Recontruction/Reanalysis (RR) Assessment in the Mediterranean Sea

Abstract

This document describes the quality of the Reconstruction/Reanalysis (hereafter RR) products that have been produced, in the framework of Nextdata Project, for the period 1955-2015.
The quality of the products has been assessed by comparing the results with available observations, consolidated climatology products and current knowledge of the ocean circulation. The International standards, defined by the GODAE metrics, have been followed in terms of consistency, quality and performance. The consistency has been validated with the current knowledge of the ocean circulation and climatology, while quality and performance have been measured through comparison with reference observational datasets.

The so-called **Class1**, **Class3** and **Class4** have been applied as follows:

- **Class1:** long-term averaged maps of a particular ocean variable compared to reference datasets;
- **Class3:** integrated quantities, such as temperature and salinity volume as a function of time, in standard layers, surface heat and water fluxes;
- **Class4:** measure of the performances of the reanalysis and of its capability to represent the ocean state consistently with the observations.

Introduction

The Mediterranean Reconstruction/Reanalysis (hereafter RR) has been produced by INGV by combining, every day, the output of the ocean model, forced by atmospheric surface fluxes and relaxed to SST, and quality controlled ocean observations, through the data assimilation scheme.

The aim of the RR is to provide an integrated set of information coherent and consistent across space-time dimension, through an optimal melding of observations and appropriate space and time numerical model, covering the period 1955-2015.

1 Overview of the Reconstruction/Reanalysis system

The Mediterranean RR system relies on three main components:

- **ocean model:** is a hydrodynamic model, supplied by Nucleous for European Modelling of the Ocean (NEMO);
- **data assimilation scheme:** is a variational data assimilation scheme, called OceanVar, for temperature and salinity profiles and satellite Sea Level Anomaly along track data;
- **quality controlled data:** are in-situ temperature and salinity profiles and Sea Level Anomaly along track satellite data.

1.1 Description of the ocean circulation model

The OGCM used to produce the RR are NEMO version 3.2 and Nemo version 3.4, respectively for the period 1955-2012 and 2013-2015. The two codes were used with the same physical settings and the validation task performed on the entire time series didn't show any change in the quality of the products due the updating.

The model solves the primitive equations in spherical coordinated and has 1/16° horizontal resolution (ca. 6-7 km) and 72 unevenly spaced vertical layers as implemented by *Oddo et al., 2009*. It uses vertical partial cells to fit the bottom depth shape and it is located in the Mediterranean Basin, also extending into the Atlantic in order to better resolve the exchanges with the Atlantic Ocean at the Strait of Gibraltar.

The model is nested in the Atlantic within monthly mean climatological fields computed from ten years of daily output of the 1/4° x 1/4° degrees PSY3 global model provided by MERCATOR (*Drevillon et al., 2008*).

The model is forced by momentum, water and heat fluxes interactively computed by bulk formulae adapted to the Mediterranean case, using AMIP data (*Cherchi and Navarra, 2007*). AMIP data are available from 1900 and were created through a set of experiments performed with the ECHAM4 atmospheric AGCM on a T126 grid (1.125° of horizontal resolution) forced by HadISST and have a 12 hours temporal resolution. Heat flux is corrected proportionally to the difference between the model and observed SST (*Pinardi et* *al., 2003*), with a relaxation coefficient equal to -60 Wm-2 k-1, corresponding to about 2.5 day scale over a depth of 3m. The observed SST dataset consist of monthly SST provided by Met Office Hadley Centre (HadISST) on regular grid of 1° x 1° starting from 1870 (*Rayner et al., 2003*) and this choice is consistent with using AMIP atmospheric forcing, which is also forced by HadISST.

Water balance is computed as Evaporation minus Precipitation and Runoff. The evaporation is derived from the latent heat flux while the precipitation and the runoff are provided by monthly mean dataset. Precipitation is taken from Climate Prediction Centre Merged Analysis of Precipitation (CMAP) data (*Xie and Arkin, 1997*). Runoff is provided by monthly mean datasets: the Global Runoff Data Centre dataset (*Fekete et al., 1999*) for the Po, Ebro, Nile and Rhone rivers; the dataset from Raicich (*Raicich, 1996*) for the Vjosë and Seman rivers; the UNEP-MAP dataset (Implications of Climate Change for the Albanian Coast, Mediterranean Action Plan, MAP Technical Reports Series No.98., 1996) for the Buna/Bojana river. The Dardanelles Strait is closed but considered as net volume input (*Kourafalou and Barbopoulos ,2003*) through a river-like parametrization.

1.2 Description of the ocean data assimilation scheme

The data assimilation system is the three-dimensional variation scheme called OceanVar, set up by *Dobricic and Pinardi* (2008), that allows to correct model fields for the dynamic variables. The vertical covariance matrixs are represented by 20 seasonally and regionally vertical EOFs of surface elevation and vertical profiles of temperature and salinity, estimated from the temporal variability of parameters in a historical model simulation (*Dobricic et al., 2005*). The MDT used for SLA data assimilation has been computed by *Dobricic et al., 2005*. In order to handle historical observations, which are normally given with regularly and finely sampling, a localization technique was implemented in OceanVar in order to decrease the correlation length scales in the background error covariance matrix.
The assimilation cycle is daily and both in-situ and satellite data are jointly assimilated to estimate the initial condition for numerical model.

1.3 Description of quality controlled data

The assimilated data consist of satellite SLA data and in-situ temperature and salinity profiles (see Table 1).

The SLA dataset used to produce RR is the so called Reprocessed data, that are deleyed mode data, homogenized with respect to a reference mission, which is currently Jason2, and using the same model and corrections for each satellite missions. This product is computed with an optimal and centered computation time window (6 week before and after the date).

The in-situ temperature and salinity profiles considered for the RR production belong from different instrumental data type: CTDs, XBTs, MBTs, bottles, ARGO floats. In situ data sets have been collected from European Marine databases and have been archived in a specific format to be assimilated. They were downloaded from different sources: 1)

SeaDataNet European infrastructure (DG-Research-FP6); 2) MEDAR-MEDATLAS dataset covering the period 1985-1999 (*Maillard et al. 2005*); 3) MFS (Mediterranean Forecasting System) operational observation infrastructure based on Enea and Coriolis data centers and 4) MyOcean and CMEMS In-situ TAC. Considering the time lag between the sampling and the insertion of the data inside different data collection infrastructures, the in-situ dataset used in the production is a combination of reprocessed data and near-real time observations in the recent period.

The SST dataset are not assimilated but they are used to correct the surface heat flux by a relaxation of the numerical model surface layer temperature towards the observed SST. The observed SST dataset consist of monthly SST provided by Met Office Hadley Centre (HadISST) on regular grid of 1° x 1° starting from 1870 (*Rayner et al., 2003*).

Table 1 summarizes the atmospheric forcing and data assimilated in the RR system.

ATMOSPHERIC FORCING	AMIP
SLA	SEALEVEL_MED_SLA_L3_REP_OBSERVATIONS_008_020 SEALEVEL_MED_SLA_L3_NRT_OBSERVATIONS_008_019
ARGO	Coriolis and INSITU TAC dataset INSITU_MED_NRT_OBSERVATIONS_013_035 INSITU_GLO_NRT_OBSERVATIONS_013_030
XBT	MEDATLAS, MFS (Enea), INSITU-TAC dataset
CTD	SeaDataNet, MEDATLAS, MFS (Enea), INSITU-TAC dataset in-situ SeaDataNet product (FREE access temperature Salinity Observations) in-situ SeaDataNet product (RESTRICTED access temperature Salinity Observations) MEDAR MEDATLAS (Historical data)
SST	Met Office Hadley Centre SST dataset (HadSST1)

Table 1: Atmospheric forcing and data assimilated details.

2 Validation framework

One of the main issues related to the use of reanalysis products is their quality assessment. Building on consolidated practices, this task is related to the need of providing a range of uncertainty associated with the results of the reanalysis.

The RR products have been evaluated for the period 1 January 1955 – 31 December 2015, considering a set of standardized metrics grouped by ocean state variables and applied in order to assess scores that measure to the quality of the products.

The reanalysis outputs were compared to available observational datasets, using both in-situ and satellite data; the model estimates were interpolated at the location of the observations. The general methodology used to validate RR products consists in an extension of the diagnostics developed by *Adani et al.,* 2011, based on the misfits.

In the data assimilation process, the observation operator h is used to interpolate the model field (background) xf to the location (in time and space) of the observations, y. This enables the calculation of misfits:

$$m = [y - h(x^f)]$$

Misfits have been calculated before observations are included; observations can be considered independent since the they are sparse in space and time. The deviations between the background and the observations are quantified in terms of RMSE and BIAS scores.

The RMSE provides estimates of the precision of the model in reproducing the amplitude of the signals and serves to aggregate time varying differences or errors into a single measure of predictive power. The RMSE undervalues the phase errors in the fields. The RMSE value is not dimensionless but exhibits the same units as the validated field.

The BIAS indicates possible systematic errors in the products, assuming that the observational dataset represents the truth.

These statistics have been calculated considering the observations listed in Table 1

3 Validation Results

3.1 Sea Surface Temperature quality

The assessment of the Sea Surface Temperature (SST) has been performed in terms of:

Class1: Maps of annual mean monthly mean RMSE and BIAS for different variables;
Class3: Time series of domain averaged monthly surface heat flux computed from RR products;
Class4: Time series of monthly RMSE for different variables.

Figure 1 shows the RMSE and BIAS, as function of time, between monthly mean SST from the RR and the satellite Hadley data over the period 1955-2015. Both statistics present a seasonal signal, with largest RMSE values during spring-early summer, to which a warm BIAS corresponds.

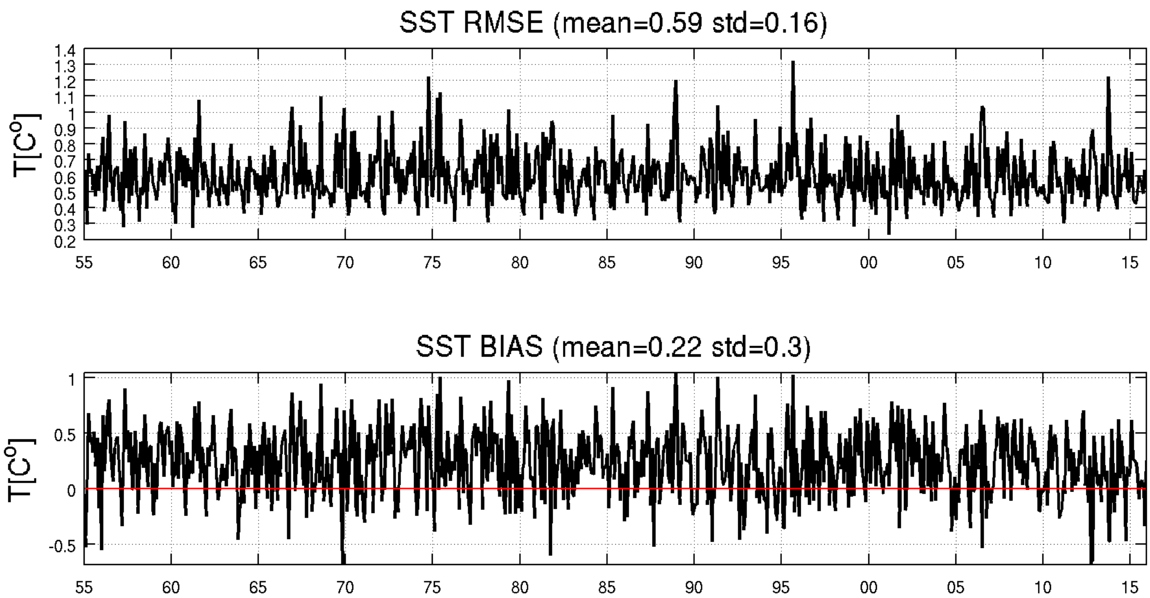

Figure 1: SST RMSE (top) and BIAS (bottom) computed from monthly mean RR SST and satellite Hadley SST.

Figure 2 shows SST RMSE and BIAS averaged maps over the entire period 1955-2015. The maps highlight the areas where the major model deficiencies are found, which correspond to the regions where, owing to uncertainties in atmospheric forcing, a positive bias is found, as shown in *Pettenuzzo et al.*, 2010. Negative BIAS and large positive RMSE values appear in the upwelling areas of the Mediterranean Sea, such as the Eastern Adriatic, over Southern Sicily and in the eastern Aegean Sea. Larger errors are also present in open ocean areas such as the northwestern Mediterranean and the Southern Ionian Sea, as well as in areas influenced by river runoff, such as the Northern Adriatic Sea.

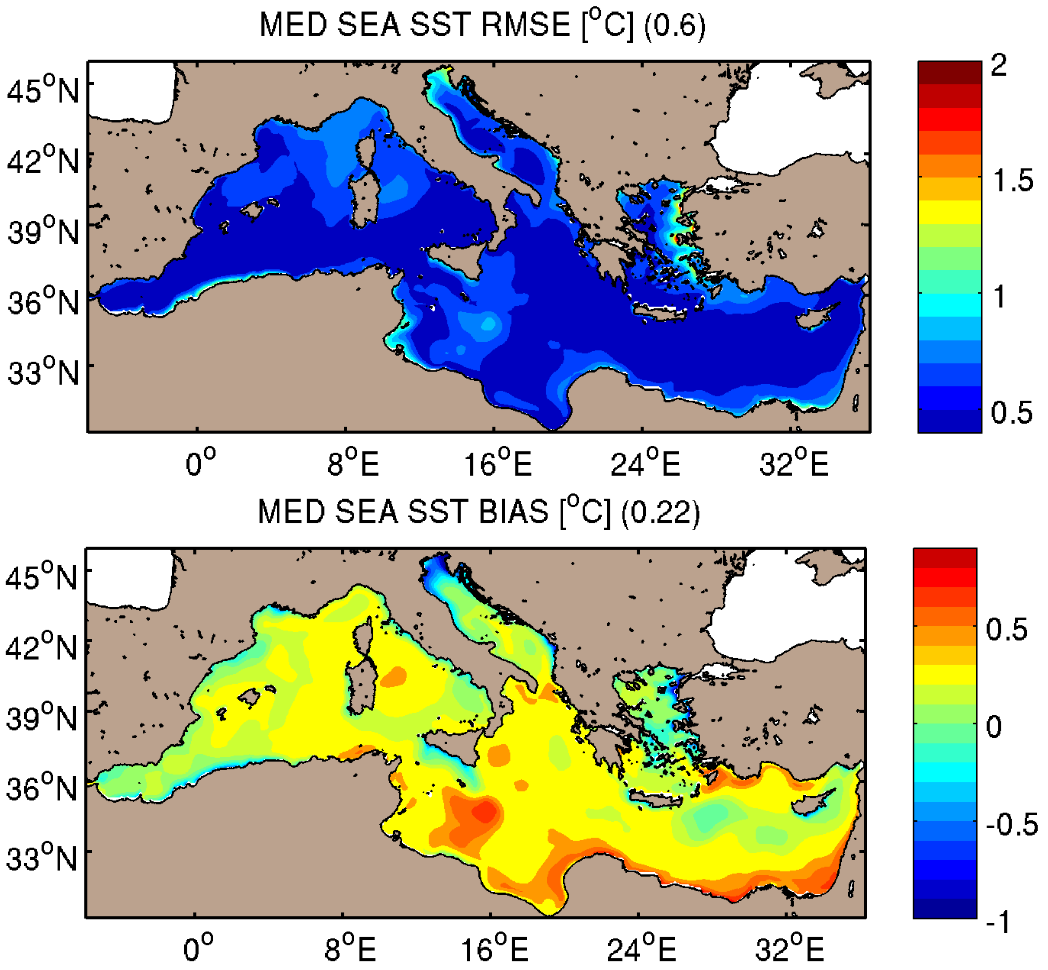

Figure 2: SST RMSE (top) and BIAS (bottom) maps computed on monthly basin from RR products and satellite reference dataset.

The performance of RR for SST is summarized in **Table 2**:

Parameter	BIAS	RMS
SST [°C]	0.22±0.3	0.59±0.16

Table 2: Summary of SST performance.

Figure 3 shows the net heat flux time series computed from RR products. The net heat budget is equal to 0 W/m2, higher than the negative heat flux value of -4 ± 3 W/m2 found in *Pettenuzzo et al.,* 2010.

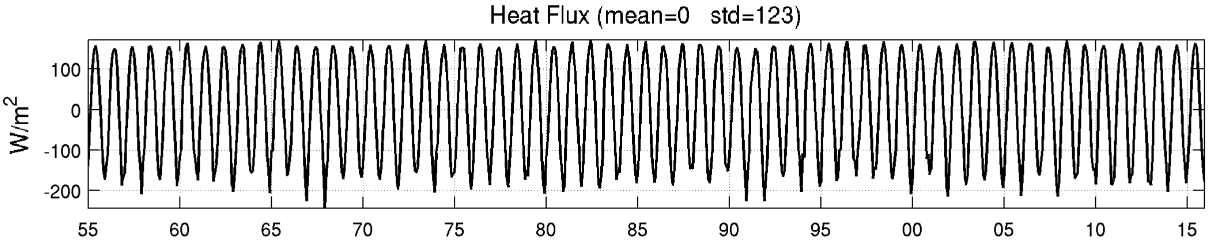

Figure 3: Monthly mean net heat flux computed from RR products.

3.2 Temperature profiles quality

The vertical temperature structure has been evaluated considering the following metrics:

Class3: Comparison between RR products and reference data (SDN climatology) of monthly climatology and monthly profiles averaged over the basin;
Class3: Time series of RR temperature at different layers;
Class4: RMSE and BIAS, computed for different layers as function of time and depth.

Figure 4 shows the difference of the monthly climatology of temperature and of the monthly temperature profiles (averaged over the basin) between the RR product and the SeaDataNet (SDN) climatology (our reference) as a function of depth, up to 1000m. Starting from the surface, and considering the differences as monthly climatology (upper panel), from May to September, the reanalysis product is warmer (~0.3 °- 0.8°C) than the SDN climatology within the first 15 m, while it is colder (~0.1°-0.2°C) between 15-50m of depth. From September to December, the largest differences are found between 20-50m and they are positive, indicating that the reanalysis is warmer than the SDN climatology. Positive differences (~0.2°C) are present also from January to March, around 120m.

The differences between reanalysis and SDN climatology as monthly basin averaged profiles (bottom panel of Fig.4) oscillate between negative and positive values, owing to the large interannual variability of the summer thermocline. Starting from the late 1900s positive anomalies extends from the surface up to 200m of the water column almost all year long, while below 200m a negative anomaly (~0.5°C) dominates.

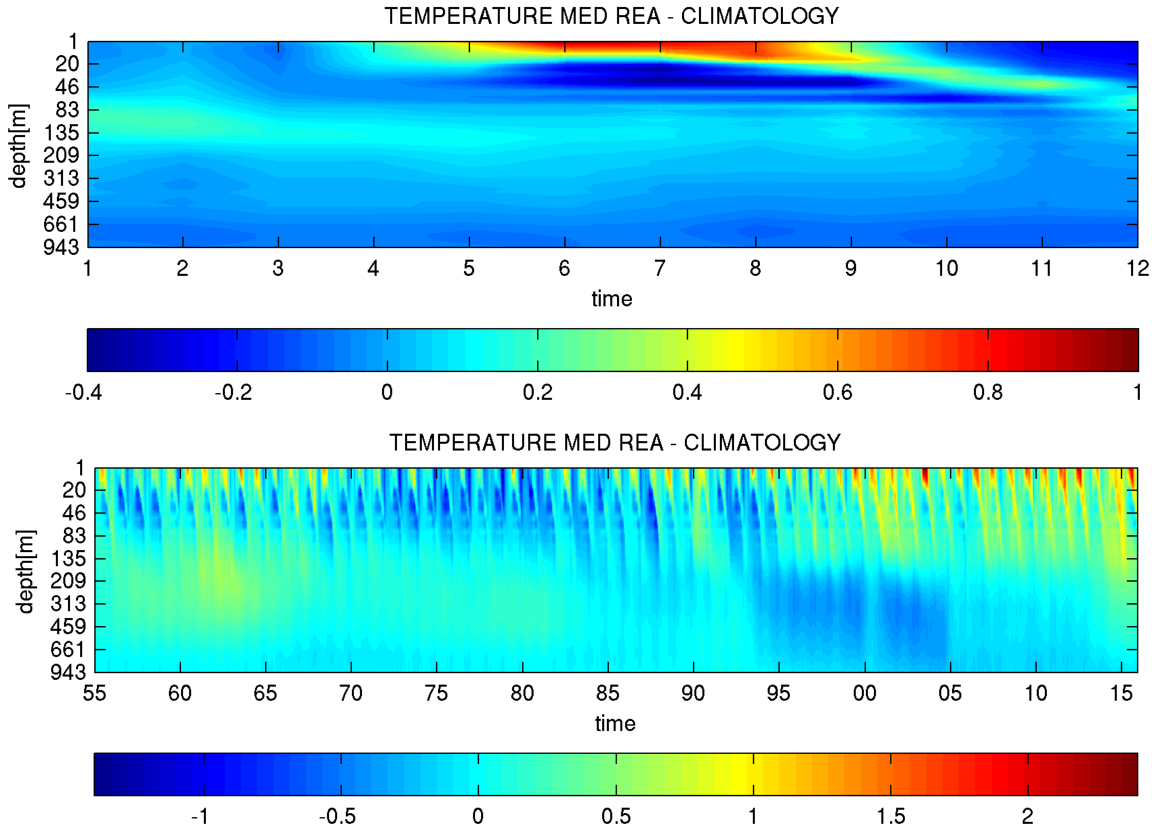

Figure 4: Monthly climatology (up) and monthly basin averaged profiles (bottom) comparison between RR products and SDN climatology.

Figure 5 shows the time series of temperature in different layers over the Mediterranean Sea. The first layer (0-30m) presents a clear seasonal signal with the highest values during summertime (~26°C) and lowest values during wintertime (~15°C). This layer is highly influenced by the atmospheric forcing and is where the seasonal thermocline evolves.

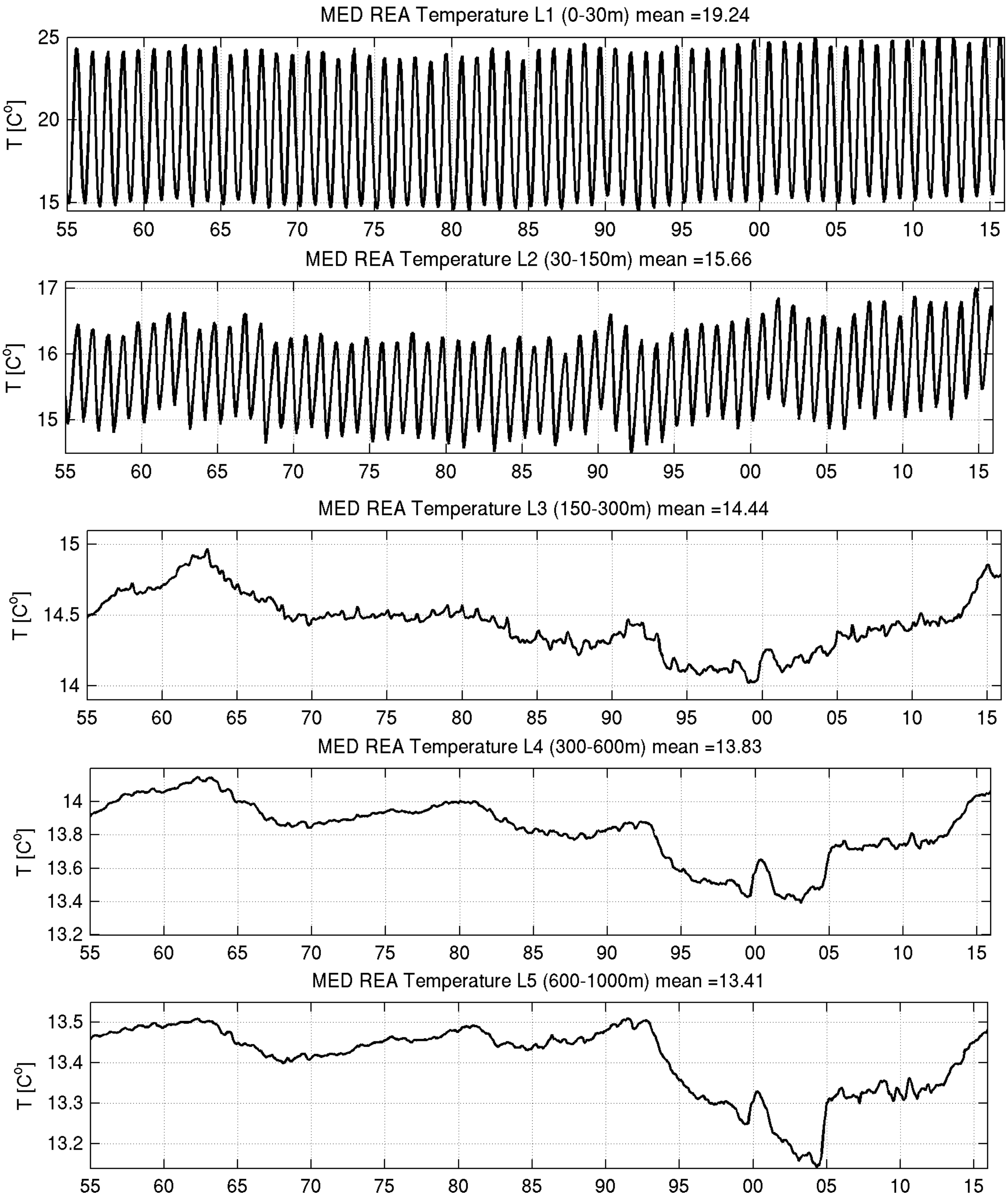

Figure 5: Temperature monthly mean from RR products.

Figures 6 and 7 present the RMS and BIAS computed in different layers at the location and time of the observations.

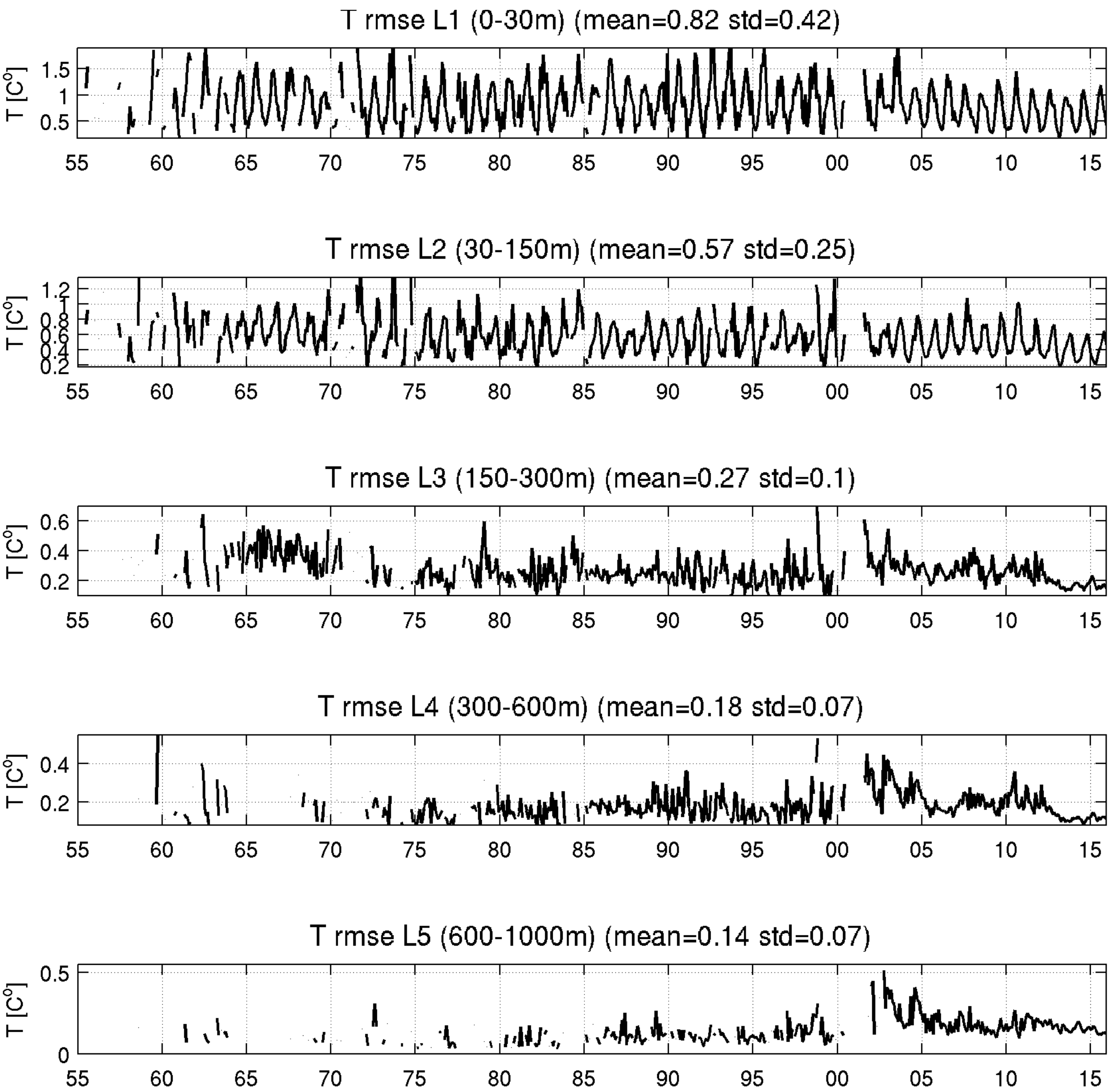

Figure 6:Temperature RMSE computed from misfits

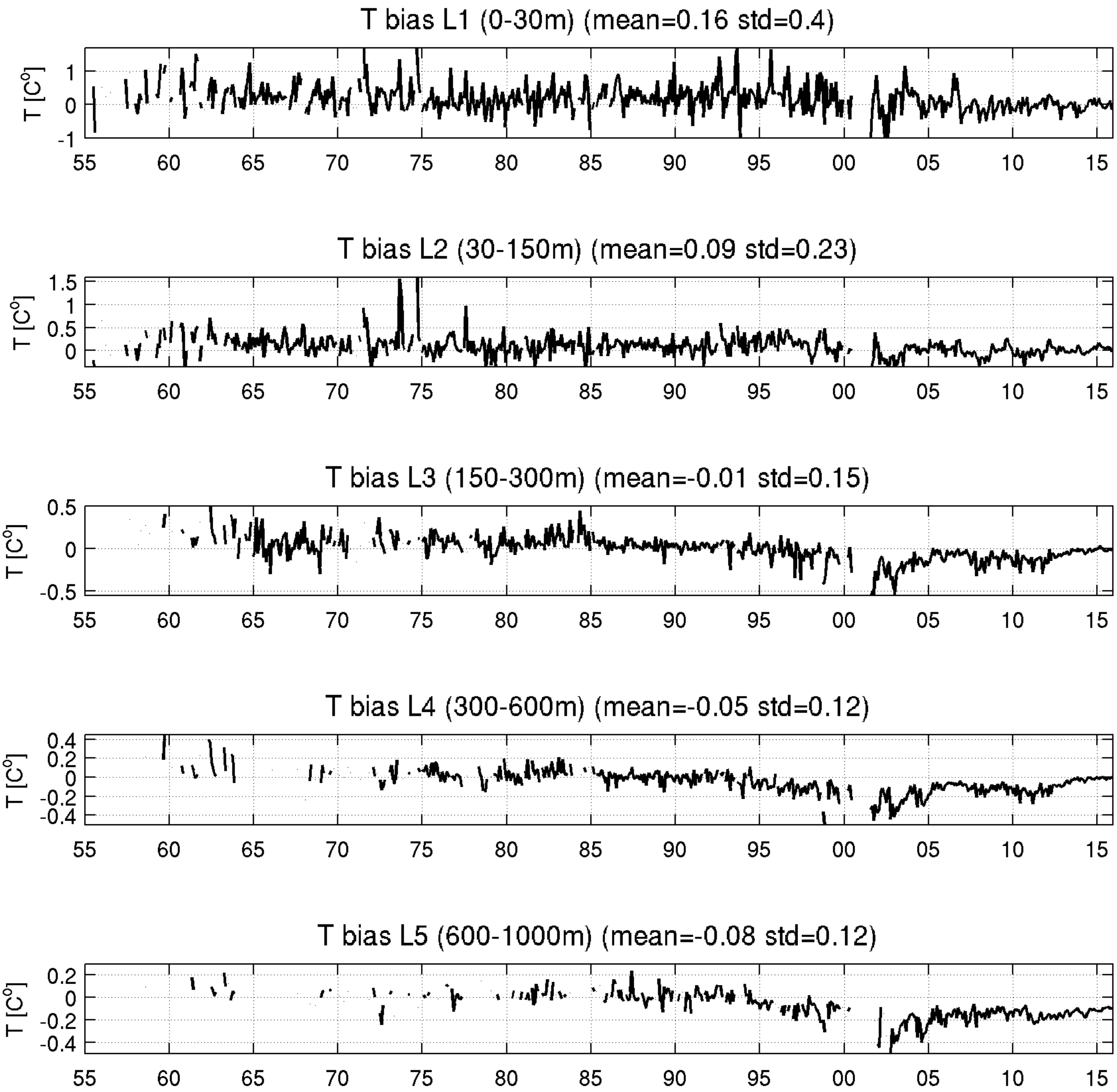

Figure 7: Temperature BIAS computed from misfits.

Figure 8 shows the temperature BIAS and RMSE as a function of depth, averaged up to 1000m over the entire reanalysis period. Deeper layers have not been considered because observations are too sparse in both time and space to provide statistically significant results. The BIAS exhibits maximum positive values (~0.2°C) at the surface, while below 200m it is negative. The RMSE peaks at about 30m of depth (>0.8°C). The water column averaged BIAS and RMSE are, respectively, 0.02°C while and 0.4°C.

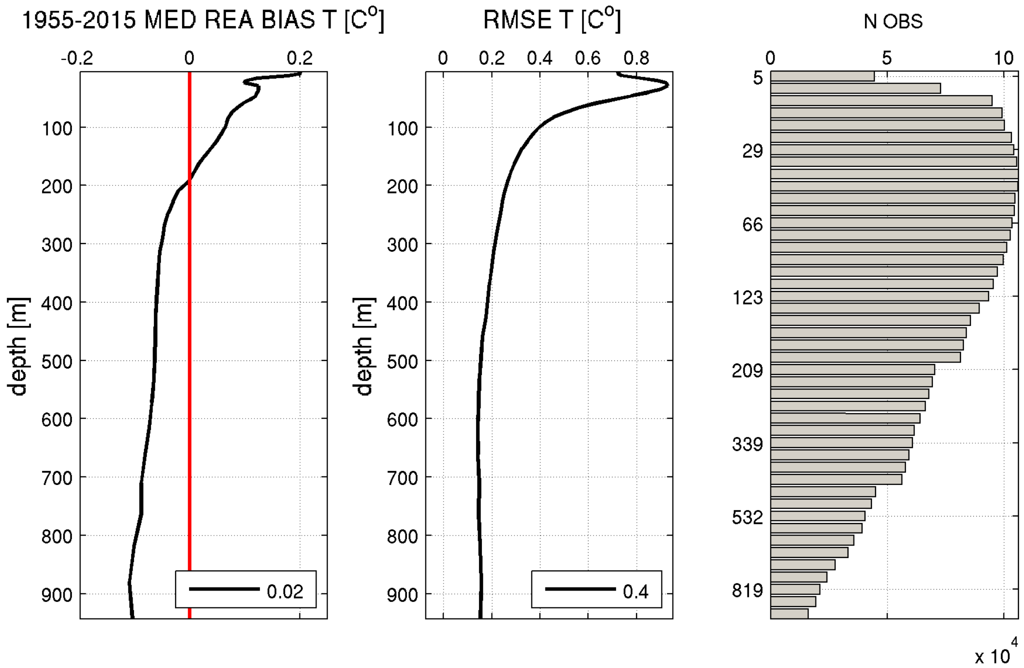

Figure 8:BIAS and RMSE profiles.

Overall metrics of the comparison between the RR and reference temperature are summarized in **Table 3.**

TEMPERATURE [°C]	BIAS	RMS
0 -30 m	0.16 ± 0.4	0.82 ± 0.42
30 -150 m	0.09 ± 0.23	0.57 ± 0.25
150 - 300 m	-0.01 ± 0.15	0.27 ± 0.1
300 - 600m	0.05 ± 0.12	0.18 ± 0.07
600 -1000m	-0.08 ± 0.2	0.14 ± 0.07
Total	-0.02 ± 0.004	0.4 ± 0.02

Table 3: BIAS and RMSE at different layers and in total.

3.3 Salinity profiles quality

The assessment of salinity vertical structure has been performed in terms of:

Class3: Averaged monthly mean over the Mediterranean Sea;
Class3: Mediterranean Sea averaged monthly fresh water flux;
Class3: Monthly climatology and monthly basin averaged profiles comparison against SDN climatology;
Class4: RMSE and BIAS time series computed from misfits as a function of time at different layers and as function of depth.

Figure 9 shows the temporal evolution of the Sea Surface Salinity (SSS). Its long-term average is 38.14 psu and it oscillates around 38.1psu until 2005 when starts to increase.

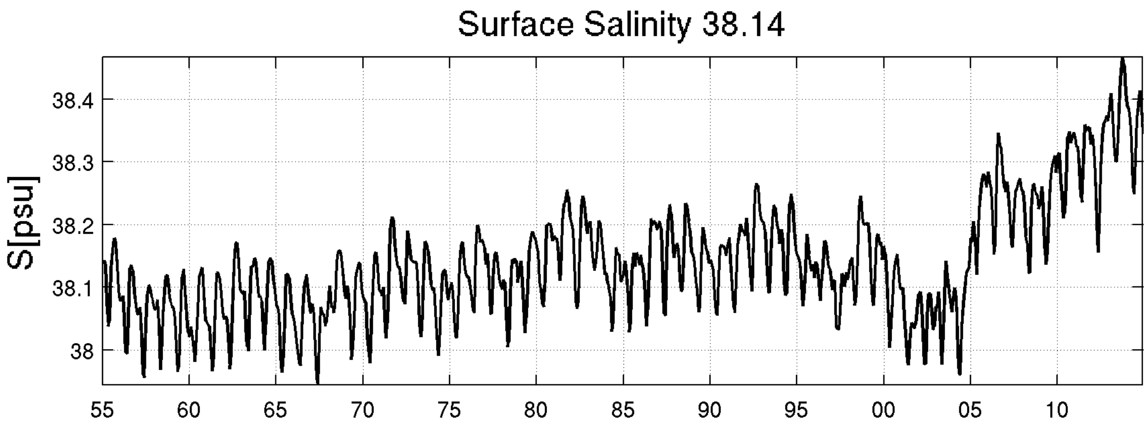

Figure 9: SSS monthly mean.

Figure 10 shows the net water flux that does not show any signal of abrupt change. This suggests that the reason for its increase cannot be due to the water budget change and could be connected to the ARGO profiles, which started to provide systematic measurements in the Mediterranean Sea since 2005.

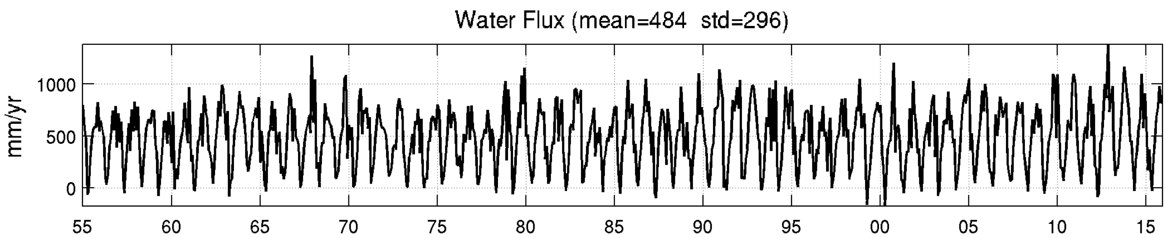

Figure 10: Net water flux.

Fig. 11 shows the salinity monthly climatology and monthly averaged profiles comparison against SDN climatology up to 1000m. Considering the monthly climatology (top), RR is fresher than the SDN climatology within the first 200m of depth, while below it is saltier.

Considering the comparison as function of time (bottom), starting from 2005, RR presents a positive trend.

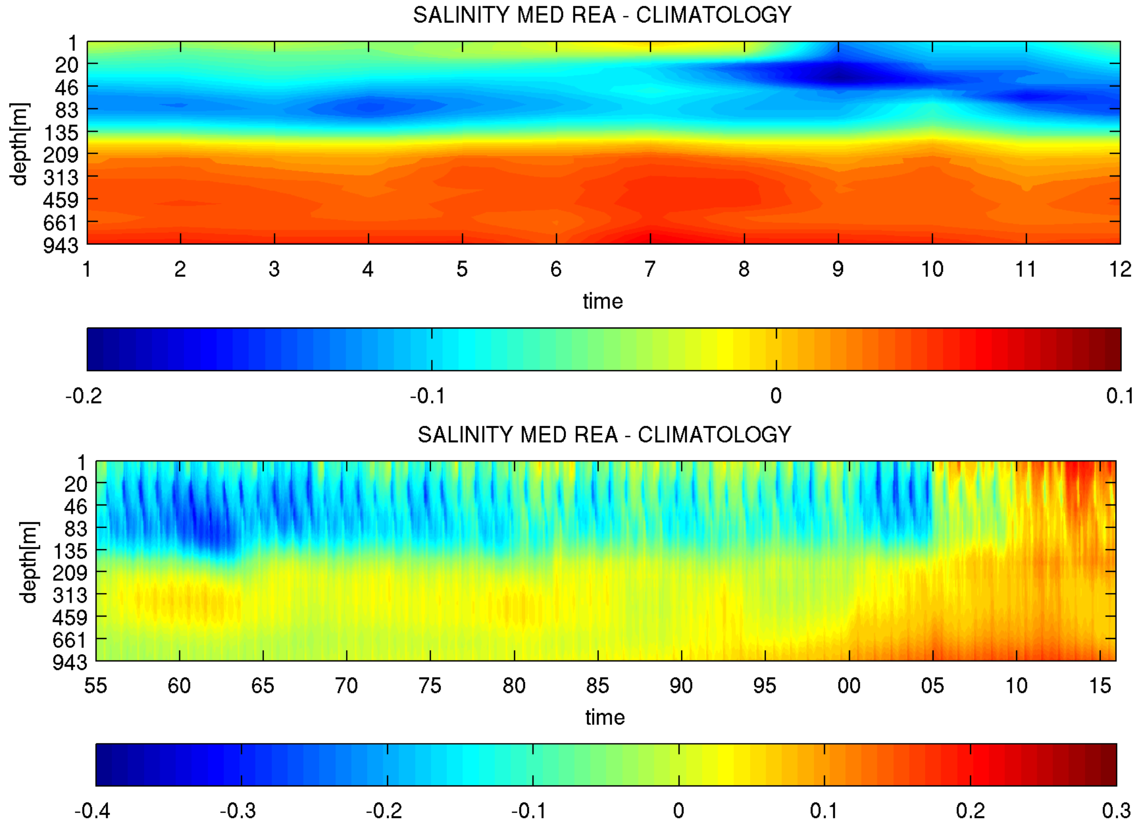

Figure 11: Monthly climatology (up) and monthly basin averaged profiles (bottom) comparison between RR products and SDN climatology.

Figure 12 - Figure 13 present the RMS and BIAS computed in different layers at observation space-time location. The RMSE starts to decrease together with the advent of ARGO in the Mediterranean Sea (2005).

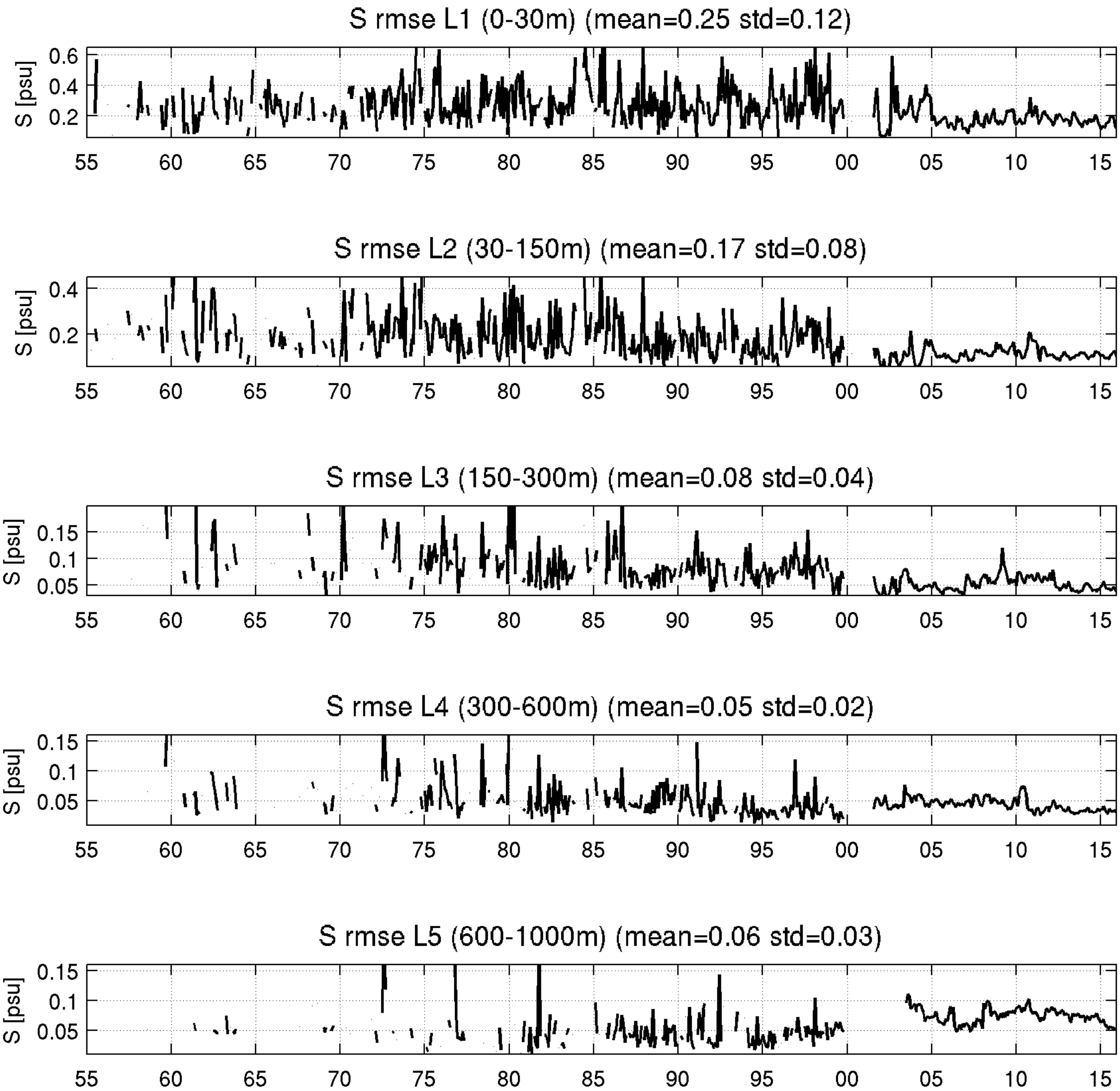

Figure 12: Salinity RMSE from misfits.

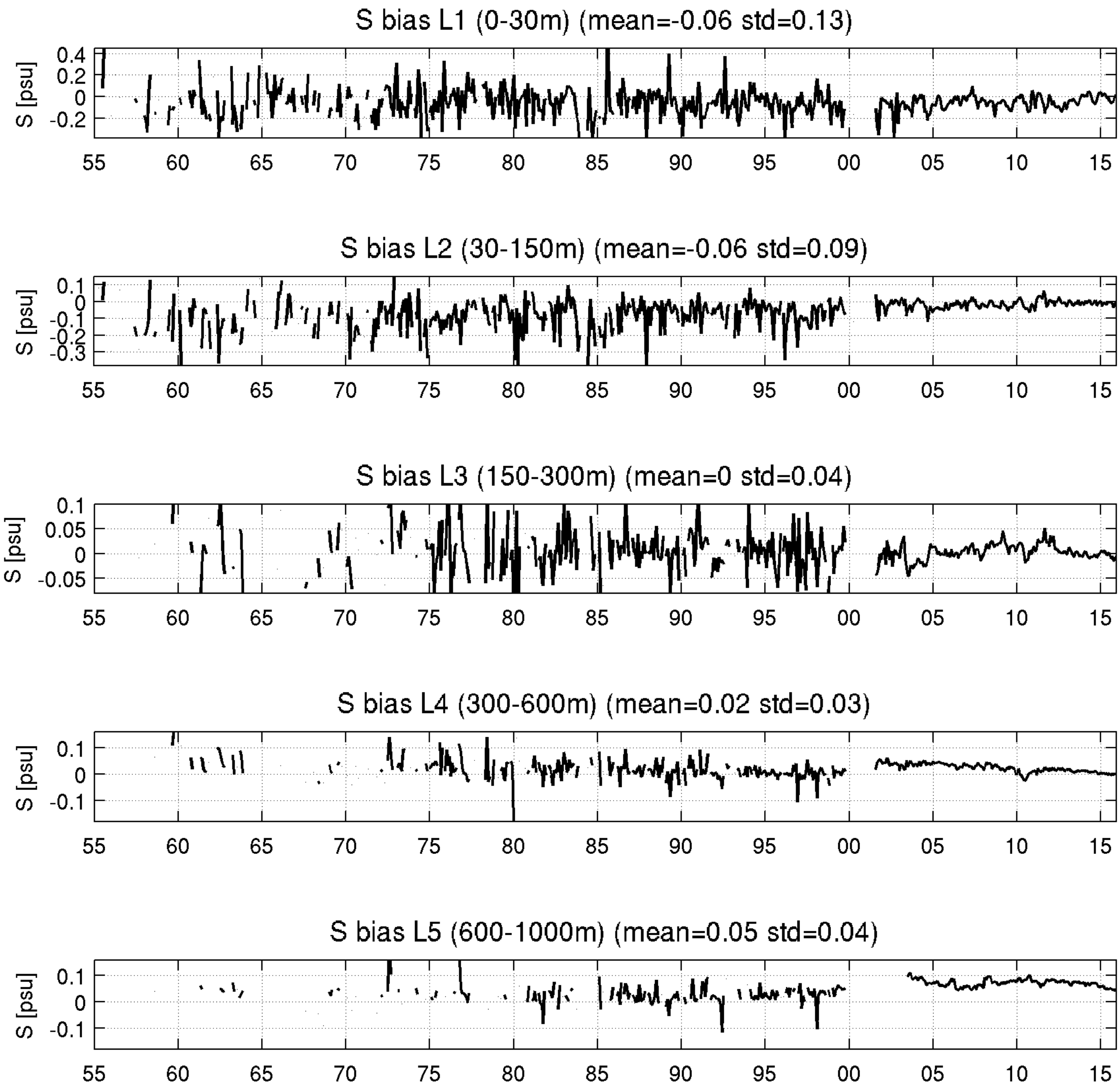

Figure 13: Salinity BIAS from misfits.

Figure 14 displays salinity BIAS (left) and RMS (middle) mean profiles computed on the misfits. Salinity BIAS is negative within the first 200m and positive below. The RMSE reaches maximum value of 0.3psu at the surface where the atmospheric and land forcing play a fundamental role and decreases below 0.1psu below 150m of depth.

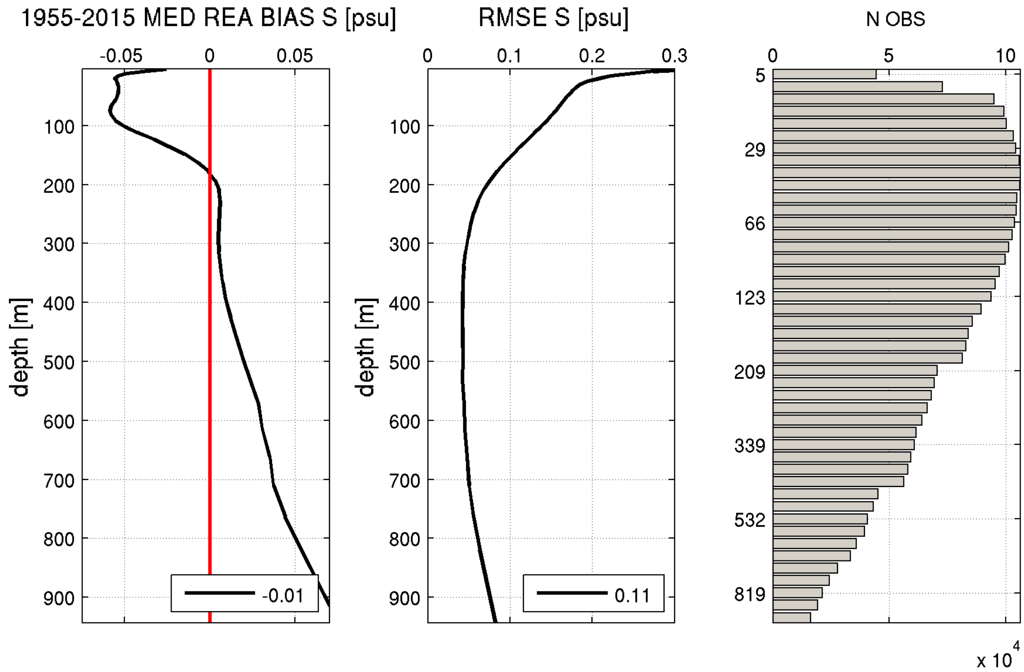

Figure 14: BIAS and RMSE profiles.

The total statistics are included in **Table 4**

Salinity [psu]	**BIAS**	**RMS**
0 -30 m	-0.06 ± 0.13	0.25 ± 0.12
30 -150 m	-0.06 ± 0.09	0.17 ± 0.08
150 - 300 m	0 ± 0.04	0.08 ± 0.04
300 - 600m	0.02 ± 0.03	0.05 ± 0.02
600 -1000m	0.05 ± 0.04	0.06 ± 0.03
Total	0.01 ± 0.004	0.12 ± 0.01

Table 4: BIAS and RMSE in different layers and in total.

3.4 Sea surface height quality

The Sea Surface Height has been evaluated considering:

Class4: Sea Level RMSE averaged over the whole domain.

Figure 15 shows the time evolution of basin-averaged RMS of the SLA misfit computed along satellite tracks over the altimeter time period (1993-2015) on a monthly basin. The RMSE remains quite stable up to 2012, then it starts to increase due to the decrease in the number of observations. The mean value is around 3.7cm, smaller than the RMSE of the observations which is estimated of about 5cm for the Mediterranean Sea.

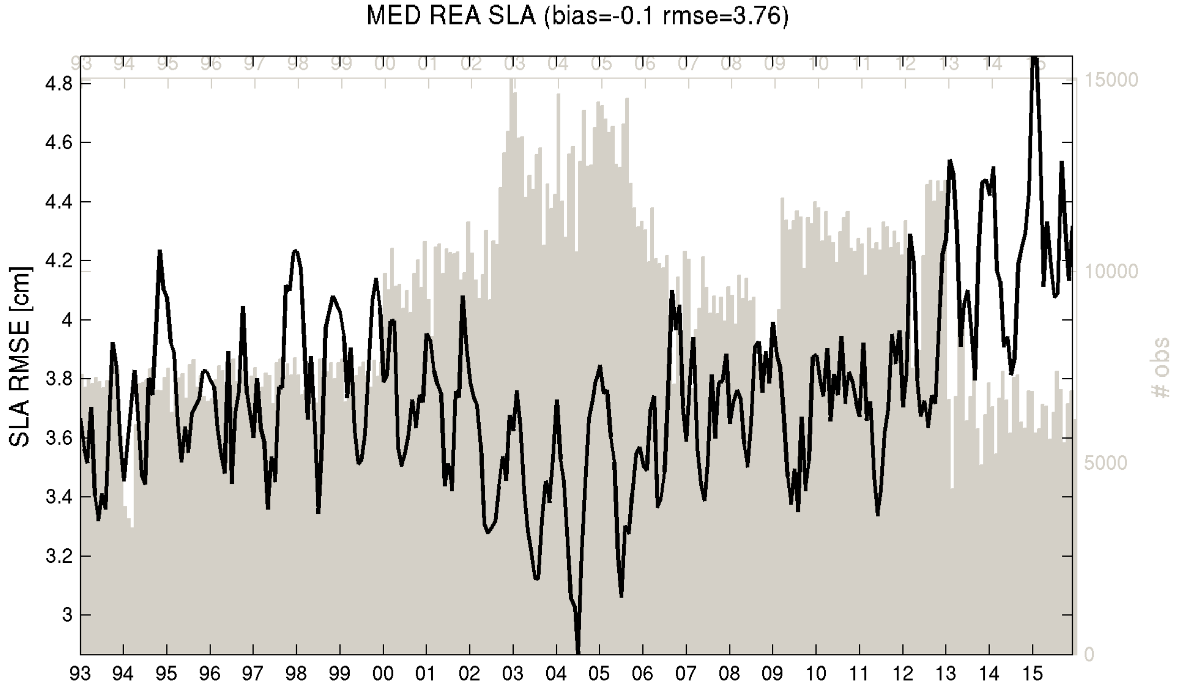

Figure 15: RMSE of SL misfits.

The total statistics are included in Table 5

Sea Level Anomaly [cm]	BIAS	RMS
SLA	-0.09± 0.02	3.76 ± 0.65

Table 5: SLA BIAS and RMSE.

3.5 Gibraltar transport quality

The Gibraltar transport has been evaluated considering:

Class3: Monthly time series of net volume transport through the Gibraltar Strait.

Monthly time series of net volume transport through the Gibraltar Strait is displayed in **Figure 16** together with the westward and eastward components. The eastward inflow component is slightly higher than the westward outflow component determining a long-term net value of 0.04Sv with a standard deviation of 0.06Sv. These values are coherent with the literature (*Menemellis et al., 2007*).

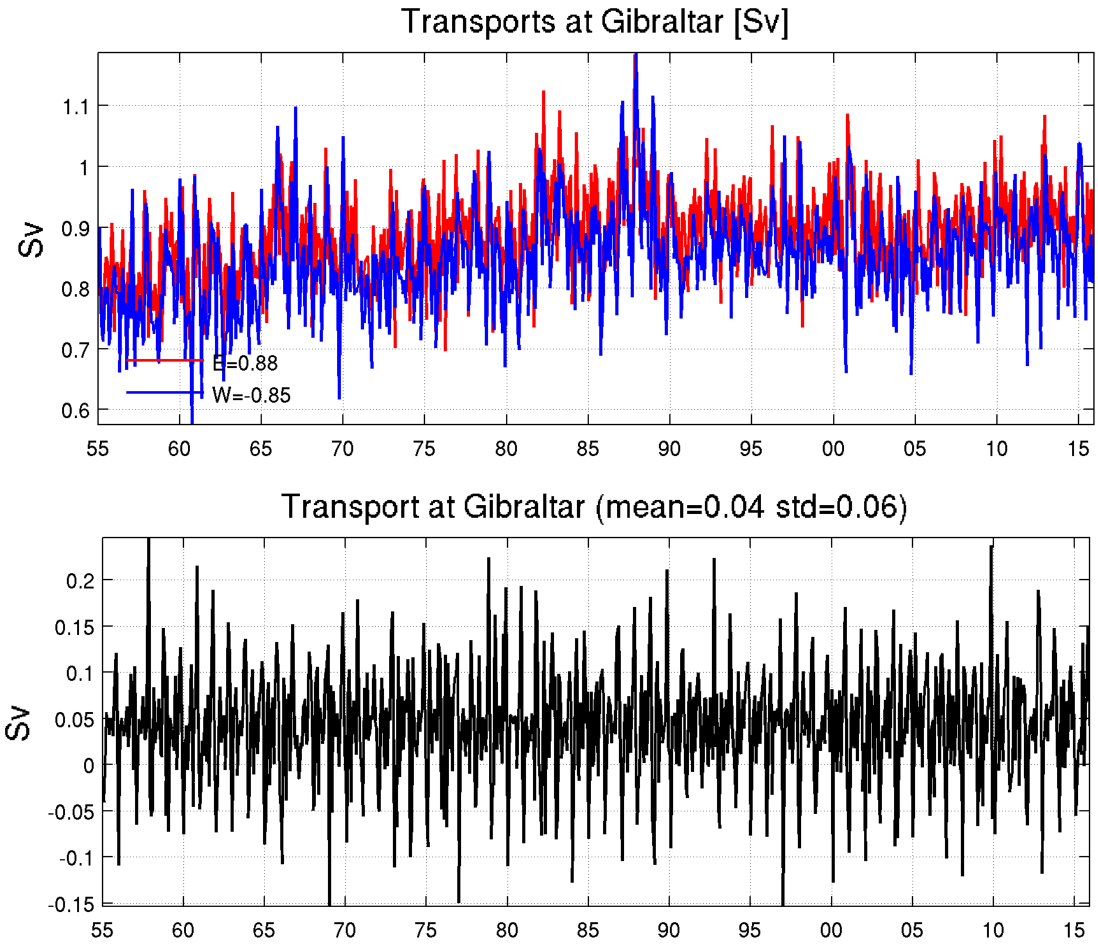

Figure 16: Gibraltar Net volume transport (upper) and its components (bottom).

3.6 Circulation structure quality

The general circulation structure has been evaluated considering the following metric:

Class1: Maps of Mediterranean Sea surface mean currents at 15m depth computed over different time periods.

Figure 17 displays maps of surface mean currents at 15m of depth computed from the reanalysis product over two different time periods, 1987-1996 and 1997-2006, in order to study the decadal variability of the Mediterranean Sea circulation as in *Pinardi et al., 2015*. The mean surface circulation is in agreement with literature results and presents the well-known Mediterranean surface circulation features.

The changes between 1987-1996 and 1997-2006 occur in the Alboran Sea and in the Tyrrhenian Sea (Western Mediterranean), while the circulation becomes stronger in the Eastern Mediterranean Sea. The major change occurred in the Eastern Mediterranean where a current reversal took place in the Northern Ionian Sea related to the Eastern Mediterranean Transient phenomena.

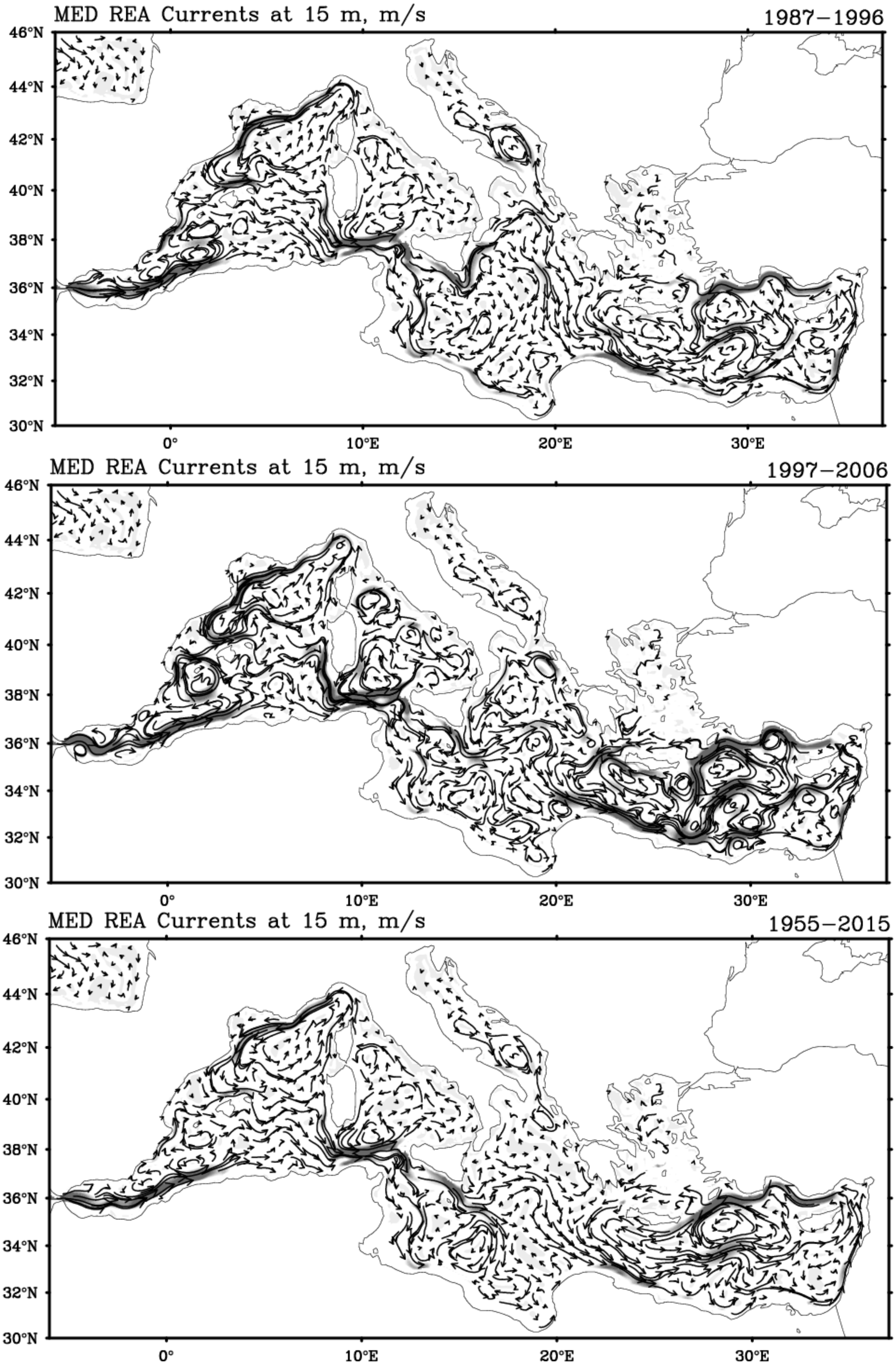

Figure 17: Mean circulation at 15m for different time averaging periods.

4 Conclusions

The quality of the RR has been assessed for the period 1955 to 2015 by comparing results with available observations, consolidated climatological products and current knowledge of the ocean circulation.
The quality of the product changes proportionally to the data availability, as shown in the assessment of ocean state variables (salinity, temperature and sea level anomaly), and the performance of the reanalysis increased with time, partially due to the number of assimilated ocean observations.
The product quality suggests that the overall performance of the reanalysis is satisfactory: the ocean state is well constrained by the observations and the ocean physics represents the major climatic change occurred between the 1980s and 1990s in the Northern Ionian Sea.

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