DEVELOPMENT OF A MULTIGRID OPERATIONAL FORECAST SYSTEM FOR THE OCEANIC REGION OFF RIO DE JANEIRO STATE

1) INTRODUCTION

The development of an operational ocean forecast system and its important role for human activities, including search and rescue at sea, oil spill modelling, and plankton transport, have been described in a variety of studies, as in Breivik *et al*. (2013), Strand *et al*. (2017), and Röhrs *et al*. (2018a). Robust systems are successfully implemented for oceanic and coastal regions of the United States, Europe, Australia, Japan, and China. In Brazil, most operational efforts were executed associated with a research and development consortium called Oceanographic Modelling and Observation Network (with the Portuguese acronym REMO) (Marta-Almeida *et al*., 2011). REMO currently delivers for the oceanic region off Brazil hindcast with Data Assimilation (DA) and forecast products with HYCOM in the resolutions of 1/4°, 1/12°, and 1/24°.

So far, Brazil still lacks an operational forecast system covering regional and shelf regions, as the ones implemented for California (<https://www.cencoos.org/observations/models-forecasts/>, Moore *et al.,* 2013), Delaware Bay (<https://tidesandcurrents.noaa.gov/ofs/dbofs/dbofs.html>), New Jersey and New York shelf (<http://www.myroms.org/espresso/>), the Mediterranean (<https://www.socib.es/?seccion=modelling&facility=forecast>, SOCIB; Tintoré *et al.* 2013), among others. In common, all these systems employ the ROMS model nested, in the outermost grid for multigrid systems, in a global circulation model. In this context, following the best practices in the ocean forecast field, we propose the development of a multigrid high-resolution operational ocean forecast system off Rio de Janeiro State (RJ), as part of a bigger project to be extended for other Brazilian regions. The coastal and oceanic region off RJ is paramount for Brazil’s economy, as it boasts major port structures and oil/gas reserves. This project aims at reproducing both the submesoscale and mesoscale components of the ocean circulation, which are known to play a crucial role in this region due to its strong interaction with the large-scale circulation.

The system is composed by three nested ROMS domains (Fig. 1) with resolutions 1/12°, 1/36°, and 1/72°, using Mercator to force the lateral open boundaries of the outermost grid, and GFS to force the surface open boundary of all grids. Tides are not being resolved. Two schemes were built for the operational forecast workflow, with and without the DA method 4D-var (Moore *et al*., 2011), in order to account for limited computational resources, as most DA schemes requires a cluster or cloud computing.

The routines for interpolation of input data, grid configuration, ingestion of oceanic and atmospheric data, the workflow of the forecast system, and the observation file for DA were written with open source languages, including Python, Shell Script, GrADS, and Octave. They are freely available for the scientific community through the following Github page ….

A quantitative comparison of the model results with observations is necessary to evaluate the performance of the routines. To this end, were performed hindcast simulations using in the open boundaries data from Mercator reanalysis and Era5, with the results compared against U and V velocity components from the Brazilian National Buoy Programme (with the Portuguese acronym PNBOIA), Sea Surface Temperature (SST) from Ultra-high Resolution Sea Surface Temperature (TSM-MUR), and Sea Surface Height (SSH) from Aviso. Different domains were established to test the modelled velocity field along three regions of the Brazilian coast, off Vitória (Latitude), Cabo Frio (Latitude), and Florianópolis (Latitude), encompassing different regimes of the Brazil Current system.

This paper describes the operational forecast system and presents a validation for the implemented codes. The paper is organized as follows. The description of the validation set-up and the development of the forecast system are presented in section 2. The results of the validation are presented and discussed in section 3. In this section we also present results from the forecast system. Conclusions and future developments are given in section 4.

2) MATERIAL AND METHODS

2.1) The Ocean Model

The numerical model implemented in the operational system was the Regional Ocean Modeling System (ROMS), a free-surface, terrain-following, primitive equation ocean model, which is advantageous for regional applications (Shchepetkin and McWilliams 2005; Haidvogel et al. 2008). The ROMS prognostic variables are potential temperature (), salinity (), horizontal velocity (,), and sea surface displacement (). When the primitive equations are discretized and arranged in a ROMS grid, the individual grid point values at the time ti define the components of a state vector , where superscript denotes the vector transpose. The state vector is propagated forward in time through the discretized nonlinear ocean model and is subject to surface boundary conditions (denoted ), for momentum, heat and freshwater fluxes, and lateral open boundary conditions (denoted ). A complete description of ROMS and the extensive set of numerical algorithms available can be found in Shchepetkin and McWilliams (2005). **(copiei de fragoso et al 2016)**

This model was chosen due to its advanced and robust rapidly evolving community-code model, being employed in a great number of forecast systems, as can be found in Powell *et a*l., (2009), Röhrs *et. al.* (2018), Mourre *et al.* (2018), and Hirose *et al.* (2019).

2.2) OPERATIONAL MODELLING SET-UP AND EVALUATION

A system composed by three nested grids was established with the innermost grid centered in the Rio de Janeiro state (Fig ds). The outermost grid is initialized and forced at the lateral open boundaries by the global model results of the Mercator analysis (Global Ocean 1/12° Physics Analysis and Forecast updated daily), and at the surface from results of NCEP-GFS (3-hourly average Global Forecast System at a base horizontal resolution of 28 kilometers).

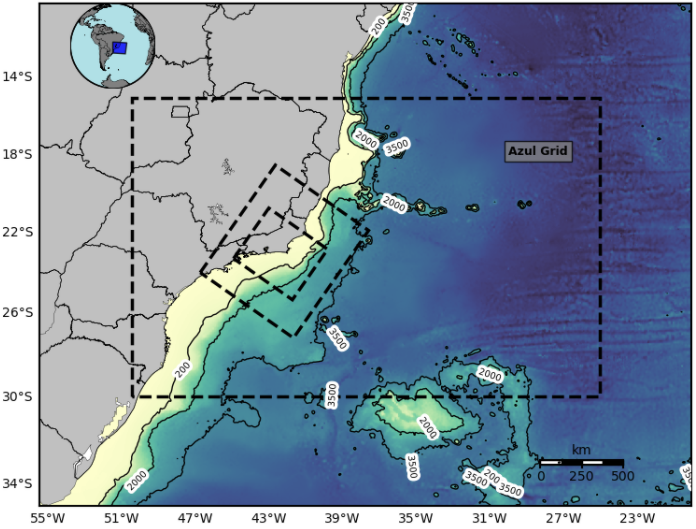


Fig ds:

For the outermost grid we used the Azul grid from Fragoso *et al.* (2016), as it was successfully applied to a regional ocean observing system in the southeastern Brazilian coast with the strong constraint 4D-variational (I4D-Var) data assimilation (DA, Moore *et al*., 2011). This grid covers the domain from 49° W to 30° W and from 15° S to 30° with a horizontal grid resolution of 1/12° and 40 vertical levels. The numerical grid presents 306 × 181 grid cells with three open boundaries in the model domain: northern, southern, and eastern boundaries, while the western is bounded by the coast.

The two inner grids were rotated to maximize the sea/land proportion, and present the resolutions of 1/36◦ and 1/72◦ (innermost grid). For nesting it was employed the one-way nesting technique as described in Marchesiello et al. (2001) and Mason *et al.* (2010).

To avoid model instability and/or spurious deep currents the final masked bathymetry of all three grids were smoothed to fulfill a requirement on the ROMS slope or rx0-factor (Beckmann and Haidvogel, 1993). The two child’s grid bathymetry was changed so that it becomes exactly equal to the parent one at the open boundaries, linearly converging to the original high resolution bathymetry, as in Mason *et al.* (2010).

The simulation is configured to conserve volume with a free-surface condition (Chapman, 1985), a condition for the 2D momentum (Flather, 1976), and radiation boundary condition with nudging for the 3D momentum and tracers (Marchesiello *et al*., 2001), with nudging timescales of 1 and 30 days for the inflow and outflow, respectively.

The interpolation and extrapolation of the data from Mercator to the ROMS grid , and between ROMS grids for nesting, were performed following the works of Mason *et al.* (2010) and Marta-Almeida *et al*. (2019). To ensure the conservation of volume the input data are initially horizontally interpolated for the ROMS grid, with the vertical interpolation resolved for each node in the next step. The extrapolation, consisting of replicating the data closest to the missing node (NaN), is applied in the two interpolation steps (horizontally and vertically) to three regions: above the uppermost input data layer, (2) below the bottommost input data layer, and (3) on the coast, within the landmask of the input data.

The codes for interpolation and extrapolation are available at the following Github page <https://github.com/fernandotcbarreto/ROMS/tree/master/bou> ndary\_ini

Tides are not being resolved, and are expected to be implemented in the next version of the system.

Two schemes were built for the operational forecast workflow, with (Fig. 65) and without (Fig. 90) the Data Assimilation (DA) method I4D-var, in order to account for limited computational resources, as most DA schemes requires a Cluster or Cloud computing.

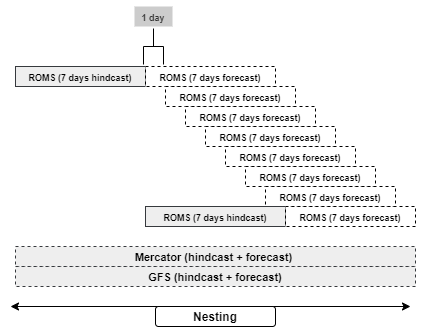


Fig. 65

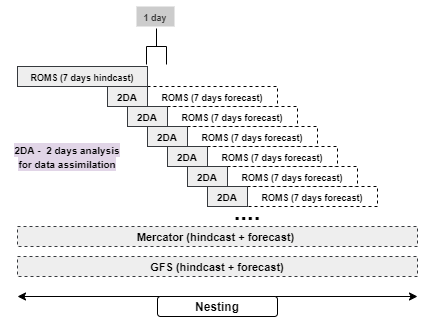


Fig. 90

The scheme without DA was based in the works of Costa *et al*. (2012) and Juza *et al.* (2016). In this scheme two systems were developed: a hindcast that runs at a specified frequency (weekly in the figure) and a forecast system that runs daily. The hindcast system (7 days) is forced on the surface by the GFS and uses Mercator as initial and lateral boundary conditions. The forecast system (7 days) uses the Mercator to build the boundary conditions and the ROMS data from the previous run to build the initial conditions. If the previous run is the hindcast system, the last available time step is used. In case of the forecast system, it is used the time step corresponding to the start day of the new run (1 day after the start day of the previous run).This workflow is repeated for all nested grids. This restart strategy was used to ensure that the ROMS solution stays close to the real evolution of the ocean in scenarios where DA is not accounted for (Costa *et al*., 2012). The frequency to perform the restart depends on the quality of input data and on the stability of the model (bathymetry smoothing playing an important role).

The codes for implementing this scheme are available at the following Github.

https://github.com/fernandotcbarreto/ROMS/tree/master/operational.

Based on the works of Mourre *et al* (2018) and Hirose *et al.* (2019), we developed the system with DA presented in Fig. 90. The main difference between the two schemes is an analysis run (a two-day analysis in the figure), where the Data Assimilation is performed. The forecast is then initialized using the last time step of this analysis as the initial condition, simulating 7 days in the future. The analysis starts from the midpoint of the running time in the previous analysis, leading to an overlap of 50%.

The velocity fields of the system without Data Assimilation will be compared for two depths (88 and 99) against Mercator to evaluate the stability of the solution inside the domain and near the boarders for the three nested grids. To evaluate the correct inclusion of the DA method into the system, the SSH and SST fields from the model was compared against satellite for the cases with and without DA.

2.3) VALIDATION SCENARIOS SET-UP

In order to validate the developed interpolation codes we established different domains for three regions along the Eastern Brazilian coast. These domains aimed to cover the variable aspects of the Brazilian Current System (BC, Silveira *et al.*, 2000) as it flows poleward.

The first domain is composed by the single Azul grid, and was run for the year long period of 2016, using at boundaries data from Mercator and Era5. The *u* and *v* velocity components were compared against the near surface and bottom available current data from Vitória buoy located at 19°55' S e 39°41' W (part of Brazilian National Buoy Programme – PNBOIA). PNBOIA velocity data extends from the depth of 5.5 m to 75.5 m, with a cell of 3.5 m. This case was executed for all 2016 year due to the availability of PNBOIA data for this period. Since this grid presented highly satisfactory results to this buoy (to be presented in next section) and is outside the region of interest, a nesting was not performed in this case.

As this domain covers the entire Eastern Brazilian coast, its results were also compared against MUR for SST, and AVISO for SSH. The MUR SST analysis (Chin *et al*., 2017) presents a 1 km resolution and is produced as a retrospective data set (four-day latency) and as a near-real-time data set (one-day latency) at the Jet Propulsion Laboratory (JPL) PODAAC using wavelets as basis functions in an optimal interpolation (OI) approach. Talk bout Aviso

A grid with resolution 1/36° was nested to the previous domain, creating a nested two-grid system (Fig) centered in the Rio de Janeiro State. This system was executed from date to date, employing a two months spin-up, with the results compared against the *u* and *v* velocity components of the Cabo Frio Buoy (PNBOIA), located at 23°37’ S and 42°12’ W. This date was selected based on the [availability](https://www.google.com/search?sxsrf=ALeKk01p7XybMtjjIIvyVrYIf-jxK4gjtg:1606008758586&q=availability&spell=1&sa=X&ved=2ahUKEwjcz77sgJXtAhUWMbkGHcR-CfYQkeECKAB6BAgEEDU) of Cabo Frio buoy.

A second domain composed by a nested two-grid system with resolutions 1/12° and 1/36° was implemented for the southern region of Brazil. This system was executed from date to date, employing a two months spin-up, with results compared against the *u* and *v* velocity components of the Itajaí Buoy (PNBOIA), located at 27°24’ S and 47°15' W. . This date was selected based on the [availability](https://www.google.com/search?sxsrf=ALeKk01p7XybMtjjIIvyVrYIf-jxK4gjtg:1606008758586&q=availability&spell=1&sa=X&ved=2ahUKEwjcz77sgJXtAhUWMbkGHcR-CfYQkeECKAB6BAgEEDU) of Itajaí buoy.

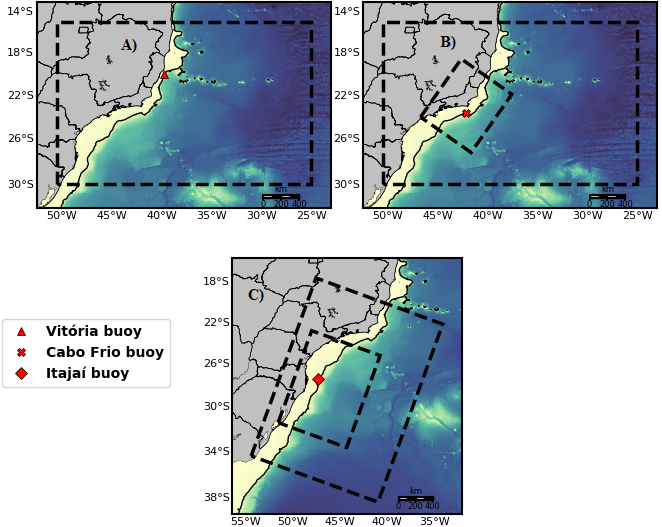


Figure 656

The quality of the model simulations relative to the observations made available and those described in the literature were assessed by means of basic statistic, such as The Pearson’s correlation coefficient, the mean absolute error (MAE, the average of the absolute value of the difference between the model and observations) and the root mean square error (RMSE, the quadratic scoring rule which measures the root average quadratic distance between the model and observations) were used as skill scores to study the performance of the model. The three scores complement each other and give different statistical information about the errors. (The BIAS typically measures the difference between model predictions and observations)The MAE measures the average magnitude of the errors, and the RMSE measures the spread of the distribution of the differences between the model and observations, thus giving information about how wide is its.

3) RESULTS AND DISCUSSION

3.1) EVALUATING THE VELOCITY COMPONENTS

The Brazil Current is unique among subtropical western boundary currents, with increasing vertical extension from its origin site (around 15°S) towards the confluence region with the Malvinas Current. It goes from 200 m to 400-500 m at 20°S with the addition of the South Atlantic Central Water (SACW), and to about 1200 m at 25°S with the addition of the Antarctic Intermediate Water (AAIW) (Silveira *et al*., 2004, Schmid *et al.*, 2000, Soutelino *et al*., 2013). This modification of the BC as it flows poleward motivated the tests of the modelling system for the buos Vitória, Cabo Frio, and Itajaí, as they cover different regimes of the BC.

The Vitória buoy was moored at a depth of 200 m, in a region with baroclic mesoscale activity resultant from the strong vertical shear of the BC with its immediate adjacent western boundary current (NBUC) (Soutelino *et al*., 2013).

In the region of the Cabo Frio buoy (moored at 200 m), besides the baroclinic mesoscale activity from the strong vertical shear of BC-NBUC system (Silveira *et al*., 2008; Mano *et al*., 2009), the dynamics are also modified by the change in the shoreline orientation from north-south to west-east at around 23 °S, resulting a highly dynamic region.

The site of the Itajaí buoy (moored at 200 m) is much less studied compared to other two due to the distance from the pre-salt oil reserves of the Campos and Santos Basin. In this region the BC is composed by the Tropical Water (TW), South Atlantic Central Water (SACW), Antarctic Intermediate Water (AAIW), and North Atlantic Deep Water (NADW) flowing towards the Malvinas Confluence.

The *u* and *v* velocity components from ROMS were compared against the *in situ* data for two months at the depths of 5.5 m and 75.5 m (top and bottom depths of PNBOIA data). The modelled data are initially linear interpolated to the in *situ* time points (smaller output time) to avoid losing information. A low-pass filter in then applied to the time series to remove the high frequencies. The Mercator output was also included in the analysis to account for the differences observed with the ROMS model.

The Pearson’s correlation coefficient and the RMSE were the chosen parameters to evaluate the modelled data and are presented in Table 324 for the three buoys.

**Table 324 - Pearson (r) and RMSE for the three buoys**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Buoy | Depth | Source | Pearson (r) \* | | RMSE (m/s) | |
|  |  |  | **u** | **v** | **u** | **v** |
| Vitória | 5.5 m | ***MERCATOR*** | 0.8775 | 0.8683 | 0.1304 | 0.1612 |
| ***ROMS*** | 0.9104 | 0.8908 | 0.1017 | 0.1637 |
| 75.5 m | ***MERCATOR*** | 0.8790 | 0.8730 | 0.1091 | 0.090 |
| ***ROMS*** | 0.8946 | 0.8901 | 0.0781 | 0.1169 |
| Itajaí | 5.5 m | ***MERCATOR*** | 0.2583 | 0.5314 | 0.1000 | 0.1182 |
| ***ROMS PARENT*** | 0.02 (0.42) | 0.3896 | 0.0979 | 0.1358 |
| ***ROMS NEST*** | 0.2061 | 0.8528 | 0.0926 | 0.0852 |
| 75.5 m | ***MERCATOR*** | 0.3358 | 0.1887 | 0.1314 | 0.1703 |
| ***ROMS PARENT*** | 0.2564 | 0.1624 | 0.1162 | 0.1934 |
| ***ROMS NEST*** | 0.4875 | 0.8309 | 0.1073 | 0.1331 |
| Cabo Frio | 5.5 m | ***MERCATOR*** | 0.1123 | 0.4096 | 0.1981 | 0.098 |
| ***ROMS*** | 0.03(0.45) | 0.3887 | 0.2418 | 0.1285 |
| ***MERCATOR*** | 0.5506 | 0.0162 | 0.1294 | 0.1238 |
| 75.5 m | ***ROMS*** | 0.2981 | 0.5877 | 0.2078 | 0.077 |
| ***MERCATOR*** | 0.1720 | 0.2659 | 0.2629 | 0.1425 |
| ***ROMS PARENT*** | 0.7206 | 0.1004 | 0.1191 | 0.1066 |

\* P-values for the correlation coefficient are zero, unless noted otherwise in brackets.

The modelled data from ROMS 1/12 (Figure 656.a) and Mercator are plotted against Vitoria Buoy in Figure 512 and Figure 513. ROMS and Mercator presented high correlation for both depths and components (> 85%), with ROMS performing slightest better. This can be confirmed in the plots, with the models reproducing the main peaks. It was not observed a significant difference between surface and bottom values for correlation coefficient values. For RMSE, the worst value was observed for Mercator *v* component at depth 5.5 m (0.1612 m/s), and the best for ROMS *u* component at depth 75.5 m (0.0781). Both ROMS and Mercator improved their RMSE values at 75.5 m. ROMS improved for *u* around 23%, and for *v* 28%.

Since ROMS performed very well for Vitória buoy, and this region is outside the region of interest for the operational system (RJ), it was not implemented a nested grid for this case.

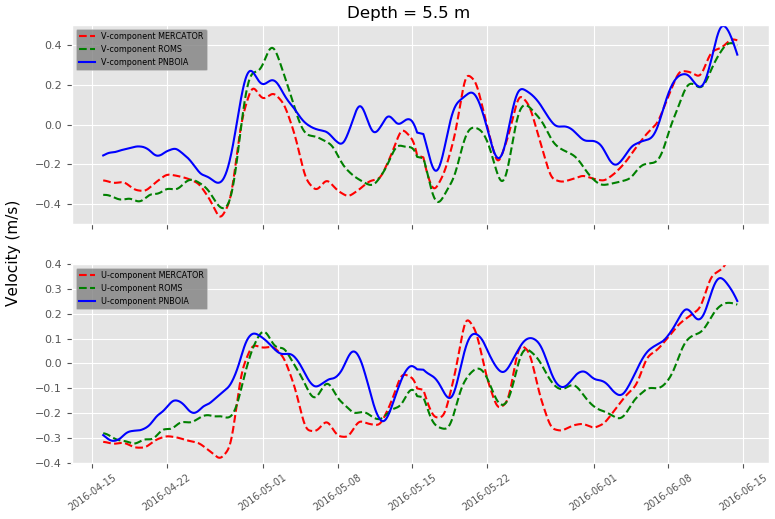


Figure 512 - Comparison of filtered *v* (upper) and *u* (bottom) velocity components between ROMS, Mercator, and Vitória Buoy at depth 12.5 m.

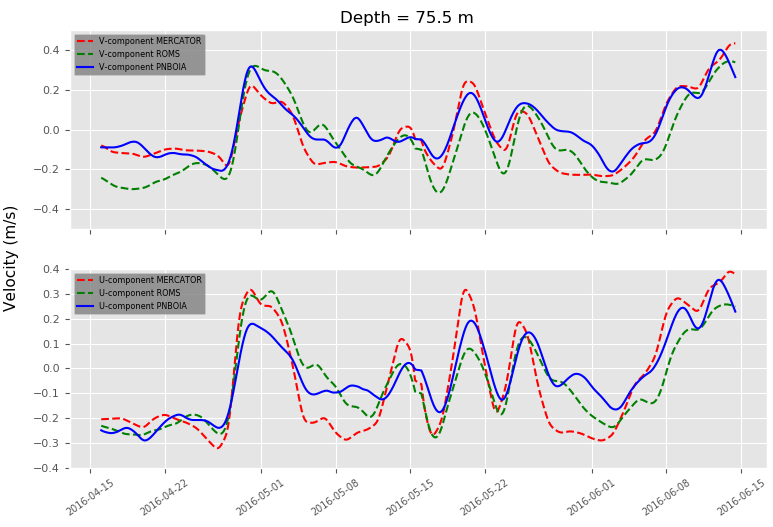


Figure 513 - Comparison of filtered *v* (upper) and *u* (bottom) velocity components between ROMS, Mercator, and Vitória Buoy at depth 75.5 m.

The modelled data from ROMS 1/12°, ROMS 1/36° (Figure 656.c) and Mercator are plotted against Itajaí Buoy in Figure 514 and Figure 515. At 5.5 m both ROMS and Mercator presented greater correlations for *v*, with the nested domain performing 60% better than Mercator, and the parent performing 26% worse. For *u* all domains presented low correlations, as can be observed in the plots, with most of the peaks not represented in the simulations. Regarding RMSE, all cases presented values around 0.1, indicating a stable solution, with ROMS Nest performing best for both *u* (0.0926 m/s) and *v* (0.0852 m/s).

At 75.5 m Mercator and ROMS Parent presented low correlations, with the nested domain performing well for *v* (83%) and regular for *u* (48%). In the work of Costal *et al.* (2018) for the northwestern Iberian coast, correlations around 50% were deemed as decent. In spite of the high correlation value for the nested domain, in Figure 515 we can observe a significant damp in all modelled results.For RMSE, Roms Nest performed better for both *u* and *v*, with the worst result associated to the *v* component from the Parent domain (0.1934 m/s).

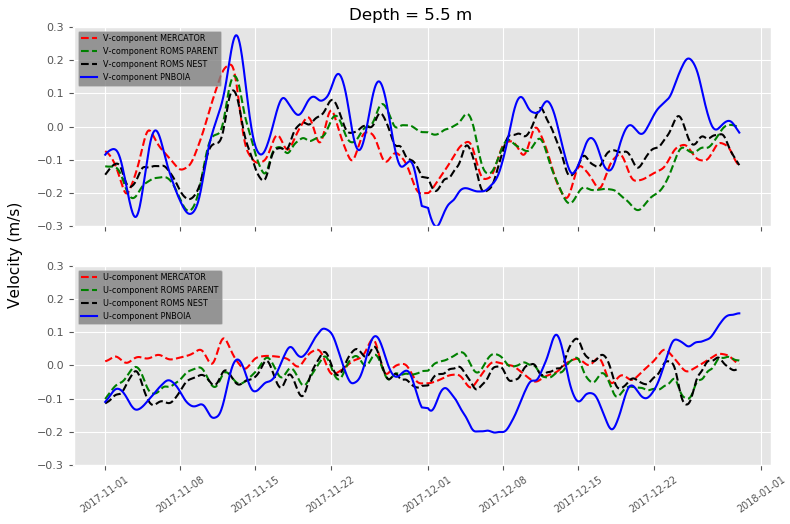


Figure 514 - Comparison of filtered *v* (upper) and *u* (bottom) velocity components between ROMS Parent (1/36°), ROMS Nest (1/36°), Mercator, and Itajaí Buoy at depth 12.5 m.

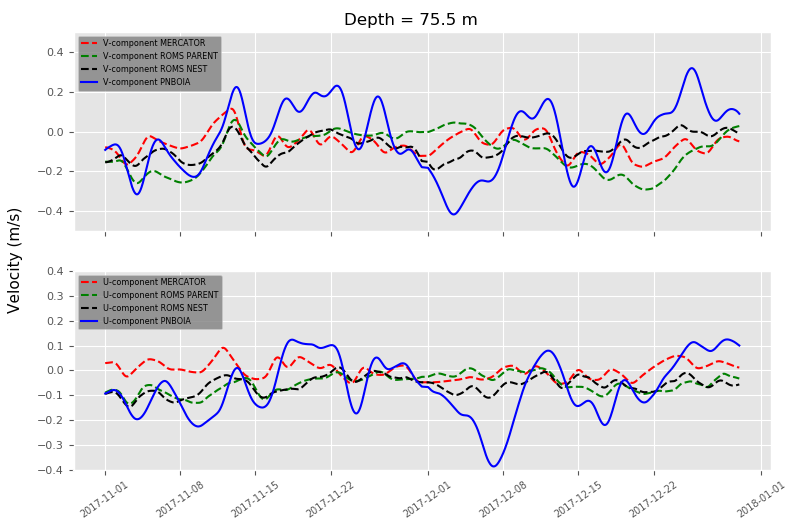


Figure 515 - Comparison of filtered *v* (upper) and *u* (bottom) velocity components between ROMS Parent (1/36°), ROMS Nest (1/36°), Mercator, and Itajaí Buoy at depth 75.5 m.

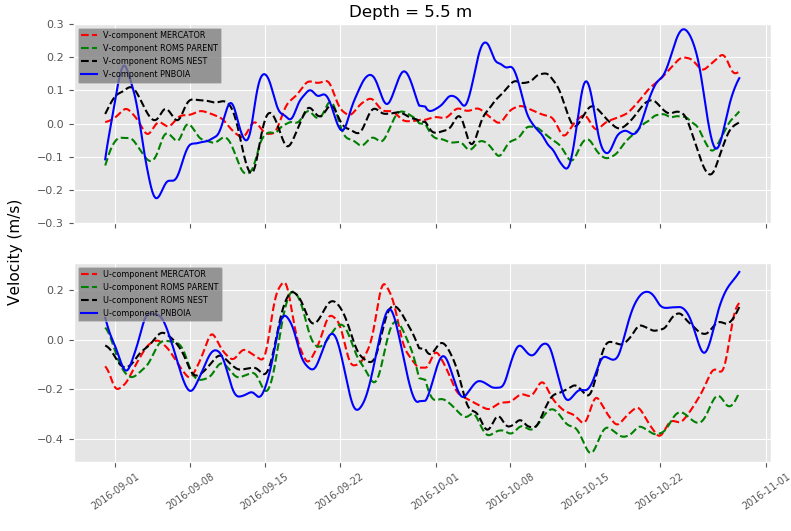


Figure 516 - Comparison of filtered *v* (upper) and *u* (bottom) velocity components between ROMS Parent (1/36°), ROMS Nest (1/36°), Mercator, and Cabo Frio Buoy at depth 12.5 m.

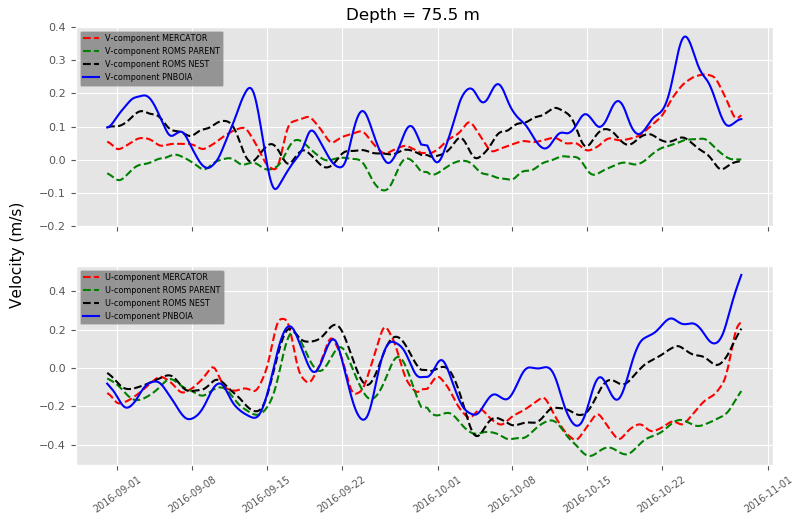


Figure 517 - Comparison of filtered *v* (upper) and *u* (bottom) velocity components between ROMS Parent (1/36°), ROMS Nest (1/36°), Mercator, and Cabo Frio Buoy at depth 75.5 m.

3.2) SEA SURFACE TEMPERATURE AND ALTIMETRY

From March 2016 to December 2016 (excluding the two first months of spin-up) it was calculated maps of RMSE and MAE for the Sea Surface Temperature (SST, Figure 465) and the Sea Surface Height (SSH, Figure 998) to be used as skill scores in the evaluation of model performance. These parameters were resolved for each grid node after the linear interpolation between the time series from ROMS, MUR (SST), and Aviso (SSH).

Most of the RMSE and MAE values for SST remained below 1, as observed in Costal *et al* (2012) for the Iberian coast, with greater values in the oceanic region below 25°S, and next in the coastal region off Rio de Janeiro (around 23°S). The discrepancies in the coastal region 23°S was expected, and is a result of the wind-driven coastal upwelling region off the Cape Frio. After comparison with *in situ* measurements, Pereira *et al.* (2020) reported strong biases in L4 SST products (like MUR), particularly during upwelling days. According to the author these discrepancies result mainly from the spatio-temporal interpolation in L4 SST analyses and the use of microwave SST.

The spatial average of RMSE and MAE presented values of 0.45°C and 0.39°C, respectively, indicating a good representation of the surface temperature field, as can be compared in the works of Al Azhar *et al.* (2006) for the Arabian Gulf and the Sea of Oman, and in Chakraborty *et al.* (2019) for the Indian Ocean.

For the SSH, most of the area presents values of RMSE and MAE below 0.1, with an average of 0.026 and 0.024 m, respectively. These vlues indicate a better representation of SSH field when comparing to the work of Pereira *et al.* (2013) for the same region, which is probability related to the climatological open boundary conditions used in their simulation.

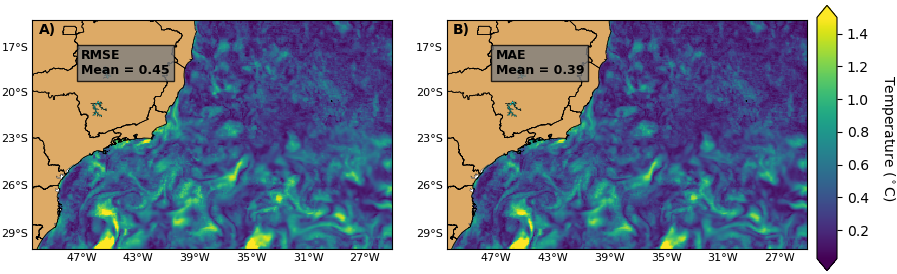


Figure 465 - Distribution of the statistical parameters RMSE (left) and MAE (right) for the Sea Surface Temperature simulated by ROMS from March 2016 to December 2016 compared against MUR SST. In the figures are also calculated the spatial average over the domain.

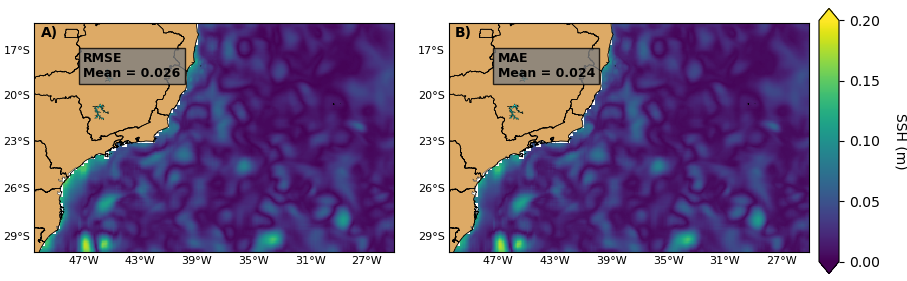


Figure 998: Distribution of the statistical parameters RMSE (left) and MAE (right) for the Sea Surface Height simulated by ROMS from March 2016 to December 2016 compared against Aviso. In the figures are also calculated the spatial average over the domain..

5) REFERENCES

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