, revealing how is common to the formation of mushroom-like-eddies. In this study, the authors shows the mushroom structures are only a few times larger than the first baroclinic deformation radius. This indicates a consistent idea on which these structures are the result of baroclinic instability, such as described on Stammer [1997]; Scott and Wang [2005]. This process makes these structures may vigorously persist for tens of days or months.

On the other perspective, Miranda [2013] through idealized models, it was revealed that the formation of eddy pairs (dipoles) along BC seems to be an unstable wave train. In this work, however, it was isolated the effect of horizontal shear and consequently the role of Barotropic instability in the formation of dipoles. In this configuration the formation of mushroom-like-eddies is evident as the CB jet detaches from the coast, indicating that the formation of the bipolar structure is induced by Barotropic instability.

The formation and evolution of eddy dipole structures for mushroom-like-eddies setting, seems to rely heavily on the horiontal shear. Thus, we can think about questions such as: How can be the evolution of BC mushroom-like-eddy? In this study, we isolated a real scenario where the CB gives off the coast, forming initially one cilonic meander, which evolves into a mushroom like eddy. The vertical structure of mushroom like current is clearly Baroclinic, revealing the complexity of forming of this structure. A possible Barotropic interaction and the induction of the Baroclinic balance turns the mushroom of opposite direction into sub-picnoclnicas depths. That is, the vertical structure of the mushroom formed on the CB frontal eddy has clear baroclinic signature [Calado et al. 2008; Silveira et al 2008; Calado et al 2010; Fernandes et al 2009].

6 The final remarks

- Essa secao deve descrever explicitamente os principais resultados desse estudo (listei alguns exemplos)

- Primeiro paragrafo sumariza o estudo e a motivacao. Segundo paragrafo segue como T̈he main finding of this study is that Eddy dipoles in the BC behave as ...älguma coisa assim

Alguns exemplos do que deve ser enfatizado

(a) This study revealed that eddy dipoles are a common feature linked with the

BC mesoscale variability. During 1993-2014, at least 62 events were identified using satellite altimetry data.

(b) Numerical simulations based on the FORMS technique captured the evolution of the dipole event of July 2006.

(c) Numerical simulations for the July 2006 event suggest that mean eddy dipoles in the BC behave as ....

(d) According to Ro and λ plane analysis, it is possible to conclude that in the region between Cabo Frio (23^o) and the São Paulo Bight (25^o) the probability is the occurrence of symmetrical mushroom-like-eddy.

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Table 1
Table of condition for symmetric or asymmetric mushroom-like-eddy, according the variation of the $H1$ thickness for the fisrt density layer. The parameter $2b = 50\,km$.

	H1 = 100 m	**H1 = 200 m**	**H1 = 400 m**
$\mathbf{g'}$	$0.012\,m/s^2$	$0.013\,m/s^2$	$0.014\,m/s^2$
Rd	$1.9 \times 10^4\,m$	$2.7 \times 10^4\,m$	$3.9 \times 10^4\,m$
λ	$2.624\,m$	$1.799\,m$	$1.252\,m$
Ro	$0.614\,m$	$0.614\,m$	$0.614\,m$

Table 2
Table of condition for symmetric or asymmetric mushroom-like-eddy, according the variation of the U. In this cas the thickness for the fisrt density layer $H1 = 400\,m$ and the parameter $2b = 50\,km$.

	$\mathbf{U = 1\,m/s}$	$\mathbf{U = 1.7\,m/s}$	$\mathbf{U = 2.7\,m/s}$
$\mathbf{g'}$	$0.014\,m/s^2$	$0.014\,m/s^2$	$0.014\,m/s^2$
Rd	$3.9 \times 10^4\,m$	$3.9 \times 10^4\,m$	$3.9 \times 10^4\,m$
λ	$1.252\,m$	$1.252\,m$	$1.252\,m$
Ro	$0.351\,m$	$0.614\,m$	$0.948\,m$

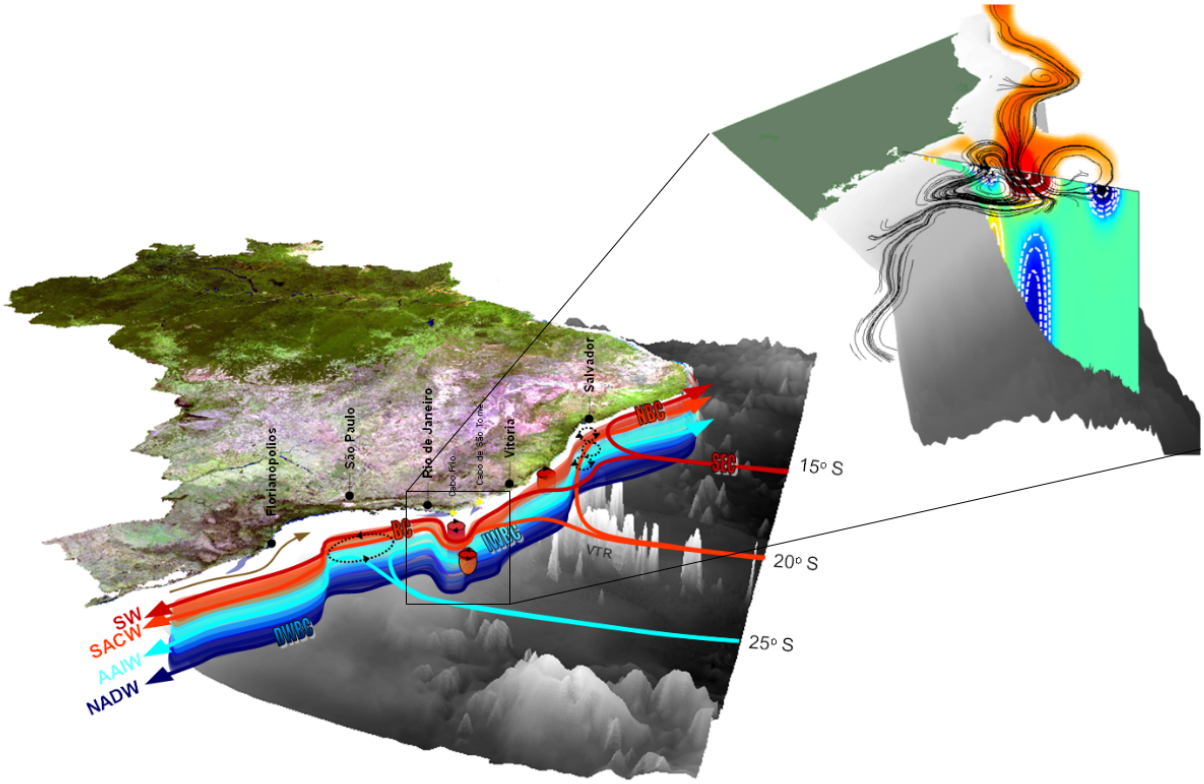

Fig. 1. Schematic circulation on the Brazilian coast and it's associated bottom topography. Solid arrows show major currents while dashed arrows means possible recirculation cells. The colored gradient presents the main oceanic water masses present in the domain. Mesoscale features such as eddies, dipoles and upwelling regions are also ilustraded. The upper panel is the zoom at mushroom development area, it shows the corss section mushroom-like-eddy feature.

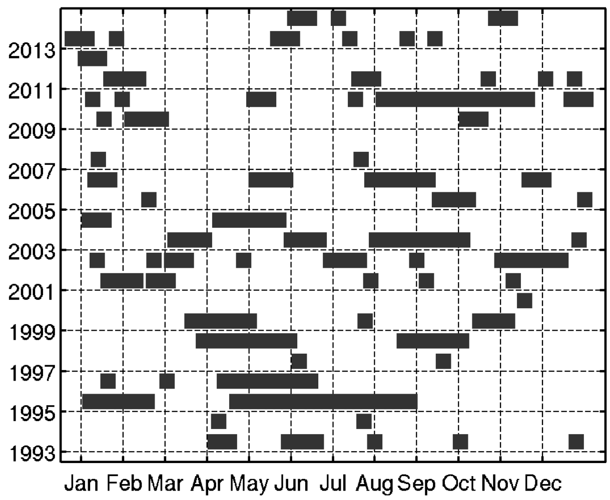

Fig. 2. Table with the occurrence of dipoles near Cabo Frio between 1993 to 2014. The eddy dipole events identified at the BC region using satellite altimetry data. Individual bars indicate timing and duration of each event. Total of 62

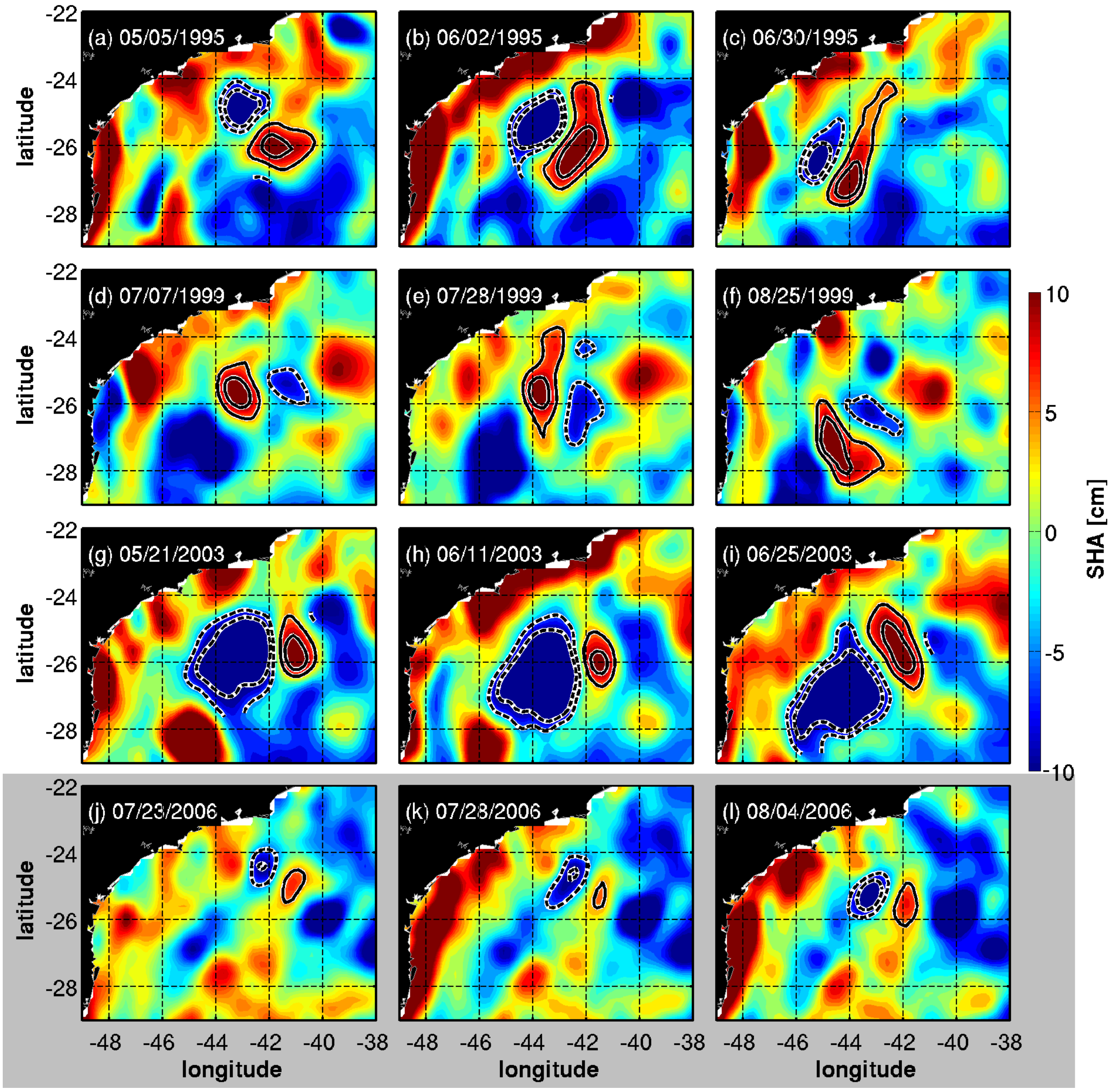

Fig. 3. Cabo Frio AVISO SSH data. Examples of eddy dipole features at the BC as identified using satellite-derived SHA data. The last three panels highlighted by the gray shading emphasize the event of July 2006, which is the focus of this study.

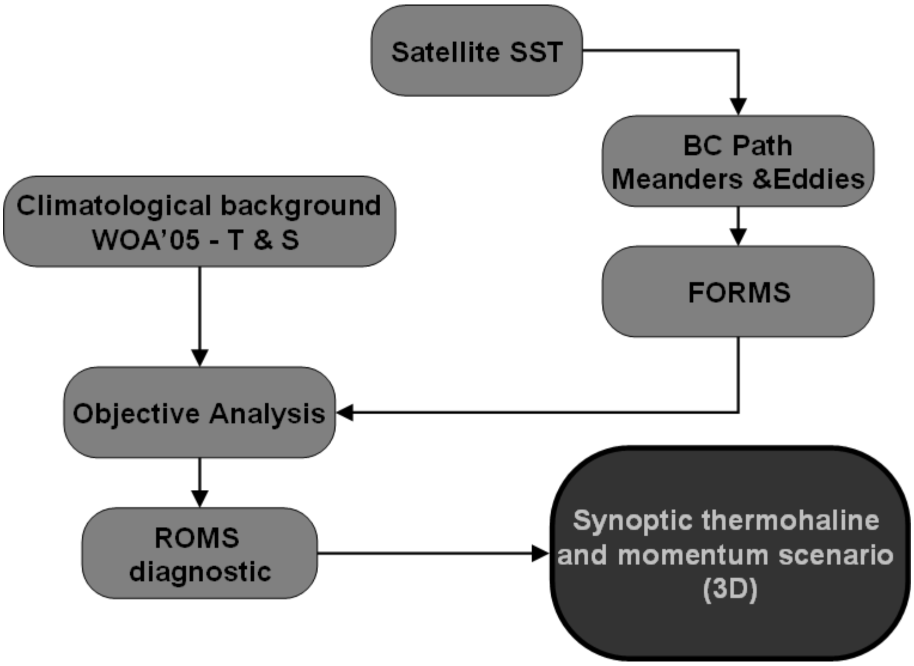

Fig. 4. Metodology of the present FORMS for the BC nowcast Simulation

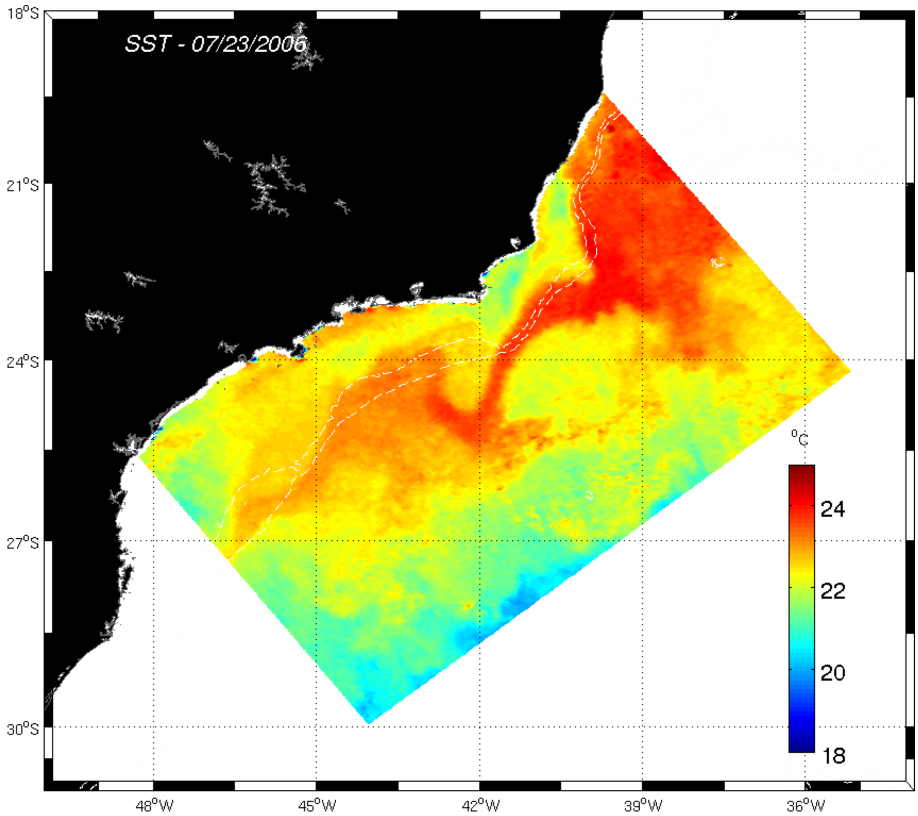

Fig. 5. Sea Surface Temperature for July 23, 2006.

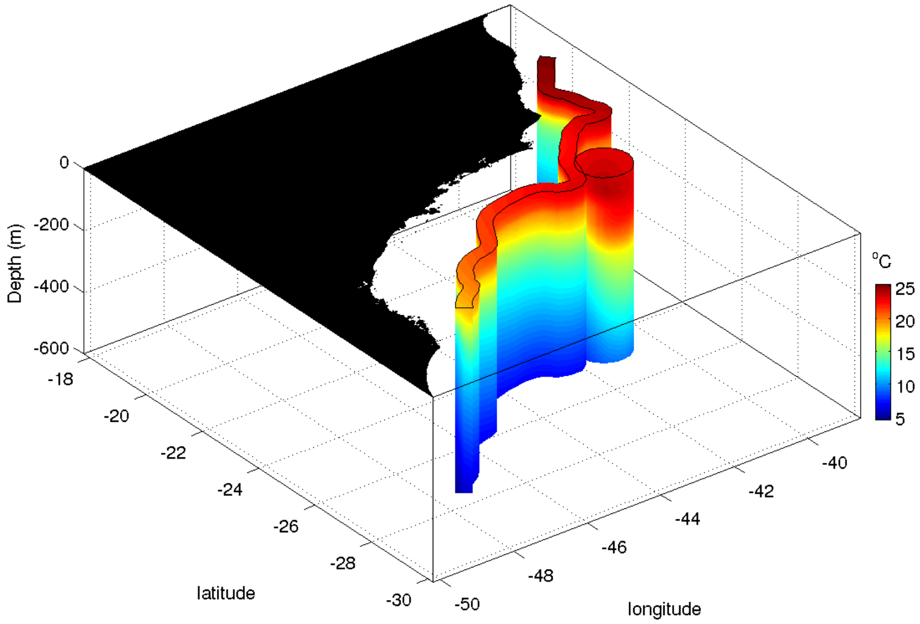

Fig. 6. Individual Temperature based Features Models 3D representation for BC and a Anticyclone Eddy at Cabo Frio region.

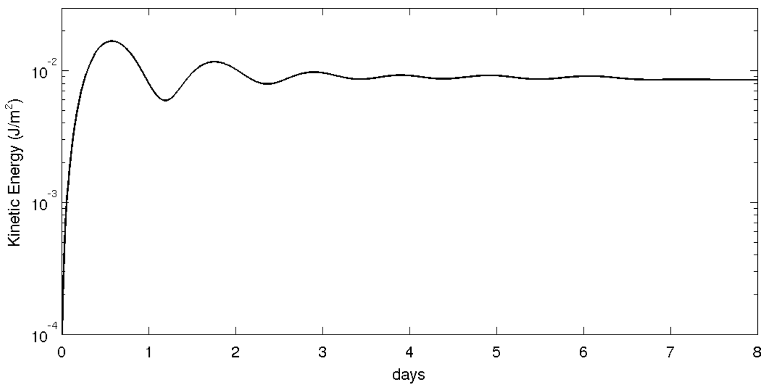

Fig. 7. Kinetic energy evolution. the energy can show how the FORMS scheme can stabilize the model. The results can be observer after few hours before the forecast initialize.

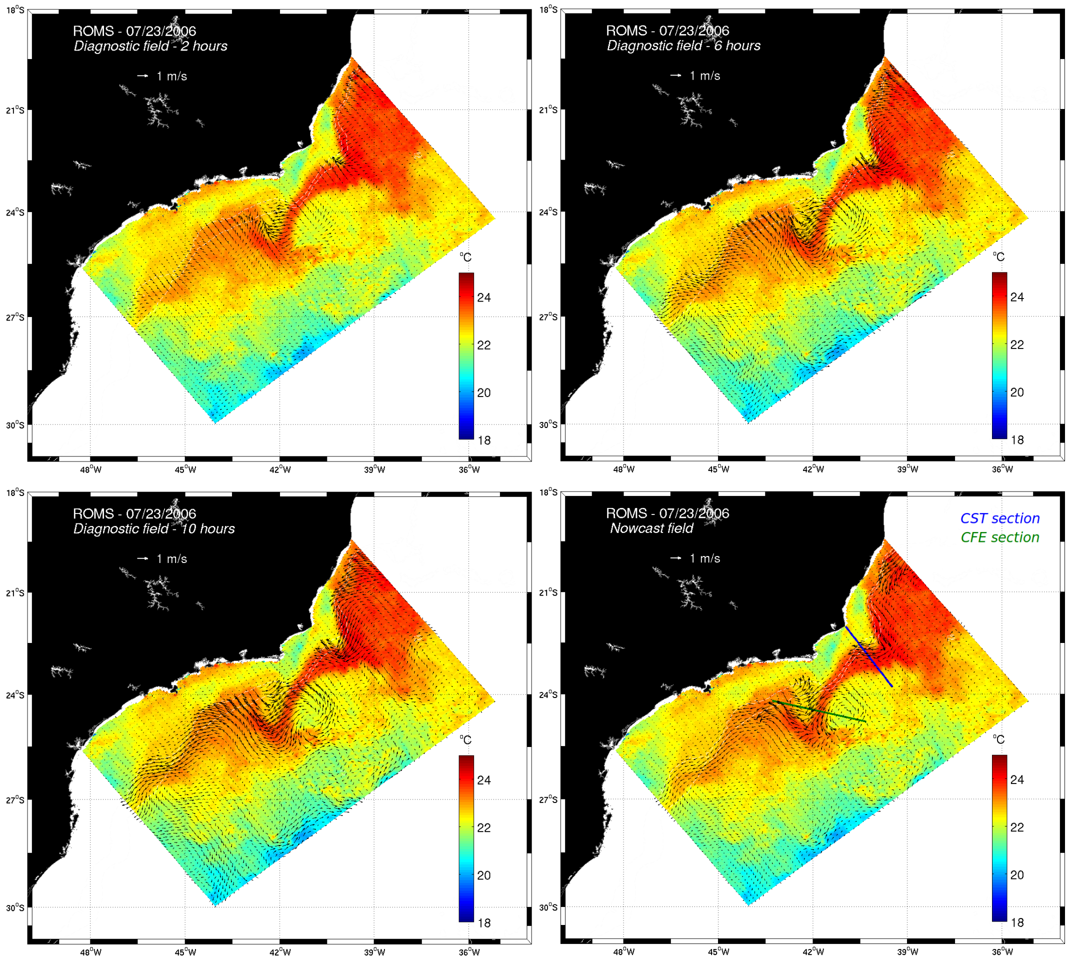

Fig. 8. FORMS diagnostic outputs showing the balance development and the resulting Nowcast field.

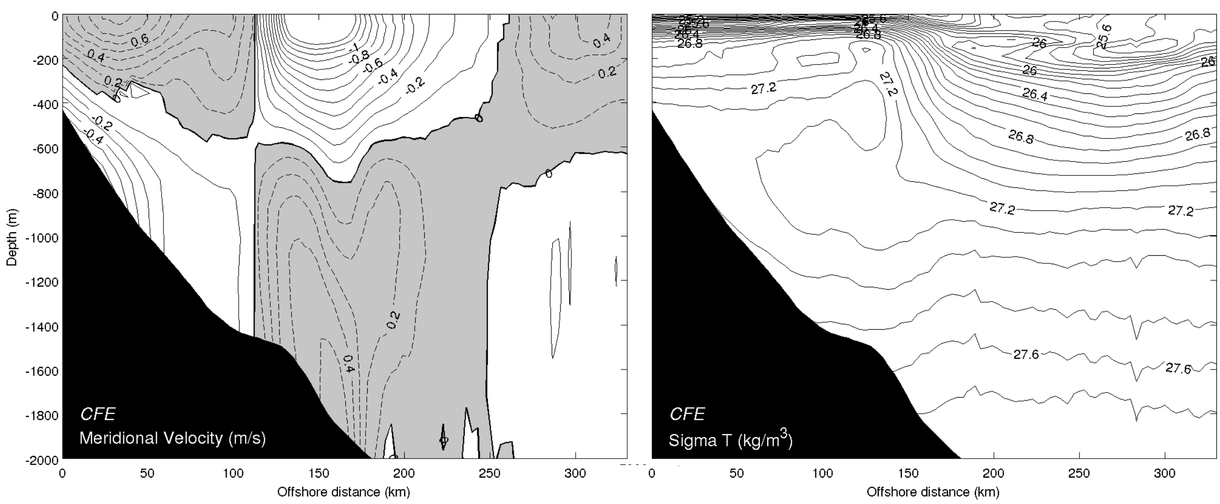

Fig. 9. Velocity cross section on the initial field.

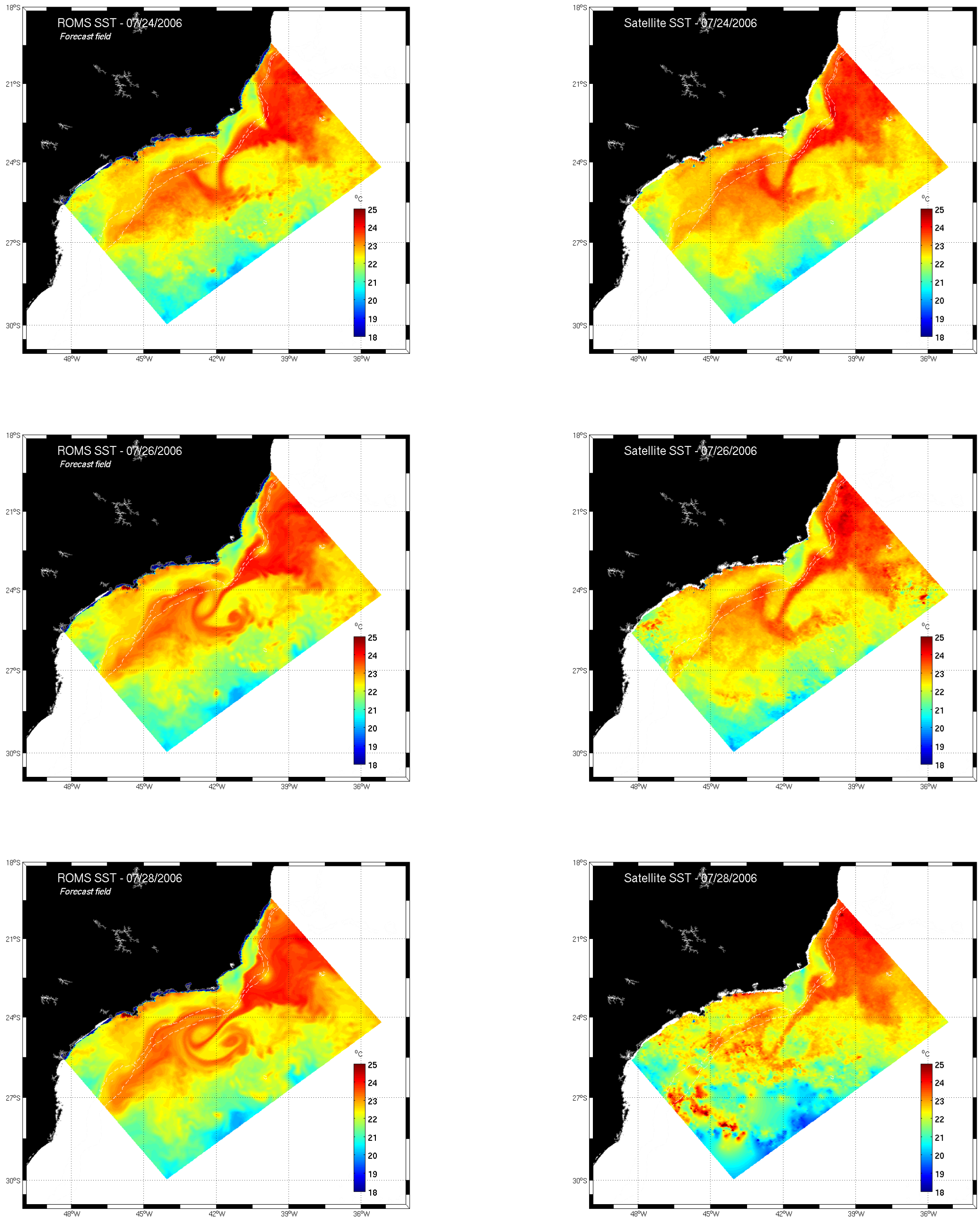

Fig. 10. SST forecasting. The left panel is the model forecasting SST field and the right panels is the SST from satellite based on OSTIA blended product.

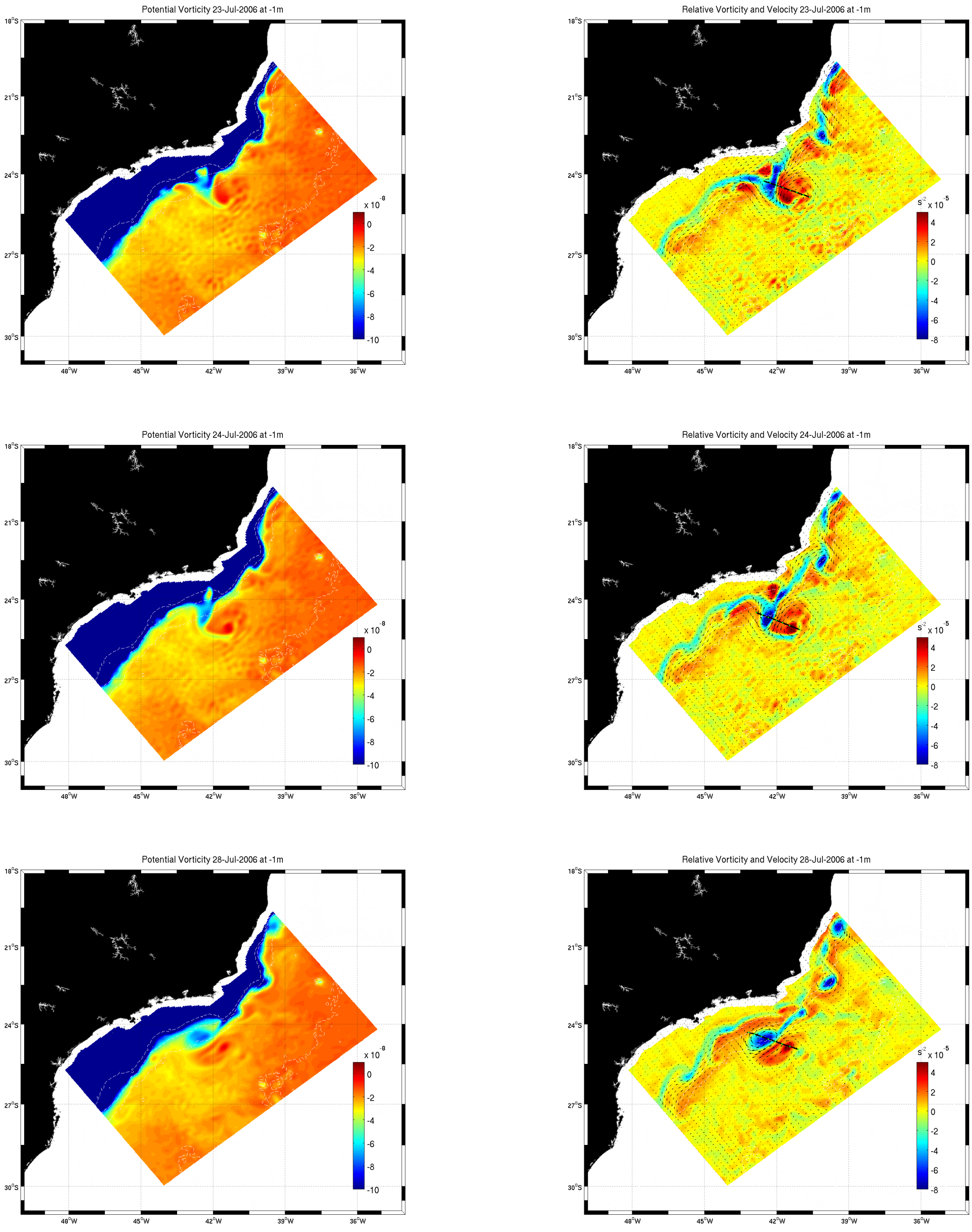

Fig. 11. Surface Potential vorticity field, Surface Relative vorticity for days 23, 24 and 28 of july 2006

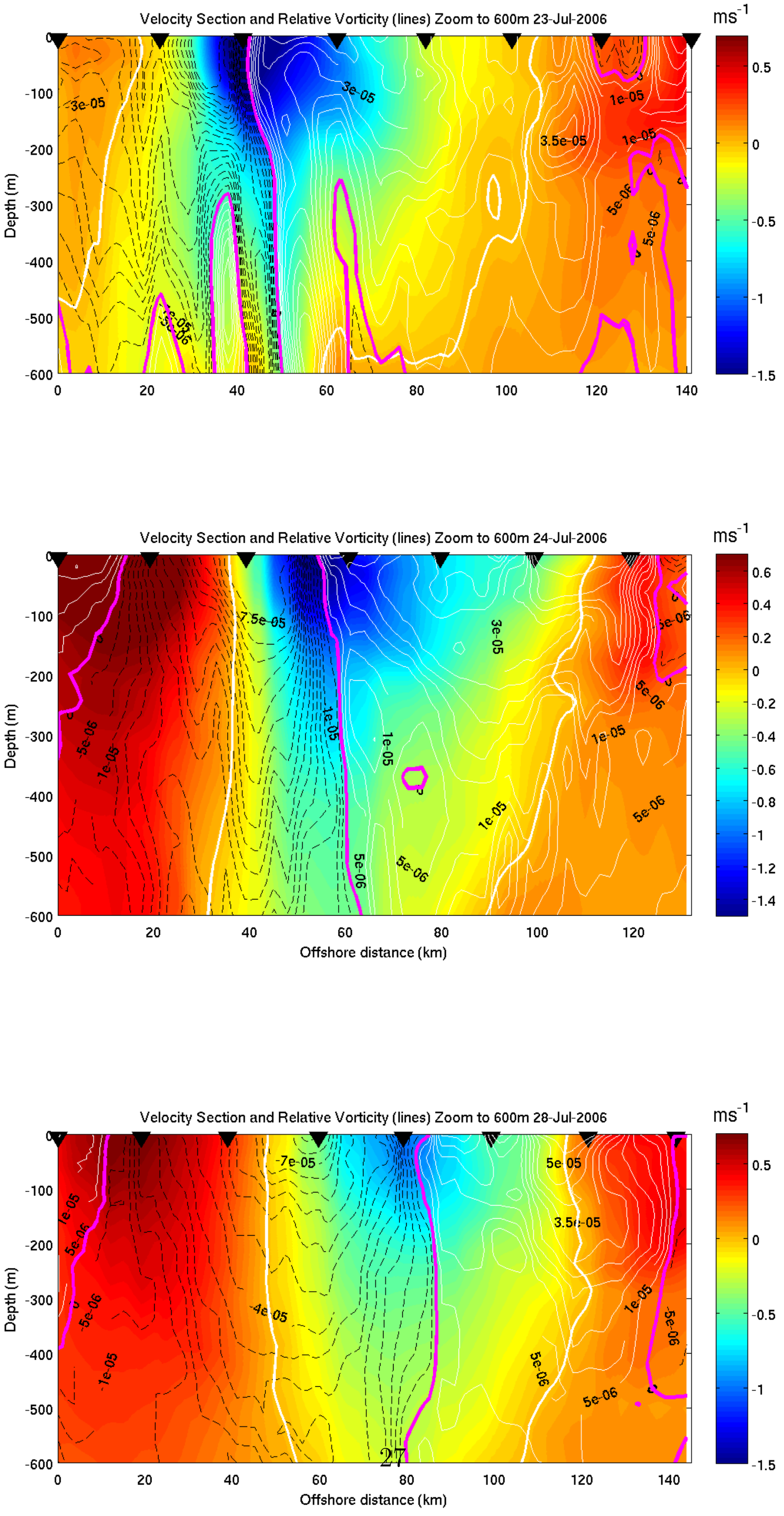

Fig. 12. Section of Relative vorticity (lines) over velocity on the mushroom-like-eddy. The zero vorticity are highliths by the magenta lines and the zero velocities are highliths by white lines.

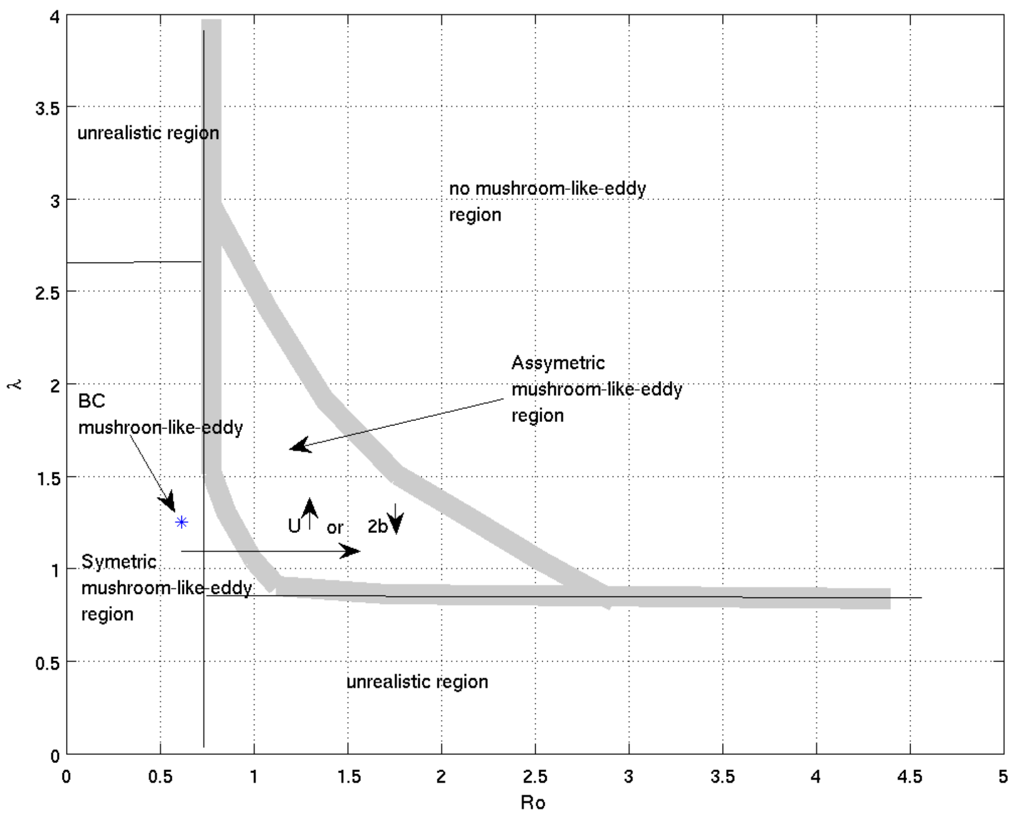

Fig. 13. Ro and λ plane. For the BC exeriment the $Ro = 0.6142\,m$ and $\lambda = 1.2520\,m$. The paramters for the initial field is: $H1 = 400\,m$, $H2 = 5000\,m$, $2b = 50\,km$, $g' = 0.0140\,m/s^2$, $Rd = 3.9 \times 10^4\,m$