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MODELING THE BRAZIL-MALVINAS CONFLUENCE: MODEL CONFIGURATION

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Abstract. *The upper ocean circulation near the western margin of the South Atlantic Ocean is dominated by the southward flow of the warm and salty Brazil Current and the northward flow of the cold and relatively fresh Malvinas Current. The collision, near 38 ^{o}S, of the two jets produces a strong frontal zone known as the Brazil-Malvinas Confluence (BMC). The BMC is populated with eddies and meanders and is known to be one of the most energetic areas of the world oceans (Chelton et al) [1]. In this article we describe the numerical strategies used to implement a regional, eddy resolving, three-dimensional numerical model of the BMC. The numerical experiments consisted of integrations using idealized set-ups and experiments with a realistic basin configuration. The experiments in idealized basins were used to test the numerical implementation of open boundary conditions in a dynamical setting that includes both passive and active lateral boundaries. The simulations in a realistic basin ere forced with climatological wind stress and heat fluxes at the surface and mass and heat fluxes extracted from global simulations across the lateral boundaries. The numerical results so obtained appear to reproduce the general features observed in hydrographic and remote sensed data, including the observed mean position of the BMC and volume transports of the boundary currents, and the development of warm intrusion eddies.*

1 INTRODUCTION

The upper ocean circulation in the southwestern Atlantic Ocean is dominated by the opossite flow of two major western boundary currents: the Brazil and Malvinas currents. The Brazil Current carries warm and salty subtropical waters poleward along the continental slope of South America while the Malvinas Current transports cold and relatively fresh subantartic waters equatorward. The collision near 38°S between these currents, known as the Brazil-Malvinas Confluence (BMC), generates one of the most mesoscale energetic regions of the world ocean (Chelton *et al* [1]). The BMC is typically characterized by a band of intermediate temperature surface waters up to 300 km wide and filled with eddies lying between the strong thermal fronts associated with each current (Olson *et al* [3] , Gordon [4]). After their juncture, both currents turn eastward and flow offshore in a series of large scale meanders.

The line of confluence close to the coast is oriented almost parallel to the shore and is usually considered to be located near 38°S on the shelf break (Olson et al [2]). Although there is no general agreement on what might determine the mean position of the BMC the main factors seem to be related to the wind stress curl (Smith *et al*, [5]) and transport balance of the two colliding jets (Matano, [6]). Satellite-derived sea surface temperature have also revealed that the latitude of the location of the BMC front varies seasonally, lying further north during the austral winter than during the austral summer (Matano *et al* [7]). The cause of this oscillations has not been yet firmly established but numerical investigations carried with basin scale models indicate that the meridional motions of the confluence may be related to changes in the transport of both currents (Matano *et al*, [7], Gan *et al*, [8]). The seasonal variability of the BMC, superposed to the intense mesoscale (eddy) motion generates a complex regional sea surface temperature, and its interaction with climate variability is a subject of growing interest (Campos *et al* [9]).

The major objective of our study is to investigate those aspects of the dynamics of the confluence and the interaction between the deep ocean and the coastal waters that has not been adressed in previous modelling studies. The fist step in our strategy is to build a relatively high resolution model of the BMC. This model can be thought of as a regional continuation of previous numerical studies where the BMC have been considered mostly as part of basin-scale South Atlantic models (Matano [6], Smith *et al* [5], Gan *et al* [8], De Miranda *et al* [10], Penduff *et al* [11]). The purpose of the regional model is two-fold. On one hand it permits the study, with enough resolution, of processes like boundary current separation and eddy sheding. On the other hand we can investigate the impact of remote forcing on the dynamics of the BMC through the control of the boundary transports. Both objectives will requiere the prescription of artificial "open boundaries" around the borders of the model domain. The boundary conditions must be able not only to handle the perturbations generated inside the domain but also to prescribe the influence of the outer ocean as lateral forcing.

The present paper describes the efforts that have been made to reach a model configuration that we consider adapted to study the circulation of the BMC. It describes the treatment of the open boundary and the flux conditions giving the most realistic model circulation. The paper is divided into 4 sections. Section 2 features a short presentation of the numerical model and the open boundary schemes. This is followed in section 3 by a description of idealized experiments designed to test the selected schemes in a dynamical setting that includes outgoing disturbances and the prescription of boundary transports. The analysis of the realistic model configuration, its forcing functions and numerical results is described in section 4. Finally section 5 summarizes and presents the conclusions.

2 MODEL CONFIGURATION.

2.1 Numerical model.

The model used in our experiments is the Princeton Ocean Model (POM), a primitive equation, sigma coordinate, finite-difference model. The prognostic variables of this model are the sea surface elevation, the three components of velocity, temperature, salinity, and turbulent kinetic energy and length scale. The computation is split into an external barotropic mode, which solves the time evolution of the free surface elevation, and depth averaged velocities and an internal baroclinic mode that solves the vertical velocity shear. Vertical mixing in the model is calculated through an embedded turbulence closure scheme (Mellor and Yamada [12]), while horizontal mixing is parameterized following Smagorinsky [13]. A detailed description of the model can be found in Blumberg and Mellor [14].

2.2 Open boundary conditions (OBCs).

The OBC scheme to be used for the barotropic mode is the radiation condition originally proposed by Flather [15]. It combines a Sommerfeld's type radiation condition with a one-dimensional version of the continuity equation to yield an equation for the normal velocity at the open boundary:

$$U = U_o(t) \pm \frac{C_o}{H}\left[\eta - \eta_o(t)\right] \qquad (1)$$

where U_o and η_o are prescribed values, H is the undisturbed water depth and C_o the shallow water wave speed ($Co=\sqrt{gH}$). The plus sign is applied during inflow while the minus sign is used during outflow. This OBC scheme is particulary suited to account for the effects of outer regions (not modelled) to the degree possible through U_o and η_o, and differences from this are treated as a radiation condition to minimise reflections at the boundary of waves generated within the model domain. The scheme had the best performance in a recent intercomparison study of barotropic radiation OBCs (Palma and Matano [16]).

For the baroclinic mode we calculate the baroclinic velocities (*u* and *v*) at the open boundary using the following one-dimensional radiation condition:

$$\frac{\partial\phi}{\partial t} \pm C_i \frac{\partial\phi}{\partial x} = 0 \qquad (2)$$

where ϕ stands for *u* and *v*, C_i is the baroclinic internal wave phase speed, and the plus (minus) sign applies to the right (left) open boundary. To solve (2) at the open boundaries we employ an implicit and upstream method for the evaluation of the partial derivatives while C_i is computed using an implicit numerical scheme originally developed by Orlanski [17] :

$$C_i = \frac{\phi_{B\mp1}^{n-1} - \phi_{B\mp1}^{n+1}}{\phi_{B\mp1}^{n+1} + \phi_{B\mp1}^{n-1} - 2\phi_{B\mp2}^{n-1}} \qquad (3)$$

where B is a boundary node, n is a time level index and the upper (lower) sign corresponds to the left (right) boundary. Note that in using (2), the vertical variation of velocity at the boundary is free to adjust to any interior changes in the dynamics. Fixing the baroclinic velocities would lead to inconsistencies with the prescribed density field.

Finally, to update the temperature and salinity values at the open boundaries we employed a simplified version of the advection equation, i. e:

$$\frac{\partial T}{\partial \mathrm{t}} + u\frac{\partial T}{\partial \mathrm{x}} = 0 \qquad (4)$$

where *u* and $\partial(.)/\partial x$ are the component of velocity and the derivative normal to the boundary respectively. We implement (4) at the open boundaries using an upstream in space and forward in time:

$$T_B^{n+1} = T_B^n + r_1\left(T_B^n - T_{B-1}^n\right) + r_2\left(T_e^{n+1} - T_B^n\right) \qquad (5)$$

where

$$r_1 = 0.5(\Delta t_i / \Delta x)\left(u_B^n + \left|u_B^n\right|\right); \qquad r_2 = 0.5(\Delta t_i / \Delta x)\left(u_B^n - \left|u_B^n\right|\right)$$

and Δt_i is the internal time step, Δx is the grid size, u_B is the velocity normal to the boundary and T_e is a prescribed external temperature at the same boundary. The prescribed data is obtained from climatologies and is only used during inflow. A thorough analysis of the above baroclinic OBCs in a variety of dynamical situations, including intercomparison with other possible algorithms can be found in Palma and Matano [18].

3 THE IDEALIZED EXPERIMENTS.

In order to simulate the collision of two western boundary currents with a simple geometry we selected as benchmark experiment the double gyre ocean box model. This experiment (hereinafter DGC) consists in a rectangular closed domain forced at the surface with an analytic sinusoidal wind. Such a model is well known as a simple prototype of eddy active large-scale circulation in the midlatitudes and provides us with a broad range of input/output flow patterns to test active and pasive open boundary conditions. For further details on this experiment the reader can refer to Chassignet and Gent [19].

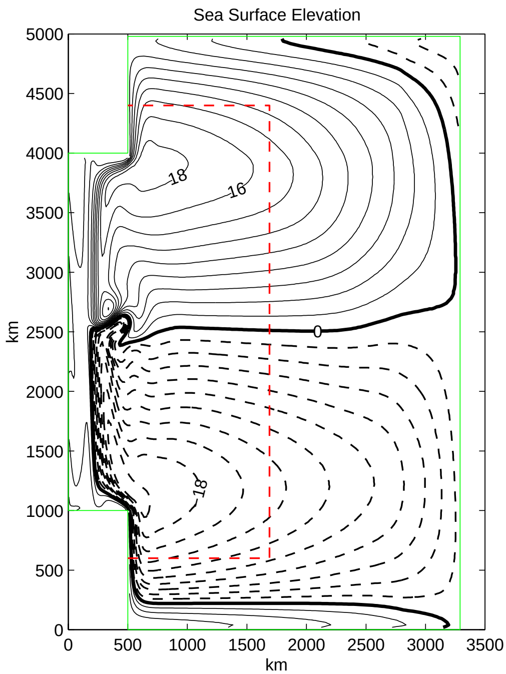

Fig.1. Mean Sea surface elevation after year 3 from the closed domain experiment (DGC). Elevations in cm. Countour interval = 2 cm. The dashed line indicates the domain of the open boundary experiment (DGO).

The horizontal dimensions of the model are 3500 km zonally and 5000 km in the meridional direction with bottom topography constant at 2000m except near the western boundary where a steep continental shelf 250 km wide is included. Temperature varies only with depth and salinity is kept constant. Horizontal resolution varies from 5 km near the coast (western boundary) to 20 km elsewhere. Vertical resolution includes 15 sigma levels. The DGC experiment was run for 2 years in order to reach a statistically steady state (Fig. 1).

The strategy to test the open boundary conditions is as follows. The model solution at the end of the DGC run was taken as the initial condition for the open bounday experimet (DGO) with domain size equal to the dashed portion indicated in Fig.1. The new domain has three open boundaries (south, north, and east) and boundary conditions extracted from the DGC

mean state. Each model was then run for a sequence of two years and mean flow and statistically significant fields were computed and compared to access the efectiveness of the open boundary conditions. Examples of mean surface circulation are displayed in Fig. 2.

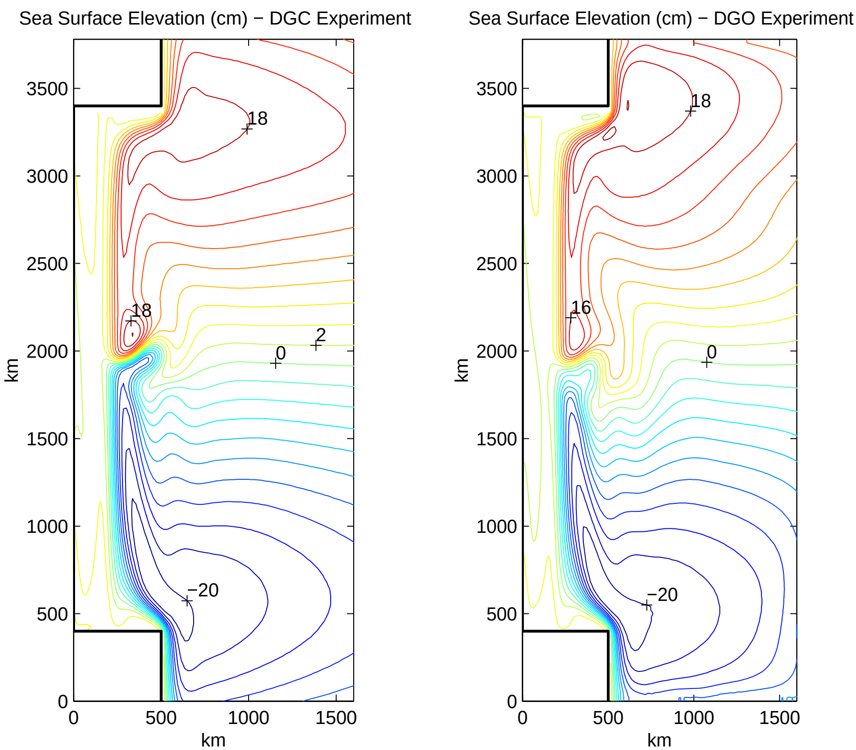

Fig.2. Sea Surface Heigth afer two years of model run. Contour interval is 2 cm. The left panel Shows the results of the DGC (closed) experiment (only the dahsed portion of Fig. 1 is shown). The right panel shows the results of the DGO (open) experiment.

As can be seen in the figure the global pattern of the mean circulation is rather similar in both experiments. The midlatitude jet exhibits a slight assymetry in DGC, the mean position of the separation point being north of the zero wind-stress curl line. This result is consistent with the response of primitive equation non-linear models (Chassignet and Gent [19]). In DGO, the mean separation point is located 100 km south compared with DGC. The maximum transport of the boundary currents in DGO (not shown) are within 10% of the DGC results.

The OB method seems able to reproduce the mean pattern and the eddy activity of the flow observed in the box case without introducing perturbations close to the boundaries. We cannot, of course expect experiment DGO to give exactly the same results as experiment DGC. The main question here is rather to determine if the solution provided by the OB method is acceptable from an oceanographic point of view and if its discrepancies with regard to a closed experiment are balanced by the gain in CPU. To try to answer this question we computed some statistics over the 2 year period. The spatial distribution of eddy kinetic energy (Fig. 3) is rather correctly reproduced with the OB method, with a discrepancy of typically 5-10% in the numerical values. We have also examined other diagnostic variables such as sea surface height variability (not shown) which confirm the preceding statement that the OB method leads to the same flow statistics within a 5-10% range.

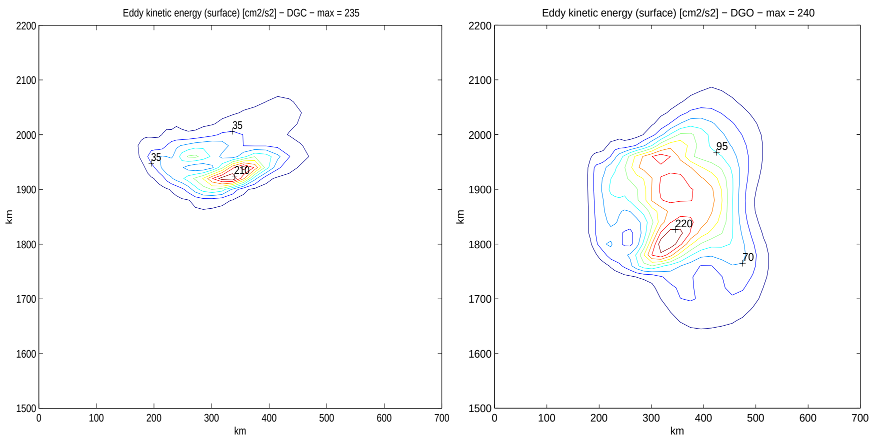

Fig. 3. Surface Eddy Kinetic Energy (EKE) form the double gyre experiment. The left panel shows the Results form the DGC (closed) experimet. The right panel shows the results form the DGO (open) experiment. Only a zoom area where the EKE is significant is shown.

4 THE BRAZIL - MALVINAS CONFLUENCE MODEL.

4.1 Model geometry.

The domain for the BMC model included the region from 55°S to 23°S and 70°W to 40°W (Fig. 4). The horizontal model grid is designed using an orthogonal coordinate transformation with a total grid points of 250 (along shelf) x 150 (cross shelf), which provides a horizontal resolution of about 5 to 20 km in the cross shelf direction and 7.5 to 10 km in the along-shelf direction. The total number of sigma levels is 25, where vertical spacing is nonuniform to provide higher resolution within the surface and bottom boundary layers. The horizontal boundary conditions over the land in the west are implemented by a land mask, which ensures that the normal velocity along the coastline is zero. The model domain has three open boundaries in the south, east and north.

4.2 Model bathymetry, initialization fields, and lateral boundary forcing.

The determination of bottom topography is the most crucial element in a sigma coordinate model (Barnier *et al* [20]). The model topography was constructed by averaging depth data. The depth data for the shelf was obtained from nautical charts available form the Argentine Hydrographic Service. It was necessary to suplement this data with the Smith and Sandwell [21] topography for regions offshore of 250 m depth. Some smoothing was also necessary to supress instabilities associated with the pressure gradient, particulary at the shelf break and Banco Burdwood. The tecnique is similar to that proposed by Mellor *et al* [22]. Fig. 4 shows selected contours of the model bottom topography.

The temperature and salinity fields for model initialization were derived form the annual mean climatology of Levitus [23]. The wind stress fields used to drive the model were taken from Trenberth *et al* [24] (hereafter TR90). The TR90 wind-stress climatology employed seven years of wind speeds computed from wind analyses provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) for the period 1980-1986. The TR90 wind stress climatology is beleived to be the most realiable available over the southern oceans. Temperature and salinity at the surface are relaxed to the Levitus climatology with a relaxation period of 30 days. No relaxation to climatology is applied to interior nodes.

In the way it has been defined, the barotropic open boundary condition can be considered as a forcing at the lateral limits of the domain. In outflow situations these fluxes are mainly determined by the model solution inside the domain (i.e. the eastern boundary). The situation is different with inflows, as is always the case in the southern and northern boundaries where the model values at the boundary can have a significant impact in the solution and they must therefore be carefully determined. For POM the variables that determine the total transport at the boundaries are the sea surface elevation and depth-mean velocities. In this preliminary experiment, those values were obtained from the high resolution global solution of Semtner and Chervin [25], version POCM-4, and interpolated onto the model grid boundaries.

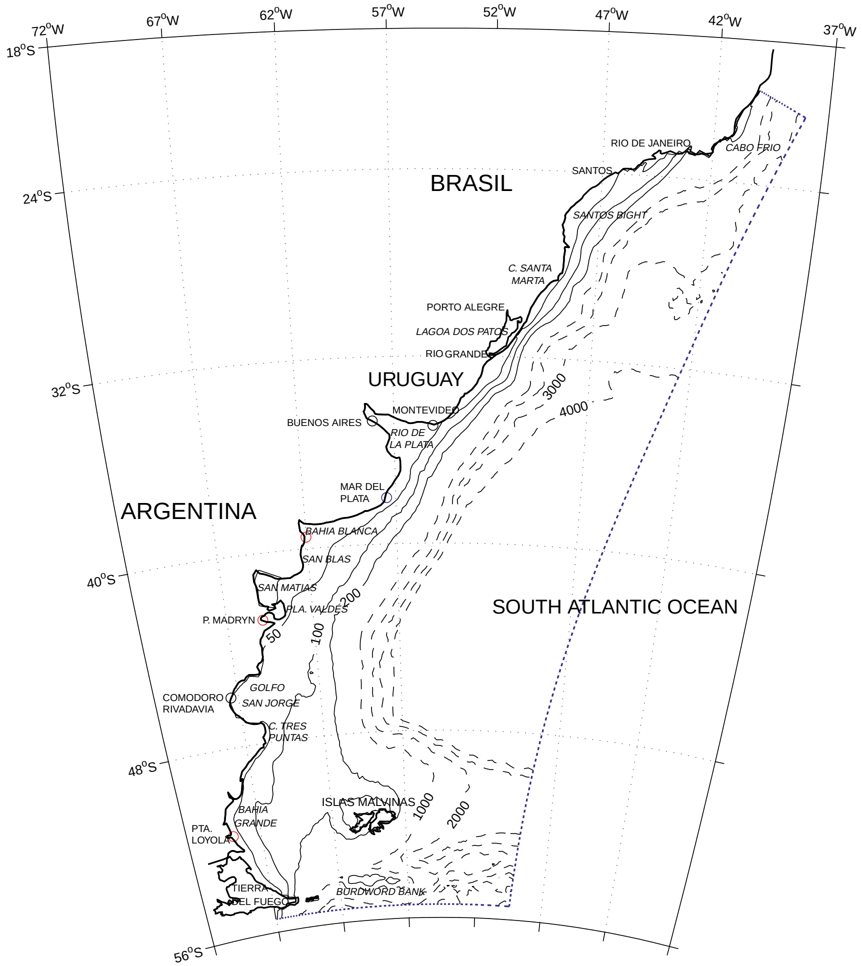

Fig. 4. Model domain and bathymetry of the BMC model. The dashed blue line indicates the open boundaries of the curvilinear grid.

4.3 Results.

The mean circulation patterns averaged over the last three years of simulation is shown in Fig. 5 and 6. The Brazil Current (BC) appears at the surface as a coherent southward western boundary current near 20°S (Fig. 5). Its mean transport increases southward from 10 Sv [1 Sv = 10^6 m^3/s) at 26°S to15 Sv at 32° S and grows to nearly 30Sv at 38°S (Fig. 6). The results are in close ageement with estimates based on hydrographic observations (Stramma, [26]) and inverted echo sounders (Garzoli and Garrafo, [2]). The BC separates from the coast around 34° S, about 1.5° north of the observed separation point (Olson, *et al* [3]). After its encounter with the retroflected Malvinas Current (MC) the BC current runs southward and its transport grows to 50 Sv at 40° S (Fig. 6).

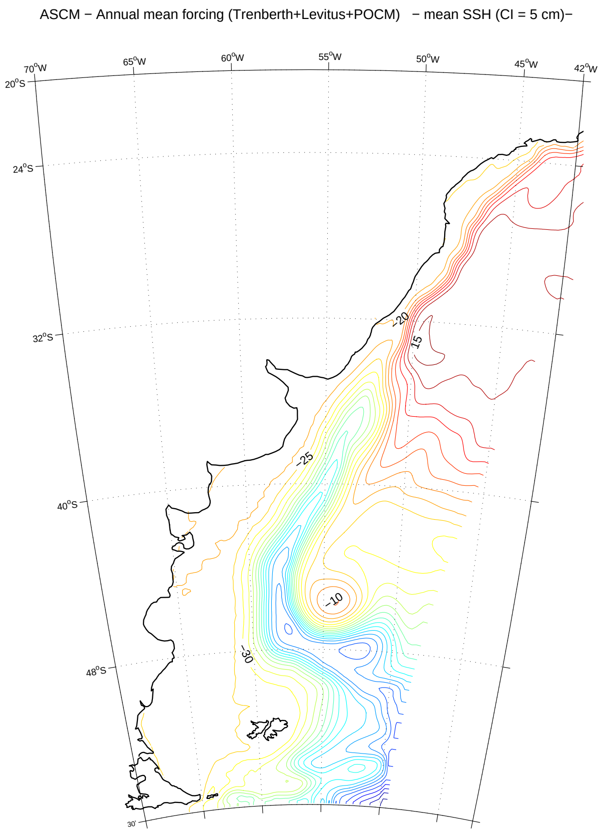

Fig. 5. Mean Sea Surface Heigth after 3 years of model run. Contour interval is 5 cm

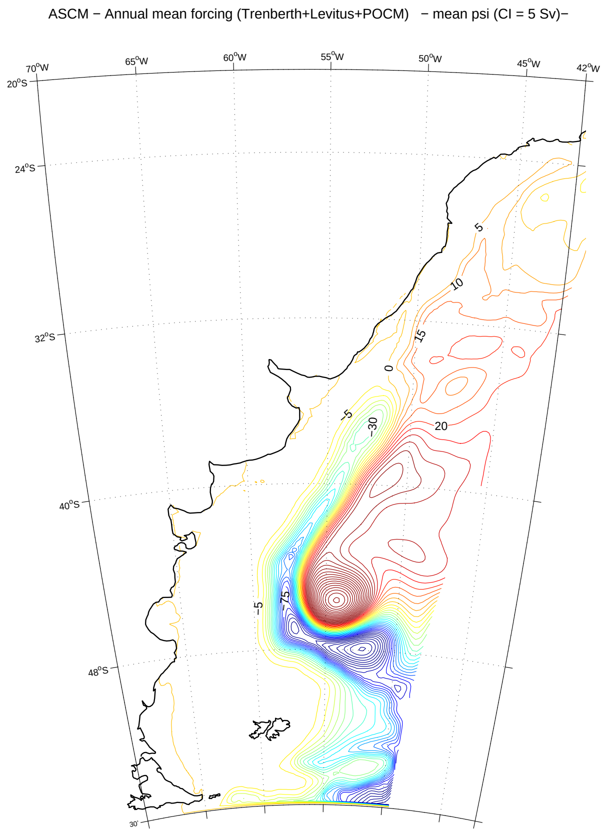

Fig. 6. Stream function obtained averaging the results after three years of model run. Contour interval 5 Sv (1 Sv = 10^6 cm^3/s)

This results are in agreement with the values estimated by direct observations (Peterson and Stramma, [27]) and regional models of the South Atlantic (De Miranda *et al* [10] ,Penduff *et al* [11]). The ability of the model to separate the BC from the coast at 34 °S and to follow the 1000 m isobath is a consequence of using sigma coordinates (Penduff *et al*, [11]).

Over the continental slope of Argentina the circulation is dominated by the northward flow of the MC. Its transport varies from 55 Sv at 45° S to 35 Sv at 41°S (Fig. 6), values in concordance with recent measurements in the area giving mean values of 41±12 Sv (Vivier and Provost, [28]). The MC retroflects after meeting the BC at 36°S and runs southward paralell to the BC. The mean circulation pattern of the MC are quite realistic, even though the northward overshoot appears exagerated in comparison with drifter trajectories. (Peterson *et al*, [29]). The mean position of the BMC at 35° 30’ S (Fig. 5), computed as the point where the maximum sea surface gradient crosses the 1000 m isobath, is close to remote sensing observations (Matano *et al*, [3]). An anticyclonic stationary eddy carrying 130Sv is centered at 56°W 46°S a result in accordance with a recent basin-scale high resolution model of the South Atlantic (De Miranda [10]). Overall the numerical results show flow characteristics that are consistent with schematic pictures of the circulation that emerge from observations (Piola and Matano, [30]).

Previous investigations of the BMC show rapid changes in the energetics and mesoscale fields. As a preliminary analysis of this high frequency variability, we compared in Fig. 7 the mean surface Eddy Kinetic Energy (EKE) diagnosed from the model with estimates based on surface drifter derived velocities. The agreement in pattern and amplitude is generally good, but maximum EKE levels in the model (5000 cm2/s2) are higher than the observational estimates (3000 cm2/s2) and located further north. It should be noted, however, that recent estimates based on remote observations present maximum values of EKE that are even closer to the model results (Ducet and Le Traon [31]). Another variable commonly used as proxy of the eddy variability is the Root Mean

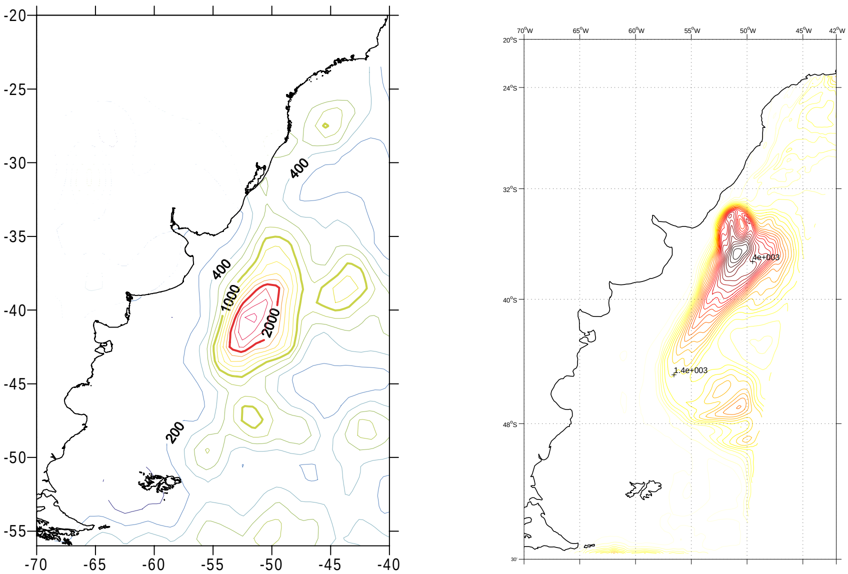

Fig. 7. Eddy Kinetic Energy comparison. Left panel are results obtained from surface drifters. The data spans the period 1989-2001. The right panel shows results obtained averaging the departures of the surface velocity from the mean during the last three years of model run. Units are cm^2/s^2.

Square (RMS) of Sea Surface Height (Fig. 8). The maximum value of 30 cm and the horizontal distribution of variability, meridionally oriented between 34°S and 48°S, obtained from the model concur with the satellite (TOPEX/POSEIDON) derived values (high pass) published by Witter and Gordon[32] . The high levels of variability found in the BMC are a consequence of the interaction between mean flow, mesoscale turbulence and sloping bottom topography, and the correspondence between modeled and observed patterns and amplitudes indicates that all processes are well captured by the model.

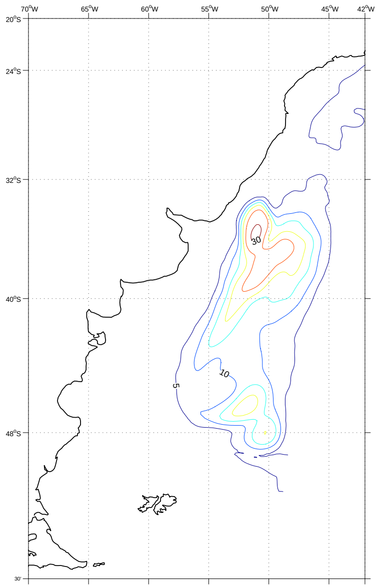

Fig. 8. The RMS sea surface variability obtained averaging model results. Contour interval is 5 cm.

There is substantial observational evidence of the production of warm-core eddies detached periodically from the Brazil Current near the BMC (Fig. 9). The SST anomalies associated with these so called “intrusion” eddies can be as large as 10° C and therefore are an important mechanism for meridional transfers of salt and heat (Gordon, [4]).

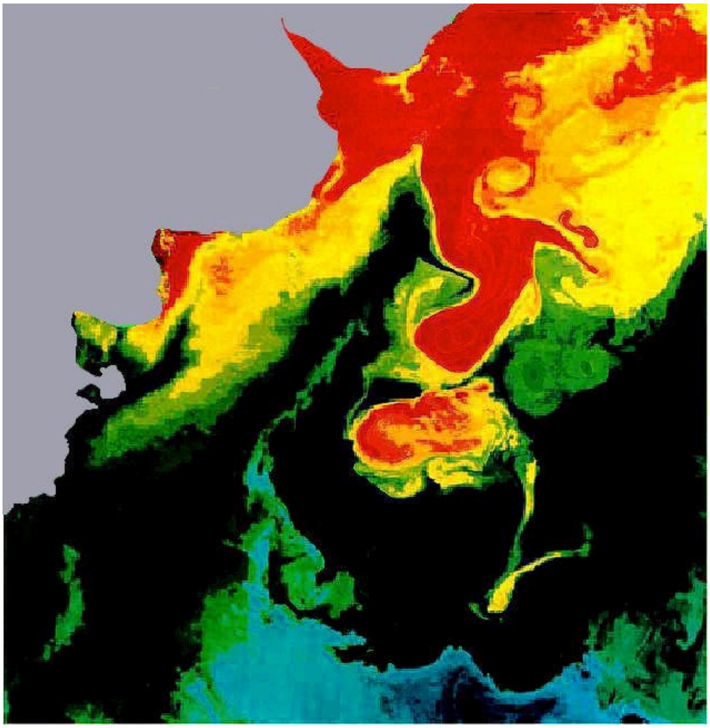

Fig. 9. Radiometer image of the BMC at a time when the Brazil Current sheds a large anticyclonic (warm) eddy. Warmest waters are coded in red (approx. 25°C), ans coldest waters in dark blue (apporx. 9°C). (Figure courtesy of O. Brown, R. Evans and G. Podestá, RMAS, University of Miami).

As a final example of the model capabilities we show in Fig 10 a snapshot of the sea surface temperature from the model simulation taken at the instant where the Brazil Current sheds and eddy. The size, vertical structure, average temperature and salinity and of the eddy are very close to those computed form hydrographic observations (Fig. 11). Despite the instant of observation does not necessarily coincide with the model snapshot, the agreement between model and observations is quite remarkable.

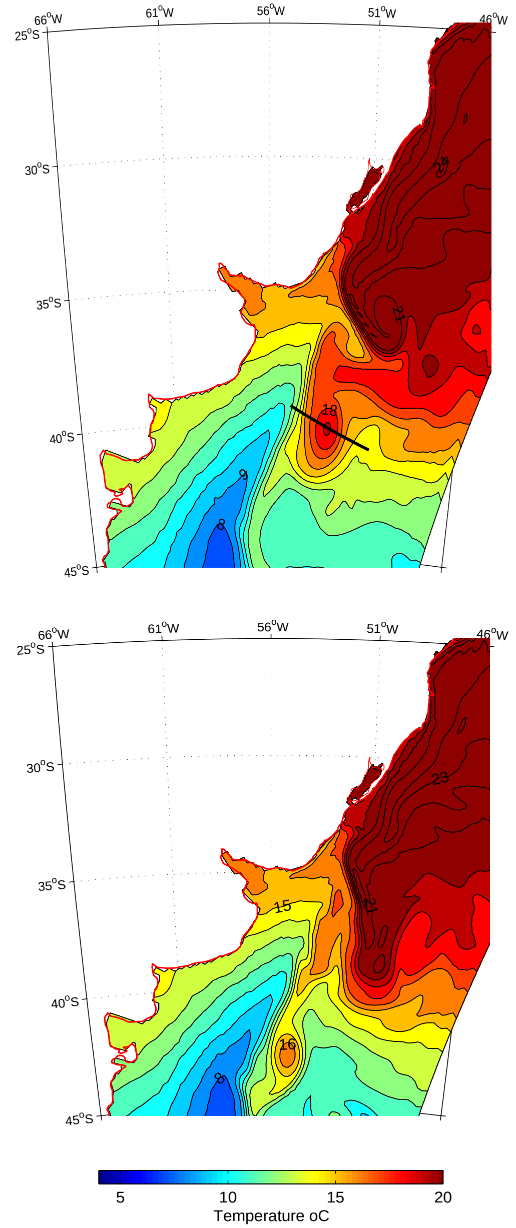

Fig. 10. Snapshots of Sea Surface Tempetature near the BMC obtained from the model. The upper panel is 21 model days before the lower one. The formation and subsequent motion of and "intrusion" eddy is clearly shown. The black line crossing The eddy in the top panel indicates the cross section shown in Fig. 11.

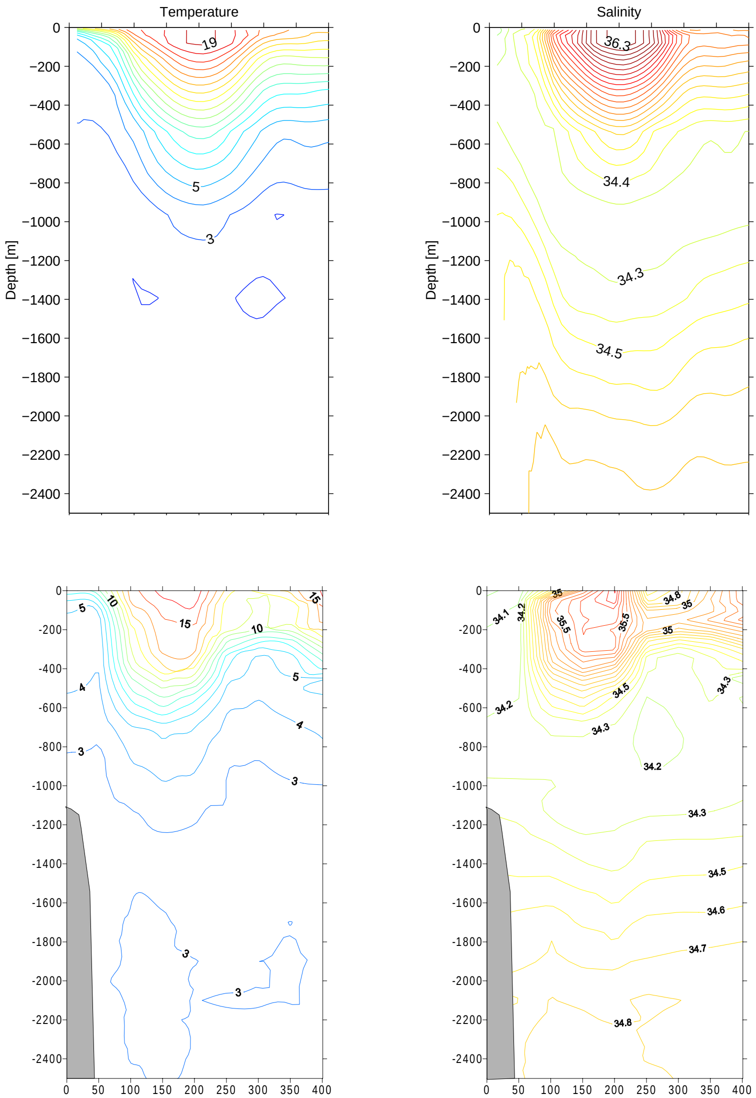

Fig. 11. Cross section of temperature and salinity taken approximately through the core of an "intrusion" eddy. Top panels show the model results, Bottom panels were obtained form an hydrographic section occupied in early november at 37 S. (see The Confluence Group [33], for details).

5. SUMMARY AND CONCLUSIONS.

In this article we described the numerical strategies used to implement a regional, eddy resolving, three-dimensional numerical model of the BMC. The numerical experiments consisted of integrations using idealized set-ups and experiments with a realistic basin configuration. The experiments in idealized basins were used to test the numerical implementation of open boundary conditions recommended by Palma and Matano[16 ,[18] in a configuration with active lateral forcing and variable bottom topography. Open boundary conditions based on radiation condition in the normal and tangential direction combined with advection/relaxation to climatology for tracers have been described and tested in the well known case of a double gyre with colliding western jets. They apperar to be numerically robust and to be capable of introducing the necessary information from the outer oceans while conserving within 5-10% range the main statistical features of the solution obtained with a benchmark (closed) model.

The simulations in a realistic basin were forced with climatological wind stress and heat fluxes at the surface and mass and heat fluxes extracted from global simulations across the lateral boundaries. The ability of the model to dynamically adjust inflows and outflows is worth noting. The model is able to produce mean flow patterns and variabilities which are in fairly good agreement with solutions provided by world ocean models (Semtner and Chervin [25]) and regional models of the South Atlantic (Matano[6] , Gan *et al* [8], De Miranda *et al* [10],Penduff *et al* [11]). Furthermore, the numerical results obtained with our model configuration appear to reproduce the general features of the ocean circulation observed in hydrographic and remote sensed data, including the average mean position of the BMC, the magnitude of the BC and MC transports and the development of warm intrusion eddies (Garzoli and Garrafo, [2]; Olson et al [3]).

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6 REFERENCES.

[1] D. B. Chelton, D. B., M. G. Schlax, D. L. Witter, and J. G. Richman, “Geosat altimeter observations of the surface circulation of the southern ocean”, *J. Geophys. Res.*, **95**, 17,877-17,903, (1990).

[2] S. L. Garzoli, and Z. D. Garraffo, "Transports, frontal motions and eddies at the Brazil-Malvinas confluence as revealed by inverted echo sounders", *Deep Sea Res.,* **36**, 681-703, (1989).

[3] D. B. Olson, G. P. Podesta, R. H. Evans, and O. Brown, "Temporal variations in the separation of the Brazil and Malvinas currents", *Deep Sea Res.*, **35**, 1,971-1,990, (1988).

[4] A. L. Gordon, "Brazil-Malvinas Confluence - 1984", *Deep Sea Res.,* **36**, 359-384, (1989).

[5] L. T. Smith, E. P. Chassignet, and D. B. Olson, "Wind-forced variations in the Brazil-Malvinas confluence region as simulated in a coarse resolution numerical model of the South Atlantic". *J. Geophys. Res.,* **99**, 5,095-5,117, (1994).

[6] R. P. Matano, "On the separation of the Brazil Current from the coast", *J. Phys. Oceanogr.,* **23**, 79-90, (1993).

[7] R. P. Matano, M. G. Schlax, and D. B. Chelton, "Seasonal variability in the southwestern Atlantic", *J. Geophys. Res.*, **98**, 18,027-18,035, (1994).

[8] J. Gan, L. A. Mysak, and D. N. Straub, "Simulation of the South Atlantic Ocean circulation and its seasonal variability", *J. Geophys. Res.*, **103**, 10241-10251, (1998).

[9] E. D. Campos, A. R. Piola, and R. P. Matano, "The western South Atlantic and climatic variations over South America", *IAI Newsletter*, **19**, 13-19, (1999).

[10] A. P. de Miranda, B. Barnier, and W. K. Dewar "On the dynamics of the Zapiola Anticyclone, ", *J. Geophys. Res.*, **104**, 21,137-21,149, (1999).

[11] L. T. Penduff, B. Barnier, K. Beranger, and J. Verron, "Comparison of near-surface mean and eddy flows from two numerical models of the South Atlantic Ocean". *J. Geophys. Res.,* **106**, 16857-16867, (2001).

[12] G. L. Mellor, and T. Yamada, "Development of a turbulence closure model for geophysical fluid problems". *Rev. Geophys. Space Phys.,* **20**, 851-875, (1982).

[13] J. Smagorinsky, "General circulation experiments with the primitive equations, I. The basic experiment", *Mon. Weather Rev.*, **91**, 99-164, (1963).

[14] A. F. Blumberg, and G. L. Mellor, "A description of a three dimensional coastal ocean circulation model". In *Three-Dimensional coastal ocean models,* **4**, edited by N. Heaps, pp. 208, AGU, Washington, D.C, (1987).

[15] R. A. Flather,"A tidal model of the northwest European continental shelf" , *Mem. Soc. R. Sci. Liege*, *Ser.* **6,** 10, 141-164, (1976).

[16] E. D. Palma, and R. P. Matano, "Dynamical impacts associated with radiation boundary conditions". *J. Sea Res.,* **46**, 117-132, (2001).

[17] I. Orlanski, "A simple boundary condition for unbounded hyperbolic flows", *J. Comput. Phys.,* **21**, 251-269, (1976).

[18] E. D. Palma, and R. P. Matano, "On the implementation of Open Boundary Conditions for a General Ocean Model: The three dimensional case". *J. of Geophys. Res.*, **105**, 8605-8627 (2000).

[19] E. P. Chassignet and P. R. Gent, "The influence of Boundary Conditions on Midlatitude

Jet Separation in Ocean Numerical Models", *J. Phys. Oceanogr.*, **21**, 1290-1299, (1991).
[20] B. Barnier, Marchesiello, P., Pimienta de Miranda, A., Molines, J-M., and M. Coulibaly 1998, "A sigma-coordinate primitive equation model for studying the circulation in the South Atlantic. Part I: Model configuration with error estimates", *Deep Sea Research*, I, **45**, 543-572, (1998).
[21] W. H. F. Smith, and D. T. Sandwell, "Global sea floor topography from satellite altimetry and ship depth soundings". *Science*, **277**, 1956-1962 (1997).
[22] G. L. Mellor, T. Ezer, and L. -Y. Oey, "The pressure gradient conundrum of sigma coordinate ocean models", *J. Atmos. Oceanic Technol.*, **11**,1126-1134, (1994).
[23] S. Levitus, "Climatological Atlas of the World Ocean". NOAA Prof. Paper No. **13**, U.S. Govt. Printing Office, Washington D. C, (1994).
[24] K. E. Trenberth, J. G. Olson, and W. G. Large, "A global ocean wind stress climatology based on ECWMF analyses", Tech. Rep. NCAR/TN-338+STR, National Center for Atmospheric Research, Boulder, Colorado, 93 pp, (1990).
[25] A. Semtner and R. M. Chervin, "Ocean general circulation from a global eddy-resolving model", *J. Geophys. Res.*, **97**, 5493-5550, (1992).
[26] L. Stramma, "The Brazil Current transport south of 23S', *Deep-Sea Res.*, **36**, 639-646, (1989).
[27] R. G. Peterson, and L. Stramma, "Upper-level circulation in the South Atlantic Ocean", *Prog. Oceanog.*, **26**, 173, (1996).
[28] F. Vivier and C. Provost, "Volume transport of the Malvinas Current: Can the flow be monitored by TOPEX/POSEIDON?", *J. Geophys. Res.*, **104**, 21105-21122, (1999).
[29] R. G. Peterson, C. S. Johnson, W. Kraus, and R. E. Davis, "Lagrangian measurements in the Malvinas". In *The South Atlantic, Present and Past Circulation*, edited by G. Wefer, W. Berger, G. Siedler, and D. Webb, pp. 239-247, Springer, Berlin, (1996).
[30] A. L. Piola and R. P. Matano, "Brazil and Falklands (Malvinas) Currents". In *Encyclopedia of Ocean Sciences*, Vol. **1**, edited by J.H. Steele, S.A. Thorpe and K.K. Turekian, pp. 340-349, Academic Press, London, UK, (2001).
[31] N. Ducet and X. Le Traon, *Int. WOCE Newsl.*, **37**, 40-43, (1999).
[32] D. L. Witter and A. L. Gordon, "Interannual variability of South Atlantic circulation from 4 years of TOPEX/POSEIDON satellite altimeter observations", *J. Geophys. Res.*, **104**, 20927-20948, (1999).
[33] The Confluence Group, Confluence 1988-1990: An intensive study of the Southwestern Atlantic, *EOS Transactions American Geophysical Union*, **71**,1131-1137, (1990).