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Challenges of building an operational ocean forecasting system for small island regions: regional to local

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Abstract :

An ocean circulation forecasting model for the Madeira Archipelago is operational since May 2010. Developing a forecasting system for a small island oceanic region, deprived from in-situ observations, is a challenging task since there are limited ways to validate predictions. Furthermore, model resolution concurrent with insufficient computational power, locally available, are other limiting factors to consider. Regional models combined with the possibility to downscale solutions onto a higher resolution island-scale model is a way to overcome some of such limitations. Nevertheless, generalised regional models must be able to accurately represent the far-field and transport important features such as meddies onto the local systems; while island-scale models must have sufficient grid resolution as well as adequate physics and accurate atmospheric forcing to resolve the near-field phenomena. An island-induced cyclonic eddy event was successfully observed and forecasted with the current approach (regional-local). Generalised single (regional) model initiatives will prove to be insufficient to deal with mesoscale dynamic systems, islands and seamounts are important generators of mesoscale features in the NE Atlantic, with basin scale implications. The forecasting systems of the future should also consider upscaling valid local (island-scale) solutions onto Regional and/or Global models.

1. Introduction

Very little effort has been made to install and maintain operational platforms around some of the Atlantic Archipelagos. Despite the fact that Azores and Madeira Regions account for over 80% of the Portuguese Economic Exclusive Zone (EEZ), most of the operational and observational instruments have been installed in the Portuguese continental shelf. The Portuguese Hydrographic Institute of the Navy operates most of these platforms, producing tidal and wave forecasts for the whole EEZ, including the islands. Notwithstanding, after the two wave buoys (maintained by the Madeira Ports Authority) were damaged by a storm event in December 2013, forecasts validation were discontinued by lack of in-situ data. In fact, to the best of our knowledge, there has never been a long-term monitoring of environmental parameters (e.g. temperature, salinity, etc.), and there are no measurements of ocean currents speed and direction available in the Madeira region. The last systematic oceanographic campaign carried out in the Madeira EEZ, lead by the Portuguese National Institute for Fisheries took place between 1979 and 1984 (INIP, 1980; 1982; 1984a; 1984b). Sporadic oceanographic campaigns have collected some in situ information since then, but data are scarce, not catalogued and most often not freely available for scientific use.

Several research studies based on satellite, numerical modeling and in situ observations were carried out in recent years (e.g. Caldeira et al., 2002; 2014; Couvelard et al., 2012; Grubišić et al., 2015). The meteo-oceanographic phenomena known to occur around the Madeira Island are mostly due to these scientific efforts. The environmental consultancy community often cites these scientific results in their reporting (Campuzano et al., 2010), yet many coastal developments around the island were built without proper environmental assessments. The lack of oceanographic information lead to the building of coastal infrastructures such as the 'Marina do Lugar-de-Baixo' which currently adds up to ~100 million euros of public money spent in repair costs, due structural damages during ‘atypical’ wave events. The initial predicted cost for this infrastructure was ~7 million euros. Other projects which benefited from EU funds, were also not successful implemented. In the previous frameworks (e.g. FP6; FP7), EU approved funding for infrastructural investments for developing countries like Portugal, without considering (proper) environmental assessment. The Directive 2000/60/EC was Europe's key tool for protecting the quality of its coastal waters. It established a framework for Community action in the field of water policy, and obligated Member States to publish a management plan for each coastal basin within the first 9 years. In January 2014, Portugal had failed to adopt and publish the 'Sate of the Marine Environment' in the scope of this Directive.

On a volunteer basis, and in the scope of several scientific projects, efforts were made to implement the first and the only ocean circulation forecasting system currently available for the Madeira Archipelago. At first, the system was available through a University website (http://wakes.uma.pt), however most recently (January 2014) it has been moved to CIIMAR-Madeira, a non-profit organization in order to be freed from the administrative burden of academic institutions and continue to be improved (http://ciimarmadeira.org). The development of the Madeira ocean circulation forecasting system started in December 2009 and the first forecasts were available online in May 2010. Apart from the ocean forecasting system itself, the institution also provides a series of satellite observations for comparison. To overcome the limited computational resources available on the island, the forecasts and observations are processed on a High Performance Computational (HPC) unit located in Oporto (the second largest city in the north of Continental Portugal). Only a partial amount of the results are transferred to the local servers (on the island) for further processing.

The aim of this article is to document all the efforts, challenges and results achieved during the last 5 years, after the implementation of the first operational oceanic system in the region. After this introduction, the forecasting system components and procedures are described in section 2; section 3 addresses some the efforts that were made to cross-validate model predictions, whereas section 4 offers some general conclusions and future prospects.

OCEANIC FORECASTING SYSTEM: REGIONAL TO ISLAND-SCALES

Implementing an open-ocean circulation forecasting system on a small island poses several logistical and technical difficulties. Madeira Island is located ~400 km offshore of the African Coast and ~900 km from the European Continent (Portugal). Running numerical models with four open-boundaries (OB) can be unstable (i.e. hard to keep mass conservation) and climatic nudging often provides inaccurate reference states to produce daily forecasts. Climatic profiles of temperature and salinity are often very different from daily and/or seasonal profiles. Moreover, large numerical domains at medium to high resolutions (temporal and/or spatial) have high computational costs, thus the availability of a global and/or regional model solutions to force local models permits the production of forecasts for isolated archipelagic regions such as Madeira.

The Madeira ocean circulation modeling system was initiated with climatological data at the oceanic boundaries and reanalysed atmospheric solutions from the National Centers for Environmental Prediction (NCEP). The spin-up period lasted three (model) years and computed solutions until April 2010. The forecasting mode started in May of 2010, whereby the ocean climatology was replaced by the

Regional model solution (MERCATOR) and the atmosphere by its forecasting counterpart i.e. Global Forecasting System (GFS). Every week, the MERCATOR model solution (PSY2V4R4) is used to force the Regional Ocean Modeling System (ROMS).

The GFS at 1/4º, provides the atmospheric wind, humidity, pressure, temperature, precipitation and radiation to the Regional Ocean Modeling System (ROMS). ROMS uses this data to calculate the air-sea fluxes internally through the bulk formulae. The atmospheric fields (7 days hindcast + 7days forecast) are renewed every day, whereas the oceanic model boundary fields (7 days hindcast + 7 days forecast) are renewed once a week. Every Wednesday (T0) the whole oceanic forecasting system renews 7 days of hindcast (incuding nowcasts) for the previous 7 days and produces 7 new days of forecasts (figure 2). GFS reanalysis (hindcast) products are identified in the figure as NCEP to differentiate form its forecast counterpart (GFS).

The MERCATOR PSY2V4R4 system uses version 3.1 of NEMO ocean model. The physical configuration is based on the tripolar ORCA grid type with a horizontal resolution of 9 km at the equator, 7 km at Cape Hatteras (mid-latitudes) and 2 km toward the Ross and Weddell seas. The 50-level vertical discretization retained for these system has 1 m resolution at the surface decreasing to 450 m at the bottom, with 22 levels within the upper 100 m. “Partial cells” parametrization was chosen for a better representation of the topographic floor (Barnier et al., 2006) and the momentum advection term is computed with the energy and enstrophy conserving scheme proposed by Arakawa and Lamb (1981). The advection of the tracers (temperature and salinity) is computed with a total variance diminishing (TVD) advection scheme (Lévy et al., 2001; Cravatte et al., 2007). The high frequency gravity waves are filtered out by a free surface (Roullet and Madec, 2000). A laplacian lateral isopycnal diffusion on tracers and a horizontal biharmonic viscosity for momentum are used. In addition, the vertical mixing is parametrized according to a turbulent closure model (order 1.5) adapted by Blanke and Delecluse (1993), the lateral friction condition is a partial-slip condition with a regionalisation of a no-slip condition (over the Mediterranean Sea) and the Elastic-Viscous-Plastic rheology formulation for the LIM2 ice model (hereafter called LIM2_EVP; Fichefet and Maqueda, 1997) has been activated (Hunke and Dukowicz, 1997). The bathymetry used in the system comes from a combination of interpolated ETOPO and GEBCO8 (Becker et al., 2009) databases. The monthly river outflow climatology is built with data on coastal runoffs and 100 major rivers from Dai and Trenberth (2002) together with an annual estimate of Antarctica ice sheets melting given by Jacobs et al. (1992).

The atmospheric fields forcing NEMO are taken from the ECMWF (European Centre for Medium-Range Weather Forecasts) Integrated Forecast System. A 3 h sampling is used to reproduce the diurnal cycle, in order to force the upper layers of the ocean model, with a thickness of 1 m for the uppermost level. Momentum and heat turbulent surface fluxes are computed from CORE bulk formulae using the usual set of atmospheric variables: surface air temperature at a height of 2 m, surface humidity at a height of 2 m, mean sea level pressure and wind at a height of 10 m. Downward longwave and shortwave radiative fluxes and rainfall fluxes are also used in the surface heat and freshwater budgets. MERCATOR forecasting system does not include tides.

The data in MERCATOR are assimilated by means of a reduced-order Kalman filter with a 3D multivariate modal decomposition of the forecast error. It includes an adaptive-error estimate and a localization algorithm. A 3D-Var scheme provides a correction for the slowly-evolving large-scale biases in temperature and salinity (Dombrowsky, et al., 2013). 'MyOcean' altimeter data, in situ temperature and salinity vertical profiles from ARGO drifters, and satellite Sea Surface Temperature (SST) are jointly assimilated to estimate the initial conditions for numerical ocean forecasting. In addition to the quality control performed by data producers, the system carries out an internal quality control on temperature and salinity vertical profiles in order to minimize the risk of erroneous observed profiles being assimilated in the model. Note that in addition to Jason-2 and CryoSat-2 altimetry observations, Jason-1 altimetry observations are assimilated until June 2013 (until the end of the mission on June 21st) and SARAL/Altika observations start being assimilated in August 2013. As expected, the assimilation only pursued in hindcast products to produce the analysis. The analysis is not performed at the end of the assimilation window but at the middle of the 7-day assimilation cycle. The objective is to take into account both past and future information and to provide the best estimate of the ocean centred in time. With such an approach, the analysis, acts like a 'smoother algorithm' of the hindcast solutions.

In October 2010, the Envisat altimeter was brought to a lower orbit, which has led to a slight degradation of data quality (Ollivier and Faugere, 2010). This degradation is due to the fact that Sea Level Anomalies (SLA) is computed with respect to a Mean Sea Surface of lower quality because it falls outside the historical repeated track. This is particularly true at high latitudes where no tracks from other missions are available. For this reason, the Envisat error was increased by 2 cm over the entire domain and by 5 cm above 66° N. In view of this, 2-5 cm differences as calculate for the North East Atlantic (NEA) region are not as significant as originally considered.

To resolve the island-scales the ROMS-AGRIF numerical system was used, which is described in detail in Shchepetkin and McWilliams (2003, 2005). ROMS is a split-explicit, free-surface and terrain-following vertical coordinate oceanic model, where short time steps are used to advance the surface elevation and barotropic momentum equation, and a larger time step is used for temperature, salinity, and baroclinic momentum. ROMS employs a two-way time-averaging procedure for the barotropic mode which satisfies the 3D continuity equation. The specially designed predictor-corrector time-step algorithm allows a substantial increase in the permissible time-step size. The third-order, upstream-biased, dissipative advection scheme for momentum allows the generation of steep gradients, enhancing the effective resolution of the solution for a given grid size (Shchepetkin and McWilliams, 1998). For tracers, the RSUP3 scheme, where diffusion is split from advection, is used and represented by a rotated geopotential biharmonic diffusion scheme (Marchesiello et al., 2009) in order to avoid excessive spurious diapycnal mixing associated with sigma coordinates. Explicit lateral viscosity is null everywhere in the model, except in sponge layers near the OB where it increases smoothly on several grid points. A K-Profile Parametrization (KPP) boundary layer scheme (Large et al., 1994) accounts for the subgrid-scale vertical mixing processes.

The model grid, the atmospheric forcing, the initial and boundary conditions were all built using an adapted version of the ROMSTOOLS package (Penven et al., 2007). The bottom topography is derived from the GEBCO 30″ resolution database (www.gebco.net). Despite the current implementation of a new pressure gradient scheme associated to a modified equation of state that limits computational errors of the pressure gradient (Shchepetkin and McWilliams, 2003), the bathymetry still needs to be smoothed, so that the slope parameter $r = \Delta h/2h$ (Beckmann and Haidvogel, 1993) remains lower than 0.2. To ensure acceptable resolution of the upper ocean, we use 35 vertical levels with stretched s-coordinates, using surface and bottom stretching parameters $\theta s = 6$, $\theta b = 0$, respectively (Song and Haidvogel, 1994). At the lateral boundaries facing the open ocean, a mixed passive-active, implicit, radiation condition (Marchesiello et al., 2001), connects the regional model to the global model inputs (one-way, offline nesting). Two nested grid inside ROMS allow the increase in spatial resolution from ~3 km (1/32º) up to approximately 900 m (1/118º), near the coast (see figure 1). The Adaptive Grid Refinement in Fortran (AGRIF) package implementation in ROMS was thoroughly discussed in Debreu et al. (2012). One of the major advantages of AGRIF is the ability to manage an arbitrary number of fixed grids and an arbitrary number of embedding levels. In the Madeira forecasting system, AGRIF was used in two-way mode between parent and child grids, thus eddies, fronts and oceanographic dynamic structures were allowed to move between the two model-grids. In order to preserve the CFL criterion, for a typical coefficient of refinement (say, a factor of 3; e.g. a 5 km resolution grid embedded in a 15 km grid), for each parent time step the child must be advanced using a time step divided by the coefficient of refinement as many time as necessary to reach the time of the parent (Blayo and Debreu, 1999; Debreu and Blayo, 2008; Debreu et al., 2010; 2011). In the Madeira system, grid refinement between the two adjacent domains was kept to a factor of 3 (900m child-grid embedded in the 3 km parent-grid). A Newtonian nudging is used to adjust Mercator data to ROMS dynamics at lateral boundaries of the parent-grid only. Nudging is performed during the hindcast and nowcast steps and released during forecast.

A Shell script manages the whole procedure automatically: download and pre-processing, hindcast and forecast simulations, post-processing, data storage and preparation of the next nowcast/forecast cycle.

MODEL VALIDATION

Despite the fact that the model is operational in forecasting mode since May 2010, there was a need to discard historical results in order to clear space for more recent ones. Nevertheless, the 2014 results were preserved enabling an evaluation of the models performance relative to observations.

Representing the sea surface

In general, MERCATOR represents well the NEA (known) sea surface circulation patterns. In some instances, MERCATOR under- or over-estimates current speed but in general most of the surface dynamics are well represented. In order to analyse the accuracy of the model, the Brier skill score (SS) developed by Wilks (2006), was used.

$$SS = 1 - \frac{\sum_{k=1}^{n} [\frac{1}{M} \sum_{m=1}^{M} (Forecast_m - Obs_m)^2]}{\sum_{k=1}^{n} [\frac{1}{M} \sum_{m=1}^{M} (Ref_m - Obs_m)^2]}$$

The reference data (Ref_m) are the climatological values obtain from WOA13 (Locarnini et al., 2013; Zweng et al., 2013); the observed values (Obs_m) were extracted from the ARGO profiles (http://www.argo.ucsd.edu) available for the N. Atlantic region of the model domain, whereas the $Forecast_m$ were the model calculated values. When the SS values are close to 0 the model results are close to the climatology; for SS values close to 1, the model offers a better estimate, comparatively to the climatology i.e. observed values were far from climatological values. Negative values represent erroneous predictions. In order to obtain several ARGO profiles in the same region to compare to model profiles, regions of 4º of latitude by 4º of longitude were considered. A total of 9215 ARGO profiles were used for the 2014 SS calculations and 11337 for 2015. Several depth ranges were evaluated: i) 0-2000m; ii) 10-500m; iii) 501-1000m; iv) 1001-1500m; v)1501-2000m. Data for 2014 and 2015 were independently considered.

As can be depicted from figure 3, MERCATOR forecast for temperature is often better than the salinity forecasts (values closer to 1). Perhaps due to the larger ARGO dataset available to assimilate in hindcast-mode, 2015 showed an improvement in the model skill factor, relatively to 2014. Less accurate prediction are often associated to highly dynamic regions such as the Gulf Stream, Azores Current and Equatorial regions. Although not shown, temperature between the 10-500m depth range were very well predicted by the model, remaining positive in the deeper layers, particularly in the center and northern parts of the MERCATOR model domain. The analysis also showed a substantial decrease of available ARGO data in the deepest layers to compare with the model i.e. 1001-1500m; 1501-2000m; thus we choose to show an integrated calculation considering as much of the data available as possible.

Considering that the surface currents are well represented by the regional model, the comparisons between MERCATOR and AVISO (Archiving, Validation and Interpretation of Satellite Oceanographic) for 2014 shows striking similarities. The strong Eddy Kinetic Energy (EKE) signal from the Gulf Stream, NW of the Azores, as well as on the Azores Front are present in both datasets (figure 4). Seasonal comparisons (not shown) also show similar results. The geostrophic currents (ug, vg) were calculated from Sea Surface Height (SSH) for both datasets, which in turn were used to calculate EKE (=0.5*[ug^2+vg^2]). Most notable differences between model and AVISO EKE are in the NW of Portugal, over the Galician seamount, where the model shows stronger EKE activity than AVISO. North of the Azores and south of the Canary Archipelago, the model shows weaker EKE than AVISO. Considering that these small islands are 50 km wide (or less), MERCATOR with 10 km resolution (1/12º) is clearly not adequatly resolving all the island induced perturbations. If we consider the Rossby deformation radius (Rd=Nh/*f)*, where N is the Brunt-Vaisala frequency (the vertical density gradient is parametrized as $N^2 = -g\, \partial z\, \rho/\rho$), h is the surface layer thickness (i.e. depth of upper thermocline) and *f* the Coriolis parameter (*f*=2Ωsinφ, where Ω is the angular speed of the earth and φ is the latitude); considering typical NEA profiles near Madeira and Canary islands we obtain 10 < Rd < 25 km. Therefore, *a priori* small mesoscale oceanographic features (10-20km) are not going to be appropriately resolved by the 10 km model grid.

The regional model (ROMS) by increasing its spatial resolution around the islands improves the representation of surface currents, relative to the observations. Figure 5 shows how ROMS represents the formation of a cyclonic vorticity on the 12th of July 2014 detected with altimetry data, whereas MERCATOR misses an accurate representation of this phenomenon. Although the global model represents well the basin scale currents as shown above, higher-resolution regional models are essential to calculate the island-induced mesoscale dynamics.

Figure 6 shows further evidences of the occurrence of this cyclonic structure which formed leeward of Madeira. Cyclones induce upwelling of cold, nutrient-rich water to the surface promoting phytoplankton growth. The Moderate-resolution Imaging Spectroradiometer (MODIS) is a radiometer flying onboard the NASA Terra and Aqua satellite platforms. MODIS Aqua Global Level-3 Mapped Thermal SST products consists of Sea Surface Temperature (SST) data with 4 km resolution extracted during daytime. These MODIS SST products captured the cyclonic eddy activity forming on the Madeira region during summer months. Figure 6a shows the cold sea surface signature of the cyclonic eddy, forming SW of Madeira Island on the 15th June 2014. The eddy core has temperatures as low as 19.2 ºC, whereas in the surrounding regions the highest SST reaches 22.7 ºC. Figure 6b shows a 'bloom' of sea surface chlorophyll with concentrations of 0.1 mg/m^3 from a concurrent MODIS image for the same day. Madeira waters are generally considered oligotrophic (with small productivity), therefore high chlorophyll values are not expected, unless the ocean currents pumps nutrients to the sea surface, promoting phytoplankton growth, as it is the case in core of cyclonic eddies. ROMS forecasted SST (parent grid) also shows the formation of the June 2014 cyclonic eddy.

Although with different absolute SST values, the eddy size and location are very well resolved by the ROMS. As can be seen from both the MODIS-SST image and ROMS-SST (figure 6a and 6c), small features such as the advection of coastal water into the eddy are also depicted by both (measurements and by the model). The model is 1-2 ºC cooler when compared to the satellite measurements. Apart from the cyclonic eddy the model also resolves an anticyclonic vortice observed to the south of the cyclonic one. In fact, a vorticity map of the sea surface currents, derived from altimetry measurements also shows these dipole features forming leeward of Madeira (figure 6d). Due to the interaction of the bathymetry with the incoming ocean currents, Madeira Island is know to induce the formation of both cyclonic and anticyclonic eddies, and there are several observations of these reported in the scientific literature (Caldeira et al., 2002; 2014). The forecast of these island-induced features are important in order to be able to use the system to forecast pollution events, larval transport, costal drift, search and rescue missions, etc.

Due to the formation of atmospheric von Kármán vortex streets, Madeira leeward side is often exposed to higher solar radiation inducing the formation a warm 'skin layer' (1-5 m), particularly during summer months. This layer is well depicted by the satellite sensors and it has been frequently observed and documented (Caldeira et al., 2002; Caldeira & Tomé, 2013). Nevertheless, recent (unpublished) studies by the authors have shown that without a high-resolution coupled atmosphere-ocean modeling system is not possible to (numerically) resolve this 'skin layer' effect in a realistic manner. Therefore, considering that nor the global model nor ROMS are currently coupled to high-resolution atmospheric model fields, absolute SST values will be hard to obtain with the current forecasting systems.

Figure 7 shows the SST anomalies calculated from subtracting satellite measurements from model calculations (MERCATOR 7a; ROMS 7b), confirming that while ROMS under-estimates (-1 to -2 ºC) SST values MERCATOR over-estimates absolute values by +/- 1 ºC. Notwithstanding, the importance of this 'skin-layer' to mediate air-sea interactions, it is not expected that this imprecision would compromise the representation of the deeper layer dynamics. Previous studies and observations have suggested this to be a daily feature with 24 h cycles, affecting the first 5m of the water column, during the warmer months (e.g. Caldeira et al., 2002).

Water mass representation

In terms of water mass representation, the Theta-S analysis shows a good relationship between MERCATOR-forecasts and ARGO profiles, for 2014 (figure 8). This is somewhat expected since most of these profiles are assimilated onto MERCATOR-hindcasts. Most interesting to observe however, is the fact that in periods when the surface mixed layer is destroyed (Winter and Autumn), there are less variability when compared to periods with greater atmospheric and surface gradients, such as in the summer months. Thus, the seasonal variability is also well depicted by MERCATOR (not shown).

Despite of having no data assimilation, the regional model (ROMS) maintains the realistic representation of the water masses around the Madeira Archipelago, inherited from the MERCATOR model solution. Figure 10 shows a comparison between ARGO and ROMS Theta-S profiles for the whole year (2014). ROMS shows slightly more variability at the surface but it keeps a realistic representation of the North Atlantic Central Surface Water (NACSW; T: 4 – 20 ºC; S: 35 – 36.8 PSU); of the Mediterranean Intermediate Water (MIW; T: 6 – 11.9 ºC; S: 35.3 – 36.5 PSU); as well as of the North Atlantic Deep Water (NADW; T: 3 – 4 ºC; S: 34.9 - 35. 0 PSU). The MIW is a prominent feature in the NEA and it often reaches the Madeira Island region between 1000 and 2000 m. In fact, the Black scabbardfish (*Aphanopus carbo*, Lowe 1839) is an important commercial exploited fish that lives in this MIW layer. Thus forecasting the MIW occurrence around Madeira could be important to support fish stock management in the future.

The Mediterranean outflows the Gibraltar Strait in two main layers (a.k.a. cores): an upper layer, between 600 and 1000 m and a lower layer which forms between 1000 and 2000 m (e.g. Ambar et al., 2008). The interaction of this water with the topographic promontories and seamounts breaks the outflow inducing the generation of vortices, often named after its dominant water mass component i.e. MEDDIES – Mediterranean Eddies. Both cyclones and anticyclones are formed during these interactions. (e.g. Richardson et al., 2000), with typical radii varying between 10-50 km (Bower et al., 1997). Numerical models have successfully resolved these vortices which result from the interaction of MIW with the seamounts. Aguiar et al. (2013), has completed a 20 year (numerical) census of Meddies for the NEA (see also Carton et al., 2002; Aiki and Yamagata, 2004). Since Meddies are responsible for the re-distribution of salt on the North Atlantic Basin, forecasting their occurrence, tradjectory and interactions is of outmost importance.

As shown above by the Theta-S analysis, the MERCATOR does solve for the Mediterranean Outflow layer and their interaction with the Iberian shelf and with the Madeira-Tore seamounts, which results in the generation of MEDDIES (figure 10). There are also two main trajectories for the MIW in MERCATOR: a northward trajectory, which is often associated with the upper layer (600-1000 m), and a southward traveling outflow, which is associated with the lower layer (1000-2000 m). Most of the MIW/Meddies that reached Madeira travel in this lower MIW layer (figure 10).

The MIW interacts strongly with the Madeira Islands, often reaching the Archipelago from the northeast. As it occurs around the NEA seamounts the

Archipelago bathymetry also seems to induce further fragmentation and re-distribution of Mediterranean waters (Figure 11).

Figure 11a shows the incoming salty outflow that reaches Madeira at 1500 m, interacting with the island (27th of June 2014). Without having this signal from MERCATOR transported onto ROMS, it would have not been possible to forecast MEDDY interactions within the islands, in the first place. Therefore apart form having a local model with adequate grid resolution solving the near-field, it is equally important that the far-field is being adequately represented. Meddies are features often misrepresented in climatic models and not well resolved in many numerical studies of the NEA. Thus, forecasting them is a challenging task yet extremely important to fully represent the regional dynamics.

Figure 11b shows the EKE derived from ROMS velocity fields at 1500 m enhancing the intense vortex generation at these depths occurring around the islands (30th June 2014). The vortices are 20 - 50 km wide, and are well depicted by the 3 km ROMS grid (as in Aguiar et al., 2013). It is important to note that Madeira is about 1000 km from the source of MIW, yet Meddies are often observed interacting and/or fragmenting in this region, hence their importance in the redistribution of salt across the Atlantic Basin.

GENERAL DISCUSSION AND FUTURE WORK

As it was demonstrated herein, building and maintaining a realistic forecasting system for a small island region is a challenging task. Islands are small territories, often isolated in deep oceanic regions and models need to consider adequate grid resolutions and four stable OB conditions. Large high-resolution domains are expensive to calculate in small computational structures, often available in these remote archipelagos. Thus most often island forecasting systems depend on global and/or basin (regional) scale models to provide adequate far-field conditions, as well as on powerful computational resources available over the internet, yet Global and Regional forecasting systems do not realistic represent the oceanic dynamics without resolving these island-induced features. In the Madeira Island case, MERCATOR weekly forecasts were used to force a Regional Ocean Circulation Modeling System. With data assimilation MERCATOR maintains an adequate representation of both, the surface and deep-water systems, and the currents and water masses that are known to reached Madeira compare well to satellite and *in situ* datasets. MERCATOR delivers MEDDIES and MIW to the Archipelago, and the regional model can resolve the interaction processes. At the island (coastal) scales data is often scarce and mesoscale processes are hard to validate, nevertheless a cyclonic eddy episode was accurately forecasted by ROMS and detected by satellite observations. High resolution global forecasting models are not sufficient to resolve all the near-field dynamics which occur around these small islands. Forecasting atmospheric island-scale phenomena, such as the warming of the sea surface 'skin-layer' due to intense solar radiation, as it often occurs in the lee of Madeira during summer months, is not achievable without a fully couple atmospheric-oceanic system. Thus apart from promoting a (generalized) European effort to improve one forecasting system such as MERCATOR, EU should also start to consider the geophysical processes that often form around these small Atlantic Archipelagos and seamounts, thus increasing efforts to promote numerical studies concurrent with intense local observations. The climatic representation and importance of these mesoscale (localized) phenomena have only recently started to be considered (e.g. Fox-Kemper et al., 2011). Future forecasting systems will need to better resolve these island-induced phenomena, including continuing the validation of numerical calculations with adequate observations, which are very scarce for these fine scales. Upscaling these validated model solutions onto Regional and Global systems using assimilation techniques might also be a way of addressing the limitations of these generalized (Global) systems. In brief, Global systems would continue to provide the forcing fields for small regional forecasting systems, which in turn should aim to adequately resolve and validate the local dynamics, before being incorporate back onto the Global system, using data-assimilation techniques. The downscaling of generalized models onto regional models could benefit from an upscaling of representative local solutions. It is not expected that a singular numerical approach and/or a single institution will be able to manage data collection in all the North Atlantic sub-regions at all scales, thus monitoring islands and seamounts to improve global and regional forecasting systems can be considered somewhat visionary, particularly if Europe aims to achieve a truly Atlantic dimension, with their forecasting systems.

In the near future, the current configuration should be replaced by a coupled atmosphere-ocean system in order to improve the representation of the SST fields. Recent (unpublished) studies have demonstrated that the best way to replicate the Madeira warm wake which often occurs in the leeward side of the island is to have the correct radiation fluxes, which can only be achieved with coupled systems. In the scope of the recently formed Oceanic Observatory of Madeira (OOM: http://oom.arditi.pt), the collection of new datasets are also expected to help improve the island forecasting system.

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FIGURE LEGENDS

Figure 1 – Graphical representation of the Madeira forecasting system whereby the MERCATOR model is nudged onto ROMS. ROMS has two sub-domains with grid-resolutions of 1/36º (ROMS-1) and 1/118º (ROMS-2). The two ROMS domains are coupled in two-way mode using AGRIF.

Figure 2 – Timeline of the Madeira oceanic forecasting system. Atmospheric forcing is renewed daily, whereas the oceanic lateral boundary forcing (MERCATOR) is renewed weekly, nevertheless the modeling forecasting system renews forecasts every day in order to update atmospheric conditions. NCEP represent hindcast atmospheric forcing (reanalysis), whereas GFS represent forecast only products. Weekly-MERCATOR product has 21 days (14 hindcasts and 7 forecasts), thus allowing to advance hindcast / forecasts every day.

Figure 3 – Skill Score (SS) values for MERCATOR. When SS is close to 0 the model results are close to the climatology; left panels are for temperature; righ panels salinity. For SS values close to 1, the model offers a better estimate, relative to the climatological value i.e. observed values are far from climatological range. Negative values represent an erroneous prediction. For (a) 2014; (b) 2015.

Figure 4 – Mean EKE (cm^2/s^2) calculated from (a) MERCATOR; (b) AVISO for 2014.

Figure 5 – Relative vorticity (X10^-5 s^-1) for the Madeira Archipelago Region (27-Junho-2014), comparing ROMS (a) with (b) MERCATOR. The mesoscale island-induced cyclonic eddy (C1) is well resolved in ROMS (see figure 6 for observations).

Figure 6 – Cyclonic eddy episode April-June 2014. Best concurrent independent observations (a) SST (ºC); (b) Chlorophyll-a concentration (mg/m^3); (c) ROMS-SST (ºC); (d) Vorticity calculated from altimetry data (X10^-5 s^-1). Same cyclonic (C1) and Anticyclonic (A1) mesoscale eddies are observed in (c) and (d).

Figure 7 – Sea surface maps of SST anomalies, comparing (a) MERCATOR-SST and (b) ROMS-SST; with satellite derived SST (GHRSST), for the 27th June 2014.

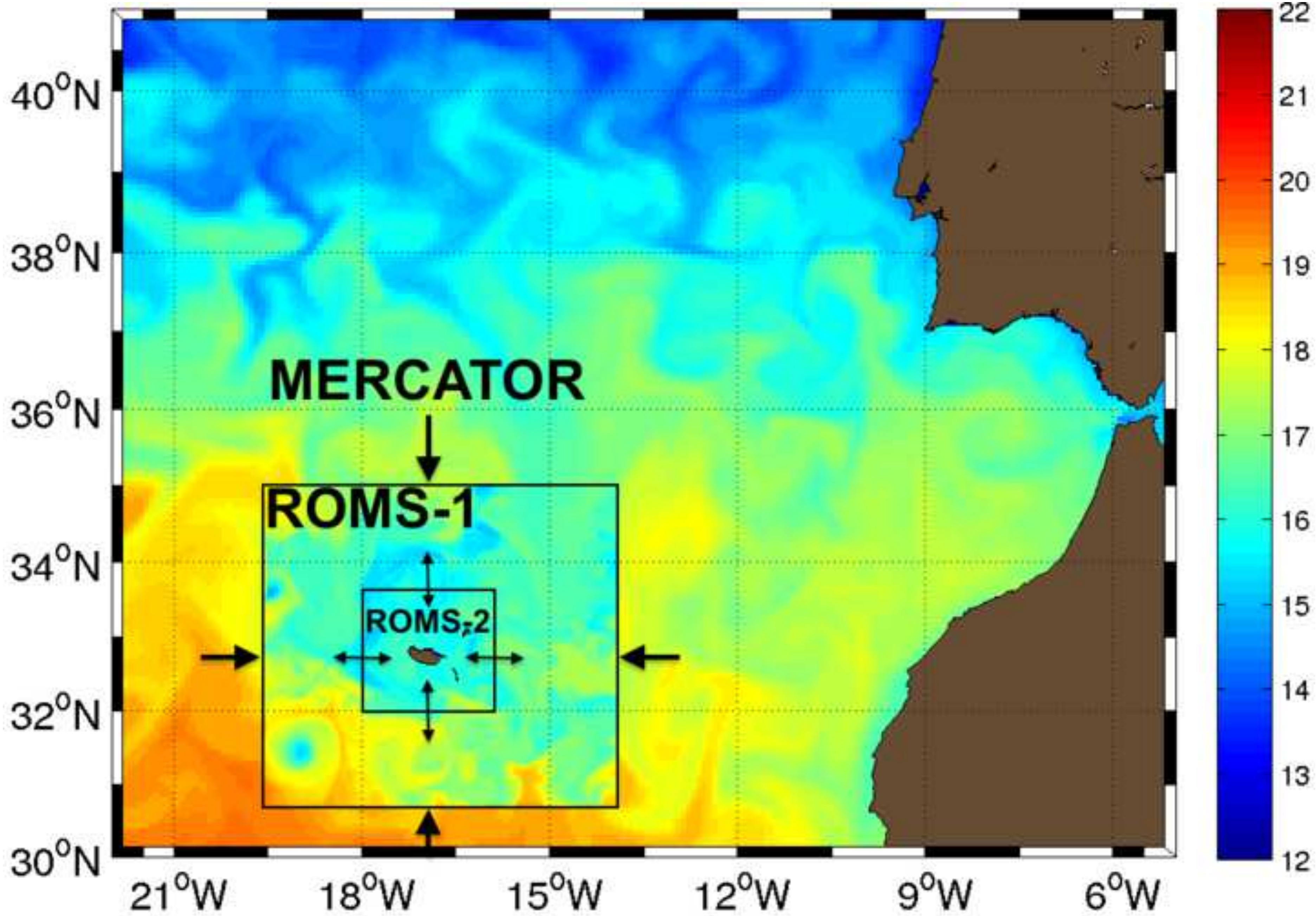
Figure 8 – Map showing (a) the MERCATOR grid points (black dots) and the CORIOLIS-ARGO profiles (red dots); (b) Theta-S diagrams comparing MERCATOR T-S variability with the observed Coriolis-ARGO dataset for 2014.

Figure 9 – Comparison between ROMS profiles (black dots) and CORIOLIS-ARGO profiles (red dots) in the Madeira Archipelago Region during 2014.

Figure 10 – Maps of salinity (PSU) and currents at 1941 m extracted from MERCATOR for the 27th of April 2014. The MIW lower layer transports MEDDIES southward to the Madeira region. Bathymetry isolines sown for 1000 to 3000m every 500m.

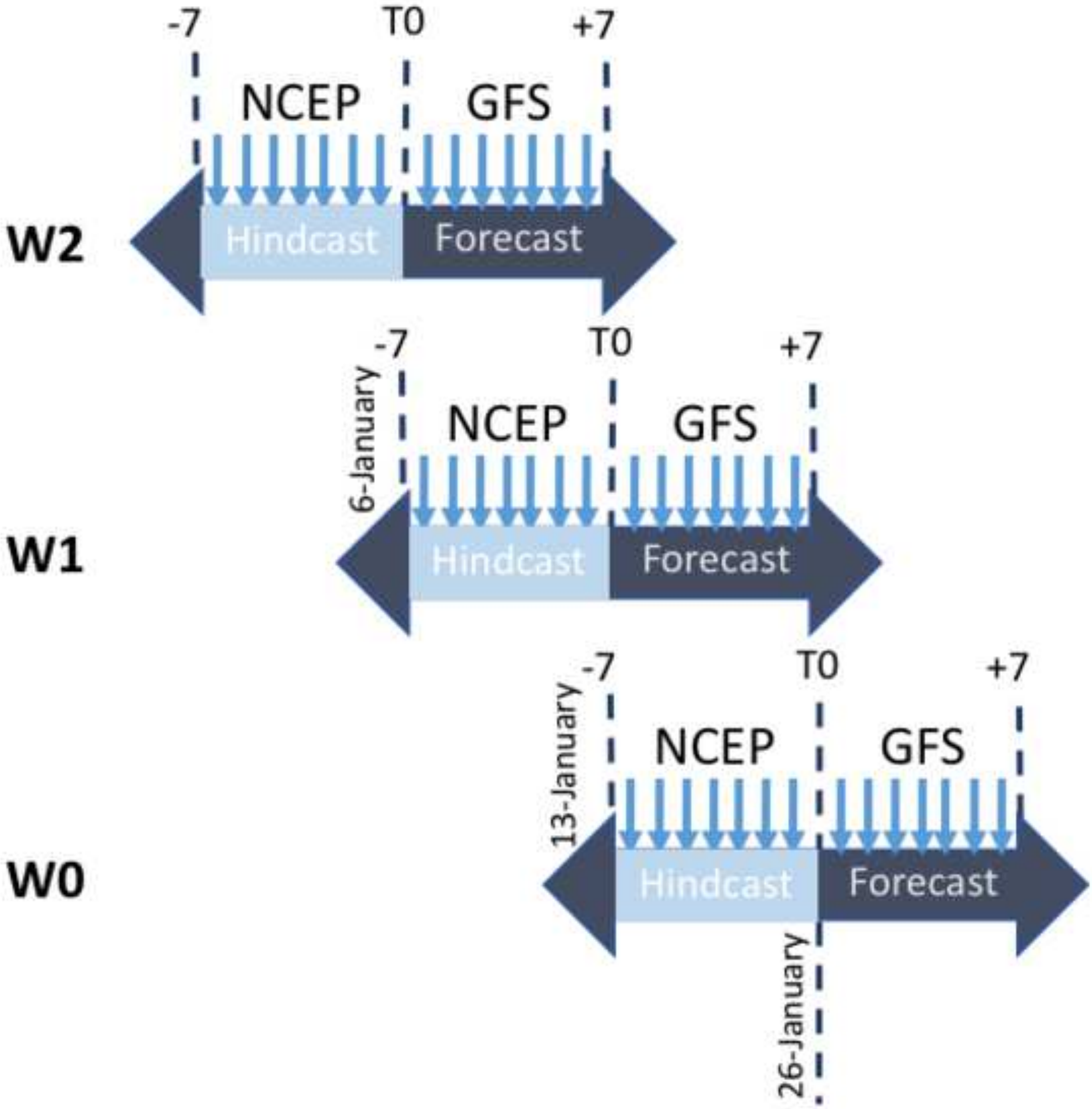
Figure 11 – (a) 3D plot representing ROMS Salinity (PSU) over the bathymetry showing the incoming Mediterranean at 1500 m interacting with the islands, for the 12th of June 2014; bathymetric isolines (white) from 0 to 1500m every 500m. (b) Relative vorticity (X10^-6 s^-1) calculated from ROMS velocity fields at 1500 m for the 30th June 2014, showing vortices forming due to the interaction of the incoming mediterranean flow with island's bathymetry. Showing bathymetric isolines from 500 to 2500m every 500m.

Figure_1



MERCATOR
ROMS-1
ROMS-2
40°N
38°N
36°N
34°N
32°N
30°N
21°W
18°W
15°W
12°W
9°W
6°W
22
21
20
19
18
17
16
15
14
13
12

Figure_2



-7
T0
+7
NCEP
GFS
W2
Hindcast
Forecast
6-January
-7
T0
+7
NCEP
GFS
W1
Hindcast
Forecast
13-January
-7
T0
+7
NCEP
GFS
W0
Hindcast
Forecast
26-January

Figure_3a

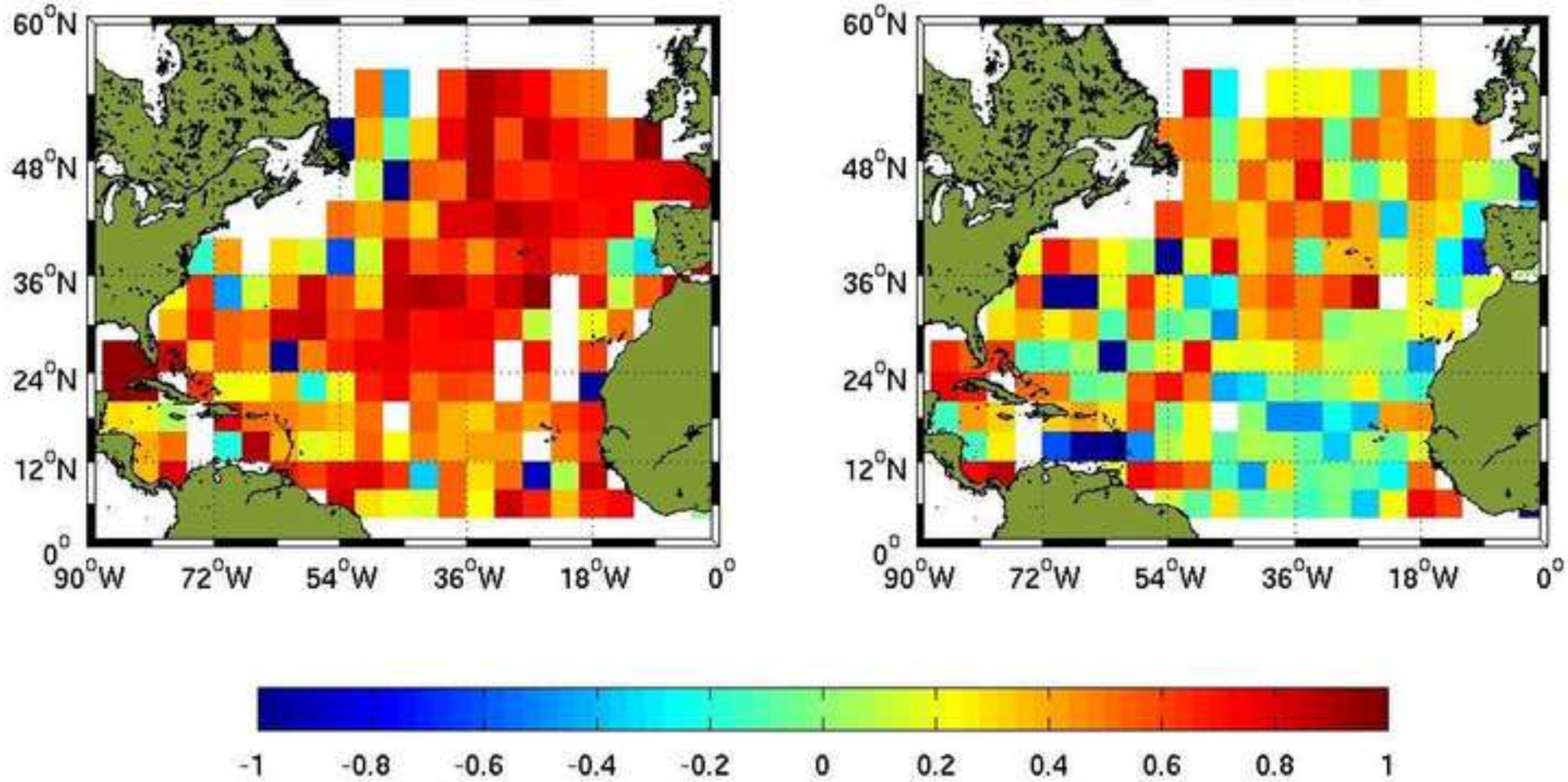

60°N
48°N
36°N
24°N
12°N
0°
90°W
72°W
54°W
36°W
18°W
0°
60°N
48°N
36°N
24°N
12°N
0°
90°W
72°W
54°W
36°W
18°W
0°
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1

Figure_3b

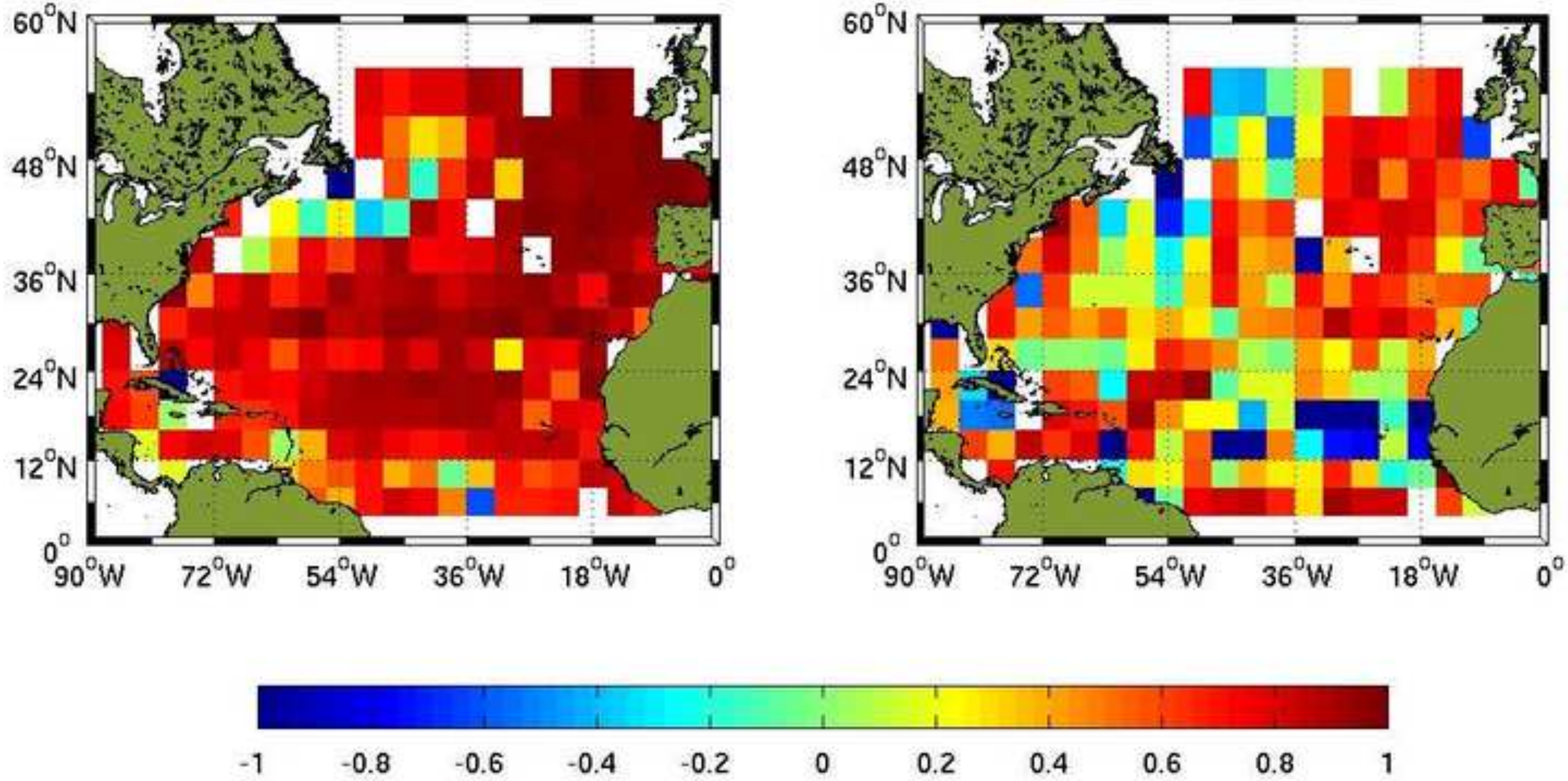

60°N
48°N
36°N
24°N
12°N
0°
90°W
72°W
54°W
36°W
18°W
0°
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1

Figure_4a

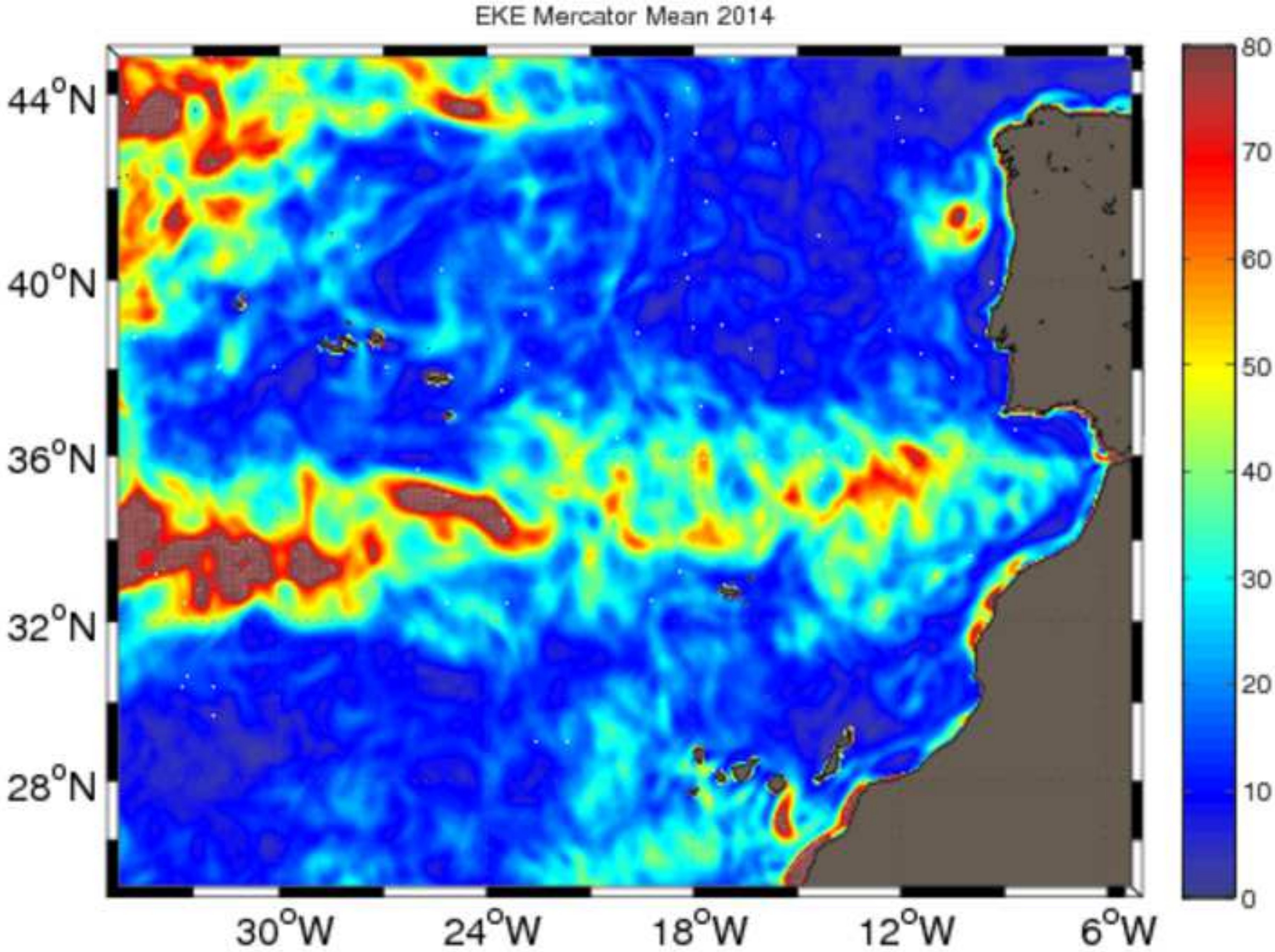
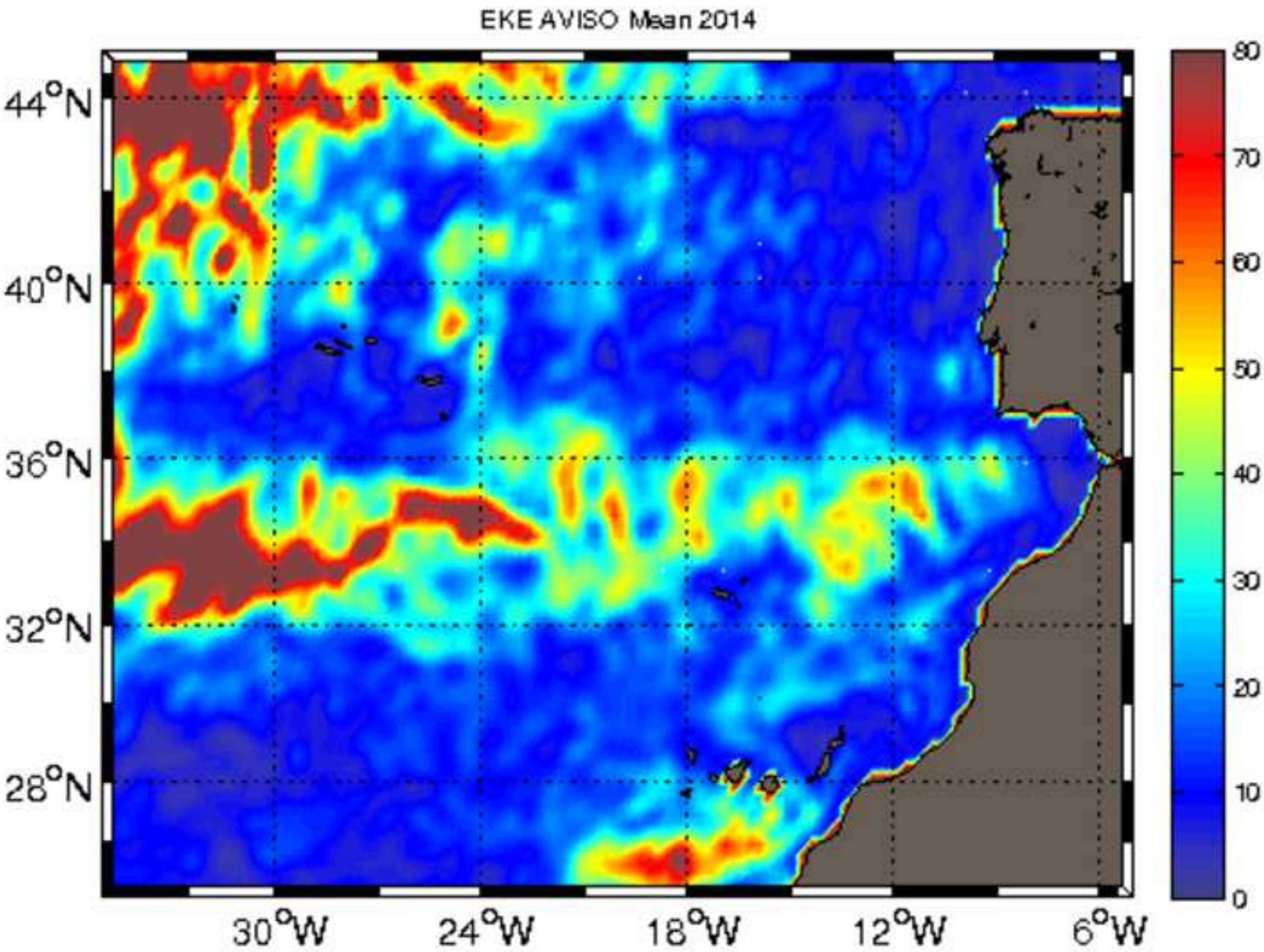
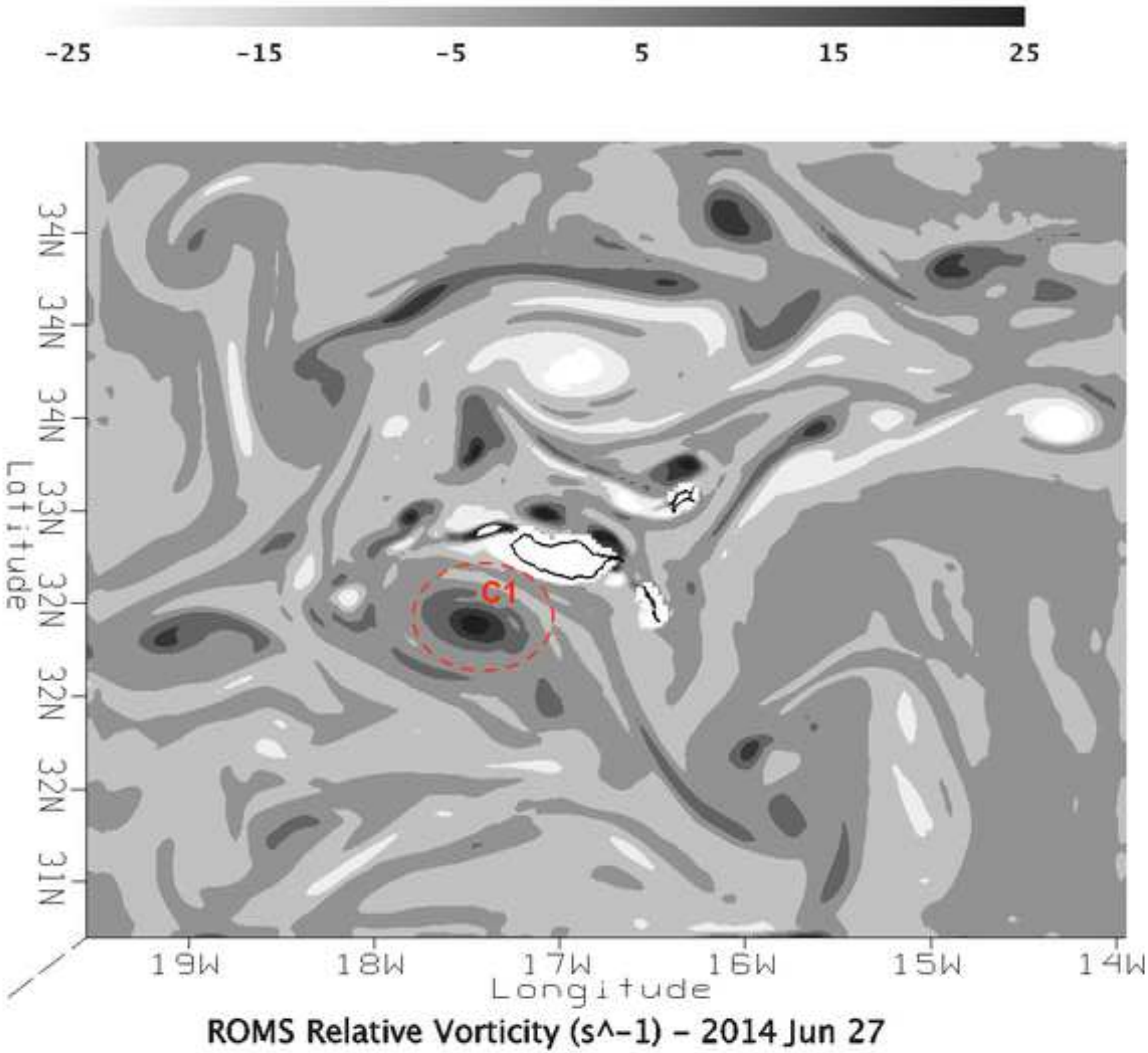

EKE Mercator Mean 2014
44°N
40°N
36°N
32°N
28°N
30°W
24°W
18°W
12°W
6°W
80
70
60
50
40
30
20
10
0

Figure_4b



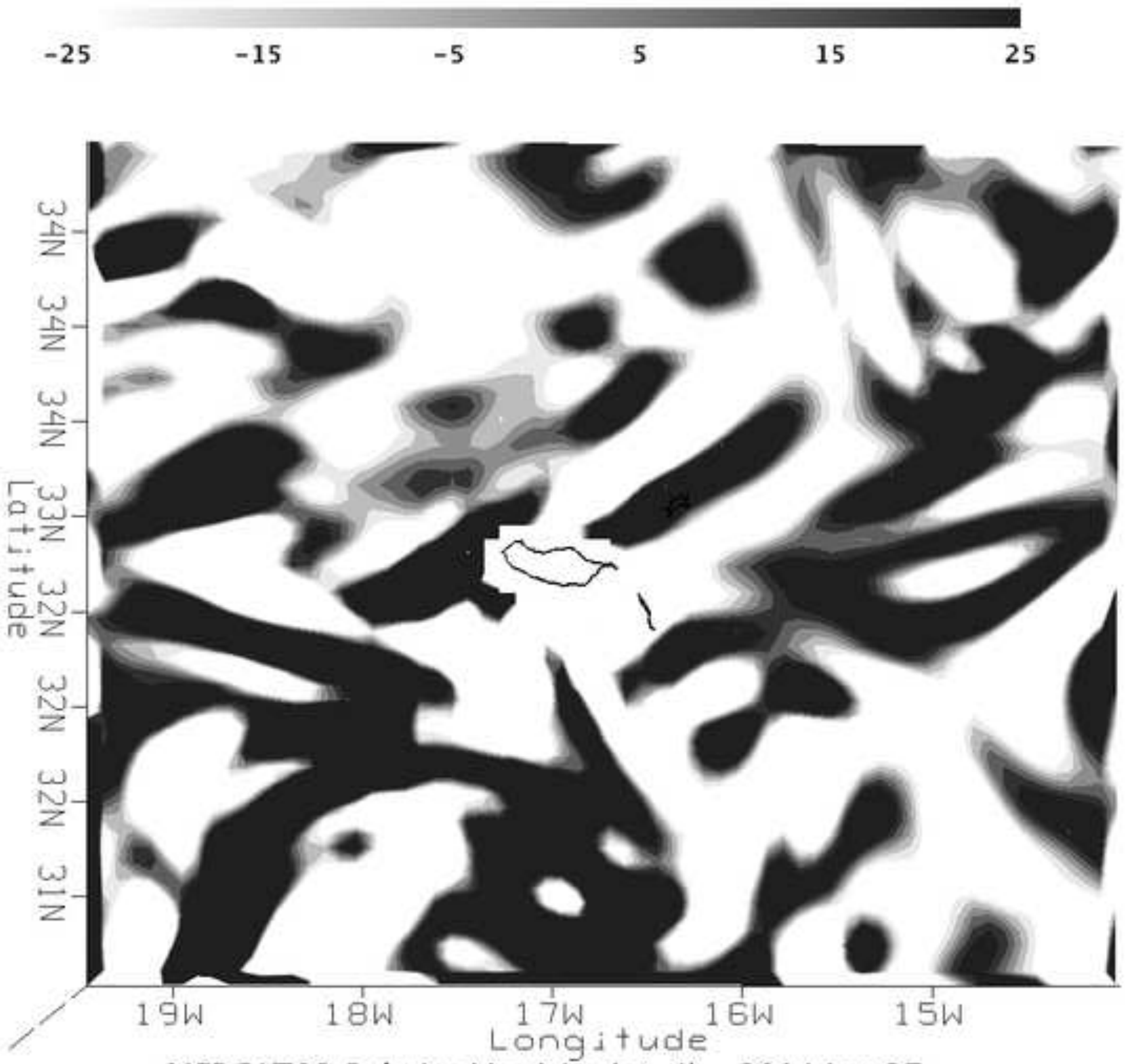
EKE AVISO Mean 2014
44°N
40°N
36°N
32°N
28°N
30°W
24°W
18°W
12°W
6°W
80
70
60
50
40
30
20
10
0

Figure_5a



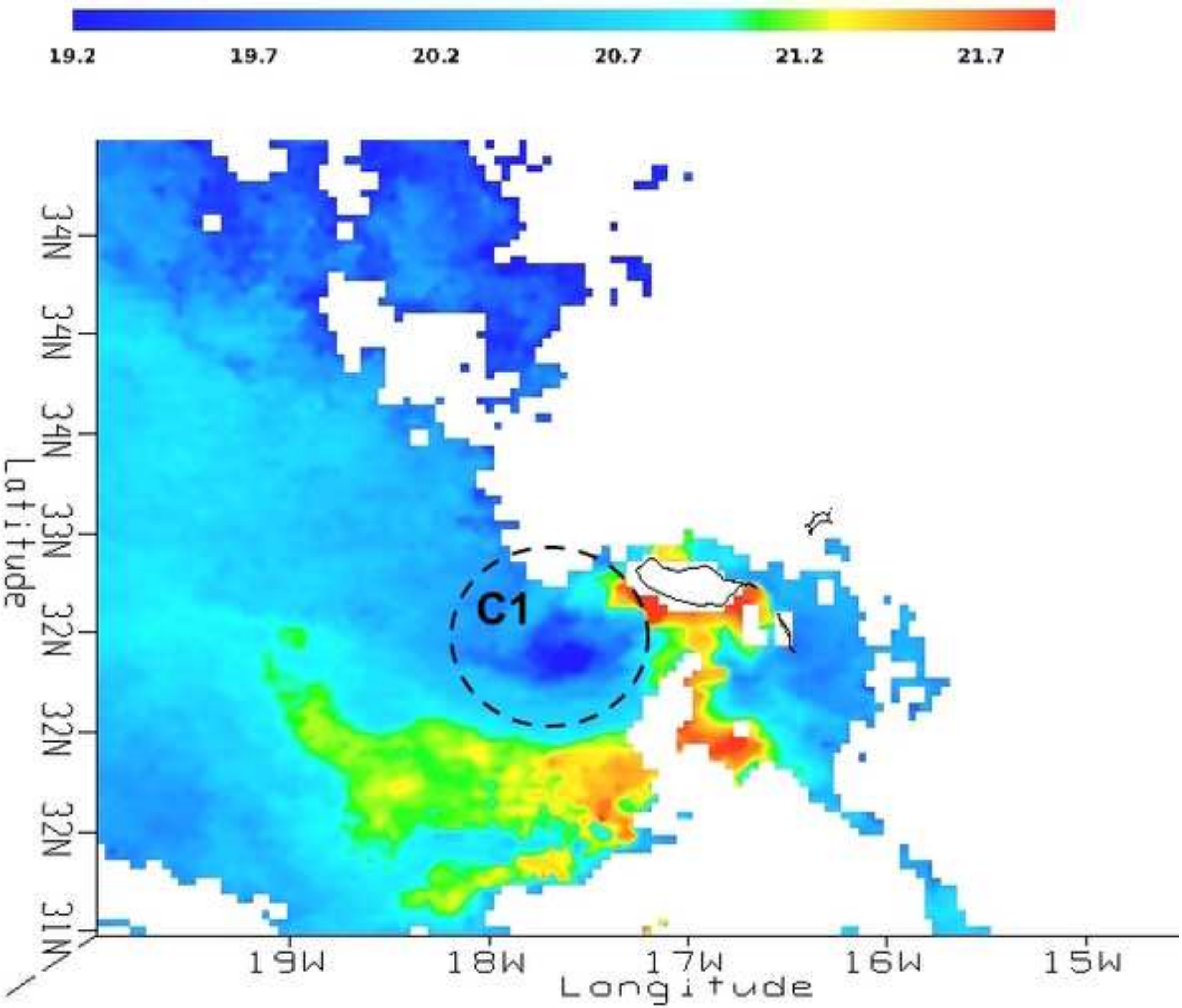
-25
-15
-5
5
15
25
34N
34N
34N
33N
32N
32N
32N
31N
Latitude
C1
19W
18W
17W
16W
15W
14W
Longitude
ROMS Relative Vorticity (s^-1) - 2014 Jun 27

Figure_5b



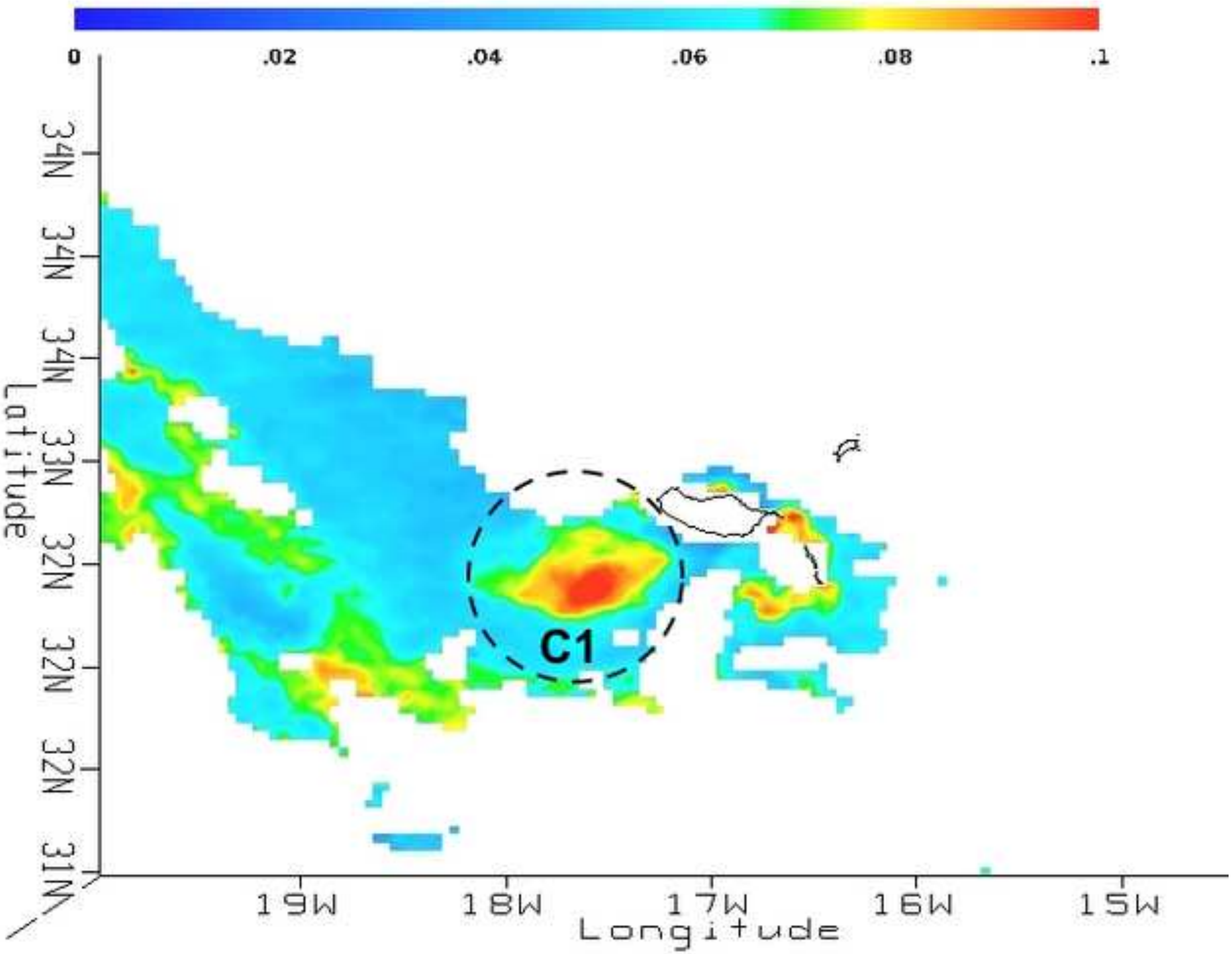
MERCATOR Relative Vorticity (s^-1) - 2014 Jun 27

Figure_6a



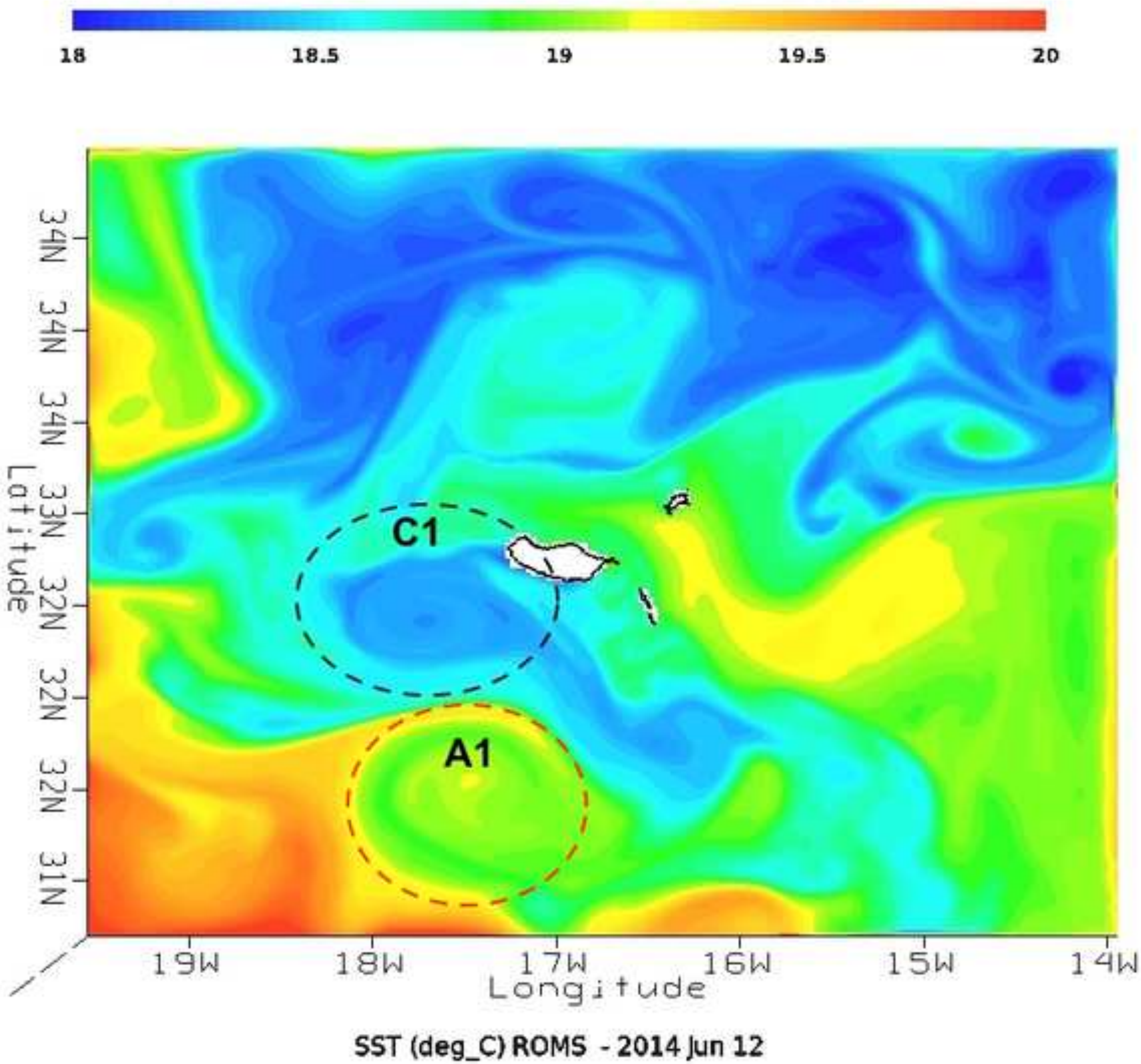
SST (deg_C) MODIS daily - 2014 Jun 15

Figure_6b



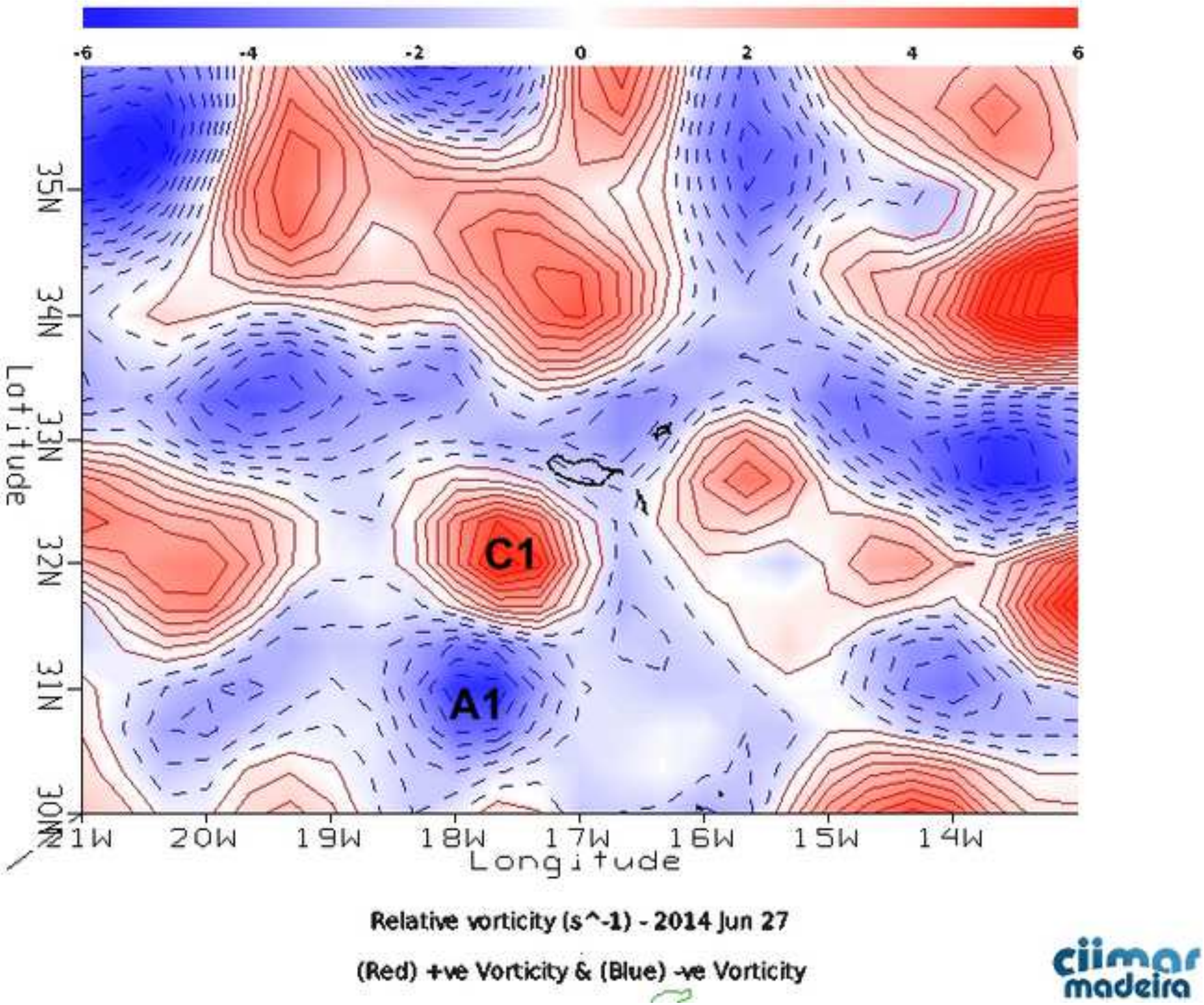
Chlorophyll-a (mg m^-3) MODIS daily - 2014 Jun 15

Figure_6c



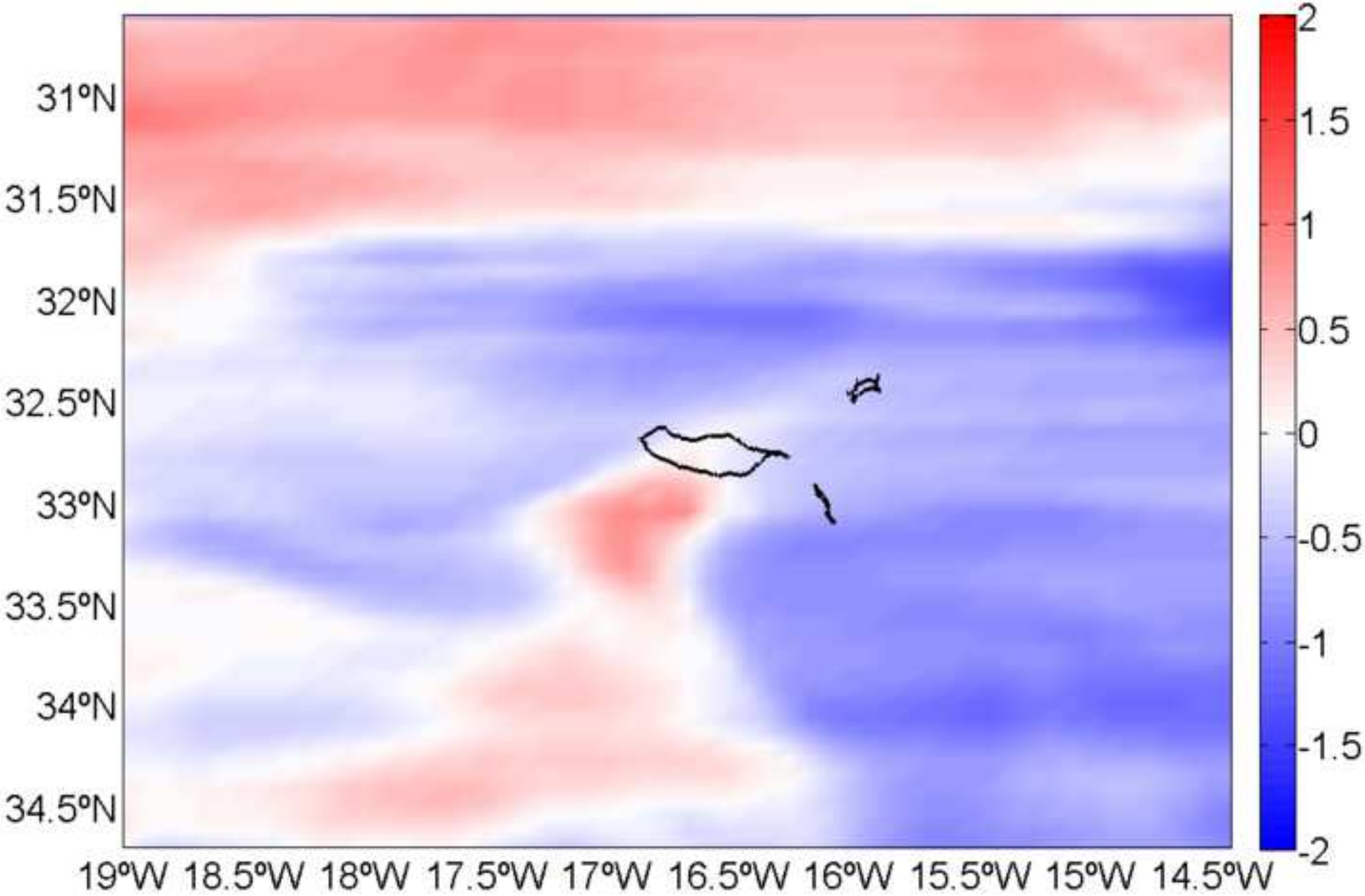
18
18.5
19
19.5
20
34N
34N
34N
33N
32N
32N
32N
31N
Latitude
C1
A1
19W
18W
17W
16W
15W
14W
Longitude
SST (deg_C) ROMS - 2014 Jun 12

Figure_6d



-6
-4
-2
0
2
4
6
35N
34N
33N
32N
31N
30N
Latitude
21W
20W
19W
18W
17W
16W
15W
14W
Longitude
C1
A1
Relative vorticity (s^-1) - 2014 Jun 27
(Red) +ve Vorticity & (Blue) -ve Vorticity
ciimar madeira

Figure_7a



31ºN
31.5ºN
32ºN
32.5ºN
33ºN
33.5ºN
34ºN
34.5ºN
19ºW 18.5ºW 18ºW 17.5ºW 17ºW 16.5ºW 16ºW 15.5ºW 15ºW 14.5ºW
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2

Figure_7b

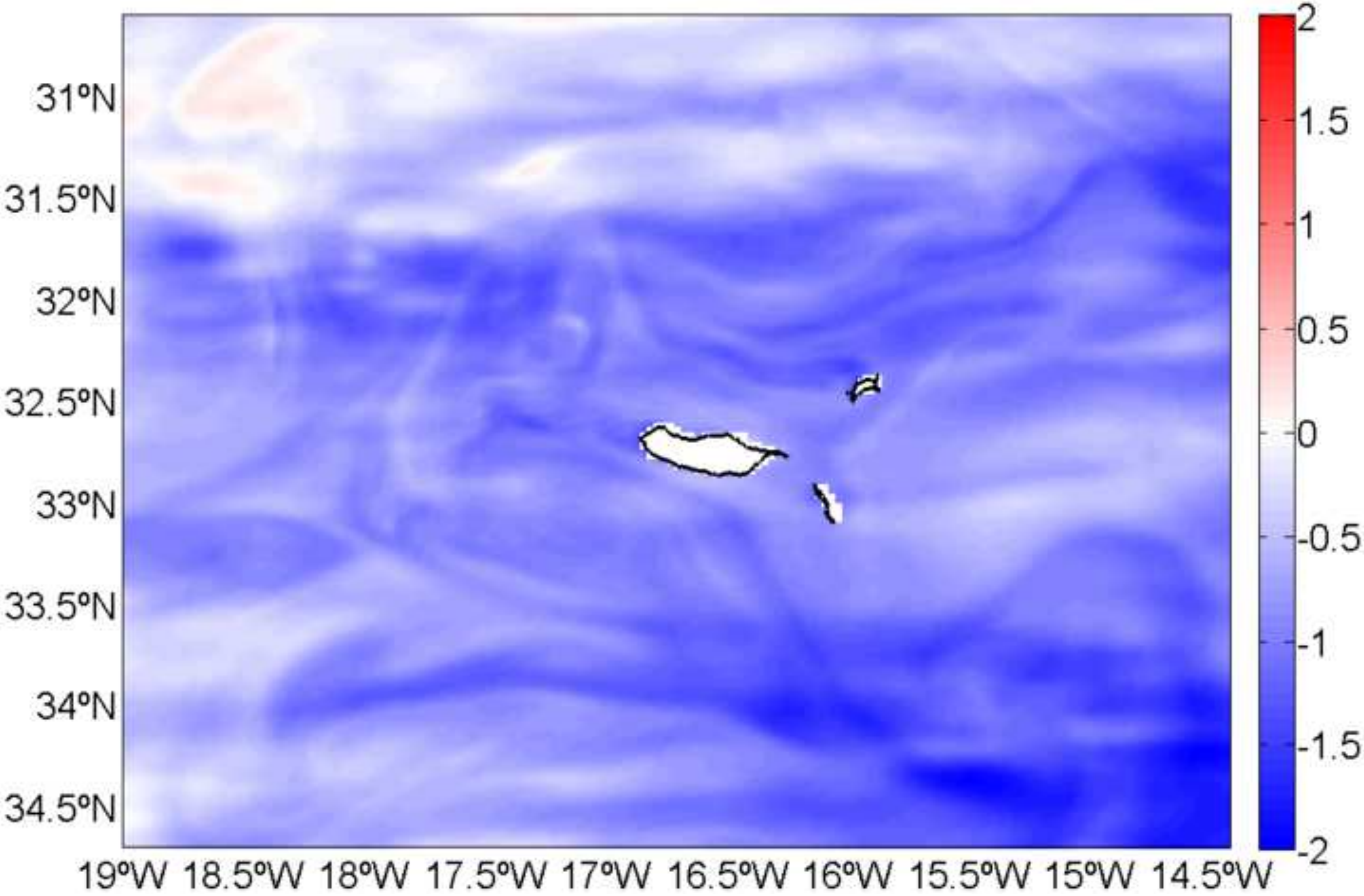

31ºN
31.5ºN
32ºN
32.5ºN
33ºN
33.5ºN
34ºN
34.5ºN
19ºW
18.5ºW
18ºW
17.5ºW
17ºW
16.5ºW
16ºW
15.5ºW
15ºW
14.5ºW
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2

Figure_8a

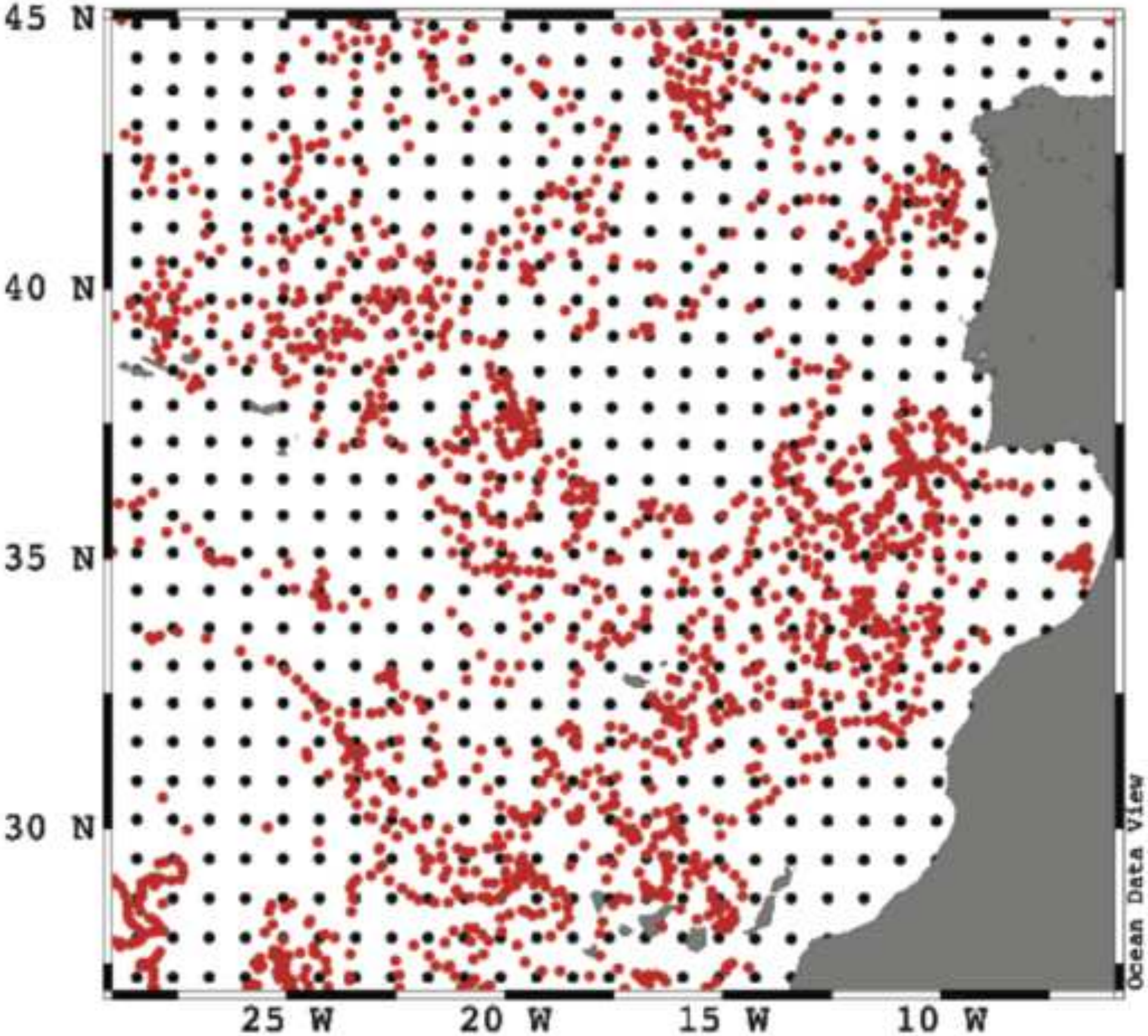
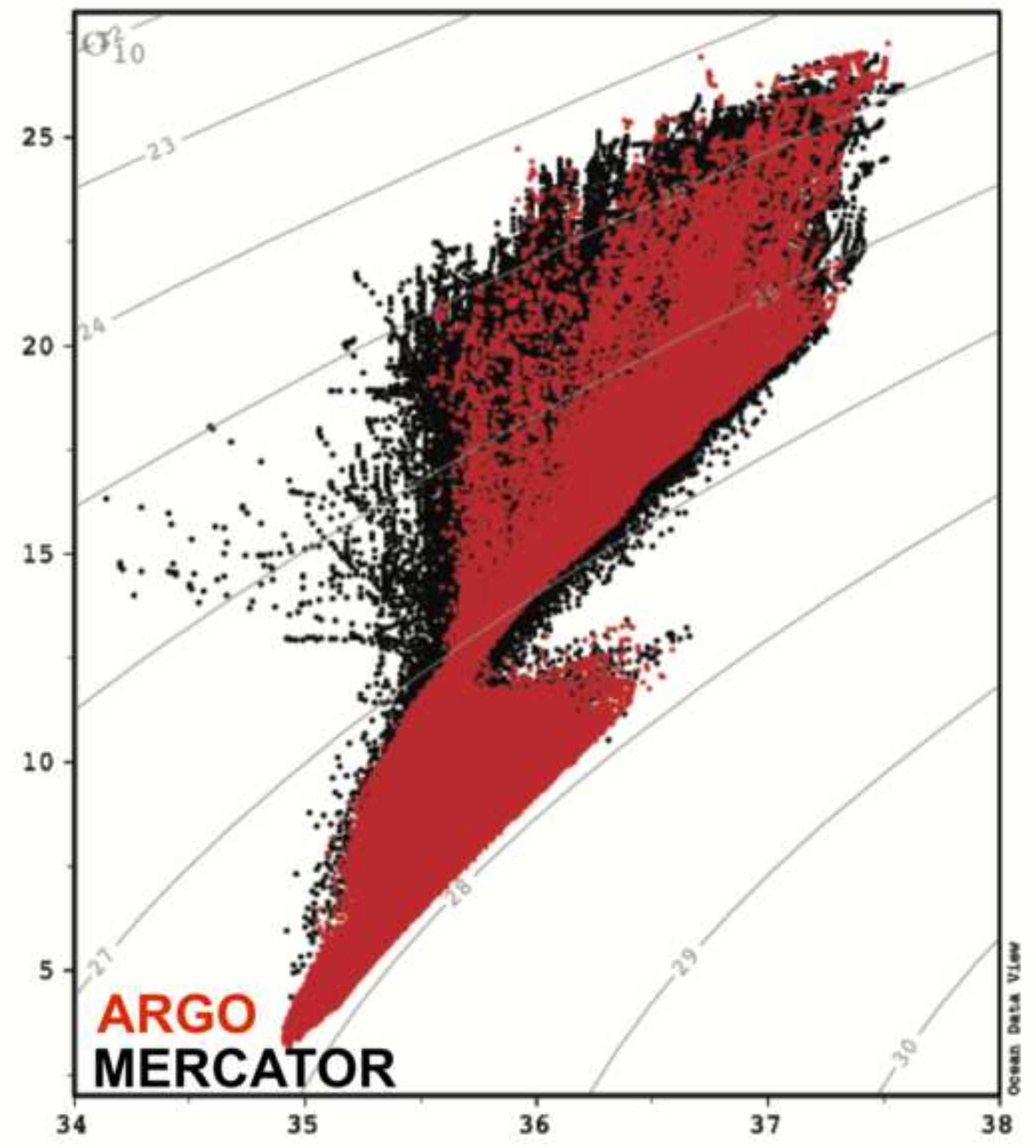


Figure_8b



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ARGO
MERCATOR
Ocean Data View

Figure_9a

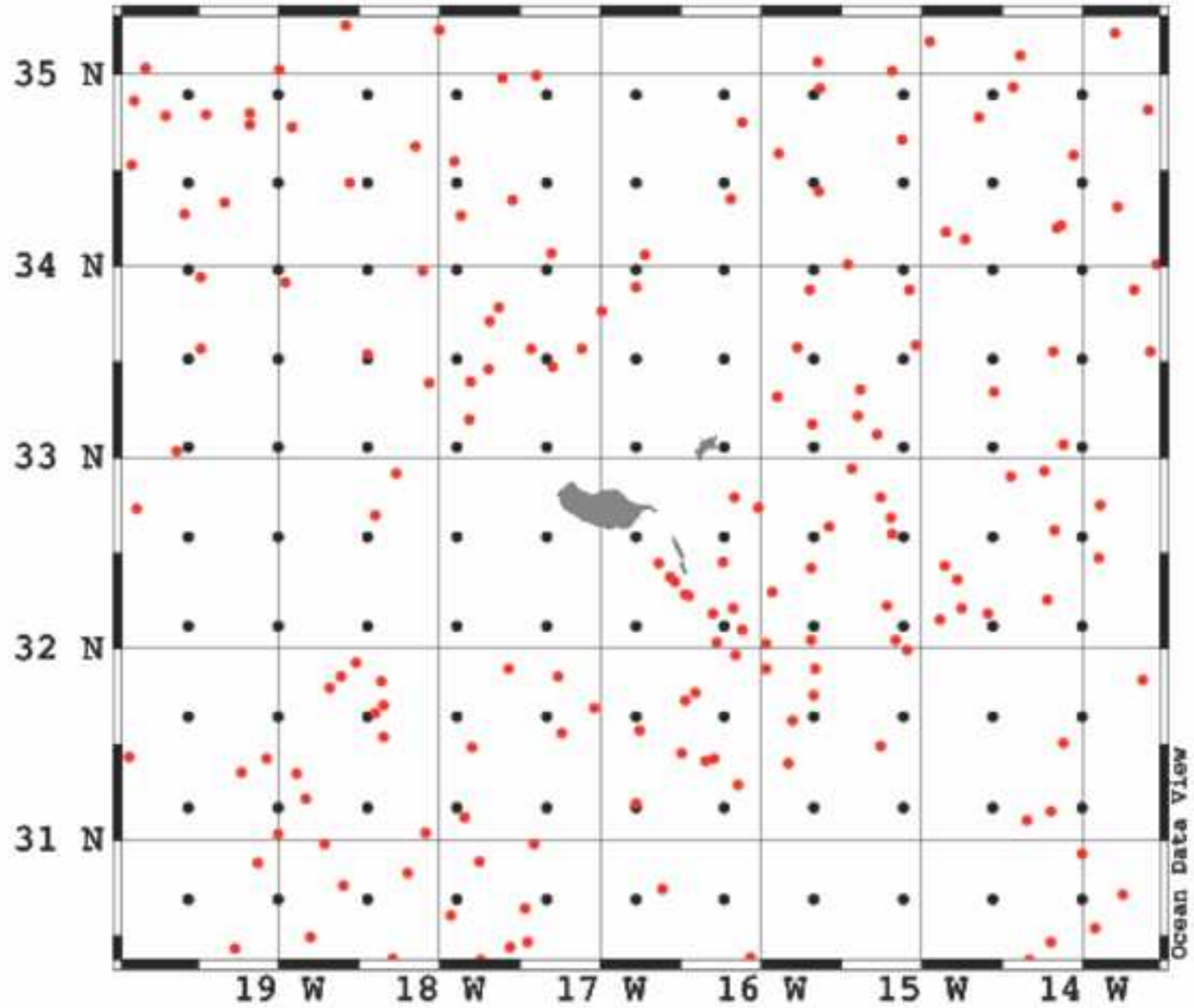


Figure_9b

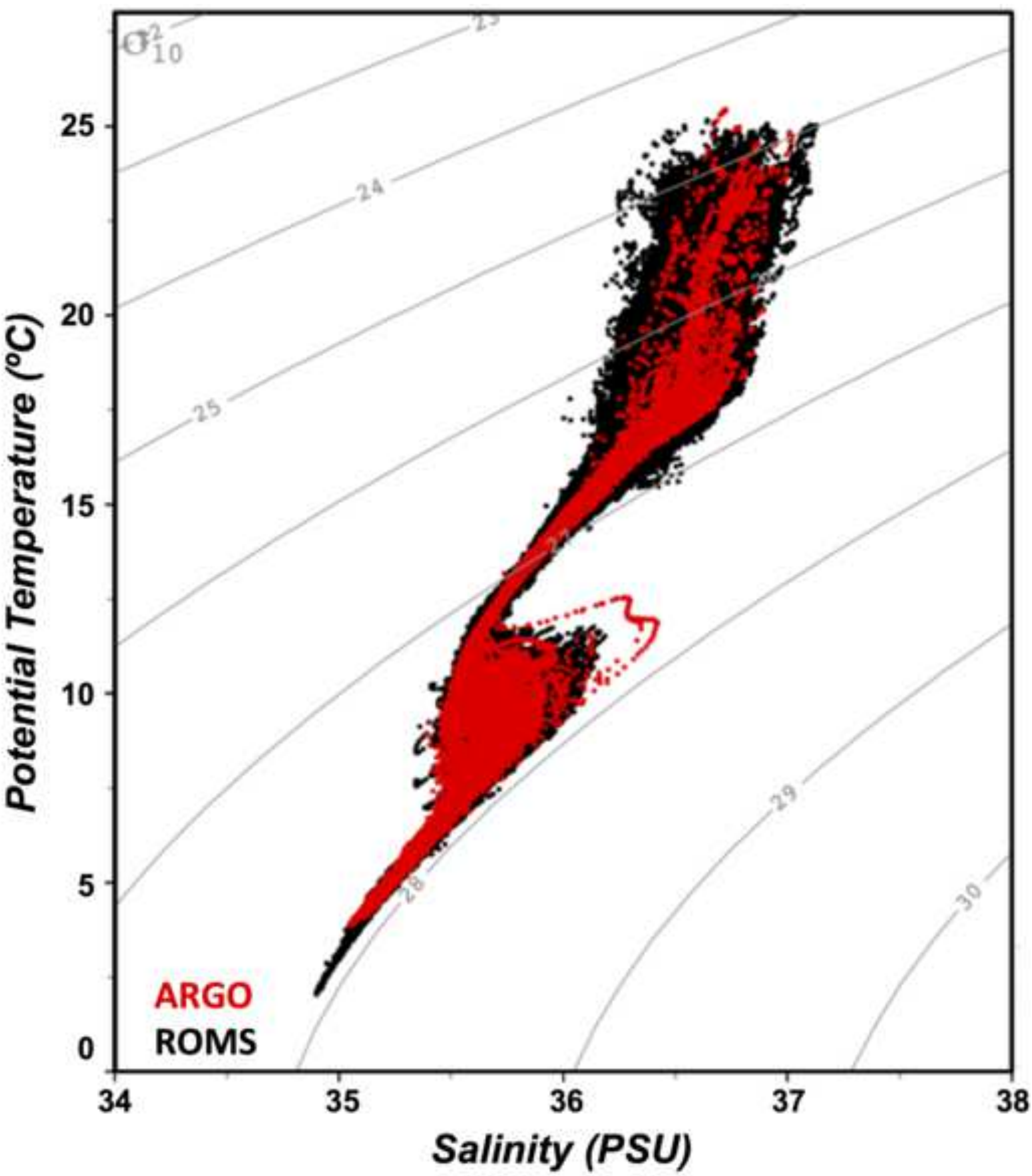
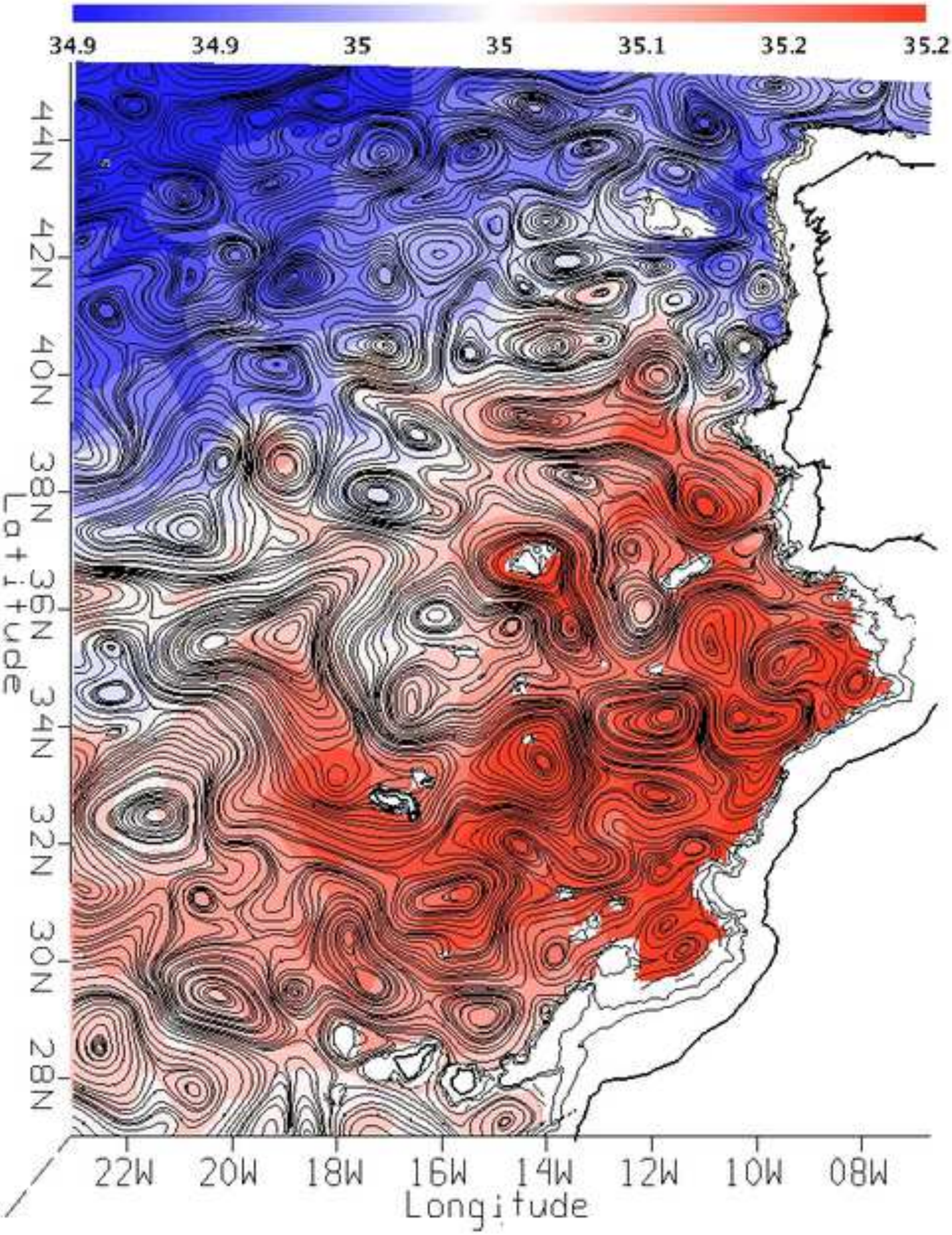


Figure_10



MERCATOR Salinity (PSU) & Streamlines @-1941m 2014 Apr 27

Figure_11a

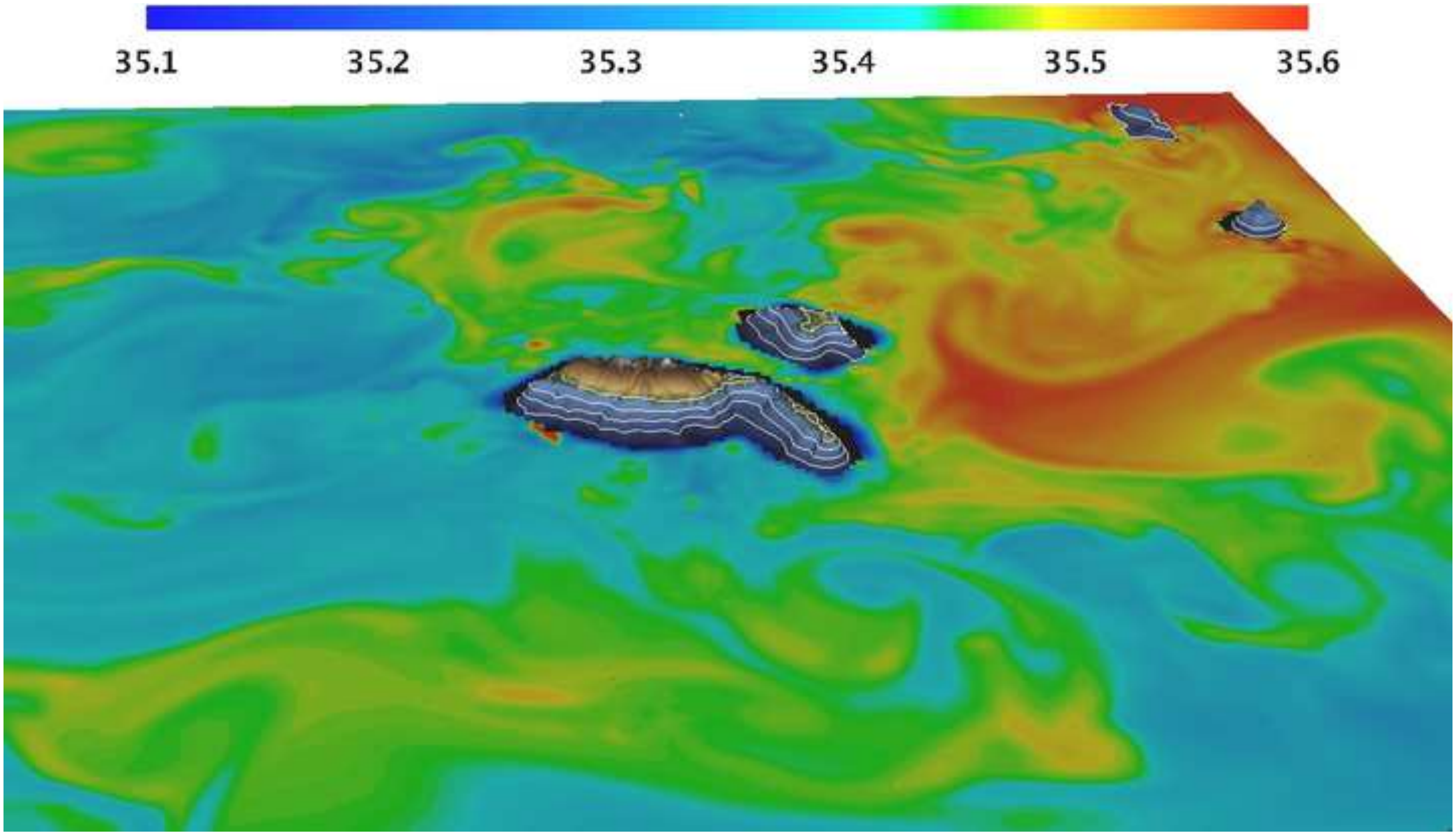
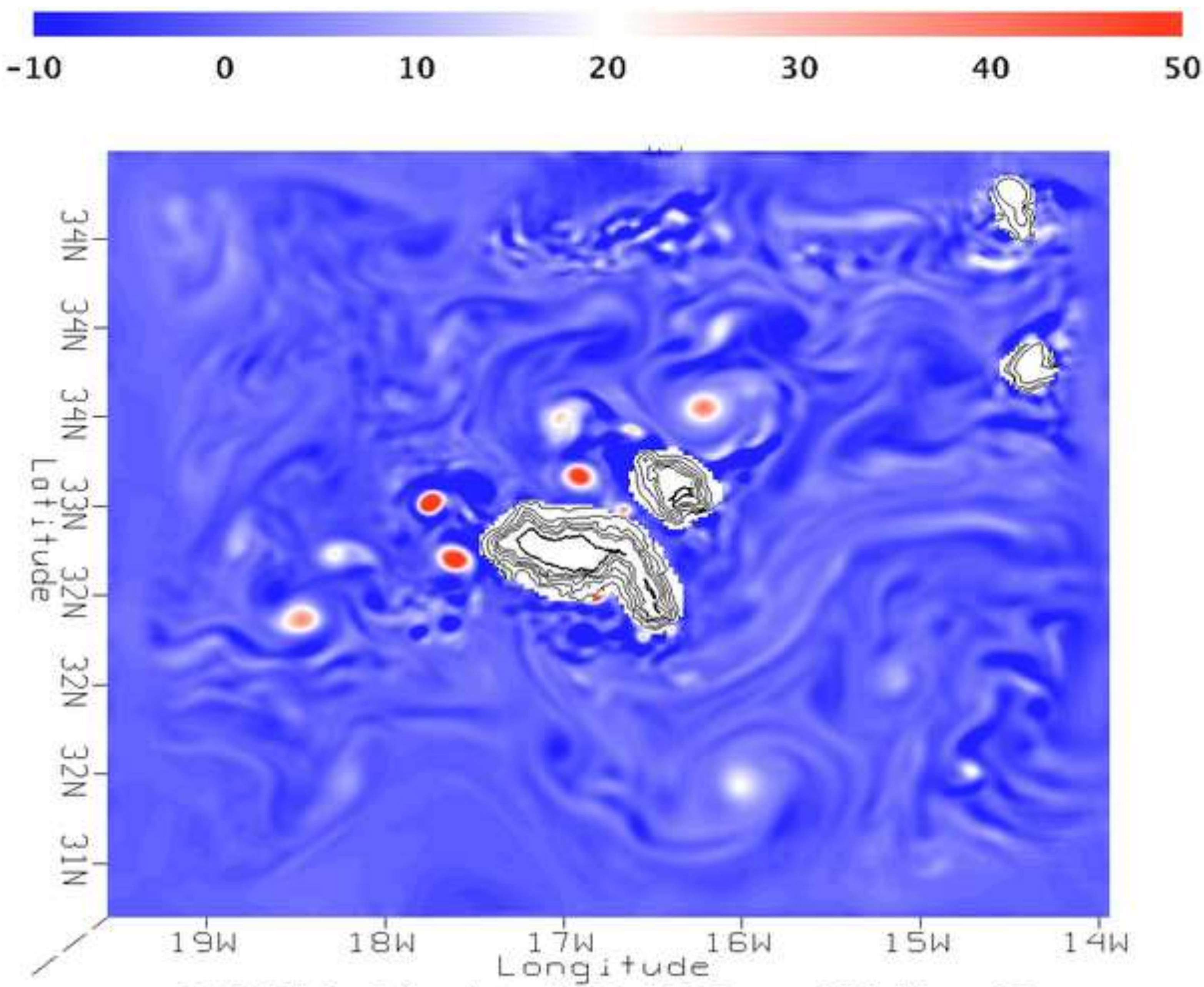


Figure_11b



ROMS Vorticity (s^-1) @-1500m - 2014 Jun 30