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Impact of SLA assimilation in the Sicily Channel Regional Model: model skills and mesoscale features

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Abstract

The impact of the assimilation of MyOcean Sea Level Anomalies along track data on the analyses of the Sicily Channel Regional Model was studied. The numerical model has a resolution of 1/32° degrees and is capable to reproduce mesoscale and sub-mesoscale features. The impact of the SLA assimilation is studied by comparing a simulation (SIM, which does not assimilate data) with two analyses, AN0 and AN1, assimilating different reprocessing versions (V0 and V1) of the same set of Along Track altimetric measurements. The quality of the analyses was evaluated by computing RMSE of the misfits between analyses background and observations (sea level) before assimilation. A qualitative evaluation of the ability of the analyses to reproduce mesoscale structures is accomplished by comparing model results with Ocean Color and SST satellite data, able to detect such features on the ocean surface. CTD profiles allowed to evaluate the impact of the SLA assimilation along the water column. We found a significant improvement for AN1 solution in terms of SLA rmse in respect to SIM (the averaged RMSE of AN1 SLA misfits over 1.5 years is about 0.5 cm smaller than SIM) and a weaker improvement in respect to the assimilation of the V0 dataset (0.1 cm average over the same period). Comparison with CTD data shows a questionable improvement produced by the assimilation process in terms of vertical features: AN1 is better in temperature while for salinity it get worse than SIM at the surface. The qualitative comparison of simulation and analyses with synoptic satellite independent data proves that SLA assimilation of V1 data allows to correctly reproduce some dynamical features (above all the circulation in the Ionian portion of the domain) and mesoscale structures otherwise misplaced or neglected both by SIM and AN0.

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Impact of SLA assimilation in the Sicily Channel model

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1 Introduction

The Sicily Channel (sub-)Regional Model (SCRM Sorgente et al., 2003; Gaberšek et al., 2007; Olita et al., 2007; Sorgente et al., 2011) produces, since 2003, forecasts and simulations of the central Mediterranean sea including the southern Thyrrenian Sea, the Sardinia Channel, the Sicily Channel, the Western part of the Ionian Sea and a wide area over the Tunisian and Lybian continental shelves. SCRM is part of the national and mediterranean networks of operational oceanography, namely GNOO (Italian National Group of Operational Oceanography) and MOON (Mediterranean Operational Oceanography Network).

The modeling system, built with the support of several EU Operational Oceanography projects (MFSPP, MFSTEP, ECOOP, MyOcean), covers a crucial area of the Mediterranean Sea as the Sicily Channel governs the exchanges of water masses between Eastern and Western Mediterranean sub-basins (Manzella et al., 1988). The capability to resolve mesoscale dynamics in such an area is of crucial importance for a correct representation of the water flows as eddies can mediate the transport of surface and even intermediate water masses, namely the Levantine Intermediate Waters (Millot and Taupier-Letage, 2005).

The SCRM system account for four main parts: (a) finite difference numerical model simulating the hydrodynamics, forced with appropriate atmospheric fields; (b) observational platform retrieving data for assimilation and cal-val activities; (c) data assimilation scheme(s) merging the information coming from model and observations, providing the best estimate of the *true state*; (d) web-based interfaces and visualization tools for intermediate and final users. Up to now the SCRM did not encompass any sophisticated assimilation scheme, as it relied on simple methods for incorporating observations on the numerical solution like the relaxation of heat fluxes to the observed satellite Sea Surface Temperature (SST) or water fluxes to the climatological salinity. In the present work we show the results of the first implementation of a 3-D-variational assimilation scheme in the SCRM and the impact of the assimilation of Sea Level Anomaly (SLA)

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along track data MyOcean V1 data on such a system. Satellite SLA are the most effective data today available for assimilation in ocean numerical models.

To accurately evaluate the impact of SLA assimilation we performed three interannual experiments integrating the period 2008–2009: a reference run (free simulation) and two analyses each one assimilating a different reprocessing version of the same SLA Along track dataset. We quantitatively evaluated the results through basic statistics using SLA and CTD data but, as we are especially interested to observe how the assimilation can improve the dynamic solution of the model and its reproduction of mesoscale features, we also accomplished a qualitative comparison using synoptic (single swaths) satellite observations (SST and Ocean Color) capable to detect the footprints of mesoscale structures (eddies and meanders) on the area. Then the present study has a double aim: to evaluate the impact of the SLA assimilation in respect to a free-run and to assess the changes deriving by the assimilation of a improved dataset of observations.

In Sect. 2 the numerical model setup, the assimilation scheme and the data used for assimilation and for validation are described. Results are presented and discussed in Sect. 3, while conclusion are drawn in Sect. 4.

2 Methods and data

To evaluate the impact of SLA assimilation three experiments have been performed: a simulation (SIM), that does not assimilate anything, and two analyses (AN0 and AN1) assimilating two different reprocessing versions (V0 and V1 MyOcean products) of a multi-mission satellite Along Track SLA dataset. SIM and AN1 are integrated for two years, from 15 January 2008 to 15 January 2010, while AN0 was stopped on October 2009 as the V0 data flow was interrupted on July 2009. The experiments encompass the use of: (1) numerical model; (2) Data Assimilation (DA) scheme; (3) data for assimilation and validation of model results.

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2.1 Numerical system

SCRM is a free surface three-dimensional primitive equation finite difference hydrodynamic model based on the Princeton Ocean Model (Blumberg and Mellor, 1987). It solves the equations of continuity, motion, conservation of temperature, salinity and assumes hydrostatic and Boussinesq approximation. It uses the Mellor and Yamada (1982) turbulence closure scheme, while the horizontal viscosity terms are provided by the Smagorinsky parameterization (Smagorinsky, 1993). The model domain is 9° E to 17° E and 31° N to 39.50° N with a horizontal resolution of 1/32° (~3.5 km). In the vertical it uses 30 sigma levels, denser at the surface following a logarithmic distribution. The external time step is set to 4 s, the internal to 120 s. The model bathymetry is the US Navy Digital Bathymetric Data Base-DBDB1 at 1/60°, interpolated on the model grid. The minimum depth is set to 5 m.

The model has been initialized using dynamically balanced analyses fields from the 1/16° coarse operational model of the mediterranean sea MFS1671 (Tonani et al., 2009) through an innovative tool based on the Variational Initialization and Forcing Platform (VIFOP, Auclair et al., 2000; Gaberšek et al., 2007). This tool reduces spin up times and improve the fields at boundaries by filtering out the high frequency noise (Gaberšek et al., 2007). MFS1671 also provides boundary conditions for the present experimental setup, through a simple off-line one way asyncronous nesting as described in details in Sorgente et al. (2003). Surface fluxes, computed through the bulk formulae of Castellari et al. (1998), use the 6-hourly atmospheric analyses from European Centre for Medium range Weather Forecast (ECMWF) at 0.25° of resolution. The parameters used are the 10 m wind, the 2 m air temperature, the cloud cover, dew-point temperature and the atmospheric pressure.

2.2 Data assimilation scheme and analysis cycle

The Data assimilation is accomplished through the 3-D-variational scheme named OceanVar (Dobricic and Pinardi, 2008). The OceanVar finds the minumum of the following cost function:

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$$J = \frac{1}{2}(\boldsymbol{x} - \boldsymbol{x}_b)^T \mathbf{B}^{-1}(\boldsymbol{x} - \boldsymbol{x}_b) + \frac{1}{2}(\mathbf{H}(\boldsymbol{x}) - \boldsymbol{y})^T \mathbf{R}^{-1}(\mathbf{H}(\boldsymbol{x}) - \boldsymbol{y}), \quad (1)$$

where $\boldsymbol{x}$ and $\boldsymbol{x}_b$ are respectively the analysis and background (first guess) state vectors (containing temperature, salinity, and velocity components three-dimensional fields and the surface elevation bi-dimensional field), **B** and **R** the background and observational error covariance matrices, **H** is the linearized observational operator and $\boldsymbol{y}$ is the observational state vector. The observational operator is evaluated for $\boldsymbol{x} = \boldsymbol{x}_b$. The cost function is minimized using the control vector:

$$\boldsymbol{v} = \mathbf{V}^+(\boldsymbol{x} - \boldsymbol{x}_b), \quad (2)$$

where the superscript "+" indicates the generalized inverse matrix and **V** is the square root of **B**:

$$\mathbf{B} = \mathbf{V}\mathbf{V}^T, \quad (3)$$

In this specific application of the 3-D-variational scheme, the matrix **V** is modelled as sequence of linear operators:

$$\mathbf{V} = \mathbf{V}_D \mathbf{V}_{UV} \mathbf{V}_\eta \mathbf{V}_H \mathbf{V}_V, \quad (4)$$

where operator $\mathbf{V}_D$ applies a divergence damping filter to correct features near the shorelines, $\mathbf{V}_{UV}$ computes velocities from surface height, temperature (T) and salinity (S), $\mathbf{V}_\eta$ computes free surface elevation error from T and S, $\mathbf{V}_H$ applies the horizontal gaussian covariances to T and S, $\mathbf{V}_V$ reconstructs the vertical profiles of T and S from the Empirical Orthogonal Functions (EOFs) a-priori computed. In the OceanVar the vertical covariances are represented by the EOFs of surface elevation, T and S. The EOFs are computed on the basis of an already existing interannual simulation. For each new estimation of the cost function, the vector $\boldsymbol{v}$ multiplies expansion coefficients and EOFs and transforms them into corrections of T, S and surface elevation. For further details about the OceanVar (linear operators description, numerical minimization

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algorithm) please see Dobricic and Pinardi (2008). The data are assimilated in a daily analysis cycle, schematized in Fig. 1. In practice the simulation providing the analysis background simulates one day per analysis cycle. The misfits are computed during the model integration at the exact time of the available SLA observations (Dobricic et al., 2007, First Guess at Appropriate Time method, FGAT). At the end of the integration the analysis is done with the OceanVar software which finds the minima of the cost function and computes the innovations that will be applied at the model solution at the begin of the following analysis cycle.

2.3 Data and analysis

The assimilated data is the Along Track (AT) Delayed Time (DT) SLA V0 and V1 MyOcean (the latter is the present MyOcean official product) data produced and distributed by CLS (Collecte Localisation Satellites). The altimetric data have been collected by Jason-1, Jason-2, TOPEX/Poseidon, Envisat and Geosat Follow-On (G2) satellites. The use of multi-mission altimeter data for assimilation purposes in mediterranean was proven to have a positive impact in the analyses (Pujol et al., 2010). V0 and V1 sintetically indicate different reprocessing versions of the same raw dataset. V1 is the product specifically developed by CLS for MyOcean project, while V0 corresponds to the elder AVISO SSALTO/DUACS product. Details about reprocessing changes between the two versions can be found at http://www.aviso.oceanobs.com/fr/donnees/informations-sur-les-produits/duacs/presentation/updates/index.html#c7681. Accordingly to the cited documentation, the major improvements of V1 products are: orbit error reduction and long wavelength error minimization; presence of data closer to the coast.

The misfits between the background (first guess) and the observations, calculated at each iteration of the assimilation process on a daily window, are used to assess the overall quality of the experiments. The Root Mean Square Error (RMSE) of misfits is computed for AN0, AN1 and SIM. To reassure the reader about the indipendence of the data used for this quantitative assessment is important to underline that the SLA misfits are calculated before the data are actually assimilated in the analyses. RMSE statistics are calculated for the three experiments only using the V1 dataset (chosen as reference as it is presently the official product) in order to simplify the interpretation of the results about simulation/analysis quality.

In situ measurements of temperature and salinity collected through CTD samplings are used to evaluate the impact of the assimilation on sub-surface and deep layers. In order to skip partially the space-time mismatching issue between simulated and measured profiles (CTD profiles represents a point measurement while a model grid element can be thought as a region of about 12 km^2) the four grid point surrounding each sampling point were interpolated to the CTD profile location and depth, so obtaining a corresponding *simulated* profile. The CTD data have been collected during two oceanographic cruises conducted, on board of the the R/V *Urania*, in August and November 2009. So the profile data allowed to validate only AN1 and SIM run, as the V0 data flow stops in July 2009.

We also qualitatively evaluated the impact of the assimilation in terms of change/improvement in the reproduction of surface features by comparing the surface analyses fields with synoptic observations of the sea state provided by optic and infrared satellite images. In order to do this, MODIS AQUA and TERRA level-2 data of Chlorphyll-*a* concentration and SST have been downloaded and mapped to compare the footprints of mesoscale and other dynamical features can be individuated in the images with the results of the three experiments.

3 Results and discussion

As previously pointed out, the first evaluation of the quality of the analyses was done through a comparison of the RMSE of the SLA misfits. In top panel Fig. 2 the weekly time series of the RMSE of SLA misfits for SIM and AN1 and AN0 experiments are shown. The RMSE have been weekly averaged in order to simplify the reading of the figure, as the daily series have many gaps due to the absence of valid data in some days (about 10 % of the dataset). The mean RMSE over the two years of integration for AN1 and SIM are respectively 3.68 cm and 4.20 cm. Considering the period July 2009 the values for AN0, AN1 and SIM are respectively 3.72 cm, 3.60 cm and 4.11 cm. The central panel of Fig. 2 shows the difference between the SIM RMSE series and the two analyses, while bottom panel shows the weekly number of observations assimilated during the analyses (the V0 curve goes to zero when its production was stopped). In the bottom panel are also indicated, with red crosses and blue squares, the dates when there where no data to be assimilated respectively for AN1 and AN0. It is noteworthy that the high frequencies signal drawn by the RMSE time series (top panel) is due to the large variability on the number and availability of data to be assimilated (bottom panel), in turn firstly depending by the number and position of the orbital passes of the satellite altimeters over the model domain. SIM RMSE increases as the simulation proceeds: this positive trend (also shown in figure) is strongly corrected in the AN1 experiment, while AN0 still preserve a significant trend as well visible in the central panel. The drift of SIM experiment seems faster during the first 6–7 months, after which it slows down significantly. The worse performance of V0 in respect to V1 could be due to different reason. As previously pointed, V1 reprocessing reduced orbital error and minimized the long wavelength error. Furthermore, there are data closer to the coast. Addictionally we can notice, in the bottom panel of Fig. 2, that the V0 series presents more gaps in respect to V1, i.e. there are more days with no data to be assimilated. This discontinuity in the assimilation process could be also the reason why the V0 series presents an high frequency variability larger than V1, showing also some spikes in RMSE exceeding the SIM RMSE.

The distribution of the misfits for SIM and AN1 experiments is shown in Fig. 3. The misfits for AN0 are not shown as their distribution is really similar to those of AN1, just presenting minima slighter larger. The maps are generated from the along track misfits calculated for the whole period then interpolated on the model grid. As can be seen by comparing the two maps, the main corrections due to the assimilation process are concentrated in the Ionian area, East of Malta and some spots in the Sardinian Channel.

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To better understand the difference between the two experiments argued by comparing the SLA RMSE residuals, a visual comparison of the simulated features with those detectable through satellite independent observations (MODIS SST and Chlorophyll-*a* data) was performed. The selection of the dates for such a comparison was done as function of the cloud cover (limiting the optical and infrared satellite measurements) and trying to emphasize the differences between the experiments, then chosing days that maximize the difference observed in the RMSE time series and maps.

Figure 4 shows the salinity fields of AN0, AN1 and SIM for 22 April 2008 (daily average) compared to the MODIS Chlorophyll-*a* concentration field for the same date. In this case we used an optical product (Chlorophyll-*a*) instead of the SST product, because of the small thermic gradient between Atlantic waters and resident water masses during this period of the year. The main differences are related to the different behaviour of the Atlantic Water (AW) crossing the Sardinian and Sicilian Channel, detected in model results by salinity ranging 37.5 to 37.8 psu. In SIM the AW, crossing the Sardinian Channel (10° E), is squeezed against the Tunisian coast and proceeds straight eastward, while it shows a meandering behaviour in both AN0 and AN1. The satellite image shows the clear signature of sub-mesoscale anticyclonic meanders approximately located at 10° E and 38° N, which signature can also be observed in both the analyses experiments. Another difference can be noticed in the AW flowing along the southern Sicilian Coast. This branch of the AW reaches the Island of Malta (14° E and 36° N) in both AN0 and SIM, while for AN1 experiment it does not reach such a longitude, forming a more defined meridional front with resident waters of Ionian origin. The presence of such a small frontal area is also suggested by the satellite Chlorophyll-*a* observation (which is known to be well correlated to salinity and density fronts). In other words, both satellite and AN1 suggest that the AW does not properly form a northern branch along the southern Sicilian coast. This is also in agreement with literature (e.g. Robinson et al., 1999; Sorgente et al., 2011) that describes this branch, which transport is associated to the Atlantic Ionian Stream (AIS), as a typical summer feature that reduces its intensity during late autumn, winter and early spring in favour

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of an increase of the AW flow along the African coast spreading over the Tunisian shelf.

Figure 5 shows surface elevation model and analyses fields for 18 October 2008 compared to satellite SST signature. The big difference is the large meander that the AIS, the jet current flowing eastward along the southern Sicilian coast, draws northward once overpassed the SE margin of the Sicily Island: this meander is only present in the SIM, while it disappears in both the analyses. Satellite imagery confirms the absence of this feature east of Sicilian east coast. On the contrary the AIS once passed the Ionian Shelf break at about 15.5° E accomplishes a wide cyclonic meander (both in satellite and analyses fields). Differences between the two analyses can be noticed in the formation two mesoscale anticyclonic eddies, present only in AN0, centered respectively at about 16° E–37° N and 13.5° E–36° N, and well visible in the surface elevation fields, that have not been evidenced by satellite SST imagery. Further, the upwelling area south of Sicily already present in SIM is still mantained and enhanced in AN1 (where it is associated to the presence and formation of a strong cyclonic meander of the AIS at about 13° E–36.5° N) while in AN0 the elevation lows south of Sicily, footprints for coastal upwelling, in part disappear considerably reducing the AN0 upwelling SST signature (not shown). We observed that the nortward overshooting of the AIS along the Eastern coast of Sicily is the main structure constantly reproduced by the SIM and corrected in the analyses. To further investigate this feature, corresponding to the area subject to the main correction by the assimilation, in Fig. 6 the SST simulated/analysed fields for 17 July 2009 are shown, zoomed on the area of interest, and compared to the satellite SST. Here, SIM shows the wide anticyclonic meander in the Ionian Sea that is strongly corrected by the SLA assimilation: the AN1 field shows this structure lowered in latitude and forming a coherent anticyclone. The same can be observed in the satellite SST image that clearly shows the anticyclone approximately at the same location and with a similar shape and size. AN0 shows an intermediate situation, in which the northern meandering of the AIS partially disappears, but the formation of a southern coherent anticyclonic structure is not evidenced.

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The impact of the SLA assimilation on reproducing the water column properties was evaluated by comparing the simulated/analysed salinity and temperature with those collected by CTD during two oceanographic cruise conducted in August and November 2009. Figure 7 shows the RMSE between modelled profiles of AN1 and SIM experiments and observations for temperature (left) and salinity. AN0 experiment cannot be validated with these CTD set as the V0 data stop on June 2009. In August the model solution is improved by the assimilation of V1 data above all between 100 and 300 m for both T and S, while at surface the analyses shows worse performances in salinity. The salinity maximum, that in the Sicily Channel is related to the LIW flow, is sistematically underestimated by SIM while in AN1 the salinity range is wider, reaching higher and more realistic maxima. This is one of the reasons why the major improvement that the assimilation produces in the vertical is located at intermediate depths. November 2009 cruise draws a similar situation in terms of impact produced by the assimilation on the vertical dimension. The main difference is that salinity is always worse for the top 200 m for analyses. At higher depths cannot be noticed for salinity any significant difference between simulated and analysed profiles. On the other hand, temperature shows more or less the same improvement as observed for the former cruise.

We would underline that big improvements were not expected in terms of vertical profiles cause no profile data was assimilated in the analyses. So the corrections in the vertical structure of the water column are only function of the free surface corrections and their covariance with T and S vertical profiles, as prescribed by the vertical background error covariance matrix calculated through EOFs.

4 Summary and conclusions

The present work investigates on the impact of SLA assimilation in the Sicily Channel Regional Model. The impact was studied through the intercomparison of a free-simulation (SIM) and two analyses (AN0 and AN1) assimilating respectively V0 and V1 SLA MyOcean Along Track data. The evaluation of the analyses quality was done

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against an observational dataset encompassing: (a) Along Track V1 SLA (misfits are calculated against the analyses background, then completely independent); (b) salinity and temperature profiles, collected in August and November 2009; (c) synoptic satellite images for the detection of mesoscale features.

The assimilation of SLA is proven to bring important improvements on the 2-years simulation of the circulation of the Sicily Channel area. Firstly the model drift (in terms of misfits of free surface elevation) affecting the SIM is reduced drastically. RMSE of SLA misfits for AN1 (background minus observations) does not show any significant trend, while SIM and AN0 RMSEs increase with time. Secondly, corrections are scattered in space accordingly with the tracks of assimilated data and are obviously larger where SIM shows larger errors. The patches with largest corrections are in the Ionian Sea and in the eastern part of the Sardinian Channel. In particular in the Ionian the corrections are associated to the incorrect reproduction of the circulation along the eastern coast of the Sicily. Here SIM often simulates the Atlantic Ionian Stream overshooting and turning northward along eastern Sicilian coast, then again eastward describing an anticyclonic meander just east of Sicily. On the contrary in AN1 this anticyclonic feature often disappears or is moved to the south, often transformed in anticyclonic eddie. AN0 often offers an intermediate solution between these two patterns, showing some correction of the circulation in such an area but often retaining many signals of the "wrong" circulation depicted by SIM. These modifications of the circulation features have been verified through satellite visible and infrared imagery. Finally, the impact on the vertical profiles is noticeable but the results are contrasting in terms of quality of the analyses. In August 2009 both salinity and temperature profiles are improved by the SLA assimilation in terms of RMSE (with the exception of the 0–20 m layer), while in November 2009 salinity profiles are worse for the analyses (while temperature is still improved). Considering that no TS profiles have been assimilated in the analyses, it is clear that the quality of the analyses on the vertical is only function of the background error covariances. In OceanVar (Dobricic and Pinardi, 2008), the background covariances on the vertical dimension are calculated as point-by-point EOFs of pre-existing interannual model outputs. For the present work the EOF set used is based on a 3-years model run having a similar setup as SIM experiment. Therefore, a critical point to improve the quality of the analyses on the vertical is to improve the quality of the background error covariances for T and S by recomputing EOF using a longer and better model run or preferably using outputs of several experiments having even slightly different setups (in order to increase the variability described by the EOFs). Furthermore, Pujol et al. (2010) showed that the best results are obtained, once introduced the assimilation of SLA, in analyses that also assimilate vertical profiles data. Therefore, to fix the questionable impact that the assimilation of SLA has shown on the vertical, the future work will be addressed on the re-computation of vertical EOFs on the basis of better and longer model runs and on the assimilation of vertical profiles data.

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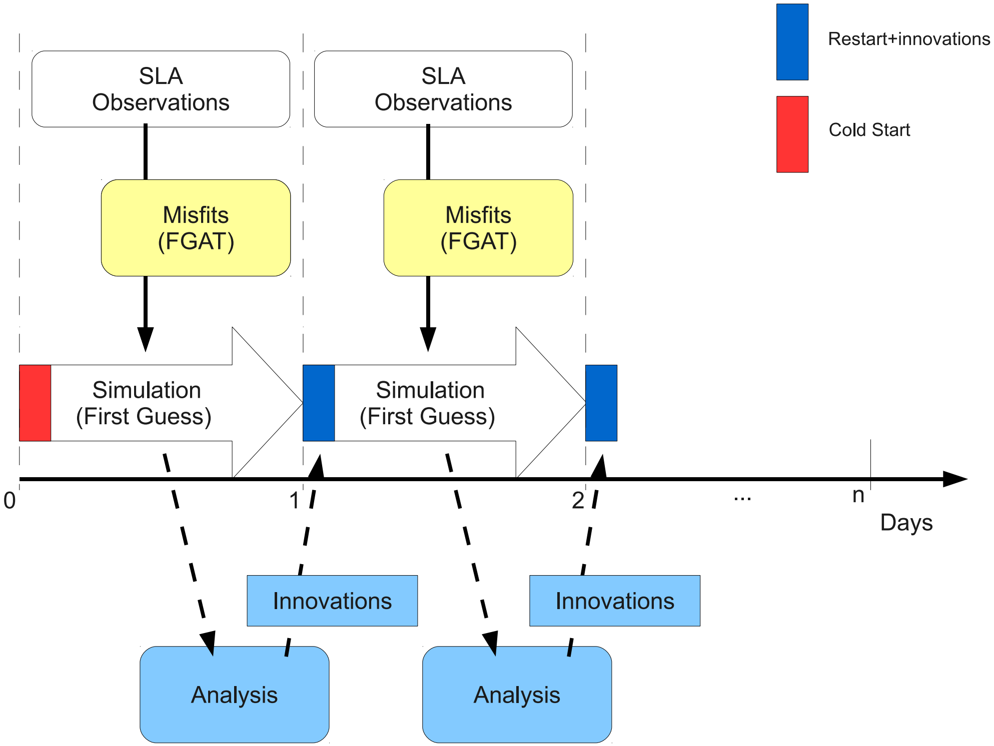

Fig. 1. Daily analyses cycle scheme. FGAT is the First Guess at Appropriate Time method for misfits calculation.

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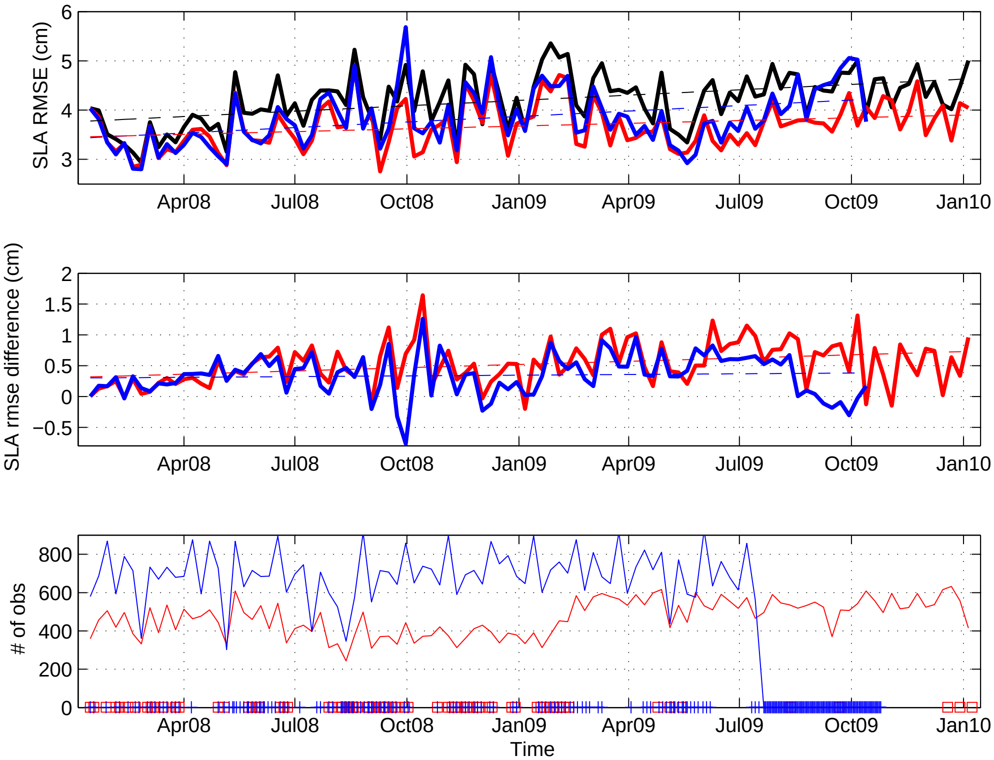

Fig. 2. Top panel: RMSE of SLA misfits with observations for AN1 (red line) AN0 (blue) backgrounds and simulation (black). The respecvite trends are also plotted (dashed lines); central panel: differences between RMSE curves: SIM-AN1 (red) and SIM-AN0 (blue); bottom panel: number of observations assimilated for AN0 (blue) and AN1 (red). Days with no observations to be assimilated are also indicated for AN0 and AN1 by blue crosses and red squares, respectively. RMSE values are weekly averages while the weekly sum was calculated for the number of observations.

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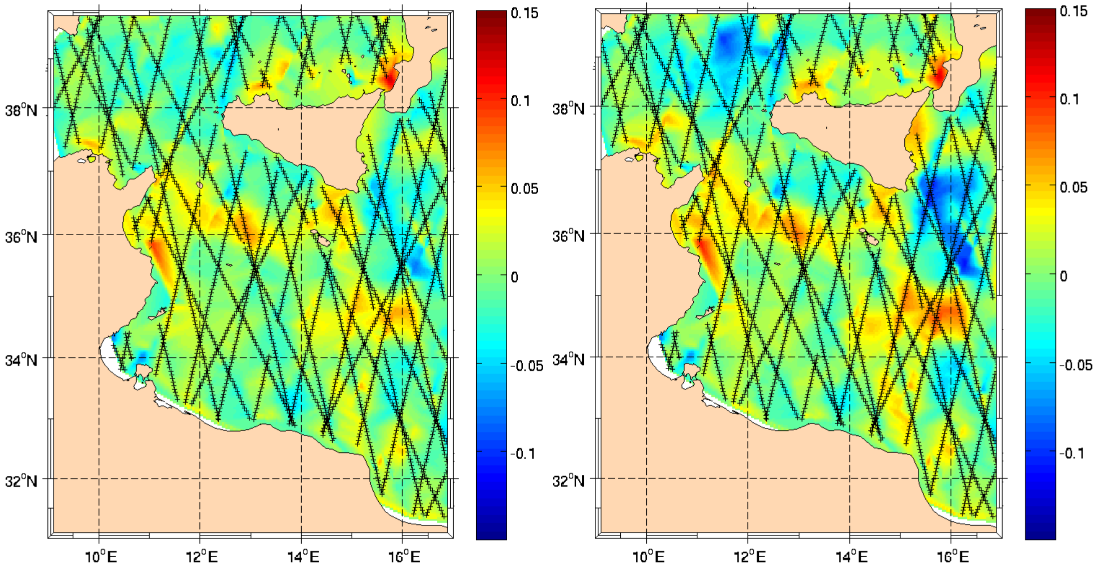

Fig. 3. Misfits for AN1 background (left) and SIM (right). The maps are obtained trough linear interpolation of the misfits between model and Along Track SLA V1 data whose position is also shown.

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Impact of SLA assimilation in the Sicily Channel model

A. Olita et al.

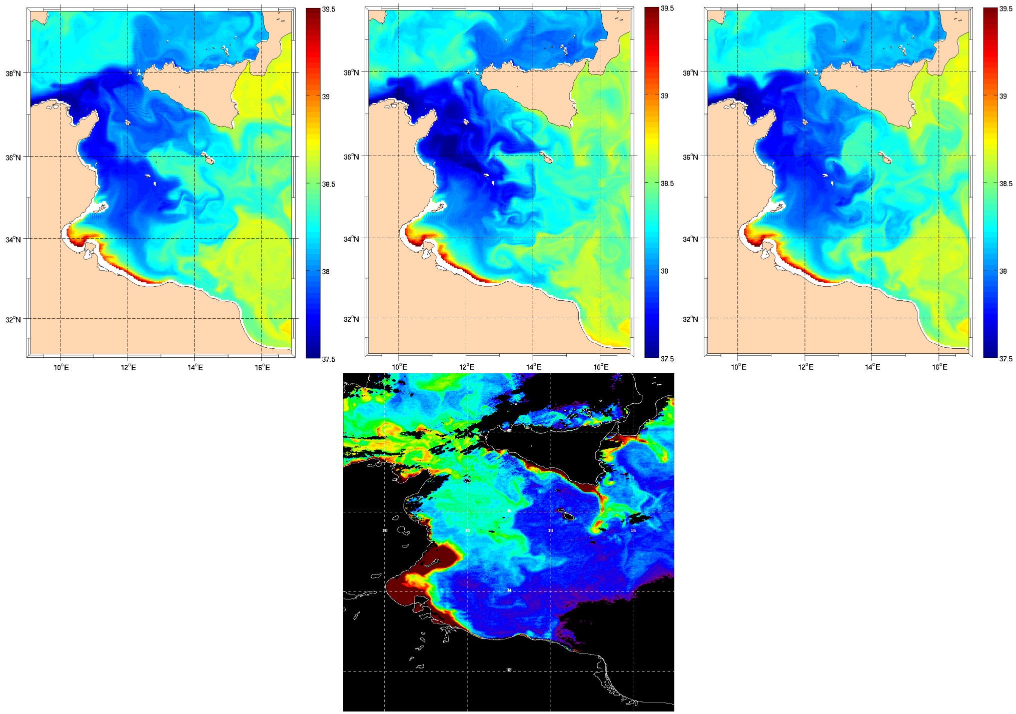

Fig. 4. 22 April 2008. Top panel: salinity (psu) for SIM (left), AN0 (center), AN1 (right). Bottom: satellite Chlorophyll-*a* from MODIS-AQUA.

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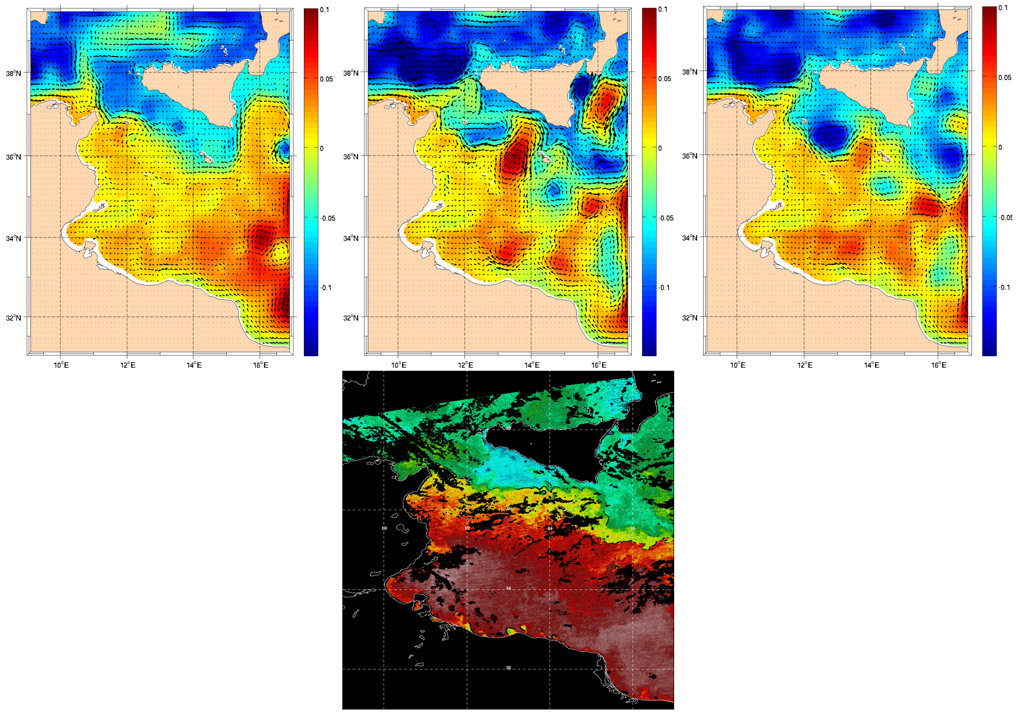

Fig. 5. 18 October 2008. Top panel: free surface elevation in cm for SIM (left), AN0 (center), AN1 (right). Bottom: satellite SST.

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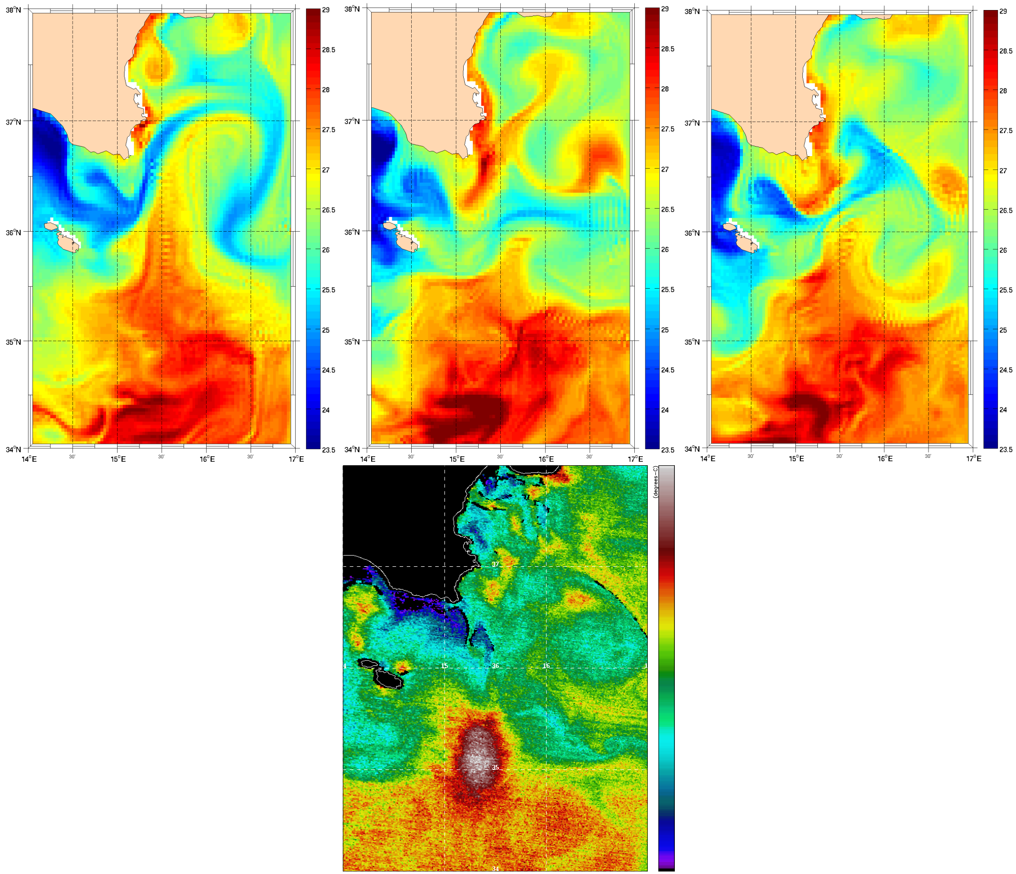

Fig. 6. 14 July 2009. Top panel: SST (°C) for SIM (left), AN0 (center), AN1 (right). Bottom: satellite SST.

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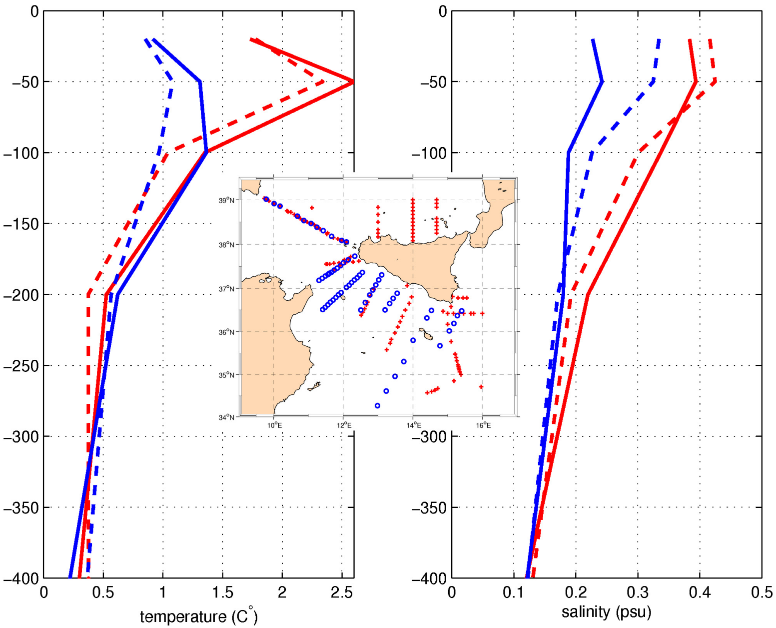

Fig. 7. RMSE profiles for AN1 (dashed) and SIM (full) vs. CTD observations collected in August (red) and November 2009 (blue). Left panel shows temperature and right salinity. The locations of CTD stations are also shown in the reference map.

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