Project of Strategic Interest NextData

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Implementation of the numerical model and the data assimilation scheme of the Mediterranean Sea Reconstruction/Reanalysis System (RR)

Resp: Nadia Pinardi, INGV

Introduction

The RR feasibility study concerned the quality control of the different components of the Mediterranean RR system, schematized in Figure 1, based on the previous INGV reanalysis production for the past 25 years (1985-2010). Table 1 summarizes the INGV Mediterranean Reanalysis system developments:

I. **MedReanV2** (*Adani et al 2011*) produced in the framework of CIRCE Project (http://www.circeproject.eu/);
II. **MedReanV4** in production within the framework of MyOcean Project;
III. **Mediterranean RR system** under investigation.

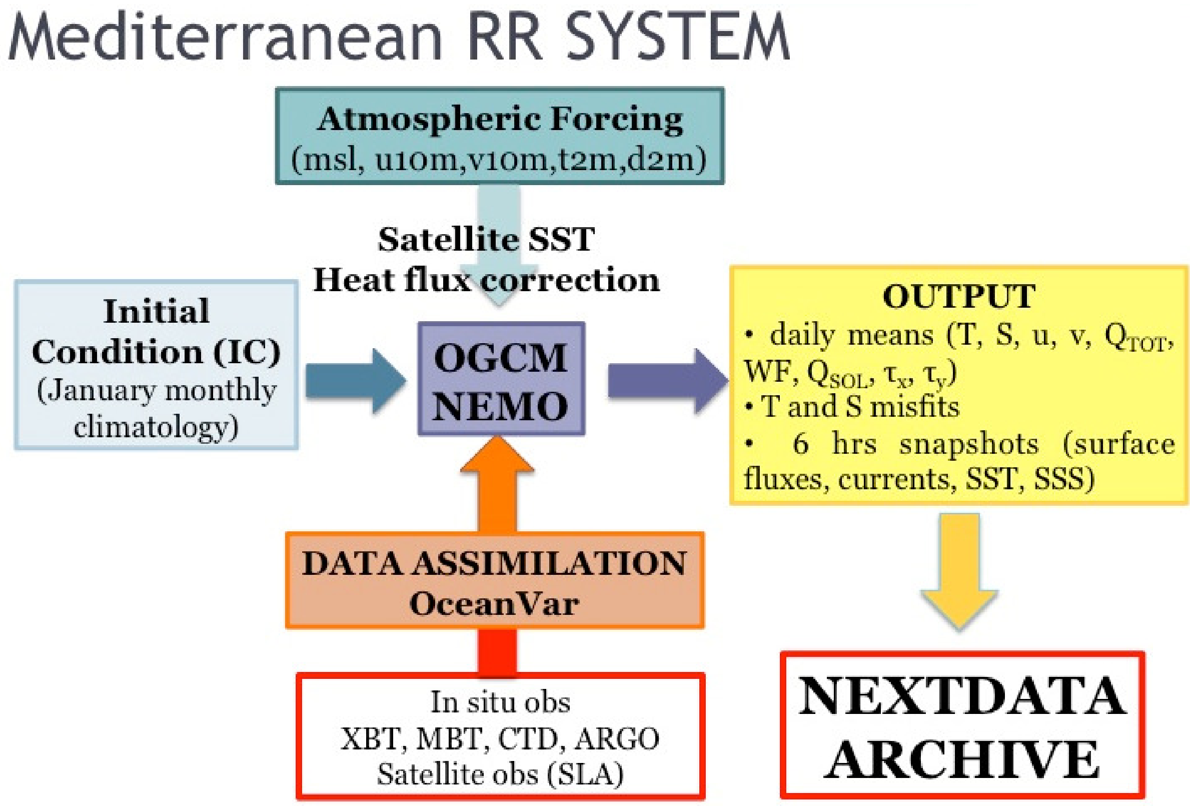

Figure 1. Schematic description of the Mediterranean Reconstruction/Reanalysis (RR) system and its components: (center) the Ocean General Circulation Model (OGCM) based on NEMO code *(Madec, 2008)*; (left) the Initial Conditions (IC); (top) the atmospheric forcing (mean sea level perssure-msl, u and v wind components at 10 meters- u10m, v10m, air temeperature at 2 meters-t2m, dew point temperature-d2m); (bottom) the OceanVar assimilation scheme (*Dobricic and Pinardi 2008*) and in situ and satellite (SLA-sea level anomaly) observations collected in the dedicated archive by WP2.2; (right) RR output fields of 3D temperature, salinity, currents, 2D total heat flux at the air-sea interface, water flux-WF, solar radiation-Qsol, momentum flux components-τ, misfits between model and observations, and snapshots every 6 hours of 2d surface temperature, salinity, currents and the total heat flux components. All these model data will populate the NEXTDATA archive.

One of the main tasks of the first year of the project was the design of the feasible technical improvements to include in the **RR system** regarding the **Ocean General Circulation Model (OGCM) and the data assimilation scheme implementations**. The RR system consists of daily three-dimensional variational analysis followed by a 1-day OGCM integration, as implemented by *Adani et al. 2011*. The three-dimensional variational data assimilation scheme is the OceanVar (*Dobricic and Pinardi, 2008*). The differences with previous reanalysis efforts (**MedReanV2** and **MedReanV4**) are schematized in Table 1. It will follow a description of the principal characteristics of the **OGCM** and the **OceanVar** data assimilation scheme to be used in the Mediterranean Sea RR production scheduled in the next year of the project. **RR system calibration** was carried out for the years 1985-1987 considering MedReanV2 as our reference product skill.

	MedReanV2 (1985-2007)	MedReanV4 (1985-2010)	RR (1912-2011)
Project	CIRCE *Adani et al. 2011*	MyOcean	NEXTDATA
OPERATIONAL SYSTEM	Sys3a2(OPA8.1) *Tonani et al.2008*	Sys4c1 (OPA9.0) *Oddo et al.2009*	(NEMO3.4)
LBC (Atlantic Box)	closed	open	open
Initial Condition IC	MedAtlas Climatology (obs 1995-1999) *Maillard et al. 2005*	SDNV2aa climatology (obs until1987)	SDNV2aa climatology (obs until1987)
ATM Forcing	ERA15 1.125° (1985-1992) ECMWF analysis 0.5° (1993-2007)	ERAInterim 0.75° (1985-2010)	**AMIP** 1.125° (1912-1957) **ERA40** 1.125° (1958-1978) **ERAInterim** 0.75° (1979-2011)
Total Cloud Cover TCC	NCEP–NCAR (1985–92) ECMWF analyses 0.5° (1993-2007)	ERAInterim 0.75° (1985-2010)	**AMIP** 1.125° (1912-1947) **NCEP–NCAR**(1948-1978) **ERAInterim** 0.75° (1979-2011)
Precipitations	NCEP–NCAR (monthly climatology)	CMAP (monthly climatology)	**AMIP** (montly climatology) **NCEP–NCAR** (monthly climatology) **CMAP** (monthly climatology)
SST	SST reconstruction (1985-2007) *Marullo et al.2007*	SST reconstruction (1985-2007) *Marullo et al.2007* MyOcean data (2008-2010)	**HadISST1** (1912-1985) **SST reconstruction**(1985-2007) *Marullo et al.2007* **MyOcean data** (2008-2011)
Partial Cells	NO	YES	YES
True Stress	NO	YES	YES

Table 1. INGV Mediterranean Reconstruction/Reanalysis system developments: 1) MedReanV2 already available from *Adani et al. (2011)* within the framework of CIRCE Project (http://www.circeproject.eu/); 2) MedReanV4 in production within the framework of MyOcean Project; 3) RR100 NEXTDATA developing system for the Mediterranean Sea.

The circulation model for the Mediterranean RR

Second component of the RR system (Figure1), after observations, is the **ocean general numerical model** (OGCM) first implemented by *Tonani et al. 2008* based on OPA8.1 code (*Madec, 2008*), then developed and upgraded to OPA9.2 code (NEMO) by *Oddo et al. 2009.* First model implementation was used to produce **MedReanV2** (*Adani et al 2011*) while second model implementation is now running for **MedReanV4** reanalysis production (see Table 1).

The OGCM domain covers the entire Mediterranean Sea extending also into the Atlantic with a 1/16th of a degree horizontal resolution, 72 unevenly spaced vertical z-levels. The OGCM uses vertical z coordinates with **vertical partial cells** to better fit the bottom depth shape (*Oddo et al. 2009*). Figure 3, extracted from *Madec* (*2008*), shows how varies the bottom shape representation with standard vertical coordinates (a) and with vertical partial cels (b).

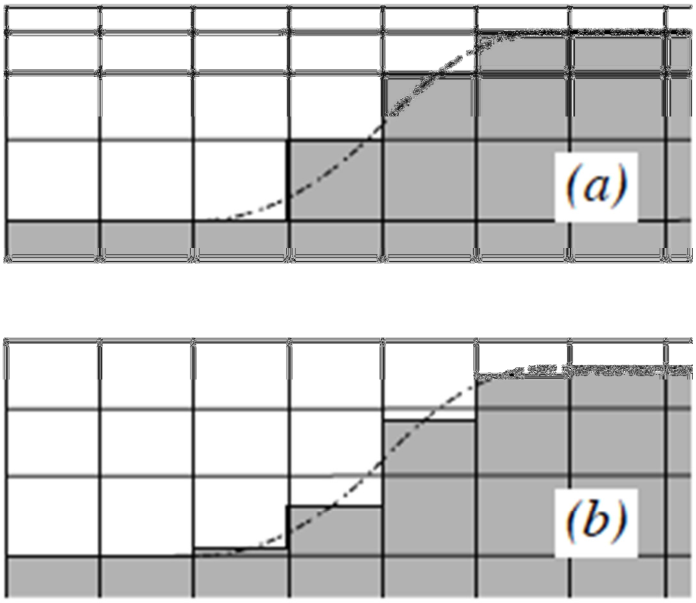

Figure 2. Sea bottom representation in (a) z standard coordinates; (b) z-coordinates with partial cell. (From *Madec 2008* – fig 3.5 –pag 44)

The Atlantic part of the domain (Atlantic box) presents three lateral boundaries where the model is nested within monthly mean climatological fields computed from 10 years of daily output (1993-2003) of the 1/4 degrees global model MERCATOR-1/4 (*Drevillon et al., 2008*).

Air-sea fluxes are computed through bulk formulae which need the following input atmospheric data: 1) air temperature at 2m; 2) dew point temperature; 3) zonal and meridional wind components at 10m; 4) mean sea level pressure; 5) total cloud cover. A specific study on the **air-sea fluxes** parameterization has been done. We evaluated for RR production the usage of:

- **extrapolation technique** for air temperature and specific humidity from 2 to 10m, as required by the bulk formulae;
- **true stress** which considers the wind speed relative to marine currents to compute the momentum flux.

To evaluate the air temperature and specific humidity extrapolation we used COSMO-Med data that provide values at 10m of the variables. We used NEMO routine *turb_core_2z.f90* that computes turbulent transfer coefficients of surface fluxes according to *Large and Yeager (2004)* to extrapolate COSMO air temperature and specific humidity values from 2m to 10m and we compared the results with COSMO data at 10m (see Figure 3).
To evaluate the introduction of true stress in the momentum flux parameterization we performed two simulations with and without true stress computation and we validated model results with in situ temperature and salinity profiles and with satellite SST.

The **Initial Condition** (IC) definition needed the production and analysis of many temperature and salinity climatologies that consider different temporal periods to be able to better represent the mean hydrodynamic conditions of the initialization period. A new temperature and salinity monthly climatology (named SDN_V2aa) has been calculated utilizing the extensive historical data set from 1900 to 1987, which only partially comprehends MEDAR-MEDATLAS data (1985-1999) used instead in **MedReanV2** IC (*Adani et al., 2011*). We considered all the observations available in January from 1900 to 1987 to compute the initial condition (January monthly climatology) because we did not want the climatology to be affected by the Eastern Mediterranean Transient (EMT), since it is not clear yet that an equivalent of the EMT has occurred before 1993. Mediterranean observations have been blended to the World Ocean Atlas climatology (WOA) in the Atlantic Box. The climatology has been computed with DIVA software tool (Data-Interpolating Variational Analysis), which allows to spatially interpolate observations on a regular grid in an optimal way.

The **atmospheric forcing** is the third component of the RR system (Figure1 and Table 1). After previous experiences (*Adani et al. 2011* used ERA15 atmospheric reanalysis in MedReanV2) we will consider in the RR a concatenation of the latest ECMWF (European Centre for Medium-Range Weather Forecasts) atmospheric reanalysis data products that have been archived by WP2.2:

- **ERAInterm** (*Dee et al. 2011*) data cover the time period **1979-nowadays** with horizontal resolution of **0.75°**
- **ERA40** *(Uppala et al. 2005)* data cover the time period **September 1957-August 2002** with horizontal resolution of **1.125°;**

Both data sets present 6 hours of temporal resolution.
For the hundred years RR production is taken into consideration the quality of **AMIP** type (*Gates, 1992*) of forcing in order to cover the entire period of study. AMIP type of data (*Cherchi and Navarra, 2007)* are available starting from **1900 up to 2003** and were created through a set of experiments performed with the ECHAM4 atmospheric GCM on a T126 grid (**1.125°** of horizontal resolution) forced by HadISST1 (*Rayner et al. 2003*) interpolated onto model grid. AMIP data have 12 hours of temporal resolution. In particular 7 experiments are available in our archive with similar characteristics but they must be analyzed and compared to the ECMWF reanalysis products to choose the best one to use.

During this year we started also the **implementation of the higher resolution OGCM** based on the upgraded NEMO3.4 parallel code. The increment of model horizontal resolution goes from 1/16th to 1/24th of a degree. DBDB1 bathymetry has been interpolated onto model grid and particular investigation was dedicated to model topography (coastline, minimum depth) and vertical discretization definition. We tried various configurations with different number of vertical levels (72, 81, 91, 101) to be able to represent in an optimal way the stratification and its seasonal variability. The OGCM configuration with 91 vertical levels was selected. A preliminary simulation has been performed to assess that the input data (bathymetry, initial condition, atmospheric data, river outflow data) are read correctly and that the surface fluxes are computed correctly.

The Data Assimilation Scheme

Fourth component analyzed is **data assimilation scheme** that uses both in situ (temperature and salinity profiles) and remote sensed data (Sea Level Anomaly) to correct the OGCM results. **OceanVar** is a three-dimensional variational scheme, set up by *Dobricic and Pinardi,* (*2008*) for the operational forecasting system (*Dobricic et al 2007*), that allows to correct model fields for all dynamic variables (T, S, sea level, u and v current components).
The assimilation cycle to be used in the RR system differs from the operational one described in *Dobricic et al* (*2007*). The assimilation cycle is daily, as implemented by *Adani et al. (2011)* in the **MedReanV2**, and takes into consideration the observations within the 24 hours time

interval that spans from 12:00 of day J and 12:00 of day J+1. The correction estimated is applied at model restart at 12:00 of day J+1.

OceanVar **calibration analysis** was performed in order to handle an increasing number of observations. Another issue encountered was the different observation distribution pattern that characterizes the operational prediction system, for which the OceanVar has been originally designed, and the RR system. The different data distribution pattern are related to the different characteristics of the NRT observations used for the forecast production and the DM observations considered for the RR production, that include high resolution surveys regularly spaced on monitoring arrays or transects.

Many experiments have been conducted to tune **horizontal correlation length scales**, the **instrumental error**, to evaluate the possible usage of **vertical super observations** (average computation within vertical layers to avoid redundant information) and to improve the **horizontal filter** that spreads vertical corrections in the horizontal introducing a multi-scale approach. This RR system calibration focused mainly on August/September 1987 when a lot of observations are available thanks to an extensive POEM surveys (*Malanotte-Rizzoli and Robinson, 1988*) which sampled intensively the Eastern Mediterranean. The evaluation of the results has been done using in situ and satellite SST observations but also comparing the obtained circulation with the reference extensive literature about the Eastern Mediterranean circulation in that period, in particular *Robinson at al. 1991*.

Results obtained during the reference period

The OGCM analysis of **air-sea fluxes** parameterization brought about two important results. We first decided to avoid the extrapolation of air temperature and specific humidity from 2m to 10m.
The overall effect of extrapolation is an increase of air temperature during summer and a reduction of specific humidity during spring/summer with respect to the simulated behavior of COSMO dataset. Moreover a numerical experiment, which considers the extrapolation procedure, presents a general decrease of model SST that can be explained by an increase of evaporation during spring/summer due to very low specific humidity (not shown)

Figure 3 shows the results of the extrapolated air temperature and specific humidity at 10m computed from the NEMO routine *turb_core_2z.f90* versus the values at 2m and the values at 10m: one year test has been considered and then we compared time series of daily basin averages. The extrapolated air temperature at 10m (T10m) is on average higher than that at 2m (T2m) during spring and summer season (see Figure 3 - left), while the extrapolated specific humidity at 10m (SH10m) is always lower than that at 2m (SH2m) (see Figure 3 - right).

The air temperature extrapolation might be an advantage during winter season when the extrapolated values are on average closer to COSMO values at 10m than that at 2m, but it produces too high air temperatures during the summer season. The specific humidity extrapolation might be an advantage for specific humidity computation during fall/winter seasons but it creates very low values during spring/summer seasons.

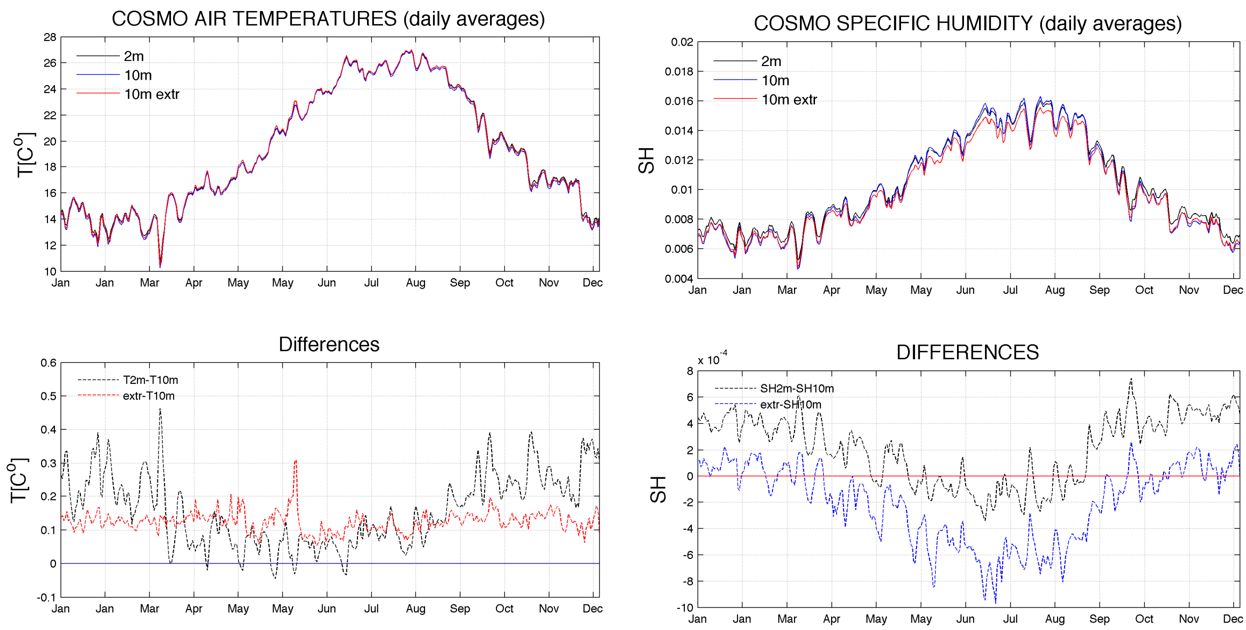

Figure 3. (Top Left) Air temperature time series from COSMO data at 2m (black line), at 10m (blue line) and the extrapolated value at 10m using turb_core_2z.f90 subroutine of NEMO. (Bottom Left) Differences between Air temperature at 2m and at 10m (dashed black line), difference between extrapolated air temperature at 10m and COSMO value at 10m (dashed red line). (Top Right) Specific humidity time series from COSMO data at 2m (black line), at 10m (blue line) and the extrapolated value at 10m. (Bottom Right) Differences between specific humidity at 2m and at 10m (dashed black line), difference between extrapolated and COSMO values at 10m (dashed red line).

Second the **true stress analysis** did not produce significant differences in terms of temperature and salinity misfits computed from in situ and satellite observations, we thus decided to keep the true stress implementation.

Figure 4 shows time series of monthly basin averages of SST bias and rmse computed from model simulations with and without true stress computations. **Figure 5** present maps of bias and rmse from the two model simulations that are characterized by similar patterns. The results suggest that there are no significant differences in terms of SST in using or not the true stress parameterization in momentum flux computation.

Figure 6 and 7 show the basin-averaged profiles of bias and rmse computed for temperature and observations in the Western and Eastern Mediterranean obtained from two simulations with (V4SM) and without true stress (V4SMno_ts) for the time period 1985-1987. None significant difference appears between the two model configurations.

Figure 8 presents the mean circulation computed for the month of October with true stress on top panel (V4SM) and without it on the middle plot (V4SMno_ts). The two maps are qualitatively compared to the circulation of the Eastern Mediterranean depicted by *Robinson et al. 1991* which has been computed from POEM observations collected between August and October 1987. The dynamic height anomaly refers to 30m depth and considers 450m as reference level. The circulation without true stress computation is more intense and smaller scales features characterize it. From a qualitatively point of view the upper thermocline circulation without true stress computation resembles more the circulation proposed by *Robinson et al. 1991,* at least in terms of intensity, but we would like to extract synthetic profiles from model data at observations locations and use the same Objective Analysis technique to draw the maps instead of using the monthly averaged temperature and salinity model field. Model circulation has to go closer the one proposed by *Robinson et al. 1991* when observations will be assimilated.

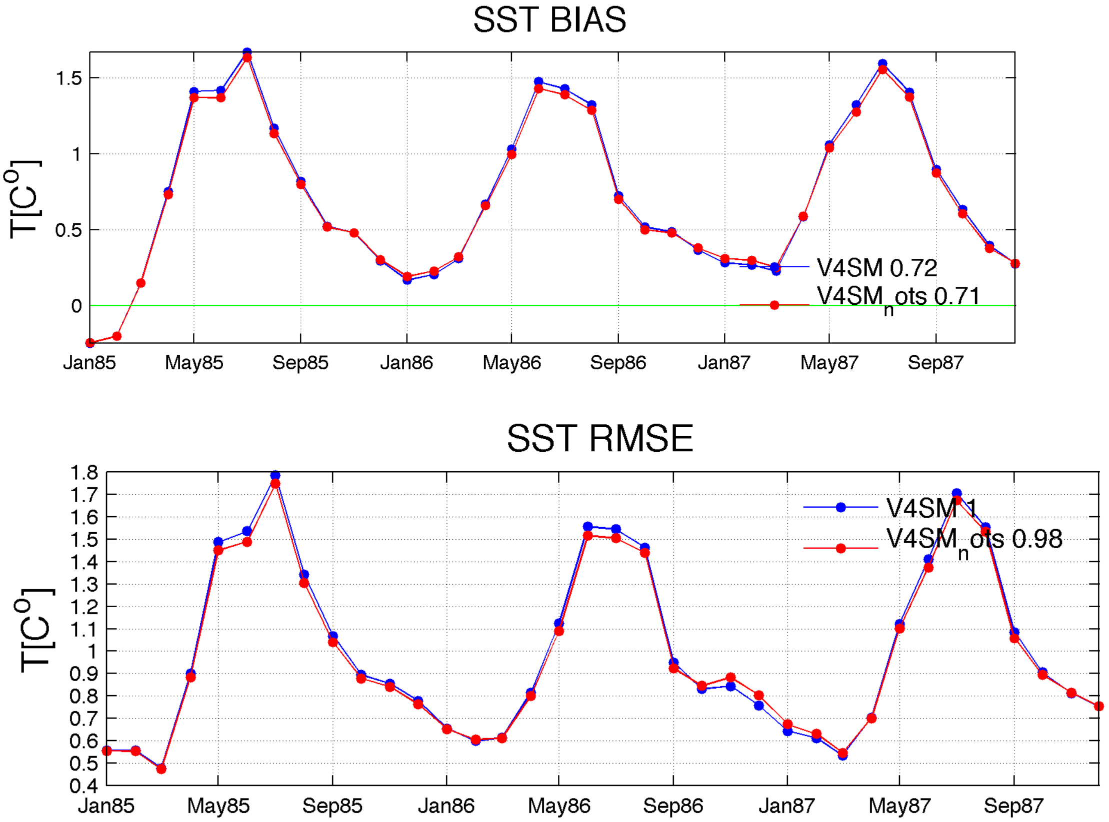

Figure 4. Basin averaged SST bias (top) and rmse (bottom) time series from two model simulations with true stress (V4SM, blue line) and without true stress computation (V4SMmo_ts, red line) for the time period 1985-1987.

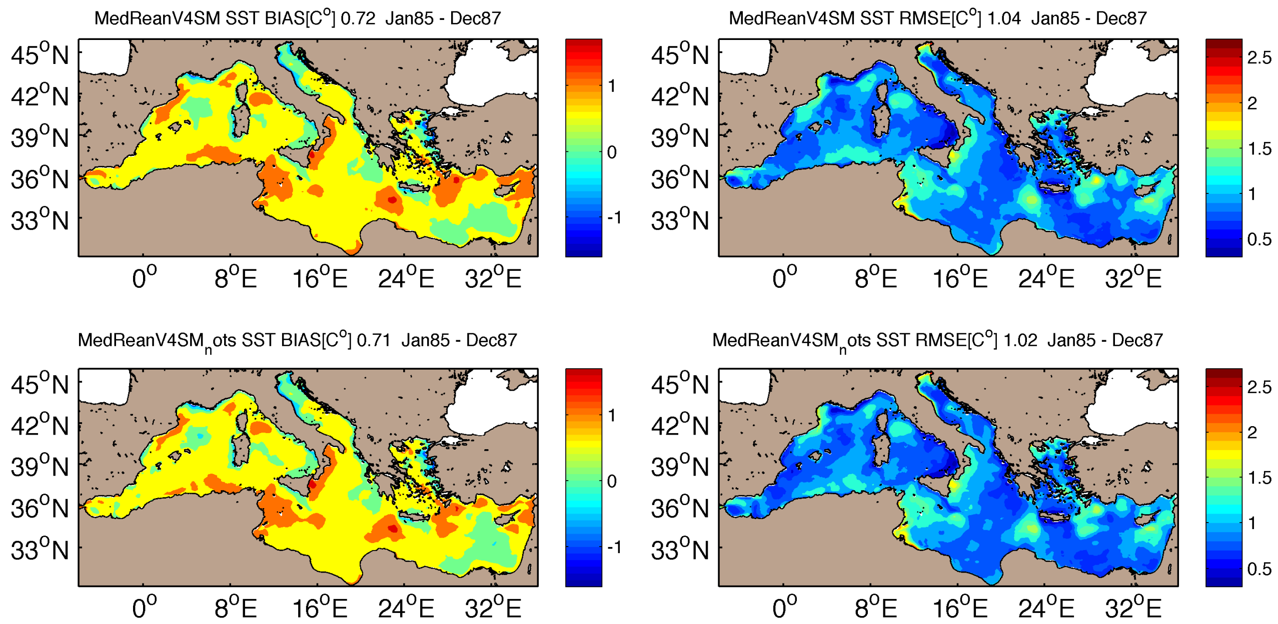

Figure 5: SST bias (left) and rmse (right) maps from two model simulations with true stress (V4SM, top) and without true stress computation (V4SMmo_ts, bottom) for the time period 1985-1987.

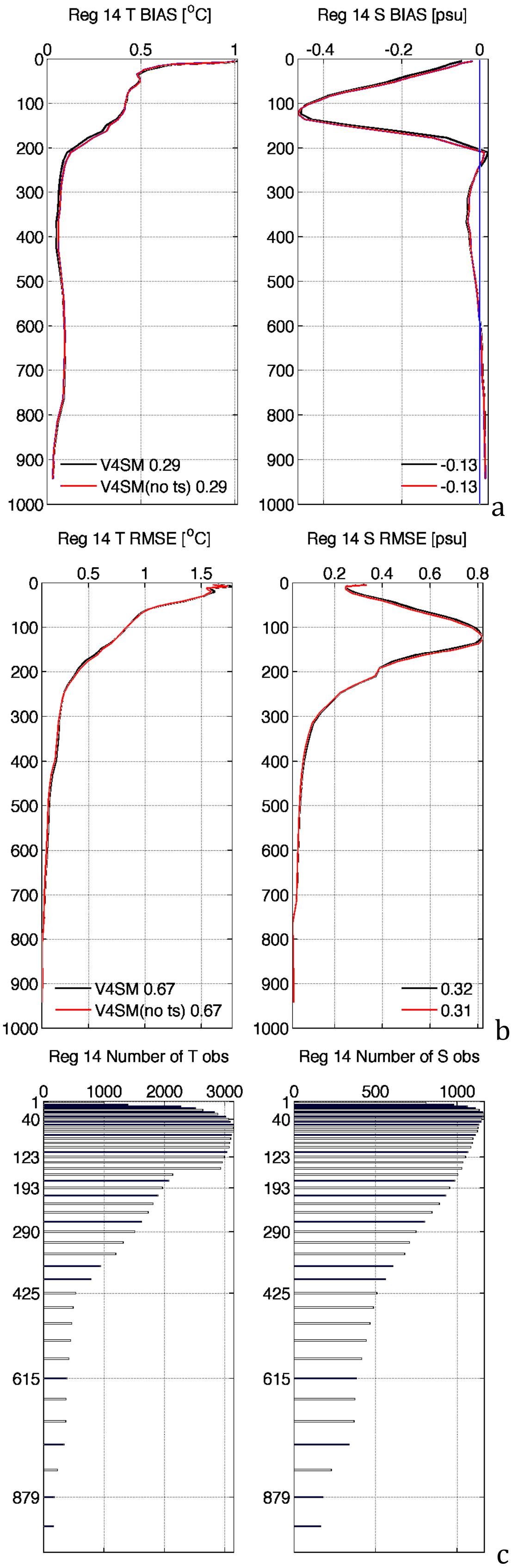

Figure 6. Results from the simulation for the time period 1985-1987 in the Western Mediterranean: (a - left) temperature mean bias profile computed from all temperature observed profiles; (a - right) salinity mean bias profile; (b - left) temperature mean rmse profile computed from all temperature observed profiles; (b - right) salinity mean rmse profile; (c-left) vertical distribution of the number of temperature observations; (c-right) vertical distribution of the number of salinity observations.

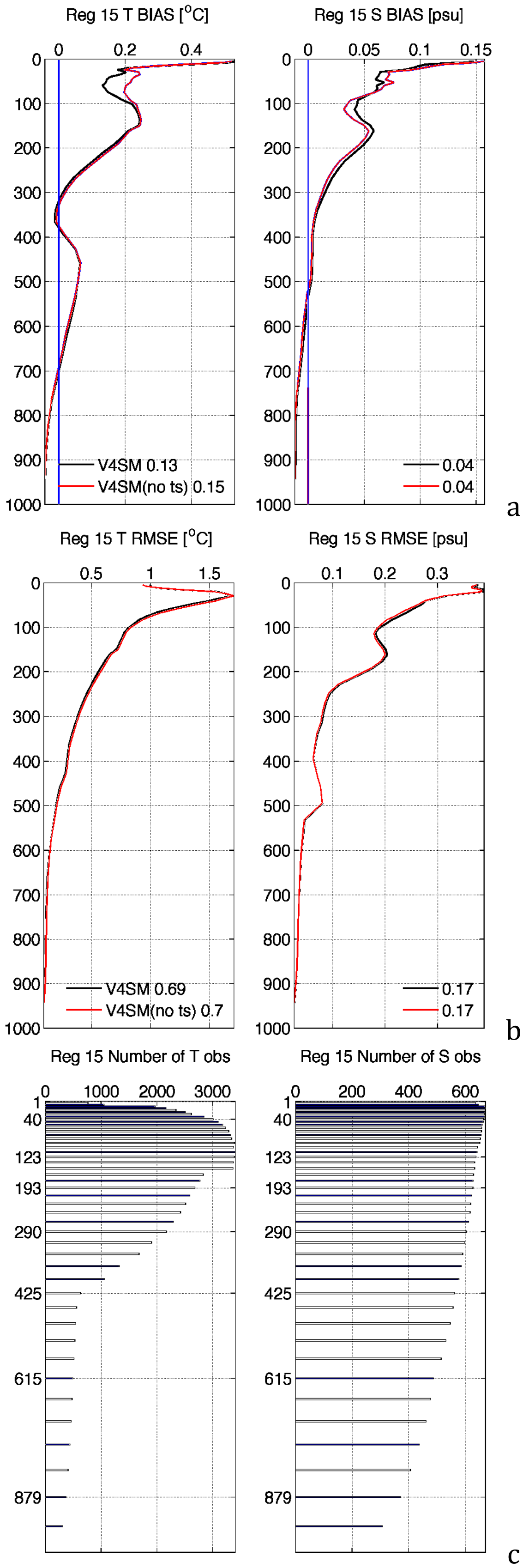

Figure 7. Results from the simulation for the time period 1985-1987 in the Eastern Mediterranean: (a-left) temperature mean bias profile computed from all temperature observed profiles; (a-right) salinity mean bias profile; (b-left) temperature mean rmse profile computed from all temperature observed profiles; (b-right) salinity mean rmse profile; (c-left) vertical distribution of the number of temperature observations; (c-right) vertical distribution of the number of salinity observations.

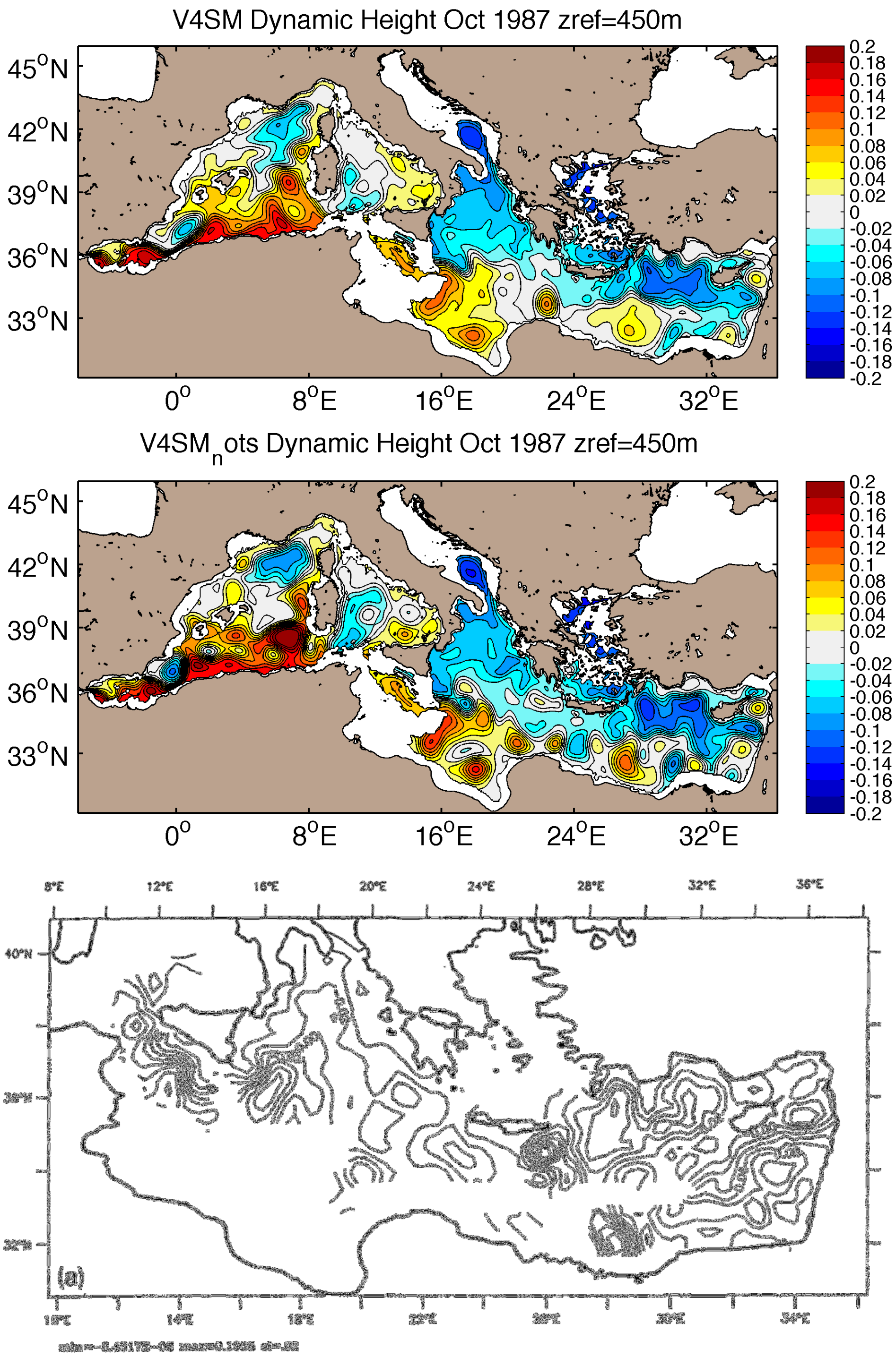

Figure 8. Dynamic height anomaly in the upper thermocline (30/450m) computed in October 1987: (top) model simulation with true stress (V4SM) ; (middle) model simulation without true stress (V4SMno_ts); (bottom) extracted from *Robinson et al. (1991)* computed from POEM observations collected between August and October 1987.

We then compared V4SM (with true stress) results with MedReanV2 (V2SIMU) simulation produced by Adani et al. (2011).

Figure 10 shows on top how the new model implementation reduces on average the SST bias, in particular V4SM bias is larger than V2SIMU during summer time but much smaller between fall and winter seasons. V4SM presents also on average a smaller rmse than V2SIMU, even if this is not true during the summer months. **Figure 11** shows the different patterns of bias and rmse for V2SIMU (top) and V4SM (bottom). The different forcing fields determined the different SST skill score patterns.

Figure 12 shows the MedReanV2 (Adani et al. 2011) circulation in the upper thermocline, as in **Figure 8**, that did not consider the true stress computation and has been forced by ERA15 atmospheric reanalysis at 1.125° instead of ERAInterim at 0.75°.

The results of model tuning and calibration analysis allowed us to define the OGCM numerical set up and to conclude that V4SM brings about better results than V2SIMU in terms of model SST when compared with satellite observations. The next phase focused on the OceanVar assimilation scheme.

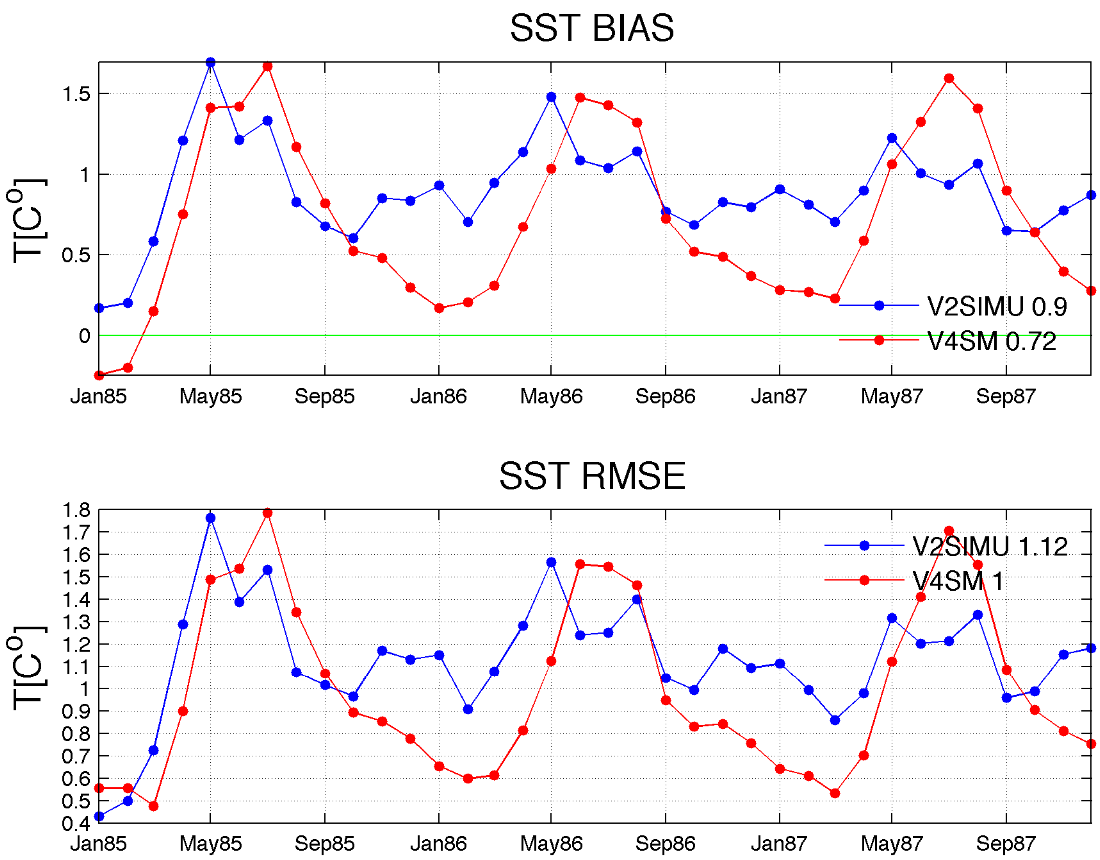

Figure 9. Basin averaged SST bias (top) and rmse (bottom) time series from two model simulations: (blue line) MedReanV2 from Adani et al. 2011; (red line) V4SM simulation with true stress for the time period 1985-1987.

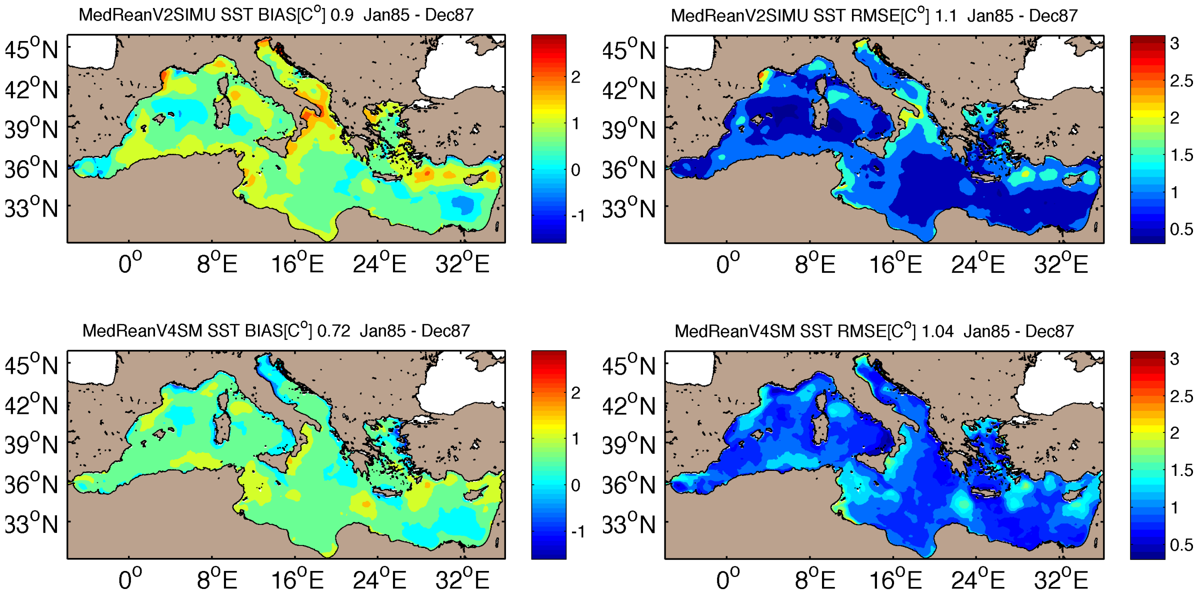

Figure 10. SST bias (left) and rmse (right) maps from two model simulations: (top) MedReanV2SM from *Adani et al. 2011*; (bottom) MedReanV4SM with true stress for the time period 1985-1987.

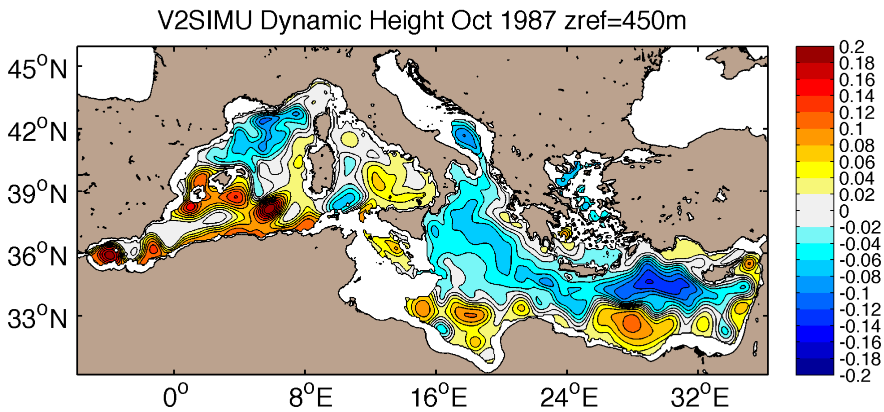

Figure 11. Dynamic height anomaly in the upper thermocline (30/450m) computed in October 1987 for MedReanV2 (V2SIMU) from *Adani et al (2011)*.

Data Assimilation calibration analysis focused in two test cases:

- at the beginning of October 1986 in the Alboran Sea;
- August and September 1987 in the Eastern Mediterranenan;

Tab. 2 synthesizes some of the experiments conducted to tune the correlation length scales, first considering the original recursive filer and later trying a new multi filter configuration.

The calibration analysis allowed to:

- identify a code bug on the vertical misfit interpolation;
- to discard vertical super observation computation;
- to reduce the correlation length scale in order to minimize the occurrence of overshooting phenomena in the 3D correction field estimation;
- to improve the horizontal filter;

- to test a multi-scale horizontal filter which selects the horizontal correlation length scale on the base of the observed variability.

We concluded that the implementation of a multi-scale filter does not give satisfying results, thus we kept the original recursive filter but to decrease the correlation length scale from 30km, used by *Adani et al. (2011)*, to 15km in accordance with the one implemented in the operational forecasting system.

	T5	T6	T7	T8	T9	T10	T11	T12
L [km]	30	15	10	7	30	15	15	15
	one scale filter				Multi-scale filter			

Table 2. Experiments conducted to calibrate the correlation length scale with the original OceanVar recursive filter and with the new multi-scale filter.

Conclusions and Future Work

It is necessary a re-formulation of our activities for the next year of the project respect to what it has been stated in the project Executive Plan (RR production at 1/24 starting from 1912). While further time will be dedicated to the higher resolution RR system implementation/calibration and the validation of the AMIP atmospheric forcing, we will begin an interim RR production covering the time period 1958-2011 using the 1/16th of a degree configuration.

We propose to begin the RR production next year with the 1/16th of a degree configuration starting from 1958 when ERA40 data are available.
Further efforts will be invested on:

- higher resolution RR system implementation;
- AMIP data quality assessment;
- the improvement of OceanVar data assimilation scheme for the higher resolution RR system;
- the estimation of a new monthly climatology on the 1/24th of a degree to initialize the higher resolution RR system.

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