Trends in the Brazil/Malvinas Confluence region


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Key Points:
- The model experiment reproduces the observed trends.
- A weakening of the ACC leads to a weakening of the MC and a southward BMC drift.

Citation:

Abstract: Observations show abrupt changes in the oceanic circulation of the southwestern Atlantic. These studies report a southward drift of the Brazil/Malvinas Confluence (BMC) and a change in the spectral characteristics of the Malvinas Current (MC) transport. We address the cause of these changes using the result of a high-resolution numerical experiment. The experiment, which is consistent with observations, shows a southward BMC displacement at a rate of 0.62°/decade between 1993 and 2008, and a shift of the spectral characteristics of the MC transport after 1999. We find that these changes are driven by a weakening of the northern branch of the Antarctic Circumpolar Current, which translates to a weakening of the MC transport and a southward BMC drift. The drift changes the spectral characteristics of the MC transport, which becomes more influenced by annual and semiannual variations associated with the BMC.

1. Introduction
The deep ocean circulation of the southwestern Atlantic region is characterized by the confluence of the poleward flowing Brazil Current (BC) and the equatorward flowing Malvinas Current (MC) (Figure 1a). The location of the Brazil/Malvinas Confluence (BMC), which on average is located near 38°S, is determined by the dynamical balance between the opposing transports of the BC and the MC [Matano, 1993]. Several studies have linked periodic variations of the BMC location to the controlling factors of these transports, namely, the wind stress curl over the subtropical gyre and the Antarctic Circumpolar Current (ACC) transport at the Drake Passage [Matano et al., 1993; Garzoli and Giulivi, 1994; Wainer et al., 2000; Goni and Wainer, 2001; Fetter and Matano, 2008; Combes and Matano, 2014]. Recent studies have also shown that in addition to these periodic fluctuations, the BMC has also been drifting southward. Using satellite data, Goni et al. [2011] reported a southward drift of the BMC during the period between 1993 and 2008, at a rate that varies between 0.81°/decade and 0.39°/decade, depending on whether the drift is computed from sea surface height (SSH) or sea surface temperature (SST) data. Lumpkin and Garzoli [2011] used surface drifters and along-track satellite SSH to confirm the BMC drift and reported that during the period between 1992 and 2007, the BMC has moved southward at a rate of 0.64 ± 0.20°/decade. There is still no solid evidence of what drives the observed BMC drift. Lumpkin and Garzoli [2011], however, observed that the BMC drift is correlated with a southward trend of the latitude of maximum wind stress curl across the South Atlantic. It is unknown if this trend in the wind stress produced the observed BMC shift because no concurrent observations of the BC and MC transports exist. Spadone and Provost [2009] analyzed a 13 year record of the MC transport near 40–41°S and found no significant trend but reported a significant increment in seasonal variability of the MC transport after the year 2000.

Here we investigate the drift of the BMC and the change of MC spectral characteristics using the results of a high-resolution model. We investigate the relationship between the southward displacement of the model BMC, changes of the MC spectral characteristics, variability of the ACC transport, and variability of the atmospheric forcing over the last decades. To summarize, we show that the southward drift of the BMC results from a weakening of the ACC produced by a weakening of the westerly winds over the Southern Ocean. We also show that the southward displacement of the BMC (strongly seasonal) increases the annual and semiannual variability of the MC transport after 1999–2000.

2. Model Description
The numerical simulation used in the present analysis has been described in detail in Combes and Matano [2014]. For the sake of completeness, we present a synopsis of the general model configuration. The numerical model is the ROMS_AGRIF version of the Regional Ocean Modeling System [Shchepetkin and McWilliams, 2005]. It includes a nested grid configuration in which a high-resolution “child” model is embedded into a coarser resolution “parent” model [Debreu et al., 2011]. The parent grid extends 360° in
Figure 1. (a) The gray contours represent the mean transport stream function of the 34 year integration (1979–2012). Solid lines represent positive values and dashed lines represent negative values. The thick, full line marks the zero (contour interval is 10 sverdrup (Sv)). Background colors represent the transport differences between the 2000–2009 and the 1990–1999 periods. “MC_Spadone” indicates the transect used by Spadone and Provost [2009]. “MC” shows the location of Malvinas Current transect discussed in the text. Note that this transect has two sections. The inner portion is marked with dark blue color, and the outer portion is marked with light blue color. The red transect indicates the ACC transect north of 56°S. (b) Dashed and dotted lines mark the seasonal variations of the Brazil/Malvinas Confluence computed from SSH and SST satellite data [Goni et al., 2011]. Solid lines mark the seasonal variations of the Brazil/Malvinas Confluence in the model (gray contour) and the Malvinas Current transport (blue contour). The Malvinas Current transport was computed along the MC transect (see Figure 1a).
longitude and from Antarctica to 15.2°N. It has a spatial resolution of 1/4° in the horizontal and 40 sigma levels in the vertical. The child grid extends from 82°W to 41°W and from 64°S to 20°S and has a spatial resolution of 1/12° (Figure 1a). The bottom topography is a smoothed version of ETOPO1 (1° resolution [Amante and Eakins, 2009]), to prevent from horizontal pressure gradient errors [Beckmann and Haidvogel, 1993]. The model forcing includes a 23,000 m³ s⁻¹ discharge from La Plata River (~34.4°S) and the M2 tidal component. At the northern boundary of the parent grid, the model is nudged to the monthly mean climatology provided by the Simple Ocean Data Assimilation (SODA) model [Carton and Giese, 2008]. The SODA model also provides the initial condition. To spin-up the model we first integrated the parent model during a 10 year period and then the parent/child configuration for an additional 5 years period. Both model configurations were forced with monthly mean climatological fields constructed with ERA-Interim data corresponding to the period 1972–2012. The spin-up was followed by a 34 year integration (1979–2012) using 3 day averaged fields from the ERA-Interim data set, which has a spatial resolution of 0.75° [Dee et al., 2011]. The following analyses are based on a 10 day averaged model output.

3. Results

The mean stream function of the model describes the time- and depth-averaged velocity field (gray contours in Figure 1a). Cyclonic flow, which includes most of the circulation in the subpolar gyre (except the Zapiola anticyclone), is represented by positive values of the stream function; anticyclonic flow, which includes the circulation in the subtropical gyre and the Zapiola Anticyclone, is represented by negative values of the stream function. There is good correspondence between the circulation patterns produced by our model and in situ and remote observations. Combes and Matano [2014] provide a detailed description of the circulation patterns generated by the model as well as a general discussion of the model’s performance. To assess the model’s skill to simulate the variability of the BMC, we compare the time series of the seasonal variations of the BMC location computed from the model and from satellite observations (Figure 1b). The latter were computed by Goni et al. [2011] combining advanced very high resolution radiometer (sea surface temperature (SST)) and Archiving, Validation, and Interpretation of Satellite Oceanographic data (sea surface height (SSH)) data sets. The location of the model BMC is defined as the latitude where the 1000 m isobath intersects the 10°C isotherm at the 200 m level [Garzoli and Bianchi, 1987]. The mean location of the BMC in the model is approximately 0.8° farther south than the observations. Note that this difference can be reduced by better adjusting the bottom stress model parameter. As shown in Combes and Matano [2014], the bottom friction is one adjustable parameter to control the mean northern ACC transport and therefore the position of the mean BMC. Aside from that difference, both time series show similar variations with comparable amplitudes (~1° of latitude; Figure 1b). The BMC moves southward during the astral fall (March-April-May) and northward during the astral spring (September-October-November) with seasonality more pronounced after 1992 (Figures 2a–2c). The BMC also exhibits strong interannual variations, with anomalies amplitudes of up to 2° (Figures 2a and 2b). The interannual variations of the model BMC are also in reasonable agreement with the satellite and drifter estimates of Goni et al. [2011] and Lumpkin and Garzoli [2011]. The BMC trends in both model and observations are not uniform. The model trend is 4 times larger during 1998–2002 than during 1993–2008. In fact, the model time series indicates that during the 1994–1999 and 2000–2005 periods, there was no significant trend, which is consistent with Goni and Wainer [2001]. Model and observations, therefore, suggest that the location of the BMC underwent an abrupt southward drift during the 1999–2000 period rather than a gradual southward displacement over the last 2 decades.

To identify the changes of the oceanic circulation associated with the 1999–2000 transition, we calculated the difference between the mean stream functions corresponding to the periods 1990–1999 and 2000–2009 (color map in Figure 1a). Negative/positive stream function anomalies in regions of cyclonic/anticyclonic flow correspond to a weakening of the circulation and vice versa. The anomaly field indicates a generalized weakening of the circulation in the subpolar region after 2000 and negligible changes in the subtropical region. The circulation changes predicted by the model are in agreement with observations. The lack of significant changes to the circulation of the subtropical gyre, for example, is in agreement with Goni et al. [2011] observations, while the model-predicted weakening of the ACC transport during the 2000–2009 period is consistent with the recent observations of A. M. C. Hogg et al. (submitted to Journal of Geophysical Research, 2014). Of particular interest is the stream function anomaly field that indicates a weakening of the MC transport during the 2000–2009 period, which is associated with the weakening of the ACC across the
Drake Passage (Figure 1a). Note that although there are no significant changes of the circulation in the subtropical gyre, there is strengthening of the BC transport near the BMC region, which is associated with the southward shift of the BMC rather than an intensification of the BC transport upstream. The model solution therefore indicates that the southward drift of the BMC is due to a weakening of the ACC transport rather than to an intensification of the subtropical gyre.

As noted above, observations show that the BMC drift was accompanied by a change of the spectral characteristics of the MC transport [Spadone and Provost, 2009]. A similar phenomenon is observed in the numerical simulation. We use Morlet wavelet analysis [Torrence and Compo, 1998], which considers the bias rectification [Liu et al., 2007], to identify the modes of variability of the time series of the MC transport and the BMC location. The time series of the MC transport shows a sharp change of its spectral characteristics during 1999, which is characterized by a sudden strengthening of the annual and semiannual oscillations (Figure 3a). Further analysis indicates that this change is a local phenomenon and does not reflect upstream changes in the MC transport. A wavelet analysis of the MC transport at ~42°S, for example, shows no change in the spectral characteristics after 1999 (Figure 3b). It is therefore the southward drift of the BMC, which is strongly seasonal before and after 1999–2000 (Figure 2c), that increases the amplitude of the annual and semiannual variability in the oceanic circulation of the surroundings and explains the changes of the MC transport at 40°S.

To determine the drivers of the observed shift of the BMC, we first examine the temporal variations of the Southern Annular Mode (SAM), which is the leading mode of atmospheric variability in the subpolar region. The SAM index is computed as the difference between the sea level pressure averaged over 65°S and 40°S.
SAM is highly correlated with the zonal wind stress (averaged over the same latitudinal band) \( r = 0.97 \) (figure not shown), so that increases/decreases of the SAM index are associated with a strengthening/weakening of the westerlies over the Southern Ocean. The positive linear trend of the SAM index over the last 3 decades is not temporally uniform but more accentuated in the period prior to 1999 than afterward (Figure 4a). The trend in the strengthening of the westerly winds is not spatially uniform, but it is largely concentrated over the Pacific and Indian basins (Figure 4c). To evaluate the effect of the SAM change on the westerly winds, we calculated the difference between the westerly winds averaged during the 2000–2009 and 1990–1999 periods. There is a significant weakening of the westerlies after 1999–2000 in the southeastern and southwestern Pacific and in the Atlantic basins (Figure 4d).

![Figure 3. Wavelet analyses of the Malvinas Current Transport at (a) 40.3°S and (b) 42.4°S. Cross-hatched regions indicate the cone of influence, where edge effects become important. The right column indicates the time-averaged wavelet power spectra.](image)

![Figure 4. (a) Comparison of the ACC Transport across the drake passage (blue; Sv) with Sea Level Pressure difference between 60°S and 40°S (green; in Pa). (The mean and seasonal cycles have been removed). (b) Comparison of the zonal wind stress (in N/m²) at location A in Figure 4c. (c) Trend of the zonal wind stress for the period 1979–2012 (in N/m²/yr). (d) Difference between the zonal wind stress averaged between 2000 and 2009 and zonal wind stress averaged between 1990 and 1999 (in N/m²). Dashed lines in Figures 4a and 4b indicate the linear trends of the sea level pressure (+5.5 Pa/decade) and zonal wind stress at point A (+0.016 N/m²/decade).](image)
example, by taking the difference between the periods 2000–2004 and 1995–1999. Over the South Pacific, where the 1979–2012 trend is maximum (point “A” in Figure 4c), the westerly wind strengthens on average between the periods 1990–1999 and 2000–2009 (Figure 4d) but weakens between the periods 1995–1999 and 2000–2004 (Figure 4b). To assess the impact of the atmospheric variability on the oceanic circulation, we correlated the transport of the Antarctic Circumpolar Current (ACC) across the Drake Passage (calculated from the model) with the SAM index; the correlation is relatively high: \(r = 0.49\). The ACC transport across the Drake Passage remains constant until the year 2000 but decreases during the period 2000–2007 (Figure 4a), when the westerly winds weaken (Figure 4d). Note that the weakening of the ACC transport predicted by the model is consistent with the observations of A. M. C. Hogg et al. (submitted manuscript, 2014). A closer inspection of the model ACC transport (Figure 4a), however, indicates a strengthening of the ACC around 2002, which is not consistent with the 1999–2000 shift of the BMC. The ACC variability, however, varies along the Drake Passage. The northern portion of the ACC transport (north of 56°S; Figure 5a), which forms the MC, exhibits a clear weakening during the period 1998–2002, when the southward trend of the BMC is the highest. The weakening of the model ACC transport produces a weakening of the MC transport, which is particularly strong near shelf break ("inner portion"; Figure 5a). The weakening of the inner portion of the MC transport then triggers the southward migration of the BMC.

4. Summary and Discussion

Our study indicates that the southward drift of the BMC during the 1993–2008 period is associated with a generalized weakening of the Southern Ocean circulation produced by a weakening of the westerly wind forcing. The BMC drift is not associated with a steady trend but with an abrupt shift of the circulation during the 1999–2000 period. Similar shifts appear in time series of the ACC transport and the Southern Ocean winds. The southward migration of the BMC increases the annual and semiannual variability of the MC transport at 40°S. Over the period 1992–2008, it is noteworthy mentioning that the maximum wind stress curl across the South Atlantic also exhibits a southward trend both in the National Centers for Environmental Prediction/National Center for Atmospheric Research [Lumpkin and Garzoli, 2011] and ERA_interim (figure not shown) data sets, which may also impacts the position of the BMC [Lumpkin and Garzoli, 2011]. Note that, however, we do not notice a significant trend of the maximum wind stress curl over the period 1998–2002 when the BMC trend is the highest.

The southward drift of the BMC and the associated changes of the MC variability are the best-documented consequences of changes in the Southern Ocean winds, but they are not the only ones. Further model analysis also indicates a substantial change of the magnitude of the Patagonian shelf break upwelling (PSU)
after 1999–2000. The PSU is maintained by intrusions of the MC into the continental shelf and depends on the magnitude of the MC transport [Matano and Palma, 2008], in particular on the magnitude of the inner portion of the MC [Combes and Matano, 2014]. To assess the response of the PSU to changes of the inner portion of the MC, we compare the MC transport variability and the upwelling index, which is defined as the time series of the vertical velocity integrated from 200 m to the surface and averaged over the green box shown in Figure 1a. The correlation is high and significant ($R = 0.70$ using a 1 year low-pass and detrended time series; Figure 5b). As a consequence of the trend in the MC transport described previously, the PSU also undergoes an overall weakening after the period 1999–2000. Since the PSU brings subsurface nutrient-rich water into the photic zone, its changes may affect the rich local ecosystem.

The model results also show a weakening of the Zapiola Anticyclone from 1994 to 2006 (Figures 1a and 5c). The Zapiola Anticyclone is a large barotropic vortex (~10° wide) centered over the Argentinean basin (~44°S, 45°W) that is controlled by bottom friction [De Miranda et al., 1999; Combes and Matano, 2014] and driven by eddy fluxes [Dewar, 1998]. The time series of the Zapiola Anticyclone transport shows a strong interannual variability (70.7 ± 9.7 Sv) and a negative trend from 1994 to 2006. The model shows that the variability of the Zapiola Anticyclone transport is linked to the local eddy kinetic energy field (Figure 5c), in agreement with the satellite observations discussed by Saraceno et al. [2009] and consistent with Dewar [1998] theory. Although the time series of the satellite-derived EKE is not correlated with the model EKE (since the present model does not assimilate observational data), both model and observations exhibit a weakening during the period 2002–2007 (Figure 5c). This is consistent with a decrease of the ACC transport south of the Zapiola anticyclone (Figure 1a).

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**References**


