A Parametric Model for the Brazil Current Meanders and Eddies off Southeastern Brazil

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Abstract. The eddies off of southeastern Brazil are unique in that their water-mass composition is made up of both upwelling waters and the southward flowing Brazil Current. We present a simple asymmetric model parameterization for the temperature and salinity structure of these eddies. Previous hydrographic data and analytical expressions are used to generate the 3-D fields for the Cape Frio and Cape São Tomé eddies. The resulting geostrophic velocity and transport estimates compare well with previous studies. An example forecast with the Princeton Ocean Model illustrates the usefulness of such parametrization in understanding the eddy-meandering activities.

1. Introduction

The Brazil Current (BC) develops intense meso-scale activity [*Silveira et al.,* 2004] while flowing adjacent to the South American coastline. Large amplitude meanders are frequently observed off the southeastern Brazilian coast, especially between Vitória (20°S) and Cape Frio (23°S). These meanders sometimes enclose eddies that pinch off from the BC, and are otherwise reabsorbed by it [*Mascarenhas et al.*, 1971; *Garfield*, 1990]. In this region, there are three important locations frequently portrayed in literature as sites of recurrent formation of vortical structures such as these meander troughs and isolated eddies: Vitória (20°S), Cape São Tomé (22°S) and Cape Frio (23°S).

In a typical configuration, the meander troughs are situated in the zone between the BC axis and the continental shelf. The BC axis is located at around the 800-1000 m isobaths and has a typical deformation radius of 22 km.

These cyclonic features are essentially in the meso-scale range and present diameters of 2-6 deformation radii typically [*Garfield*, 1990; *Silveira et al.*, 2004]. Another marked characteristic of the BC meander troughs is their temporal growth. *Garfield* [1999], who employed AVHRR images to map the BC thermal front and investigated its variability, found that the most unstable meanders have very low phase speeds.

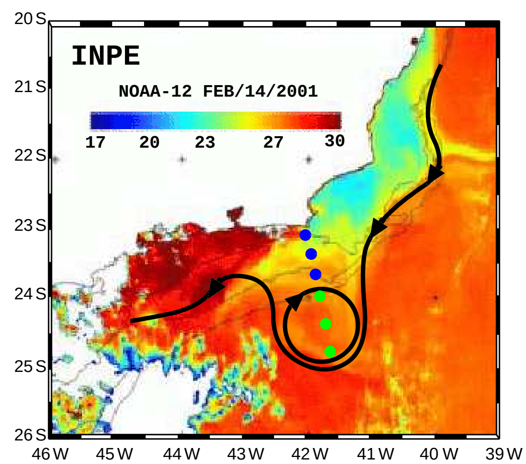

Figure 1. AVHRR image of Brazil current eddies (Cape Frio and Cape São Tomé) in February 2001. The blue and green dots mark the DEPROAS Summer 2001 transect hydrographic stations. Data from the green stations will be used in this work. Adapted from Kampel [2003].

These meanders can be easily tracked by excursions of the cooler Coastal Waters (CW) onto the oceanic area [as observed in Figure 1]. The thermal contrast can however be even stronger, mainly during the summer period, when strong upwelling occurs near the shore. It is the cold South Atlantic Central Water (SACW) that is associated with the shoaling of the oceanic thermocline. A mixture of CW and the upwelled SACW can be entrained in the growing cyclonic meanders, as sketched in Figure 2.

The interaction between the meander troughs and the upwelling system was investigated by *Campos et al.* [2000] that suggested that the conjugation of the presence of these cyclonic structures and favorable winds would explain why the upwelling near Cape Frio is more robust than those observed around other topographic features of the Brazilian coastline. On the other hand, while investigating the Vitória Eddy, *Schmid et al.* [1995] speculated that the strong coastal upwelling observed near the coast might lead to a BC meander growth in the summer.In other words, feedback mechanisms between upwelling enhancement and meander growth are possible.

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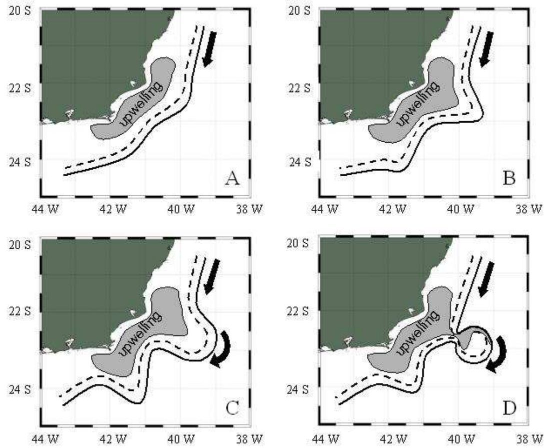

Figure 2. Schematic representation of a Brazil Current meander formation and growth as it interacts with the upwelling system.

The meander troughs are however part of a baroclinic Rossby wave train, and meander crests are then also observed [*Signorini*, 1978; *Garfield*, 1990; *Campos et al.*, 1995]. Unlike their cyclonic counterparts, the anticyclonic crests can be seen as projections of Tropical Water (TW) onto the continental shelf. Their thermal signature is attenuated by mixture with CW on the shelf and their amplitude growth is limited by the presence of the coast. As for the interaction with the Ekman-driven dynamics, the meander crests could help to enhance coastal downwelling during the winter. In this season, cold front passages are more frequent and vigorous, being able to invert the wind from north-easterlies to downwelling favorable south-westerlies.

Therefore, these interaction processes occurring off of SE Brazil set up a a dynamic meander-eddy-upwelling system (MEUS).

As described above, few works have been done in the area to elucidate the dynamics of the MEUS. Moreover, few data sets are available to seek a possible seasonal modulation on this phenomenon. No process study has been conducted to evaluate the role of the upwelling system on the BC meander growth and a MEUS isolated eddy formation (as sketched in Figure 2.

The present study intends to be the initial step toward a dynamical investigation of the BC meander formation, development and eddy shedding by means of feature oriented regional numerical modeling. In order to achieve that goal, we use a recent data set to describe the vertical structure of a MEUS eddy and to develop a parametric feature model for such structure. In order to fulfill the last regard, we generalize the *Gangopadhyay and Robinson* [2002] formulation. We focus here on the summer upwelling-favorable scenario and use the DEPROAS ("Dinâmica do Ecossistema da Plataforma da Região Oeste do Atlântico Sul" Experiment) Cruise Summer 2001 data to validate and test the parametric model [see *Silveira et al.*, 2004 for details].

2. The MEUS Vertical Structure

Even though the understanding of BC meander interaction with the coastal upwelling in promoting growth is presently at qualitative level, it certainly determines the vertical structure of the MEUS. As coastal upwelling occurs, SACW "climbs" the shelf break and the isotherms (as well as isopycnals) bend upwards in the vicinities of the continental slope. In the presence of a BC meander nearby, such temperature-salinity behavior introduces an asymmetry in the meander: a gentler horizontal T-S gradient in the inshore side of the meander compared to the offshore side. Figure 3 exhibits a cross-section of a MEUS off Cape Frio observed during the DEPROAS Summer 2001 cruise. The upper panel clearly shows the asymmetry in the temperature field while the lower panel illustrates distinct temperature profiles. It can be seen that between the depth of 100 m (200 m), the MEUS structure is characterized by a thermal contrast of about 5° C (2° C) between its inshore and offshore edges.

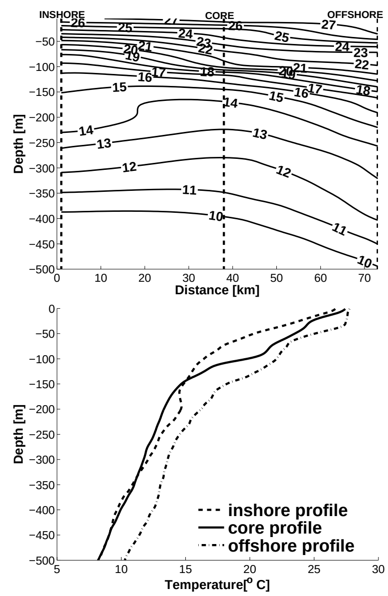

Figure 3. A Cape Frio Eddy temperature structure from the DEPROAS Summer 2001 Cruise data set. The upper panel represents a temperature section with dashed lines indicating where the the profiles shown in the lower panel were collected.

3. An Asymmetric Eddy Parametric Model

As described above, the water mass characteristics of the eddies off of Cape São Tomé and Cape Frio (and possibly off of Vitória) which set up this asymmetric configuration. The inshore part of the meander [Figure 3] will have water masses closer to the upwelling region (relatively colder and fresher), while the offshore part of the eddy would have water masses akin to the shoreward side of the BC meander (relatively warmer and saltier).

We developed this new parametric model by modifying the *Gangopadhyay and Robinson* [2002] formulation of a symmetric eddy. In their parameterization, the edge temperature salinity profiles are uniform, a characteristic of the Gulf Stream rings. Therefore, for such symmetric eddies, the hydrographic property profiles are identical along the whole eddy edge. For the MEUS, we must consider varying T-S profiles by adopting the tracer formulation given by

$$T(r,z,\theta) = T_k(z,\theta)(1-\exp{(\frac{-r}{R})}) + T_c(z)\exp{(\frac{-r}{R})};$$

where $T_c(z)$ is the core profile, r is the distance between the center to the edge of the eddy and $R = 3R_0$, where R_0 is the internal Rossby deformation radius. The chosen R value here roughly matches the eddy diameter. $T_k(z,\theta)$ is the edge profile value. This latter quantity can be written as

$$T_k(z,\theta) = [T_i(z) + \frac{(T_o(z) - T_i(z))}{2}\exp{(\frac{\theta}{\gamma})}(1 + cos\theta)];$$

where θ ranges from 0 to 2π. T_o is the temperature/salinity profile of the offshore part of the eddy edge. We establish T_o position to be at $\theta = 0$ in the model. T_i is the temperature/salinity profile of the inshore eddy edge part where $\theta = \pi$. Hence, by such configuration, the location $\theta = 0$ along the eddy edge is where the highest temperature occurs (due to the T_o profile) [Figure 4].

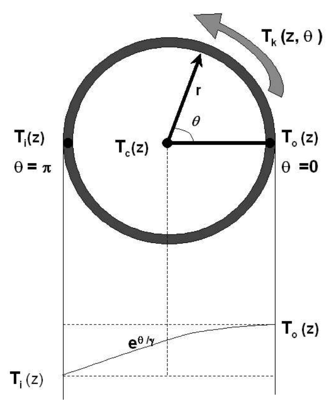

Figure 4. The MEUS asymmetric model parameters.

The function $\mathbf{exp}\,(\frac{\theta}{\gamma})$ provides the azimuthal distribution between inshore and offshore edges of the eddy. In fact, the gradient between T_i and T_o in the MEUS edge varies with this "asymmetry" function. Therefore, γ can be called the asymmetry parameter and determines how the exponential function azimuthally varies [Figure 4]. If γ is a high positive value, temperature and salinity tend to vary linearly from T_o and T_i along the edge. On the other hand, γ also establishes the percent contribution of coastal/SACW upwelled waters and oceanic waters within the eddy. If $\gamma > 0$ as θ increases, T_o contributes to a general warming of the eddy edge. Thus, through the γ parameter, we can also control how warmer or colder the MEUS is. The equation for T_k (Eq. 2) can be applied at other oceanic regions as well.

For Gulf Stream eddies/rings, T_k is uniform along the eddy edge and thus there is only one tracer profile in the background. However, in the case of MEUS, the tracer profiles in the edge of the eddies are not the same. These meanders are located near the continental margin, and are influenced by upwelling and interaction with bathymetry. Thus the eddies exhibit horizontal temperature/salinity gradient between the coast and offshore. For example, in the Cape Frio Eddy the temperature profile near the coast (T_i) is colder than that of offshore (T_o) [Figure 3].

4. Parametric Model Validation

We use DEPROAS Summer 2001 cruise data set to apply and calibrate the parametric model to the Cape Frio Eddy. With DEPROAS temperature and salinity fields, we choose and extract the three profiles that represent inshore eddy edge, eddy core and offshore eddy edge, These three profiles are ones presented in the lower panel of Figure 3. With those, we are able to implement the formulation described in Section 3.

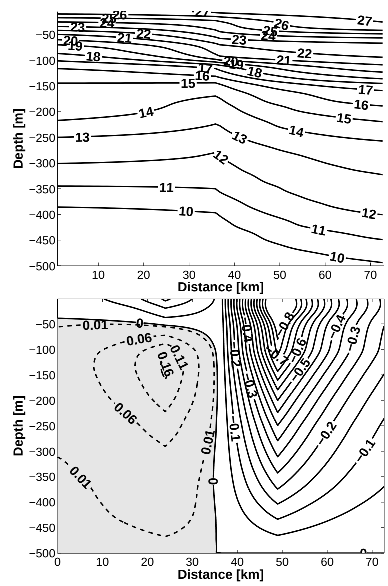

Figure 5. The temperature and corresponding geostrophic velocity normal to the coast sections and therefore across the modeled Cape Frio Eddy.

Figure 5 shows results for the parametric Cape Frio Eddy model. Temperature [Figure 5, upper panel] and geostrophic [Figure 5, lower panel] sections across the meander 0^o orientation. This orientation is perpendicular to the shelf break, and is also transversal to the BC path. The parameter γ for this eddy is 100 π. An inter-comparison between the lower panels of Figures 3 and 5 is very favorable. We computed geostrophic velocities for the original observed fields [Figure 3] using a 500 m reference level. We found volume transports of -4.7 Sv for the southwestward flow (the eddy offshore lobe), while we obtained -4.4 Sv for the parametric model [Figure 5]. The northeastward transport values found for the inshore lobe were 0.58 Sv using the observed data and 0.55 Sv for model. These figures encouraged a three-dimensional reconstruction of this feature via the proposed parametric formulation.

5. An Example Numerical Forecast with the MEUS Parametric Model

We intend to employ the parametric feature modeling for numerical prediction schemes in the Brazil Current System off Southeast Brazil since observations are scarce and there is no regular oceanographic monitoring program available for the area. The technique proposed originally by *Gangopadhyay and Robinson* [1997] may represent a way to circumvent the lack of a regular data base for numerical model initialization and assimilation.

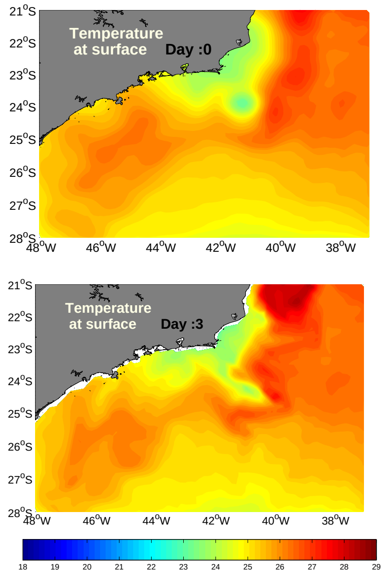

Figure 6. Numerical model application for the parametric model using Feature Model technique

Just as an exercise to exemplify the strength of such technique, we apply the MEUS parametric formulation by performing a numerical simulation with a regional implementation of the full POM version. It is the oceanic area adjacent to the SE Brazil coastline. First, we employ the nondimensional profiles for temperature/salinity to create the MEUS structure, as described in Section 5. With the surface temperature extracted from satellites images and salinity inferred from T-S climatological relationships, we redimensionalize the profiles and generate the 3D MEUS model. Also, in this simulation we applied a BC feature model to conduct the experiment with MEUS feature model. After that step, we merge the parametric model with appropriate background climatology via multi-scale objective analysis [*Lozano et al.*, 1996]. Resulting temperature and salinity fields, as well as the derived geostrophic velocity field are used to initialize the numerical simulation [Figure 6, upper panel]. In this particular simulation, we did not apply any other forcing. The lower panel of Figure 6 shows the shedding of the Cape Frio cyclonic meander the results after three days of model evolution. More sensitivity studies and analysis of observations are needed to validate, calibrate and verify such dynamical statistics.

6. Final Remarks

The details of the numerical methodology for nowcasting and forecasting the Southeastern Brazilian Coast are being developed and tested under a newly funded program. Systematic sensitivity studies with MEUS-like parameterization to initialize numerical models such as POM, Regional Ocean Modeling System (ROMS) and Harvard Ocean Prediction System (HOPS) are underway.

Morever, this methodology will allow for a series of process studies that will aim to answer unresolved issues of the study area, Such as the dynamical interaction of the BC meander troughs (and crests) with the coastal ocean, in particular, with the upwelling-downwelling system off Cape Frio; the dynamical role of topography and changes in the continental margin orientation for the behavior of the MEUS; and the mechanisms leading to the BC meander growth and their propagation downstream

Acknowledgments. This research was funded by CNPq/CT-PETRO Grant no. 504750/2004-6. A. Gangopadhyay was partially funded by Office of Naval Research (N00014-03-1-0411) and L. Calado was funded by CAPES.

References

Campos E. D. J., D. Velhote and I.C.A. da Silveira (2000), Shelf break upwelling driven by Brazil Current cyclonic meanders, *Geophys. R. Letters, 27(6)*, 751-754.

Campos, Edmo J. D., J. E. Gonçalves *&* Y. Ikeda (1995), Water Mass Structure and Geostrophic Circulation in the South Brazil Bight – Summer of 1991, *J. Geophys. Res.*, *100*(C9), 18537-18550.

Gangopadhyay A., A. R. Robinson *&* H. G. Arango (1997), Circulation and dynamics of the western north Atlantic. I. Multiscale feature models, *J. Atmos. Oceanic. Technol., 14(6),* 1314-1332.

Gangopadhyay A. *&* A. R. Robinson (2002), Feature-oriented regional modeling of oceanic fronts, *Dynam. of Atms and Oceans, 36,* 201-232.

Garfield III, N. (1990), The Brazil Current at Subtropical Latitudes, Ph.D. dissertation, *University of Rhode Island*, 121 pp.

Kampel, M. Estimativa da produção primária e biomassa fitoplanctônica através de sensoriamento remoto da cor do oceano e dados *in situ* na costa sudeste brasileira (2003), Ph.D. dissertation, *Instituto Oceanográfico da Universidade de São Paulo*, 286 pp.

Lozano, C.J., A. Robinson, H.G. Arango, A. Gangopadhyay, Q. Sloan, P.J. Haley, L. Anderson, & W. Leslie (1996), An interdisciplinary Ocean Prediction System: Assimilation Strategies and Structured Data Models, In: Modern Approaches to Data Assimilation in Ocean Modeling, (Ed. P. Malanotte-Rizzoli), *Elsevier Sciences*, 413-452.

Mascarenhas, A. S.,Jr., L. B. Miranda *&* N.J. Rock (1971). A study of oceanographic conditions in the region of Cabo Frio. In Fertility of the sea, *J. D.Costlow, ed., v.1 Gordon and Breach, N.Y.*, 285-308.

Schmid, C.H., H. Schafer, G. Podesta & W. Zenk (1995), The Vitória Eddy and its relation to the Brazil Current, *J. Phys. Oceanogr. 25*(11), 2532-2546.

Signorini, S. R. (1978), On the circulation and the volume transport of the Brazil Current between the Cape of São Tomé and Guanabara Bay, *Deep-Sea Res., 25* 481-490.

Silveira, I.C.A., L. Calado B. M. Castro, M. Cirano, J. A. M. Lima and A. S. Mascarenhas (2004), On the baroclinic structure of the Brazil Current-Intermediate Western Boundary Current System at 22° -23°S, *Geophys. Res. Lett.*, *31*, L14308 doi:10.1029/2004GL020036.

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