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Ocean-atmosphere in situ observations at the Brazil-Malvinas Confluence region

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[1] This paper presents a description of marine atmospheric boundary layer (MABL) and oceanic boundary layer (OBL) interactions at the Brazil-Malvinas Confluence. Although this region is known as one of the most energetic zones of the World Ocean, very few studies have addressed the mechanisms of OA interaction there. Based upon novel, direct in situ simultaneous OA observations, our results show that the OBL-MABL exchanges are closely correlated with the sea surface temperature (SST) field. The heat fluxes range from 110 W.m^{-2} over warm waters down to 18 W.m^{-2} over cold waters. Higher heat fluxes and air-sea temperature differences are associated with stronger near-surface winds. This suggests that the MABL is modulated at the synoptic temporal and spatial scale by the strong surface thermal gradients between the (warm) Brazil and the (cold) Malvinas (Falklands) currents. **Citation:** Pezzi, L. P., R. B. Souza, M. S. Dourado, C. A. E. Garcia, M. M. Mata, and M. A. F. Silva-Dias (2005), Ocean-atmosphere in situ observations at the Brazil-Malvinas Confluence region, *Geophys. Res. Lett.*, *32*, L22603, doi:10.1029/2005GL023866.

1. Introduction

[2] Early studies investigating the processes of Ocean-Atmosphere (OA) interactions [*Lindzen and Nigam*, 1987; *Hayes et al.*, 1989; *Wallace et al.*, 1989], emphasized the influence of Sea Surface Temperature (SST) on surface winds over the eastern Equatorial Pacific Ocean. These studies suggested two distinct mechanisms for the OA interaction. One hypothesis [*Lindzen and Nigam*, 1987] attributes surface wind modulations to the variations of the Sea Level Pressure (SLP). Lower (high) pressures would be found over warmer (cooler) waters and, as a consequence, stronger winds would be found where the highest pressure or SST gradients are located. *Wallace et al.* [1989] proposed an alternative hypothesis where the Marine Atmospheric Boundary Layer (MABL) vertical mixing adjusts to oceanic frontal regions. Positive SST anomalies would induce changes of the MABL static stability. In this case, the air buoyancy and turbulence would increase over warmer waters thus reducing the vertical wind shear at the boundary layer, generating stronger winds at the sea surface. An opposite situation would be expected over colder waters.

[3] It has been hypothesized that wind modulation is the most likely mechanism for explaining the impact of SST anomalies on MABL stability [*Hayes et al.*, 1989]. This has been confirmed by recent works of *Chelton et al.* [2001] and *Hashizume et al.* [2002], who used satellite data and in situ radiosonde observations, respectively. Recently, *Xie* [2004] published a comprehensive review study emphasizing the mechanisms of OA interactions at the Equatorial Pacific, Equatorial Atlantic and Southern Ocean.

[4] New studies are now concentrating on regions of the World Ocean where the interaction of oceanic fronts with the atmosphere is as yet not fully understood. One example is the Brazil-Malvinas Confluence (BMC) region in the extra-tropical (Southwestern) Atlantic Ocean. Although the nature of the thermal, sea height and chlorophyll gradients between the (warm, high, oligotrophic) Brazil Current (BC) and the (cold, low, eutrophic) Malvinas Current (MC) at the BMC have been object of study of many authors in the last decades [e.g., *Legeckis and Gordon*, 1982; *Chelton et al.*, 1990; *Garcia et al.*, 2004], they are often only investigated from the oceanographic viewpoint. However, the spatial/temporal variability of the BMC region is also expected to impact the MABL (in a similar manner to OA interactions in other regions of the World Ocean). *Saraiva* [1996] demonstrated that the thermal gradients at the BMC can cause contrasting heat fluxes in the cold air masses which cross the South American continent from the Pacific Ocean towards the Atlantic. The latent heat could play an important role in the cyclogenesis energy budget. Her findings are mostly based upon a regional atmospheric model and reanalysis data, lacking in situ measurements.

[5] In a recent study, *Tokinaga et al.* [2005] described for the first time the effects of SST on the surface winds and MABL near-surface stability at the Brazil-Malvinas Confluence (BMC) region. They also made use of the known strong SST gradients (10°C or more between BC and MC waters at the surface) to demonstrate the applicability of a newly constructed set of high resolution in situ (ships of opportunity) data in combination with satellite data. *Tokinaga et al.* [2005] provided a detailed analysis of the climatological OA patterns of the BMC and showed that in this region a positive correlation occurs between SST and surface wind speed.

[6] The main objective of this paper is to investigate the mechanisms of OA interaction at BMC region based on synoptic data collected simultaneously at both the MABL and the oceanic boundary layer (OBL). We used meteorological and oceanographic data collected on board a Brazilian research vessel crossing the BC/MC front in November 2004 (Figure 1). This was combined with satellite SST and wind

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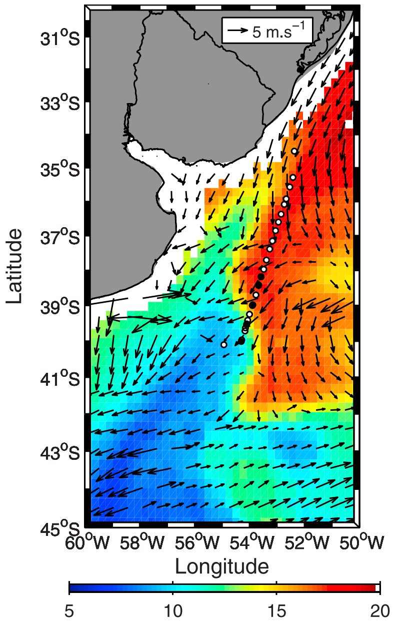

Figure 1. QuikScat wind vectors (m.s^{-1}) of 2 November 2004 superimposed onto an AMSR-E SST image of the same day at the BMC region. The colorbar denotes SST in °C. The XBTs (white circles) and radiosondes (black circles) launching positions are also indicated.

data. Our results are compared to those of *Tokinaga et al.* [2005] and represent the first simultaneous observations of the OBL and MABL taken in this region.

2. Experiment

[7] The Research Vessel (RV) Ary Rongel departs from Brazil for Antarctica every November as part of the Brazilian Antarctic Program (ProAntar). During its transit it crosses the BMC region. In 2004, prior to the vessel's departure, an analysis of the surface thermal gradients between BC and MC waters was made using high resolution AVHRR (Advanced Very High Resolution Radiometer) images. Aiming at deploying air and sea instrumentation exactly in the region of maximum SST gradient, the ship was guided along a straight path crossing the BC/MC front (Figure 1). The measurements were made from 2–3 November 2004. During this period, no large scale synoptic systems, such as atmospheric fronts, extra-tropical storms and associated deep convection cells were present or developing over the study region. According to onboard observations, the sky was partially cloud covered. Using both GOES images and NCEP analysis fields (not shown) we diagnosed that the observed clouds were mainly associated to instabilities produced by the subtropical jet stream and to a weak atmospheric through located at high levels (200 hPa).

[8] XBTs were launched in order to measure the water temperature as a function of depth along the vessel's track. When at the close vicinity of the BC/MC front, 5 Vaisala RS80 radiosondes were also launched to measure pressure, temperature, humidity, wind speed and direction at the frequency of 2 Hz, which guaranteed a fair number of observations within the MABL. From the raw data, the turbulent fluxes of latent heat (Q_e), sensible heat (Q_h) and zonal (τ_x) and meridional (τ_y) wind stress components were calculated following the bulk scheme of *Fairall et al.* [1996].

[9] Cloud cover have not allowed the SST mapping of the BMC region using AVHRR or any other infrared satellite data in early November 2004. Nevertheless, the relatively new microwave-derived SST data from the AMSR-E (Advanced Microwave Scanning Radiometer onboard the Aqua satellite) sensor were fully available for the date of this experiment. This satellite develops a polar orbit which guarantees global coverage. AMSR-E SST images are gridded to a spatial resolution of 25 km. Synoptic wind data were obtained from the QuikScat satellite at 25 km spatial resolution. The satellite data were obtained from the Remote Sensing Systems (RSS, http://www.remss.com).

[10] We also had access to synoptic, ship-borne air temperature (T_{air}), bulk SST (SST_{bulk}) measured at around 1 meter depth and sea surface wind data collected by the RV Ary Rongel's instruments. Atmospheric data were collected above the ship's bridge at about 15 m height. The data is expected to be consistent to QuikScat measurements. The near-surface stability was computed for XBT (SST_{xbt}) minus radiosonde (T_{rsonde}) with 5 stations and $SST_{bulk} - T_{air}$ with 11 stations.

3. OBL and MABL Observations

3.1. Surface Structure

[11] Figure 1 presents the satellite-measured synoptic condition of the SST and near-surface winds in 2 November 2004 at the BMC region. The BC/MC front is clearly seen with wind vectors adjusted to the SST field. Wind speed minima are observed over the cold waters of the MC core. Winds are remarkably stronger away from the MC core in coastal waters and over the BC warm waters. This synoptic pattern of wind modulation agrees with the annual climatology presented by *Tokinaga et al.* [2005] for the BMC region. Ship-borne synoptic measurements of SST_{bulk}, wind speed ($Wind_{ship}$) and air temperature (T_{ship}) are displayed in Figure 2. Figure 2 also includes QuikScat wind speeds measures along the ship's track for comparison. Wind speeds are higher at the north of the BC/MC front (39°S) decreasing towards the southern part of it. Both the ship-borne and satellite data sets corroborate the independent radiosonde and XBT observations. The noticeable bias seen between the wind measured by the radiosondes, ship and satellite can be explained by the temporal mismatch between the measurements and/or by the discrepancies of the height on which the different instruments operate (not corrected here).

[12] The near-surface MABL stability parameters derived from both ship ($SST_{bulk} - T_{ship}$) and sondes ($SST_{xbt} - T_{rsonde}$) measurements are similar (Figure 2). $SST_{bulk} - T_{ship}$ is negative south of the BC/MC front. The MABL is more stable having weaker winds over the MC cold waters. The reverse situation is observed to the north of the front. The $SST_{xbt} - T_{rsonde}$ parameter follows the same tendency, albeit not presenting negative values over the cold waters. These observations seem to support the vertical mixing mechanism described for the BMC region [*Tokinaga et al.*, 2005] and other regions [*Wentz et al.*, 2000; *Thum et al.*, 2002; *Xie*, 2004]. *Tokinaga et al.* [2005] have also shown that the stability parameter presents an interannual variability at the BMC region owing to the changes of the

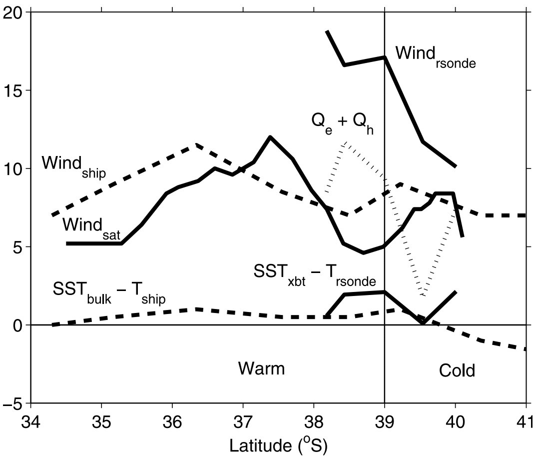

Figure 2. Synoptic, in situ measurements taken along RV Ary Rongel track in November 2004. (Wind$_{ship}$): wind speed measured at the vessel; (Wind$_{rsonde}$): radiosonde wind speed; SST$_{bulk}$ − T$_{ship}$); (SST$_{xbt}$ − T$_{rsonde}$): Stability parameters (°C); ($Q_e + Q_h$): Heat fluxes (10 W.m^{-2}) derived from radiosonde and XBT data. QuikScat wind speeds (Wind$_{sat}$) measured along the ship's route are also included. Wind speed units in m.s^{-1}. The vertical line at 39°S approximately denotes the BC/MC front position.

BMC position. Although working in a synoptic temporal scale and covering a smaller study area, our stability parameter values ranged from −1°C to 2°C in strong agreement with the values presented by *Tokinaga et al.* [2005].

[13] Figure 2 also presents the heat fluxes (positive values for fluxes from the sea surface towards the atmosphere) computed from the radiosonde and XBT data. The maximum value of $Q_e + Q_h$ found at 38.43°S (110 W.m^{-2}) are associated with larger positive values of the OA temperature differences and to higher wind speeds at this location. This is characteristic of regions where the MABL is more unstable and flux exchanges are increased. The minimum value of heat flux (18 W.m^{-2}) is found at 39.5°S. The magnitude of our fluxes are also in close agreement to *Tokinaga et al.* [2005] who found fluxes ranging from 40 W.m^{-2} to 140 W.m^{-2}.

[14] Different to the BMC region climatological pattern presented by *Tokinaga et al.* [2005], the meridional component of our wind stresses (not shown) is more intense over the northern part of the domain where the warm waters are located. Both wind components are weaker over the cold waters, producing a consequent wind stress reduction associated to the OA decoupling under stable profiles. As expected, larger fluxes due to the increase on both SST and wind intensity are found over warm waters. These results are in agreement with previous studies made in other parts of the World Ocean such as those of *Rouault et al.* [2000], *Chelton et al.* [2001], *Hashizume et al.* [2002], and *Pezzi et al.* [2004].

3.2. OBL and MABL Vertical Structure and Interaction

[15] Figure 3 presents the air and ocean temperature (units converted into *K* for comparison) profiles taken simultaneously along the RV Ary Rongel's track by radiosondes and XBTs. The OBL vertical structure shows that the sharp thermal gradients between BC and MC extend from surface to about 500 m depth. At the vicinity of 39°S is the BC/MC front, where surface, sub-Antarctic (MC) waters meet the sub-Tropical (BC) waters to form the South Atlantic Central Water and spreads itself below BC waters towards the north. This last water mass is the one found bellow 500 m in latitudes lower than 39°S in Figure 3. Figure 3 also shows lateral thermal gradients at surface and subsurface of about 0.1°C.km^{-1} and mesoscale structures in close agreement with the literature [*Garzoli and Garraffo*, 1989; *Saraceno et al.*, 2004; *Souza et al.*, 2005].

[16] The upper half of Figure 3 presents the air temperature expressed as the potential virtual temperature (θ_v) with meridional wind vectors superimposed. At the south of 39°S where the BC/MC front is located, the air temperature is lower than at the north of this latitude. Figure 3 suggests that during 2 November 2004 the OA exchanges were closely correlated with the SST field: over cold waters we observe weak winds on a colder atmosphere (stable MABL) and vice-versa. This process has been documented at the synoptic scale for other regions of the World Ocean [*Rouault et al.*, 2000; *Hashizume et al.*, 2002] but not yet for the BMC region. Supposing that the atmosphere at the BMC region is not being affected by the passage of a frontal system or any other factor disrupting its mesoscale pattern (as it was the case in 2 November 2004), one would expect the OA interactions to occur as they do across other ocean fronts. In this case, the coupling mechanism works over warm waters with the static stability of the near-surface atmosphere being reduced and the downward momentum turbulent flux being increased. As a consequence, the surface winds are more intense owing to a vertical wind-shear adjustment. Conversely, over cold waters the atmosphere is expected to display an opposite situation: the wind shear is increased and surface winds decrease. Our results show that this mechanism occurs in the BMC region at the synoptic scale, agreeing with *Tokinaga et al.*'s [2005] climatological study. It is also interesting to notice that the atmosphere responds to the strong BMC SST gradients with a consequent strong thermal vertical gradient as well. This is

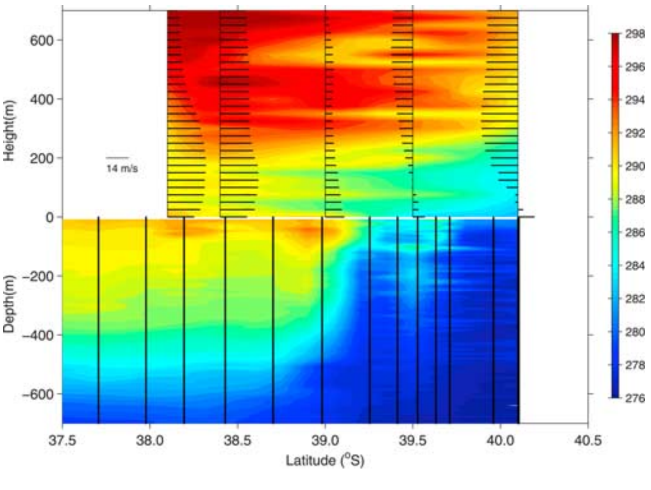

Figure 3. Temperature profiles (*K*) of the atmosphere and ocean taken simultaneously by radiosondes and XBTs along the RV Ary Rongel's route during 1–3 November 2004. Meridional wind vectors (m.s^{-1}) are also displayed.

showed in Figure 3 at the vicinity of 39°S where the stronger vertical thermal gradients of the MABL are present in the 200–300 m height levels.

[17] We finish our analysis commenting about the potential virtual temperature (θ_v), specific humidity (q) and wind components measured by the 5 radiosondes (not shown). The first three sondes show a shallow convective MABL, especially noticed on the northernmost vertical profile. This feature is present on both θ_v and q. Strong thermal gradients are observed between 300–800 m above which a less accentuated increasing of θ_v occurs up to about 1200 m. The humidity is well mixed and a northerly meridional wind (v) maximises in the vicinity of the top of the MABL (h 300 m). The final two radiosondes, over cold waters, display a stable θ_v profile and a significant reduction on q between 200–400 m. The v is predominantly from the south, except on the high levels (>1100 m) and at surface, where a pronounced wind shear occurs. These profiles present a larger static stability, stronger stratification and vertical shear at lower atmospheric levels in comparison to the warmer side of the front.

4. Concluding Remarks

[18] Despite the fact that BMC region is known as one of the most energetic regions of the world ocean, very few studies have addressed the mechanisms of OA interaction in this particular zone of the extra-tropical Atlantic Ocean. Direct measurements of the OBL and MABL in this region are still very sparse. As pointed out by *Saraiva* [1996], the thermal gradients at the BMC can cause contrasting heat fluxes that could play an important role in the cyclogenesis energy budget. The study of the OA interaction processes from in situ and satellite observations can be, in the near future, the basis for a better weather prediction of the region. We believe this paper offers a novel description of both OBL and MABL structures measured simultaneously in situ at the BMC region. With the help of commonly available satellite data, our research indicates that the MABL is modulated by the strong SST gradients present at the study region. Previous studies [see *Xie*, 2004] suggest an explanation for this modulation which is based on the fact that the MABL adjusts itself to the SST modifications. This process has been proposed as an explanation for the OA interactions at other frontal regions. Despite of having based our analysis on a single cruise and on a one day satellite data, we provide evidences that the process described here can explain the modulation of OBL-MABL at the BMC region.

[19] However, it is worth mentioning that the complementary role of the local forcing mechanisms (SSTs) inducing local OBL-MABL interactions and large scale forcing mechanisms (e.g., frontal atmospheric system, extra-tropical cyclones) modulating the OA interaction is still a matter for further investigation. Apart from being very dynamical from the oceanographic viewpoint, the BMC region is situated alongside the storms tracks which bring frontal, transient systems and cold air masses from the Pacific and Austral Oceans to the Atlantic Ocean. The high atmospheric variability of these systems might affect the OA interactions at the BMC region. Continuing efforts for in situ data collection together with the application of a regional numerical model will allow in the future a better understanding OA interaction processes in the BMC region.

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