Development of a pilot Brazilian regional operational ocean forecast system, REMO-OOF

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An oceanic forecast system was created for the southeastern Brazilian region. A 9.5 years spin up, from January 2000 to July 2009, was used to adjust the model Regional Ocean Modelling System (ROMS) forced by oceanic climatologies and National Centers for Environmental Prediction (NCEP) surface fluxes. After this period, the system became operational with the atmospheric fluxes from the Global Forecast System (GFS). The system produces daily oceanic analysis and five days forecasts in a fully automatic manner. In addition to the routine task of running the oceanic model, this operational implementation also collects data from global datasets (maps of sea surface elevations and temperatures, profiles of temperature and salinity), for validation and improvement of the model parameterisations. Daily outputs from the operational analysis of surface temperature and altimetry, averaged over the first operational year, compare reasonably well with satellite and *in-situ* observations and the main features of the southeastern Brazilian dynamics are reproduced by the operational model.

In the near future the system aims to incorporate the usage of large scale assimilated ocean modelling products as lateral forcing and high resolution local area atmospheric forecasts to provide the surface fluxes for the ocean model. Operational outputs and other relevant data are made available online in real time.

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INTRODUCTION

Mankind's vulnerability and dependence on ocean conditions and their variability has increased slightly through the centuries but asymptotically in the last few decades. The explosive growth of the world population since World War II and urban concentration near sensitive coastal regions associated with the increase of frequency and amplitude of extreme environmental events, due to climate change, persuaded world leaders of the necessity to observe and forecast the ocean in an operational manner. Moreover, many economically important activities take place at sea, which also provides a unique source of food that needs to be studied and controlled.

Observational and numerical meteorology has been an operational activity for several decades. Meteorological forecast models are very mature and include advanced numerical techniques to assimilate the grand quantity of real-time observations available. During the late 1990s it was realised there was a need to create worldwide ocean observational programs,[1,2] to develop a system for ocean predictability, and to improve atmospheric forecasts, since the latter two are connected at the sea surface boundary and exchange momentum, salt and heat fluxes. Since then, numerical oceanography has experienced rapid development and ocean state estimation, through observational data assimilation, is already a reality in various research centres and in an implementation phase in many others. The experience of the meteorological community was important in the development of ocean observational and assimilation systems, and in turn they benefit from better sea surface boundary conditions. Coupled ocean/atmosphere models are also under development and are viewed as an important advance for oceanic and atmospheric reanalysis and forecasts studies.

Potential users of global and regional oceanic operational outputs include safety and regulatory authorities, marine and coastal management agencies, and the offshore oil and gas industry. The release of information to such a vast public may take the form of statistics of extreme events, real-time oceanic data and forecasts, or indirect ocean related variables. Possible applications are in the administration of marine resources (aquaculture and fisheries efficiency and stock management), environmental monitoring, naval tactical planning, search and rescue operations, recreational activities, drift of container or oil spill, drift of eggs and larvae of marine species, drift of ice, prediction of the effects of waves and storms, laying of pipes and cables, etc.

The availability of operational global or large-scale data from models (reanalysis, nowcasts and forecasts) and observations (*in-situ* and satellite), in a wide range of time-scales, together with the increasingly improved definition of coastlines and topography and the recent advances in ocean modelling techniques (namely in the small scale dynamics) has led to wide-spread implementation of regional high resolution ocean modelling (shelf/slope and coastal regions, estuaries and lakes/lagoons), which benefit from the necessary information for model initialisation, boundary conditions and quality control. Among the possible scientific uses are water quality assessment, waves, biological (like IBMs), biogeochemical, atmospheric and climate models. Knowledge of the current and future ocean state is also useful to support oceanographic cruises or to more efficiently specify the regions and periods of study and the places to deploy new observational facilities.

Forecasting future ocean conditions as far ahead as possible is nowadays a routine activity in many oceanographic institutions located throughout the world. Besides collecting data and producing model outputs in an automated manner, these institutions have also several other tasks, like development/optimisation of the observing system design, implementation of the processing procedures, establishment of the control experiments and model validation, definition of the error statistics, development of techniques for estimating the ocean state, and finally the delivery of data for the end users, including issuing warnings and bulletins. Among the operational institutions and projects currently active are the National Oceanic and Atmospheric Administration (NOAA) in the USA, the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia with the BLUElink[3] project, the wide MERSEA Integrated Project in Europe: in France with MERCATOR;[4,5] in the UK with FOAM;[6] in Italy with the MFS – Mediterranean Ocean Forecasting System;[7] and in Norway with TOPAZ.[8]

Many operational and pre-operational prediction systems are being implemented, as aforementioned. In Brazil, in a joint effort between groups of institutions, a research and development consortium called Oceanographic Modelling and Observation Network (with the Portuguese acronym REMO) was built in 2007. Among the objectives of this network is the contribution for a better understanding of the ocean, including mesoscale, shelf and tidal circulation, and to provide oceanographic forecasts for the Brazilian shelf/slope to support the activities of the oil industry. In addition, there is a genuine end-user demand for ocean products of the Brazilian region, in a variety of time and space scales.

The regional pilot REMO Operational Ocean Forecasting (REMO-OOF) has been routinely operated by the Federal University of Bahia (UFBA) in near-real-time since 1 July 2009. The REMO-OOF service estimates the circulation for the Brazilian coast south of 13°S. This system provides a full 3D depiction of the ocean dynamics and thermohaline circulation (T, S, currents, mixed layer depth), with a priority given to high resolution (eddy resolving) scales. Information is currently available on daily analysis and five day forecasts.

The aim of this paper is to present the implementation of this regional operational system, which has been used as a pilot study for future developments, to detail the model set-up, from spin-up to operationality, and some results. Data visualisation and distribution is then explained and future plans presented.

OPERATIONAL MODELLING SET-UP

The ocean model

The numerical model implemented in the operational system was the Regional Ocean Modelling System,[9,10] nesting enabled, ROMS-AGRIF (Adaptive Grid Refinement in Fortran).[11] ROMS is a three-dimensional free surface, terrain-following model that solves the Reynolds-averaged Navier-Stokes equations using the hydrostatic and Boussinesq approximations. The model is highly configurable to be used in realistic regional applications.

This model was chosen because it is an advanced and robust rapidly evolving community-code model. ROMS has been applied in deterministic simulations in a wide range of space and time scales and oceanic systems types. A description of the model and its newest features and applicability on forecast systems can be found in.[12]

In the authors' configuration, a curvilinear grid covering the Brazilian coast was used with an inclination that approximately follows the coastline (Fig 1). The domain extends offshore about 900km from the latitudes (at coast) of ~31°S to ~13°S. The distance between the southern and northern boundaries is about 2400km. This domain was chosen because it included most of the South Equatorial Current (SEC) through the boundaries. The northern boundary was chosen based on the northernmost latitude reached by the SEC bifurcation at surface, which is 13°S. The southern boundary was chosen based on two criteria: i) the inclusion on the deep SEC bifurcation, around 25°S and ii) the exclusion of the confluence between the Brazil Current and the Malvinas Current. A variable cross-shore grid resolution was used, from 2km near the coast, where higher bathymetric gradients are found, to 12km offshore. The resolution in the alongshore direction was ~9km. The vertical axis has 32 s-levels and the bathymetry was obtained from the ETOPO1 Global Topography database,[13] which has a resolution of about 1km. Mesh refinement is not (yet) currently implemented.

Steps towards operationality

The operation of a modelling system requires (at the very least) realistic initial, lateral boundary and atmospheric forcing conditions provided on a regular continuous basis. The lateral boundary can be controlled with climatology data or preferably with real-time conditions from a global or larger-scale model.

At the present state the REMO network has two operational grids designed for large scale studies, which are based on the Hybrid Coordinate Ocean Model (HYCOM). One grid releases forecasts for the South Atlantic Ocean in a 1/4° × 1/4° horizontal resolution. The other grid, with a 1/12° × 1/12° horizontal resolution, releases forecasts for the so-called METAREA V, which is the area included in the Brazilian Meteorological Service. These grids do not include data assimilation, but various techniques that will enable data assimilation are already under development and being tested at the moment.

While the near future goal is to use lateral boundary conditions from the REMO large scale model that includes data assimilation, as an alternative solution it was decided to use a

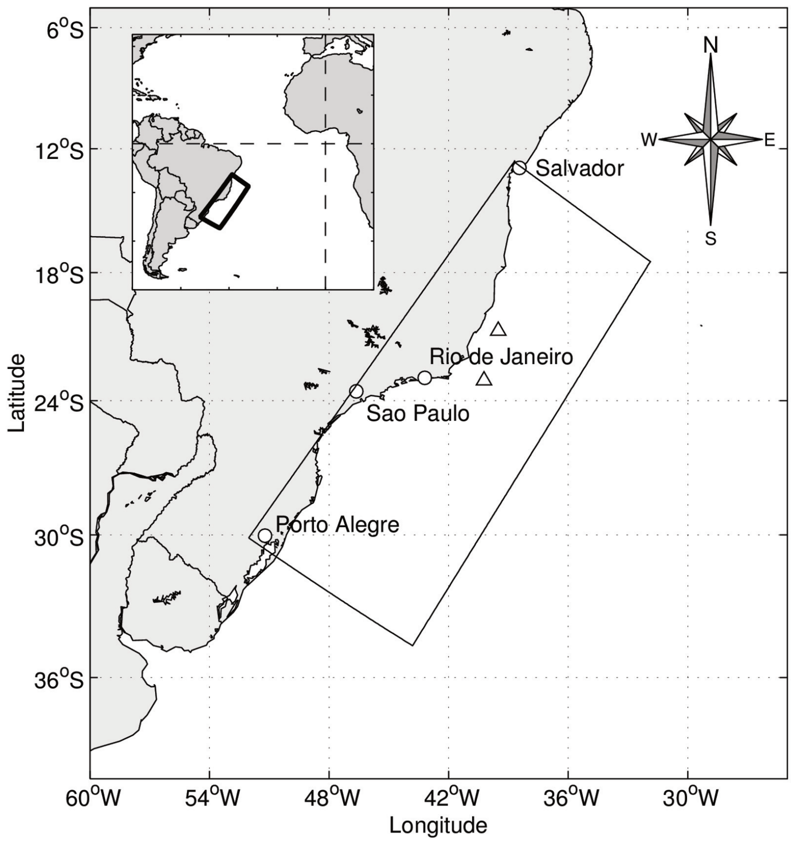


Fig 1: Operational model domain. The model grid covers the most part of the Brazilian coast south of Salvador and has a variable resolution, increasing shoreward. The triangles near 40°W × 22°S indicate the position of profiles referenced in the manuscript

climatological dataset to interpolate the initial conditions and to obtain monthly boundary data. Thus, instead of a regular re-initialisation of the model, only one initial state was created, for 1 January 2000, from which a spin-up followed in order to obtain later initial conditions to be used by the operational model.

The spin-up comprised two phases: the first phase ran nine years from 1 January 2000 to 1 January 2009; the second phase ran the next six months, until 1 July 2009. These spin-up stages produced a steady repetitive annual cycle, as can be observed in the volume averaged kinetic energy (Fig 2). After the first months of simulation it exhibits annual periodic temporal oscillations. The tracers, temperature and salinity also exhibit a regular behaviour and without evidence of model shift along time (not shown). The spin-up simulations ran with lateral climatological conditions from the Ocean Circulation and Climate Advanced Modelling Project (OCCAM) model which provided the required data (momentum, temperature, salinity and free surface) for both the initial condition and the lateral information.

OCCAM is a global model with improved model physics and parameterisation and a full surface forcing. A description of the model can be found in Coward and Cuevas.[14] Two OCCAM datasets were used. The first, with horizontal resolution of 1/4° × 1/4° (hereinafter OC4) consists of averages of monthly mean data from a 20-year integration, from the beginning of 1985 to the end of 2004. The second OCCAM climatology presents horizontal resolution of 1/12° × 1/12° (hereinafter OC12) and corresponds to monthly mean data from a 17-year run, from the beginning of 1988 to the end of 2004. In the vertical both OCCAM simulations used a scaled vertical coordinate with 66 levels at fixed depths (with 14 levels in the upper 100m). OC4 was used for the spin-up stages, while OC12 was used in a later step (the 2nd operational stage, to be described below).

As surface conditions, the first spin-up stage used NCEP Reanalysis-2 fields of wind, humidity, pressure, temperature, precipitation and radiation.[15] ROMS uses this data to calculate the air-sea fluxes internally through bulk formulation. The resolution of these forcings is about 1.8° × 1.8° (192 × 94 Gaussian grid points or approximately 200km horizontal spacing). The data time interval was 6h.

The six months spin-up phase 2 was an intermediate step towards operationality and differs from phase one in the use of a different atmospheric forcing. This new data is provided by Global Forecast System (GFS), from NCEP,[16] a global spectral data assimilation forecast model. GFS has vertical resolution of 64 sigma layers and the simulations used in this stage have a horizontal resolution of about 1° and an output sampling rate of 6h. The data used was the daily forecast of the 00h GFS run (GFS restarts every 6h and each run simulates several days).

The ROMS ocean model was also forced with real-time tidal inputs, which were used in all stages of the implementation, from the spin-up to the operational stages. Tidal data was obtained from the TPXO 7.1 global database[17] which provides amplitudes and phases of sea surface elevation and barotropic currents for eight primary (M_2, S_2, N_2, K_2, K_1, O_1, P_1, Q_1) and two long period (M_f, M_m) harmonic constituents with a resolution of 1/4°.

After the second spin-up phase the model was implemented operational. A schematic illustration with the differ-

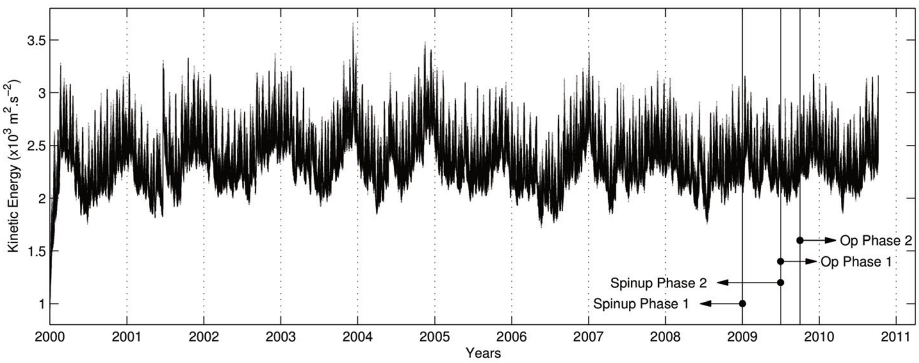


Fig 2: Volume averaged kinetic energy of the model spin-up and operational stages until October 2010

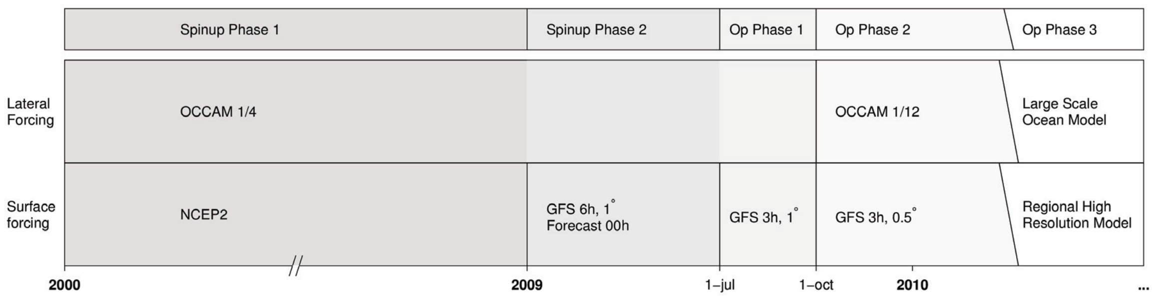


Fig 3: Development scheme of the oceanic operational system. The spin-up and operational steps are divided in terms of the differences in lateral boundary forcing and surface atmospheric forcing. The current stage is Op Phase 2 (second stage of operationality). The evolution to a 3rd operational step is expected during the first months of 2011. In this next step better representation of lateral and boundary forcing will be implemented

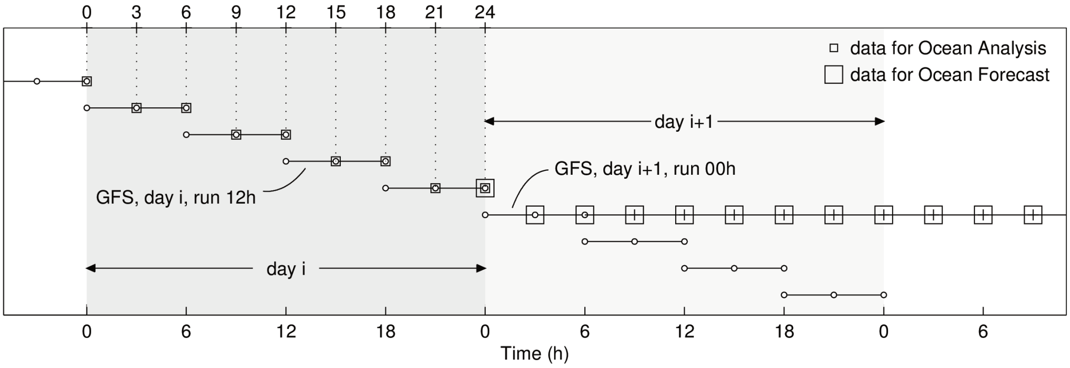


Fig 4: Representation of how surface forcing data from the GFS atmospheric model is used by the ocean model. GFS restarts every 6h and saves output snapshots each 3h. The ocean analysis step runs every day using data of the first two GFS outputs of the four daily runs (00h, 06h, 12h and 18h). The ocean forecast step uses five days of GFS data from the 00h run. The initial data of each GFS run is not used since it does not include some required variables

ences between the several phases of the modelling system, in terms of lateral boundary and atmospheric forcing, is presented in Fig 3. The scheme illustrates the differences between the two spin-up phases already explained and also between the operational phases, to be analysed in the next section.

The operational model

The model has been operational since 1 July 2009, with the spin-up phase 2 providing the initial conditions. The operationality underwent a first stage of three months until the end of October, and is currently on stage 2 (Fig 3). The first operational stage continued using the monthly averages of OC4 as lateral climatological forcing. At the surface the GFS atmospheric analysis and forecast data was used with a sampling rate of 3h (previously, in spin-up phase 2, the time interval between the atmospheric data was 6h and the data used corresponded to forecasts of the 00h run). The second stage started on 1 October 2009 and is the present stage. This uses the higher resolution OC12 climatology at lateral boundaries and GFS higher resolution surface data from GFS 0.5° simulations.

The operational system runs in two steps: analysis and forecast. In the first analysis, atmospheric data is collected from the GFS database for the previous day. This data is as close as possible from what can be called analysis data. Since the GFS global model runs each 6h, the data is used in the first two model outputs, ie, close to the initial analysis conditions of GFS. The initial data cannot be used because it includes only diagnostic variables, ie, some of the variables required for the ocean surface conditions are only ready after the first GFS output. Thus the analysis data used each day are the outputs 3h and 6h of the four daily GFS runs (00h, 06h, 12h and 18h) with the initial condition the output 6h of the run 18h from the day before (Fig 4).

The second operational step corresponds to the forecast. It uses the end of the previous day's analysis run as the initial condition and simulates five days using GFS forecast data (five days of the run 00h, Fig 4).

This is the current status of the operational system, although the next step of the system is now being studied and implemented (Fig 3, Op Phase 3). In this next phase the lateral monthly climatological conditions will be replaced by real-time data provided by a large-scale operational ocean model, already under advanced stages of development, which uses data assimilation procedures to estimate the ocean state. With respect to surface forcing, the atmospheric variables will come from a high-resolution regional model.

In terms of technical operations, the tasks needed for the operational ocean model to run, like the creation of input files, extraction of atmospheric data, as well as the control of the successfulness of the simulations and all the operational flow, is done with Operational Ocean Forecast Engine (OOF_ε), a collection of Python modules prepared to perform all the work required for the operational modelling system, including data visualisation. Due to its design, OOF_ε requires almost no human intervention, and except for some initial refinements and performance issues, OOF_ε is now working in a totally automatic manner. A detailed description of the OOF_ε Python engine can be seen in.[18]

Results of the first operational year

As a first attempt to access the quality of the operational model results, the outputs from the first operational year (1 July 2009 to 30 June 2010 – OP_{y1} hereinafter), were compared with several worldwide datasets, namely Sea Surface Height (SSH), Sea Surface Temperature (SST) and temperature and salinity profiles.

The modelled SSH was compared with AVISO satellite altimetry. AVISO altimeter products are merged data combining measurements from several satellites and have a resolution of 1/3° × 1/3°. They were produced by Ssalto/Duacs and distributed by AVISO, with support from Centre National d'Etudes Spatiales (CNES)[19]. The OP_{y1} averaged model SSH (Fig 5a) compares well with the AVISO averaged absolute dynamic topography (ADT) (Fig 5b, with spatial mean removed, ie, $\overline{ADT} = 0$). Negative heights of about 10cm are found in the shelf and positive values are found after the shelf break spanning the whole domain between the latitudes 27.5°S and 20°S. The main differences between the model and observations are in regions near the boundaries, with

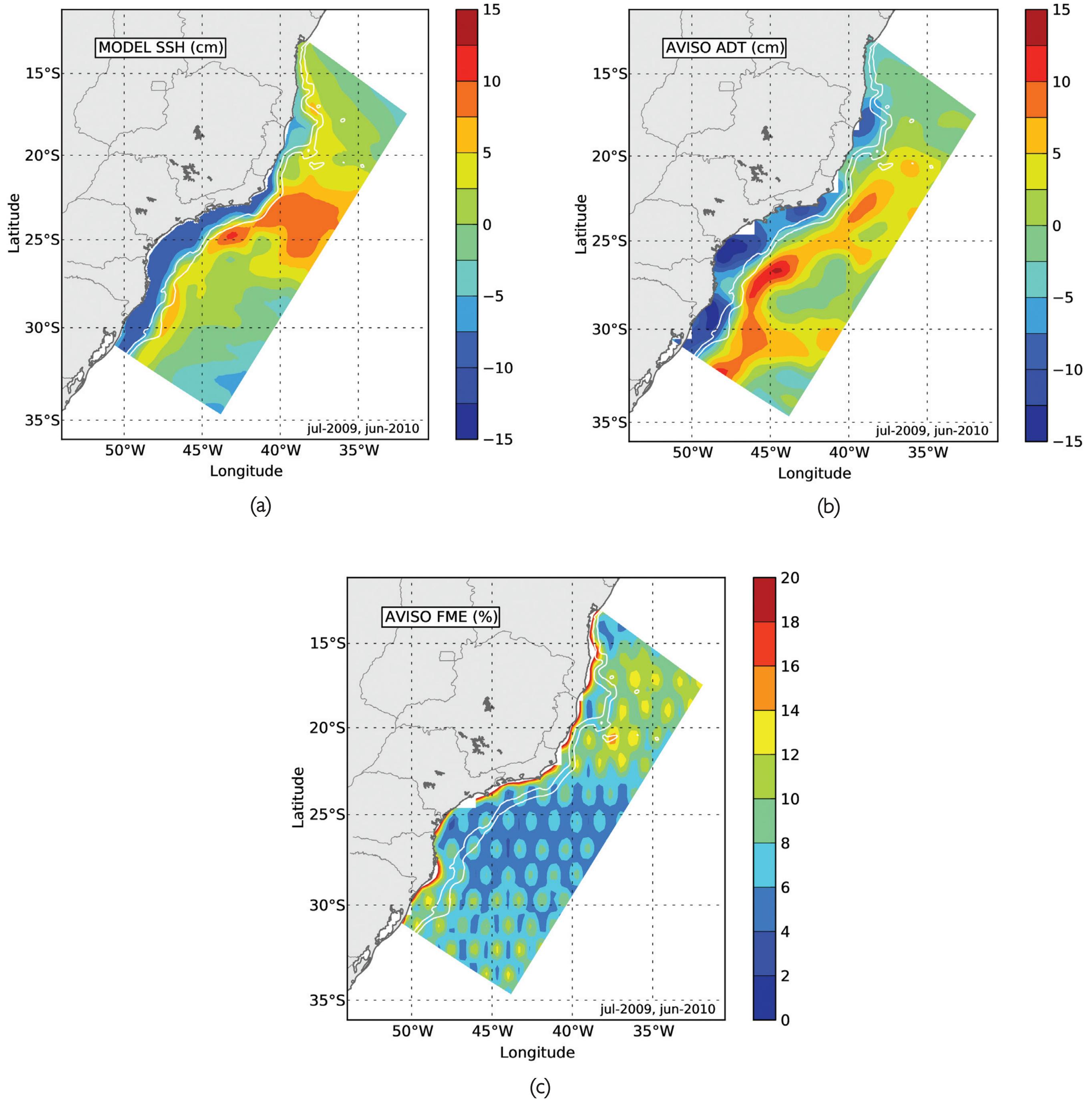
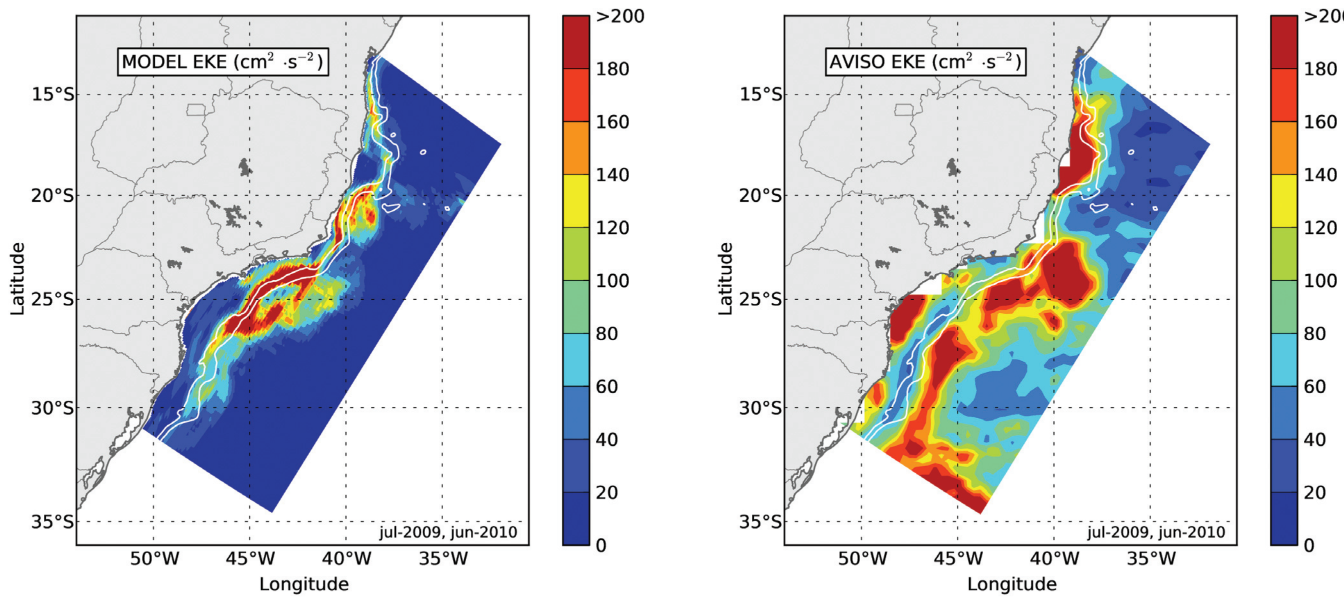


Fig 5: Model SSH (a), AVISO absolute dynamic topography with spatial mean removed (b) and AVISO formal mapping error (c). The values correspond to averages over the first operational year, OP_{y1} (1 July 2009 to 30 June 2010)

higher ADT south of 25°S, reaching 10cm, whereas model data is lower than 5cm. The same happens in the lower part of the eastern boundary. In contrast, at the northernmost coastal region, the model gives higher SSH, reaching 5cm against -5cm from AVISO. These differences do not result from AVISO error measurement. Fig 5c shows the AVISO formal mapping error (FME) which represents the error fields for sea level anomalies based on objective analysis and are mainly due to altimeter instrumental errors, errors associated to the travel of the pulse across the atmosphere and orbit error. FME values are typically lower than 14% and reach 20% only in regions very close to coast.

The average model and AVISO eddy kinetic energy (EKE), computed using the geostrophic approximation from model and AVISO sea surface anomalies, is shown in Figs 6a & b. As happens with sea level, the EKE has also higher differences away from the central region towards the boundaries. In fact, simulated EKE is near zero, except around the mid-shelf and slope. In general, AVISO presents a much greater activity, especially near the south and eastern frontiers, indicating stronger mesoscale activity.

The very high resolution OSTIA SST (Operational Sea Surface Temperature and Sea Ice Analysis) was also compared with the simulated data (Fig 7). OSTIA uses satellite



(a) (b)

Fig 6: Model (a) and AVISO (b) eddy kinetic energy based on surface elevation anomalies, averaged over the period OP_{y1}

data and *in-situ* observations to determine SST with a resolution of 1/20°.[20] Bearing in mind that the model has no relaxation to the SST, the model pattern of averaged SST represent fairly well the OSTIA observed data. The OC4 and OC12 averaged climatological SST shows erroneous too-smooth values over the shelf and in general with higher differences with OSTIA than the authors' model. Maximum temperatures are found in the Tropical Water (TW) in the northern region, with values between 27°C and 28°C. This TW extends until the south domain boundary with temperatures around 23°C. The results are also consistent with the hydrographic measurements in Brazilian coastal waters between 22°S and 23°S.[21]

Likewise, the model reproduced the colder shelf waters at the known Cabo Frio upwelling region, around the latitude 22°S.[22,23] To point out the model SST accuracy on this feature, the model and OSTIA temperatures of one day during the upwelling season (12 January 2010), are compared against MetOP Advanced Very High Resolution Radiometer (AVHRR) SST from EUMETSAT Ocean Sea Ice Satellite Application Facility (OSISAF), with spatial resolution of 1/20°C[24] (Fig 8). Minimum temperatures of about 22°C are found at the Cabo Frio upwelling waters. Such low values are not present in OSTIA composite data. The OC12, used to force the model boundaries, also does not present these low temperatures, and shows a very long, unrealistic, southward upwelling filament (Fig 8a). In general, in the higher resolution regions of the model, on the shelf, the results are more energetic, with stronger, more realistic spatial gradients, eg, the high temperature coastal waters south of the Cabo Frio upwelling filament. The same discussion applies to the relatively colder coastal waters between 16°S and 18°S, which is also very well represented by the model.

ARGO profiles of potential temperature and salinity are presented to illustrate the capacity of the model to reproduce the thermal and density vertical structure and its seasonal variability. ARGO is an array of free-drifting profiling floats measuring temperature and salinity of the upper 2000m of the ocean. Two profiles were chosen, one for the Austral summer and the other for winter (Fig 9). The profiles were selected as close as possible and the positions are shown as triangles in Fig 1 and correspond to the dates 17 January and 28 August 2010. Differences between model and ARGO profiles are very small. Near the surface, temperature differs about 1°C for both seasons, and winter salinity differs by about 0.2 psu.

The model reproduces the characteristic water masses in the southwestern Atlantic. The TW appears in the upper 200m in the vertical temperature and salinity profiles, with the thermohaline indices of T>20°C and S>36. Below TW, the South Atlantic Central Water (SACW, 6°<20°C and 34.6<36) are in the depths between 200–500m. At intermediate levels, the low salinity water mass, named Antarctic Intermediate Water (AAIW), 3°<6°C; 34.2<34.6), is represented. Below 1000m is found the North Atlantic Deep Water (NADW, T<4°C and S>34.6). A schematic view of these water masses formation regions has been presented.[25] The seasonal stratification of the upper ocean mixing layer is well evidenced with the cooling of the surface waters and the pronounced increase of the mixing depth.

DATA VISUALISATION AND AVAILABILITY

In order to make the results available for everyone, a very simple, yet powerful and robust, interactive website has been created[26] to display some graphical model inputs and outputs. As inputs, currently are shown horizontal maps of the wind vectors, and wind roses for some locations. As model outputs, the site shows horizontal slices of temperature, salinity and currents at several depths, and horizontal slices of free

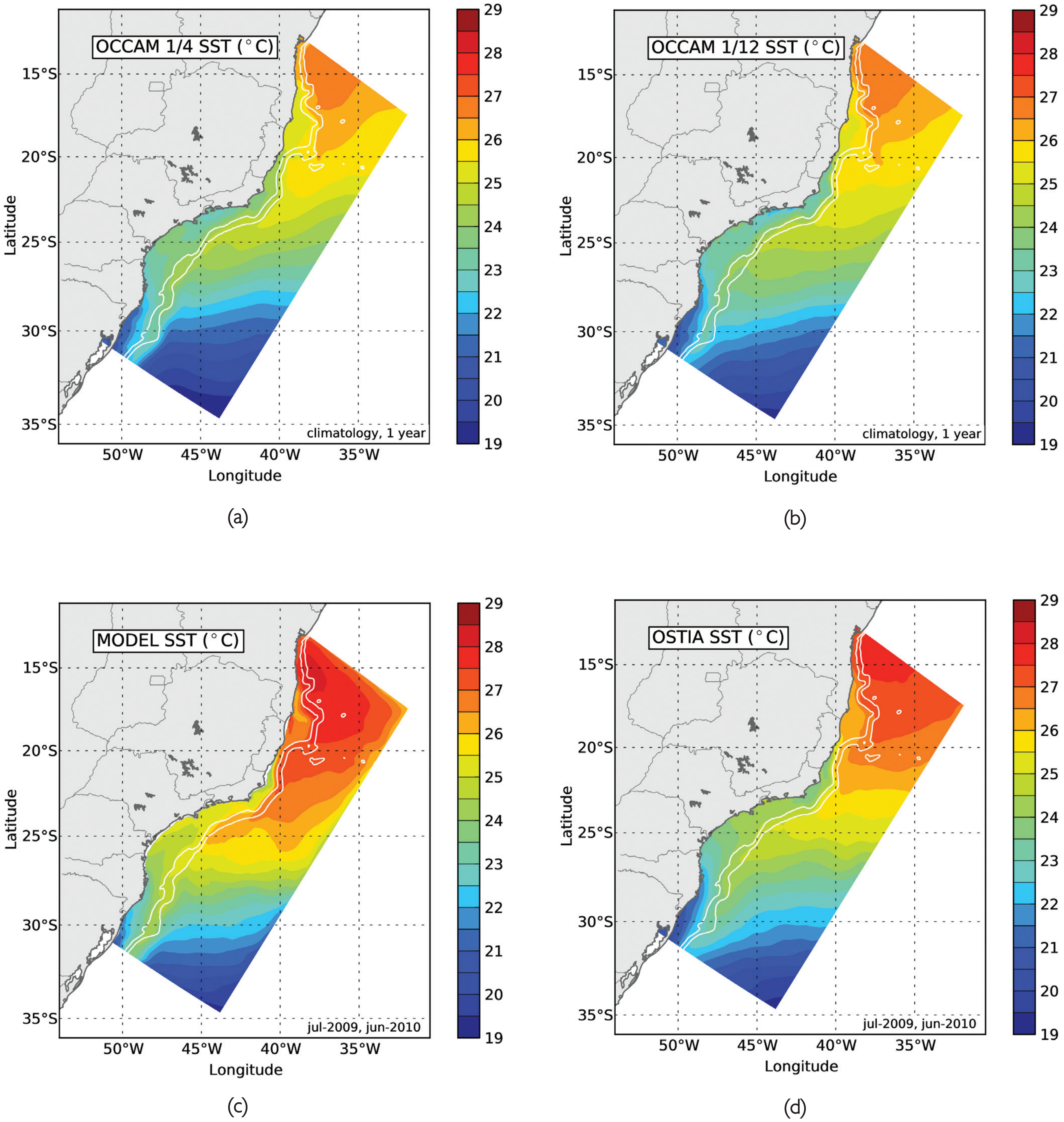


Fig 7: OC4 and OC12 annual averaged sea surface temperature (a) and (b); ROMS model and OSTIA sea surface temperature averaged over the period OP_{y1}, (c) and (d)

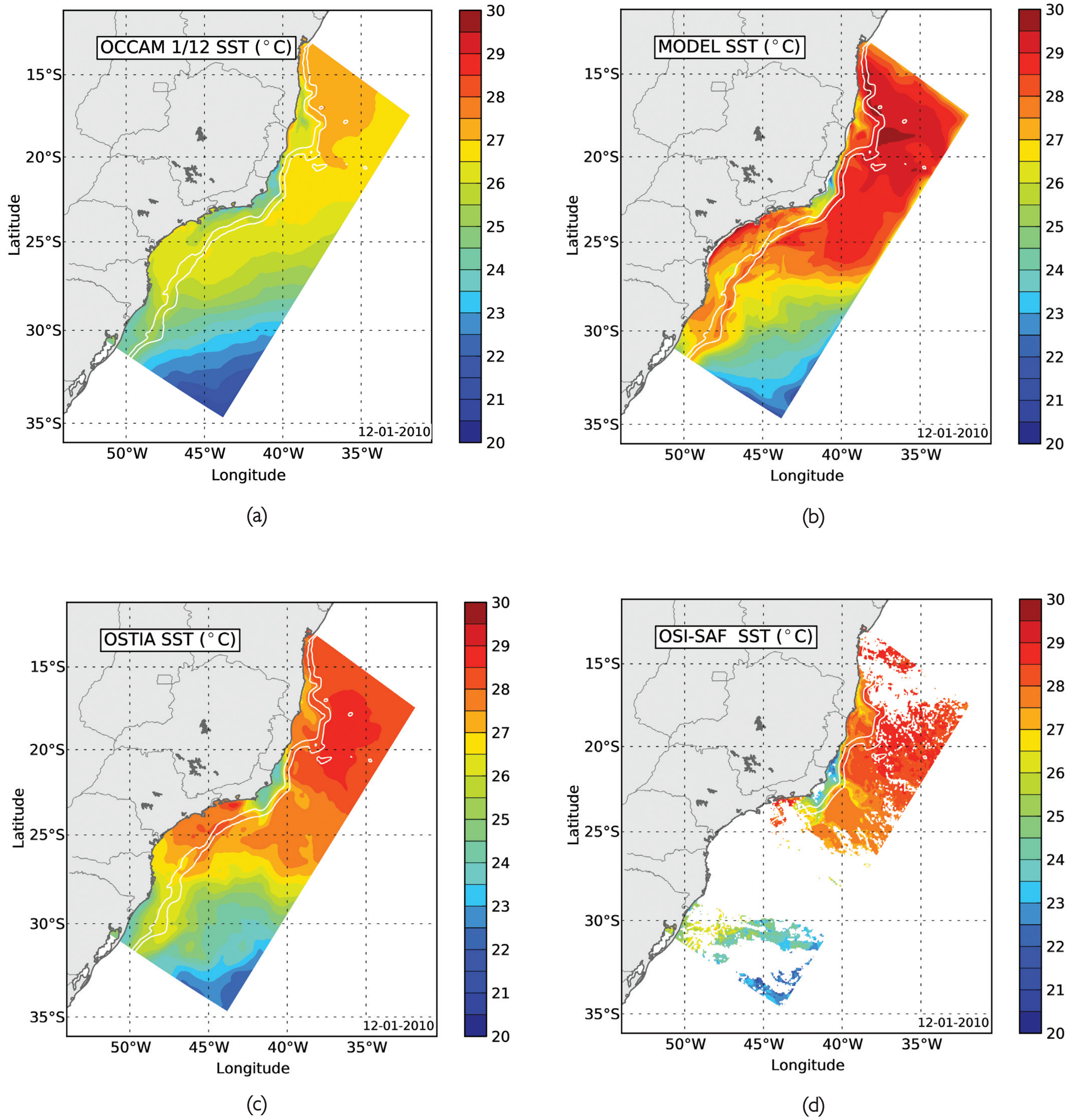


Fig 8: Sea surface temperature at 12 January 2010 from OC12 (a), ROMS model (b), OSTIA (c) and OSI-SAF (d)

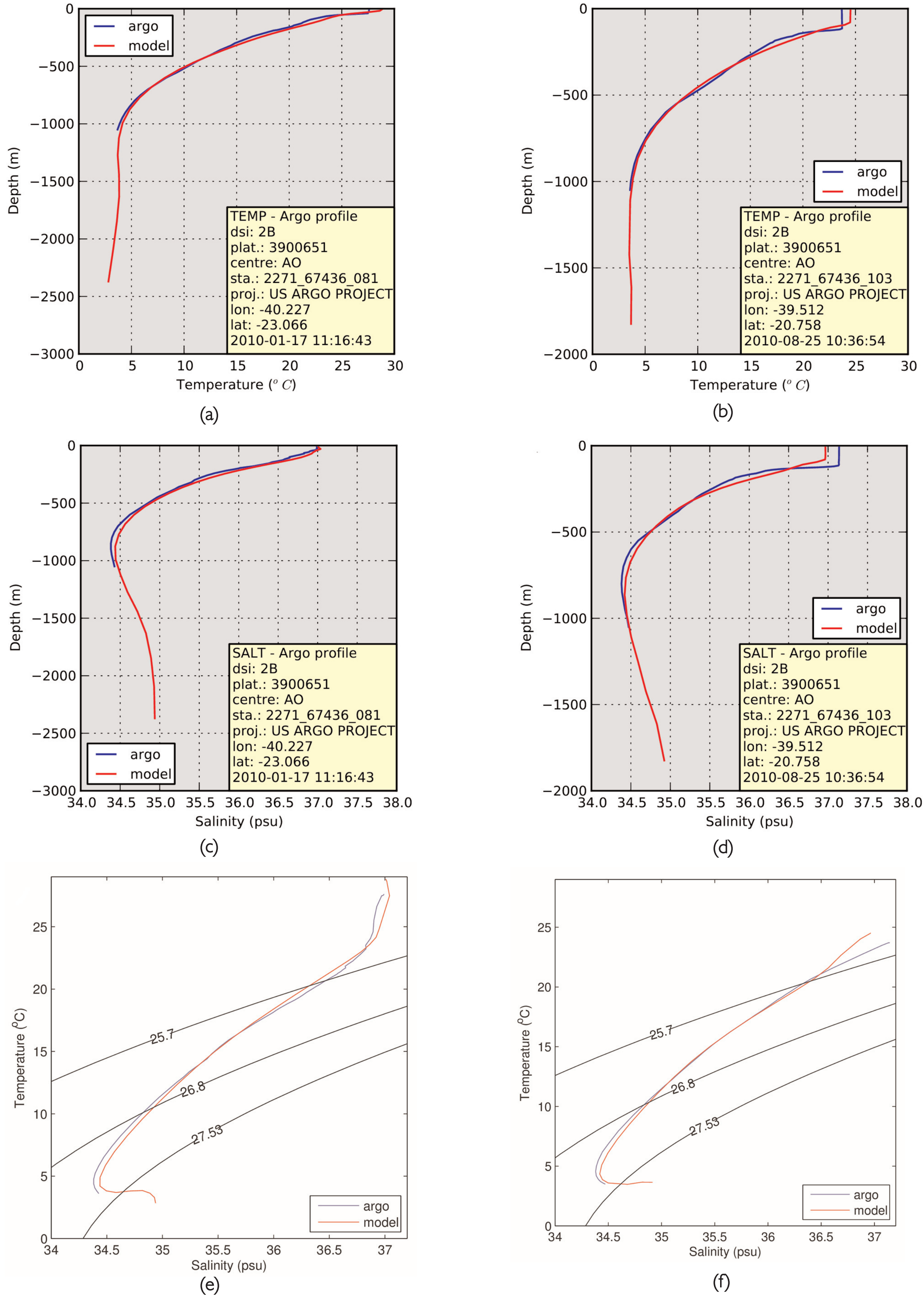


Fig 9: Model and ARGO profiles of potential temperature (a,b) and salinity (c,d) and the associated TS diagrams (e,f), near 40° W x 22°S at 17 January 2010 (a,c,e) and 25 August 2010 (b,d,f). The exact position of the profiles is shown in Fig 1 as two triangles

surface and depth integrated currents. Another output is the prediction of surface Lagrangian drifters' displacement for the model forecast days (these drifters initial location span the whole domain area providing an idea of the overall displacement of the surface waters). The site also shows SST images, produced based on AVHRR data of the satellite MetOp-A (from the EUMETSAT Meteorological Operational satellite programme), processed by Meteo-France/CMS-Lannion in the context of the OSISAF project[24]. The SSTs are presented for quick validation of the model surface temperature, and, of course, for any other purpose of the site visitors. An example of this product is Fig 8d.

Comparison of ARGO temperature and salinity profiles with model results is as well accessible online, as shown in Fig 9. The operational system everyday identifies, extracts and plots ARGO data inside the model domain. The daily locations of the available buoys are shown in a clickable Google map (Fig 10 for an example). Any other model related data can be added to the site with little effort. SSTs from several datasets, AVISO altimetry data, ARGO profiles, and other relevant data is routinely stored and used as part of the operational system.

The possibility of making the model input and output data available to the community is currently being analysed. In order to limit the volume of data transferred, the framework Open-source Project for a Network Data Access Protocol (OPeNDAP) is under consideration. OPeNDAP allows the extraction of sub-grids, subsets of variables, and allows server-side operations. For instance, the user can request the time average of some variable. If this involves the server doing some calculations, it may decrease the size of the data required by several orders of magnitude. OPeNDAP has many other features and advantages, and is already implemented to deliver data at most of the atmospheric/oceanographic data centres.

SUMMARY AND FUTURE PLANS

A robust operational modelling system of the Brazilian oceanic region was created and is under continuous development. The model underwent a 9.5 years spin-up being forced at the boundaries with climatological data from global simulations of the OC4 model, and at surface with data from NCEP (first nine years) and GFS 1°. The operational stage started on 1 July 2009 and is producing daily analysis and five-day forecasts. Currently the model uses OC12 boundary climatology and GFS 0.5° surface forcings. Some results and inputs can be accessed online.[26]

This first implementation of an automatic operational ocean modelling system in the Brazilian region is already producing ideas on the required observational facilities and on ways to optimise and improve the observing system. The observations will contribute to the improvement of the modelling results and predictability, and thus will extent the applicability of the operational system. The importance is recognised of having not only good model parameterisation but also high quality data for model inputs, like bathymetry, lateral boundary data, and surface atmospheric data. The observing system is, thus, a fundamental component of the operational oceanographic system. It provides data for model initialisation, quality control, validation and also provides hints for better parameterisations. In this manner, it can help contribute to improve the configuration of the ocean and atmosphere models towards higher realism and better understanding of the oceanic system, both in terms of dynamics and all possible applications related to the ocean.

Some modelling improvements are already underway and others are being studied, like the use of larger scale real-time ocean model data to force the lateral boundaries of the domain; the creation of a different grid which may allow a better representation of the mesoscale features of the region;

Fig 10: Example of locations of ARGO buoys in a Google map as shown in the REMO-OOF website. By clicking at the pointers the user accesses the corresponding ARGO and model plot of temperature and salinity profiles

the use of surface fluxes from higher resolution regional atmospheric models; ocean-atmosphere model coupling; implementation of the tidal forcing using the potential tides formulation instead of boundary sea level and barotropic currents; and introduction of model assimilation for the regular estimations of the initial ocean state. Work is also being done on data quality control, model validation, data control, storage, distribution and visualisation.

The modelling system creates open doors for endless research opportunities, namely higher resolution small scale regional models, biological and biogeochemical applications, etc.

ACKNOWLEDGEMENTS

This research was supported by PETROBRAS and approved by the Brazilian oil regulatory agency ANP (Agencia Nacional de Petróleo, Gás Natural e Biocombustíveis), within the special participation research project Oceanographic Modelling and Observation Network (REMO). Mauro Cirano was supported by a CNPq research grant. The authors thank OSISAF, MyOcean and OSTIA for the SST data, AVISO for the altimetric data and ARGO for the TS profiles.

REFERENCES

1. Le Traon P-Y, Rienecker M, Smith N, Bahurel P, Bell M, Hurlburt H and Dandin P. 2001. Operational oceanography and prediction – a GODAE perspective. In: Koblinsky CJ and Smith NR (Eds). Observing the Oceans in the 21st Century. GODAE project office, Bureau of Meteorology, pp529–545.

2. Harrison DE and Smith N. 2002. Ocean observing systems and prediction – the next ten years. In: Perry RI, Livingston P and Bychkov A (Eds). PICES Science: the first ten years and a look to the future. Vol. 22 of PICES Scientific Report. North Pacific Marine Science Organization, Sidney BC.

3. Brassington GB, Pugh T, Spillman C, Schulz E, Beggs H, Schiller A and Oke PR. 2007. *BLUElink> Development of operational oceanography and servicing in Australia*. J. Res. Pract. Inf. Tech. 39, 151–164.

4. Bahurel P, MERCATOR Project Team. 2006. Ocean weather forecasting. Springer, Netherlands, Ch. Mercator Ocean Global to Regional Ocean Monitoring and Forecasting, pp.381–395.

5. Drévillon M, Bourdallé-Badie R, Derval C, Drillet Y, Lellouche J-M, Rémy E, Tranchant B, Benkiran M, Greiner E, Guinehut S, Verbrugge N, Garric G, Testut C-E, Laborie M, Nouel L, Bahurel P, Bricaud C, Crosnier L, Dombrowsky E, Durand E, Ferry N, Hernandez F, Galloudec OL, Messal F and Parent L. 2008. *The GODAE/Mercator-Ocean global ocean forecasting: results, applications and prospects*. J. Oper. Oceanogr. 2008, 51–57.

6. Bell MJ, Forbes RM and Hines A. 2000. *Assessment of the FOAM global data assimilation system for real-time operational ocean forecasting*. J. Mar. Syst. 25, 1–22.

7. Pinardi N, Demirov E, Tonani M, Giacomelli L, Fratianni C, MFSPP partners. 2002. *Mediterranean ocean forecasting system: First phase of implementation*. In: Fiemming, N, Vallerga S, Pinardi N, Behrens H, Manzella G, Prandle D and Stei J. (Eds). Operational oceanography – Implementation at the European and regional scales. Proceedings of the second international Conference on EuroGOOS. Vol66 of Elsevier Oceanography Series. Elsevier, pp189–197.

8. Brusdal K, Brankart JM, Halberstadt G, Evensen G, Brasseur P, van Leeuwen PJ, Dombrowsky E and Verron J. 2003. *A demonstration of ensemble- based assimilation methods with a layered OGCM from the perspective of operational ocean forecasting systems*. J. Mar. Syst. 40–41, 253–289.

9. Shchepetkin AF and McWilliams JC. 2003. *A method for computing horizontal pressure-gradient force in an oceanic model with a non-aligned vertical coordinate*. J. Geophys. Res. 108, 1–34.

10. Shchepetkin AF and McWilliams JC. 2005. *The Regional Ocean Modelling System (ROMS): A split-explicit, free-surface, topography-following coordinates ocean model*. Ocean. Model. 9, 347–404.

11. Penven P, Debreu L, Marchesiello P and McWilliams JC. 2006. *Evaluation and application of the ROMS 1-way embedding procedure to the central California upwelling system*. Ocean. Model. 12, 157–187.

12. Haidvogel D, Arango H, Budgell W, Cornuelle B, Curchitser E, Lorenzo ED, Fennel K, Geyer W, Hermann A, Lanerolle L, Levin J, McWilliams J, Miller A, Moore A, Powell T, Shchepetkin A, Sherwood C, Signell R, Warner J and Wilkin J. 2008. *Ocean forecasting in terrain-following coordinates: Formulation and skill assessment of the Regional Ocean Modelling system*. J. Comput. Phys. 227, 3595–3624.

13. GLOBE TaskTeam and others (Hastings D.A, Dunbar PK, Elphingstone GM, Bootz M, Murakami H, Maruyama H, Masaharu H, Holland P, Payne J, Bryant NA, Logan TL, Muller J-P, Schreier G, and MacDonald JS). 1999. The Global Land One-kilometer Base Elevation (GLOBE) Digital Elevation Model, Version 1.0. Digital database on the World Wide Web (URL: http://www.ngdc.noaa.gov/mgg/topo/globe.html) and CD-ROMs, National Oceanic and Atmospheric Administration, National Geophysical Data Center, 325 Broadway. Boulder, Colorado 80305–3328, USA.

14. Coward AC and Cuevas BA. 2005. The OCCAM 66 Level model: physics, initial conditions and external forcing. Southampton Oceanography Centre Internal Document 99, Southampton Oceanography Centre, Southampton, UK.

15. Kanamitsu, M, Ebisuzaki W, Woollen J, Yang SK, Hnilo JJ, Fiorino M and Potter GL. 2002. *NCEP-DOE AMIP-II Reanalysis R-2*. Bull. Am. Meteorol. Soc. 83, 1631–1643.

16. Environmental Modelling Center. 2003. Global Climate & Weather Modelling Branch: The GFS Atmospheric Model. Tech. rep., NCEP Office Note 442, Camp Springs, Maryland, USA.

17. Egbert G, Bennett A and Foreman M. 1994. *TOPEX/Poseidon tides estimated using a global inverse model*. J. Geophys. Res. 99, 24821–24852.

18. Marta-Almeida, M, Ruiz-Villarreal M, Otero P, Covas M, Peliz A, Nolasco R, Cirano M and Pereira J. 2011. *OOF$_\varepsilon$: A Python engine for automating regional and coastal ocean forecasts*. Environ. Modell. Soft. 26, 680–682.

19. http://www.aviso.oceanobs.com/duacs

20. Stark JD, Donlon CJ, Martin MJ and McCulloch ME. 2007. *OSTIA: An operational, high resolution, real time, global sea surface temperature analysis system*. In: Marine challenges: coastline to deep sea. Oceans 07 IEEE Aberdeen, Scotland.

21. Campos EJD, Gonçalves JE and Ikeda Y. 1995. *Water mass structure and geostropic circulation in the South Brazil Bight – Summer of 1991*. J. Geophys. Res. 100, 18537–18550.

22. Rodrigues RR and Lorenzzetti JA. 2001. *A numerical study of the effects of bottom topography and coastline geometry on the Southeast Brazilian coastal upwelling*. Cont. Shelf Res. 21, 371–394.

23. Castelão RM and Barth JA. 2006. *Upwelling around Cabo Frio, Brazil: The importance of wind stress curl*. Geophys. Res. Lett. 33, L03602.

24. http://www.osi-saf.org

25. Stramma L and England M. 1999. *On the water masses and mean circulation of the South Atlantic Ocean*. J. Geophys. Res. 104, 20863–20883.

26. http://oceano.fis.ufba.br/oof