

Abstract

A high resolution simulation covering the Iberia–Biscay–Ireland (IBI) region is set-up over July 2007–February 2009. The NEMO model is used with a $1/36^\circ$ horizontal resolution on 50 z-levels in the vertical. It is forced by the astronomical potential and atmospheric forcing fields which consist of 3-hourly ECMWF analyses. Initial hydrographic conditions are derived from an Atlantic and Mediterranean Sea analyse at $1/12^\circ$ from Mercator Ocean (PSY2V3 model). At the open boundaries, IBI is forced with PSY2V3 temperature and salinity fields. It is also forced with tidal currents and elevations and inverse barometer elevations. In this study we evaluate the realism of the simulation through comparisons with an extensive observational dataset including climatology, temperature and salinity profiles, satellite SST data, sea surface buoys, tide gauges, altimeter data and HF radar data. A specific interest is given to the procedure used for the validation. General aspects of the simulation and its quality are analysed and particular attention is given to the validation of high frequency processes including the diurnal cycle, barotropic and internal tides, and surges. Finally, we focus on specific aspects of the circulation on the European sea shelves and give a qualitative assessment by studying tidal fronts, and specially the Ushant front, and the winter extension of the Iberian Poleward Current along the Northern Spanish coast during winter 2007–2008.

1 Introduction

The North East Atlantic (NEATL) region covers areas of important economic and social activities that include fisheries, transportation of oil and gas, commercial ship traffic, coastal management and protection and energy production. The increasing number of users over this region requires a good knowledge of the marine environment to suitably develop these activities. Regional modelling is a tool of particular interest required by this concern. The IBI system (Iberia–Biscay–Ireland) has been developed within this context. It aims at improving our knowledge of the circulation and our understanding

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of the dynamics in the NEATL region. The latter encompasses large scale physical processes but also local ones such as slope currents, coastal upwellings, fronts, river plumes and tides (barotropic and internal). In the deep ocean area, the near-surface large-scale circulation of the North Atlantic Ocean is primarily driven by the wind and is characterized by the anticyclonic North Atlantic sub-tropical gyre (Schmitz and Mc-
Cartney, 1993). The main currents associated with the eastern part of this gyre are the North Atlantic Current and the Azores Current. They meet off West Iberia, a region also characterized by a poleward slope current flowing along the Eastern Atlantic margin in subsurface and still observed off Northwest Ireland (White and Bowyer, 1997). Over large shelf regions currents are dominated by tides. In the presence of stratification, interactions between tidal currents and strong bathymetry gradients generate internal tides that propagate onto the shelf and into the deep ocean (Pingree et al., 1986). Over the European continental shelf strong tidal currents also induce vertical mixing which creates thermal fronts between stratified and tidally mixed waters (Simpson and Hunter, 1974).

To ensure the realism of the model in a region that comprises a large spectrum of regimes specific to coastal, shelf, slope and deep ocean regions, a high resolution configuration is set up over the IBI region. We use the NEMO/OPA 9.0 model (Madec et al., 1998) in a realistic configuration, with a $1/36^\circ$ horizontal resolution and 50 z-levels in the vertical. As NEMO was originally developed for large scale modelling, new developments have been implemented to make it suitable for shelf and coastal modelling. In particular, missing physics have been added for the free surface, vertical mixing and bottom friction. The model now includes a tidal potential and 3-h atmospheric forcing which are likely to resolve the diurnal cycle and surges.

In this study, our objective is to define a methodology to assess the realism of the model that takes into account the specificities of the coastal dynamics and of the type of observations available in coastal and shelf seas. In particular, a new and challenging issue is the assessment of high-frequency dynamics, such as barotropic and internal tides, surges or circulation variability at daily time-scales. Our approach is inspired by

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the strategy developed within the MERSEA European project (Le Provost et al., 2001). We demonstrate the feasibility of our methodology by applying it to the NEMO model in the IBI realistic configuration over the year 2008. This leads us to draw first conclusions on the ability of the model to represent the circulation over a broad range of spatial and time scales: from the large-scale of the deep ocean dynamics to the small scales on the slope and on the shelf, and from seasonal time scale to a few hour time scale.

This work was carried out within the MyOcean project, which aims at developing Marine Core Services within the GMES initiative (Global Monitoring for Environment and Security). One major activity within MyOcean is modelling and forecasting, both at global and regional scales where shelves are present. The assessment of numerical models in shelf areas is scientifically relatively uncharted territory, while being critical in a community approach where several teams and models are involved. Therefore our aim in this article is twofold: propose a set of diagnostics and metrics which could serve as a basis for community model assessment, and show their results for NEMO in its IBI implementation.

The paper is organized as follows. Section 2 focuses on the NEMO model and its new developments. It also describes the forcing, the input parameters, the model configuration and the experiment. Sections 3 to 6 provide an assessment of the model realism by investigating circulation, hydrological structures, SST, and barotropic and internal tides. In each section, data used for the comparisons are first presented and then we assess the model performances from large scales and low frequencies to high frequencies. In Sect. 7, we focus on specific processes in the Bay of Biscay. Temperature fronts induced by tidal mixing are analysed. In particular, we analyse the model quality in the Ushant front region by comparing vertical temperature section with observations collected during the MOUTON cruise. We also focus on a well-known pattern of the Bay of Biscay seasonal circulation: the winter warm extension of the Iberian Poleward Current along the Northern Spanish coast (Navidad event). The event of winter 2007–2008 is studied in detail. Finally, Sect. 8 gives a summary and conclusions.

2 Modelling

2.1 Numerical model

The IBI model numerical core is based on the NEMO v2.3 Ocean General Circulation Model (Madec et al., 1998; Madec, 2008). It solves the three dimensional primitive equations in spherical coordinates, discretized on an Arakawa C-grid, assuming hydrostatic and Boussinesq approximations. While the bulk of the numerical code is similar to the one described in Barnier et al. (2006) (including the vector invariant form of the momentum equations and the discretization of vorticity terms), there are important differences related to the specific coastal and tidal dynamics studied here that are briefly described in the following.

In order to allow fast external gravity waves, the “filtered” free surface formulation (Roullet and Madec, 2000) has been replaced by a time-splitting scheme: the barotropic part of the dynamical equations is integrated explicitly with a short time step while depth varying prognostic variables (baroclinic velocities and tracers) that evolve more slowly are solved with a larger time step. The mode coupling procedure as well as the barotropic scheme (a “generalized forward backward”) follow the work of Shchepetkin and McWilliams (2004) adapted to the standard NEMO leap-frog time stepping of “slow” varying variables.

Because of the explicit simulations of tides, sea level elevation can become large on the shelf compared to the local depth so that linear free surface approximation needs to be relaxed. In practice, the model vertical levels are remapped on the vertical to account for the varying fluid height. This has some important consequences on tracers’ conservation and on the generation of compound waves in shallow areas (Fanjul et al., 1997).

Vertical turbulent mixing processes are parameterized with a k-epsilon two-equation model implemented in the generic form proposed by Umlauf and Burchard (2002). The model is complemented with the type “A” full equilibrium form of Canuto et al. (2001) stability functions (all model parameters exactly follow Holt and Umlauf

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Along lateral boundaries, free slip boundary conditions are used everywhere except inside Gibraltar strait where no slip conditions are applied. This somewhat reduces the flow to more realistic values and prevents the Alboran jet from turning into a quasi-permanent “coastal mode”. At the bottom, a quadratic bottom drag with a logarithmic formulation is calculated as:

$$C_d = \max\left(C_{d\min}, \left\{\kappa \ln(0.5\Delta z_b/z_0)\right\}^2\right) \quad (4)$$

Where $\kappa = 0.4$ is the Von Karman constant, $C_{d\min} = 2.5 \times 10^{-3}$ a minimum drag coefficient, Δz_b is the lowermost bottom cell thickness and $z_{0b} = 3.5 \times 10^{-3}$ m, the bottom roughness. With the reference geopotential discretization chosen here, the logarithmic formulation applies for depths shallower than 170 m, ie on most of the continental shelf.

Lateral sub-grid scale mixing are parameterized according to horizontal bi-harmonic operators for both momentum ($A_m = -2.5 \times 10^8 \text{ m}^4 \text{ s}^{-1}$) and tracers ($A_t = -2.5 \times 10^7 \text{ m}^4 \text{ s}^{-1}$), the latter value leading to particularly small explicit diffusion. Tracers’ advection is computed with the QUICKEST scheme developed by Leonard (1979).

2.2 Model configuration

The model domain covers the North East Atlantic ocean from the Canary Islands to Iceland (Fig. 1). Even if the focus of the IBI forecasting system remains on the Iberian, French, and Irish coasts, the computational domain has been extended to include the Western Mediterranean Sea and the North Sea; this strategy was chosen to set connections with the global model where it suffers the less from not simulating the physical processes of interest here. Moreover, it allows for the explicit computation of mass, heat and salt fluxes in the narrow Gibraltar and Kattegat straits which may be better resolved due to the improved resolution. Also shown on Fig. 1 are the main surface features of the mean and transient circulation in the IBI area: the Azores Current (AC), the Canary Current (CaC), the Northern Current (NC), the Iberian Poleward Current

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(IPC), the Norwegian Coastal Current (NwCC), the North Atlantic Current (NAC) as well as eddies in the Mediterranean Sea and in the Bay of Biscay.

The primitive equations are discretized on an horizontal curvilinear grid which is a refined subset at $1/36^\circ$ ($\sim 2\text{--}3$ km) of the so-called “ORCA” tripolar grid, commonly used in other NEMO based large scale and global modelling experiments (Barnier et al., 2006). This is also an exact 3:1 refinement of the North Atlantic model grid (PSY2V3 grid) that provides initial and boundary conditions. This strategy greatly simplifies interpolation procedures, allows for exact boundary fluxes/bathymetry matching, the latter increasing the overall robustness of the coupling. The same 50 reference z-levels as in the parent grid model are used in the vertical, with a resolution decreasing from ~ 1 m in the upper 10 m to more than 400 m in the deep ocean. A partial step representation of the very last bottom cell is used which improves the large scale circulation, but also gives a fairly smooth and accurate representation of the shelf bathymetry (Barnier et al., 2006).

The original bathymetry is derived from the 30 arcsec resolution GEBCO 08 data set (Becker et al., 2009) merged with regional bathymetries provided by Ifremer, the French Navy (SHOM, Service Hydrographique et Océanographique de la Marine) and the North West Shelf Operational Oceanographic System (NOOS). Local bathymetric grids cover the Mediterranean Sea, the Gibraltar Strait, regions off Portugal and off North Spain, regions along the French coasts, the Southern Celtic Sea, part of the North Sea and the Baltic Sea. Independent ICES (International Council for the Exploration of the Sea) soundings have been used to validate the new bathymetry dataset. Significant improvements have been achieved in shelf sea regions in comparison to the original GEBCO08 bathymetry (Fig. 2). The model bathymetry is then bilinearly interpolated from the resulting composite and slightly smoothed using a Shapiro filter to remove grid scale noise and remaining discontinuities between local databases. At open boundaries, within 30 points wide relaxation areas, bathymetry is exactly set to the parent grid model bathymetry and progressively merged as a 7 point sine with the interpolated dataset described above.

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velocities, temperature and salinity. For the latter variables a 30-points relaxation area with a minimum time-scale of 1 day is used which strongly damps outgoing perturbations from the prescribed fields while allowing for the explicit simulation of high frequency fluctuations related to the atmosphere in the surface layers.

5 Temperature, salinity, velocities and sea surface height (hereafter SSH) from PSY2V3 daily outputs are used as the slow component of open boundary data. PSY2V3 is an operational forecasting system covering the North Atlantic and the Mediterranean Sea at $1/12^\circ$ resolution. It does include a multivariate, Kalman based, weekly data assimilation procedure of along track altimetry data, sea surface temperature (SST) and hydrological observations (Dréville et al., 2008; Dombrowski et al.,
10 2009). SSH tidal forcing is then added as the sum of 11 constituents (M_2 , S_2 , K_2 , N_2 , K_1 , O_1 , P_1 , Q_1 , M_4 , M_f , M_m) provided by the TPXO7.1 global tide model (Egbert et al., 1994). A 35 days barotropic experiment (e.g. without stratification) with clamped boundary conditions for sea level (and Neumann conditions for velocities) is used to
15 estimate the 6 major barotropic tidal velocities constituents (similar to the run_{bt} experiment described in the following). This method, reminiscent of the iterative procedure of Flather, 1987, clearly improved the overall tidal statistics compared to direct use of TPXO velocity data for all constituents. Finally, since surface atmospheric pressure forcing is explicitly considered in the dynamical equations, approximate sea level re-
20 sponse in the inverse barometer form is added to sea level data.

2.4 Experimental set-up

Results from two simulations are considered in the following: a “tide only” run (experiment T91, hereafter run_{bt}) which consists in a 35 day “barotropic-like” simulation (homogenous density, no atmospheric forcing, only tidal forcing) is used to perform
25 a 3-D harmonic analysis that provides tidal elevations and currents for a reduced set of harmonics (M_2 , S_2 , N_2 , K_1 , O_1 , Q_1 , M_4), and a second simulation (experiment T102, run_{bc}) is run with stratification but the harmonic analysis is only performed onto sea surface currents and vertical profiles at buoy locations (see Table 1). In the latter case,

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the model is initialized on 25 July 2007 from analysed temperature, salinity, sea level and velocities bilinearly interpolated from PSY2V3 analysis. Tidal and surface pressure forcings are smoothly introduced (both at open boundaries and in dynamical equations) thanks to a 2 days linear ramp. Meanwhile, horizontal viscosity linearly decreases from 4 times its nominal value, to damp instabilities arising from the use of unbalanced initial fields. The simulations ends in February 2009. Model analysis shown hereafter concerning year 2008 only.

3 Assessment of the circulation

3.1 Surface eddy kinetic energy

As a first check of the model self-consistency, we analyse the eddy kinetic energy (EKE). Note that the investigation of the EKE is not part of the so-called metrics but is a necessary step to assess the model quality. The EKE distribution gives good indications of the ocean dynamics in our region of study. Maps of surface EKE are computed using hourly velocity fields and are presented in Fig. 4 for periods shorter and longer than 25 h. Filtering at 25 h is a standard processing to separate high frequency signal such as tides from the lower frequency dynamical effects. Strong values of the high frequency EKE (HFEKE) are located on the European continental shelf where tides are particularly large and contribute to most of the HFEKE (Van Aken, 2002). In particular, the highest values of EKE are located in the English Channel, in the Irish Sea, off Southeast English coasts, in the German Bight, North of Scotland and around the Faeroe Islands where tidal currents are the most important (Davies et al., 1997; Holt et al., 2001). On the European shelf seas, regions of separation between low and high HFEKE, as the entrance of the English Channel or in the Irish Sea, correspond to well identified tidal front locations (Bowers and Simpson, 1987; Holt and Umlauf, 2008). Over the Armorican shelf, at 48° N, we clearly distinguish bands parallel to the shelf break due to successive maxima and minima of HFEKE. The distance between

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of Atlantic Water from outflow of MW. However comparisons of hydrological fields with climatology have shown that MW are too light in the model (Fig. 11) and the 31.7 iso-density may not be appropriate to separate the two water masses. When choosing a density threshold value of 30.3 in the Gulf of Cadiz region, we obtain transports of 2.0 Sv and -1.1 Sv across the Gulf of Cadiz and a transport of -1.3 Sv for the MW. The results are closer to the estimates from observations and the transport lies within the range of published values for the inflow but the westward flow is still underestimated (Howe, 1984; Rhein and Hinrichsen, 1993; Mauritzen et al., 2001). South of Portugal the MW flows northward with a transport comparable with previous estimations (Jorge da Silva, 1996; Mazé et al., 1997; Coelho et al., 2002). Off West Iberian Peninsula the transport is slightly overestimated at 40° N but is in good agreement with previous estimates at 43° N (Jorge da Silva, 1996; Mazé et al., 1997; Mauritzen et al., 2001; Coelho et al., 2002; Alvarez et al., 2004; Lherminier et al., 2007). Transports of the slope current across the Celtic shelf slope and along the Ellett line are of the same order of magnitudes than published values (Ellett and Martin, 1973; Pingree and Le Cann, 1990; Holliday et al., 2000). However we note that the transport across the Celtic slope is mainly constrained within the upper slope in the model while it is more evenly distributed along the slope in the study of Pingree and Le Cann (1990). The distribution of the transport with depth is comparable with estimations from data across the Ellett line section. Through the Dover Strait the transport is consistent with previous estimates (Otto et al., 1990; Prandle et al., 1996). Around the Faeroe Islands, heat transport, freshwater transport and volume transport of ENACW are similar to observation based estimates. However the export of deep water is too small in this region. As this flow is imposed at the OBC this suggests that the water mass transformation rate in the Norwegian Sea may be too small in the PSY2V3 model. The problem may also be due to difficulties of the model to represent the deep water overflow adequately as the vertical resolution is not sufficient enough at these depths. The transports of water masses originating from the Atlantic between the Shetland Islands and Norway and at the entrance of the Baltic Sea are in good agreement with previous studies suggesting

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that the circulation is properly modelled in the region (Otto et al., 1990; Rydberg et al., 1996; Rodhe, 1996). The Norwegian Coastal Current transports 1.23 Sv in the model which is consistent with values from Otto et al. (1990).

3.3 Focus on transports at the Gibraltar Strait

5 The transport through the Strait of Gibraltar is controlled by various processes at different time scales. Among these processes tides are the most energetic influencing the mean flow (Tsimplis and Bryden, 2000). Thus hourly transport through the Gibraltar Strait has been computed to analyse the outflow variability. Following the study of Sánchez Román et al. (2009) the interface to separate the inflow from the outflow
10 has been computed as the time dependent depth of the surface of zero low-pass frequency velocity. The modelled outflow transport estimated with this interface is noted $Q_{mod,V}$. The outflow transport computed using the commonly used 37.25 isohaline ($Q_{mod,S}$) is also computed for comparisons. Fig. 6 illustrates time series of observed and modelled transports and also the depth of the interface for $Q_{mod,V}$ and $Q_{mod,S}$
15 over a period overlapping the model simulation and the transport estimates of Sánchez Román et al. (2009), noted $Q_{obs,V}$. The definition of the interface based on the depth of the zero velocity gives better results than the isohaline interface. In comparison to the $Q_{obs,V}$ mean transport of -0.72 Sv, the mean outflow of $Q_{mod,V}$ is -0.74 Sv and the correlation coefficient with $Q_{obs,V}$ is 0.71, while a lesser agreement is found for
20 $Q_{mod,S}$ with a too small transport of -0.69 Sv and a correlation coefficient of 0.66. The time series of the $Q_{mod,V}$ associated interface presents strong oscillations that can reach up to 40 m. Its mean depth is 181 m over the period. The $Q_{mod,S}$ interface presents more pronounced fortnightly oscillations with deeper values reached during neap tides. The $Q_{mod,V}$ has also a strong fortnightly variability with maximum outflow
25 values during spring tides. Differences between peak values and lower values at neap tides reaches 0.70 Sv both in $Q_{obs,V}$ and $Q_{mod,V}$.

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3.4 Residual sea surface elevation

The in situ sea level dataset consists in 115 tide gauges located along the European coasts (Fig. 1). Tide gauge data used for comparisons are provided by Puertos del Estado, the Marine Institute and the Danish Meteorological Institute; data from SHOM, BODC (British Oceanographic Data Center) and GLOSS provided by CLS via the Badomar specific database are also used (see red dots on Fig. 1). Residual elevations (e.g. detided sea levels) are used to diagnose the model performance at different time scales. Comparisons between residual elevations from the model and the observations are shown in Fig. 7. The elevations due to the IB effects have been added to the comparison. This classical correction corresponds to the static response of the ocean to atmospheric pressure while the model residual elevations also include the non static response and the elevations due to wind forcing effects. The model shows very good agreement with data over the whole domain and it performs better than the IB response. However this result strongly depends on the latitude and the frequency band. The model is the most effective at high latitudes which are more energetic areas and where the ocean dynamical space and time scales are smaller, while at mid latitudes the model response to atmospheric forcing is closer to the IB approximation. Besides, the ocean response to atmospheric pressure generally differs from the IB at periods below 3 days (Carrère and Lyard, 2003) and we observe that for longer periods the IB performance and the model performance are very similar at mid latitudes (Fig. 7c shown for periods larger than 10 days). On the other hand, for periods below 10 days where wind effects prevail, the model is clearly more relevant over the whole domain. We also notice that model results are in a lesser agreement with data at low frequencies. At these frequencies the elevations signal is dominated by steric effects which are not represented in the model.

3.5 Residual currents

Data used for comparisons of residual currents consist in surface buoys provided by Puertos del Estdo and data provided by AZTI off Cabo Matxixako and San Sebastian on the Basque Country coasts that include current records between 10 m and 150 m and allow comparisons of residual currents along the water column depth (Table 1).

Wind stress observed at the buoy station and extracted from the model forcing using ECMWF wind fields is presented for the Estaca de Bares buoy station (Fig. 8). Wind stress has the same distribution in data and in forcing fields. It shows predominant zonal orientation but magnitudes are significantly higher in the ECMWF fields especially during strong wind events. The distribution of modelled residual currents is in good agreement with observations. Surface currents are mainly oriented zonally with axes slightly to the right of the wind axes attesting for the importance of the wind driving forcing on the residual currents. Nevertheless, there are noticeable discrepancies in the distribution: observations show non negligible meridional current components that are weak in the model. The depth as measured at the data location is 382 m while it is 405 m in the model bathymetry. Local discrepancies in the bathymetry and particularly in the representation of slope may explain the differences in the modelled dynamics. There are also differences in the current amplitudes that are overestimated in the model. This may be a direct consequence of overestimated wind stress magnitudes in the forcing.

Figure 9 shows observed and modelled current speed at the Matxixako location (AZTI data). Current magnitudes are of the same order in the data and in the model. They show short intensifications during winter that are associated with an eastward flow. The intensifications are underestimated in the model. In summer, the currents are weaker. Some current pulses are also distinguished in the data from June to September 2008 and are well reproduced in the model. The currents are well mixed in winter and stratified in summer both in data and in model. Comparison with thermohaline properties at the same station (Fig. 10) suggests that vertical shear is not sufficient to

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destruct the strong seasonal stratification (Rubio et al., 2012). At last, note that as the depth at the Matxitxako buoy location is 550 m in the data (observations are recorded over the first 200 m) and 780 m in the model, which means a slightly different location of the North Iberia continental slope. This difference is expected to induce model-data discrepancies.

4 Assessment of water masses and stratification

4.1 Climatology and profiles data

The “Analyse, Reconstruction et Indicateurs de la Variabilité Océanique” (ARIVO) climatology is a global climatology covering latitudes from 77° S to 77° N (von Schuckmann et al., 2009). It is a synthesis of ARGO array and profiling floats (www.argo.net) representing 95 % of the data, and drifting buoys, CTD and moorings over 2003–2008. An optimal analysis was performed with a radius of influence bounded at 300km and varying proportionally to the radius of Rossby with respect to the different scales of the dynamics in the shelf regions and in the abyssal plain. The resulting climatology provides monthly temperature and salinity fields on a 0.5° horizontal Mercator isotropic grid and on 152 standard levels between 0 m and 2000 m. Mean θ –S diagram derived from the climatology are compared to the model to ensure that the main water masses of the region of study are correctly rendered in the model.

Subsurface ocean temperature and salinity profiles from the UK MetOffice EN3 data set are used to assess the model hydrology in realistic conditions. The data are obtained from the World Ocean Database 2005 (Boyer et al., 2006), the Global Temperature and Salinity Profile Project and the Argo Project. They are quality controlled using a comprehensive set of checks (Ingleby and Huddleston, 2007). For each profile, mean bias and RMS between observations and model are computed. Comparisons of the mixed layer depth are also performed. We also use data from the two deep sea buoys of AZTI-Tecnalia (Rubio et al., 2012, Fig. 1, Table 1); they provide measurements of

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scheme that generates spurious extremis. Below the MW, the deep layers envelope the Labrador Sea Water (LSW) characterized by a salinity minimum, the Eastern North Atlantic Deep Water (ENADW) identified by a relatively deep salinity maximum which is weaker in the model than in the climatology, the Iceland-Scotland Overflow Water (ISOW), the Lower Deep Water (LDW) originating from modified Antarctic Bottom Water, and the cold Denmark Strait Overflow Water (DSOW). The modelled thermohaline properties of the deep and bottom waters are in reasonable agreement with the climatology.

4.3 Rossby radius of deformation

To verify that biases in temperature and salinity do not introduce errors on the physical process representation we have computed the first Rossby radius of deformation (λ_1) using the formula published in Chelton et al. (1998) computed from yearly averaged hydrological fields of the climatology and the model (Fig. 12). In this formula, the Brunt-Vaisala frequency N is integrated over the whole water column. The Rossby radius decreases from ~ 27 km at 30° N to ~ 10 km at 60° N. The lower values between 35° N and 44° N are due to shallower regions at these latitudes. The Rossby radius is larger by up to 15% in the model. However, we know that for depth deeper than 1500 m, the climatology is less accurate than in shallower layers as it incorporates less temperature and salinity profiles. Thus we have integrated the formula presented in Chelton et al. (1998) over the upper 1500 m (Fig. 12b). The values of λ_1 obtained with the model are very close to climatological values. The integration of the hydrological properties over the water column depth (first 1500 m) smoothes out discrepancies in the MW core depth and the model shows a good realism for the representation of the dynamical processes studied in this paper.

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4.4 Temperature profiles and mixed-layer depth

Figure 13 represents the RMS of the model-data misfits in temperature over the upper 200 m and the mixed layer depth (MLD) computed from the model and EN3 profiles. Results are shown for two months with different stratification: February, with deeper MLD due to strong mixing during winter period, and August with a more stratified water column. About the spatial distribution during these months, note that in August more profiles are available over the European shelf. In February, modelled temperatures show very good agreement with data almost everywhere over the upper 200 m (RMS globally lower than 0.5°C). The profile of temperature RMS computed over the whole IBI domain (not shown) indicates that maximum RMS values are reached between 50 m and 130 m which is consistent with differences in modelled and observed MLD distribution at these depth ranges (Fig. 13c). During August the water column is more stratified. Larger RMS in temperature profiles (up to 2°C) are found on shelves as well as in the deep ocean. The model globally overestimates the temperature over the upper 200 m in the deep ocean, in the Iroise Sea and the English Channel. In the North Sea, larger RMS values are associated with warm as well as cold bias. Discrepancies between the model bathymetry and the observed bathymetry are possible source of errors in this shallow water region. Another possible source of error may be the wave mixing parameterization coefficient. Sensitivity experiments performed with a $1/12^{\circ}$ resolution configuration have shown that the modelled MLD (and consequently temperatures in the upper ocean layers) is very sensitive to the wave mixing parameterization coefficient. The model MLD representation can be enhanced by tuning this parameter but the parameterization seems to be inadequate in semi-enclosed seas as the Mediterranean Sea or the North Sea. Thus the parameter used is a compromise to minimize the MLD errors both in the open ocean and in the semi-enclosed seas. The maximum RMS is found between 20 m and 60 m (the temperature RMS reaches nearly 1.1°C at 30–35 m), which correspond to the MLD value ranges over the region during August. The MLD distribution shows that modelled MLD is underestimated and

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may result in warmer temperature profiles in the upper layers. In the model, wave-induced mixing, which is incorporated through a parameterization, is underestimated when wind stress is too weak. In winter, winds are strong and mixing is correctly modelled but in summer wind stress is weaker causing too small wave-induced mixing and underestimated MLD in the modelled.

4.5 Local stratification off the Basque country

The time evolutions of temperature and salinity as observed and modelled at the Matxitxako station ($43^{\circ} 37.9' N/2^{\circ} 41.6' W$) are presented in Fig. 10. The profiles show clear seasonal stratification which is a typical pattern of shelf region away from frontal zones. The model reproduces well the rapid heating and freshening of spring 2008. The cooling and mixed-layer deepening during winter are also correctly represented. However the model underestimates the MLD-equivalent in winter (the MDL-equivalent is computed as the depth at which the density changes from the density at 10 m is 0.01). This underestimation may be linked to uncertainties in the previous section. In summer 2007 we also notice that the model salinity is too low in the upper layers. This is due to the initialization from PSY2V3 which is too fresh in this region. On the contrary the model is slightly saltier in the surface layers during summer 2008. This may be due to river runoffs northeast of Spain which induce low salinity buoyant surface waters and which are not included in the model. However, note that rapid freshening pulses during September 2008 are well represented in the model. In November 2007, a rapid cooling of surface layers appears over a few day period. This event corresponds to an upwelling and is well reproduced in the model. During winter 2007–2008, the ocean becomes warmer and saltier over the whole water column. This phenomenon is more marked in the model and affects the 350 m upper layer. It corresponds to a warm extension of the Iberian Poleward Current (IPC) also called “Navidad event” (Frouin et al., 1990). The winter 2007 Navidad occurrence is studied in Sect. 7.

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5 Assessment of SST spatial distribution and diurnal cycle

5.1 SST datasets

We used SST processed at Météo-France/CMS (Le Borgne et al., 2011) for comparisons with the model SST. The data consist in L3 multi-sensors products built from bias-corrected L3 mono-sensor products based on AATSR, METOP, NAR, AVHRR, SEVIRI, AMSRE, TMI and MODIS sensors. SST satellite data consists in daily produced fields covering the 40° W/55° E–20° N/70° N region with a 0.02° resolution and an accuracy of 0.5 °C. These data are used to assess the model ability at reproducing SST both in the deep ocean and in shelf regions. Statistical comparisons are made over a one year period.

The in situ buoy datasets include near surface observations of atmospheric pressure, air and sea surface temperature and, on some platforms, wind speed, wind direction and sea surface currents. They are provided by 4 networks: Puertos del Estado on the Spanish Shelf, Météo France on the Armorican shelf slope, in the Iroise Sea and in the Mediterranean Sea, and the Marine Institute on the Porcupine Bank and in the Celtic Sea (Fig. 1, Table 1). The dataset consists in hourly time series which enable the computation of the diurnal cycle. Our metrics using buoys data rely on time series comparisons and aim to evaluate the behaviour of the system at high frequencies (diurnal cycle) and at seasonal scales.

5.2 SST spatial distribution

For the SST comparisons, the model outputs were interpolated onto the data grid using tools adapted from Juza (2008). Model and data fields were monthly averaged to avoid spatial data gaps. Figure 14 represents maps of seasonally averaged SST and time series of monthly averaged bias and RMS between regional SST data and model SST for the year 2008. Maps of monthly bias show discrepancies that are significantly higher during summer months where it exceeds 0.6 °C (Fig. 14e). This is due to strong

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heating and weak mixing that causes enhanced variability. The spatial averaged bias is small but is not evenly distributed over the domain. The model SST tends to be warmer in the south of the IBI region, in the Mediterranean Sea and around the Faeroe Islands while it is globally too cold over the European shelf. In the Mediterranean Sea the model is too cold along the Northern Current during summer and fall. East of the Gibraltar Strait, discrepancies between modelled and observed SST are found. In this region, the model does not well capture the Western and Eastern Alboran Gyres which strongly vary in time and space (Vélez-Belchí et al., 2005). In the Cadiz Gulf the modelled SST is too warm. In this region the upper slope southeastward current is mainly driven by a coupling with the MW outflow (Peliz et al., 2009). Transport estimations in the model have shown that the MW outflow is underestimated in the Gulf of Cadiz region. Thus the surface current which flows toward the Gibraltar Strait and which carries colder waters from higher latitudes may also be underestimated. This could explain why the model is too warm in this region. Along the West Iberian coast the SST presents a warm bias during winter, a period characterized by the warm extension of the poleward current, while it is too cold in summer when upwelling appears. Negative bias is also found during upwelling episodes off French coasts and in the Canary region of West Africa (Fig. 14c). The underestimated model SST may be associated with too strong wind stress which may induce too strong summer coastal upwelling. The overestimated wind stress used in the model may also explain the too warm modelled SST during the winter 2007–2008 Navidad event whose one of the driving mechanisms is the wind stress (Le Cann and Serpette; 2009). Northeast of Spain, the discrepancies between data and the model during the upwelling event and the Navidad event are clearly visible at the Estaca de Bares buoy station (Fig. 15). In the Irish Sea, at the entrance of the English Channel and in the Iroise Sea, discrepancies in spring and summer SST may be explained by inaccurate thermal frontal positions which are dependent on the tidal propagation in these regions (Holt and Umlauf, 2008). In the rest of the domain, discrepancies are in the order of magnitude of satellite data accuracy (e.g. between -0.5°C and 0.5°C).

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Dsst amplitudes are underestimated in the model and the median observed Dsst is 0.25 °C while the median modelled Dsst is only 0.20 °C. When looking regionally at the distribution, we found that Dsst is underestimated almost everywhere for the 50 % of the data with smaller amplitudes (e.g., Dsst amplitudes below the median value). In the Mediterranean Sea, Dsst amplitudes are underestimated for all data and for all ranges of Dsst amplitudes. The resolution of the model and of the forcing, the surface heat fluxes and the vertical mixing in the upper ocean are critical aspects for the diurnal cycle modelling and may explain discrepancies between the observed and the modelled Dsst (Bernie et al., 2005; Pimentel et al., 2008). According to Bernie et al. (2005), a minimum of a 1 m vertical resolution in the upper ocean and of a 3 h temporal resolution of surface fluxes is required to resolve 90 % of the observed Dsst. The model is forced with 3 h atmospheric fields but has a coarser vertical resolution with 8 levels (respectively 18 levels) in the top 10 m (resp. 50 m). Such a configuration only enables to represent 70 % of the Dsst (Bernie et al., 2005). This could partly explain the underestimation of the Dsst in the model. Overestimated wind stress may also lead to an underestimation of the Dsst by inducing too strong vertical turbulent mixing and preventing from diurnal heating. In the Canary region, Dsst amplitudes are overestimated for the last quartile of amplitudes. As the model is warmer than SST data all over the year in this region (Fig. 14), these discrepancies may be due to local errors in surface heat fluxes. Elsewhere, the model distribution of Dsst amplitudes is in good agreement with data.

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to investigate the capability of the model to reproduce tidal surface ellipses in a region characterized by intense tidal currents.

6.1.3 FES2004

We use the last release of the Finite Element Solution (FES), called FES2004, for comparisons of barotropic tidal elevations (Lyard et al., 2006). The FES2004 tidal atlas is computed from the tidal hydrodynamic equations and tide gauge and satellite data assimilation. It has a global coverage and has been regridded onto a regular grid with a $1/8^\circ$ resolution. It is very accurate in the open ocean but larger errors can occur in shelf regions in coastal areas with complex shorelines. Thus, in addition to tide gauges, the FES2004 solution is useful tool to assess the modelled barotropic tidal solutions in the open ocean.

6.1.4 Altimetric data

We use 10 yr of TOPEX/Poseidon data combined with 7 yr of Jason-1 altimeter data spanning the period from September 1992 to January 2009 for the estimate of the internal tides signature in sea surface elevation. Altimetric data are not used for the validation of barotropic tides, as barotropic tides are compared to the FES2004 solution which assimilates altimetric data. The fraction of internal tides which is phase-locked with astronomical potential has sufficient coherence in both space and time for its surface signal to be detected in altimetric multi year time series (Ray and Mitchum, 1997). Along track sea surface heights have been extracted using the X-Track data processing tool (Lyard, 2008; Roblou et al., 2010). Data have been previously corrected from the barotropic response of the ocean to high-frequency atmospheric pressure and wind forcing (Carrère et Lyard, 2003) but no ocean tidal corrections were made. Along track harmonic analysis was performed to estimate the M_2 components which are used to study the time coherent internal tide signal.

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6.2 Tidal elevations

The amplitudes and phases of the tidal constituents are derived from an harmonic analysis performed over the hourly modelled elevations of the ‘tide only’ run (run_{bt}, see Sect. 2.4) Comparisons between the model and the sea level observations at the tide gauge locations are made for the four principal tidal constituents (M_2 , S_2 , K_1 , O_1) and for the M_4 compound tidal constituent which is a non linear wave resulting from the interaction of M_2 with itself. The M_4 wave has negligible contribution in the open ocean but it is studied as it can reach large amplitudes on the European Shelf and especially in the English Channel (Le Provost and Fornerino, 1985). For each tidal constituent we have computed the RMS of the complex difference amplitude over the whole domain and over specific areas (Table 3). Errors are larger for the M_2 constituent that is the main harmonic over the area; mean error of the complex amplitude difference is 21.6 cm. Errors are not evenly distributed over the region. Mean error is lower than 3.3 cm around the Canary Islands, in the Mediterranean Sea and off West Iberia. Discrepancies between the model and the data are larger over extensive shelf areas where the model overestimates tidal amplitudes by up to 18% (RMS error up to up to 23 cm in the Bay of Biscay, in the English Channel, in the Irish Sea and in the Baltic Sea). In shelf regions, accurate bathymetry is a critical aspect of modelling as it strongly impacts the tidal wave propagation and the tidal amplitudes. Despite of significant improvements in the new bathymetry accuracy, some uncertainties may remain in shallow water regions, in particular in estuaries and small bays where some tide gauges are located. The bottom friction coefficient is also an important parameter for the tidal solution quality. In shallow water areas the flow is much more dependent on bottom friction and bottom friction dissipation is particularly large over the European shelf (Sternberg, 1968; Davies and Aldridge, 1993; Le Provost and Lyard, 1997). We used a constant bottom friction coefficient while it is highly variable over the domain due to the local nature of the seabed (Guillou and Chapalaina, 2010). This can yield inaccurate tidal solution and might partly explain local discrepancies in the English Channel

the strongest discrepancies are also located along the eastern edge of the radar data coverage where there is less confidence on the measurement quality. Everywhere else the modelled phase and inclination of tidal ellipse are in good agreement with data but the modelled tidal current magnitudes are underestimated by up to 15 %.

5 Surface tidal currents from run_{bc} are also compared to observed currents at buoy stations for the M_2 constituent (Table 4, Fig. 20a). The model tends to overestimate the current amplitudes almost everywhere. The largest differences are found for the Villano Sisargas station ($43^\circ 29.4' N/9^\circ 12.6' W$) where the modelled semi major axis is more than twice as large as observations. García-Lafuente et al. (2006) also found the M_2 barotropic tidal currents were much greater than expected in this area; they attributed it to internal tides of considerable amplitudes. Pichon and Corréard (2006) confirmed this study and showed that the Northwest Spanish continental slope is an area of internal tide generation. In the vicinity of Villano Sisargas differences of the M_2 surface current amplitudes between the run with stratification (run_{bc}) and the run without stratification (run_{bt}) present high values due to internal tides (Fig. 20a). As internal tide generation is very sensitive to the bathymetry gradient, errors in the slope position may explain the differences observed at this station. At the Cabo Silleiro station ($42^\circ 7.2' N/9^\circ 24' W$) tidal ellipse parameters are not correctly modelled. The model ellipse inclination is parallel to the isobath which is consistent with the study of Visser et al. (1994) in well mixed conditions. Visser et al. (1994) also showed that in a region of freshwater influence, the stratification significantly influences the cross-shore component that can reach 40 % of along-shore component; this is coherent with the observed ellipse orientation. Thus the inclination error may be due to local stratification due to Galician ria runoffs that are not included in the model. At Donostia and Matxitxako station ($44^\circ 33.8' N/2^\circ 1.4' W$, $43^\circ 37.9' N/2^\circ 41.6' W$) modelled ellipses are also oriented along the slope while observed ellipses are oriented across the slope. Indeed vertical profile of observed M_2 semi major axis shows a clear stratification in the surface layers which is not represented in the model (Fig. 21). In addition Fig. 10 shows that surface layers are fresher in the observations than in the model during periods on which the harmonic analysis

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has been performed, that is December 2007–January 2009 for the Donostia current time series and April 2008–February 2009 for the Matxitxako time series. Thus errors in the Donostia and Matxitxako modelled ellipses may be due to freshwater discharges that are not included in the model and may affect the tidal currents in surface. Below this layer (upper 30 m) the modelled profile is in good agreement with observations for the two current profiles (see Fig. 21 for the Matxitxako station). In the Gulf of Cadiz and in the Canary Island region, the modelled tidal currents are in good agreement with observations.

6.4 Internal tides

We used sea surface height data from altimetry to examine the M_2 internal tide signal in the Bay of Biscay. We consider the track TOPEX/Poseidon/Jason1 137 that crosses the Armorican shelf slope at nearly right angle (Fig. 1) as we expect the M_2 internal tides to propagate almost in the same direction. The method used to separate the barotropic tides from the time coherent internal tide signal consists in spatial filtering of the M_2 real and imaginary parts to remove the barotropic large scale signal (Ray and Mitchum, 1997). According to Pairaud et al. (2010) the wavelength of baroclinic mode 1 and mode 2 are, respectively 141 km and 75 km in the abyssal plain. Note that these values have been obtained using data collected during September-October 1994 and may vary with the stratification. To take into account the angle between the altimeter track and the internal tide direction of propagation we use a spatial cut-off slightly larger than the wavelength. We also filter at shorter scales to reduce the altimeter noise. Finally along track tidal components are filtered between 140 km and 210 km for mode 1 and between 60 km and 110 km for mode 2. The “residual tides” are obtained by removing the filtered signal to the harmonic components. Figure 22 presents the along track amplitudes and phase as computed from the altimetric data and from the model for mode 1 and for mode 2. It also presents the along track bathymetry. Indications attesting that the small oscillations are internal tides are: 1) oscillations are generated in the Armorican shelf slope region (45.8°N–46.0°N), 2) south of the shelf break the

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with weaker tidal currents. The simulated temperature section exhibits a similar pattern. The mixed layer depth in the stratified waters is in good agreement with observations but the model is slightly colder by $\sim 0.3^\circ\text{C}$ below the MLD. The relaxing isopycnal slope between stratified and well mixed water is in good agreement with data. In the frontal region the model well represent the non coincidence between surface and bottom front positions. However the vertical resolution and the $1/36^\circ$ horizontal resolution are still not sufficient to correctly represent small structures in frontal and transition regions. The position of the front is relatively well reproduced in the model. Small differences in the frontal position may be due to tides. As the Ushant front is tidally induced it is very sensitive to the water column depth. In the mixed region the model bathymetry is about 20 m deeper than in the observations which may induce discrepancies in the frontal position. In this region, the temperature is more mixed in the model. As the MLD is relatively accurate in the stratified region, one can suppose that the bottom mixed layer is overestimated and reaches the MLD which induces a vertical mixing over the whole water column in the model. East of the internal front, data indicate thermal stratification while the model is well mixed. Between 5.05°W and 5°W , there is also a warmer layer in the upper 15 m in the data which is not modelled. This may be explained by local circulation: East of the transect very strong tidal currents are due to the presence of the island of Sein (48.0°N , 4.8°W). The model grid resolution is not sufficient to represent the island of Sein and the associated tidal currents are not modelled. In spite of some misfits, the model simulates well most of the dynamical aspects in the Ushant front region.

7.2 A focus on the circulation in the Southern Bay of Biscay

The analysis of the modelled SST and sea surface salinity (SSS) in the Bay of Biscay shows a warm and salty current flowing poleward along the Western and the Northern Iberian Peninsula and reaching the SW of France during winter 2007–2008 (Figs. 15 and 25, SSS not shown). The extension of the IPC at or near surface along the

provide a driving mechanism of the poleward current. When the current has reached Cap Finistere and turns eastward, its poleward flow is maintained by positive τ_x .

8 Conclusions

The aim of this study was 1) the definition of metrics for regional coastal simulations and 2) the assessment of the NEMO model on the IBI region using these metrics. It has been carried out for an hindcast simulation in 2008. Comparisons with the climatology, transport estimations, in situ and satellite data have been performed to assess the model performance.

The main contribution of the study was the definition of new metrics to validate the new model improvements which include the resolution of high frequency dynamics such as tides, the diurnal cycle and surges. A common methodology for validation procedures based on a validation plan and metrics implementation has been built. The procedure includes metrics developed within the MERSEA project for the verification of the model consistency, quality and performances in the deep ocean. It also includes complementary metrics upgraded for shelf and coastal regions. In particular, the contribution of the high-frequency and low-frequency dynamics has been investigated separately for EKE, SSH, currents and SST. Self-consistency metrics have also been used to evaluate the ability of the model to reproduce specific physics of the IBI region such as tidal front extensions and the Navidad SST signature. The validation exercise of the procedure has been tested during the MyOcean project. It has allowed a synthetic and complete assessment of the IBI configuration. The new metrics developed within this work could be used for other regional model assessment. Besides, the procedure defined in this article will serve as a basis for the IBI real-time validation and could also be used for defining Cal/Val strategies in an operational context for other regional forecast systems. From this extensive scientific assessment, a procedure has already been derived to assess the necessary improvements between versions of the MyOcean IBI system based on Taylor diagrams. A subsample of these metrics was

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also be improved by further improvements in the bathymetry and further tuning in the bottom friction as a spatial dependence with the seabed nature. This study was a first step towards the setup of an operational ocean forcing system in the IBI area. We have characterized the model uncertainties to highlight elements that will need future model developments. Data assimilation will be the next step to improve the simulation. Further work on model assessment should also rely on altimetric data. In particular, we plan to explore metrics that would allow us to characterize the mesoscale and sub-mesoscale activity in the simulation.

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Table 1. List of in situ buoys used in this study. For each buoy, the longitude, latitude, and variable available at the station and the organism providing the data are indicated. The variables that may be available are: sea surface temperature (SST), sea surface salinity (SSS), currents (U,V) at the surface for Puertos del Estado buoys and in the first 200 m currents along the water column depth for AZTI buoys and atmospheric variables (AV) that include air temperature, atmospheric pressure and wind velocity.

Mooring name	Lon	Lat	SST	SSS	UV	AV	Organism
Cadiz_Buoy	-6.96	36.48	✓	✓	✓	✓	Puertos del Estado
Cabo Silleiro	-9.40	42.12	✓	✓	✓	✓	Puertos del Estado
Villano Sisargas	-9.21	43.49	✓	✓	✓	✓	Puertos del Estado
Estaca Bares	-7.62	44.06	✓	✓	✓	✓	Puertos del Estado
Cabo Penas	-6.17	43.73	✓	✓	✓	✓	Puertos del Estado
Sanatander	-3.77	43.84	✓	✓	✓	✓	Puertos del Estado
Bilao	-3.04	43.63	✓	✓	✓	✓	Puertos del Estado
Tenerife	-16.58	28.00	✓	✓	✓	✓	Puertos del Estado
Gran Canaria	-15.81	28.19	✓	✓	✓	✓	Puertos del Estado
M1	-11.20	53.13	✓				Marine institute
M2	-5.42	53.48	✓				Marine institute
M3	-10.55	51.22	✓				Marine institute
M4	-10.00	55.00	✓				Marine institute
M5	-6.70	51.69	✓				Marine institute
M6	-15.93	53.06	✓				Marine institute
Brittany	-8.50	47.50	✓				Météo France
Gascogne	-5.00	45.20	✓				Météo France
Lion	4.70	42.10	✓				Météo France
Ouessant	-5.75	48.50	✓				Météo France
Donostia	-2.02	43.56	✓	✓	✓		AZTI
Matxitxako	-2.69	43.63	✓	✓	✓		AZTI

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Table 2a. Transport estimates from the model and the literature. Model transports are estimated from monthly fields and mean and RMS values are presented. Units are Sv. Values in green (resp. in red) indicate net northward transports (resp. net southward transports) or net eastward transports (net westward transports) for zonal sections as computed from observations. Values in black indicate net transports. Estimations in bold are used for Fig. 5.

	Ext. 1	Ext. 2	Transport classes	Model values Mean/StdDev	Published Estimations	References
Gibraltar	−5.74E 35.70N	−5.74° E 36.20° N	S < 37.25 S > 37.25	0.48/0.05 −0.49/0.5	0.66−0.97 −0.84−−0.57	Tsimplis and Bryden, 2000; Lafuente et al., 2002
Mallorca-Spain	3.10° E 39.80° N	2.00° E 41.40° N	NO	−091/0.55	1.5−−0.75	Béthoux, 1980; Font et al., 1988; Schroeder et al., 2008
Ibiza Channel	0.00° E 38.75° N	1.37° E 39.00° N	NO	0.65/0.27 −1.33/0.47	0.2−0.7 −1.6−−0.2	Béthoux, 1980; Font et al., 1988; Pinot et al., 2002
Sardinia Channel	9.00° E 36.80° N	9.00° E 39.37° N	S < 38.5 S > 38.5	1.24/0.58 −078/0.28	0.50−1.85 1.30−−0.20	Garzoli and Maillard, 1979; Béthoux, 1980; Sammari et al., 1999; Onken et al., 2002
North Corsica	7.20° E 43.70° N	8.75° E 42.50° N	0 < z < 200	0.90/0.12 −1.28/0.35	0.7 −1.5−−0.9	Béthoux, 1982; Astraldi and Gasparini, 1992; Sammari et al., 1995; Barth et al., 2005
			200 < z < 700	0.75/0.21 −0.80/0.22	0.2 −0.4−−0.2	
			0 < z < 700	1.65/0.27 −2.07/0.52	0.9−1.15 −1.9−−1.0	
Gulf Lion	5.12° E 42.50° N	5.12° E 43.40° N	0 < z < 500	−1.51/0.44	1.18	André et al., 2009
Cadiz Gulf	−8.50° E 32.00° N	−8.50° E 38.20° N	$\sigma_1 < 31.7$ 31.7 < σ_1	1.77/0.24 −0.04/0.16	3.1 −2.8	Mauritzen et al., 2001
North Cadiz Gulf	−8.50° E 35.40° N	−8.50° E 38.20° N	32.0 < σ_1 < 36.8	−0.74/1.07	−6.5−−2.7	Howe, 1984; Rhein and Hinrichsen, 1993; Mauritzen et al., 2001
Azores Current	−14.00° E 33.00° N	−14.00° E 37.00° N	z < 1500	15.10/4.53 −12.25/6.17	13.7 −4.7	Peliz et al., 2007
Algerian Current	2.00° E 36.50° N	2.00° E 38.00° N	$\sigma < 29.0$ 29.0 < σ < 33.465 33.465 < σ	0.63/0.50 0.58/0.45 1.01/0.56	1.07−2.26 0.02−0.20 −0.16	Béthoux, 1980; Benzhora and Millot, 1995; Schroeder et al., 2008
Lanzarote-Africa	−11.10° E 28.70° N	−13.90° E 28.70° N	$\sigma < 27.3$ 27.3 < σ < 7.7	−0.41/1.14 0.02/0.42	−2.50−−0.60 0.1	Hernandez-Guerra et al., 2002; Machin and Pelegrí, 2006; Machin et al., 2006
Fuerteventura-Gran Canaria	−14.40° E 28.10° N	−15.50° E 28.10° N	$\sigma < 27.3$	−0.82/0.56	−0.9	Hernandez-Guerra et al., 2002
South Portugal	−8.70° E 37.60° N	−11.00° E 37.60° N	$\sigma < 27.25$ 27.25 < σ < 32.35	0.15/0.42 3.02/2.73	2.7−5.7 1.2−5.2	Jorge da Silva, 1996; Mazé et al., 1997; Coelho et al., 2002
Portugal	−20.00° E 40.10° N	−8.10° E 40.00° N	$\sigma < 27.7$ 27.7 < σ < 36.98 36.98 < σ < 45.85 45.85 < σ	1.07/0.61 1.35/3.17 0.27/1.32 0.68/0.54	0.5−2.8 −1.4−0.5 −1.3−0.5 0.8−1.6	Alvarez et al., 2004; Lherminier et al., 2007

Table 2a. Continued.

	Ext. 1	Ext. 2	Transport classes	Model values Mean/StdDev	Published Estimations	References
Galicia	-9.10° E 43.00° N	-10.50° E 43.00° N	$\sigma < 27.25$ 27.25 < $\sigma < 32.35$ $z < 400$ $400 < z < 900$ $900 < z < 1500$	0.32/0.33 3.63/1.66 1.71/1.11 1.72/0.69 1.23/0.81	1.31-4.7 0.42-1.8 0.9 0.7 0.2	Jorge da Silva, 1996; Mazé et al., 1997; Mauritzen et al., 2001; Coelho et al., 2002
Celtic shelf	-10.10° E 47.60° N	-9.40° E 48.40° N	$200 < z < 1500$ 200 < z < 3000	4.31/2.85 4.71/3.49	1 3	Pingree and Le Cann, 1990
Biscay	-4.00° E 48.20° N	-8.10° E 43.10° N	$S < 35$ 35 < S < 35.6 $35.6 < S$	-024/0.31 0.04/0.31 0.23/0.55	-0.1-0.1 -0.2-0.0 -2.6--2.0	Frail-Nuez et al., 2008
Ellett line	-7.70° E 56.80° N	-13.80° E 57.50° N	$z < 500$ z < 1200 $1200 < z < 1800$	2.86/0.54 3.89/0.93 -0.19/0.09	2.5-2.7 3.5-3.7 0.2	Ellett and Martin, 1973; Holliday et al., 2000
St. Georges Channel	-6.45° E 52.30° N	-5.10° E 51.80° N	NO	0.08/0.06	0.18	Brown et al., 2003
North Irish Sea Channel	-5.00° E 54.90° N	-5.60° E 54.60° N	NO	0.01/0.05	-0.175-0.14	Howarth, 1982; Brown and Gmitrowitz, 1995
Dover Strait	1.80° E 50.90° N	1.35° E 51.20° N	NO	0.07/0.06	0.094-0.17	Otto et al., 1990; Prandle et al., 1996
Faeroe Bank Channel	-7.00° E 61.80° N	-8.50° E 61.00° N	$T < 0$ T < 3 NO	-0.0/0.00 -1.23/0.22 -3.10/0.44	-1.5--0.5 -2.8--1.0 -2.8--0.5	Saunders, 1990; Krauss, 1995; Van Aken and Becker, 1996
Wyville Thomson Ridge	-8.80° E 60.50° N	-6.50° E 59.70° N	$T < 0$ T < 3 NO	0.00/0.00 0.03/0.02 2.32/0.42	-0.3--0.06 -0.35--0.1 -1.0--0.2	Ellett et al., 1986; Saunders, 1990; Van Aken and Becker, 1996; Hansen and Østerhus, 2000; Sherwin and Turrell, 2005
Faeroe Shetland Channel	-6.60° E 61.40° N	-3.50° E 60.10° N	$T < 0$ 0 < T	1.19/0.19 2.43/0.86	1.7--1.5 2.0-3.8	Saunders, 1990; Krauss, 1995; Van Aken and Becker, 1996; Østerhus et al., 2005
North Faeroe	-6.10° E 62.30° N	-6.10° E 65.00° N	NO	5.12/1.59 -1.03/0.42	2.9-5.0 -3.2	Krauss, 1995; Saunders, 1996; Van Aken and Becker, 1996; Hansen et al., 1998
Scotland-Shetland	-3.10° E 58.60° N	-1.30° E 60.00° N	NO	0.36/0.21	0.3-0.4	Otto et al., 1990
Shetland-Norway Trench	-1.30° E 59.90° N	3.70° E 59.90° N	NO	-0.70/0.26	-0.6	Otto et al., 1990
Norway Trench-Norway	3.70° E 59.90° N	5.10° E 59.90° N	NO	1.24/0.44	1.8	Otto et al., 1990
Skagerrak	10.08° E 60.00° N	10.08° E 57.00° N	NO	1.31/0.30	0.5-2.1	Rydberg et al., 1996; Rodhe, 1996
Kattegat	10.00° E 57.00° N	13.00° E 57.00° N	NO	0.02/0.02	0.055	Andersson and Rydberg, 1993

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Table 2b. Heat flux estimates from the model and the literature. Model transports are estimated from monthly fields and mean and RMS values are presented. Units are TW.

	Ext. 1	Ext. 2	Transport classes	Model values Mean/RMS	Published Estimations	References
Faeroe Shetland Channel	–6.60° E 61.40° N	–3.50° E 60.10° N	0 < T	117.17/33.36	123–156	Turrell et al., 2003; Østerhus et al., 2005
North Faeroe	–6.10° E 62.30° N	–6.10° E 65.00° N	0 < T	95.84/23.75	110–139	Hansen et al., 2003

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Table 2c. Freshwater flux estimates from the model and the literature. Model transports are estimated from monthly fields and mean and RMS values are presented. Units are kT s^{-1} .

	Ext. 1	Ext. 2	Transport classes	Model values Mean/RMS	Published Estimations	References
Faeroe Shetland Channel	–6.60° E 61.40° N	–3.50° E 60.10° N	$0 < T$	86.55/30.51	115–139	Turrell et al., 2003; Østerhus et al., 2005
North Faeroe	–6.10° E 62.30° N	–6.10° E 65.00° N	$0 < T$	123.88/34.69	115–143	Hansen et al., 2003

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Table 3. RMS error of the complex amplitude difference between observed and modelled tidal components.

Regional	M2	S2	K1	O1	M4
Global	21.6	8.0	1.8	1.3	7.1
Canary	2.8	1.7	0.4	0.2	0.1
Mediterranean Sea	3.3	0.7	0.9	0.2	0.4
Gibraltar	6.4	1.7	0.8	0.5	1.0
Gulf of Cadiz and West Iberian Plateau	3.2	3.4	0.9	0.4	0.6
Bay of Biscay	29.5	10.6	1.2	0.8	0.8
Irish Sea	25.9	10.1	1.7	1.3	11.1
English Channel	23.6	8.1	1.5	1.9	7.5
North Sea	14.7	4.7	2.7	1.0	6.2
Baltic	29.8	9.0	2.4	2.1	0.9

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Table 4. RMS between observed and modelled tidal ellipse parameters.

	SEMA	SEMI	Inc	Pha
Barotropic ellipses (M_2)				
IBI domain	4.8	3.9	23.8	27.0
Gibraltar	13.3	5.6	8.3	26.4
Portugal Plateau	4.2	0.4	31.6	22.6
Armorican and Celtic Shelves	4.1	6.9	33.7	45.5
North Sea	3.3	2.3	9.5	9.0
Irish Sea	5.3	3.0	3.0	3.9
Baroclinic ellipses (buoys, M_2)				
IBI domain	4.4	2.6	22.1	31.3
Baroclinic ellipses (radar, M_2)				
Iroise sea (depth > 50 m)	4.6	2.5	5.1	5.6
Baroclinic ellipses (radar, M_4)				
Iroise sea (depth > 50 m)	1.1	0.3	17.1	39.6

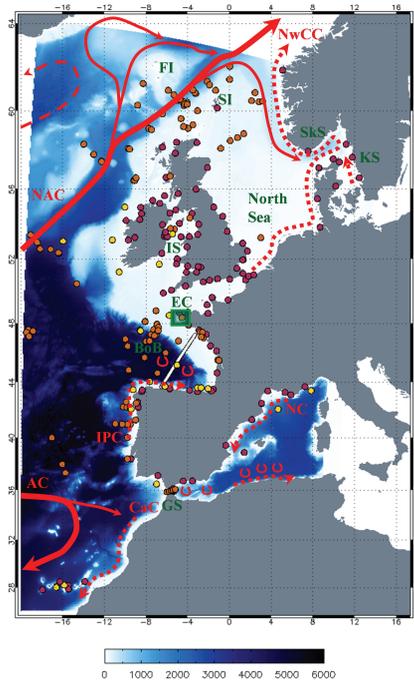


Fig. 1. Bathymetry of the domain (in meter). Superposed are the tide gauge positions (red dots), the buoy locations (yellow dots), the current meter data for tidal comparisons (orange dots), the altimeter track crossing the Bay of Biscay (white line) and the area covered by the HF radar for surface current measurements off West Brittany (green box). The main surface dynamical features are also shown: the Azores Current (AC), the Canary Current (CaC), the Northern Current (NC), the Iberian Poleward Current (IPC), the Norwegian Coastal Current (NwCC), the North Atlantic Current (NAC). Red symbols represent mesoscale activity in the Mediterranean Sea and in the Bay of Biscay. Some geographical features of the area are also mentioned: the Gibraltar Strait (GS), the Bay of Biscay (BoB), the English Channel (EC), the Irish Sea (IS), the Shetland Islands (SI) and the Faeroe Islands (FI), the Skagerrak Strait (SkS) and the Kattegat Strait (KS).

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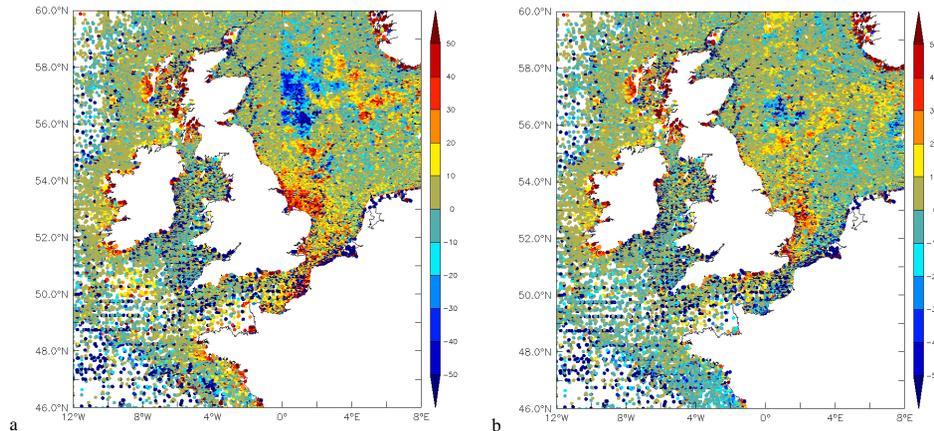


Fig. 2. Comparisons of the bathymetry GEBCO08 (a) and the new bathymetry used in the model (b) with ICES profile depth. The results represent percentage of error between data and bathymetry grids. ICES depth is deduced from ICES measurements by taking the difference between the deepest and the shallowest measurements.

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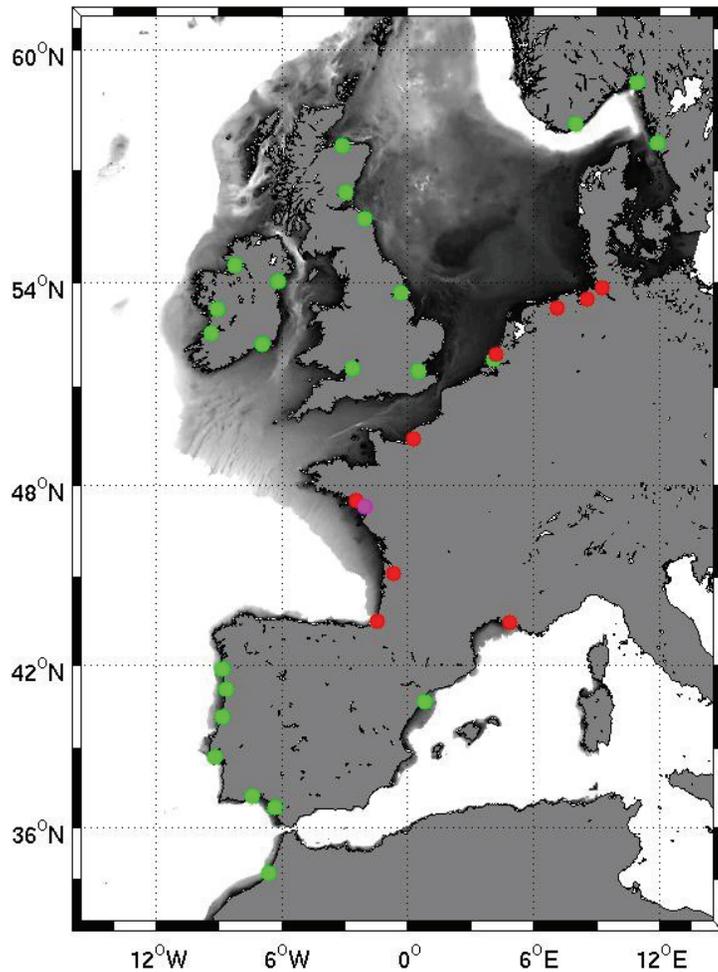


Fig. 3. Runoffs of the IBI configuration.

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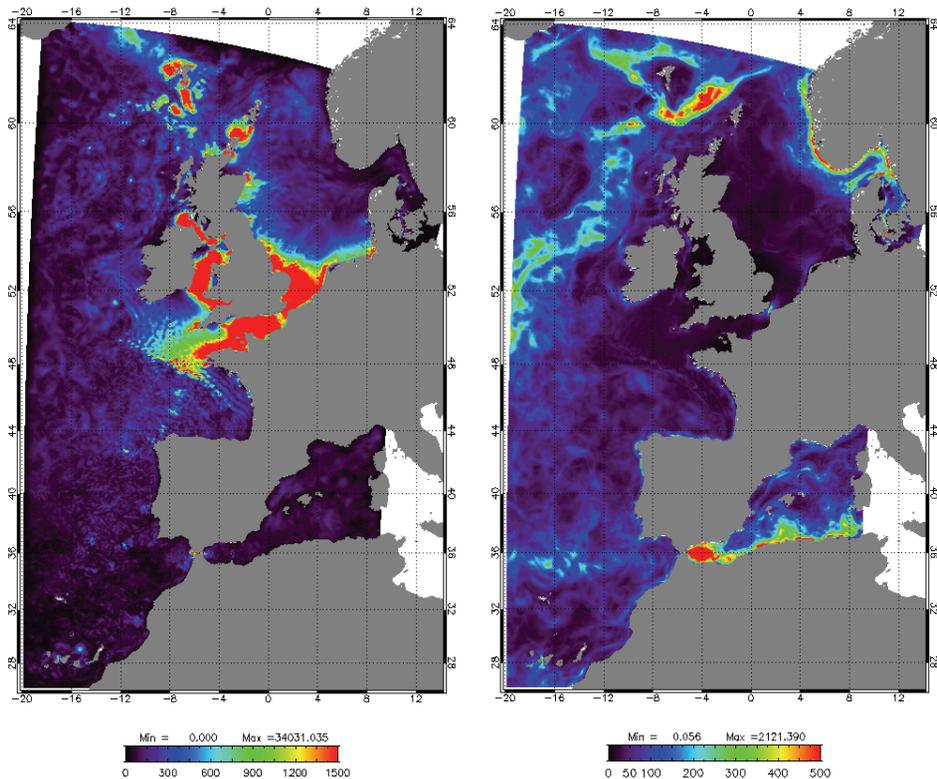


Fig. 4. Surface EKE for periods below 25 h **(a)** and for periods above 25 h **(b)**. **(a)** is computed over July 2008 and **(b)** is computed over year 2008.

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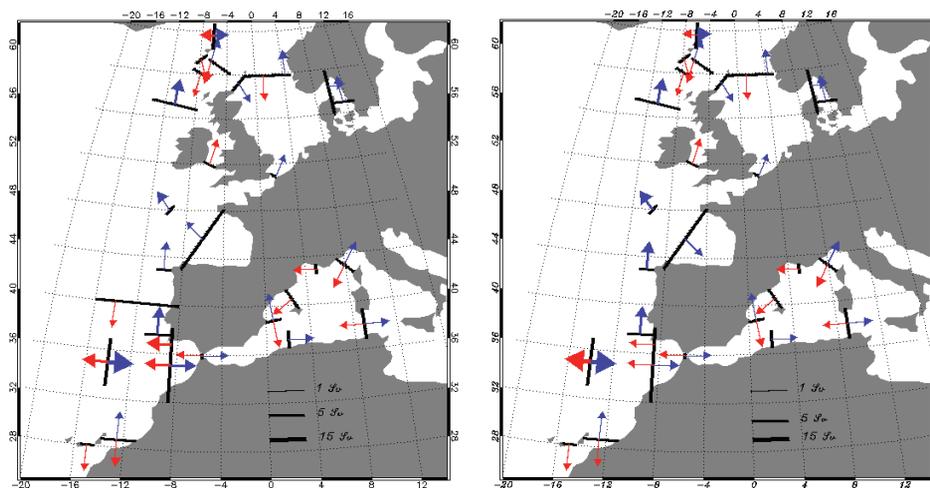


Fig. 5. Transport estimates from the literature **(a)** and from monthly model fields **(b)**. The thickness of the arrow indicates the volume in Sv. The blue color (resp. red color) indicates northward (resp. southward) transports or eastward (westward) transport for zonal sections as computed from observations. Estimations used for the plot are in bold in Table 2a. Model transports corresponding to the estimations computed from observations are plotted using the same color than published estimations.

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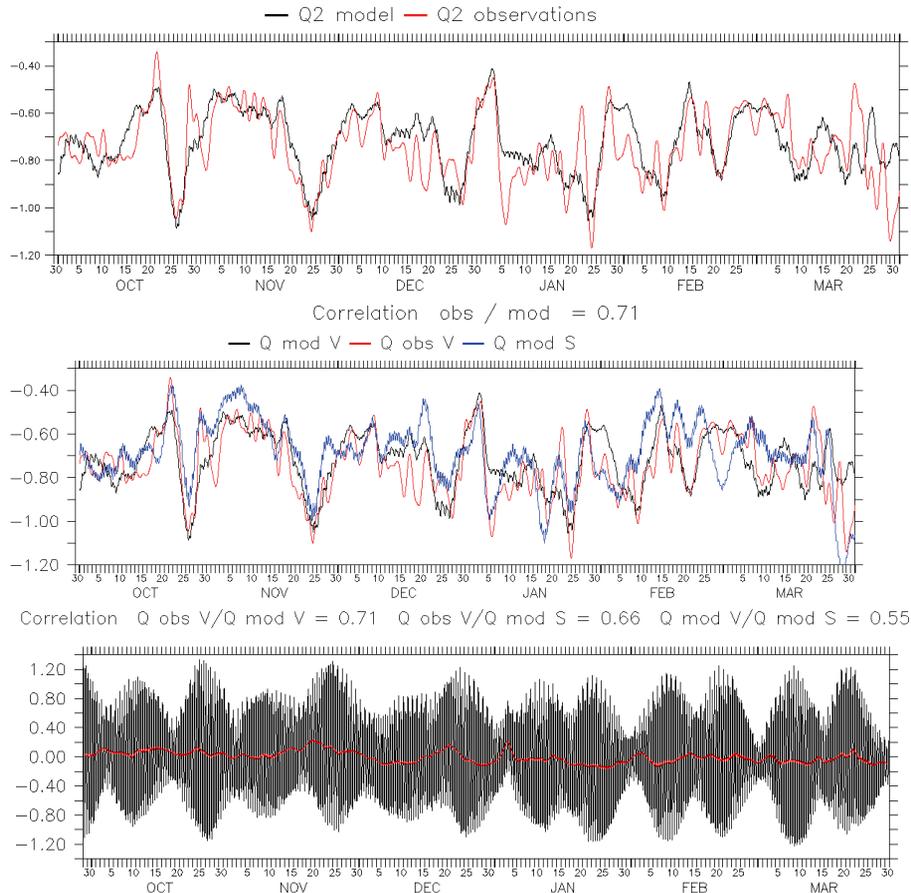


Fig. 6. Transports (outflow) at Gibraltar Strait for QobsV, QmodV and QmodS (a). Depth of the interface for QmodV and QmodS (b). Unfiltered sea surface elevations (e.g. includes tidal elevations) in black and 2-day low-pass filter sea surface elevations in red at the Gibraltar Strait (c).

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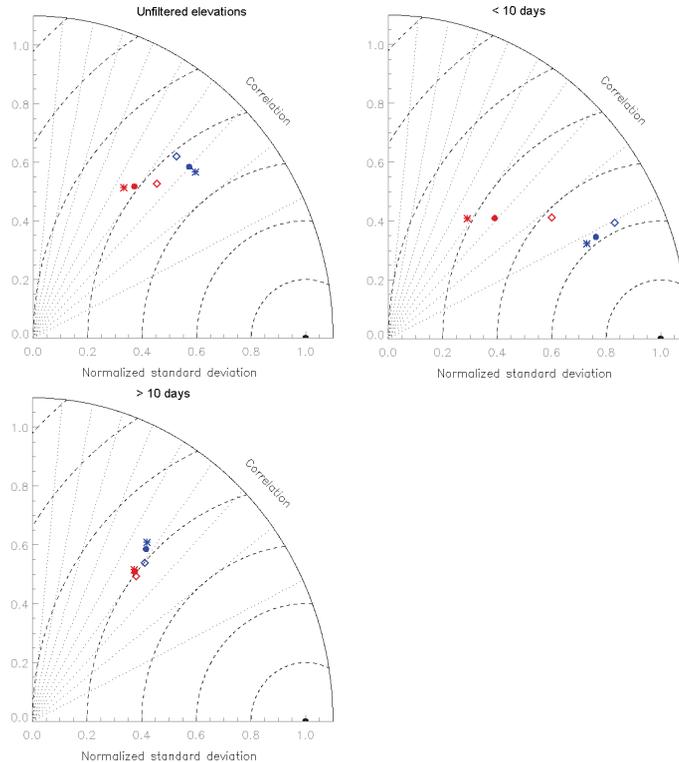


Fig. 7. Taylor diagram for comparisons between tide gauge data and the model residual elevations (blue) and the inverse barometer (red). The radial coordinate indicates the standard deviation normalized by the data standard deviation and the angular coordinate represents the correlation with observations. The observations are indicated with the black point and distances between the colored model points and the data point indicate the RMS difference error. Plain dots are for the whole area, stars are for locations north of 50° N and diamonds are for locations south of 50° N. Results are shown for the unfiltered time series (a), for periods below 10 days (b) and for periods above 10 days (c).

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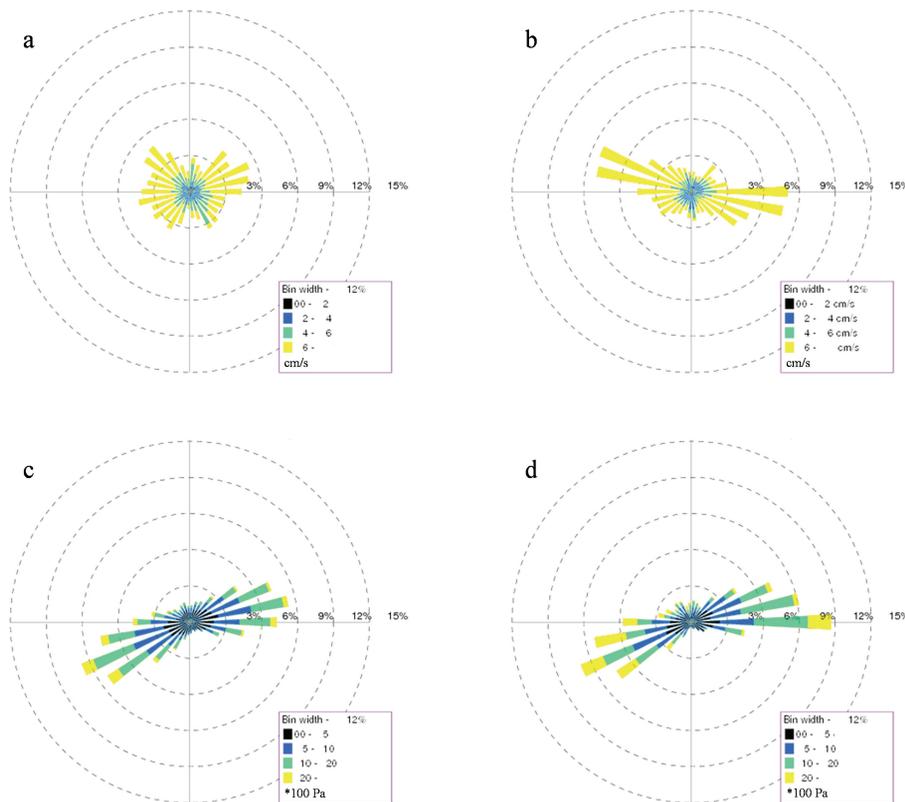


Fig. 8. Wind rose of the 2-day low pass filtered residual currents as observed **(a)** and modelled **(b)** at the Estaca de Bares buoy station. Corresponding wind stress as observed at the buoy station **(c)** and as extracted from the model forcing fields using ECMWF wind speed **(d)**.

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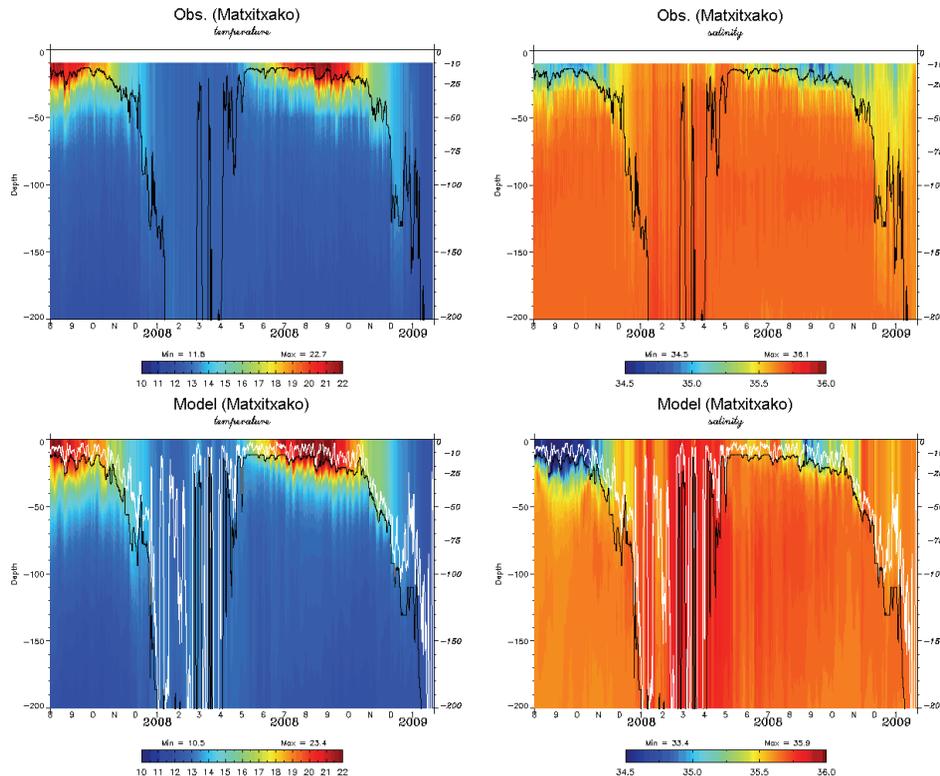


Fig. 10. Temperature and salinity at station Matixxako from the observations (**a, b**) and from the model (**c, d**). The mixed layer depth is also represented with a white line. It is computed as the depth at which the density change from the surface density is 0.01. It is not represented on the observation plots as the observation shallowest depth is 10 m. The black line represents the depth at which the density change from the 10 m density is 0.01.

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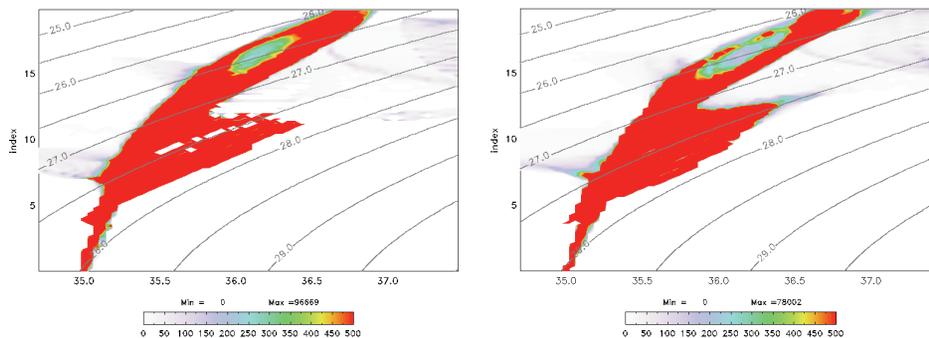


Fig. 11. Volumetric TS diagram (10^3 m^3) for the ARIVO climatology **(a)** and for the model **(b)** over the IBI domain. The diagram is presented for bathymetry depth deeper than 200 m. The data are yearly averaged and the model thermohaline fields are averaged over 2008.

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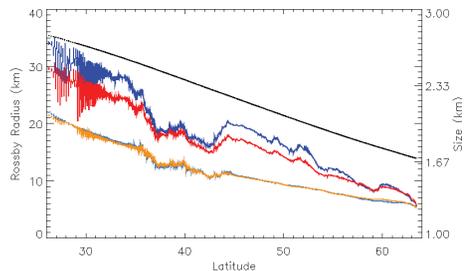
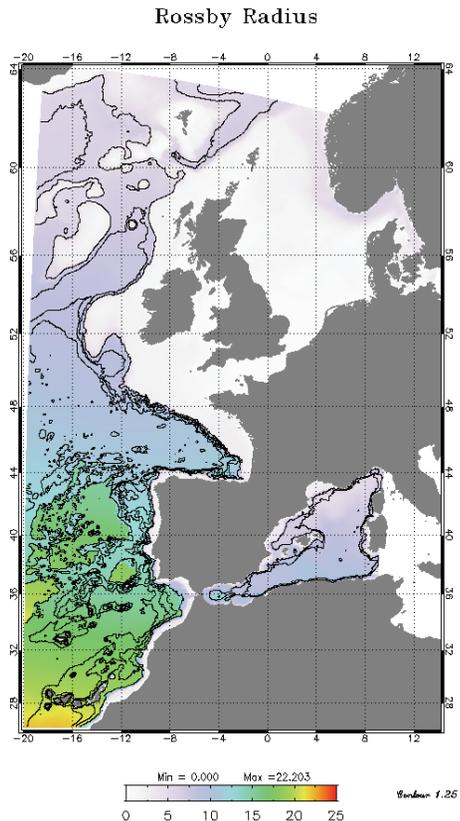


Fig. 12. (a) First Rossby radius of deformation for the model (in km). **(b)** First Rossby radius as a function of latitude. The radius is averaged for bathymetry points deeper than 1000 m. We distinguish two cases: 1) N is integrated over the full water depth as in the formula of Chelton et al. (1998) for the model (dark blue) and the climatology (red), 2) N is integrated over the upper 1500 m for the model (light blue) and the climatology (orange). We also show the variations of the grid size with latitude (black line).

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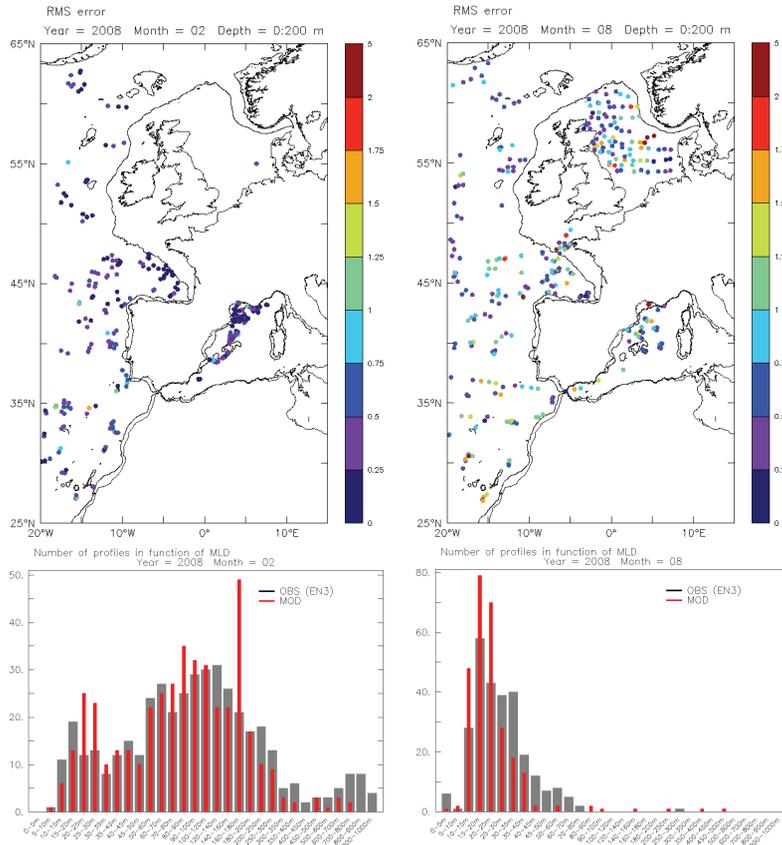


Fig. 13. RMS of temperature differences between EN3 profiles and model profiles computed over the first 200 m. Results are presented for February 2008 (a) and August 2008 (b). Distribution of profiles in different mixed layer depth ranges computed from EN3 data (grey) and model fields (red) for February 2009 (c) and August 2008 (d).

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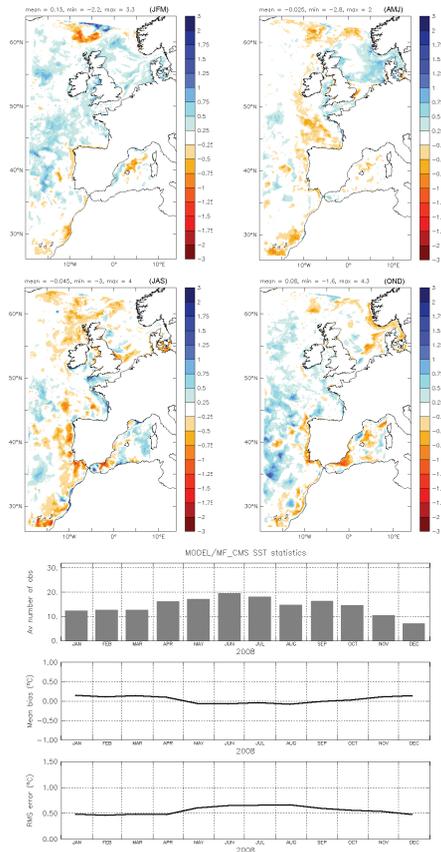


Fig. 14. Map of mean bias between Météo-France/CMS satellite data and model SST over January–March 2008 (a), April–June 2008 (b), July–September 2008 (c) and October–December 2008 (d). Negative bias indicates that the model is too cold. (e) Number of observations, monthly bias and RMS over the whole IBI area. Units are in °C.

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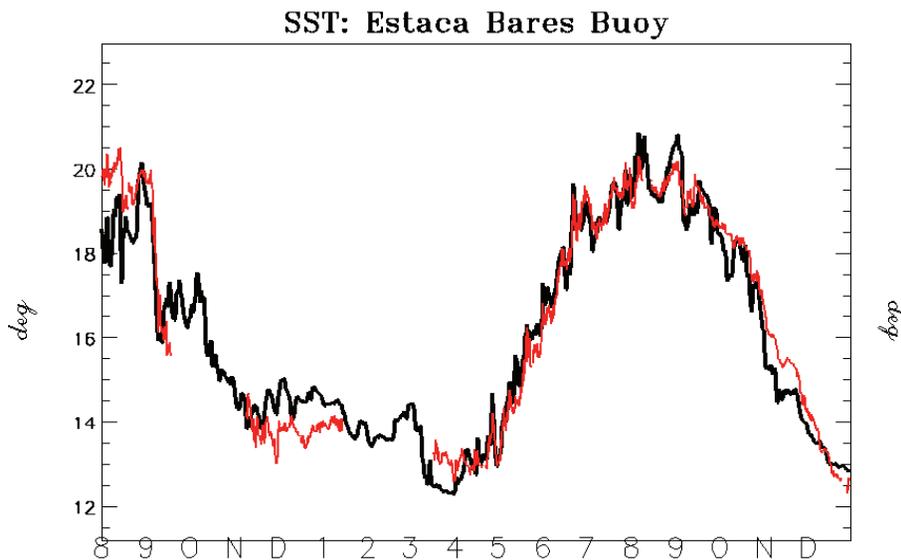


Fig. 15. Modelled (black) and observed (red) sea surface temperatures at the Estaca de Bares buoy station ($44^{\circ} 3.6' \text{ N}$ – $7^{\circ} 37.2' \text{ W}$) from August 2008 to December 2009. Note that there is no data during September–October 2007 and January–March 2008.

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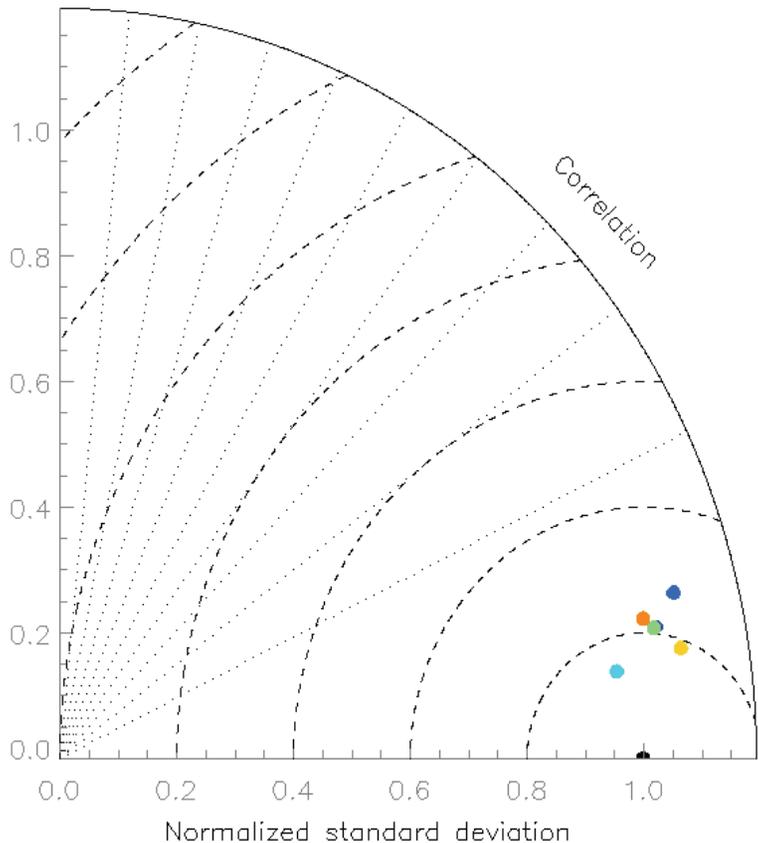


Fig. 16. Taylor diagram of the 1-day low pass filtered SST at buoy locations. The dark blue point is for comparisons within the whole domain, the turquoise blue point for the Canary region, the light blue point for the Mediterranean Sea, the light green point for the Iberian Peninsula region, the yellow point for the Bay of Biscay and the orange point for the Celtic sea and the Irish sea.

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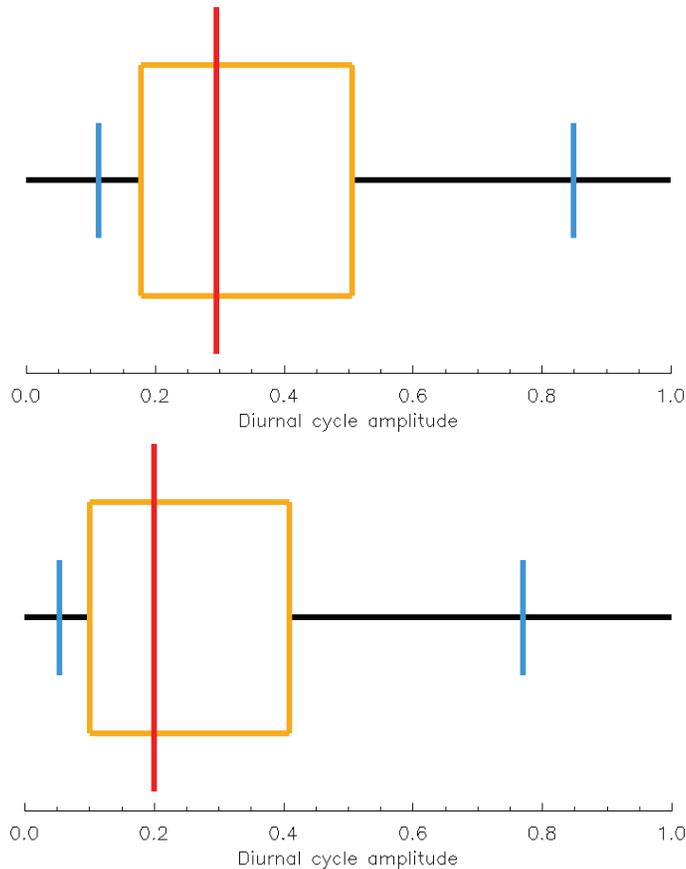


Fig. 17. Boxplot of the diurnal cycle computed from data **(a)** and from model **(b)**. The distribution is described with percentiles of data (vertical lines). From the left to the right we indicate the position of the 10th percentile (blue), the lower quartile (yellow), the median (red), the upper quartile (yellow) and the 90th percentile (blue).

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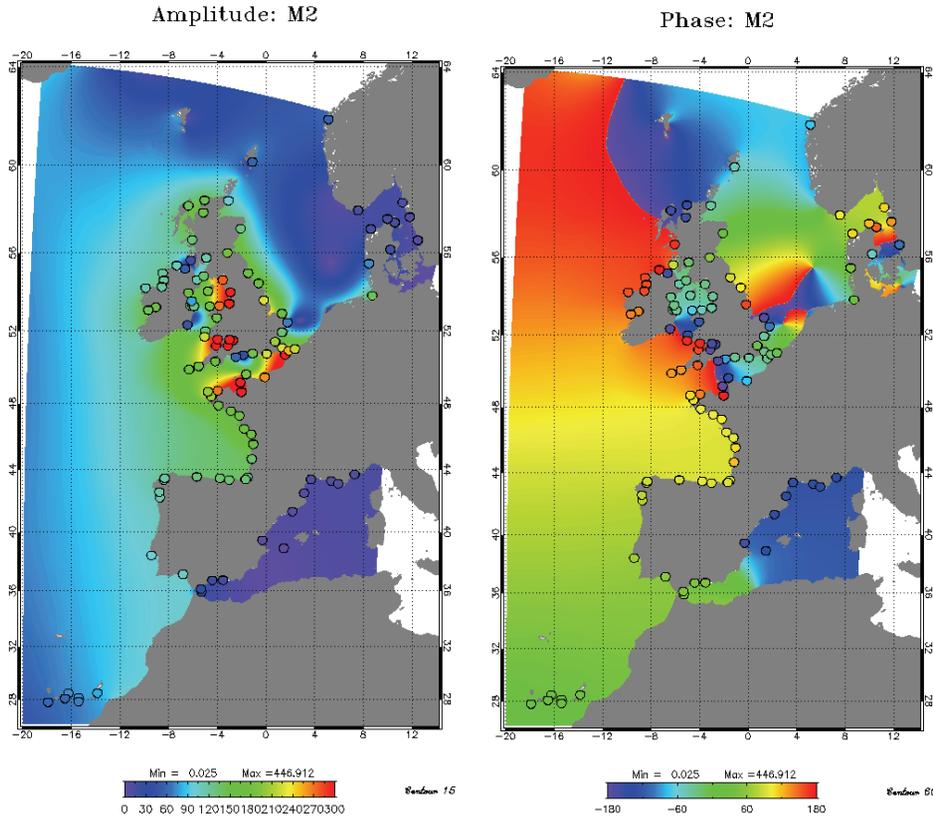


Fig. 18. Amplitude in cm (a) and phase in degrees (b) of the M_2 tidal constituent computed from the model over the whole domain. Overplotted filled dots represent the M_2 observed harmonic constants. Differences of amplitude (c) and phase (d) between the FES2004 solution and the model for the M_2 constituent. Overplotted filled dots represent amplitude and phase differences between tide gauges and the model.

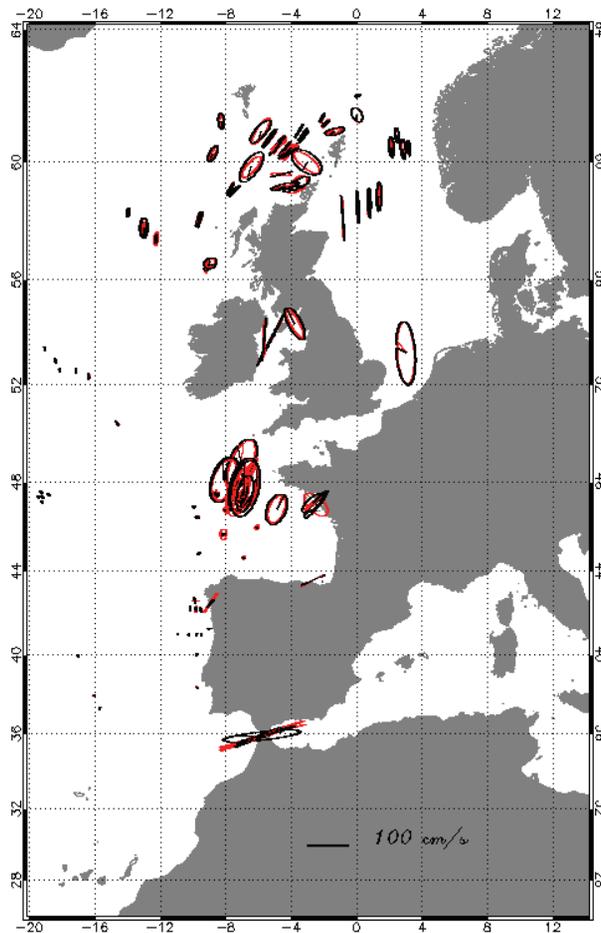


Fig. 19. Modelled (black) and observed (red) M_2 barotropic tidal ellipses. Observations encompass historical data from BODC, BSH and data collected within the framework of the WOCE experiment.

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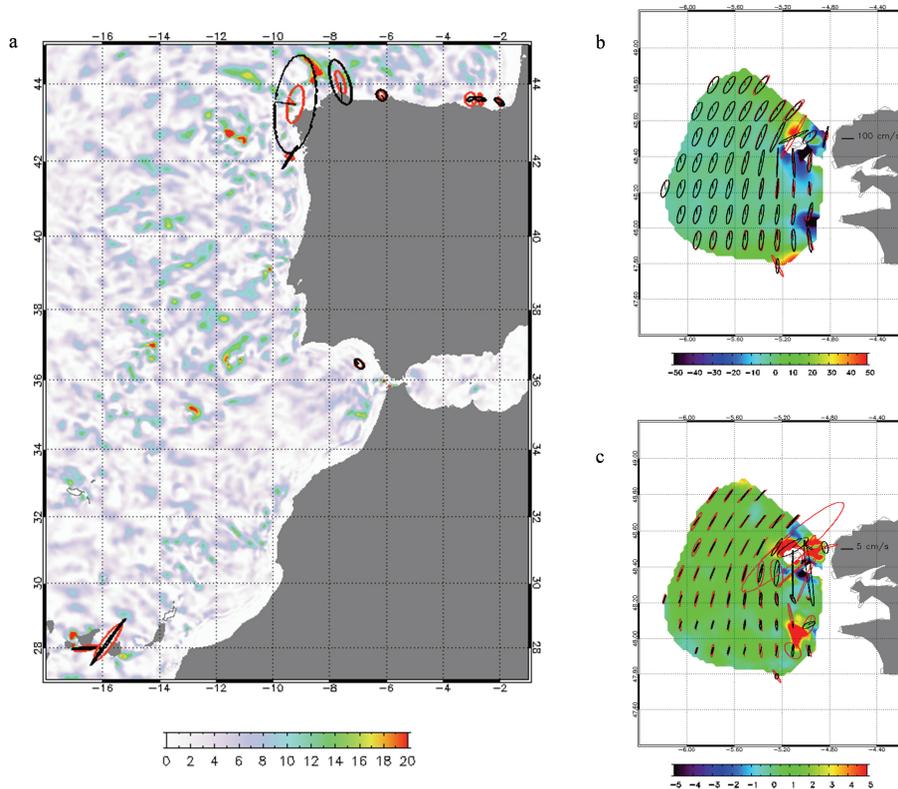


Fig. 20. (a) Modelled (black) and observed (red) surface tidal ellipses at buoy locations for the M_2 component. The map represents the difference of the M_2 surface velocity amplitudes between the run with stratification (run_{bc}) and the run without stratification (run_{bt}). (b, c) Modelled (black) and radar (red) surface tidal ellipses for the M_2 and the M_4 components. The map represents the difference between the observed and modelled semi major axis ($cm\ s^{-1}$).

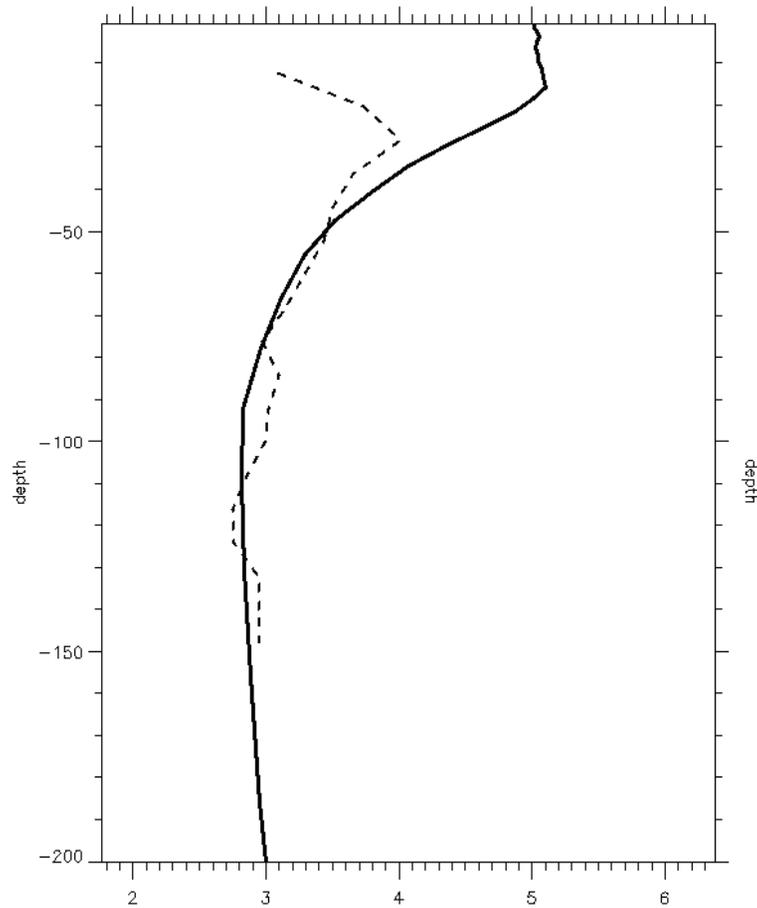


Fig. 21. Vertical profiles of the M2 semi major axis as observed (dashed line) and modelled (full line) at the Matxitxako buoy location.

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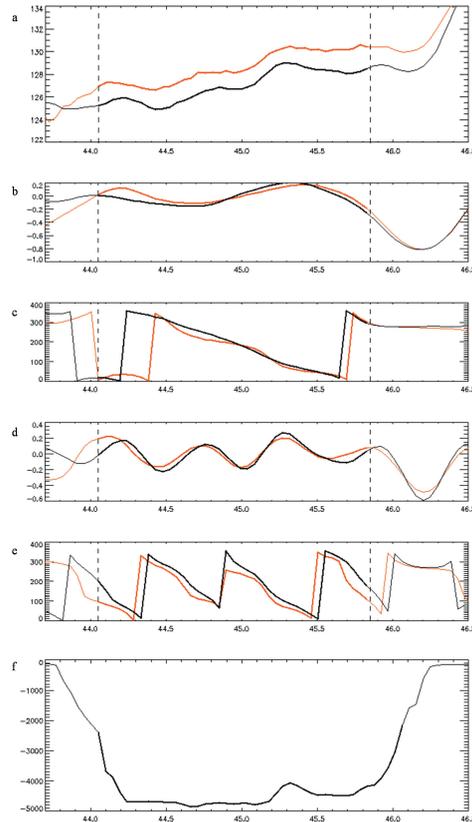


Fig. 22. (a) Along track amplitudes (cm) deduced from the M_2 harmonic analysis of altimetric data (red) and model (black). (b) Baroclinic amplitudes in cm and (c) phase of the residual tides for the altimetric data (red) and the model (black) and for the first baroclinic mode. (d) Baroclinic amplitudes in cm and (e) phase of the residual tides for the altimetric data (red) and the model (black) and for the second baroclinic mode. (f) Along track bathymetry (m).

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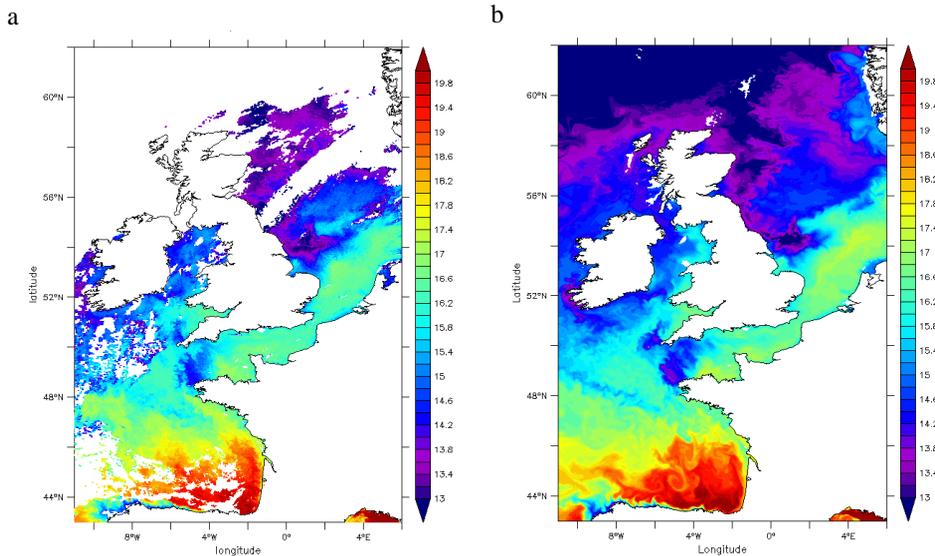


Fig. 23. Sea surface temperature ($^{\circ}\text{C}$) from MODIS data **(a)** and from the model **(b)** on 27 September 2008.

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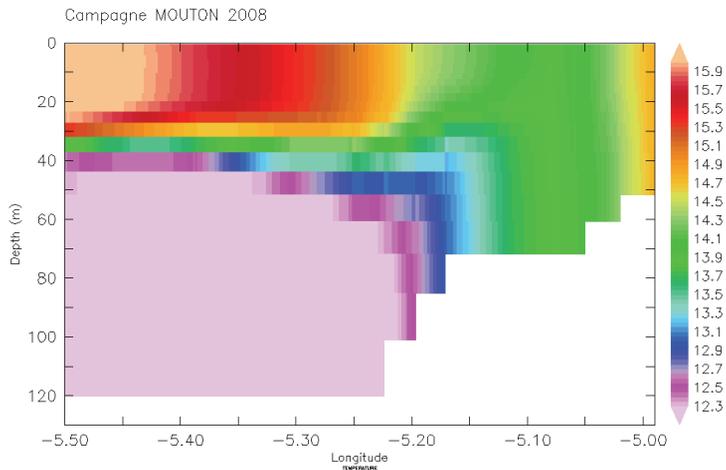
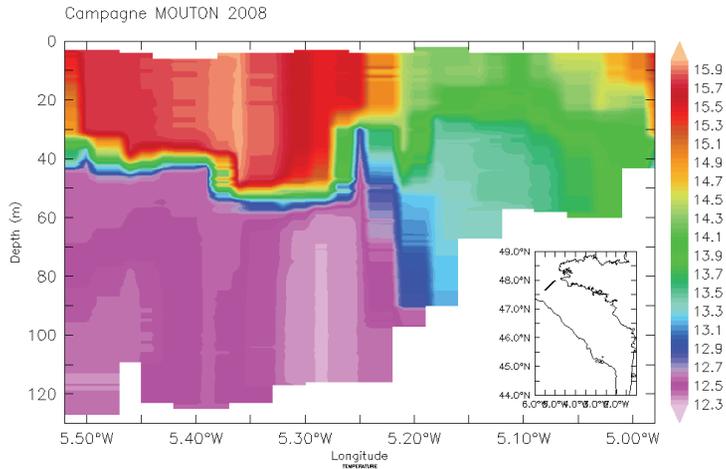


Fig. 24. Temperature ($^{\circ}\text{C}$) transect crossing the Ushant front as observed during the MOUTON cruise **(a)** and as modelled in IBI **(b)** on the 1 October 2008.

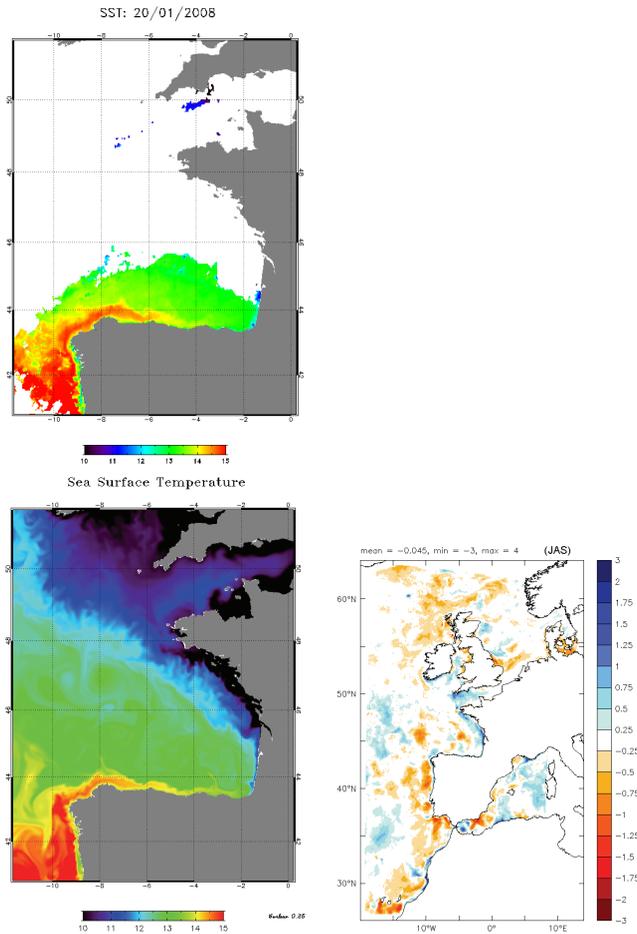


Fig. 25. Sea surface temperature ($^{\circ}\text{C}$) from AVHRR data **(a)** and from the model **(b)** the 20 January 2008. Modelled temperature at 200 m the 20 January 2008 **(c)**.

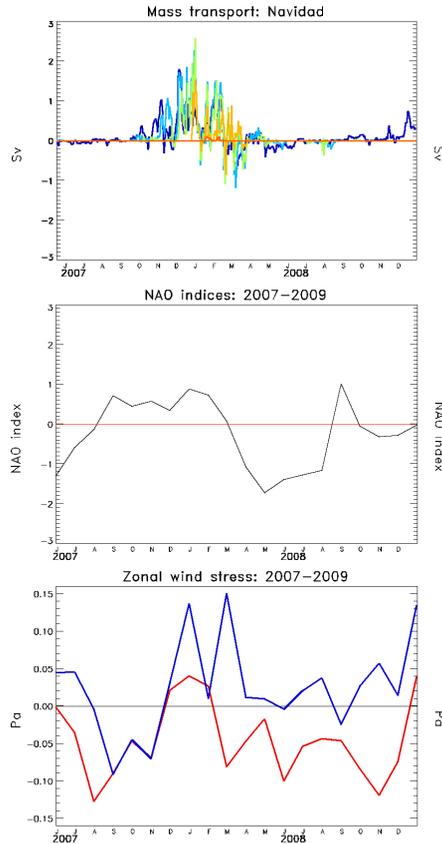


Fig. 26. (a) Transport of the poleward flow for water mass warmer than 13.0 °C and saltier than 35.7 psu at 43.24° N (blue), at 7.61° W (turquoise blue), at 6.2° W (green), at 3.8° W (yellow) and at 44.4° N (orange). **(b)** NAO index. **(c)** Meridional wind stress τ_y off Western Iberia (red) and of the zonal wind stress τ_x off Northern Iberia. Boxes (blue). Boxes chosen for the spatial average of τ_x and τ_y have been chosen following the study of Le Cann and Serpette (2009).