On the Separation of the Brazil Current from the Coast

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ABSTRACT

A series of numerical experiments, using analytical and numerical models, leads to the conclusion that the separation of the Brazil Current from the coast can be related to the northward momentum of the Malvinas Current. Experiments in which the Malvinas Current has a low transport show the Brazil Current separating where the curl of the wind stress vanishes, seven degrees south of the observed separation latitude of 38°S. If, however, the flow distribution at the Drake Passage is adjusted so that the transport of the Malvinas Current is increased, then the model predicts that the latitude where the Brazil Current separates from the coast is near its observed value.

1. Introduction

The Brazil Current is the western boundary current of the South Atlantic Ocean. Geostrophic calculations based on hydrographic data indicate that its maximum transport may be no larger than 20 Sv ($\equiv 10^6$ m^3 s^{-1}) (Gordon and Greengrove 1986; Signorini 1978), which is less than the value estimated from the curl of the wind stress alone. The current flows south along the continental slope of South America to a point near 38°S where it separates from the coast and turns offshore in a series of meanders. Satellite and drifter data analyzed by Olson et al. (1988) indicate that the latitude where the current separates from the coast may migrate seasonally, being farther north during the austral winter (July to September) than during the austral summer (January to March). While the cause of the separation and its seasonal variation are still unknown, simple dynamical arguments involving the wind-stress curl and inertial effects indicate that the point where the Brazil Current leaves the coast should be located farther south than the observed latitude, perhaps as far south as 50°S. Veronis (1973) speculated that the current path is affected by the northward flow of the Malvinas Current. On the other hand, Brandhorst and Castello (1971) and Zyranov and Severov (1979) suggested the possibility that the separation is related to the forcing of the local winds over this area.

Since the pioneering works of Stommel (1948) and Munk (1950), several investigators have tried to explain why western boundary currents in general, and the Gulf Stream in particular, leave the bounding coast at latitudes other than those where the wind-stress curl is zero. Greenspan (1962), Carrier and Robinson (1962), and Spiegel and Robinson (1968) used purely inertial jets to model the Gulf Stream circulation; their prediction of the location of the separation of the current from the coast was independent of the wind-stress curl and based upon the hypothesis that inertial layers can be joined smoothly to the interior flow. Parsons (1969) used a reduced two-layer gravity model to predict where the Gulf Stream will separate from the coast. In his model, the separation occurs where the lower of the two layers outcrops; it is independent of topography or friction and depends only on the global wind field. Warren (1963) was the first to investigate the effects of topography on the Gulf Stream path. His study showed that the current can indeed be controlled by topography. Using potential vorticity conservation arguments he computed Gulf Stream paths for given bottom topographies, and his results agreed very well with observations of meander trajectories. Bryan (1963) and Holland (1972) employed numerical techniques to study the large-scale ocean circulation. Bryan (1963) investigated the effect of an abrupt discontinuity in the western coast but found that the boundary current had no inclination to separate permanently. Holland (1972) suggested that the boundary layer may separate as a result of topographic influences. In another numerical study Thompson and Schmitz (1989), using a two-layer model, showed that the separation of the Gulf Stream can be strongly influenced by the presence of a deep western boundary current flowing southward; its effect is to provide a source of negative relative vorticity to the Gulf Stream. It was observed

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that by increasing the transport of the deep current the point where the Gulf Stream leaves the coast moves farther south.

Neither topography nor inertia seems to be the cause of the separation of the Brazil Current from the coast. The continental slope of South America is reasonably smooth compared to those of other western boundary regions, and in the absence of bottom irregularities, inertia would force the Brazil Current to overshoot the latitude of zero wind-stress curl instead of producing an early separation. The aim of this paper is to try to understand why the Brazil Current leaves the western boundary where it does. The paper is organized into five sections. Following this introduction, section 2 presents a simple analytical model that is used to clarify the roles played by the wind forcing, topography, and the Antarctic Circumpolar Current (ACC) on the separation process. Section 3 describes the numerical model to be used in this study. Section 4 presents the results of several experiments. Finally, section 5 gives a summary and some concluding remarks.

2. A simple analytical model of the South Atlantic circulation

The separation process is a local phenomenon that depends on the global aspects of the circulation. The offshore veering of the Brazil Current may thus be related either to local, or remote conditions, or both. The wind-stress distribution over the southwestern Atlantic is an example of a local condition. The nature of the flow within the ACC at the Drake Passage or south of Africa are examples of remote conditions. The goal of studying the analytical model presented here is to explain, in simple terms, how different local and remote conditions may affect the separation of the Brazil Current from the coast.

As a simple representation of the South Atlantic Ocean, consider a rectangular ocean basin of uniform depth H with partially open boundaries on its east and west sides. If a rectangular coordinate system in a β plane is used with x and y measuring distances eastward and northward, respectively, then, in the steady state, the quasigeostrophic limit to the linear vorticity equation can be written in nondimensional form as (Veronis 1973)

$$\epsilon\nabla^2\psi + \frac{\partial\psi}{\partial x} = \mathrm{curl}_z\vec{\tau}, \tag{1}$$

where $\psi(x, y)$ is the mass transport streamfunction and $\vec{\tau}\,(x, y)$ is the wind-stress forcing. The nondimensional parameter $\epsilon = r/\beta L$ measures the importance of frictional processes, where r is the coefficient of bottom friction, L is a typical spatial scale, and β is the gradient of planetary vorticity.

The stress exerted on the surface of the ocean by the wind is assumed to be of the form $\tau = \tau^x\,(y)$. Since there can be no flux across solid boundaries, ψ must be constant there. On open boundaries ψ will satisfy the open boundary conditions,

$$\psi(0,y) = g(y) \quad 0 < y < y_1 \tag{2.1}$$

$$\psi(1,y) = f(y) \quad 0 < y < y_2. \tag{2.2}$$

Here f and g will be specified for the different cases studied in the following. It is easy to show that an approximate solution to the system formed by Eq. (1) and (2) is

$$\psi(x,y) = [f(y) - \frac{\partial\tau^x}{\partial y}(x-1)](1 - e^{-x/\epsilon}) + g(y)e^{-x/\epsilon}. \tag{3}$$

Given the open boundary conditions $f(y)$ and $g(y)$ and the wind-stress distribution $\tau^x(y)$, Eq. (3) can be solved for the streamfunction ψ.

As a first application of this model, consider the circulation that arises when $f(y)$ and $g(y)$ represent the conditions sketched in Fig. 1. At the western boundary the streamfunction distribution $g(y)$ (Fig. 1c) represents a general inflow. At the eastern boundary there is inflow and outflow (Fig. 1b). The inflow is a crude representation of the Agulhas Current. The outflow stands for the broad eastward flow of the ACC. Figure 1a shows the streamfunctions that satisfy these boundary conditions if there is no wind-stress forcing. The northern gyre (dotted lines) is a consequence of the inflow of the Agulhas Current. Since there are no vorticity sources, this current flows westward until the western margin of the basin (the South American coast). There it forms a southward flowing, western boundary current that follows the coast briefly before separating and returning to the east. In the southern portion of the basin there is a broad eastward flow. The circulation in the open ocean follows latitude lines. At the western boundary, the presence of a viscous northward current (Malvinas Current) is necessary to modify the vorticity distribution and match the eastern and western boundary conditions. In this current, the dynamical balance is between friction and planetary vorticity advection. It is interesting to note that in this example the presence of a Malvinas Current is not the result of direct wind forcing but rather of the open boundary conditions, which in turn parameterize the effect on the South Atlantic of the winds in the Pacific and Indian oceans.

If the open boundary conditions are kept as in the previous case and the wind-stress distribution is assumed to be as shown in the left-hand side of Fig. 2, then the resulting streamfunction solution of (3) is that shown in Fig. 2. The northern portion of the basin is dominated by an anticlockwise gyre by a southward flowing western boundary current (Brazil Current). Now the flow from the Agulhas Current is part of the subtropical gyre. The circulation is similar to the previous case with the exception of some interesting dif-

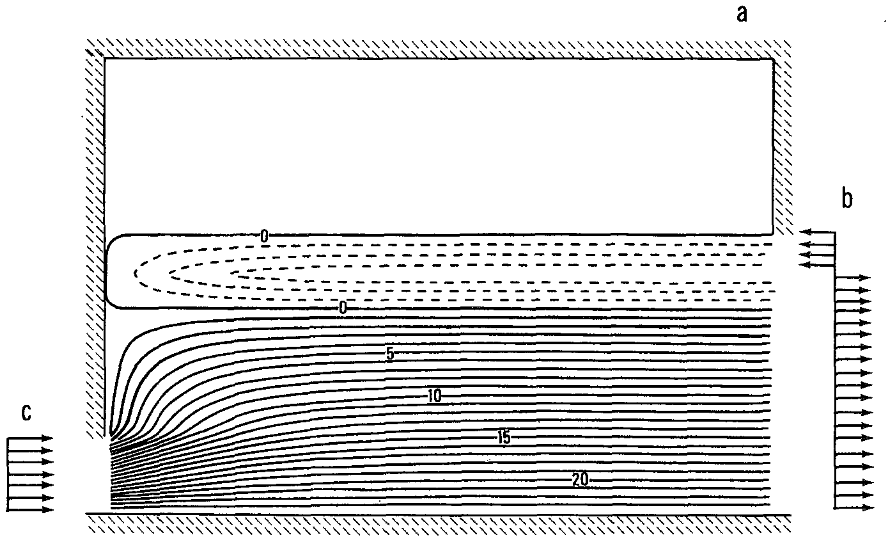

FIG. 1. (a) The streamfunction solution to the potential vorticity equation in the idealized South Atlantic domain without wind forcing. (b) The boundary conditions imposed at the eastern boundary. The inflow in the northern part of the basin represents the Agulhas Current. The outflow stands for the broad eastward flow of the ACC. (c) The inflow imposed as open boundary condition at the western boundary.

ferences in the southwestern portion of the basin. Note the tilt of the zero streamline, which in the previous case was coincident with a latitude line. This tilt is due to the competing effect of wind stress and boundary conditions. The point at which the boundary currents separate from the western boundary is coincident with the location of the zero of the wind-stress curl and lies to the south of the point of separation of the previous model (marked by an arrow). The vorticity supplied by the wind acts to increase the flow south of the latitude of zero wind-stress curl and weaken the flow north of that point. Thus, the location of the confluence of the Brazil and Malvinas currents (the location where the Brazil Current leaves the coast) depends not only on the winds in the South Atlantic basin but also on more remote conditions, such as the wind in the Indian or Pacific Ocean. The open boundary conditions that, in this example, parameterize the wind stress over the

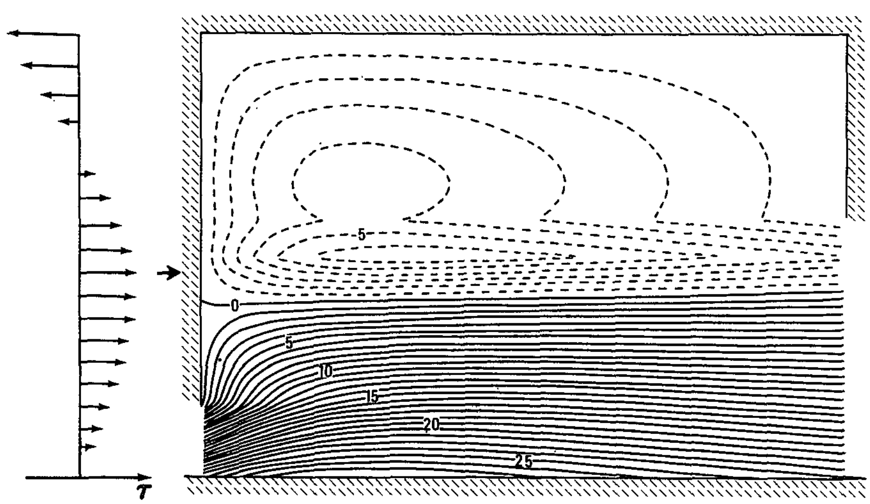

FIG. 2. Streamfunction for an ocean forced by the wind stress sketched in the left-hand side and the open boundary conditions of the previous examples. The arrow signals the latitude where the western boundary current separates in the case of no wind-stress forcing. The east–west tilt of the zero streamline is the result of the competing effects of the wind-stress forcing and the open boundary conditions.

Indian and Pacific basins may be correlated with the wind stress over the South Atlantic. If so, the only new effect brought by the local winds will be an intensification of the western boundary current. In the more general case of winds with zonal variations, the local patterns may be an important factor for changes in the location of the confluence of the Brazil and Malvinas currents.

This simple model shows that the Malvinas Current can be produced by a western intensification similar to the Brazil Current or the Gulf Stream. It, however, can also be the result of topographic effects. To illustrate this point, consider a basin with variable bottom topography. In the absence of dissipation, the potential vorticity equation for linear, steady, unforced flow can be written as:

$$\frac{\partial \psi}{\partial x}\frac{\partial (f/H)}{\partial y} - \frac{\partial \psi}{\partial y}\frac{\partial (f/H)}{\partial x} = 0. \quad (4)$$

Equation (4) states that lines of constant planetary vorticity (f/H) and constant ψ coincide in the x, y plane. It implies that by knowing the values of ψ at the boundaries we can determine the solution in the interior of the ocean basin by simply propagating these values along the characteristics f/H. Consider the case in which $H = H(x)$ only. Then (4) can be written in nondimensional form as

$$\frac{\partial \psi}{\partial x} + \frac{\delta}{H}\frac{dH}{dx}\frac{\partial \psi}{\partial y} = 0, \quad (5)$$

where $\delta = f_0/\beta L$. Given $H(x)$ and the simple boundary conditions of Fig. 1 (but where the inflow of the "Agulhas Current" at the eastern boundary was suppressed) Eq. (5) can be solved analytically using the method of

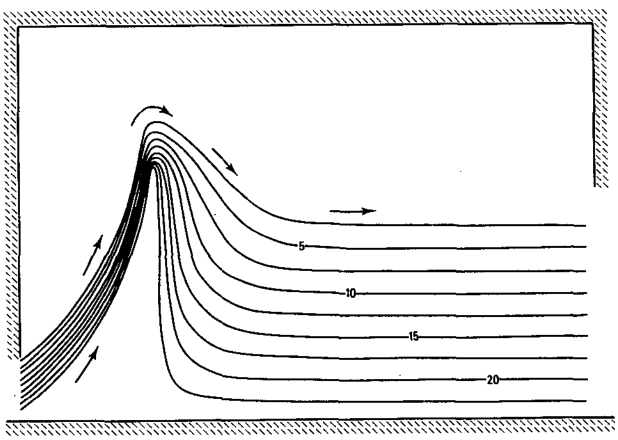

FIG. 3. The streamfunction solution to the potential vorticity equation in an ocean with the bottom topography described in the text. There is no wind forcing. The western boundary condition is as shown in Fig. 1c, while the eastern boundary condition is similar to 1b but without the inflow of the Agulhas current.

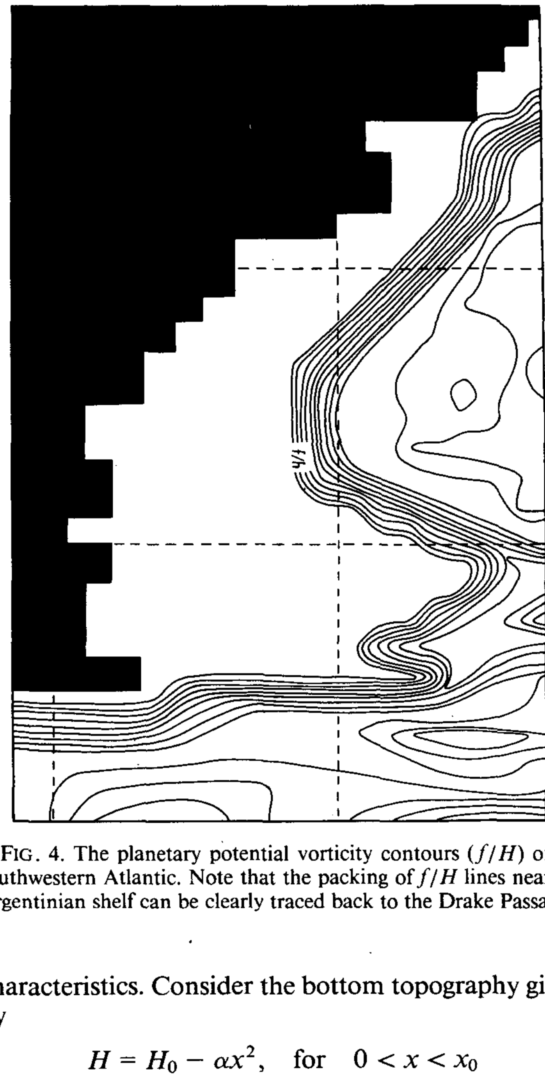

FIG. 4. The planetary potential vorticity contours (f/H) of the southwestern Atlantic. Note that the packing of f/H lines near the Argentinian shelf can be clearly traced back to the Drake Passage.

characteristics. Consider the bottom topography given by

$$H = H_0 - \alpha x^2, \quad \text{for} \quad 0 < x < x_0$$

$$H = H_0, \quad \text{otherwise.}$$

The solutions obtained by propagating the characteristics emanating from the eastern and western boundaries were matched at $x = x_0$ by adding a frictional term to (5). Figure 3 shows the resulting streamfunction. Outside of the frictional zone at $x = x_0$, the flow is constrained to conserve potential vorticity. After leaving the Drake Passage the current turns northward to compensate the vortex squeezing resulting from the decreasing depth by a reduction of the Coriolis parameter. East of the depth discontinuity, the planetary vorticity contours coincide with latitude lines and the flow is zonal. The important point to notice is that, in contrast with the previous flat bottom cases, the intense northward flow near the western margin of the ocean is not produced by the wind-stress curl but by a bottom-trapping effect.

Figure 4 shows the contours of planetary vorticity near the coast of South America. The lines of constant f/H at the continental slope of Argentina can be clearly

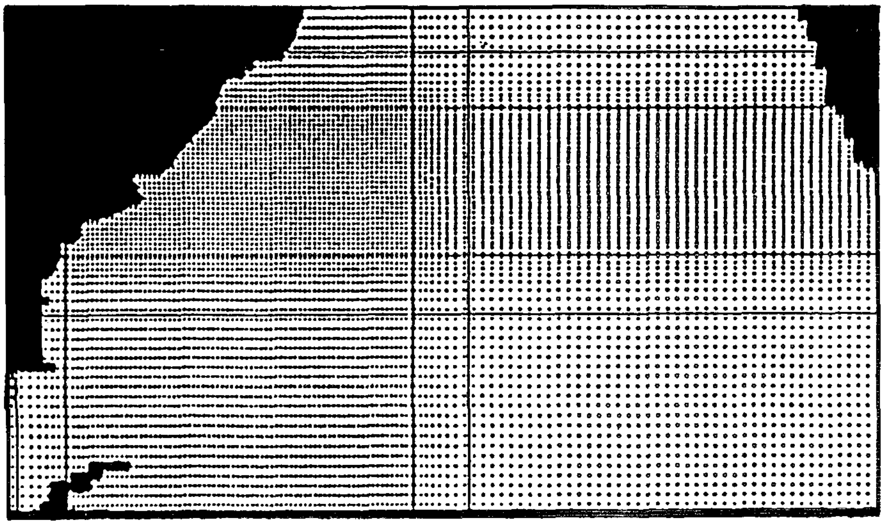

FIG. 5. The domain and grid of the numerical model described in the text. The domain extends from 20°S to 70°S and from 70°W to 12°E. The resolution varies from one-half degree near the coasts of South America to one degree elsewhere.

traced back to the Drake Passage. It will be argued that because of its predominantly barotropic structure a portion of the ACC flow will tend to follow these lines. This portion will then form the Malvinas Current. As we will see, the origin of the Malvinas Current is important for determining the exact position of its confluence with the Brazil Current, and the separation of the latter from the coast.

3. The numerical model

The analysis presented in the preceding section shows that the latitude where the Brazil and Malvinas currents is located depends on local wind conditions, bottom topography, and the flows at the Drake Passage and between Africa and Antarctica. To analyze how changes in these conditions may affect the separation of the Brazil Current from the coast we will use a numerical model of the South Atlantic region. For the sake of completeness, a brief summary of the model and its boundary conditions will be given here. The reader interested in a more complete description is referred to Matano (1991).

a. The model

The model used in this study is the multilevel numerical model described by Bryan (1969) and Cox (1984). Figure 5 shows the domain of the model. It extends from 20°S to 70°S and from 70°W to 12°E. The bottom topography and coastlines are realistic with the exception of an east–west solid boundary at 70°S and the placement of the Palmer Peninsula and the South Atlantic islands under 60 m of water. The horizontal resolution varies from one-half degree near the coast of South America to one degree elsewhere. The model has 15 vertical levels, and it is initialized by the climatological annual mean fields of temperature and salinity taken from Levitus (1982).

b. The boundary conditions

At the continental solid boundaries both velocity components and the normal gradients of temperature and salinity are zero. The northern boundary of the model is also solid, at which both components of velocities are set to zero and a Newtonian damping is applied to temperature and salinity. At the free surface the wind stress is parameterized by an analytical approximation to the zonally averaged annual meal wind stress of Hellerman and Rosenstein (1983). In this approximation $\vec{\tau} = [\tau^x(y), 0]$, where

$$\tau^x(y) = 0.2 + \tanh\left[\frac{(y+90)}{20}\right], \quad y > 45°\mathrm{S}$$

$$\tau^x(y) = -0.2 + \tanh\left[\frac{(y+30)}{8}\right], \quad y \leqslant 45°\mathrm{S} \qquad (14)$$

and the y coordinate denotes latitude. Figure 6 shows the latitudinal distribution of the wind-stress forcing. Note that in (14) the zero of the wind-stress curl is located at 45°S.

The streamfunction is specified at the lateral open boundaries. Different boundary conditions are used for temperature, salinity, and the baroclinic velocities depending on whether there is inflow or outflow. The streamfunction at the open boundaries determines the total transport of the ACC and the spatial distribution of the barotropic velocities. The first goal is to reproduce the mean circulation, so it is appropriate to specify conditions that represent the average state. At the

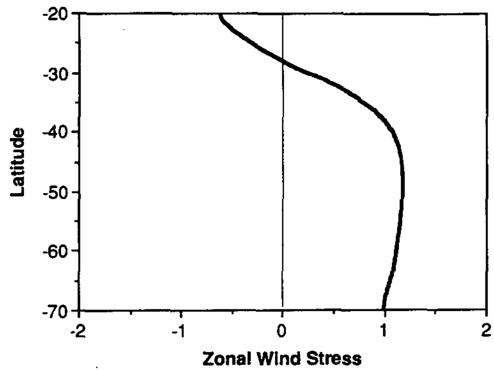

FIG. 6. Latitudinal distribution of the zonal wind stress used as a forcing for the numerical model described in the text. The units are dynes per square centimeter^{-2}.

Drake Passage, data collected by several expeditions (Whitworth and Peterson 1985) indicate that a reasonable estimate for the mean transport of the ACC is 120 Sv in an eastward direction. Mass must be conserved, so the total transport between Africa and Antarctica must equal the inflow at the Drake Passage. Since the grid size of the model does not permit the resolution of the jetlike structure of the observed flow, the barotropic velocity distributions chosen for the eastern and western boundaries of the South Atlantic are as shown in Fig. 7. At the Drake Passage the velocity varies with the cosine of latitude. The distribution of the barotropic velocities at the eastern boundary includes a small westward flow near South Africa, representing the Agulhas Current, and a broad eastward flow farther south.

Once the barotropic component of the transport has been imposed, boundary conditions for the baroclinic variables must be chosen. At an open boundary there can be inflow and outflow. When there is inflow, temperature and salinity are prescribed and the baroclinic velocities are adjusted geostrophically. At boundaries with outflow, it is necessary to impose a condition that allows phenomena generated in the interior domain to pass through without distortion and without affecting the interior solution. The one used in this study is the Sommerfeld radiation condition (Sommerfeld 1954).

4. The experiments

Five numerical experiments have been made to determine what causes the separation of the Brazil Current from the coast. The first experiment shows the circulation that results from the initial and boundary conditions described earlier. The second experiment was designed to study the sensitivity of the Brazil Current to changes in the curl of the wind stress. The third experiment investigates the dependence of the latitude of the separation of the Brazil Current from the coast on the eastern boundary conditions. The fourth experiment examines the effect of the ACC transport, and the fifth analyzes how the Brazil Current separation is affected by changes in the distribution of the ACC transport at the Drake Passage.

a. The mean circulation

The time adjustment of the model, in all the experiments, was controlled by the spatial average of the absolute value of the temperature tendency; that is,

$$\sum_x \sum_y \sum_z \frac{|\Delta T|}{\Delta t}. \tag{15}$$

Figure 8 shows the time behavior of (15) in the first case. This figure is almost identical in all the experiments reported in this study. There is a rapid initial adjustment of the variables in the first year, followed by a slow convergence to a quasi-steady state. The dynamic adjustment of the ocean is usually associated with the formation of the thermocline slope by the westward propagation of planetary waves. This is a process with an associated time scale of weeks near the equator and decades at high latitudes. In the present experiments, however, the adjustment is more rapid. Because of the realistic density field specified as initial condition there is no need for the buildup of a thermocline slope. The adjustment of the model is then primarily related to the generation of the currents associated with the density gradients and the open boundary conditions. These are processes with time scales of a few months, as reflected in Fig. 8. Experiments in which the model was integrated for longer

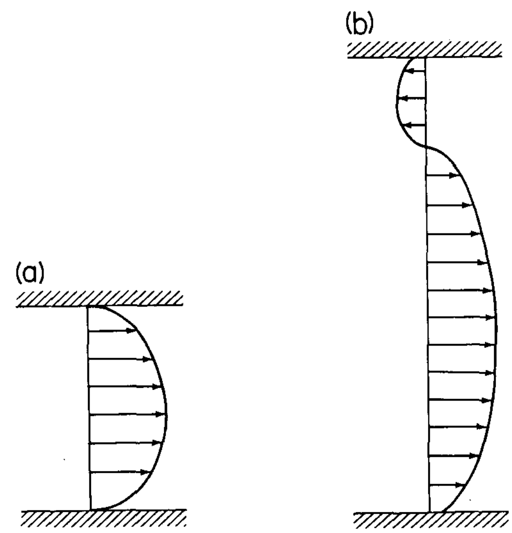

FIG. 7. The inflow–outflow conditions imposed to the barotropic component of the transport in the numerical model: (a) at the Drake Passage; (b) at the eastern boundary. The total transport in both cases is 120 Sv.

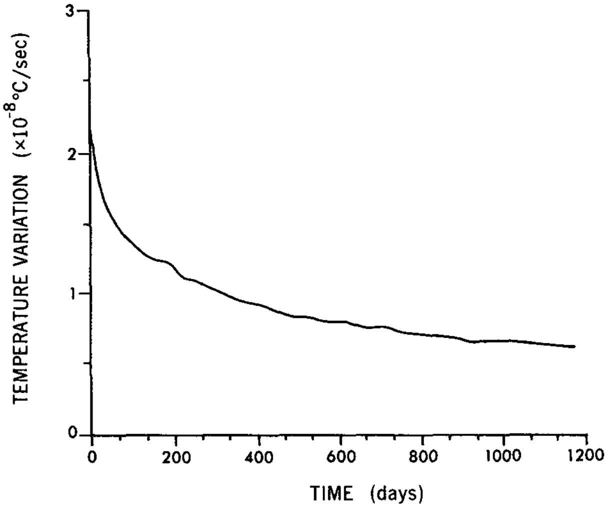

FIG. 8. The global integral of the absolute value of the temperature variation. This integral represents the temporal response of the model.

periods gave the same results for the separation of the Brazil Current from the coast.

Figure 9 shows the streamfunction that evolved by the end of the integration. For reference, this figure can be compared with Fig. 2. It is observed that the gross features of the South Atlantic circulation can be explained by the simple physics of Eq. (1). After leaving the Drake Passage the ACC flows eastward and diverges. Part of the flow turns northward while the remainder continues to flow to the east. The intensification of streamlines in the southwestern Atlantic indicates the presence of the Malvinas Current. This current flows northward until it converges with the Brazil Current, near 45°S, and then turns offshore. North of 45°S, the flow is dominated by an anticlockwise gyre with a clear western intensification.

The top-to-bottom transport of the currents in the western margin of the subtropical gyre is about 60 Sv. This value includes the wind-driven Brazil Current in the upper layers and the thermohaline-forced North Atlantic Deep Water (NADW) in deep layers. Transport estimates for the Brazil Current based on hydrographic data vary, although one characteristic common to the several reports available is the agreement in a low transport north of 25°S. Average values, based upon geostrophic calculations, are generally less than 10 Sv (Peterson and Stramma 1991). South of 25°S transport estimates increase. Near 38°S geostrophic calculations result in estimated transport values lying between 19–22 Sv, relative to depths of 1400–1500 m (Gordon and Greengrove 1986; Garzoli and Garrafo 1989). Other estimates, in the same region but using reference levels depths of 3000 m or more (McCartney and Zemba 1988; Zemba and McCartney 1988; Peterson 1990), gave values of near 70 Sv. For the depth-integrated flow, Mellor et al. (1982) estimated a value of 60 Sv using a diagnostic model with wind stress and real bottom topography, while Rintoul (1988), applying inverse methods to the trans-Atlantic IGY hydrographic data, found a value of 63 Sv at 32°S.

The vertical structure of the currents in an experiment similar to the present has been described by Matano and Philander (1993). The mean meridional circulation, in the subtropical gyre, consists of a poleward flow of surface and deep waters and a northward flow of intermediate and bottom waters. In the upper ocean the most notable feature of the wind-driven circulation is the southward flow of the warm waters from the

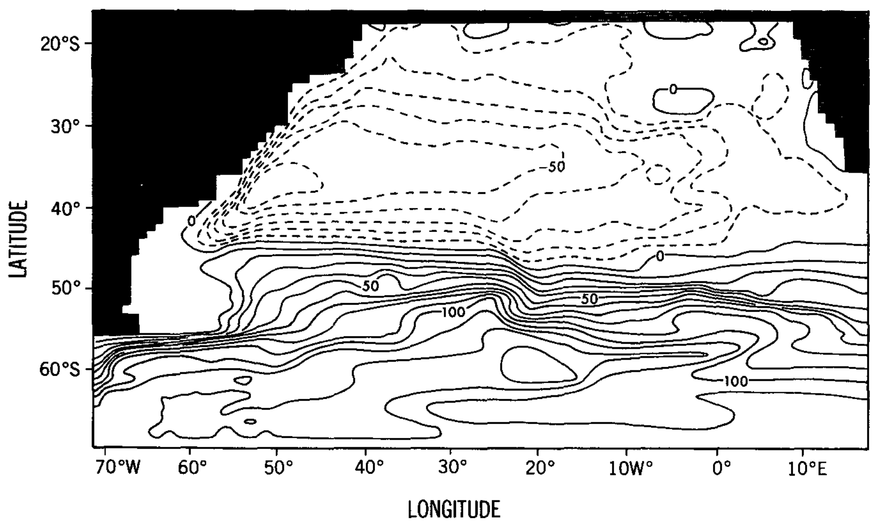

FIG. 9. Volume transport streamfunction after three years of integration for the primitive equation model. As reference, this figure can be compared with Fig. 2. The contour interval is 10 Sv.

Brazil Current. This current, which flows along the western margin of the basin, penetrates to depths of 1000 m at 30°S, but its maximum velocities, up to 50 cm s^{-1}, are observed near the surface of the ocean. Below this current, and at depths of 2000–3000 m, there is a southward flow of NADW. In the model simulations the flow of NADW is maintained by the thermal forcing (Newtonian damping) acting near the northern boundary of the model.

South of the subtropical gyre, density and velocity sections become markedly more uniform with depth. Over the continental slope of Argentina the circulation is dominated by the northward flow of the cold Malvinas Current. This current branches from the core of the Antarctic Circumpolar Current at approximately 50°S. While maximum velocities, up to 20 cm s^{-1}, are observed near the surface the vertical structure of the current is highly barotropic and relatively high velocities can be observed near the ocean floor. The barotropic structure of this current has already been noted in descriptions of the water-mass characteristics of this region (Peterson and Stramma 1990). The transport estimated by the model for the Malvinas Current is approximately 8 Sv. There are few hydrographic estimates with which to compare. Zyranov and Severov (1979) calculated the depth-integrated transport to be 32 Sv at 45°S during the summer and 40 Sv in winter. Gordon and Greengrove (1986) estimated a northward transport of 9.8 Sv at 42°S and 11.4 Sv at 46°S using a reference level of 1400 m. Piola and Bianchi (1990) estimated a transport between 10 and 12 Sv for a reference level of 1000 m.

Although in general terms the model results compare well with known oceanographic features, the latitude where the Brazil Current leaves the coast does not. During the first stages of the numerical integration, when the solution is dominated by the initial conditions, the separation of the Brazil Current from the coast is located near its observed position at 40°S (Fig. 10a). As the model adjusts to the boundary conditions, the Brazil Current moves southward. Figure 10b shows the velocity vectors in the southwestern Atlantic after three years of integration. In this quasi-stationary state the location of the confluence has been displaced from 40°S to 45°S.

It is not clear why this particular simulation fails to predict the separation latitude of the Brazil Current. Although most numerical models are unsuccessful in predicting the correct separation latitude of the Gulf Stream, in the South Atlantic Ocean the situation is quite the opposite. A quick review on past attempts to simulate the global circulation (Cox 1975; Semtner and Chervin 1988) shows models that, regardless of their resolution, are able to capture the correct path of the Brazil Current. In the following experiments we will see why this particular simulation failed to predict the correct separation latitude, and an explanation will be offered as to why other models succeed in this regard.

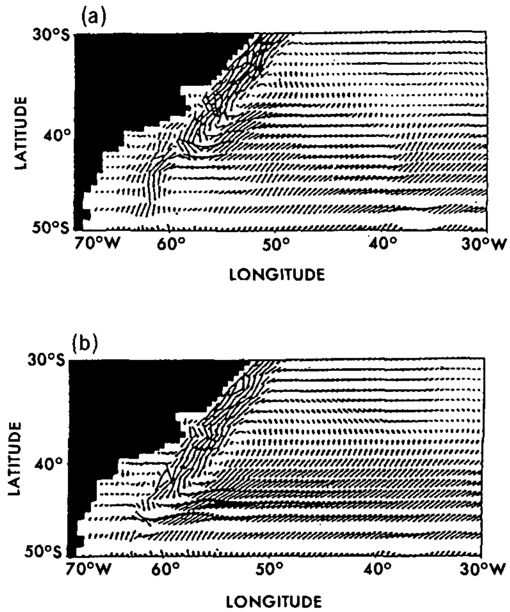

FIG. 10. Surface velocity vectors of the numerical model in the southwestern Atlantic: (a) after three months of integration, (b) after three years of integration. Note the southward drift of the Brazil Current.

b. The wind curl

To test the sensitivity of the Brazil Current separation latitude to changes in the wind field, the model was run using two additional wind fields. First, the climatological wind-stress data of Hellerman and Rosenstein (1983) were used. This modification did not improve the performance of the model with respect to the separation of the Brazil Current. In fact, the separation was predicted to occur at 47°S, even farther south than in the previous experiment. This result raised the possibility that in this model the latitude where the Brazil Current leaves the coast is primarily determined by the latitude of the zero of the wind-stress curl. To test this hypothesis, the climatological wind stress was replaced by an analytical expression similar to (14) but with the zero of the wind-stress curl located at 40°S. Figure 11 shows the surface velocity vectors in the quasi-steady state for this case. As hypothesized, the Brazil Current separates approximately at the latitude where the wind-stress curl vanishes. This experiment highlights a flaw of the model. According to the climatological information (Hellerman and Rosenstein 1983), the zero of the wind-stress curl in the Southern Hemisphere is usually found at latitudes much higher than those of the separation (Olson et al. 1988). Based on the analysis of satellite data it has been suggested that maximum winds can be located at even higher latitudes than those indicated by Hellerman's data (Chelton et al. 1990). Since global models of the ocean circulation that use climatological winds (e.g., Semtner and Chervin 1988;

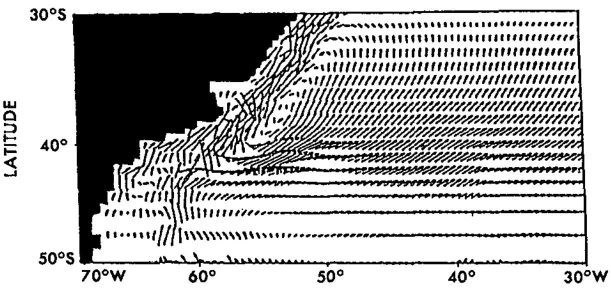

FIG. 11. Surface velocity vectors of the numerical model at the southwestern Atlantic when the zero of the wind-stress curl is moved to 40°S.

Cox 1975) tend to produce the correct separation latitude of the Brazil Current, it is possible that the sensitivity of this model to the wind forcing is related to the conditions imposed at the open boundaries. This possibility will be explored in the following experiments.

c. The eastern boundary condition

As discussed in the previous section, the streamfunction distribution at the eastern boundary parameterize the flow conditions of the Pacific and Indian oceans. To examine how extreme changes in this boundary condition could affect the latitude where the separation is located, the westward flow of Fig. 7b was removed. Physically, this amounts to suppressing the Agulhas Current. The wind-stress field was represented by the same analytical expression as in the first experiment. The results obtained after three years of integration are displayed in Fig. 12. Comparing this figure with Fig. 10b shows a small northward displacement of the separation, which is now located near 43°S. In spite of the extreme change at the eastern boundary, the separation latitude is not significantly affected and the results still do not agree with observations.

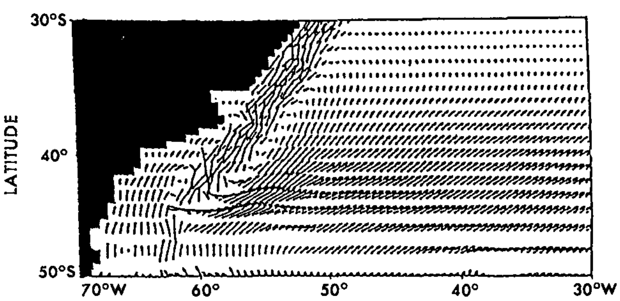

FIG. 12. Surface velocity vectors of the numerical model in the southwestern Atlantic when the zero of streamfunction at the eastern boundary has been moved to the southern tip of Africa. Physically this amounts to suppressing the Agulhas Current.

d. The ACC transport

If the confluence between the Brazil and Malvinas currents is considered as a linear superposition of two currents flowing in opposite directions, then the location where these currents separate from the coast will be located where their transports per unit area (or equivalently, their mean meridional velocities) are the same. From the Sverdrup relation, the mean meridional velocity for the Brazil Current can be estimated as

$$V_{\text{Brazil}} = -\frac{1}{\beta L_w}\int_{-L}^{0}\frac{\partial \tau^x(y)}{\partial y}\,dx, \tag{6}$$

where L_w is the width of the western boundary current ($\sim$100 km) and L_w is the basin width. It is not clear how to estimate the mean meridional velocity of the Malvinas Current. If this current is assumed to be driven by the wind stress, then a calculation similar to (6) shows that its northward transport vanishes where the curl of the wind stress is zero. For the confluence of the Malvinas and Brazil currents to be north of this latitude there must be an increase in the inertia of the Malvinas Current, which can only result from nonlinear effects. If, however, the Malvinas Current is the result of a topographic trapping of part of the ACC flow, then it seems reasonable to suppose that its transport will be more or less independent of latitude. In such a case its mean meridional velocity can be roughly estimated as

$$V_{\text{Malvinas}} = \frac{\text{ACC Transport} \times \mu}{\text{Depth} \cdot L_w}, \tag{7}$$

where μ represents the fraction of the ACC transport at the Drake Passage that is channeled to the Malvinas Current. It follows that an increase in the ACC transport can result in an increase in the Malvinas transport, which, in turn, may force the Brazil Current to separate north of the latitude of zero wind-stress curl.

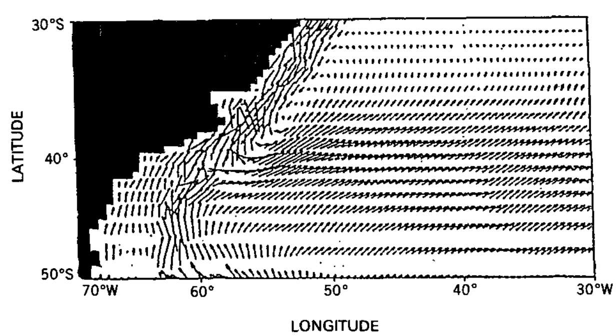

FIG. 13. Surface velocity vectors of the numerical model in the southwestern Atlantic when the transport of the Antarctic Circumpolar Current is increased from 120 Sv to 180 Sv. This is the most commonly observed value in general circulation models that predict the correct separation latitude of the Brazil Current.

To test this hypothesis, an experiment was designed in which the total ACC transport was raised from 120 Sv to 180 Sv. The decision to increase the ACC transport to 180 Sv is not arbitrary, but based on observations that this is roughly the value found in most global models that are successful in predicting the separation of the Brazil Current (Cox 1975; Semtner and Chervin 1988). The plot of the surface velocities after three years of integration is shown in Fig. 13. As result of the increased transport in the ACC, the northward momentum of the Malvinas Current now dominates the separation process and the confluence between the two currents is at 40°S, even though the zero of the wind-stress curl is located at 45°S. It should be noted that whether the Malvinas Current is produced by the wind stress or by topographic effects, inertia plays the same role; in both cases it will tend to produce a confluence and the resulting separation, north of the zero of the wind-stress curl. The difference is that if the Malvinas Current is produced by the curl of the wind stress, then nonlinearities in its flow are the only explanation for the northward position of the confluence.

e. The ACC distribution at the Drake Passage

If the Malvinas Current is the result of a topographic effect, then it is not necessary to assume a large value of the ACC transport in order to correctly model the separation of the Brazil Current since it is the fraction, μ, of the ACC diverted to the Malvinas Current and not the absolute value of the ACC transport that matters. To demonstrate this, an experiment was designed in which the transport distribution of the ACC at the Drake Passage was changed in such a way as to concentrate a major portion of the flow in the north, while its total value was kept at 120 Sv. Figure 14 shows the new mass transport distribution and, for the purpose of comparison, the one used in the previous cases. It can be argued that this transport distribution is not

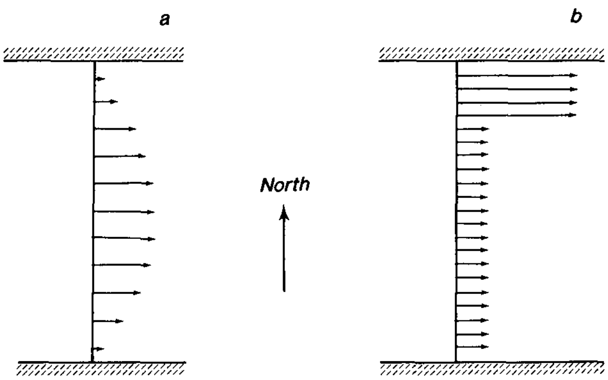

FIG. 14. Mass transport distributions imposed as boundary conditions at the Drake Passage: (a) in the previous experiments, (b) a new transport distribution. The total transport of the Antarctic Circumpolar Current was kept at 120 Sv.

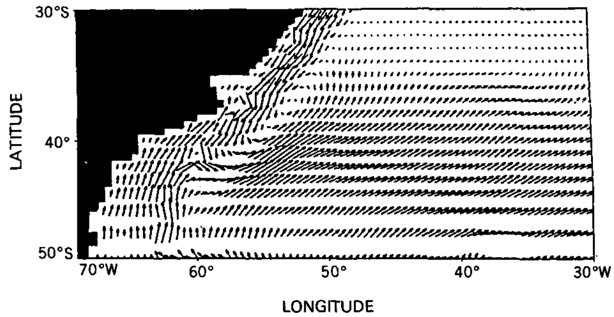

FIG. 15. Surface velocity vectors in the southwestern Atlantic using the mass transport distribution at the Drake Passage shown in Fig. 14b.

unrealistic. According to data taken during several cruises (Nowlin and Klink 1986), most of the ACC transport at the Drake Passage seems to be associated with high-velocity cores separated by transition zones, and the strongest ones are located near the northern part of the channel.

Using this new boundary condition, the numerical model was integrated again for three years. Figure 15 shows the surface velocity vectors in the area of the confluence in the quasi-steady state. As expected, the Brazil Current separates near 40°S, even though the zero of the wind-stress curl is still at 45°S. This suggests that the cold, northward flowing Malvinas Current is not produced by a western intensification, like the Brazil Current or the Gulf Stream, but by topographic control of the ACC. At the Drake Passage, the northern portion of the ACC is trapped against the shelf edge of South America and is then channeled northward. As a consequence, the position where the confluence region is located, or alternatively where the Brazil Current leaves the coast, is dependent not only on the wind forcing in the subtropical region but also on conditions at the Drake Passage.

5. Summary and conclusions

A numerical model has been used to determine what causes the separation of the Brazil Current from the coast. A series of experiments leads to the conclusion that if the transport of the Malvinas Current is low then the path of the Brazil Current, and the confluence between the two currents, is governed by the curl of the wind stress. If, however, the ACC mass transport distribution at the Drake Passage is adjusted so that the transport of the Malvinas Current is increased, then the latitude at which the Brazil Current separates from the coast moves to nearly its observed position. The Brazil Current is not the only current that meets a flow in an opposite direction; others examples are the Gulf Stream, which converges with the Labrador Current, and the Kuroshio, which meets the Oyashio Current. The confluence of the Brazil and Malvinas currents is different from these other examples because both currents carry comparable volumes of water. In contrast, in the Northern Hemisphere, the transports of the Gulf Stream and the Kuroshio are an order of magnitude bigger than those of their opposing flows.

Estimates of the transport of the Malvinas Current based on reference levels of 1000–1500 m suggested that this was a relatively weak current with an approximate transport of 10 Sv. As the Malvinas Current is mostly a barotropic flow, baroclinic calculations may underestimate its transport. Peterson (1990) reported the depth-integrated flow at 42°S to be as high as 70 Sv. Although this may be not an unreasonable figure, a value near 40 or 50 Sv seems more likely.

In the North Atlantic Thompson and Schmitz (1989) suggested that the presence of a deep western boundary current flowing southward may cause the separation of the Gulf Stream from the coast at Cape Hatteras. A similar mechanism in the South Atlantic Ocean, involving the northward flow of Atlantic Bottom Water (AABW), seems unlikely. There are few direct measurements of AABW transport, although all of them seem to consistently indicate a value near 4 Sv (Hogg et al. 1982; Wright 1969; Rintoul 1991). This value, if representative, is an order of magnitude smaller than those estimated for the surface currents.

It has been observed that numerical models of the global circulation correctly predict the latitude at where the Brazil Current leaves the coast. According to the present results, this is the result of the high ACC transport obtained by these models; the ACC pushes the position of the Malvinas–Brazil confluence north of the latitude of zero wind-stress curl. It may be that if the ACC transport, in such global models, is reduced to more realistic values then the predicted confluence region will move southward because of the inability to resolve the jetlike structure of the ACC at the Drake Passage and, hence, the resulting Malvinas Current.

According to hydrographic and satellite observations (Legeckis and Gordon 1982; Olson et al. 1988) the confluence between the Malvinas and Brazil currents is characterized by strong fluctuations at nearly all frequencies. Given the characteristics of this region, it is likely that part of this variability results from the presence of unstable waves that grow at the expense of the potential energy of the system. However if, as proposed here, the location where the Brazil Current leaves the coast is determined by its confluence with the Malvinas Current, it seems logical to suppose that variations in the transport of either of these currents can also be correlated with latitudinal oscillations of the confluence. The transport of the Malvinas Current can be affected by fluctuations of the ACC at the Drake Passage or by the forcing of local winds in the Southern Ocean. Fluctuations in the wind-stress field in the subtropical basin can produce changes in the mass transport of the Brazil Current (Matano 1991). As discussed by Matano and Philander (1991), these north–south excursions can have consequences for the thermohaline properties of the Atlantic Ocean. The importance of these mechanisms is the subject of ongoing research.

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