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The Western South Atlantic Sea Surface Temperature and Brazil Current Volume Transport at 30°S: a Study Based on the Brazilian Earth System Model 2.5 Historical Simulations

A Temperatura da Superfície do Mar no Oeste do Atlântico Sul e Transporte de Volume da Corrente do Brasil em 30°S: um Estudo Baseado nas Simulações Históricas do Modelo Brasileiro do Sistema Terrestre 2.5

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Abstract

The analyses of sea surface temperature (SST) in the western portion of the South Atlantic and the integrated volume transport of the Brazil Current (BCVT) at 30°S were conducted using historical results (Jan/1993-Nov/2005) from the Brazilian Earth System Model version 2.5 (BESM-OA2.5) and comparing them with those from the 2M version of the Geophysical Fluid Dynamics Laboratory Earth System Model (GFDL-ESM2M) and the Global Ocean Physics Reanalysis 12V1 (GLORYS12V1). The GHRSST Level 4 AVHRR_OI Global Blended Sea Surface Temperature Analysis (GHRSSTL4) product was used to validate these results. A tendency of overestimation of SST values by the Brazilian model was observed by approximately 1.07°C compared to GHRSSTL4. The BCVT results at 30°S indicated an average value of 10.54±4.68, 6.79±1.40, and 11.99±4.16 Sv for BESM-OA2.5, GFDL-ESM2M, and GLORYS12V1, respectively. For the Brazil-Malvinas Confluence region, the authors found a mean Bias of 3.76 °C with a maximum of 10.38 °C according to BESM-OA2.5 results in relation to GHRSSTL4. Compared to other studies, the BCVT values obtained were lower due to the use of more direct observational data, such as current meters and buoys by other authors. Additionally, the low spatial resolution of the models used may limit the detailed representation of the Brazil Current.

Keywords: BESM-OA2.5; Coupled modeling; Oceanographic analysis

Resumo

As análises da temperatura da superfície do mar (TSM) na porção oeste do Atlântico Sul e do transporte de volume integrado da Corrente do Brasil (TVCB) em 30°S foram conduzidas utilizando resultados históricos (jan/1993-nov/2005) do Modelo Brasileiro do Sistema Terrestre versão 2.5 (BESM-OA2.5) e comparando-os com os da versão 2M do Modelo do Sistema Terrestre do Laboratório de Dinâmica dos Fluidos Geofísicos (GFDL-ESM2M) e da Reanálise de Física Oceânica Global 12V1 (GLORYS12V1). O produto GHRSST Level 4 AVHRR_OI Global Blended Sea Surface Temperature Analysis (GHRSSTL4) foi usado para validar esses resultados. Observou-se uma tendência de superestimação dos valores de TSM pelo modelo brasileiro em aproximadamente 1,07 °C em comparação com o GHRSSTL4. Os resultados de TVCB em 30°S indicaram um valor médio de 10,54±4,68, 6,79±1,40 e 11,99±4,16 Sv para BESM-OA2.5, GFDL-ESM2M e GLORYS12V1, respectivamente. Para a região de Confluência Brasil-Malvinas, os autores encontraram um Bias médio de 3,76 °C com um máximo de 10,38 °C de acordo com os resultados do BESM-OA2.5 em relação ao GHRSSTL4. Comparados a outros estudos, os valores de TVCB obtidos foram menores devido ao uso de dados observacionais mais diretos, como medidores de correntes e boias por outros autores. Além disso, a baixa resolução espacial dos modelos utilizados pode limitar a representação detalhada da Corrente do Brasil.

Palavras-chave: BESM-OA2.5; Modelagem acoplada; Análise oceanográfica

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1 Introduction

The Earth System encompasses various complex interactions, including oceanographic, geological, atmospheric, biological, chemical, and anthropogenic processes. To understand it better, the scientific community developed Earth System Models (ESMs) to simulate these interactions in a laboratory environment, aiming for realistic replication (Flato *et al.* 2013; Hurrell *et al.* 2013). ESMs contribute significantly to society, providing valuable information for forecasting extreme weather events, enhancing early warning systems, aiding resource planning and management, and raising public awareness about climate change (Grundmann & Rödder 2019; Scholze *et al.* 2012).

The Brazilian National Institute for Space Research (INPE) BESM Project is of paramount importance for the scientific advancement of the country, as it places Brazil among the nations engaged in the establishment and enhancement of ESMs and as a member of a coalition of nations that contribute significantly to the Intergovernmental Panel on Climate Change (IPCC) reports on global climate change scenarios (INPE 2015).

Previous studies, such as Nobre *et al.* (2013), Veiga *et al.* (2019) and Broggio, Garcia & Silva (2021), indicated that BESM-OA2.3 and 2.5 versions tends to exhibit a systematic warm bias spread throughout all of the oceans. The authors attributed this bias to the formulation of the model itself in representing the formation processes of stratocumulus clouds over colder water regions, which would affect its radiative balance. While existing literature includes notable studies like these, which provide a comprehensive global evaluation of the model outcomes, there is limited information available regarding the representation of this model in the South Atlantic region, particularly in the Brazil Current (BC) and Brazil-Malvinas Confluence (BMC) area and specially using the version 2.5.

The present article aims to evaluate and quantify that SST bias along the BC and in BMC region, in addition to the BCVT, by comparing BESM-OA2.5 results (from Jan/1993 to Nov/2005) with GHRSSTL4 observational data. To support this, the authors also chose to compare the results of GFDL-ESM2M and the GLORYS12V1 reanalysis with the observational base. Both BESM-OA2.5 and GFDL-ESM2M follow the Coupled Model Intercomparison Project Phase 5 (CMIP5) protocols. Further details of each dataset are described in Chapter 3.

2 Study Area

The research area lies in the western part of the South Atlantic, spanning latitudes 10 to 50°S and longitudes 30 to 70°W (Figure 1). It is primarily influenced by the South Atlantic Subtropical Gyre (SASG) and the South Atlantic Subtropical High (SASH), with the SASG's spatial and temporal variability linked to seasonal and sometimes interannual fluctuations of the SASH (Stramma, Ikeda & Peterson 1990).

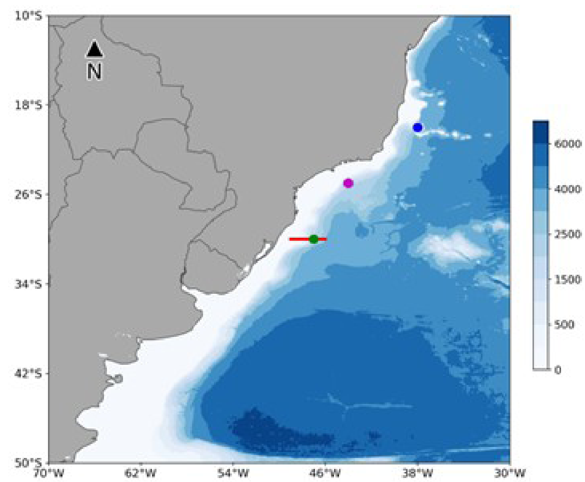

Figure 1. Bathymetry (m) of study area. The red line indicates the cross-section used to estimate the BCVT. The T1, T2 and T3 points used to estimate the SST points are marked in blue, purple and green, respectively.

The BC is the western boundary current in the region, originated from the bifurcation of the South Equatorial Current around 10 to 15°S, flowing southward along the shelf break (Matano, Schlax & Chelton 1993). According to Silveira *et al.* (2000), its water mass field is composed by the stacking of Tropical Water (TW) and South Atlantic Central Water (SACW) with depths ranging from 200, near its formation region, to 800 m further south (Cataldi *et al.* 2010; Evans & Signorini 1985; Peterson & Stramma 1991). As it moves southward, the BCVT increases. By 30°S, the BC reaches depths of 750 to 800 m, as SACW thickness is greater at these latitudes (Evans & Signorini 1985).

As the current moves farther away from the coast, approximately between 33 and 38°S, it intersects with the northward flow of the cold and low-salinity Malvinas Current (MC), causing the BC to deflect eastward, forming the South Atlantic Current (Chelton *et al.* 1990). This convergence of currents is known as the Brazil-Malvinas Confluence (BMC), one of the most energetic regions in the global ocean (Chelton *et al.* 1990; Peterson & Stramma 1991).

A total of three points were selected: one at 20°S, 38°W; the second at 25°S, 44°W; and the third at 30°S, 47°W to assess the SST behavior corresponding to the BC region along the coast during the analyzed period for all the datasets. These points were named: T1, T2 and T3, respectively. Furthermore, a cross-section located at 30°S ranging from 46 to 49°W was selected to evaluate the BCVT.

3 Methodology and Data

The timeframe (Jan/1993 - Nov/2005) was chosen within the overall historical experiment period (1850 - 2005) since GLORYS12V1 data were only accessible starting from January 1993. For the two ESMs, historical simulation data were available until November 2005. These files were obtained from their official websites, in NetCDF format, with monthly mean resolution. GHRSSTL4 data were acquired via the EarthAccess Python Tool with daily resolution, later aggregated to monthly mean. Spatial resolution alignment used BESM-OA2.5 numerical grid as reference for the interpolation process.

The SST analysis consisted on mean surface fields of the entire study area and time series of the three selected coastal points mentioned before. As for the BMC region, the monthly mean differences between the datasets (Bias) were assessed using time series plots. The BCVT was obtained using Equation 1 described in section 3.4 to create representative time series of the cross-section. The ESM results (for BCVT) were validated using GLORYS12V1 results, since the GHRSSTL4 is an SST dataset only. The robustness/reliability of GLORYS12V1, which justify its choice, are detailed in the next sections.

3.1 ESMs Specifications

The oceanic component of the CPTEC/INPE BESM-OA2.5, which employs the Modular Ocean Model version 4p1 (MOM4p1), uses a tripolar grid with a horizontal resolution of 1° in longitude. Between 10°S and 10°N, the resolution decreases uniformly to 0.25°, reaching 1° at 45°N/S, and 2° at 90°N/S. It consists of 50 vertical levels, offering a resolution of approximately 10 m in the upper 220 m, gradually transitioning to around 370 m of resolution at deeper levels. As for the atmospheric component (Brazilian Atmospheric Model – BAM), the dynamic equations are discretized using a spectral transform with a horizontal resolution truncated at a triangular wavenumber 62, equivalent to an approximate grid size of 1.875°. Vertically, it features 28 layers unevenly spaced in the vertical sigma coordinate, with the top level positioned around 2.73 hPa (if considering the surface pressure as 1000 hPa) (Veiga *et al.* 2019).

As for the National Oceanic and Atmospheric Administration (NOAA) GFDL-ESM2M, the horizontal resolution varies from 1° to 0.3344° towards the equator and is tri-polar above 65°N. On the vertical axis, GFDL-ESM2M and BESM-OA2.5 are very similar considering that both models use the same ocean component. In terms of atmosphere, the model has 2° latitude × 2.5° longitude with 24 vertical levels. Both ESMs use the coupling system known as Flexible Modeling System, from NOAA (Dunne *et al*. 2012; Lin 2004).

3.2 GLORYS12V1 Specifications

The GLORYS12V1 product is a reanalysis provided by the Copernicus Marine Environment Monitoring Service (CMEMS), offering global ocean data with eddy-resolving capabilities at a horizontal resolution of 1/12° and 50 vertical levels derived from an Arakawa C Grid. It covers the altimetry period from 1993 onward. Primarily, it relies on the CMEMS operational forecasting system, with the oceanic component based on the NEMO3.1 platform. Surface forcing is derived from European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim and ERA5 reanalysis for recent years. The assimilated observations data are obtained by Reynolds 0.25° AVHRR-only SST, Delayed Time SLA from all altimetric satellites, *in situ* T/S profiles from Copernicus Marine CORAv4.1 database and CERSAT Sea Ice Concentration (CMEMS 2018).

3.3 GHRSSTL4 Specifications

The GHRSSTL4 from NOAA-National Centers for Environmental Information (NOAA-NCEI) has daily temporal resolution with a 0.25° spatial resolution. It uses a combination of Advanced Very High-Resolution Radiometers (AVHRRs) and *in situ* platforms (*i.e.*, ships and buoys). Optimal Interpolation (OI) is used to interpolate and extrapolate the SST observations, resulting in a smoothed complete field. This OI algorithm is called Daily 0,25° Optimum Interpolation SST (OISST) Climate Data Record (CDR) version 2 and it was submitted to the National Climatic Data Center (NCDC) by Banzon & Reynolds (2013).

3.4 Brazil Current Volume Transport Calculation

For BCVT, the Equation 1 was used:

$$BCVT = \int_{-H}^{0} \int_{L_1}^{L_2} V(x,z)dxdz \quad (1)$$

Where -H represents the chosen lower depth limit, with the upper limit determined by the shallowest depth of each dataset. L1 and L2 represent the west and east boundary longitudes. V(x, z) is the meridional velocity function varying in the longitude (x) and depth (z) dimensions. The latitude chosen for calculation was 30°S, so that y dimension is constant, as well as the time dimension (t), assuming that it was performed for each time step. The values of H, L1, and L2 are 800 m, 46°W, and 49°W, respectively. The BCVT is measure in Sv ($10^6 m^3.s^{-1}$).

3.5 Statistical Evaluation

The following set of statistics was employed to evaluate the performance of each dataset in terms of SST and BCVT representation: minimum/maximum values, mean, Standard Deviation (STD), Centered Root Mean Squared Error (CRMSE), Mean Absolute Percentage Error (MAPE), Spearman Rank Correlation Coefficient (CORR) and Bias (Pincus *et al.* 2008). The Equation 2 was used for the calculation of CRMSE:

$$CRMSE = \sqrt{\frac{1}{n}\sum_{t=1}^{n}[(x_t^{obs} - \bar{x}^{obs}) - (x_t^{mod} - \bar{x}^{mod})]^2} \quad (2)$$

Where n is the length of the results, x_t^{obs} are the GHRSSTL4 values at a given time t and $\bar{x}^{obs}$ is the mean value. The same notation applies to the ESMs and GLORYS12V1 results (x^{mod}). The CRMSE instead of the RMSE metric was chosen because it is often used in applications where it is important to compare the performance of different models or simulations on data with different mean values, and where the mean values need to be controlled for. For this study, the SST and BCVT mean values are crucial to drawing conclusions. A lower CRMSE indicates better model performance in reproducing the variability of a determined variable (Guseva *et al.* 2020; Pincus *et al.* 2008)

For the calculation of MAPE, the Equation 3 below was used:

$$MAPE = 100 * \frac{1}{n}\sum_{t=1}^{n} \frac{|x_t^{obs} - x_t^{mod}|}{x_t^{obs}} \quad (3)$$

The MAPE metric can be useful when there is a need to understand the relative size of errors in the predictions. Lower values indicate better performance (Hanke & Reitsch 1995)

To choose the appropriate correlation coefficient, a Shapiro-Wilk Test was applied to verify if the SST and BCVT series followed a normal distribution. The null hypothesis of this test states that the data was drawn from a Normal Distribution. If the p-value is less than α (*i.e.* the Significance Level) which is 5%, the null hypothesis is rejected (Table 1).

Since the majority of p-values are much smaller than the conventional significance level of 5%, the authors rejected the null hypothesis and opted to use the Spearman Rank Correlation Coefficient, a non-parametric coefficient, instead of the Pearson Correlation Coefficient (Benesty *et al.* 2009; Spearman 1987). The Equation 4 was used for Bias calculation:

$$Bias = x_t^{mod} - x_t^{obs} \quad (4)$$

Table 1 Shapiro-Wilk Test results for SST and BCVT obtained by BESM-OA2.5, GFDL-ESM2M, GLORYS12V1 and GHRSSTL4 for each location (T1, T2, T3 and BMC).

p-value	Loc	BESM-OA2.5	GFDL-ESM2M	GLORYS12V1	GHRSSTL4
SST	T1	8.4×10^{-7}	1.3×10^{-5}	1.3×10^{-5}	1.5×10^{-5}
	T2	1.2×10^{-5}	4.3×10^{-5}	3.6×10^{-5}	0.6×10^{-3}
	T3	4.2×10^{-7}	3.9×10^{-6}	0.9×10^{-3}	0.7×10^{-3}
	BMC	7.5×10^{-8}	5.2×10^{-8}	5.4×10^{-7}	1.1×10^{-6}
BCVT	30°S	0.3×10^{-3}	0.6	0.4×10^{-1}	----

4 Results

4.1 Sea Surface Temperature

The SST fields (Figure 2) exhibit a good similarity among the datasets, yet GLORYS12V1 and GHRSSTL4 display thermal intrusions of the BC and MC more distinctly compared to the ESMs. Brazilian model overestimates the average SST of the study area by 1.07 °C taking as reference the GHRSSTL4. The SST Bias fields clarify these differences where the largest differences between the Brazilian model and GHRSSTL4 are concentrated in the BMC region, along the coast of Southern Brazil and in the southeast contour. The maximum Bias exceeded 5 °C at 54.50°W and 37.58°S (Figure 2E), near the center of the BMC region marked by the red rectangle. This positive Bias signal is also evident, albeit reduced (4.30 °C), in the difference field between the two ESMs (Figure 2E). Notably, the Bias between GLORYS12V1 and GHRSSTL4 (Figure 2G) is minimal, indicating a better representativeness, corroborated by the statistics summary presented in Table 2. The BC thermal front, delimited by the 18 °C isotherm, varies from 35 to 42°S and from 45 to 58°W, consistent with findings in scientific literature (Cataldi *et al.* 2010; Evans & Signorini 1985).

The ESMs and GLORYS12V1's performances in representing the SST fields relative to the GHRSSTL4 are presented in Table 2.

The SST time series (Figure 3) indicate that BESM-OA2.5 results are on average higher by 0.56, 0.46, and 1.19 °C than GHRSSTL4, GLORYS12V1, and GFDL-ESM2M's, respectively, at point T1. At point T2, these differences become 0.89, 0.71, and 1.23 °C, and at point T3, the differences obtained were 1.00, 1.02, and 0.71 °C.

Table 3 contains the SST time series performance results in relation to the GHRSSTL4. The statistics indicated a positive Bias in BESM-OA2.5 results. The model at T1 point had the best performance indicated by the lower Bias, bigger CORR values, reduced MAPE and lower CRMSE in relation to the other points. As for GFDL-ESM2M, the T1 and T2 points presented negative Bias. The highest absolute MAPE and Bias were obtained by BESM-OA2.5 at T3, indicating that the results errors have more weight (*i.e.* bigger relative size of the error compared to the reference data).

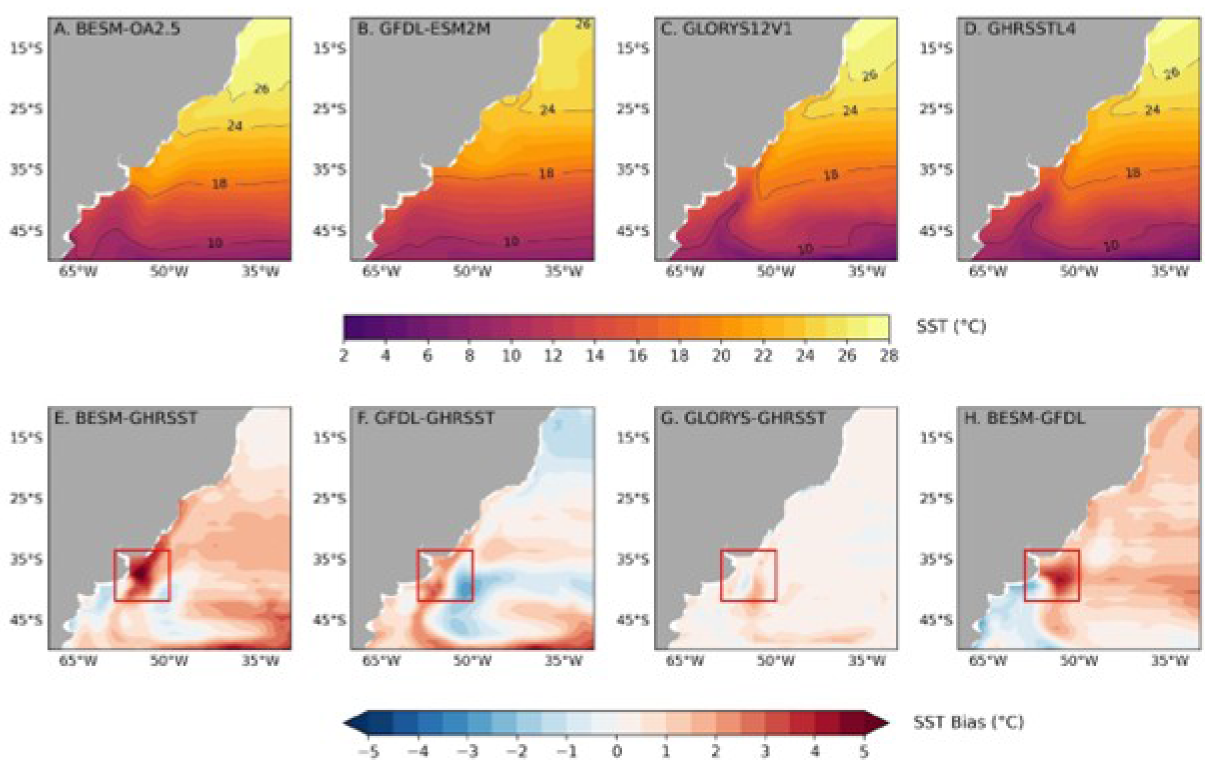

Figure 2. Mean SST fields (°C) of: A. BESM-OA2.5; B. GFDL-ESM2M; C. GLORYS12V1; D. GHRSSTL4. Average SST Bias fields (°C) of: E. BESM-OA2.5 – GHRSSTL4; F. GFDL-ESM2M – GHRSSTL4; G. GLORYS12V1 – GHRSSTL4; H. BESM-OA2.5 – GFDL-ESM2M. The red polygon on the SST Bias fields represents the BMC region.

Table 2 SST mean fields statistical results. The table contains the Mean/STD (°C) values for each dataset, as well as the CRMSE (°C), MAPE (%), CORR and Bias (°C) values considering the GHRSSTL4 mean field as reference.

	Mean	STD	CRMSE	MAPE	CORR	Bias
BESM-OA2.5	19.52	6.69	1.03	10.14	0.993	1.07
GFDL-ESM2M	18.60	6.30	1.48	9.42	0.976	0.16
GLORYS12V1	18.62	6.92	0.36	1.96	0.999	0.17
GHRSSTL4	18.44	7.01	0.00	0.00	1.00	0.00

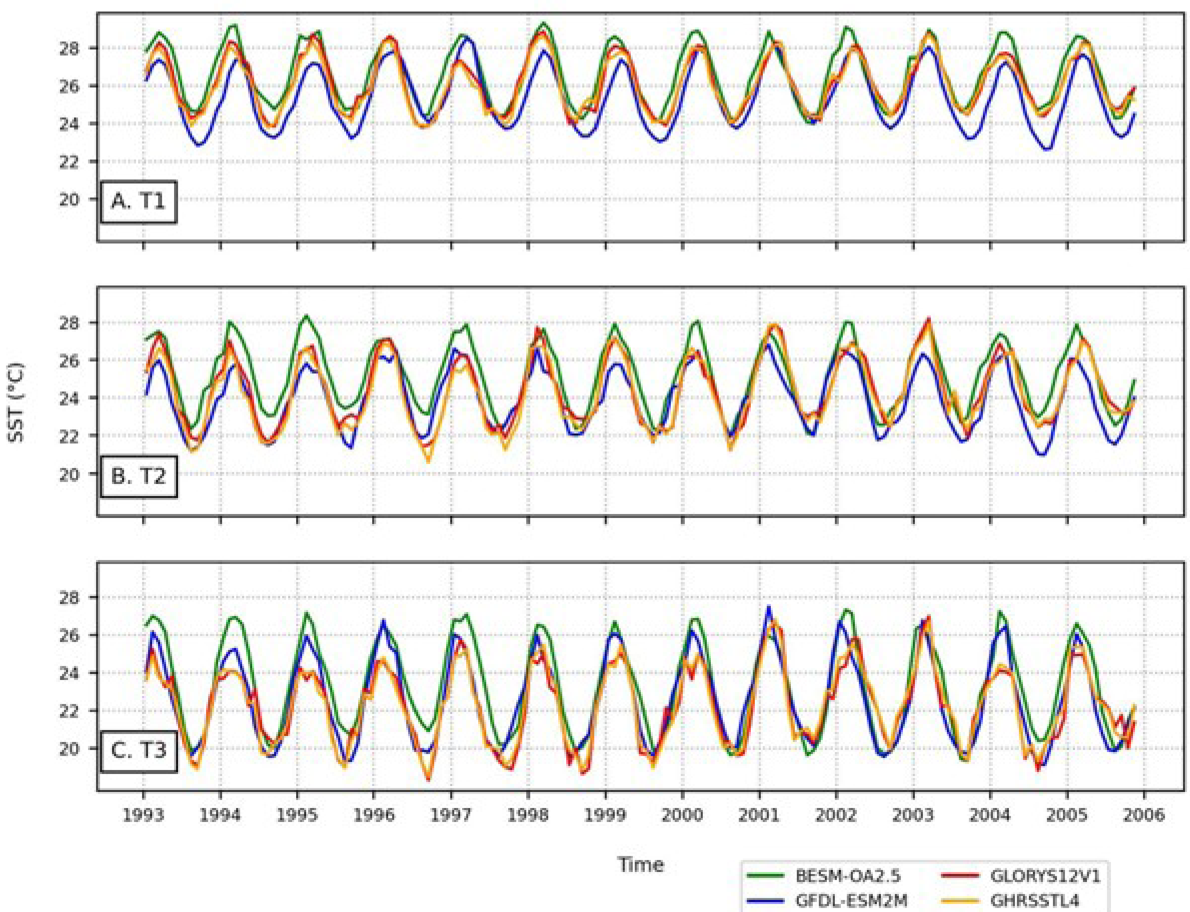

Figure 3. SST (°C) time series of BESM-OA2.5 (green), GFDL-ESM2M (blue), GLORYS12V1 (red) and GHRSSTL4 (orange) from January 1993 to November 2005, for A. T1 location; B. T2 location; C. T3 location.

Table 3 SST time series statistical results. The table contains the Mean/STD (°C) values for each dataset, as well as the CRMSE (°C), MAPE (%), CORR and Bias (°C) values considering the GHRSSTL4 time series as reference.

	Loc	Mean	STD	CRMSE	MAPE	CORR	Bias
BESM-OA2.5	T1	26.58	1.57	0.60	2.56	0.92	0.56
	T2	25.16	1.78	0.86	4.41	0.88	0.90
	T3	23.29	2.44	1.13	5.67	0.89	1.00
GFDL-ESM2M	T1	25.39	1.58	0.75	3.12	0.87	-0.63
	T2	23.93	1.60	0.87	3.06	0.86	-0.34
	T3	22.58	2.27	0.95	3.58	0.91	0.29
GLORYS12V1	T1	26.12	1.45	0.25	0.82	0.98	0.10
	T2	24.45	1.76	0.35	1.25	0.98	0.18
	T3	22.27	2.05	0.41	1.40	0.98	-0.02
GHRSSTL4	T1	26.02	1.38	0.00	0.00	1.00	0.00
	T2	24.27	1.76	0.00	0.00	1.00	0.00
	T3	22.29	2.02	0.00	0.00	1.00	0.00

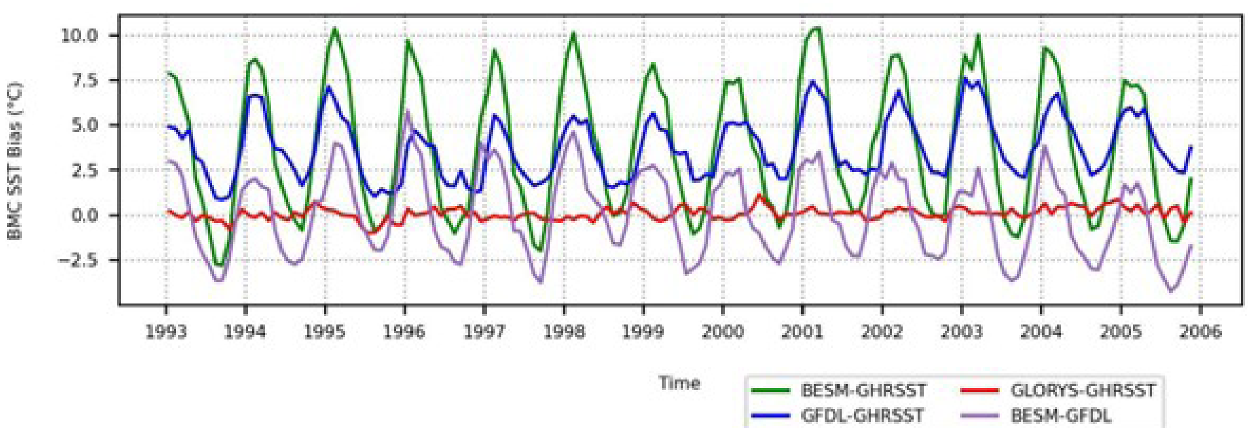

Figure 4. SST Bias (°C) time series for BMC region, considering as reference the GHRSSTL4 results, for BESM-OA2.5 (green), GFDL-ESM2M (blue), GLORYS12V1 (red). The purple series is the Bias between BESM-OA2.5 and GFDL-ESM2M.

Table 4 Statistical results, in °C, of Mean, Minimum/Maximum values and STD for the BESM-OA2.5, GFDL-ESM2M and GLORYS12V1 SST Bias time series shown in Figure 4. The dates of minimum and maximum values are also displayed.

	Min	Datemin	Max	Datemax	Mean	STD
BESM-OA2.5	-2.82	Sep/1993	10.38	Mar/2001	3.76	3.63
GFDL-ESM2M	0.84	Sep/1993	7.61	Jan/2003	3.73	1.70
GLORYS12V1	-1.02	Jul/1995	1.12	Jun/2006	0.05	0.34

The time series of average SST Bias for the BMC region (Figure 4) indeed indicate greater intensity in the differences of the Brazilian model compared to other datasets, using GHRSSTL4 as reference. Table 4 displays the minimum, maximum, mean, and standard deviations obtained for the series using GHRSSTL4 as reference. Note that BESM-OA2.5 shows the largest amplitudes and deviations, while GLORYS12V1 exhibits nearly zero mean bias and reduced standard deviation.

Regarding the bias between the two ESMs represented by the purple series in Figure 4, the minimum, maximum, mean, and standard deviation obtained were -4.26, 5.77, 0.02, and 2.30 °C, respectively. The mean value close to zero, however, does not represent the overall behavior of the series, as significant seasonal variations can be observed.

4.2 Brazil Current Volume Transport

The Figure 5 shows the BCVT results from the three climatic bases over the analyzed period. The minimum and maximum values for BESM-OA2.5 occurred on July, 2000 and February, 1997, respectively. For GFDL-ESM2M, the minimum occurred on June, 1998, and the maximum on February, 1993. Finally, the minimum in GLORYS12V1 results was on March, 1999, and the maximum on December, 2003.

The Table 5 summarizes the statistical results obtained for each ESMs in relation to GLORYS12V1. The results indicate that, compared to BESM-OA2.5, the GFDL-ESM2M tends to have smaller errors in relation to the reference and a slightly higher correlation, although still relatively low to be considered a good result. The Bias obtained by GFDL-ESM2M is significantly larger than the Brazilian model's, which may indicate a certain difficulty of the NOAA model in representing the intensity of BCVT for the latitude of 30°S adequately, as it can be observed in Figure 5.

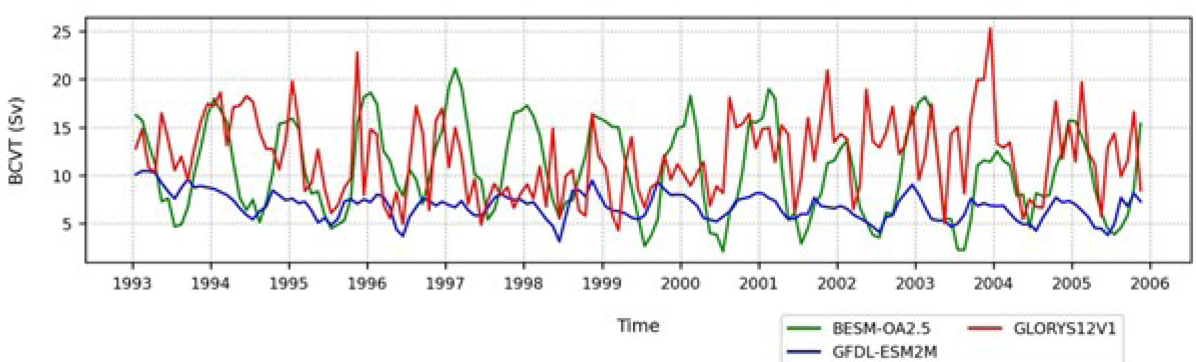

Figure 5. SST Bias (°C) time series for BMC region, considering as reference the GHRSSTL4 results, for BESM-OA2.5 (green), GFDL-ESM2M (blue), GLORYS12V1 (red). The purple series is the Bias between BESM-OA2.5 and GFDL-ESM2M.

Table 5 Statistical results of Mean/STD (Sv), Min/Max (Sv), CRMSE (Sv), MAPE (%), CORR and Bias (Sv) for the BESM-OA2.5, GFDL-ESM2M and GLORYS12V1 BCVT time series shown in Figure 5.

	Mean	Min	Max	STD	CRMSE	MAPE	CORR	Bias
BESM-OA2.5	10.54	2.05	21.11	4.67	5.66	42.97	0.18	-1.45
GFDL-ESM2M	6.79	3.09	10.44	1.40	4.10	39.33	0.21	-5.20
GLORYS12V1	11.99	4.24	25.32	4.16	0.00	0.00	1.00	0.00

5 Discussion

The Bias obtained by BESM-OA2.5 SST results (1.07 °C for the mean surface fields and 0.56, 0.90 and 1.00 °C, for T1, T2 and T3, respectively) suggests a systematic error in the model, as observed in previous studies such as Nobre *et al.* (2013), Veiga *et al.* (2019) and Broggio, Garcia & Silva (2021).

Nobre *et al.* (2013) compared SST results (year 1960 to 2035) from version 2.3 of BESM with the Hadley Centre Coupled Model version 3 (HadCM3) and the Fourth Generation Canadian Coupled Global Climate Model (CanCM4). The authors used an Optimal Interpolation SST (OISST) dataset, a combination of *in-situ* and satellite SST interpolated onto an 18 grid with weekly resolution (Reynolds *et al.* 2002). They identified a warm bias across much of the South Atlantic region, particularly in the BMC region (~3 °C) and the southern and eastern portions of the ocean (~2 °C), with an average bias of 0.9 °C globally.

Veiga *et al.* (2019) compared the BESM-OA2.5 historical SST results (year 1850 to 2005) with the ERSSTv4 dataset and detected a warm SST bias (~1.5 °C) that spread throughout all of the oceans. They noted a lower bias in the western Atlantic compared to the eastern portion, potentially attributed to weaker-than-observed alongshore winds and deficient simulation of stratocumulus clouds over cold waters (Richter 2015).

In the study by Broggio, Garcia & Silva (2021), the historical results of BESM-OA2.5 were compared with five other global climate models and validated against the Ocean Reanalysis System 5 from ECMWF (ORAS5-ECMWF). They found a positive average bias in the South Atlantic basin, pronounced in the BMC region and the eastern portion of the basin, with maximum bias values exceeding 6 °C. The average temperature values for the South Atlantic basin were 19.26 °C, approximately 1.6 °C higher compared to ORAS5. Moreover, the study concluded that BESM-OA2.5 exhibited the largest deviations from the ORAS5 reference base, consistent with the present study results using GHRSSTL4.

All authors attributed this Bias to the formulation of the model itself in representing the formation processes of stratocumulus clouds over colder water regions, which would affect its radiative balance. In contrast, the GFDL-ESM2M model showed a reduction in positive SST bias along the coast and an increase in negative SST bias in offshore oceanic regions compared to GHRSSTL4. GLORYS12V1 results closely resembled the reference data, indicating a robust SST representation.

In terms of robustness and reliability, according to the Quality Information Document of GLORYS12V1 (CMEMS 2018), the reanalysis is designed to closely match observations and align with model physics. Moreover, the document states that global mean SST closely resembles observations with a slight warm bias of less than 0.1 °C throughout the simulation period (from year 1993 to 2022). It also exhibits a linear trend of global SST increase consistent with AVHRR observations. Accuracy estimates for SST for the 1993-2005 period are -0.05 °C (mean) and 0.5 °C (RMSE). Compared to GLORYS2V4 (predecessor version), it assimilates new and improved reprocessed in-situ and satellite datasets.

The BCVT time series and its statistics suggest that GFDL-ESM2M results are more similar to those from GLORYS12V1 than to those from BESM-OA2.5. However, it is worth noting that the GFDL-ESM2M bias is significantly larger than that of BESM-OA2.5. Thus, in statistical terms, GFDL-ESM2M provides a better representation, but in terms of BCVT intensity, the BESM-OA2.5 results are closer to the reference. The maximum BCVT values obtained in BESM-OA2.5 and GLORYS12V1 are significantly higher than those in GFDL-ESM2M; however, the standard deviations are also larger, indicating greater variability.

At 30°S and neighboring latitudes, according to the literature, the values are approximately 7.98 Sv higher than those found in the present study for BESM-OA2.5, 5.6 Sv higher than the GLORYS12V1 results, and 10.76 Sv higher than the GFDL-ESM2M results (Table 6).

Table 6 Summary of previous estimates of BCVT (Sv) ranging from 28 to 33ºS according to multiple works which used both observational data and model results.

Authors	Latitude	Data type	BCVT
Müller *et al.* (1998)	28	Current meter	16.00
Rocha *et al.* (2014)	28	Hydrography	10.20
Rodrigues *et al.* (2010)	30	GEM	20.90
Carvalho, Oliveira & Campos (2018)	30	HYCOM	18.47
Garfield (1990)	31	Pegasus profilers	18.00

Table 6 Cont.

Authors	Latitude	Data type	BCVT
Stramma (1989)	32	Hydrography	19.20
Pontes, Gupta & Taschetto (2016)	33	Climate models	20.10
Present study	30	BESM-OA2.5 GFDL-ESM2M GLORYS12V1	10.54 (±4.68) 6.79 (±1.40) 11.99 (±4.16)

The discrepancies observed in BCVT values between observational data and model simulations could be attributed to several factors. Firstly, authors primarily relying on observational data such as current meters, profilers, and buoys may have provided more realistic estimates. Additionally, the spatial resolution of the ESMs used might not be sufficiently high to accurately capture the dynamic processes of the BC. Moreover, the physics of the models themselves, along with initial conditions and boundary and atmospheric forcing, may not be fully calibrated to accurately represent BCVT (Beniston, Diaz & Bradley 1997). The results reported by Rocha *et al.* (2014), derived from observational data, are closer to the present results because they based their calculation of BCVT on the limit defined by the isotach of -0.05 $m.s^{-1}$, the smallest contour value obtained in their study's cross-section.

The GLORYS12V1 results are closer with literature-reported values, benefiting from significantly higher spatial resolution than the two ESMs in question. Although not the primary focus, the maximum BCVT value in BESM-OA2.5 results, occurring on February 16, 1997, might be related to the El Niño Southern Oscillation (ENSO) during the same period (Assad 2006; Azeredo 2017; Toste, Landau & Assad 2018; Venegas, Mysak & Straub 1997). According to Wolter & Timlin (1993), the monthly Multivariate ENSO Index shows a considerable increase between 1997 and 1999.

6 Conclusions

In summary, this comparative study provided valuable insights into the representation of SST and BCVT for the investigated regions. GLORYS12V1 exhibited superior performance in capturing the thermal features of the BMC and BC, while BESM-OA2.5 showed a notable positive bias compared to observational data, indicating a systematic error in the model. Generally, the ESMs demonstrated satisfactory agreement with reanalysis data. BESM-OA2.5 tended to overestimate SST values across the study area, particularly in the BMC region, with anomalies surpassing 5°C. Spatially, BESM-OA2.5 outperformed GFDL-ESM2M in representing oceanic SST conditions, although GLORYS12V1 emerged as the most accurate dataset, as expected from a reanalysis.

Regarding the BCVT results, it was observed that the average values obtained are relatively lower than those reported in existing literature. This discrepancy is likely due to the limited resolution of the models in accurately representing the dynamics of boundary currents, as well as the initialization, boundary conditions, and other forcings used in these models. Additionally, the physics embedded within each ESM may not be finely tuned to replicate BCVT accurately.

The Brazilian model exhibited superior performance compared to GFDL-ESM2M in representing BCVT, as indicated by statistical analyses. However, it is important to highlight that BESM-AO2.5 demonstrated consistent patterns of overestimating SST values both spatially and temporally. This suggests the need for further investigation and refinement of the model in future interactions to address these discrepancies.

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Leonardo Salles Köhler: conceptualization; data curation; formal analysis; investigation; methodology; resources; software; validation; visualization; writing – original draft; writing – review & editing. **Luiz Paulo de Freitas Assad:** conceptualization; funding acquisition; methodology; project administration; resources; supervision; writing – review & editing. **Alexandre Macedo Fernandes:** conceptualization; methodology; writing – review & editing.

Conflict of interest
The authors declare that they had no financial or non-financial potential conflicts of interest that could influence the objectivity, integrity, or impartiality of the scientific work they have conducted. The research described in "The Western South Atlantic Sea Surface Temperature and Brazil Current Volume Transport at 30°S: A Study Based on the Brazilian Earth System Model 2.5 Historical Simulations" has been conducted in accordance with the highest ethical standards, guidelines and regulations. Appropriate permissions and approvals were obtained for any data collection or experimentation.

Data availability statement
The original historical results of the BESM-OA2.5 model simulations can be found on the website: http://ftp.cptec.inpe.br/pesquisa/oceanmc/CMIP5/output/INPE/BESM-OA2-5/. As for the GFDL-ESM2M results, they were obtained from the website: https://esgf-node.llnl.gov/search/cmip5/. The GLORYS12V1 and ERA-Interim reanalysis results were obtained from https://doi.org/10.48670/moi-00021 and https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-interim
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