The role of vorticity fluxes in the dynamics of the Zapiola Anticyclone

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[1] The Argentine Basin in the South Atlantic Ocean is one of the most energetic regions in the ocean with complicated dynamics, which plays an important role in the global climate. A number of observations have discovered an intense anticyclonic gyre of barotropic circulation around the Zapiola Rise in the center of the basin. Theoretical studies have shown that the Zapiola Anticyclone represents an eddy-driven flow controlled by bottom friction. Recent advances in high-resolution global-ocean data syntheses, performed using NASA supercomputing facilities, provide realistic simulations of the circulation and the variability in the Argentine Basin. Using these simulations and satellite altimeter observations, we analyzed the vorticity balance of the Zapiola Anticyclone. Our results suggest the dominance of vorticity fluxes and the advection of the potential vorticity over a nonuniform bottom topography in determining the variability of the gyre, while the impact of the local wind stress is small. The divergence of the relative vorticity anomaly advection by eddies is found to be the most important contributor to the relative vorticity flux divergence influencing the variability of the Zapiola Anticyclone. Our results demonstrate that the relative vorticity influencing the variability of the anticyclone is mainly advected from the south where the northern branch of the Antarctic Circumpolar Current at the Subpolar Front is located.


1. Introduction

[2] The most energetic regions in the ocean are associated with the western boundary currents. These currents are characterized by high eddy activity and they play a crucial climatic role in transporting heat from low latitudes toward the polar regions. In this study we focus on one such region—the Argentine Basin (Figure 1), which is characterized by complicated dynamics. The Antarctic Circumpolar Current (ACC) dominates the southern part of the basin. It transports around 130−140 Sv (1 Sv = 10^6 m^3/s) of water through the Drake Passage [e.g., Whitworth and Peterson, 1985; Cunningham et al., 2003]. Part of this water turns north and forms the Malvinas Current transporting from 60 Sv up to about 90 Sv between 42°S and 46°S [Peterson, 1992; Saunders and King, 1995]. The Brazil Current, which is the western limb of the South Atlantic subtropical gyre, flows south along the continental slope of South America carrying around 20 Sv near 38°S [Olson et al., 1988; Peterson and Stramma, 1991]. The Malvinas and the Brazil currents collide at approximately 39°S [Piola et al., 1987], creating one of the most energetic regions of the World Ocean: the Brazil/Malvinas Confluence (BMC). Satellite altimetry observations (Figure 1) have revealed the spatial distribution of the high eddy energy of the region [e.g., Stammer, 1997; Ducet et al., 2000].

[3] Eddy Kinetic Energy (EKE) in the Argentine Basin (Figure 1) shows high levels in the area of BMC surrounding a region of low energy centered at around 45°S and 45°W over a topographic anomaly known as the Zapiola Rise (Figure 2) [de Miranda et al., 1999]. Eddies in the high variability BMC region are reported to have surprisingly low propagation velocities. At the same time an organized pattern of strong anticlockwise eddy propagation is situated in the area of low eddy variability around the Zapiola Rise [Fu, 2006]. In this area eddies are affected by an intense anticyclonic barotropic circulation, the Zapiola Anticyclone (from now on the ZA), with uniform current velocity from surface to bottom. Strong bottom velocities of about 10 cm/s were recorded here during hydrographic surveys [Saunders and King, 1995; Weatherly, 1993]. Saunders and King estimated the barotropic transport of the ZA to be more than 100 Sv. A theoretical explanation for the existence and large mass transport of the ZA was suggested by Dewar [1998]. He demonstrated that localized topography may generate closed geostrophic contours and suggested that the ZA was an eddy-driven flow controlled by bottom friction. These theoretical findings were supported by de Miranda et al. [1999] who produced the first realistic representation of the ZA with a numerical model simulation, consistent with satellite, in situ, and float observations.

[4] In this paper we aim to further develop our understanding of the dynamics of the ZA. We focus on domain D
(Figure 1) confined within $37.5^\circ\text{W} - 47.5^\circ\text{W}$ and $43.5^\circ\text{S} - 46.5^\circ\text{S}$ around the Zapiola Rise and encompassing the time-mean anticyclonic gyre around this topographic anomaly (Figure 2). Using numerical simulations performed on NASA supercomputing facilities and available satellite altimeter data we want to investigate the physical mechanisms involved in the variability of the anticyclone.

2. Data

2.1. Satellite Observations

The satellite observations used in this work are from the merged maps of Sea Level Anomalies (SLA) from Topex/Poseidon, Jason-1, ERS-1/2, and Envisat altimeter missions [SSALTO/DUACS User Handbook, 2006]. The Topex/Poseidon 7-year mean (from January 1993 to December 1999) was used as a reference level to derive SLA. The data are mapped on a $1/3^\circ$ Mercator projection grid using an optimal interpolation technique [Le Traon et al., 1998; Ducet et al., 2000]. There is one map every seven days from 14 October 1992 to 7 June 2006, thus yielding 713 weekly records. The data are corrected for instrumental errors, environmental perturbations (wet tropospheric, dry tropospheric and ionospheric effects), ocean wave influence (sea state bias), tidal influence (most recent GOT2000 tidal correction); long wavelength errors that include inverted barometer bias, residual orbit and tidal correction errors, and aliased high-frequency barotropic ocean response to atmospheric wind and pressure were corrected using an ocean barotropic model [Carre`re and Lyard, 2003].
2.2. Model Simulations

The simulated data are from a high-resolution global-ocean data synthesis project called Estimating the Circulation and Climate of the Ocean, Phase II (ECCO2). The ECCO2 project aims to produce an accurate, time-evolving synthesis of most available global-scale ocean and sea-ice data at eddy-permitting resolution. The global-ocean simulations were carried out using the Massachusetts Institute of Technology general circulation model (MITgcm) [Marshall et al., 1997]. The model configuration is described in Menemenlis et al. [2005a]. A cube-sphere projection is employed, which permits relatively even grid spacing throughout the domain and which avoids polar singularities [Adcroft et al., 2004]. Each face of the cube comprises 510 by 510 grid cells for a mean horizontal spacing of 18 km. There are 50 vertical layers with thicknesses ranging from 10 m at the surface to 456 m near the bottom. The bottom boundary layer is thus not resolved by the model. An ECCO2 data synthesis is obtained using Green’s function approach [Menemenlis et al., 2005b]. The solution requires the computation of a number of sensitivity experiments, all of which are made available at www.ecco2.org. Computations are performed on the Columbia Supercomputer operated by the NASA Advanced Supercomputing group at the Ames Research Center. The sensitivity experiments are free, unconstrained calculations by a forward model. They contain a tremendous wealth of information regarding model physics and can be used for many science investigations, in addition to their original model calibration purpose. In essence, the experiments are meant to be used to adjust the model parameters. Using the adjusted parameters, the model is then run forward free of any constraints, as in any ordinary model simulation.

For this study we use one sensitivity experiment forced by the 6-hourly winds from the NCEP/NCAR reanalysis. The period of the model run is from January 1992 to March 2006 inclusive. We use monthly averages of the model-simulated velocities and the monthly averages of the wind stress, computed from 6-hourly wind speeds. Because of the large number of prospective sensitivity experiments and, therefore, tremendous data storage requirements, only monthly velocity fields are saved from each model run. This yields 171 month records, which allow us to investigate the variability on the temporal scales from two months and longer. The use of the monthly velocity fields is certainly the major drawback of this study and a source of error, which will be discussed below. For comparison with satellite altimetry observations we use 6-hourly model-simulated sea surface heights (SSH). They are low-pass filtered with a 7-day running mean and resampled at the times of altimeter data. To match the altimeter SLA, the model SLA were computed by subtracting the time-mean SSH calculated over the same period as the one used to produce the altimeter SLA.

3. Temporal Variability of the Zapiola Anticyclone

The variability of the ZA is reflected in the variations of sea level averaged over domain D (Figure 3a). Because of geostrophic balance, the anticyclone spins up when the sea level at the center of the anticyclone rises and spins down when the sea level decreases. The simulated sea level variations are compared with satellite altimetry data. Despite some discrepancies the model performs reasonably well and the correlation between the simulated and altimeter-measured weekly sea levels is 0.47. Because both compared time series are autocorrelated due to the presence of the seasonal variability, the number of degrees of freedom $N^*$ differs from the number of data points N (in this case 713) and $N^*/N \leq 1$. Using the formula of Leith [1973] $N^* = -0.5 \times \ln [r(\Delta t)]$, where $\Delta t$ is the time...
interval between data points and \( r(\Delta t) \) is one-lag autocorrelation, we define 37 degrees of freedom. This gives us 0.3 as the 95% significance level for the correlation coefficient. The correlation between the simulated and altimeter-measured weekly sea levels is, therefore, significant. This confirms the realistic representation of the variability of the ZA by the ECCO2 model.

[9] The vertical profiles of the zonal and meridional velocity (not shown) illustrate that within the ZA, between about 42°S–48°S, velocities are almost uniform from surface to bottom confirming the barotropic structure of the flow. The mass transport of the anticyclone is highly variable with an amplitude of about 100 Sv. The long-term averaged eastward transport between 45°S and 48°S is around 95 Sv while the average westward transport between 42°S and 45°S is approximately 60 Sv. These values agree well with observational evidence [Saunders and King, 1995]. This is a promising result because there are a few global models capable of realistically simulating the ZA.

[10] Since the flow in the ZA is quasi-barotropic we can study it using depth averaged velocities. The depth-averaged 14-year mean velocities in the Argentine Basin are shown in Figures 1 and 2. As a quantity describing the circulation of the ZA we use the curl (the relative vorticity) of the horizontal velocity \( u(u,v) \) integrated over domain \( D \) (Figure 2):

\[
\zeta_D = \iint_D \left( \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right) dxdy \quad (1)
\]

The time series of \( \zeta_D \), calculated from the ECCO2 monthly barotropic velocities (Figure 3b) demonstrate a high level of variability on the intraseasonal and interannual time scales. The positive values of \( \zeta_D \) denote an anticyclonic character of the circulation, while the negative values indicate a cyclonic flow. As one can see, the anticyclonic circulation is dominant illustrating a quasi-permanent nature of the ZA, which agrees well with the observational evidence. To understand what factors determine the variability of the ZA, in the following section we analyze the vorticity balance of domain \( D \) (Figure 2).

4. Vorticity Balance

4.1. Model Simulations

[11] For the frictionless barotropic flow the vorticity equation can be approximated as follows

\[
\zeta_t + u \cdot \nabla \zeta + \beta v = fH^{-1}u \cdot \nabla H + \rho^{-1}H^{-1} \nabla \times \tau, \quad (2)
\]

where the subscript indicates a partial derivative, \( \beta = f \) is the meridional gradient of the planetary vorticity, \( H \) is the mean depth of the ocean, and \( \tau \) is the wind stress. The left hand side of the equation represents the local time change of \( \zeta \) plus the relative vorticity flux divergence and the planetary vorticity flux; the right hand side of the equation represents the interaction between the flow and the bottom topography (the advection of the potential vorticity \( fH \) over a spatially varying bottom topography) and the influence of the wind stress curl on the dynamics of the anticyclone. We estimated all terms of equation (2) integrated over domain \( D \) using the output of an ECCO2 model run. The balance between the sum of the terms on the left hand side of the vorticity equation (the total time-derivative of the absolute vorticity, \( d(\zeta + f)/dt \)) and the sum of the terms on the right hand side of equation (2) is shown in Figure 4a. The correlation between the two time series is 0.8, which is significant at 95% confidence. This shows that the approximation in equation (2) is valid in the study region. From now on we consider only the area-integral of the
equation (2) and the symbol of integral is omitted for simplicity.

The mismatch between the curves in Figure 4a is because of (1) the use of monthly averaged velocity fields and (2) the neglect of frictional forces. While the use of monthly velocity fields does not affect the intermonthly variability of the ZA, it affects the variability of the relative vorticity flux divergence. If we decompose velocity into monthly averaged $\langle u \rangle$ and intramonthly fluctuations $\tilde{u}$, $u = \langle u \rangle + \tilde{u}$, then

$$u \cdot \nabla \zeta = \langle u \rangle \cdot \nabla (\zeta) + \langle u \rangle \cdot \nabla \tilde{u} + \tilde{u} \cdot \nabla (\zeta) + \tilde{u} \cdot \nabla \zeta.$$

(3)

Available resources do not allow us to estimate the last three terms. Therefore the relative vorticity flux divergence estimated from the monthly velocity fields, ignores the contribution of the intramonthly variability, for example, the barotropic waves rapidly rotating around the Zapiola Rise with a period of about 25 days [Fu et al., 2001]. It is difficult to estimate to what degree the terms containing the intramonthly fluctuations affect the intermonthly variability of the relative vorticity flux divergence because of the stochastic nature of the former. Nevertheless, we can expect that at certain frequencies the relative vorticity flux divergence computed from the monthly velocities is coherent with both the relative vorticity flux divergence computed from original velocities and with the time-change of the relative vorticity. The offset in Figure 4a is also due to friction, which is ignored in our analysis. Dewar [1998] showed that friction is a key parameter controlling the circulation around the Zapiola Rise and Bigorre [2005] showed that it is an important part of the local potential vorticity budget. Most of dissipation is due to the bottom friction because viscous forces in the upper layers are weaker. The model does not resolve the bottom boundary layer and it employs a nonlinear bottom stress of the form $\tau_{bk} = C_D |u| \cdot u$ and $\tau_{by} = C_D |v| \cdot v$, where $C_D = 0.002$ is the drag coefficient.

The use of monthly averaged velocities makes it unfeasible to accurately estimate the bottom friction because the curl of the bottom stress computed from the monthly velocities ignores the contribution of the terms including intramonthly velocity fluctuations (similar to the relative vorticity flux divergence). However, we can regard frictional forces as the residual difference between the two curves in Figure 4a (Figure 4b). The largest part of this residual is due to the bottom friction and the unresolved intramonthly velocity fluctuations. The residual correlates with the curl of the bottom stress ($r = 0.3$, which is significant at 95% confidence for the given number of degrees of freedom), computed using monthly averaged velocities (Figure 4b). The mismatch between the residual and the curl of the bottom stress is because of the unresolved intramonthly velocity fluctuations in both the relative vorticity flux divergence (last three terms of the equation (3)) and the bottom stress estimates. Neither the residual nor the curl of the bottom stress correlates with the time change of the relative vorticity of the ZA. This is consistent with a rather passive role of bottom friction in the variability of the ZA. If we subtract the estimated curl of the bottom stress from the residual we will obtain the summary error due to the unresolved intramonthly velocity fluctuations. The standard deviation of this error is 0.024 m²/s².

To understand the role of each individual dynamical factor determining the circulation of the anticyclone and its variability we compare the area-integral of the time-change of the relative vorticity of the anticyclone with the area-integrals of all other terms of the equation (2). The correlation coefficients between significant terms are presented in Table 1. It appears that the wind stress accounts only for 3% of the $\zeta$ variance. Therefore we conclude that the local wind stress does not have a significant impact on the variability of the ZA. On the other hand, elsewhere there might be other topographically trapped barotropic modes that are excited by the wind [e.g., Fu, 2003]. Displayed in Figure 5a is the comparison between $\zeta_t$, the planetary vorticity flux $-\beta v$ and the advection of the potential vorticity over a nonuniform bottom topography $fH^{-1} u \cdot \nabla H$, and displayed in Figure 5c is the comparison between $\zeta_t$ and the relative vorticity flux divergence $-u \cdot \nabla \zeta$. The correlation between $\zeta_t$ and the planetary vorticity flux and between $\zeta_t$ and the relative vorticity flux divergence is 0.29 and 0.31, respectively (Table 1), which is significant at 95% confidence for the given number of degrees of freedom. The coherence plots (Figures 5b and 5d) suggest that both planetary and the relative vorticity fluxes divergence are coherent with the strength of the ZA at subannual periods, and the planetary vorticity flux is also coherent with $\zeta_t$ at interannual periods. The coherence between $\zeta_t$ and the planetary vorticity flux (Figure 5b) is statistically significant (above the 95% confidence) at frequencies $0.5–1$ cpy, $1.3–3$ cpy and at about $5.4$ cpy, while the coherence between $\zeta_t$ and the relative vorticity flux divergence (Figure 5d) is statistically significant at frequencies $1–1.5$ cpy and $2.2–4.2$ cpy. The coherence between the topographic term and $\zeta_t$ (Figure 5e) is statistically significant at frequencies $1.1–1.8$ cpy, at about $2.6$ cpy, and $5.4$ cpy. The correlation between $\zeta_t$ and the sum of all other terms is $0.37$ and the coherence between them (Figure 5d) is statistically significant at subannual frequencies. This comparisons show that all terms in equation (2) besides the wind stress curl significantly influence the variability of the ZA and that the analysis is robust despite errors, due to the use of the monthly velocity fields.

As seen in Figure 5a, the planetary vorticity flux is partly balanced by the advection of the potential vorticity over the varying bottom topography. The correlation between $-\beta v$ and $fH^{-1} u \cdot \nabla H$ is $-0.74$ (Table 1). This is because the barotropic vorticity-neutral motion follows the contours of constant $fH$ and has $\beta v$ and $fH^{-1} u \cdot \nabla H$ terms canceling each other. However, in our case $\beta v$ and $fH^{-1} u \cdot \nabla H$ do not cancel each other completely and their sum may affect the variability of the ZA. The correlation between $\zeta_t$ and $fH^{-1} u \cdot \nabla H - \beta v$ is $0.22$, and the coherence between them (Figure 5b) is statistically significant at frequencies $1.1–2.8$ cpy, $\sim 3.2$ cpy, $\sim 4.4$ and $5$ cpy. The high correlation between $-\beta v$ and $fH^{-1} u \cdot \nabla H$ is also largely responsible for $0.8$ correlation between the left and the right hand sides of the equation (2). The correlation between the total time-derivative of $\zeta$ and the sum of the remaining terms (after moving the planetary vorticity flux to the right side of the equation (2)) is $0.4$. While the planetary vorticity flux and the advection of the potential vorticity over a nonuniform bottom partly
balance each other, the remaining relative vorticity flux divergence plays an important role in the variability of the ZA. Earlier studies have suggested that the anticyclone is eddy driven [Dewar, 1998; de Miranda et al., 1999]. Eddies contribute to the relative vorticity flux divergence term in the equation (2). In order to understand the importance of eddies we can decompose the relative vorticity flux divergence into the components associated with the mean flow and with the time-dependent (or eddy) flow:

\[
\mathbf{u} \cdot \nabla \zeta = \mathbf{u} \cdot \nabla \zeta + \mathbf{u}' \cdot \nabla \zeta + \mathbf{u} \cdot \nabla \zeta' + \mathbf{u}' \cdot \nabla \zeta',
\]

where \( \mathbf{u} = \mathbf{u} + \mathbf{u}' \) and \( \zeta = \zeta + \zeta' \). The first term on the right side of equation (4) is time independent and it does not contribute to the variability of the ZA. The second term represents the divergence of the vorticity anomaly advection by the mean flow, while the last two terms represent the divergence of the time-mean vorticity and the vorticity anomaly advection by the eddy flow, respectively. As could be expected, the divergence of the relative vorticity advection by eddies appears to be the major contributor to the variability of the relative vorticity flux divergence. The correlation between \( \mathbf{u} \cdot \nabla \zeta \) and the eddy vorticity flux divergence \( \mathbf{u}' \cdot \nabla \zeta' + \mathbf{u} \cdot \nabla \zeta' \) is 0.72, while \( \mathbf{u} \cdot \nabla \zeta \) and \( \mathbf{u}' \cdot \nabla \zeta' \) are not correlated \((r = 0.13)\). The correlation between \( \mathbf{u} \cdot \nabla \zeta \) and \( \mathbf{u}' \cdot \nabla \zeta \), and \( \mathbf{u} \cdot \nabla \zeta \) and \( \mathbf{u} \cdot \nabla \zeta' \) is 0.43 and 0.65 respectively (Table 1), suggesting a more dominant role of the divergence of the vorticity anomaly advection by eddies. The latter appears to explain 37% of the variance of the relative vorticity flux divergence. The divergence of the time-mean vorticity advection by eddies \( \mathbf{u}' \cdot \nabla \zeta' \) explains only 9% of the variance of the \( \mathbf{u} \cdot \nabla \zeta \) variance, while \( \mathbf{u} \cdot \nabla \zeta' \) does not explain the variance of \( \mathbf{u} \cdot \nabla \zeta \). Thus the divergence of the vorticity anomaly advection by eddies is the main term of equation (4).

Now we want to address the question of how each time-dependent component of equation (4) influences the variability of the ZA strength. Displayed in Figure 6 are the time series of \( \zeta \) versus the time-dependent components of

<table>
<thead>
<tr>
<th>Term</th>
<th>( \zeta )</th>
<th>( -\mathbf{u} \cdot \nabla \zeta )</th>
<th>( -\mathbf{u} \cdot \nabla \zeta' )</th>
<th>( -\mathbf{u}' \cdot \nabla \zeta' )</th>
<th>( -\mathbf{u} \cdot \nabla \zeta' )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \zeta )</td>
<td>1</td>
<td>0.31</td>
<td>0.29</td>
<td>0.21</td>
<td>-0.21</td>
</tr>
<tr>
<td>( -\mathbf{u} \cdot \nabla \zeta )</td>
<td>0.31</td>
<td>1</td>
<td>0.13</td>
<td>0.43</td>
<td>0.65</td>
</tr>
<tr>
<td>( -\mathbf{u} \cdot \nabla \zeta' )</td>
<td>0.29</td>
<td>0.13</td>
<td>1</td>
<td>0.33</td>
<td>0.31</td>
</tr>
<tr>
<td>( -\mathbf{u}' \cdot \nabla \zeta' )</td>
<td>0.21</td>
<td>0.43</td>
<td>0.33</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

The 95% significance level is 0.15.

Figure 5. (a) The time series of the area-integrals of \( \zeta \) (grey curve), the planetary vorticity flux (black curve), and the topographic term (dashed curve) and (b) coherence between \( \zeta \) and the planetary vorticity flux (black curve), \( \zeta \) and the topographic term (dashed curve), \( \zeta \) and the combined effect of the planetary vorticity flux and the topographic term \( \hat{H} \mathbf{u} \cdot \nabla \zeta' \) (grey curve). (c) The time series of the area-integrals of \( \zeta \) (grey curve) and the relative vorticity flux divergence (black curve) and (d) coherence between \( \zeta \) and the relative vorticity flux divergence (black curve) and between \( \zeta \) and the sum of all other terms (dashed curve) in equation (2). The dashed line in Figures 5b and 5d is the 95% confidence limit.
It is seen that the amplitude of all components is comparable with the amplitude of $z_t$. The most significant influence comes from the divergence of the vorticity anomaly advection by eddies (Figure 6c). The time series of $z_t$ and $\frac{u_0}{C_1 r} z_0$ are significantly correlated ($r = 0.33$) suggesting that the divergence of the vorticity anomaly advection by eddies into domain $D$, according to the equations (2) and (4), accelerates the ZA. The correlation between the time series of $z_t$ and the divergence of the vorticity anomaly advection by the mean flow $\frac{u_0}{C_1 r} z_0$ is lower ($r = 0.21$), but above the 95% significance level (0.15), and the latter gives the same tendency to the strength of the anticyclone (Figure 6a). The divergence of the time-mean vorticity advection by eddies $-\mathbf{u}' \cdot \nabla \zeta'$ (Figure 6b) is negatively correlated with $z_t$ ($r = -0.21$), and it appears that the former counteracts the impact of the divergence of the vorticity anomaly advection by the mean flow $\mathbf{u} \cdot \nabla \zeta$ (Figure 6a). The time series of $-\mathbf{u}' \cdot \nabla \zeta$ and $-\mathbf{u} \cdot \nabla \zeta$ are significantly anticorrelated ($r = -0.51$) and the sum of these terms is not correlated with $\zeta$. Therefore we conclude that although the amplitudes of the divergence of the time-mean vorticity advection by eddies $-\mathbf{u}' \cdot \nabla \zeta$ and the divergence of the vorticity anomaly advection by the mean flow $-\mathbf{u} \cdot \nabla \zeta'$ are comparable to the amplitude of $\zeta$, these terms partly cancel each other and, hence, it is mainly the divergence of the vorticity anomaly advection by eddies $-\mathbf{u}' \cdot \nabla \zeta'$ that impacts the variability of the ZA the most.

As has been mentioned above, the ZA is surrounded by highly energetic and dynamic regions: there is the BMC zone northwest of the anticyclone and there is the northern branch of the ACC south of the anticyclone (Figure 1). It is, therefore, interesting to gain knowledge of where the relative vorticity influencing the variability of the ZA is advected from. The relative vorticity flux divergence integrated over domain $D$ can be computed as the sum of the integrals of the relative vorticity fluxes across each individual boundary (eastern $(e)$, western $(w)$, northern $(n)$, and southern $(s)$, as shown in Figure 2) plus the divergence of $\zeta$ integrated over $D$:

$$
-\iint_D \mathbf{u} \cdot \nabla \zeta \, dx \, dy = \int_e^n u_{w} \zeta_{w} \, dy - \int_e^n u_{e} \zeta_{e} \, dy + \int_w^n u_{s} \zeta_{s} \, dx - \int_w^n u_{n} \zeta_{n} \, dx + \iint_D \nabla \cdot \mathbf{u} \, dx \, dy. \tag{5}
$$

The flux terms are positive in the northward/eastward direction. The last term in equation (5), due to divergent flow, is rather small compared to the first four terms. The standard deviation of the divergence term (0.0015) is almost an order of magnitude smaller than the standard deviation of the sum of the flux terms (0.013). Therefore the flow can be regarded as almost nondivergent and the divergence term in equation (5) can be neglected. Displayed in Figure 7 is the comparison between the fluxes of the right side of equation (5) across each individual boundary and $\zeta$. We find that the exchange of the relative vorticity through the southern boundary plays the most influential role in the variability of the anticyclone. The time series of $\zeta$ and the flux of the relative vorticity across the southern boundary are significantly correlated ($r = 0.3$). This boundary separates the ZA from the northern branch of the eastward flowing ACC. Thus the variability of the latter seems to play an important role in the variability of the ZA.
The western boundary does not exhibit a strong impact on the variability of the anticyclone, which is surprising because this boundary lies in the vicinity of the BMC zone (Figure 1). The relative vorticity flux through the eastern boundary is relatively strong and at some periods it seems to influence the variability of the ZA, however, it is not correlated with $\zeta_t$. The amplitude of the relative vorticity flux through the northern boundary is also rather large. The correlation between this flux and $\zeta_t$ is negative ($r = -0.17$) and just above the level of significance. Therefore the exchange through this boundary may also be important in the variability of the ZA. The negative correlation also means that an inflow/outflow of the positive relative vorticity into/from domain $D$ causes an acceleration/deceleration of the ZA.

4.2. Satellite Altimetry Observations

The role of vorticity fluxes in the dynamics of the ZA can also be studied using satellite altimetry data. Assuming geostrophy, $u = -(g/f)\partial h/\partial y$ and $v = (g/f)\partial h/\partial x$, where $h$ is SSH, $g$-gravity, and $f$-planetary vorticity, therefore, $\zeta$ is proportional to the Laplacian of $h$ and hence

$$\zeta_D = \iint_D (g/f)\nabla^2 h \, dx \, dy$$

The time-dependent part of SSH $h' = h - \bar{h}$, where $\bar{h}$ is the time mean sea surface height, is measured by satellite altimetry (SLA) and can be used to compute the time-dependent part of $\zeta_D$. The altimeter-derived $\zeta_D$ shows cyclonic or anticyclonic deviations from the mean circulation.

Decomposing equation (2) into the time-mean and the time-dependent parts and for this time leaving the wind stress term out we obtain

$$\zeta_t + \mathbf{u}' \cdot \nabla \zeta' + \beta v' = fH^{-1} \mathbf{u}' \cdot \nabla H + F$$

where

$$F = fH^{-1} \mathbf{u}' \cdot \nabla \zeta - \beta \mathbf{u}' \cdot \nabla \zeta - \mathbf{u}' \cdot \nabla \zeta' - \mathbf{u}' \cdot \nabla \zeta$$

is the sum of the terms that we are unable to estimate from altimetry data, because the mean geostrophic flow cannot be derived with sufficient accuracy. Only the two last terms in equation (8) are time-dependent and contribute to the variability. In the previous section we showed that the amplitude of these terms is comparable to the amplitude of $\zeta_t$, but to a certain degree these terms may cancel each other leaving the remaining divergence of the vorticity anomaly advection by eddies, $\mathbf{u}' \cdot \nabla \zeta'$, be the most influential component of the relative vorticity flux divergence on the variability of the anticyclone. Therefore we expect that altimetry may manifest adequate description of the vorticity balance in the domain of our study.

In Figure 8 we present the balance between the sum of the terms on the left side of the equation (7) and the advection of potential vorticity by eddies over a spatially varying bottom topography $fH^{-1} \mathbf{u}' \cdot \nabla H$. For this length of independent records (713) the 99% significance level for correlation is about 0.1. The two time series are thus significantly correlated ($r = 0.4$), which means that altimetry allows a valid description of the vorticity balance in the area of the ZA. Therefore, we may conclude that altimetry provides us observational evidence that the variability of

Figure 7. The comparison between the area-integral of $\zeta_t$ (grey thin curves) and the integrals of the relative vorticity fluxes across the western, eastern, southern, and northern boundaries of domain $D$ (black bold curves). The flux terms are positive in the northward/eastward direction.
the ZA is mainly driven by vorticity fluxes and the interaction between the time-varying flow and the bottom topography.

[22] The divergence of the vorticity anomaly advection by eddies \( \mathbf{u}' \cdot \nabla \zeta' \) is found to be significantly correlated \((r = 0.21)\) with \( \zeta_r \), confirming its importance in influencing the variability of the ZA strength and supporting the results obtained from a model-simulation. The correlation between \( \zeta_r \) and the planetary vorticity flux \(-\beta v'\) is slightly lower \((r = 0.18)\) and \( fH^{-1} \mathbf{u}' \cdot \nabla H \) is also found to be correlated with \( \zeta_r \) \((r = 0.18)\). Similar to the model results, \(-\beta v'\) and \( fH^{-1} \mathbf{u}' \cdot \nabla H \) are significantly anticorrelated \((r = -0.51)\) providing motion along \( fH \) contours. However, these terms do not totally cancel each other. The correlation between the time series of \( fH^{-1} \mathbf{u}' \cdot \nabla H = \beta v' \) and the time series of \( \zeta_r \) is 0.29, implying that the combined effect of the planetary vorticity flux and the advection of the potential vorticity over a sloping topography by eddies also contributes to the variability of the ZA strength.

5. Conclusions

[23] This paper demonstrates the usefulness of the new generation data syntheses in studying the dynamics of oceanic mesoscale features. The eddy permitting simulations performed within the framework of ECCO2 project realistically reproduce the ZA—one of the most interesting phenomena in the circulation of the Argentine Basin. During the period of the study the barotropic flow of the anticyclone exhibited significant intraseasonal and interannual variability. The variability of the simulated SLA averaged over the ZA is significantly correlated with satellite altimetry observations.

[24] Through analyzing the vorticity balance derived from the model-simulated barotropic flow and from the altimeter-measured geostrophic velocity anomalies of the ZA, we find that the vorticity fluxes and the interaction between the flow and the bottom topography are the most important factors of its variability. The influence of the local wind stress is found to be small.

[25] In both the model simulations and the altimeter observations the relative vorticity flux divergence and the planetary vorticity flux are found to be significantly correlated with the variability of the ZA strength. Our results show that the planetary vorticity flux and the relative vorticity flux divergence are coherent with the strength of the ZA on subannual time scales, and the planetary vorticity flux is also coherent with the strength of the ZA on interannual time scales.

[26] The planetary vorticity flux is found to be partly balanced by the advection of the potential vorticity over a sloping bottom. The results from both the model simulation and altimeter observations show that these components of the vorticity balance equation are significantly anticorrelated. The interaction between them explains why the ZA does not move in the meridional direction to balance changes in its vorticity. The combined effect of these terms is also found to be correlated with the variability of the anticyclone. Thus the upslope/downslope advection of the potential vorticity balances the negative/positive tendencies in the planetary vorticity flux and the sum of these terms also gives a positive/negative tendency to \( \zeta_r \).

[27] The major drawback of this study is the use of monthly averaged velocity fields. These fields do not allow estimating the contribution of the intramonthly variability to the intermonthly relative vorticity flux divergence. Nevertheless, the relative vorticity flux divergence, computed from the monthly velocities, is also found to be an important dynamical factor responsible for the intermonthly variability of the ZA. By decomposing the relative vorticity flux divergence into the time-independent and the time-dependent components we find that the divergence of the vorticity anomaly advection by eddies is probably the major contributor to the relative vorticity flux divergence influencing the variability of the ZA. The other two components, i.e., the divergence of the vorticity anomaly advection by the mean flow and the divergence of the time-mean vorticity advection by eddies partly cancel each other. We demonstrate that the relative vorticity flux divergence influencing the variability of the ZA mainly occurs through the southern boundary of the domain of our study, which is adjacent to the northern branch of the ACC in the Argentine Basin.

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References


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