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Atmospheric Profiles from Radiosonde and Satellite Atmospheric Sounders in the Southwestern Atlantic Ocean[1]

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A B S T R A C T

Among the few tools that can provide consistent and accurate information about remote and inaccessible regions of the Earth is the satellite technology. This technology becomes exceptionally relevant in the characterization of ocean-atmosphere interaction processes in their different spatial and temporal scales. Given the lack of data on the South Atlantic Ocean, this study aims to evaluate the quality of AIRS/AQUA vertical profiles, air temperature, and specific humidity variables, over the Brazil-Malvinas Confluence (BMC) region by comparing them with data collected in situ by atmospheric radiosonde. According to previous studies, the observed and inferred data were previously limited to the MABL (Marine Atmospheric Boundary Layer), where its maximum height was considered or limited to 2000 m through the relationship with the 700 hPa level. The comparison between the atmospheric radiosonde data and the AIRS profiles showed a good agreement between the data on both sides of the BMC capturing them satisfactorily and slightly more accurately over colder waters, with a smaller standard deviation. The results also show that the water vapor concentration directly influences the quality of the AIRS data, where the reason for the better accuracy over colder waters is attributed to the lower concentration of water vapor over the cold region of the BMC Another reason to consider is linked to less atmospheric turbulence on the cold side of the BMC.

Keywords: AIRS/AQUA, Marine Atmospheric Boundary Layer, Brazil-Malvinas confluence.

Perfis Atmosféricos a partir de Radiossondas e Sondadores Atmosféricos por Satélite no Oceano Atlântico Sudoeste

RESUMO

Entre as poucas ferramentas que podem fornecer informações consistentes e precisas sobre regiões remotas e/ou inacessíveis da Terra está a tecnologia por satélites. O uso dessa tecnologia torna-se de extrema relevância na caracterização dos processos de interação oceano-atmosfera em suas diferentes escalas espaciais e temporais. Dada a falta de dados sobre o Oceano Atlântico Sul, este estudo visa avaliar a qualidade dos perfis verticais AIRS/AQUA, das variáveis de temperatura do ar e umidade específica, sobre a região da Confluência Brasil-Malvinas (CBM) comparando-os com dados coletados in situ por radiossondas atmosféricas. Os dados observados e inferidos foram anteriormente limitados à camada limite atmosférica marítima (CLAM), onde sua altura máxima foi considerada ou limitada a 2000 m através da relação com o nível de 700 hPa, conforme estudos anteriores. A comparação entre os dados de radiossondagens atmosféricas e os perfis AIRS mostrou uma boa concordância entre os dados em ambos os lados do CBM, reproduzindo-os satisfatoriamente e ligeiramente mais precisos sobre águas mais frias, apresentando desvio-padrão menor. Os resultados também mostram que a concentração de vapor d'água influi diretamente na qualidade dos dados AIRS onde atribui-se a razão para a melhor acurácia sobre águas mais frias à menor concentração de vapor d'água sobre a região fria da CBM. Outra razão a ser considerada está ligada a uma menor turbulência atmosférica sobre o lado frio da CBM

Palavras-chave: AIRS /AQUA, Camada Limite Atmosférica Marinha, Confluência Brasil-Malvinas.

Introduction

Remote sensing techniques have been extensively used to investigate the ocean and the atmosphere processes over a wide range of temporal and spatial scales since the 1970s. The development and deployment of the atmospheric profilers onboard satellites is important offering a unique opportunity to monitor the Earth System, particularly in remote regions, as oceans and forests, where installing instruments or launching soundings for surface observations is a challenge (Wang *et al*., 2021).

Numerical weather forecasting, which is based on mathematical models, requires a large amount of ocean and atmosphere data, which is difficult to obtain from the conventional method, particularly in the Southern Hemisphere. The satellite measurements may compensate for the absence of data through the atmospheric vertical profiles (Tian *et al*., 2013). The Aqua satellite, in orbit around the Earth, provides a new generation of sensors for monitoring the Earth's water cycle on a daily basis. The various sensors onboard the Aqua satellite platform are able to provide the measurements of the water evaporation in the oceans, water vapor content in the atmosphere, clouds, precipitation, soil moisture, sea ice, continental ice, radiative fluxes, aerosols, phytoplankton, Sea Surface Temperature (SST), air and land surface temperatures (Parkinson, 2003). The vertical profile of temperature and humidity is obtained by the Atmospheric Infrared Sounder (AIRS). The AIRS is the first hyperspectral infrared radiometer designed to support the operational weather forecast in various weather forecasting centers (Aumann *et al*., 2003).

Aumann *et al*. (2003), based on the excellent sensor performance suggested that it is expected more robustness and reliability in the weather forecasting throughout the AIRS data assimilation. Yue *et al*. (2011) used the AIRS to access the marine boundary layer clouds and lower tropospheric stability and compared to CALIOP sensor (Cloud Sat and Cloud-Aerosol Lidar with Orthogonal Polarization) and reanalyzes from the ECMWF (European Center for Medium-Range Weather Forecasts) for the period of July-2006 to July-2007. According to the authors, even with a sampling bias, the AIRS data is capable of representing the marine boundary layer for the vertical profile of temperature and water vapor in regions between 40° S e 40° N.

Dong *et al*. (2010) compared surface air temperature (SAT), SST and surface specific humidity (qo) satellite retrievals from AIRS with shipboard meteorological observation across the Drake Passage for the period from September 2002 to June 2007. According to the authors, the AIRS data provides sufficiently accurate parameters to estimate heat fluxes in the Southern Ocean. The difference between SAT and SST, the surface specific humidity, and the relative humidity is considered the major source of bias when comparing satellite and shipboard measurements. Furthermore, the AIRS data using bulk algorithms represents well the heat fluxes estimated from shipboard (Dong *et al*., 2010).

Pezzi *et al*. (2021), presented a review of the ocean-atmosphere interaction processes in regions of intense thermal gradient in the Southwestern Atlantic Ocean (SWAO). The authors, using observational data showed that the synoptic atmospheric scale plays a fundamental role in the processes of ocean-atmosphere interaction and in the modulation of the Marine Atmospheric Boundary Layer (MABL) in the SWAO, particularly over the region of strong thermal gradients known as the Brazil Malvinas Confluence (BMC). Thus, important aspects of the surface dynamics of this region, as well as the variability, should be better investigated in order to understand the importance of the SWAO in the weather and climate of South America and, especially, of the southern and southeastern regions of Brazil. In this region, transient atmospheric disturbance as frontal systems, cyclones, mesoscale convective systems, and Upper-Tropospheric Cyclonic Vortex, alter the atmospheric circulation and determine the weather conditions, and many of these processes are closely related to oceanic conditions (Pezzi *et al*., 2021).

Given the scarcity of the in situ data in the SWAO and its global relevance, particularly in the BMC, the goal of this study is to assess the quality of AIRS/AQUA in terms of vertical profiles of the air temperature and specific humidity. Here we compare the AIRS data with the in situ data collected by atmospheric radiosonde on board Brazilian Navy Vessel during the Antarctic Operations, under different atmospheric conditions, over the BMC region. We organize the article as follows: in Section 2 we present the study area, the in situ collected data, satellite, and the determination of the MABL. In Section 3, we present a broad overview of our results in terms of comparison of the AIRS and the in situ collected data in the BMC region. The article finishes with conclusions and final remarks in Section 4.

Material and methods

Study area

The study area is located in the SWAO, with focus on the BMC, recognized as one of the most energetic regions in the Global Ocean. The region is characterized by strong horizontal gradients of SST between the coldest waters of sub-Antarctic origin and the warmest waters of tropical origin (Souza *et al*., 2021). According to Pezzi *et al*. (2021), the BMC plays a key role in the modulation of the MABL, as well as in the heat fluxes at the ocean-atmosphere interface.

Figure 1 shows the study area in the SWAO. The in situ data were collected during ten Research cruises, once a year (in austral spring), for consecutive years in the period 2004 to 2015 (except for the years 2010 and 2011). The black line represents the ship's tracks by Brazilian Navy Ships throughout the INTERCONF (Ocean-Atmosphere Interaction over the region of BMC) program. The green dots represent the radiosondes launching positions.

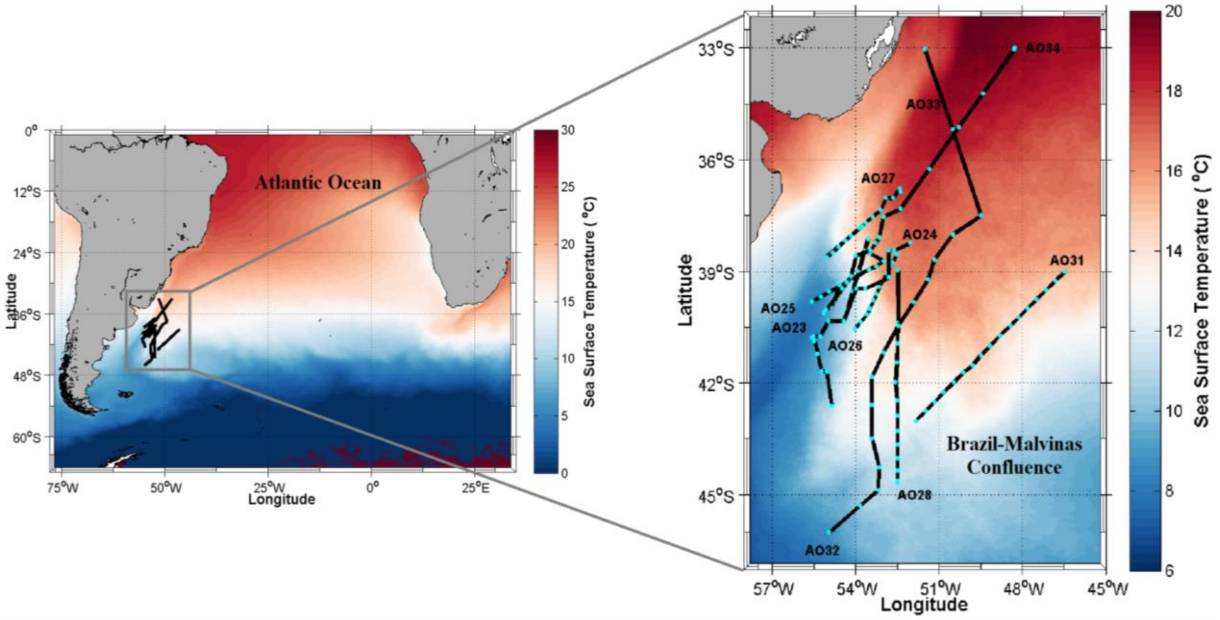

Figure 1 - Study area in the BMC region and the ship's tracks by Brazilian Navy Vessels (black line) in the period of 2004 to 2015 throughout the INTERCONF. The SST (shaded), in °C, represents the October monthly mean (2002-2015) derived from MODIS (Moderate Resolution Imaging Spectroradiometer) Sensor. The acronyms from AO23 TO AO34 (Antarctic Operation 23 to 34) represent the different oceanographic cruises collected in situ data (Table 1). The launch radiosondes' positions are represented by the green dots.

In situ measurements

The atmospheric data (air temperature and humidity) were obtained by using the atmospheric radiosonde. The radiosonde (carried by an atmospheric balloon) transmits the collect in situ data simultaneously to a ground receiver until the balloon reaches approximately 20 km. Figure 2 shows the radiosonde launches under four different atmospheric conditions investigated in this work. To access the MABL top, we used data from the surface to 2 m of height, as the methodology previously reported by (Pezzi *et al*., 2009). The in situ data (Table 1) used in this work are part of the INTERCONF program, under the umbrella of the Brazilian Antarctic Program (PROANTAR).

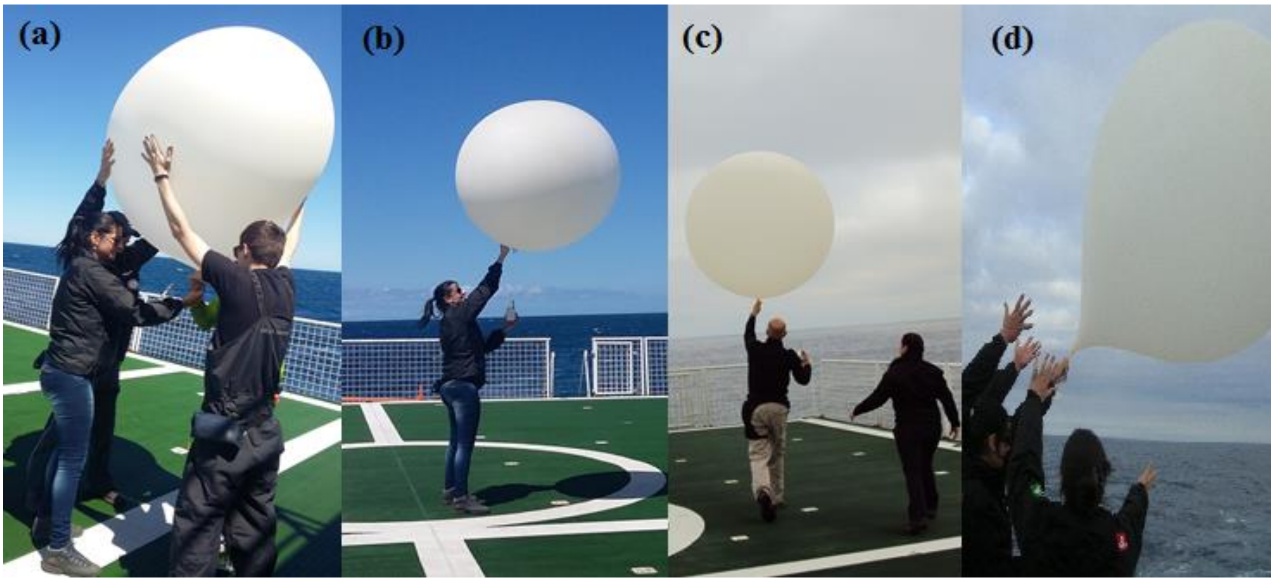

Figure 2 – Radiosondes launched during the Antarctic Operation under four different meteorological conditions. (a) Radiosondes installed/coupled in meteorological ballon (b) launching under high-pressure conditions, clear sky and low wind speed (c) launching under low-pressure conditions, 8/8 clouds and moderate wind speed (d) launching under low-pressure conditions, 7/8 clouds and intense winds. (Source: Author's record)

Table 1 - Localization transects, type, date, and the number of radiosondes launching in the oceanographic stations made by the INTERCONF during the period of 2004-2015 using atmospheric radiosondes (AR).

Antarctic Operation/Year	Data collection date	Lat/Lon start of transect	Lat/Lon end of transect	Type of AR	AR launched
AO23 / 2004	02 – 03/10/2004	38.12°S / 53.55°W	40.01°S / 54.30°W	RS80	5
AO24 / 2005	28 – 29/10/2005	38.54°S / 52.51°W	40.54°S / 54.03°W	RS90	12
AO25 / 2006	27 – 28/10/2006	38.51°S / 53.51°W	39.81°S / 55.57°W	RS90	10
AO26 / 2007	16 – 17/10/2007	39.52°S / 54.50°W	40.11°S / 55.15°W	RS90	5
AO27 / 2008	14 – 16/10/2008	36.85°S / 52.40°W	37.80°S / 53.78°W	RS92	14
AO28 / 2009	02 – 04/11/2009	37.97°S / 52.46°W	44.67°S / 52.50°W	RS92	15
AO31 / 2012	14 – 16/10/2012	39.01°S / 46.50°W	43.01°S / 51.84°W	RS92	17
AO32 / 2013	13 – 18/10/2013	33.04°S / 50.51°W	46.01°S / 54.95°W	RS92	16
AO33 / 2014	18 – 21/10/2014	22.89°S / 43.16°W	42.61°S / 54.86°W	RS92	20
AO34 / 2015	12 – 15/10/2015	33.04°S / 48.5°W	41.21°S / 56.24°W	RS92	16
Total					**130**

Satellite data

The study region was divided into the warm side (Brazil Current) and cold side (Falklands/Malvinas Current) by using a combination of Aqua/MODIS satellite data, Bathythermograph (XBT), and Conductivity Temperature Depth (CTD) probes (Pezzi *et al*., 2009; 2016). The satellite data were obtained on NASA's ocean color website, available at https://oceancolor.gsfc.nasa.gov/cgi/l3. Hereafter the warm/cold side identification by the satellite data, each point in the different sides (warm and cold) was accessed where the atmospheric and oceanographic samples are simultaneous. We found altogether 130 in situ data points, with 62 (68) in the warmer side (colder side) of the BMC region.

The atmospheric profiles from the satellite used in this work are part of the AIRS sounder data set, obtained onboard the Aqua satellite. Additionally to AIRS and MODIS, the Aqua satellite carried the AMSR-E (Advanced Microwave Scanning Radiometer - Earth Observing System), and AMSU-A (Advanced Microwave Sounding Unit-A), CERES (Cloud's and the Earth's Radiant Energy System) and HSB (Humidity Sounder for Brazil). All the instruments onboard the Aqua satellite are passive, designed to receive and measure the radiance from the Earth's surface and atmosphere that reaches to the top of the atmosphere at a given wavelength (Aumann *et al*., 2003).

According to Parkinson, (2003), the Aqua satellite, with polar orbit, crosses the equator twice a day, in an ascending orbit (at 1:30 pm local) and descending (at 1:30 am local). The sensor performs simultaneous measurements in its spectral channels 0.4 e 1.7 µm e 3.74 e 15.4 µm

Estimation of the marine atmospheric boundary layer top

The vertical profiles of virtual potential temperature (θv), relative humidity (RH), and specific humidity (q) taken from the radiosondes, are used to determine the MABL top, as the methodology used by Pezzi *et al*. (2009). This methodology determines the de height of the MABL top (or thickness) by accurately detecting the most pronounced slope of the profiles of these variables with respect to height. Pezzi *et al*. (2016) have successfully used this methodology with complementary data to those used in this work.

The estimation of the MABL height of the top was performed for all radiosonde profiles taken in situ used in this study. An example of applying these methods to determine the MABL height of the top is shown in Figure 3.

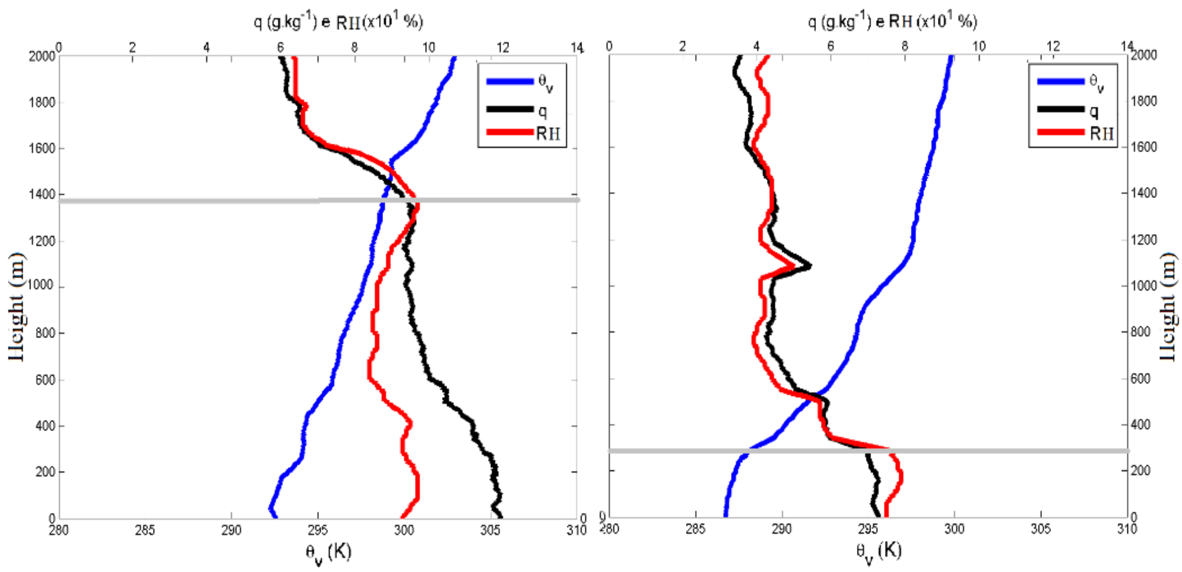

Figure 3 **-** Vertical profiles of θv (K), q (g/kg), and RH (x101 %) were taken by radiosondes during OP32 on the warm side (left) and cold side (right) of the BMC. The gray lines show the MABL height of the top.

Results and discussion

Comparison between observation atmospheric profiles and atmospheric profiles onboard satellites

Considering the lack of the in situ data in the SWAO, the quality of the AIRS vertical profiles of air temperature and specific humidity are investigated in the BMC region. The observed and inferred data were previously limited to the MABL, considering the maximum height of the MABL or 2000 m through related to 700 hPa level, according to previous studies described by Pezzi *et al*. (2009) and Acevedo *et al*. (2010).

According to Fetzer *et al*. (2003), in order to use the AIRS, AMSU, and HSB data with confidence, they must be compared with observations, thus estimating the uncertainties of the measurements. The authors recommend that comparisons should be limited to the troposphere, with an RMSE of no more than 1.0 °C for temperature (in 1 km thickness medium layers) and 10 % for water vapor (in 2 km thickness layers).

The observational data collected by INTERCONF for this study between 2004 and 2015 were compared to AIRS data, according to a criterion that sought the best match between all data in time and space. Grid points from the AIRS vertical atmospheric profile data were selected based on their proximity to the radiosonde grid, time, and satellite passage. The Aqua satellite orbits the BMC in an ascending and descending motion at approximately 17:30 and 04:30 UTC, respectively.

Figure 4 shows the dispersion diagram of air temperature and specific humidity between the data obtained by radiosondes and AIRS sensor in the BMC region. The data used here are related to the warm and cold sides, at pressure levels of 1000, 925, 850, and 700 hPa. We found a linear relationship between observational data reanalysis, as well as the observational and AIRS data. In the air temperature data, greater dispersion is associated with higher temperatures and closer to the surface. Evaluating the dispersion of data on both sides of the BMC, we found, in general, a greater dispersion of data on the warm side, compared to the cold side.

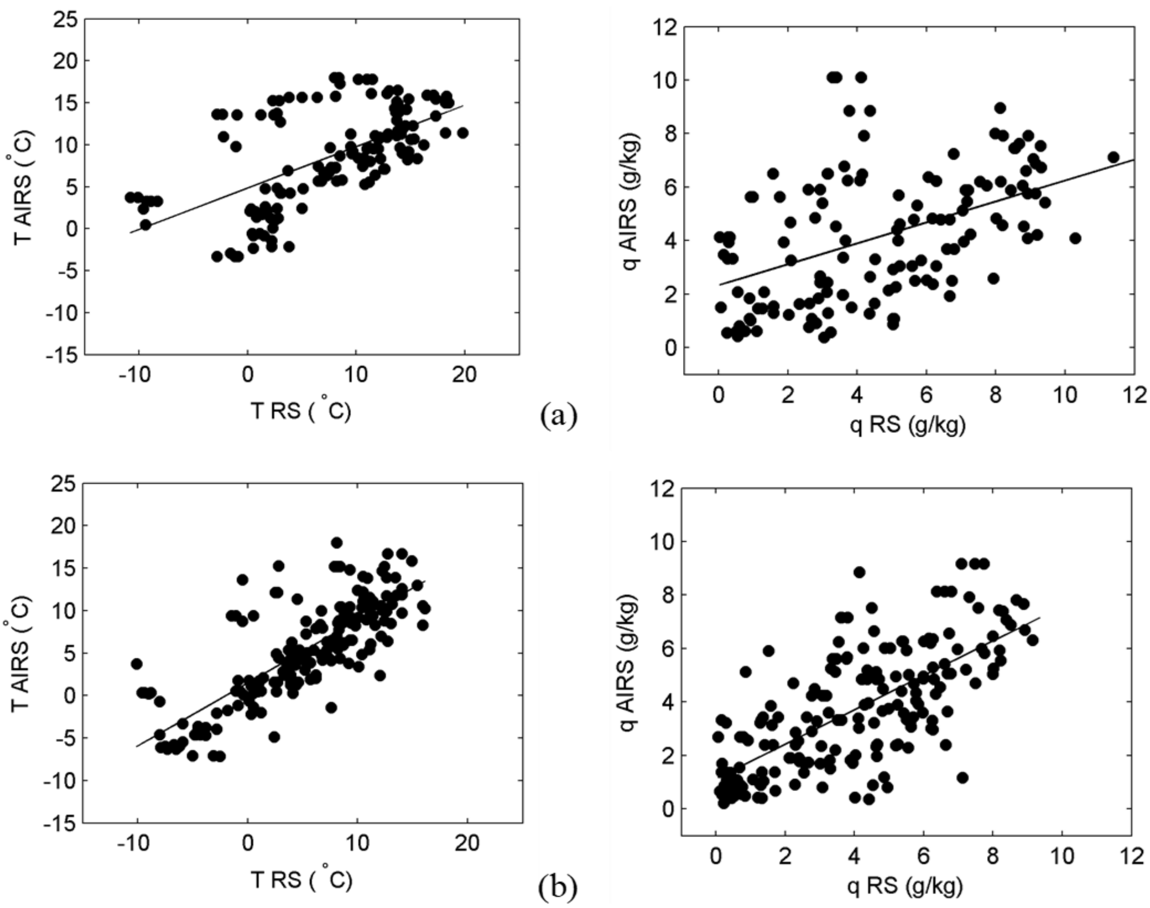

Figure 4 - Dispersion diagram comparing observational and AIRS data, temperature (a), air humidity (b). The upper panels (lower panels) refer to the warm (cold) side of the BMC.

We accessed the correlation between observational data and AIRS by using Pearson's correlation coefficient (Table 2). On the warm side of the ocean front, the correlation coefficient between observational data (radiosonde) and the AIRS/Aqua data was 0.95 and 0.84 for the air temperature and specific humidity, respectively. On the cold side of the ocean front, we found an increase in these coefficients, 0.97 and 0.89 for air temperature and specific humidity, respectively.

Figure 4 shows the linear relationship between observational data and AIRS for both the air temperature and the specific humidity data. The greatest dispersions occur where the temperature is highest, that is, generally at levels closer to the surface. On the warm side (WS) of the BMC, we found a large spread of data related to the cold side (CS). For the specific humidity data, the smallest dispersion is also found over the CS (Table 2).

Table 2 - Pearson's correlation coefficient ($\underline{\rho}$) between observed data and AIRS profilers data and the standard deviation ($\underline{\sigma}$).

	AIRS/Aqua – WS		AIRS/Aqua – CS	
	$\underline{\rho}$	$\underline{\sigma}$	$\underline{\rho}$	$\underline{\sigma}$
air temperature	0,95	0,05	0,97	0,03
specific humidity	0,84	0,07	0,89	0,27

Vertical air temperature profiles

Table 3 and Figure 5 show the air temperature profiles at the levels of 1000, 925, 850, and 700 hPa obtained by radiosondes and AIRS, for both sides of the BMC ocean front. The mean error (bias) and the mean square error (MSE) between the observational data and the other two data sets are also presented. On the warm side of the BMC, in general, the radiosonde data show lower air temperatures at all levels, resulting in positive biases (MSEs) of up to 2 °C (4 °C) along the MABL. On the cold side of the BMC, the air temperature profiles show better accuracy (less bias and MSE).

These data are summarized and compiled in Table 9 and Table 10. The errors found in the temperature profiles are within the desired quality limit of 1 °C for the temperature profile, as suggested by Aumann *et al*. (2003). MSE values also agree with other studies, such as Divakarla *et al*. (2006) who analyzed the difference in MSE for global temperature profiles and showed that satellite profiler data improves under clear sky conditions. Comparisons of satellite sounder data with radiosonde data performed by Fetzer, (2005) show errors on the order of 2 °C.

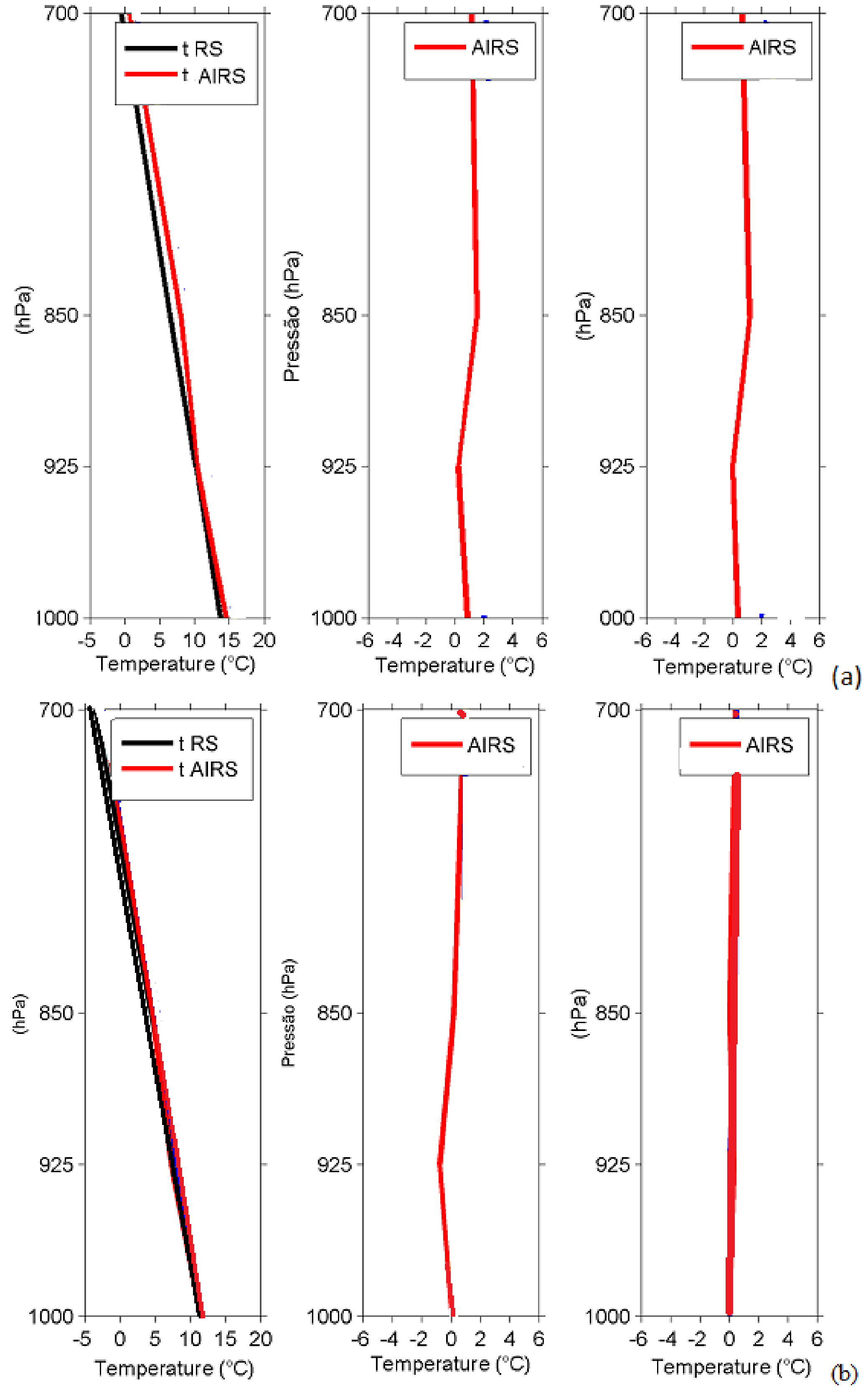

Figura 5 - (left) Mean air temperature profiles obtained by radiosondes (RS), AIRS and CFSR; (center) mean error or bias between radiosondes and CFSR and AIRS;(right) Mean squared error (MSE) between radiosondes and CFSR and AIRS. Upper panels (a) data in the warm side of the CBM and lower panels (b) data in the cold side of the CBM.

Table 3 - Mean, bias, and MSE between the observational profiles of temperature (radiosondes (AR)) and AIRS data for the warm and cold side of the BMC.

	Levels	**AR**	**AIRS**	
		Mean	Bias	MSE
WS	1000	13.77	0.86	0.37
	925	10.25	0.23	0.02
	850	6.50	1.53	1.17
	700	-0.46	0.94	0.67
	Total Mean	7.51	0.94	0.56
CS	1000	11.38	0.05	0.00
	925	8.07	-0.77	0.29
	850	4.44	0.18	0.02
	700	-3.45	0.89	0.40
	Total Mean	5.11	0.09	0.18

Specific humidity vertical profiles

Table 4 and Figure 6 show the specific humidity profiles data, bias and the MSE of the radiosondes and AIRS, obtained at the levels of 1000, 925, 850 and 700 hPa for both sides of the BMC. The specific humidity average at surface levels (1000 hPa) has values close to 8 g/kg and 6 g/kg on the warm and cold sides of the BMC, respectively. Newly, and in agreement with Dong et al. (2010), we suggest that the SST difference between the waters of the Brazil Current and the Malvinas Current directly affects the water vapor concentration in the MABL

In contrast to air temperature, the specific humidity in MABL from AIRS data performs differently when compared to observational data. In general, the AIRS data underestimates the specific humidity in the MABL for both the warm and cold sides. The biases mean and MSE are more accurate on the cold side of the BMC than on the warm side, for both observational and AIRS data comparisons (which underestimates). Average errors of less than 1.19 g/kg are below the 10% accuracy limit for satellite measurements.

One of the most important challenges in obtaining the vertical humidity profiles is the high temporal and spatial variability, which makes it difficult to compare with observational data according to Souza (2006), it is crucial for data validation and assimilating data in climate models. Satellite measurements, on the other hand, appear to have good precision on the BMC, particularly on the cold side.

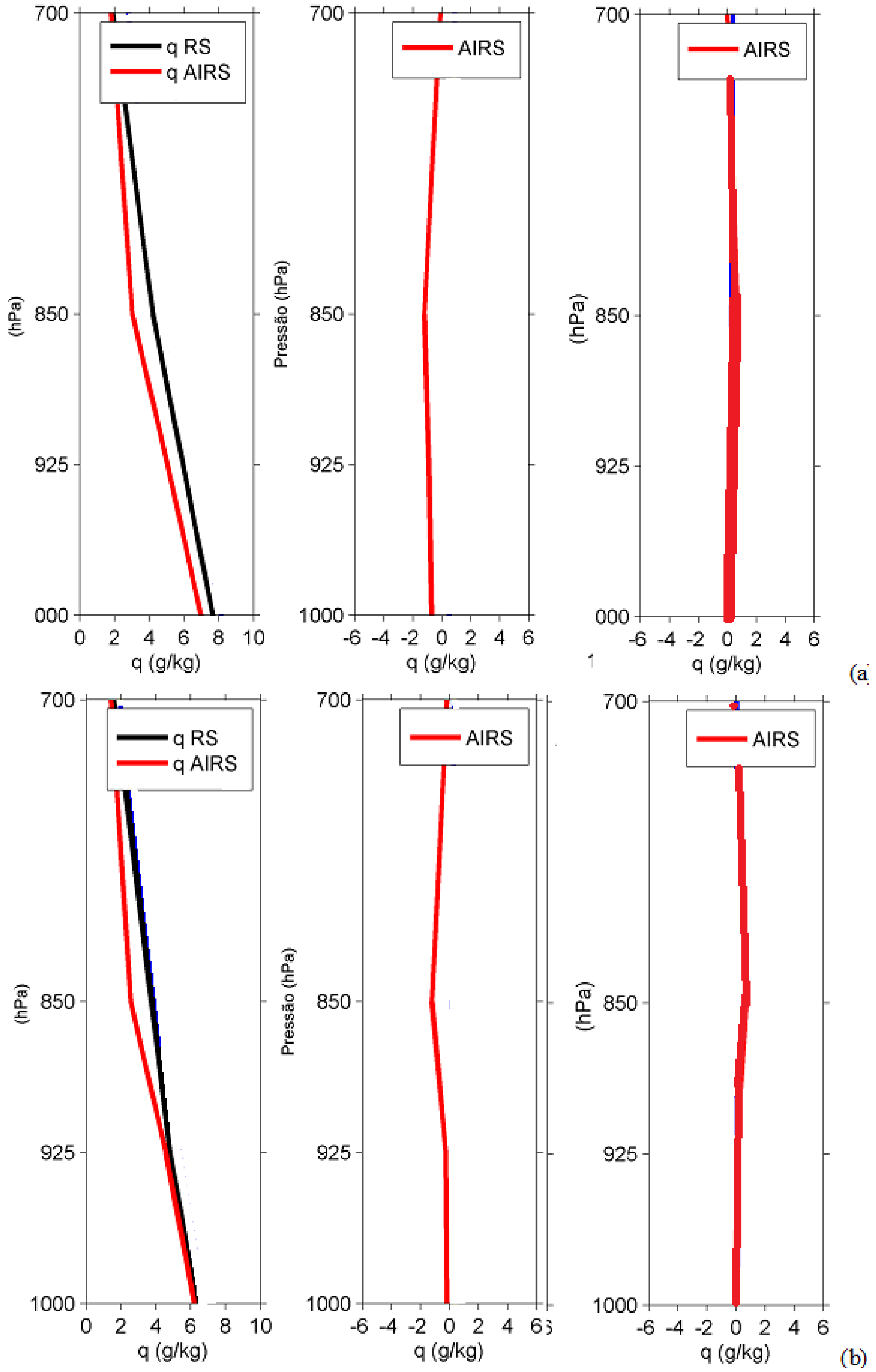

Figura 6 - (left) Mean air specific humidity profiles obtained by radiosondes (RS), AIRS and CFSR; (center) mean error or bias between radiosondes and CFSR and AIRS; (right) Mean squared error (MSE) between radiosondes and CFSR and AIRS. Upper panels (a) data in the warm side of the CBM and lower panels (b) data in the cold side of the CBM

Table 4 - Mean, bias, and MSE between the observational profiles of specific humidity (radiosondes (AR)) and AIRS data for the warm and cold side of the BMC.

	Levels	AR	AIRS	
		Mean	Bias	MSE
WS	1000	7.65	-0.67	0.22
	925	5.93	-0.88	0.38
	850	4.21	-1.19	0.71
	700	1.90	-0.09	0.00
	Total Mean	4.13	-0.71	0.33
CS	1000	6.38	-0.16	0.01
	925	4.81	-0.24	0.02
	850	3.75	-1.19	0.70
	700	1.60	-0.16	0.01
	Total Mean	4.13	-0.44	0.19

Conclusion

The in situ collected data obtained by the INTERCONF Program are essential considering the scarcity of data in remote parts of the Southern Hemisphere. The data provides a powerful tool for investigating the coupled ocean-atmosphere processes in the BMC region, which includes the vertical profiles of the atmosphere using radiosondes and the oceanic properties by using the appropriate equipment, such as CTD and XTBs. Furthermore, evaluating the performance of Aqua/AIRS atmospheric sounding systems is crucial because satellite data can be used as a tool in the absence of data collected in situ.

Here we investigate the quality of the vertical profiles of the air temperature and specific humidity measured by the AIRS and compared to radiosondes in the BMC region. In general, we found a good agreement between the radiosonde data and AIRS/AQUA profiles in both sides of the BMC. The large BIAS in the vertical profile of the air temperature was found at the MABL top. Furthermore, we suggested that the low accuracy also is associated with thermic inversions conditions.

The satellite sounding compared to radiosonde data tends to be slightly more accurate over colder water, with a smaller standard deviation. The water vapor concentration affects the AIRS data quality, so we suggest that the AIRS better performance in cold water is linked to lower vapor concentration values and atmospheric turbulence on the cold side (Pezzi *et al*., 2016; Freitas *et al*., 2019). Additionally, Salisbury (1994) suggests that the lag in times of comparison between observational data and AIRS is a limitation for this type of investigation. According to the author, in some cases, the lag of the time is more than 3.5 hours of difference between the satellite and *in situ* data, interfering with the results.

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