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The influence of the Brazil and Malvinas Currents on the southwestern Atlantic shelf circulation

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Abstract

The oceanic circulation over the southwestern Atlantic shelf is influenced by large tidal amplitudes, substantial freshwater discharges, high wind speeds and – most importantly – by its proximity to two of the largest western boundary currents of the world ocean: the Brazil and Malvinas currents. This review article aims to describe the dynamical processes controlling the interaction between the shelf and the deep-ocean. The discussion is focused on two broad regions: the South Brazil Bight to the north, and Patagonia to the south. The exchanges between the Brazil Current and the South Brazil Bight are characterized by the intermittent development of eddies and meanders of the Brazil Current at the shelfbreak. However, it is argued that this is not the only – nor the most important – influence of the Brazil Current on the shelf. Numerical simulations show that the thermohaline structure of the South Brazil Bight can be entirely ascribed to steady state, bottom boundary layer interactions between the shelf and the Brazil Current. The Malvinas Current does not show the development of eddies and meanders, but its influence on the Patagonian shelf is no less important. Models and observations indicate that the Malvinas Current not only controls the shelfbreak dynamics and cross-shelf exchanges but also the circulation in the shelf's interior.

1 Introduction

The Southwestern Atlantic Shelf extends from Cape Frio, Brazil (~23° S) to Burdwood's Bank (~55° S) (Fig. 1). Relatively narrow at its northern end (~70 km near Cape Frio), it widens progressively to the south, reaching a maximum width of approximately 860 km near Rio Coig (~51° S). The coastline geometry is dominated by the jagged indentations of several gulfs in the south, the wide chasm of the La Plata estuary in the center, and the crescent shape of the South Brazil Bight in the north. The shelf circulation consists of a northward flow of cold waters in the south and a southward flow of warm waters in the north (Bakun and Parrish, 1991; Piola et al., 2000; Palma et al., 2008)

(Fig. 1). The deep circulation is characterized by the opposing flows, and confluence, of the Brazil and Malvinas currents (Gordon, 1989). The Malvinas Current (MC) is a swift, barotropic, and narrow branch of the Antarctic Circumpolar Current that flows north along the continental slope of Argentina up to approximately 38° S (Matano et al., 1993). Its volume transport ranges between 40 and 70 Sv (Peterson, 1992; Spadone and Provost, 2009). The Brazil Current (BC) is a highly baroclinic western boundary current that concentrates the bulk of its volume transport, between 25 and 40 Sv, in the top 500 m of the water column (Piola and Matano, 2001). The collision of these two currents, known as the Brazil/Malvinas Confluence, occurs near the mouth of the La Plata River where it creates a region of high mesoscale variability.

The Sub-Tropical Shelf Front, which is located near 33° S, divides the SWAS in two distinct regions: a northern region with warm and salty waters of tropical and subtropical origin, and a southern region with cold and relatively fresh waters of sub Antarctic origin (Piola et al., 2000). Although both regions are highly influenced by the neighboring western boundary currents, there have been exiguous attempts to understand the interaction between the shelf and the deep ocean. Campos et al. (1995, 2000) and Castro and Miranda (1998) documented penetrations of meanders of the BC onto the South Brazil Bight, a phenomenon dynamically similar to that observed in the eastern coast of North America (e.g., Loder et al., 1998). Palma and Matano (2009) argued that bottom boundary layer processes largely control cross-shelf exchanges in this region. There are fewer studies on the exchanges between the MC and the Patagonian shelf. Saraceno et al. (2004) noted that unlike the BC, the inshore boundary of the MC is remarkably stable. Malvinas waters, nevertheless, still percolate over the Patagonian shelf and influence the regional ecosystems (Piola et al., 2010). The most obvious evidence of this nutrient pumping is the high level of biological activity that is found in the Patagonia region, which is considered a Class I marine ecosystem with a productivity rate larger than 300 grC/m^2 yr^{-1} (Csirke, 1987; Brandhorst and Castelo, 1971; Lutz and Carreto, 1991; Sabatini et al., 2004). In fact, compared with Patagonia the Brazilian shelf is remarkably poor. The fish catch off southern Brazilian waters, for example, is an order of magnitude smaller than that over the Patagonia region (FAO, 2009; Haimovici et al., 2006). The Patagonian shelf also absorbs large amounts of CO_2 from the atmosphere (Bianchi et al., 2005, 2009). The largest absorptions occur in close association with high chlorophyll regions, which are presumably maintained by vigorous vertical circulations near tidal fronts and along the shelfbreak. Most of the CO_2 is absorbed in austral spring and summer, but is not locally released back to the atmosphere during the winter (Bianchi et al., 2009). Assuming steady state, the net annual mean absorption of CO_2 must be balanced by net export, either to the sediments or offshore. Thus, export of shelf waters near the Subtropical Shelf Front and the Brazil/Malvinas Confluence may also be a significant regional carbon sink.

Relatively little is known about the circulation over the southwestern Atlantic shelf, and much less about its exchanges with the deep-ocean. In this article we review these subjects using the latest modeling and observational results. Our discussion is focused on the influence of the neighboring western boundary currents, the Brazil and Malvinas currents on the shelf circulation. This article is organized as follows. After this introduction, in Sect. 2, we make a brief description of the numerical simulations used in the following sections. Sections 3, 4, and 5 describe the circulation and cross-shelf exchanges in the South Brazil Bight, the Patagonian Shelf, and the region of influence of the La Plata River. Section 6 summarizes and discusses the previous results.

2 Methods

The numerical simulations discussed in this article were conducted with the Princeton Ocean Model (Blumberg and Mellor, 1987) and are described in detail in Palma et al. (2008); Matano and Palma (2008); and Palma and Matano (2009). For the purposes of completeness a brief description is included here. The model domain extends from 55° S to 18° S and from 70° W to 40° W and it has a horizontal resolution of 5 km near the western coast and 20 km near the eastern open ocean boundary. The bathymetry was interpolated from Smith and Sandwell (1997) and complemented with bathymetric observations collected by the Argentinean Hydrographic Service. The vertical resolution of the model comprises 25 vertical sigma levels with higher resolution in the top and bottom boundary layers. The model has three open boundaries where a combination of radiation and advection boundary conditions is used. Tidal amplitudes and phases were interpolated from the Egbert et al. (1994) model, and boundary inflows form the POCM-4 eddy-permitting global ocean model (Tokmakian and Challenor, 1999). Heat and freshwater fluxes were parameterized with a Newtonian restoring to observed sea surface temperature (SST) and sea surface salinity (SSS) values. The former were obtained from Casey and Cornillon (1999), while the latter were constructed with data provided by the Centro Argentino de Datos Oceanográficos (www.ceado.gov.ar). The model also includes the mean freshwater discharges from the La Plata River (23 000 m^3/s) and the Patos Lagoon (2000 m^3/s) (Piola et al., 2008). At the surface the model was forced with QuikSCAT scatterometer wind stress data (Risien and Chelton, 2008). The most realistic simulation will be referred to as EXP1. For the purposes of analysis we also did a second experiment that does not include tides or winds (EXP2), and a third barotropic experiment that does not include the western boundary currents (EXP3).

3 The influence of the Brazil Current on the South Brazil Bight (SBB)

The South Brazil Bight (SBB) is located between Cape Frio (23° S) and Cape Santa Marta (28°40′ S) (Fig. 1). Its circulation is driven by low-amplitude tides, northeasterly winds, and the poleward flow of the BC along the shelf's edge. Although the region has no significant freshwater inputs, the southern portion of the bight shows intrusions of low-salinity waters from the La Plata River (Piola et al., 2000). The influence of local (e.g., winds, tides, etc) and remote forcing (e.g., the BC) on the shelf circulation has marked regional variations. The inner shelf is predominantly driven by local winds while the middle and outer shelves are more influenced by the BC (Palma and Matano, 2009). The influence of the remote forcing is most obviously manifested in the SST

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gradients near the shelfbreak (Campos et al., 1995, 2000; Castelao et al., 2004), but is not confined to the surface or to the shelfbreak. In fact, the strongest influence of the BC is observed at depth, where onshore intrusions of relatively cold and fresh South Atlantic Central Waters (SACW) extend up to the coast. These intrusions are partially related to the meandering and eddy shedding of the BC, but mostly to bottom boundary layer processes (Palma et al., 2008; Palma and Matano, 2009).

The contribution of the SACW carried by the BC to the thermohaline structure of the SBB is modulated by seasonal changes in the local wind forcing. During the summer, the SSTs over the shelf are generally higher than 23 °C, except in the northwest where a tongue of colder waters associated with the onset of upwelling favorable winds generate a strong SST front near the coast (Fig. 2a). Winter SSTs, which are not influenced by coastal upwelling, are more homogeneous with values between 20 °C and 23 °C (Fig. 2b). SST gradients are larger near the shelfbreak due to the presence of the BC, and in the southern portion of the bight due to the northward advection of sub Antarctic shelf waters. The seasonal changes of the SST structure are associated with changes in the ocean circulation, particularly in the middle and inner shelf. Currents are stronger in summer, when they flow in a predominantly southwestward pattern and weaken appreciably (or even reverse) towards the winter (Fig. 2b). The influence of the BC on the SBB is most obvious in cross-shelf sections, which show subsurface tongues of cold and saltier waters from the BC extending from the slope to the middle shelf during the winter months (Fig. 3a). Upwelling favorable winds during the summer move these waters farther inshore where they outcrop into the surface layer (Fig. 3b).

As noted above the water mass structure of the SBB is modulated by intrusions of the BC onto the middle and outer shelf, and by wind-driven upwelling in the inner shelf. The relative importance of these mechanisms can be quantified by comparing the previous results with a twin experiment in which tidal and wind forcing was suppressed (EXP2). Thus, in this case the only source of momentum for the shelf circulation is the presence of the BC flowing along the continental slope. The surface circulation of EXP2 is characterized by a strong southwestward flow along the outer shelf that decreases rapidly towards the coast (Fig. 4a). In contrast with the previous experiment, the SST field in summer is nearly uniform over the shelf showing that the SST structure of the previous case (Fig. 2) is largely driven by coastal wind upwelling. The contribution of the local winds to the shelf circulation is also clearly appreciated in the velocity field, which shows an almost stagnant inner shelf in EXP2 (Fig. 4a). The onshore intrusions of the BC in the bottom boundary layer are appreciated in the location of the 17 ∘C isotherm, which is representative of SACW, and which moves closer to the coast during the summer months (Fig. 4b). As noted above, upwelling favorable winds (in EXP1) further draw these waters toward the coast and force their outcrop to the surface (Fig. 3b).

To further quantify the influence of the BC on the shelf circulation we calculated the alongshelf momentum balances in the bottom boundary layer (Fig. 5). There is little difference between the curves representing the Coriolis term ($f \cdot U$) in the middle and outer shelf but there are important differences in the inner shelf. This indicates that the cross-shelf velocities of the outer and middle shelf are largely driven by the barotropic pressure gradient associated with the Brazil Current, while direct wind forcing significantly influences the cross-shelf velocities in the inner-shelf. Further analysis by Palma and Matano (2009) shows that changes in the coastline orientation modify the spatial patterns of cross-shelf exchanges. In particular the latitudinal change of the shelf width reverses the direction of the alongshelf pressure gradient and augments the onshore flow towards the north.

In summary, our experiments indicate that the water mass structure and circulation of the SBB is controlled by the synergetic interaction between wind driven upwelling in the inner shelf and onshore intrusions of the BC in the middle and outer shelf. The wind effect peaks during the austral summer and decreases towards the winter while the influence of the BC shows no significant seasonal variation. As shown in previous work the circulation patterns and density structures derived from the numerical simulations correspond well with observations (Castro and Miranda, 1998; Campos et al., 2000). The interaction between the poleward flow of the BC and the bottom topography greatly influences the nearshore circulation, particularly in the bottom boundary layer. Changes of the width of the SBB modulate the alongshore pressure gradient and the magnitude of the shelfbreak upwelling and downwelling. Thus, although the summer upwelling winds extend over the entire region the SSTs are warmer in the south because of the cooling effect of the shelfbreak upwelling in the northern region. As noted by Palma and Matano (2009) the narrowing of the shelf in the southern portion of the bight leads to an enhancement of the vertical mixing that in some situations (e.g., when there is an increase in the BC transport or the magnitude of the wind stress forcing) and can overcome the unfavorable alongshore pressure gradient and promote upwelling.

4 The influence of the MC on the Patagonian shelf

The Patagonian shelf extends from the tip of South America (~55° S) to the Brazil/Malvinas Confluence (~38° S) (Fig. 1). This vast coastal region is subject to the combined effects of strong westerly winds, high amplitude tides, large low-salinity discharges, and the neighboring presence of the MC. Its mean circulation is characterized by a broad northeastward flow that intensifies towards the shelfbreak, where it merges with the MC (Fig. 6). South of ~49° S there is a well-defined jet in the inner shelf, known as the Patagonian Current that is generated through the interaction of tidal currents and the Magellan Straits discharge (Palma et al., 2008). The vertical structure of the shelf circulation is roughly equivalent to a two-layer system, with the flow in the upper layer directed towards the northeast and in the bottom layer towards the southwest (Fig. 7a and c). A simple mass balance shows that the northward outflow of surface waters is compensated by inflow of deeper waters. The largest entrainment of deep waters is observed through the Le Maire Straits (at the tip of Tierra del Fuego) and to the north of the Malvinas Islands (Fig. 7b, c). As these waters move onshore they generate coastal upwelling along the southern portion of Patagonia. This coastal upwelling however, is relatively weak and it is not easily visualized in the SST fields due to intense tidal mixing (Rivas and Pisoni, 2010).

One of the most distinct characteristics of the Patagonian region is the narrow and persistent chlorophyll maximum that closely follows the 200 m isobath (Romero et al., 2006) (Fig. 8). The peaks of this maximum are unusually high. Spring blooms, for example, have surface values of 25–30 mg/m^3, which are an order of magnitude larger than those observed in typical offshore locations (e.g., Acha et al., 2004; Romero et al., 2006; Garcia et al., 2008; Signorini et al., 2009). The chlorophyll blooms of the MC are symptomatic of the upwelling of nutrient-rich waters to the surface, but the mechanisms driving such upwelling are still poorly understood. External forcing does not appear to be the cause: the winds in the Patagonia region are not upwelling-favorable, tidal mixing is relatively small in the shelfbreak region and, as noted above, the MC does not show the eddy shedding and meandering that drive the upwelling of other western boundary systems (e.g., the Gulf Stream). It has been recently postulated that the shelfbreak upwelling of Patagonia is associated with frictionally driven intrusions of the MC onto the shelf (Matano and Palma, 2008). These intrusions generate an alongshelf pressure gradient with a secondary cross-shelf divergence cell that leads to shelfbreak upwelling. The magnitude of the upwelling is proportional to the transport of the MC and to the ratio of the bottom slopes at both sides of the shelfbreak (Matano and Palma, 2008). The upwelling of Patagonia is qualitatively and quantitatively different than that proposed for the shelfbreak of the Middle Atlantic Bight, its Northern Hemisphere counterpart, because of the fact that the former lacks the equivalent of the Labrador Current while the latter lacks the equivalent of the MC. Modeling studies indicate that the upwelling velocities along Patagonia's shelfbreak are of the same order of magnitude as those in typical wind-driven upwelling system (Matano and Palma, 2008). The difference is that, while most wind-driven events last only a few days or weeks, the upwelling of Patagonia can be continuously sustained throughout the entire year. There are coastal regions with year-round upwelling favorable winds (e.g., the western coast of Africa) but, unlike Patagonia, they are not embedded within the nutrient rich waters of the Southern Ocean and their influence is restricted to the nearshore region. The impact of Patagonia's shelfbreak upwelling on the regional ecosystems ap-

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pears to extend well beyond the shelfbreak region. Chlorophyll-a images, for example, indicate that the subpolar portion of the South Atlantic is the most productive portion of the entire Southern Ocean while the subtropical open-ocean region is a relative desert ($<0.2\,\text{mg/m}^3$, Fig. 8).

The influence of the MC on the coastal circulation is more easily appreciated by comparing the results of the benchmark experiment (EXP1) with a barotropic experiment excluding the MC (Fig. 9). The differences between these experiments are remarkable. The MC not only dominates the circulation in the outer shelf, but its influence extends also to the middle and inner shelf. The cross-shelf component of the vertically averaged momentum balance, for example, indicates a 2- to 4-fold increase of the alongshelf transport. This increase reflects the influence of the barotropic pressure gradient associated with the MC and is particularly noticeable in the middle shelf. Note that in EXP3 there is no net alongshelf transport and, therefore, the northward wind-driven transport in the surface Ekman layer is compensated by a similar southward transport in the bottom boundary layer. In EXP1, however, there is a substantial net alongshelf transport whose spatial variations reflect the mass exchanges between the shelf and the deep ocean that are generated by the MC.

The Patagonian shelf exports surface waters to the deep ocean and imports deeper waters through the Le Maire Straits and the shelfbreak region (Fig. 7). Shelfbreak upwelling draws cold and denser waters to the surface whence they move onshore and downward. After reaching the middle and inner shelf these waters are uplifted towards the surface by strong tidal mixing and are diverted to the north in the surface Ekman layer (Fig. 10). The nutrients carried by these waters add to the nutrient flux produced by re-suspension and cause additional chlorophyll blooms along the inner and middle shelf of Patagonia (Fig. 8). These cross-shelf exchange patterns are consistent with observations. A cross-shelf hydrographic section across 51° S, for example, typifies the water mass structure and circulation of this region (Fig. 11a). The density profile shows a typically weak pycnocline and a small wedge of low-density waters very close to the shore. This coastal minimum is associated with the presence of fresher waters from the Magellan Strait. Farther offshore there is a second density front at approximately 300 km from the coast. This front marks the boundary between the coastal and shelf water masses. The advection of sub Antarctic waters by the MC is evident over the outer continental shelf where there are sharp gradients of temperature and salinity in the deep layers. The isopycnals show three retrograde fronts, which have been associated with the development of baroclinic cells of circulation (Fig. 11b). Thus, model and observations suggest a cross-shelf circulation pattern dominated by upwelling and onshore intrusions of cold and dense Malvinas water in the outer shelf. After moving away from the shelfbreak these waters sink and are drawn to the inner shelf where they are lifted again by tidal forcing. As these waters reach the mixed layer they are diverted to the north by the westerly winds (Fig. 10). The inshore flux through the Patagonia shelf is compensated by offshore fluxes at the Brazil/Malvinas Confluence and at the STSF.

In a recent study Piola et al. (2010) also showed intrusions of the MC onto the northern Patagonian shelf near 41° S. These intrusions, which extend throughout the entire water column, generate low temperature and high salinity anomalies that extended through the mid-shelf region. These onshore intrusions of the MC are also associated with distinct chlorophyll peaks, such as the one observed in spring 2003 (Piola et al., 2010; Signorini et al., 2009). The mechanisms generating these intrusions are still poorly understood although it appears to be due to topographic steering of the MC, the inshore turn of isobaths within the 90–110 m depth range might drive inshore waters from the western edge of the MC.

5 The Subtropical Shelf Front (STSF)

Located near 33° S, the STSF separates the warm and salty waters of the SBB from the cold and relatively fresh waters of the Patagonian Shelf (Fig. 12a). The STSF extends from the near surface, where it is capped by low salinity waters drawn from the La Plata River and the Patos/Mirim complex, to the bottom (Fig. 12b). Although the

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front appears as a shelf extension of the Brazil/Malvinas Confluence, the contribution of the western boundary currents to its formation remains unclear. Piola et al. (2000, 2008) observed that while the Brazilian sector of the shelf shows inshore intrusions of the Brazil Current (manifested as SACW in their T-S diagrams, see also Castro and Miranda, 1998), the waters in the Argentinean sector are substantially fresher than those carried by the Malvinas Current. Thus, while there is evidence that the BC moves over the shelf, and therefore might influence the frontal structure, there is no evidence of similar behavior by the Malvinas Current. The cross-shelf sections analyzed by Piola et al. (2008) also indicate that there is neither northward penetration of sub-Antarctic shelf waters to the north of the front nor southward penetration of the subtropical shelf waters to the south. Both water masses, therefore, should be advected offshore.

As noted above, it remains unknown what are the dynamical mechanisms that lead to the formation and determine the location of the STSF. Like the Cape Hatteras Front, its Northern Hemisphere counterpart (Stefansson et al., 1971; Pietrafesa et al., 1994; Savidge, 2002), the STSF appears to be an onshore extension of the barotropic pressure gradients associated with the neighboring western boundary currents. This hypothesis is reinforced by observations showing that the front is essentially barotropic, i.e., that it has a density compensated thermohaline structure. Thus, there is a distinct front in temperature and salinity but not in density (Piola et al., 2000). Although observations show direct intrusions of waters of the BC onto the shelf, but not from the MC, numerical experiments indicate that the MC still plays an important role in the front location through its barotropic pressure gradient (Palma et al., 2008). The STSF appears to be a preferential region for the detrainment of the cross-shelf inflows from the BC and MC (Fig. 13). Thus, waters been entrained throughout the shelfbreaks of the SBB and Patagonia are ejected offshore in this region. The bio-geochemical properties of these water masses are enhanced by the freshwater discharges from the La Plata River and the Patos/Mirim Lagoon, making the STSF a critical component of the cross-shelf exchanges in the Southwestern Atlantic.

6 Summary and discussion

In this article we reviewed previous work to highlight the influence of the Brazil and Malvinas currents on the circulation of the southwestern Atlantic shelf. There are insufficient observations to draw definite conclusions but it seems obvious that in spite of the contrasting characteristics of BC and MC they exert a dominant influence on the shelf circulation. The BC is the Southern Hemisphere counterpart of the Gulf Stream, a strongly stratified western boundary current that flows against the direction of the coastally trapped waves. Like the Gulf Stream, its influence on the shelf is most visible through sporadic intrusions associated with instabilities of the mean flow and the consequent formation of eddies and meanders. However, it has been argued that this is not the only – nor the most important – influence of the BC on the shelf. In fact, numerical simulations show that the thermohaline structure of the SBB can be entirely ascribed to steady state, bottom boundary layer interactions of the BC with the shelf region. Eddies and meanders might obviously contribute to the cross-shelf fluxes but their ephemeral occurrence precludes a quantitative evaluation of their importance. The assessment of these matters will require the use of numerical models with higher spatial resolution. Such models are in development, and, once tested, they might help us to assess the contribution of eddies and meanders to the cross-shelf exchanges. One of the issues of obvious interest is the assessment of whether the impact of an Agulhas eddy on the BC influences the cross-shelf exchanges in the southwestern Atlantic region. Agulhas eddies, which are periodically shed in the Cape Basin, have been altimeter tracked in their westward journey through the subtropical gyre. However, as they approach the coast their signature is lost amid the high local variability. It is likely that some of these eddies might reach the BC and, in doing so, may trigger instabilities of the mean flow. These matters are of obvious importance since climate changes may alter the frequency and size of the Agulhas eddies and therefore their impact on Brazil's coastal region.

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It is often difficult to identify the processes controlling cross-shelf exchanges, or the preferential regions where these exchanges occur, particularly in regions influenced by western boundary currents. This difficulty is due partly to the disparity of the transports over the shelf and slope, but mostly to the fact that the eddying and meandering of the western boundary current make difficult the identification of the secondary circulation cells that connect the shelf to the deep ocean. The determination of the cross-shelf exchanges over Patagonia is much simplified by the weak density stratification of the MC ($N^2 \sim 2 \times 10^{-4}\,\mathrm{s}^{-1}$), which basically locks the path of the current to the bottom topography and inhibits the development of mean flow instabilities. Drifter trajectories in this region, for example, do not show the convoluted loops that characterize the path of unstable currents, but extend from the Drake Passage to the Brazil/Malvinas Confluence in remarkably smooth tracks (Fig. 14). This characteristic of the MC allows the use of a well-developed body of theoretical models to identify the regions most favorable for cross-shelf exchanges. For example, the arrested topographic wave theory of Csanady (1978) predicts that the onshore penetrations of the MC onto the shelf should be inversely proportional to the steepness of the continental slope. Regions of steep slope, therefore, should allow a smaller penetration than regions with gentler slopes. Based on these arguments, Hill (1995) argued that if the transition between two regions occurs in a distance smaller than that required by the geostrophic adjustment ($L \sim f h_x b^2/r$, where h_x is the bottom slope, b is the width of the western boundary current, and r is the bottom friction coefficient), ageostrophic effects should generate substantial cross-shelf flows to account for the disparity in the bottom slopes. There is a well-defined transition in the steepness of the continental slope between ~50° S and 48° S (Fig. 15). This transition occurs in a distance of less than 300 km, which is much smaller than the scale required by geostrophic adjustment, i.e., $L \sim 2000$ km (considering a $f = 2 \times 10^{-4}\,\mathrm{s}^{-1}$, $r = 10^{-3}\,\mathrm{m\,s}^{-1}$, $b = 100$ km, and $h_x = 1 \times 10^{-3}$). Hill's hypothesis is in good agreement with the results of the numerical simulation (e.g., Fig. 7c). The arrested topographic wave theory, however, is strictly valid for a barotropic fluid and although the MC is very weakly stratified it still needs to be determined whether the downstream topographic scale is indeed much smaller than the geostrophic adjustment scale for the MC. It seems likely that the strong entrainment observed in the region to the north of the Malvinas Islands is partly explained by Hill's hypothesis and partly by non-linear ageostrophic effects associated with the narrowing of the MC and the curvature of its path i.e., confronted with a sudden turn of the bottom topography inertia can force a portion of the MC to "spill over" the shelf.

The downstream widening of the continental slope in the northern portion of the Drake Passage indicates that the observed entrainment of waters through the Le Maire Straits is not driven by Hill's mechanism. The inflow moreover, is not restricted to the bottom boundary layer but extends throughout the entire water column (Fig. 7). We surmise that cross-shelf fluxes in this region are driven partly by inertial fluxes across bending isobaths, and partly by the interaction of the M_2 tide with the bottom topography. Similar processes have been identified in George's Bank where it was observed that enhanced vertical mixing and horizontal gradients lead to secondary circulation cells that account for most of cross-shelf fluxes (Franks and Chen, 1996). In these regards it should be noted that southern Patagonia has one of the largest M_2 tide amplitude range of the world ocean. Tides are unlikely to play an equally important role in the northern region because, the M_2 tide enters Patagonia through its southern boundary and travels as a Kelvin wave with its maximum amplitude largely confined to the inner shelf (Palma et al., 2004).

Wind stress forcing is another important promoter of cross-shelf exchanges. Pringle (2002) postulated that alongshelf variations of the shelf width should generate cross-shelf fluxes that compensate for changes of the wind-driven Ekman transports. According to this theory the observed narrowing of the Patagonia shelf in the region between ~50° S and 48° S, should favor an outflow of shelf waters onto the deep ocean. However, as noted in our previous discussion, this region is also characterized by an abrupt change of the continental slope that should intensify the intrusion of the MC onto the shelf. The cross-shelf fluxes associated with the MC and the shelf circulation, therefore, oppose each other and, in principle, should lead to a further strengthen-

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ing of the alongshelf circulation north of ~48° S. Interestingly this strengthening can be inferred from observations and it is a ubiquitous feature of our previous numerical simulations (e.g., Fig. 7).

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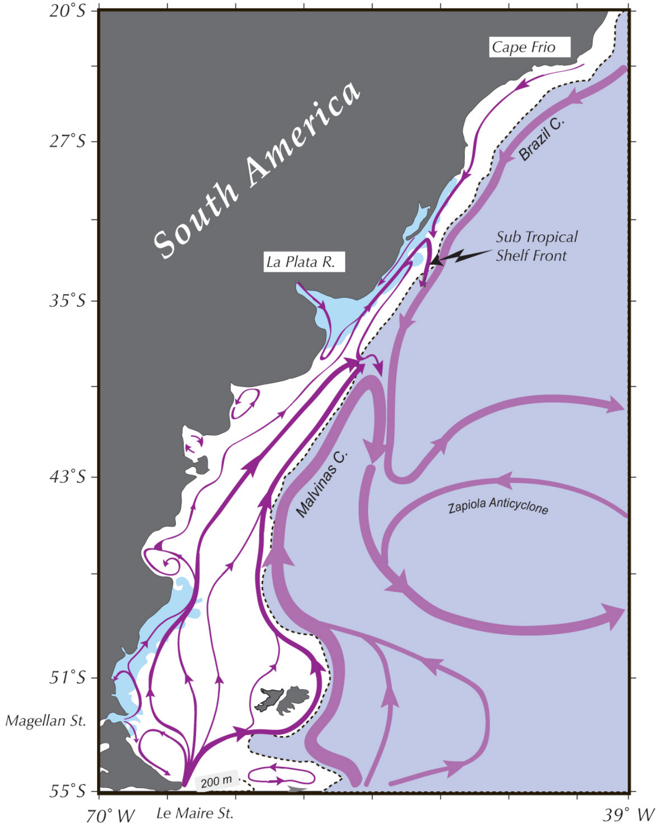

Fig. 1. Schematic representation of the depth-averaged circulation in the southwestern Atlantic region. The shelf (depths smaller than 200 m) is marked by white background.

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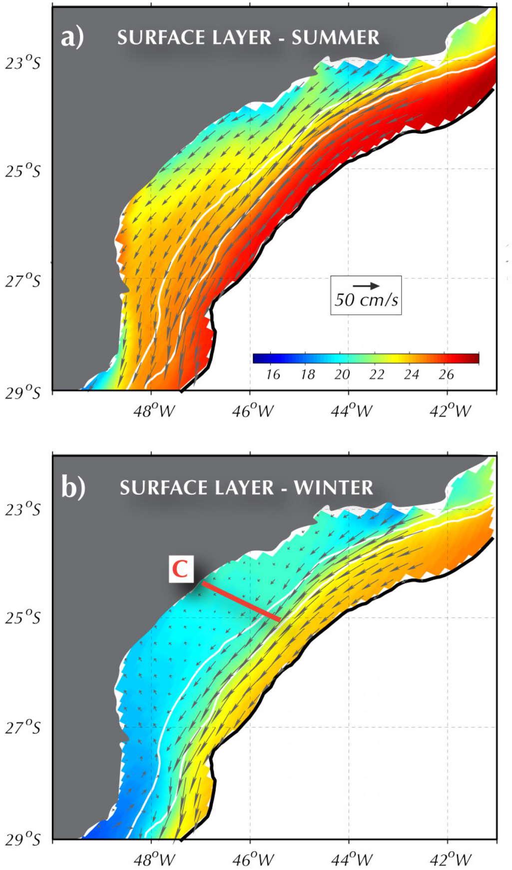

Fig. 2. Average sea surface temperatures (SSTs) and surface velocities during summer **(a)** and winter **(b)** in the numerical simulation of Palma and Matano (2009). The white line marks the position of the 100 m and 200 m isobaths. Line C marks the location of the cross-section shown in Fig. 3.

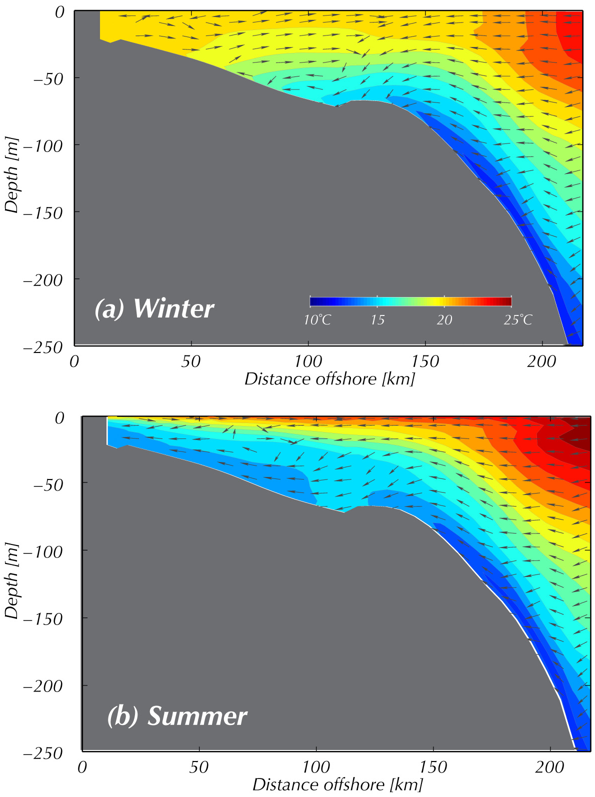

Fig. 3. Temperature and cross-shelf circulation at cross-section C from EXP1. **(a)** Winter, **(b)** Summer.

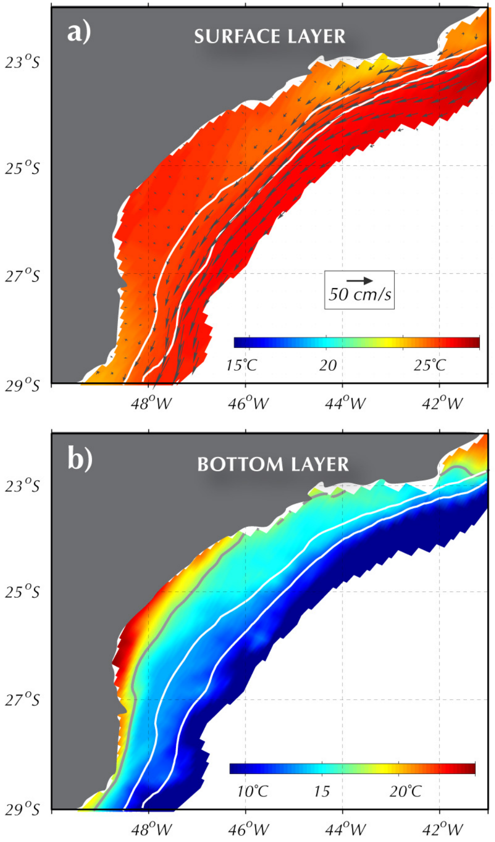

Fig. 4. EXP2: **(a)** summer sea surface temperature and surface velocity vectors and **(b)** bottom temperature. White contours mark the 100 and 200 isobaths. The black line in panel (b) is the 17 °C isotherm, indicative of the SACW penetration. Note that each panel uses a different color bar.

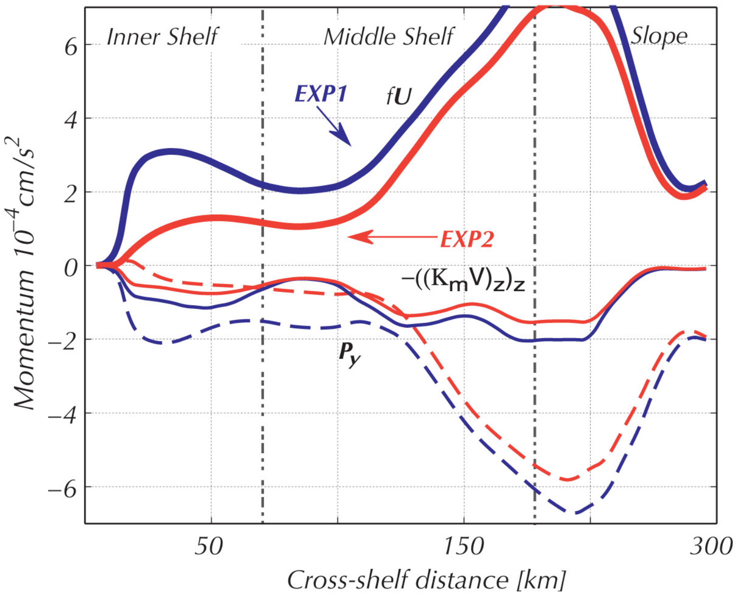

Fig. 5. Alongshelf component of the momentum balance across section C during summer.

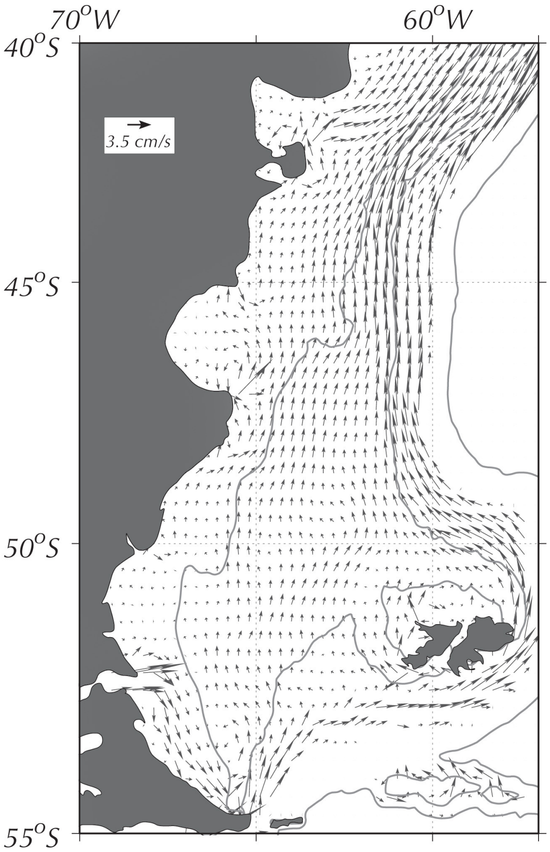

Fig. 6. Depth-averaged circulation over the Patagonia shelf (depths smaller than 500 m), in EXP1.

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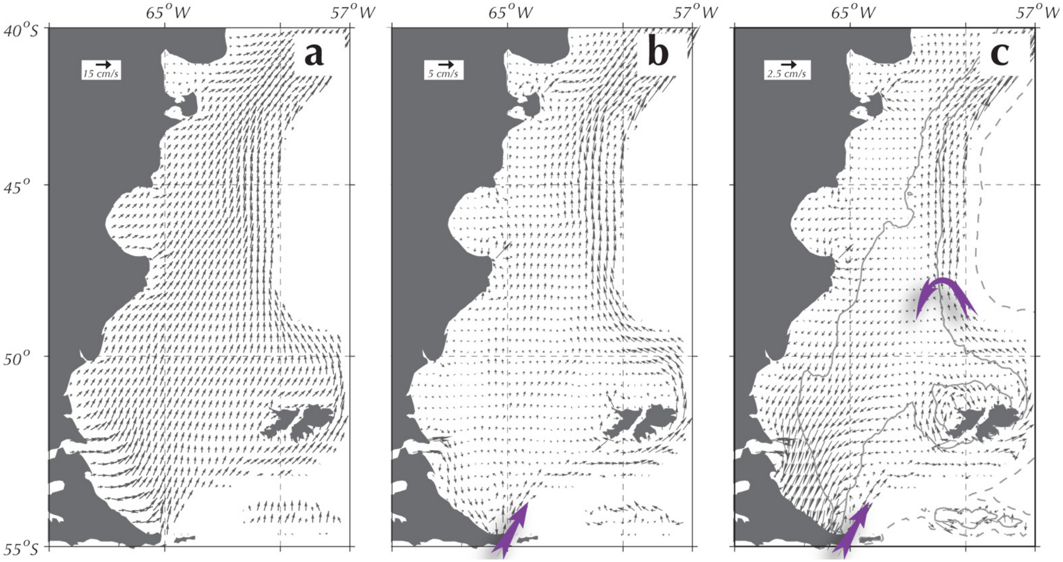

Fig. 7. Time-averaged velocities at the upper, intermediate, and bottom levels of EXP1. The purple arrows mark the regions of largest cross-shelf exchanges.

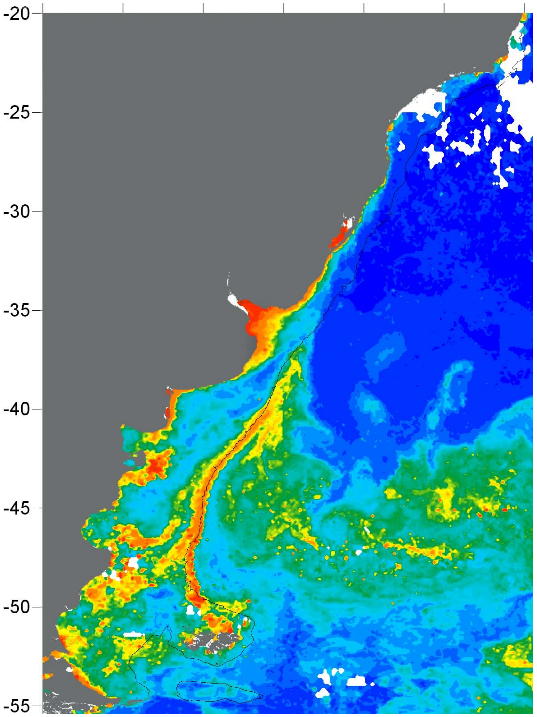

Fig. 8. SeaWiFS derived surface chlorophyll distribution averaged between 17–24 January 2009 in the southwestern Atlantic region.

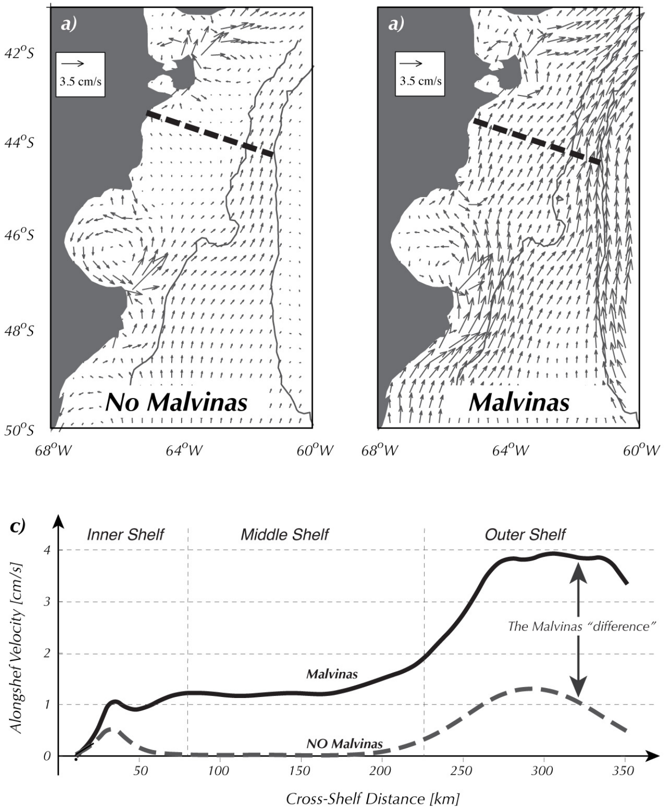

Fig. 9. **(a)** Depth-averaged velocities in EXP2; **(b)** EXP1; **(c)** Alongshelf velocities across the section shown in the upper panels.

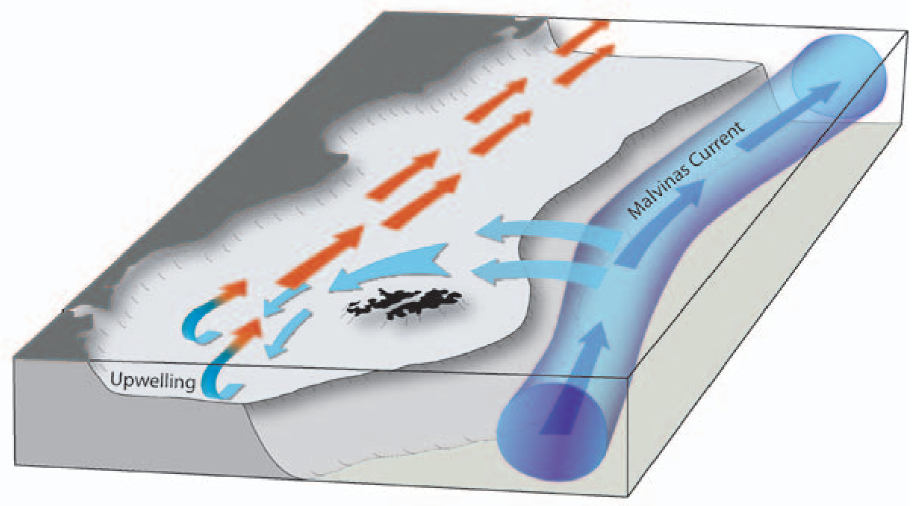

Fig. 10. Schematic representation of the cross-shelf exchanges in the Patagonia shelf region. Sub Antarctic waters upwelled along Patagonia's shelfbreak move onshelf and sink. Near the coast these waters are drawn upward by tidal mixing, and after reaching the surface they are advected to the north by the westerly winds. A portion of these waters is likely to be diverted offshore in the surface Ekman layer while the remainder might reach the Brazil/Malvinas Confluence and the STSF where they are likely to be detrained by the mean circulation.

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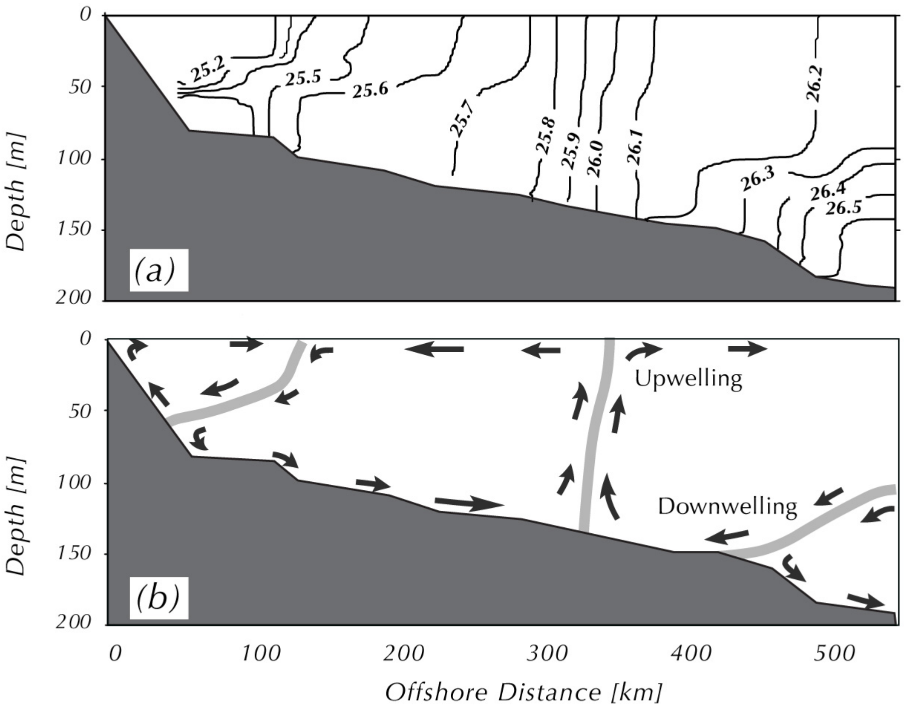

Fig. 11. Density cross-shelf section off Grande Bay (~51° S) from a hydrographic cruise in March 1994 (top panel). Schematic showing the fronts identified in this section and the inferred circulation patterns. (After Sabatini et al., 2004).

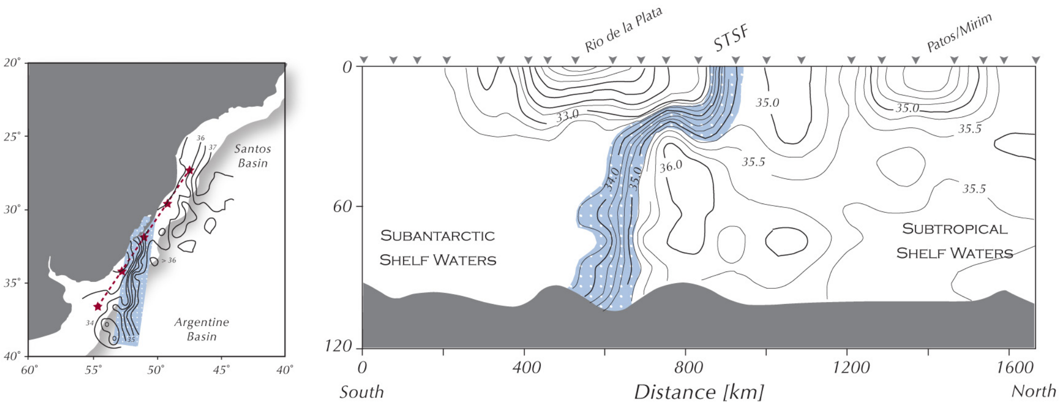

Fig. 12. Sea surface salinity (left panel) and alongshelf salinity transect (right panel). The stippled area marks the location of the STSF. Adapted from Piola et al. (2000).

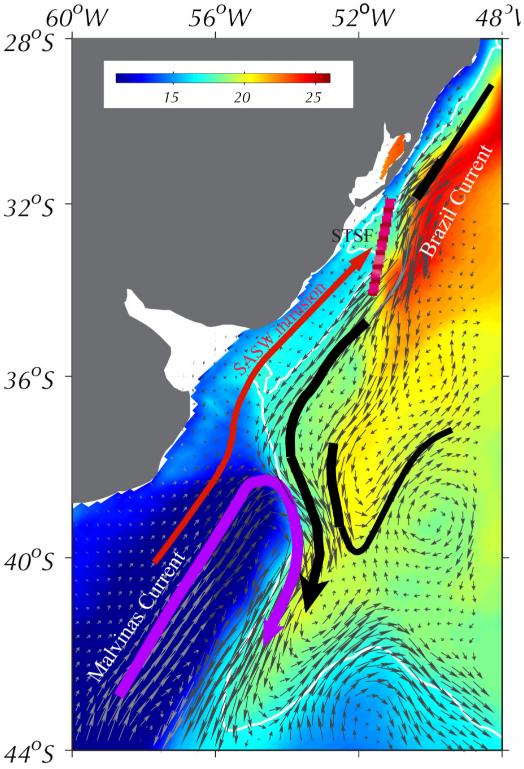

Fig. 13. Depth-averaged velocities in EXP2 (left upper panel), EXP1 (upper-right panel) and cross-shelf momentum fluxes (bottom panel).

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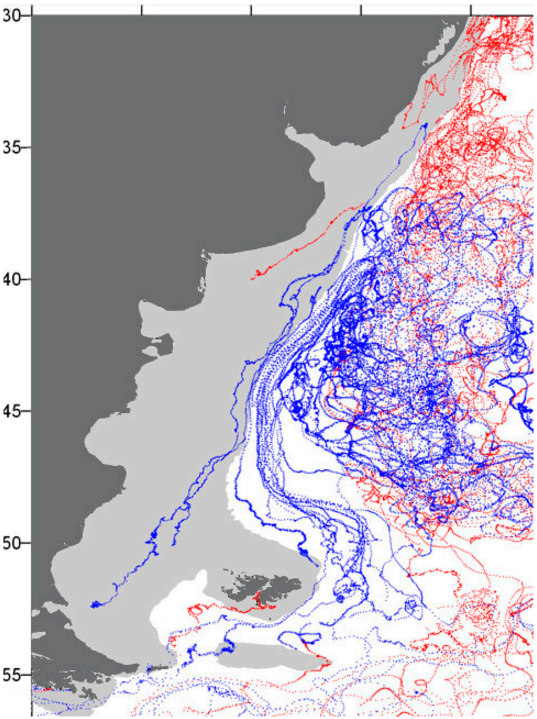

Fig. 14. Trajectories of satellite tracked "surface" drifters from WOCE-Surface Velocity Program type. The drifters are drogued to 15 m depth and designed to follow the water to within $\pm 0.013\,\mathrm{m\,s^{-1}}$ in $10\,\mathrm{m\,s^{-1}}$ winds (Niiler et al., 1995). The original position data have been quality controlled and optimally interpolated to uniform six-hour interval trajectories. Note the quasi-linear trajectoriesof the drifters in the MC.

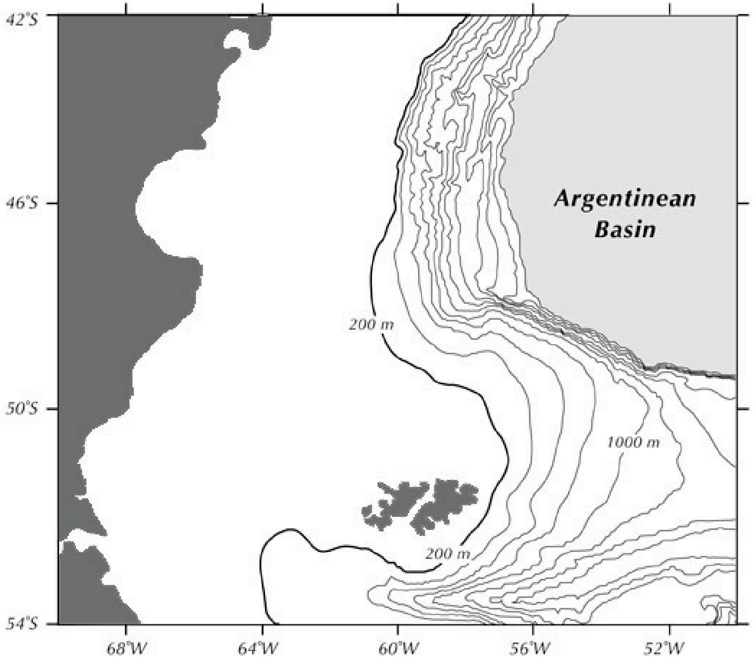

Fig. 15. Bottom topography of the Patagonian shelf. Note the rapid convergence of the isobaths north of ~50° S.