Literature review regarding the main causes of low frequency variability of the Brazil Current

The Brazil Current (BC) is the Western Boundary Current (WBC) associated to the South Atlantic Subtropical Gyre. The BC is the main dynamical feature of the South Atlantic Ocean. However, BC is a low intensity WBC, if compared to the Gulf Stream (North Atlantic WBC) (Peterson & Stramma, 1991). The most accepted explanation for this difference on the volume transport between both WBC is that the thermohaline circulation interferes positively on the Gulf Stream volume transport, whilst decreases the BC volume transport because it is oriented on the opposite direction (Figure 1). In addition, Stramma *et al*. (1990) argue that the bifurcation of the South Equatorial Current (SEC), the current that originates BC, exerts significant influence on the low BC volume transport. Approximately 12 Sv of SEC flows northward as the North Brazil Current and roughly 4 Sv originates the BC.

As mentioned before, the BC is originated by the SEC. However, as BC flow south, its flow intensities in a rate of 5% every 100 km, similar to Gulf stream growth rate (Figure 2). This occurs because other water masses inputs occur along the southward CB path in different depths (Figure 3). Pereira *et al.* (2014) stated the BC suffers 3 different bifurcation processes: a) 13° - 15° S for the Tropical Water level; b) approximately 22° S for the South Atlantic Central Water level, and c) 28° - 30° S for the Antarctic Intermediate Water.

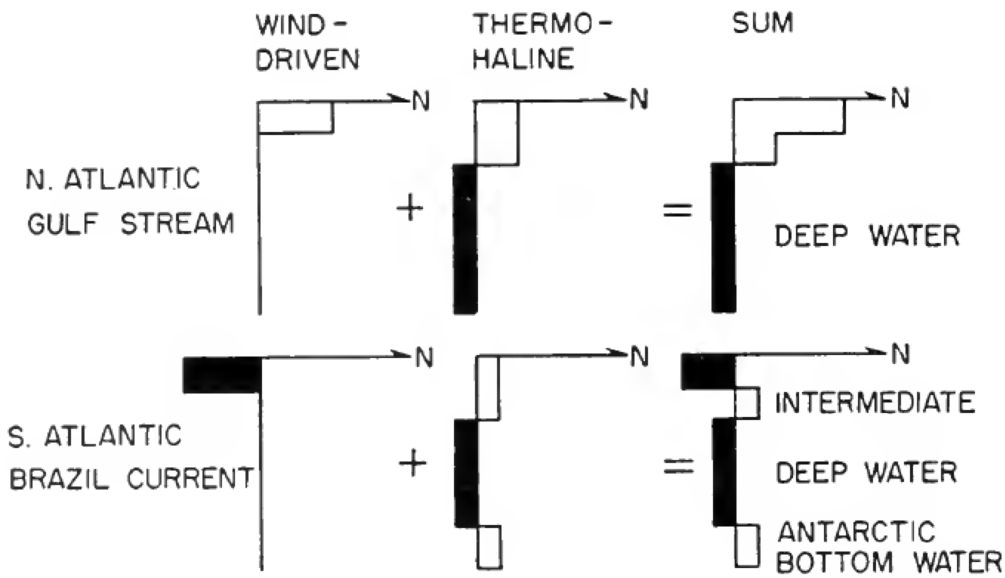

Figure 1: Schematic diagram of the possible explanation of the very different transport-per-unit-depth curves for the Gulf Stream and the Brazil Current. Source: Stommel (1965).

The BC path could be divided into 3 main areas: a) north of 20° S (upper area), b) between 20° and 28° S (middle area), and c) south of 28° S (lower area). The upper area is the less studied area. In general, the BC in the upper area, where the BC is originated, is a shallow flow and presents low volume transport. Topographic features, such as the Vitoria-Trindade Ridge, play important role on the main flow. Because of intense bathymetry changes and alternations on the Brazilian coast orientation, the BC presents zones where eddies formation is frequent and bifurcation, even trifurcation flows are possible to occur. Finally, the lower zone is characterized by the Brazil/Malvinas confluence, where the BC meets the northward flow characterized as Malvinas Current and the flow turns east, generating the South Atlantic Current, the southern branch of the South Atlantic Subtropical Gyre.

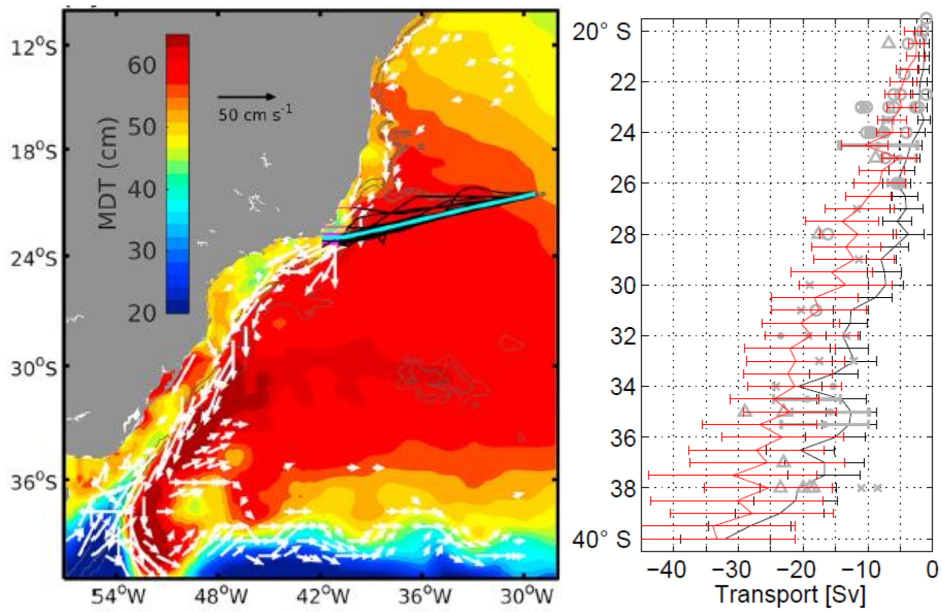

Figure 2: Distribution of Brazil Current. The left panel is a map of mean dynamic topography (MDP) overlaid by the mean climatological surface velocity (cutoff of 7 cm/s). Right panel is a climatological mean of the meridional transports of the BC as a function of latitude from observation (black) and HYCOM (red). The black line with error bars shows the mean from Argo & SSH for a layer thickness of 400 m north of 27° S and 800 m elsewhere. Gray symbols are from previous studies. Sources: Goes et al. (2019) and Schmid & Majumder (2018).

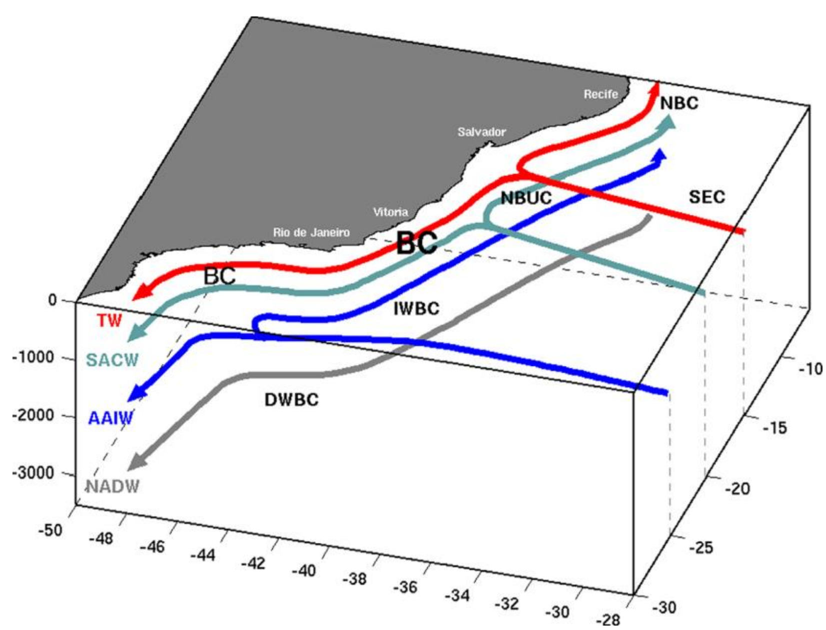

Figure 3: Schematic distribution of water masses that composes the WBC of the coast of Brazil. Source: Soutelino et al. (2013)

The upper portion of the BC is largely influenced by the bifurcation of the SEC. Soutelino *et al*. (2011) studied if the newborn BC in this area is eddy-dominated. The author argued that some anticyclonic (counterclockwise) eddy structures were presented north of 20° S (Figure 4). The authors claim that even though not mentioned in previous studies, these structures were also observed but misinterpreted by the previous studies. Where a southward flow in a zonal section was classified as BC, but a northward flow on east of this poleward flow as not considered. For Soutelino *et al.* (2011), the origin of the BC is dominated by eddy activity. However, the cause of this possible eddy dominated pattern are not analyzed, only speculated as: a) response to topographic constrains; b) geophysical stabilities arose by the opposing flows of BC and North Brazil Undercurrent (NBUC) or c) by a combination of both factors. Few years later, Soutelino *et al.* (2013) addressed this topic and concluded, based on numerical simulations, that the combination of both topographic constrain and vertical shear resulted in anticyclonic eddies. Different experiments were performed in order to identify any other forcing (atmospheric forcing and remote dynamics) capable to explain the BC eddy dominated near the SEC bifurcation but no link between the forcing mechanisms and the BC pattern were found.

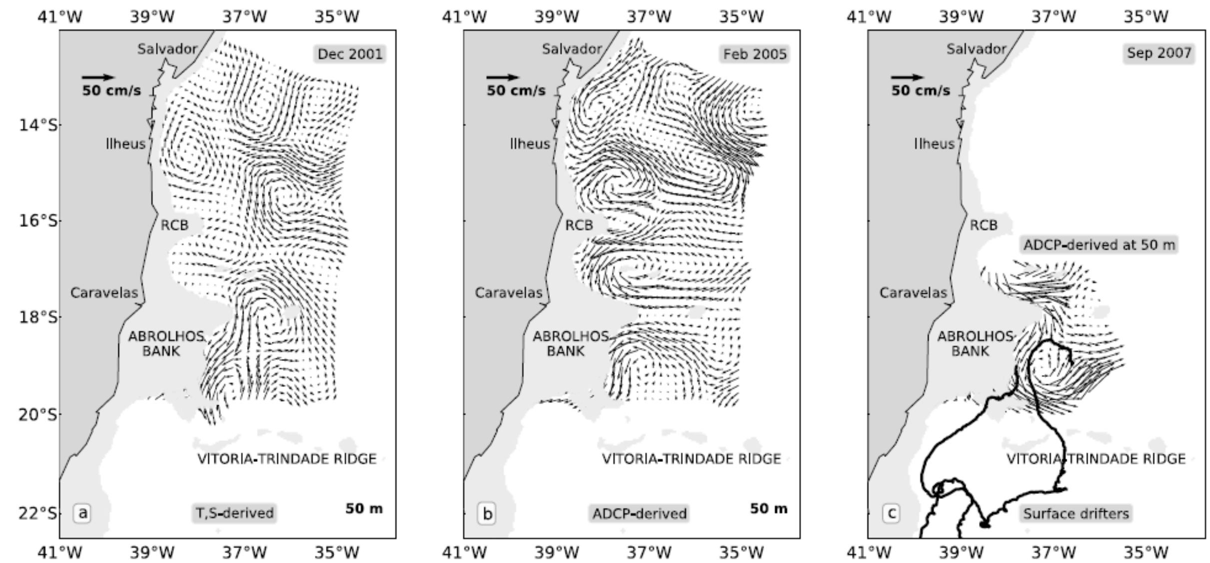

Figure 4: (a) T-S-derived geostrophic velocity calculated from OEI CTD data at 50 m. (b) Observed nondivergent velocities at 50 m calculated from OEII ADCP data. (c) Observed nondivergent velocities at 50 m calculated from PRO-ABROLHOS ADCP data. The black lines represent the PRO-ABROLHOS surface drifters trajectories. Vectors within the continental shelf are masked out. Source: Soutelino et al. (2011).

The middle area of the BC has a strong topographic influence because of the Vitoria Trindade Ridge, a quasi-zonal seamount chain that interacts with the BC and forces the current to bifurcate and even trifurcate sometimes in order to continue its poleward flow (Figure 5). Mata *et al.* (2012), based on XBT based velocity data, addressed the variability of the baroclinic velocity linked to the BC at this area to the migration of the South Atlantic gyre northern high-sea level cell and to the frequent presence of Cape São Tomé vortex, in areas closer to continental boundary. As the BC main flow is weak (4-5 Sv), those forcing mechanisms can severely influence the BC pattern both temporal and spatially. Lima *et al.* (2016) extender the XBT time series and confirmed the findings of Mata *et al.* (2012). In addition, Lima *et al.* (2016) compared the XBT based velocity profile with model outputs and observed that approximately 21% of BC flows along the continental shelf.

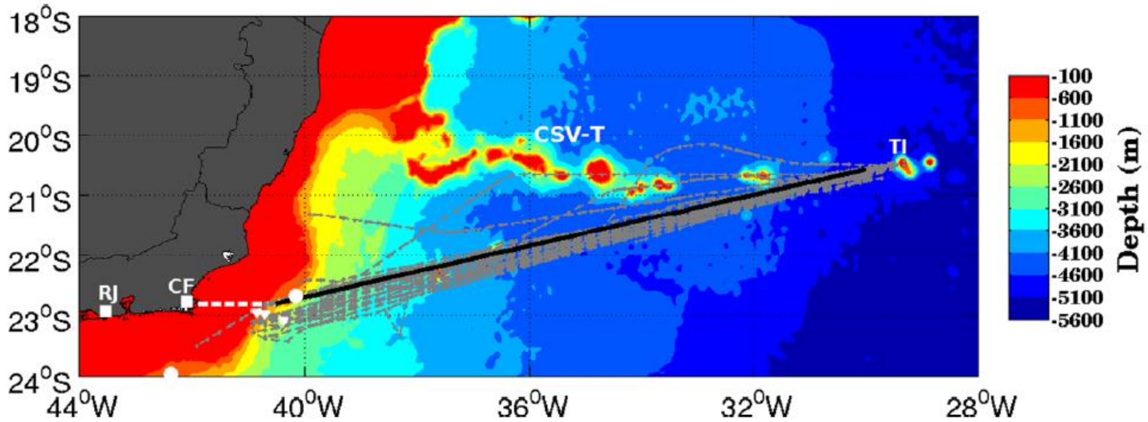

Figure 5: Bathymetry of Vitoria Trindade ridge and surrounding areas. Source: Lima et al. (2016).

In terms of BC volume transport variability in this area, Schmid & Majumder (2018) describes the BC has a relatively complex volume transport pattern and indicated that BC typically reaches its maximum volume transport in the austral summer and lower in the austral winter (Figure 6). The annual cycle presented an amplitude of 0.6 Sv for the Argo& SSH based BC transport, and 0.9 Sv for the modeled transport. In addition, a semiannual cycle can be observed on the anomaly of the transport plot, however, there was not confident level of significance.

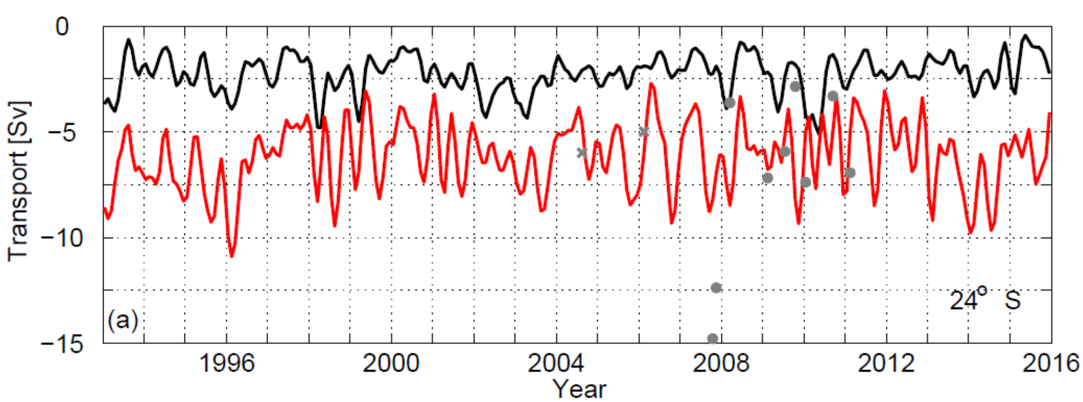

Figure 6: Time series of the meridional transports in the Brazil Current at 24° S from ARGO & SSH (black) and HYCOM (red). The depth range is 0 to 400 m. The time series were smoothed with a second-order Butterworth filter (2 months low pass). Gray symbols indicate previous studies results. Source: Schmid & Majumder (2018).

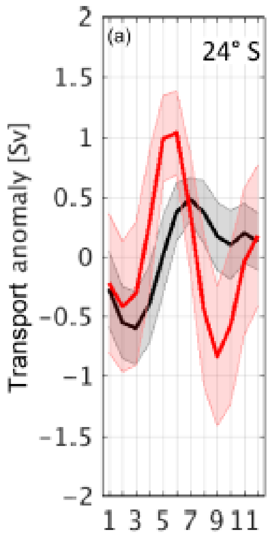

Figure 7: Annual cycle of the anomaly of the meridional transports in the BC derived from the time series of Figure 6 from Argo & SSH (black) and HYCOM (red). Shading indicates standard errors. Source: Schmid & Majumder (2018).

The existence of multi annual influencing periods had arisen from the interpretation of a wavelet power spectrum analysis of the Argo & SSH based BC transport (Figure 7). However, when considering the 5% significance level, only a period between 1997 and 1998 reached the level of significance. The wavelet analysis based on modeled data (not shown) obtained similar results to Figure 6.

In terms of interannual variability, Schmid & Majumder (2018) claimed that BC meridional transport has a cycle of 2 to 4 years (intense and weak periods). Schmid & Majumder (2018) found that BC is correlated to SAM with values of 0.5 (0.4) with lag of 5 (6) months for a 6-month (12-month) filtered time series. For the SASD, it was found values of 0.4 (0.5) with lag of 5 (1) months for a 6-month (12-month) filtered time series and values of 0.4 (0.4) with lag of 8 (8) months for a 6-month (12-month) filtered time series for the Niño 3.4 index. BC transport variability is also linked to atmospheric forcing (sea level pressure).

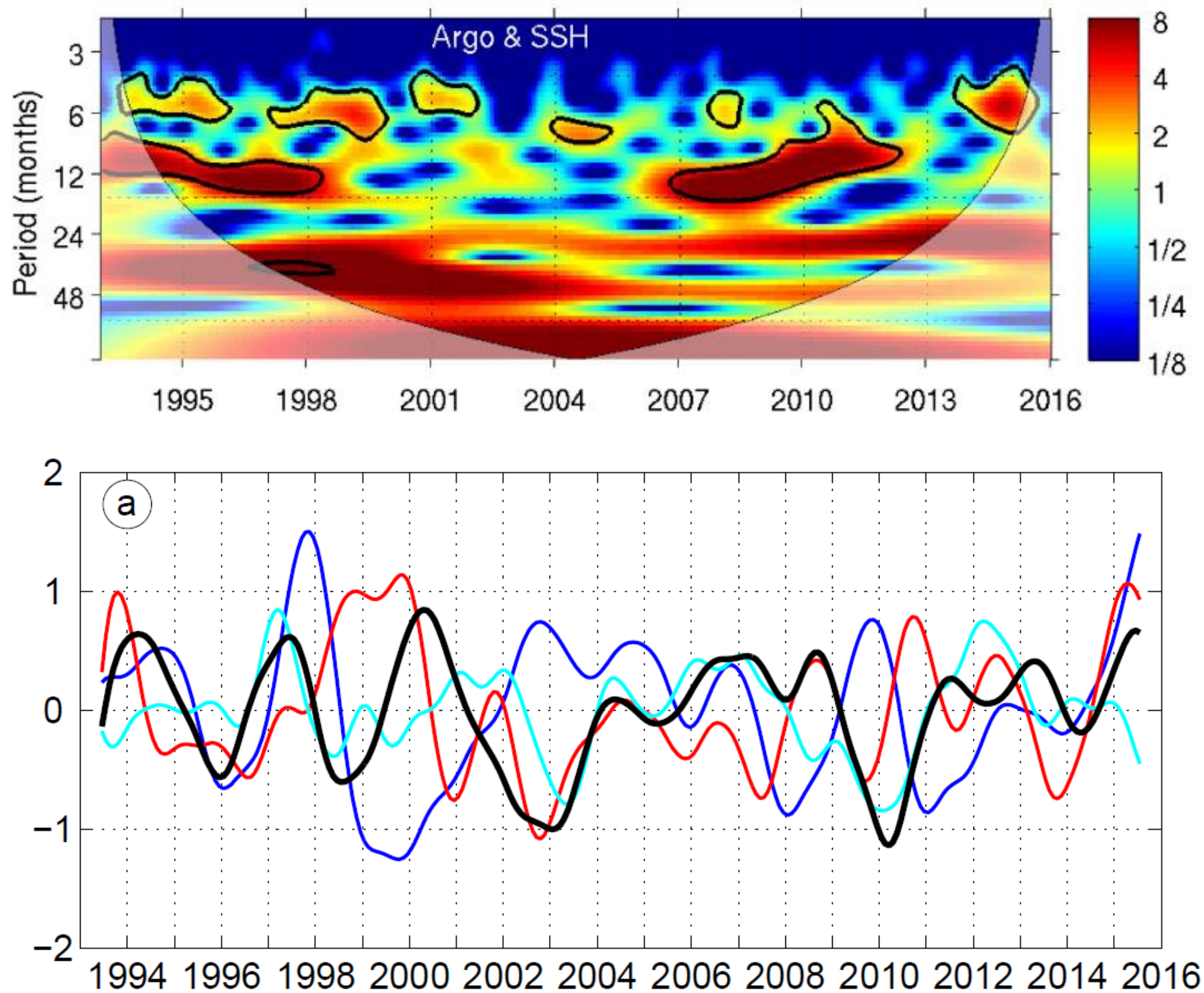

Figure 8: (Upper panel) Wavelet power spectrum at 24° S for the Brazil Current transport from Argo & SSH. The thick black line is the 5% significance level using the red noise model, and the thin black line indicates the cone of influence. (Lower panel) Southern Annular Mode (red), El Niño 3.4 index (blue) and South Atlantic Subtropical Dipole Mode (cyan) in comparison with meridional anomaly transport in the BC (black). Positive (negative) anomalies for the BC transport represents low (high) transports of this current. Source: Schmid & Majumder (2018).

An EOF first mode explains 36% of the variance and describes the effect of tropical pacific on SAM. In addition, the second mode is responsible for 15% of the variance and is related to the ENSO impact on the meridional BC transport. On the other hand, Goes *et al.* (2019) linked the variability of BC with the baroclinic adjustment of the subtropical gyre via Rossby wave mechanisms. It was found a correlation of 0.43 with lag of 19 months between CB transport and large-scale wind stress curl in the Western South Atlantic. Goes *et al.* (2019) also suggested that other mechanisms could influence BC variability, such as Coastal Trapped Waves, bathymetry influence and mesoscale eddies, but no further details about how those processes could influence BC and in which temporal scales would them occur were provided.

The middle area is also where the most intense coastal upwelling process normally occurs considering the entire Brazilian coastline. The coastal upwelling of Cape Frio is influenced by the BC variability. Paloczy *et al.* (2013) stated that the initial stage of BC is as important as the occurrence of upwelling favorable winds. In other words, the meandering of the BC could decrease by a factor of 2 the required wind impulse for coastal upwelling to occur.

The main feature of the lower arear is the frontal zone formed from the meeting of the warm relatively weak BC with the cold and fairly strong Malvinas Current (Figure 8). The Brazil-Malvinas Convergence location considers the variability of both currents. Goes *et al*. (2019) mentioned that a possible trend is that the Brazil-Malvinas Convergence zone could move southward because of a strengthening of the BC and weakening of Malvinas Current. Goni & Wainer. (2001) claim that 75% of the frontal oscillations are explained by semi and annual processes. In addition, the authors state that most of the variability is caused by BC transport variations. The Malvinas Current is only the principal factor when the BC is very weak.

Close to the Brazil-Malvinas Confluence, no correlation between BC transport and the increasing SAM anomaly was observed by Lumpkin & Garzoli (2011). Later on, this was reaffirmed by Schmid & Majumder (2018). Lumpkin & Garzoli (2011) suggested based on the correlation between the position of the Brazil-Malvinas Convergence and sea surface temperature anomalies that an important forcing mechanism of the low frequency variability of the Brazil-Malvinas Convergence comes from the Indian Ocean, the Agulhas leakage. Eddies released by the Agulhas crossed the South Atlantic Ocean and influence the frontal zone position. On the other hand, the author highlights the fact that this conclusion could be misleading, once a positive feedback could be in place. Where positive SST anomalies strength the local winds pattern, leading to maximum curls changing southward and bringing the confluence as well. Then, this process could reinforce the SST anomaly field. Therefore, it is difficult to separate the cause and effect from this feedback. Lumpkin & Garzoli (2011) could not separate them, indeed.

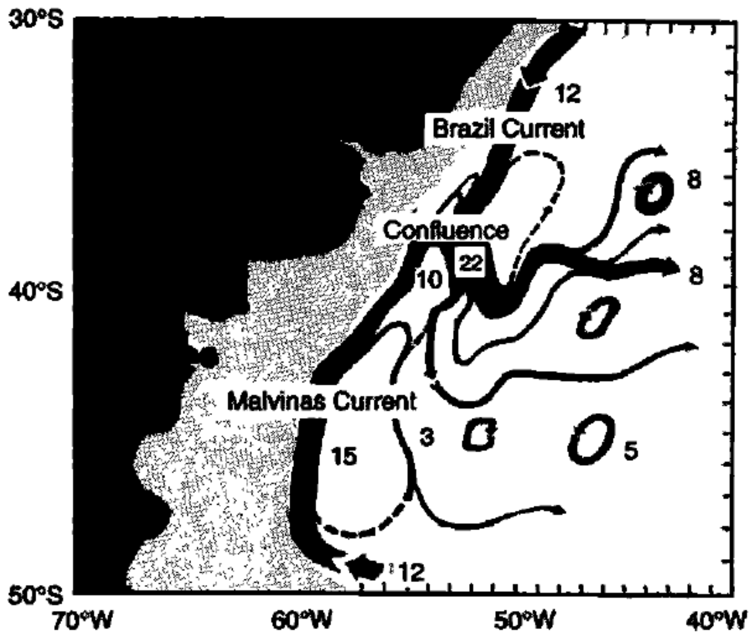

Figure 9: Schematic representation of Brazil-Malvinas Confluence. Numbers represent the transport in Sv. Source: Goni & Wainer *(2001).*

To conclude, this brief literature review brought up some important aspects of the BC distribution along the Brazilian coast. The SEC dynamics rules the uppermost portion of the BC. Quasi-permanent anticyclonic eddies are generated influenced by topographic features and vertical shear near the origin of the BC. Between 20° and 28° S, the Vitoria-Trindade Ridge is the main obstacle along the BC path. In addition, the change on the orientation of the Brazilian coastline is worth mentioning as one of the forcing for enhanced meandering and eddies. In addition, further south the ridge, there are the main upwelling feature of the Brazilian Coast and the BC variability plays an important role on providing positive conditions for the process to occur. In terms of low frequency variability, Goes *et al.* (2018) and Schmid & Majumder (2018) are the main studies in the area. The BC variability could be explained in part by the influence of SAM and ENSO events as well as the correlation with the wind stress curl showed the importance of the baroclinic adjustment on explaining BC low frequency variability. Near the Brazil-Malvinas Confluence, the effect of Brazil current variability dominates over the Malvinas Current. Finally, a positive feedback between SST anomalies and wind stress curl could drive the convergence southward. However, this feedback is hard to break down into consequence/cause effects and more studies should address this topic in order to clarify this issue.

It is possible to state that, due to scarce data, the Brazil Current low frequency influencing mechanisms are yet known, but some recent paper have been published and the trend is that there is more to come. In the near future, with consolidated long-term datasets, more studies will address the BC long period variability and improve the discussion about this complex and yet fairly unknown topic.

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