

Mediterranean Sea Production Centre MEDSEA_ANALYSIS_FORECAST_PHY_006_013

Issue: 1.4

Contributors: E. Clementi, A. Grandi, V. Lyubartsev, R. Escudier, J. Pistoia

Approval date by the CMEMS product quality coordination team: 21/12/2020

CHANGE RECORD

When the quality of the products changes, the Quid is updated and a row is added to this table. The third column specifies which sections or sub-sections have been updated. The fourth column should mention the version of the product to which the change applies.

Issue	Date	§	Description of Change	Author	Validated By
1.0	25-09-2017	All	Release of EAS2 version of the Med-Currents analysis and forecast product at 1/24° resolution	E. Clementi, A. Grandi, P. DiPietro, J. Pistoia, D. Delrosso, G. Mattia	Mercator Ocean
1.1	18-01-2018	All	Release of EAS3 version of the Med-Currents analysis and forecast product at 1/24° resolution	E. Clementi, A. Grandi, P. DiPietro, J. Pistoia, D. Delrosso, G. Mattia	Mercator Ocean
1.2	28-01-2019	All	Release of EAS4 version of the Med-Currents analysis and forecast product at 1/24° resolution	E. Clementi, A. Grandi, R. Escudier, V. Lyubartsev	Mercator Ocean
1.3	06-12-2019	All	Release of EAS5 version of the Med-Currents analysis and forecast product at 1/24° resolution	E. Clementi, A. Grandi, V. Lyubartsev	Mercator Ocean
1.4	10-09-2020	II.1 II.2 II.3 V	Use of higher resolution ECMWF atmospheric forcing	E. Clementi, A. Grandi, J. Pistoia	E. Clementi

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I EXECUTIVE SUMMARY

I.1 Products covered by this document

The product covered by this document is the MEDSEA_ANALYSIS_FORECAST_PHY_006_013: the analysis and forecast nominal product of the physical component of the Mediterranean Sea with 1/24° (~4.5 km) horizontal resolution and 141 vertical levels.

The variables produced are:

- 3D daily, hourly and monthly mean fields of: Potential Temperature, Salinity, Zonal and Meridional Velocity
- 2D daily, hourly and monthly mean fields of: Sea Surface Height, Mixed Layer Depth, Seabed Temperature (temperature of the deepest layer or level)

Product reference:

Clementi E., Pistoia J., Escudier R., Delrosso D., Drudi M., Grandi A., Lecci R., Cretí S., Ciliberti S., Coppini, G. Masina S. & N. Pinardi (2019). *Mediterranean Sea Analysis and Forecast (CMEMS MED-Currents EAS5 system, 2017-2020)* [Data set]. Copernicus Monitoring Environment Marine Service (CMEMS). https://doi.org/10.25423/CMCC/MEDSEA_ANALYSIS_FORECAST_PHY_006_013_EAS45

I.2 Summary of the results

The quality of the MEDSEA_ANALYSIS_FORECAST_PHY_006_013 analysis and forecast product provided by the EAS5 modelling system, is assessed over 1 year period from 01/01/2017 to 31/12/2017 by means of temperature, salinity, sea level anomaly, sea surface height, currents, seabed temperature and mixed layer depth using independent (for surface currents), quasi-independent satellite and in-situ observations, climatological datasets as well as the inter-comparison with the previous version of the MEDSEA_ANALYSIS_FORECAST_PHY_006_013 product timeseries corresponding to the EAS5 modelling system.

The main results of the MEDSEA_ANALYSIS_FORECAST_PHY_006_013 quality assessment are summarized below:

Sea Surface Height: the EAS5 system presents a similar accuracy in terms of sea surface height representation with respect to the previous version. The quality of the predicted SLA has been assessed by considering the RMS differences between the model daily outputs and the satellite along track observations, which is in average about 4cm.

Temperature: the temperature is accurate with an error below 0.8°C when comparing to vertical in-situ observations at surface and below 0.7°C when comparing SST to satellite observations. The accuracy of the temperature along the water column presents higher RMS differences at first layers, which decreases below 60 m. Considering the SST, the RMS differences with respect to satellite observations vary according to the different areas of the basin, ranging from 0.5°C to 0.7°C. The MED-Currents products usually have a warm SST bias. Med-Currents EAS4 and EAS5 systems exhibit similar skill in terms of surface temperature when comparing with satellite.

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Salinity: the salinity is accurate with RMS values lower than 0.22 PSU. The error is higher in the first layers and decreases significantly below 150 m. The EAS4 and EAS5 systems present very similar skill in predicting the salinity.

Currents: Surface currents RMS and bias are evaluated with respect to moored buoys and due to the reduced number of observations mainly located in coastal areas the statistical relevance of currents performance is poor. In addition to the surface currents validation assessment, a derived validation assessment is provided in terms of transport at Straits including the net, eastward and westward transport through the Strait of Gibraltar showing a good agreement with literature values.

Bottom temperature: the bottom temperature of EAS5 system has been compared to SeaDataNet monthly climatologies showing a good skill in representing the seasonal variability of the temperature at deepest level and a general overestimation with respect to the climatological dataset. The spatial pattern of the seabed temperature is correctly represented by the system and is unchanged with respect to the previous system.

Mixed Layer Depth: the MLD predicted by EAS5 system has been compared to climatological values from literature (Houpert et al., 2015) showing that the model is able to correctly represent the depth of the mixed layer with spatial and seasonal differences. In general, it can be noticed that the main differences could arise from the low resolution of the climatological dataset that moreover do not cover the whole domain of the Mediterranean Sea.

I.3 Estimated Accuracy Numbers

Estimated Accuracy Numbers (EANs), that are the mean and the RMS of the difference between the model and in-situ or satellite reference observations, are provided in the following table.

EAN are computed for:

- Temperature;
- Salinity;
- Sea Surface Temperature (SST);
- Sea Level Anomaly (SLA).

The observations used are:

- vertical profiles of temperature and salinity from Argo, XBTs and Gliders floats: INSITU_MED_TS_NRT_OBSERVATIONS_013_035
- SST satellite data from CMEMS SST-TAC product: SST_MED_SST_L4_NRT_OBSERVATIONS_010_004
- Satellite Sea Level along track data from CMEMS SL-TAC product: SEALEVEL_MED_SLA_L3_NRT_OBSERVATIONS_008_019
SEALEVEL_MED_SLA_ASSIM_L3_NRT_OBSERVATIONS_008_021
SEALEVEL_MED_PHY_ASSIM_L3_NRT_OBSERVATIONS_008_048

The EANs are evaluated for the EAS4 and EAS5 systems over 1 year period from January to December 2017 and are computed over 9 vertical layers (for temperature and salinity) and for the Mediterranean Sea and 16 sub-regions Figure 1: (1) Alboran Sea, (2) South West Med 1 (western part), (3) North West Med, (4) South West Med 2 (eastern part), (5) Tyrrhenian Sea 2 (southern part), (6) Tyrrhenian Sea 1

(northern part), (7) Ionian Sea 1 (western part), (8) Ionian Sea 2 (south-eastern part), (9) Ionian Sea 2 (north-eastern part), (10) Adriatic Sea 2 (southern part), (11) Adriatic Sea 1 (northern part), (12) Levantine Sea 1 (western part), (13) Aegean Sea, (14) Levantine Sea 2 (central-northern part), (15) Levantine Sea 3 (central southern part), (16) Levantine Sea 4 (eastern part).

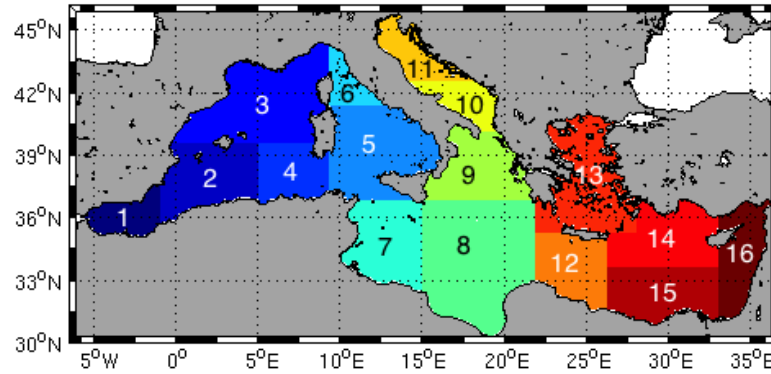


Figure 1. The Mediterranean Sea sub-regions subdivision for validation metrics

EANs of temperature and salinity are then evaluated at 9 different layers: 0-10, 10-30, 30-60, 60-100, 100-150, 150-300, 300-600, 600-1000, 1000-2000 [m] in order to better verify the model ability to represent the vertical structure of the temperature and salinity fields.

In the following tables the EANs (Mean and RMS Difference) for the EAS5 system are presented.

T prod - T ref [°C]	EAS5 system	
Layer (m)	Mean	RMSD
0-10	0.02	0.54
10-30	0.00	0.80
30-60	0.08	0.78
60-100	0.05	0.50
100-150	0.02	0.33
150-300	0.00	0.26
300-600	-0.01	0.23
600-1000	0.02	0.10
1000-2000	0.00	0.05

Table 1: EANs of temperature at different vertical layers evaluated for EAS5 system for the year 2017

SST prod – SST ref [°C]	EAS5 system	
REGION	Mean	RMSD
MED SEA	0.20	0.56
REGION 1	-0.02	0.62
REGION 2	0.08	0.53
REGION 3	0.04	0.59
REGION 4	0.17	0.49
REGION 5	0.38	0.57
REGION 6	0.29	0.54
REGION 7	0.36	0.55
REGION 8	0.18	0.50
REGION 9	0.28	0.56
REGION 10	0.42	0.66
REGION 11	0.35	0.70
REGION 12	-0.05	0.52
REGION 13	0.17	0.59
REGION 14	0.33	0.63
REGION 15	0.15	0.50
REGION 16	0.34	0.55

Table 2: EANs of Sea Surface Temperature evaluated for EAS5 system for the year 2017 for the Mediterranean Sea and 16 regions (see Figure 1).

S prod – S ref [PSU]	EAS5 system	
Layer (m)	Mean	RMSD
0-10	-0.02	0.22
10-30	-0.02	0.21
30-60	-0.02	0.18
60-100	-0.01	0.15
100-150	-0.00	0.13
150-300	-0.00	0.07
300-600	-0.01	0.05
600-1000	-0.01	0.04
1000-2000	-0.01	0.03

Table 3: EANs of salinity at different vertical layers evaluated for EAS5 system for year 2017.

SLA prod – SLA ref [cm]	EAS4 system	EAS5 system
REGION	RMSD	RMSD
MED SEA	3.9	3.9
REGION 1	5.0	5.0
REGION 2	4.1	4.2
REGION 3	3.6	3.6
REGION 4	3.9	3.7
REGION 5	3.1	3.1
REGION 6	3.9	3.8
REGION 7	4.5	4.0
REGION 8	4.2	4.0
REGION 9	3.8	3.7
REGION 10	2.2	2.4
REGION 11	NA	Nan
REGION 12	4.4	4.3
REGION 13	3.6	3.5
REGION 14	3.5	3.5
REGION 15	4.7	4.9
REGION 16	3.4	3.4

Table 4: EANs of Sea Level evaluated for EAS4 and EAS5 systems for year 2017 for the Mediterranean Sea and 16 regions (see Figure 1).

The metrics of Table 1 and Table 2 give indications about the accuracy of MEDSEA_ANALYSIS_FORECAST_PHY_006_013 temperature variable along the water column and at the surface for the Mediterranean Sea and 16 sub-regions. The values for all the vertical levels are computed using Argo profiles while the SST is evaluated by comparing with satellite observations. The temperature RMS and MEAN values are higher at the first levels and decrease significantly below the fourth layer. The error is always lower than 0.8°C along the water column, while it ranges between 0.50 and 0.70°C considering the SST.

The statistics listed in Table 3 give indications about the accuracy of the MEDSEA_ANALYSIS_FORECAST_PHY_006_013 salinity field. The values for all the levels are computed using Argo profiles. The skill of the system presents a RMS difference always lower than 0.22 PSU with higher error at surface which decreases below 150 m.

The metrics shown in Table 4 define the accuracy of MEDSEA_ANALYSIS_FORECAST_PHY_006_013 sea level anomaly. The statistics are computed along the satellite tracks. The new system presents an overall RMS difference lower than 4 cm in the whole basin, while it ranges between 2.4 and 5.0 cm in the different regions. Region 11 presents no data since the SLA data assimilation scheme (using the dynamic height) prevents the assimilation of data in areas shallower than 1000 m.

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II PRODUCTION SYSTEM DESCRIPTION

Production centre name: CMCC

Production system name: Analysis and Forecast Med-Currents EAS5 system

CMEMS Product name: MEDSEA_ANALYSIS_FORECAST_PHY_006_013

External product: Temperature (3D), Salinity (3D), Meridional and Zonal Currents (3D), Sea Surface Height (2D), Mixed Layer Depth (2D), Seabed Temperature (2D)

Frequency of model output: daily (24-hrs) averages, hourly (1-hr) averages, monthly averages

Geographical coverage: -17.2917°W → 36.29167°E; 30.1875°N → 45.97917°N (Gulf of Biscay and Black Sea are excluded)

Horizontal resolution: 1/24°

Vertical coverage: From surface to 5754 m (141 vertical unevenly spaced levels).

Length of forecast: 10 days for the daily mean fields, 5 days for the hourly mean fields.

Frequency of forecast release: Daily.

Analyses: Yes.

Hindcast: Yes.

Frequency of analysis release: Weekly on Tuesday.

Frequency of hindcast release: Daily.

The Analyses and forecasts physical product of the Med-MFC is produced with two different cycles: a daily cycle for the production of forecast data, and a weekly cycle for the production of analysis data.

The daily cycle is done each day (J), for the next 10 days. The forecast is initialized by a hindcast every day except Tuesday, when the analysis is used instead of the hindcast. Every day the product is updated with a hindcast for day J-1 and 10-day forecast.

The weekly cycle is done on Tuesday, for the previous 15 days. The assimilation cycle is daily (24hr) and is done in filter mode. Every Wednesday the product is updated with the analyses from day J-15 to day J-2, a hindcast for day J-1 and 10-day forecast.

The production chain is illustrated in Figure 2.

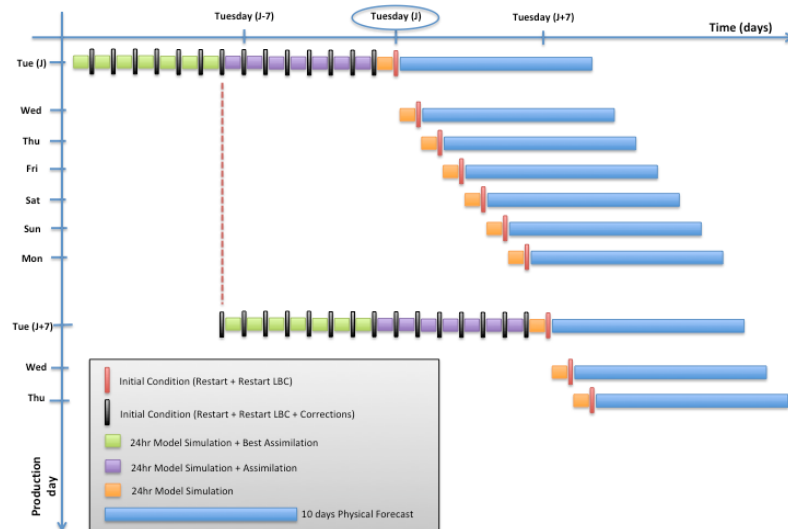


Figure 2: Scheme of the analysis and forecast CMEMS Med-Currents processing chain.

The Med-Currents system run is composed by several steps:

1. Upstream Data Acquisition, Pre-Processing and Control of: ECMWF atmospheric forcing (Numerical Weather Prediction), Satellite (SLA and SST) and in-situ (T and S) data.
2. Forecast/Hindcast: NEMO-WW3 modelling system is run to produce one day of hindcast and 10-day forecast.
3. Analysis/Hindcast (only on Tuesday): NEMO-WW3 modelling system is combined with a 3DVAR assimilation scheme in order to produce the best estimation of the sea (i.e. analysis). The NEMO+WW3+3DVar system is running for 15 days into the past in order to use the best available along track SLA products. The latest day of the 15 days of analyses, produces the initial condition for the 10-day forecast.
4. Post processing: the model output is processed in order to obtain the products for the CMEMS catalogue.
5. Output Delivery.

II.1 Description of the Med-Currents EAS5 model system

The Mediterranean Forecasting System, MFS, (Pinardi et al., 2003, Pinardi and Coppini 2010, Tonani et al., 2014) is providing, since year 2000, analysis and short-term forecast of the main physical parameters in the Mediterranean Sea and it is the physical component of the Med-MFC called Med-Currents.

The analysis and forecast Med-Currents system at CMEMS EAS5 is provided by means of a coupled hydrodynamic-wave model implemented over the whole Mediterranean basin and extended into the Atlantic Sea in order to better resolve the exchanges with the Atlantic Ocean at the Strait of Gibraltar. The model horizontal grid resolution is $1/24^\circ$ (ca. 4.5 km) and has 141 unevenly spaced vertical levels.

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The hydrodynamics are supplied by the Nucleus for European Modelling of the Ocean (NEMO v3.6) while the wave component is provided by WaveWatch-III. The model solutions are corrected by the variational assimilation (based on a 3DVAR scheme) of temperature and salinity vertical profiles and along track satellite Sea Level Anomaly observations.

Circulation model component (NEMO)

The oceanic equations of motion of Med-currents system are solved by an Ocean General Circulation Model (OGCM) based on NEMO (Nucleus for European Modelling of the Ocean) version 3.6 (Madec et al., 2016). The code is developed and maintained by the NEMO-consortium.

NEMO has been implemented in the Mediterranean at $1/24^\circ \times 1/24^\circ$ horizontal resolution and 141 unevenly spaced vertical levels (Clementi et al., 2017a) with time step of 240sec. The model covers the whole Mediterranean Sea and also extends into the Atlantic in order to better resolve the exchanges with the Atlantic Ocean at the Strait of Gibraltar.

The NEMO code solves the primitive equations using the time-splitting technique that is the external gravity waves are explicitly resolved with non-linear free surface formulation and time-varying vertical z-star coordinates.

The advection scheme for active tracers, temperature and salinity, is a mixed up-stream/MUSCL (Monotonic Upwind Scheme for Conservation Laws; Van Leer, 1979), originally implemented by Estubier and Lévy (2000) and modified by Oddo et al. (2009). The vertical diffusion and viscosity terms are a function of the Richardson number as parameterized by Pacanowsky and Philander (1981).

The model interactively computes air-surface fluxes of momentum, mass, and heat. The bulk formulae implemented are described in Pettenuzzo et al. (2010) and are currently used in the Mediterranean operational system (Tonani et al., 2015). A detailed description of other specific features of the model implementation can be found in Oddo et al. (2009, 2014).

The vertical background viscosity and diffusivity values are set to $1.2\text{e-}6 \text{ [m}^2/\text{s]}$ and $1.0\text{e-}7 \text{ [m}^2/\text{s]}$ respectively, while the horizontal bilaplacian eddy diffusivity and viscosity are set respectively equal to $-1.2\text{e}8 \text{ [m}^4/\text{s]}$ and $-2.\text{e}8 \text{ [m}^4/\text{s]}$. A quadratic bottom drag coefficient with a logarithmic formulation has been used according to Maraldi et al. (2013) and the model uses vertical partial cells to fit the bottom depth shape.

The hydrodynamic model is nested in the Atlantic within the Global analysis and forecast system GLO-MFC daily data set ($1/12^\circ$ horizontal resolution, 50 vertical levels) that is interpolated onto the Med-Currents model grid. Details on the nesting technique and major impacts on the model results are in Oddo et al., 2009.

The model is forced by momentum, water and heat fluxes interactively computed by bulk formulae using the $1/10^\circ$ horizontal-resolution operational analysis and forecast fields from the European Centre for Medium-Range Weather Forecasts (ECMWF) at highest available time frequency (1 hour for the first 3 days of forecast, 3 hours for the following 3 days of forecast and 6 hours for the last 4 days of forecast and for the analysis) and the model predicted surface temperatures (details of the air-sea physics are in Tonani et al., 2008). The water balance is computed as Evaporation minus Precipitation and Runoff. The evaporation is derived from the latent heat flux, precipitation is provided by ECMWF as daily averages, while the runoff of the 39 rivers implemented 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 Raichich (1996) for: Vjosë, 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

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river; the PERSEUS dataset for the following 32 rivers: Piave, Tagliamento, Soca/Isonzo, Livenza, Brenta-Bacchiglione, Adige, Lika, Reno, Krka, Arno, Nerveta, Aude, Trebisjnica, Tevere/Tiber, Mati, Volturno, Shkumbini, Struma/Strymonas, Meric/Evros/Maritsa, Axios/Vadar, Arachtos, Pinios, Acheloos, Gediz, Buyuk Menderes, Kopru, Manavgat, Seyhan, Ceyhan, Gosku, Medjerda, Asi/Orontes.

The Dardanelles Strait is implemented as a lateral open boundary condition by using GLO-MFC daily Analysis and Forecast product and daily climatology derived from a Marmara Sea box model (Maderich et al., 2015).

The topography is created starting from the GEBCO 30arc-second grid (http://www.gebco.net/data_and_products/gridded_bathymetry_data/gebco_30_second_grid/), filtered (using a Shapiro filter) and manually modified in critical areas such as: islands along the Eastern Adriatic coasts, Gibraltar and Messina straits, Atlantic box edge.

Wave model component (WW3)

The Wave dynamic is solved by a Mediterranean implementation of the WaveWatch-III (WW3) code version 3.14 (Tolman, 2009). WaveWatch covers the same domain and follows the same horizontal discretization of the circulation model ($1/24^\circ \times 1/24^\circ$) with a time step of 300 sec. The wave model uses 24 directional bins (15° directional resolution) and 30 frequency bins (ranging between 0.05 Hz and 0.7931 Hz) to represent the wave spectral distribution.

WW3 has been forced by the same $1/10^\circ$ horizontal resolution ECMWF atmospheric forcings (the same used to force the hydrodynamic model). The wind speed is then modified by considering a stability parameter depending on the air-sea temperature difference according to Tolman (2002).

The wave model takes into consideration the surface currents for wave refraction but assumes no interactions with the ocean bottom. WW3 model solves the wave action balance equation that describes the evolution, in slowly varying depth domain and currents, of a 2D ocean wave spectrum where individual spectral component satisfies locally the linear wave theory. In the present application WW3 has been implemented following WAM cycle4 model physics (Gunther et al., 1993). Wind input and dissipation terms are based on Janssen's quasi-linear theory of wind-wave generation (Janssen, 1989, 1991). The dissipation term is based on Hasselmann (1974) whitecapping theory according to Komen et al. (1984). The non-linear wave-wave interaction is modelled using the Discrete Interaction Approximation (DIA, Hasselmann et al., 1985).

Model coupling (NEMO-WW3)

The coupling between the hydrodynamic model (NEMO) and the wave model (WW3) is achieved by an online hourly two-way coupling and consists in exchanging the following fields: NEMO sends to WW3 the air-sea temperature difference and the surface currents, while WW3 sends to NEMO the neutral drag coefficient used to evaluate the surface wind stress.

More details on the model coupling and on the impact of coupled system on both wave and circulation fields can be found in Clementi et al. (2017b).

Data Assimilation scheme

The data assimilation system is the 3DVAR scheme developed by Dobricic and Pinardi (2008) and modified by Storto et al. (2015). The background error correlation matrices vary monthly for each grid point in the discretized domain of the Mediterranean Sea. Observational error covariance matrix is evaluated with Desroziers et al. (2005) relationship. EOFs have been evaluated from a three years simulation run (in the future a new set of EOFs will be evaluated from an analysis run).

The assimilated data include: along track Sea Level Anomaly (a satellite product accounting for atmospheric pressure effect is used, as specified in II.3) from CLS SL-TAC, and in-situ vertical temperature and salinity profiles from VOS XBTs (Voluntary Observing Ship-eXpandable Bathythermograph) and ARGO floats. Objective Analyses-Sea Surface Temperature (OA-SST) fields from CNR-ISA SST-TAC are used for the correction of surface heat fluxes with the relaxation constant of $110 \text{ Wm}^{-2}\text{K}^{-1}$ applied close to midnight since the observed dataset corresponds to the foundation SST ($\sim$ SST at midnight).

II.2 New features of the Med-Currents EAS5 system

The main differences between the CMEMS Med-Currents EAS4 and EAS5 systems are summarized in Table 5 and described hereafter.

	CMEMS Med-Currents EAS4	CMEMS Med-Currents EAS5
Model outputs	Daily outputs centred at 00.00 UTC	Daily outputs centred at 12.00 UTC
Forecast initial time	12.00 UTC	00.00 UTC
Initial conditions	Temperature and Salinity at 1/1/2016 from winter climatological fields from WOA13 V2 (World Ocean Atlas 2013 V2)	Temperature and Salinity at 1/1/2015 from winter climatological fields from WOA13 V2 (World Ocean Atlas 2013 V2)

Table 5: Differences between CMEMS Med-Currents EAS4 and EAS5 systems.

The main differences between CMEMS EAS4 and CMEMS EAS5 are:

- Daily outputs centred at 12.00 UTC: In the EAS5 new modelling system, the daily runs are initialized at 00.00 UTC (instead of 12.00 UTC as in EAS4 previous modelling system) so the daily outputs are centred at 12.00 UTC (instead of 00.00 UTC as in EAS4 previous modelling system)
- Daily forecasts are initialized at 00.00 UTC (instead of 12.00 UTC as in EAS4 previous modelling system)
- Initial conditions: the run has been initialized on the 1st January 2015 (instead of 1st January 2016 as in EAS4 previous modelling system) using Temperature and Salinity from winter climatological fields from WOA13 V2 (World Ocean Atlas 2013 V2).

Starting from December 2020, the EAS5 system has been upgraded by using higher spatial and temporal resolution ECMWF atmospheric forcing:

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- Horizontal resolution: from 0.125° to 0.10°
- Temporal frequency:
 - Analysis: 6 hours (no changes)
 - Forecast day 1 to 3: from 3 hours to 1 hour
 - Forecast day 4 to 6: from 6 hours to 3 hours
 - Forecast day 7 to 10: 6 hours (no changes)

The quality assessment of the daily analysis physical fields (which is presented in this document) carried out using the higher resolution atmospheric forcing, has provided no significantly changes with respect to the previous system.

II.3 Upstream data and boundary condition of the NEMO-3DVAR system

The CMEMS MED-Currents system uses the following upstream data:

1. Atmospheric forcing (including precipitation): NWP 6-h (1-h for the first 3 days of forecast, 3-h for the following 3 days of forecast), 0.10° horizontal-resolution operational analysis and forecast fields from the European Centre for Medium-Range Weather Forecasts (ECMWF) distributed by the Italian National Meteo Service (USAM/CNMA)
2. Runoff: Global Runoff Data Centre dataset (Fekete et al., 1999) for Po, Ebro, Nile and Rhone, the dataset from Raicich (Raicich, 1996) for the Adriatic rivers Vjosë and Seman; 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 PERSEUS project dataset for the new 32 rivers added.
3. Initial conditions of temperature and salinity at 1/1/2015 are the winter climatological fields from WOA13 V2 (World Ocean Atlas 2013 V2, <https://www.nodc.noaa.gov/OC5/woa13/woa13data.html>)
4. Lateral boundary conditions from CMEMS Global Analysis and Forecast system: GLOBAL_ANALYSIS_FORECAST_PHY_001_024 at 1/12° horizontal resolution, 50 vertical levels.
5. Data assimilation:
 - Temperature and Salinity vertical profiles from CMEMS INSITU TAC
 - INSITU_MED_NRT_OBSERVATIONS_013_035
 - Satellite along track Sea Level Anomaly from CMEMS SL TAC:
 - SEALEVEL_MED_SLA_ASSIM_L3_NRT_OBSERVATIONS_008_021 (till 29th March 2017)
 - SEALEVEL_MED_SLA_L3_NRT_OBSERVATIONS_008_019 (till 30th March 2017)
 - SEALEVEL_MED_PHY_ASSIM_L3_NRT_OBSERVATIONS_008_048 (from 1st June 2017).
 - SEALEVEL_EUR_PHY_L3_NRT_OBSERVATIONS_008_059 (from May 2019)
 - Satellite SST from CMEMS SST TAC (nudging):
 - SST_MED_SST_L4_NRT_OBSERVATIONS_010_004

III VALIDATION FRAMEWORK

In order to evaluate and assure the quality of the MEDSEA_ANALYSIS_FORECAST_PHY_006_013 product, an assimilation experiment has been performed using the system described in section II, which is going to be operational starting in December 2020, and covering 3 years from January 2015 to December 2018 (the period from January to December 2015 is considered as a spin-up time).

In particular, the qualification task has been carried out over 1 year period, from January to December 2017, based on Class 1, Class2 and 4 diagnostics.

The performance of the Med-Currents EAS5 new system has been assessed by using external products: quasi-independent satellite and in-situ observations have been used to assess the skill of temperature, salinity and sea level anomaly; independent fixed moorings have been used to qualify coastal currents; moreover, climatological datasets have been used to assess the quality of the seabed temperature and mixed layer depth.

Quasi-independent data are all the observations (Satellite SLA and SST and in situ vertical profiles of temperature and salinity from XBT and Argo) which are assimilated into the system. Diagnostic in terms of RMS of the misfits and/or bias are computed.

The datasets of observations used for the qualification task are listed below in Table 6 presenting the lists of the used quasi-independent data with the corresponding CMEMS product names.

QUASI-INDEPENDENT DATA	
TYPE	CMEMS PRODUCT NAME
ARGO, XBT, GLIDERS	INSITU_MED_NRT_OBSERVATIONS_013_035
SLA	SEALEVEL_MED_SLA_L3_NRT_OBSERVATIONS_008_019 SEALEVEL_MED_SLA_ASSIM_L3_NRT_OBSERVATIONS_008_021 SEALEVEL_MED_PHY_ASSIM_L3_NRT_OBSERVATIONS_008_048 SEALEVEL_EUR_PHY_L3_NRT_OBSERVATIONS_008_059
SST	SST_MED_SST_L4_NRT_OBSERVATIONS_010_004_a

Table 6: list of the quasi-independent observations

In this section the results of the validation task are presented in terms of: Temperature (including SST), Sea Bottom Temperature, Salinity, Sea Level Anomaly, Sea Surface Height, Currents (also in terms of transport at straits), and Mixed Layer Depth.

The list of metrics used to provide an overall assessment of the product, to quantify the differences with the available observations and to assess the improvements with respect to the previous system (CMEMS EAS4) is presented in Table 7.

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Name	Description	Ocean parameter	Supporting reference dataset	Quantity
NRT evaluation of Med-MFC-Currents using semi-independent data: Estimate Accuracy Numbers				
T-<X-Y>m-D-CLASS4-PROF-RMSD-Jan2017-Dec2017	Temperature vertical profiles comparison with CMEMS INSITU TAC data at 9 layers for the Mediterranean basin.	Temperature	Argo floats from the CMEMS INSITU TAC product: INSITU_MED_NRT_OBSERVATIONS_013_035	Time series of Temperature daily RMSs of the difference between model and insitu observations averaged over the qualification testing period (Jan-Dec 2017). This quantity is evaluated on the model analysis. The statistics are defined for all the Mediterranean Sea and are evaluated for 9 different layers (0-10, 10-30, 30-60, 60-100, 100-150, 150-300, 300-600, 600-1000, 1000-2000 m). Together with the time series, the time (2017) average RMSD value is reported in tables.
T-<X-Y>m-D-CLASS4-PROF-BIAS-Jan2017-Dec2017	Temperature vertical profiles comparison with CMEMS INSITU TAC data at 9 layers for the Mediterranean basin.	Temperature	Argo floats from the CMEMS INSITU TAC product: INSITU_MED_NRT_OBSERVATIONS_013_035	Time series of Temperature daily mean differences between model and insitu observations averaged over the qualification testing period (Jan-Dec 2017). This quantity is evaluated on the model analysis. The statistics are defined for all the Mediterranean Sea and are evaluated for 9 different layers (0-10, 10-30, 30-60, 60-100, 100-150, 150-300, 300-600, 600-1000, 1000-2000 m). Together with the time series, the time (2017) averaged BIAS value is reported in tables.
S-<X-Y>m-D-CLASS4-PROF-RMSD-Jan2017-Dec2017	Salinity vertical profiles comparison with CMEMS INSITU TAC data at 9 layers for the Mediterranean basin.	Salinity	Argo floats from the CMEMS INSITU TAC product: INSITU_MED_NRT_OBSERVATIONS_013_035	Time series of Salinity daily RMSs of the difference between model and insitu observations averaged over the qualification testing period (Jan-Dec 2017). This quantity is evaluated on the model analysis. The statistics are defined for all the Mediterranean Sea and are evaluated for 9 different layers (0-10, 10-30, 30-60, 60-100, 100-150, 150-300, 300-600, 600-1000, 1000-2000 m). Together with the time series, the time (2017) averaged RMSD value is reported in tables.

Table 7: List of metrics for Med-Currents evaluation using in-situ and satellite observation (continues overleaf).

Name	Description	Ocean parameter	Supporting reference dataset	Quantity
NRT evaluation of Med-MFC-Currents using semi-independent data: Estimate Accuracy Numbers				
S-<X-Y>m-D-CLASS4-PROF-BIAS-Jan2017-Dec2017	Salinity vertical profiles comparison with CMEMS INSITU TAC data at 9 layers for the Mediterranean basin.	Salinity	Argo floats from the CMEMS INSITU TAC product: INSITU_MED_NRT_OBSERVATIONS_013_035	Time series of Salinity daily mean differences between model and insitu observations averaged over the qualification testing period (Jan-Dec 2017). This quantity is evaluated on the model analysis. The statistics are defined for all the Mediterranean Sea and are evaluated for 9 different layers (0-10, 10-30, 30-60, 60-100, 100-150, 150-300, 300-600, 600-1000, 1000-2000 m). Together with the time series, the time (2017) averaged BIAS value is reported in tables.
SLA-D-CLASS4-ALT-RMSD-Jan2017-Dec2017	Sea level anomaly comparison with CMEMS Sea Level TAC (satellite along track) data for the Mediterranean basin and selected sub-basins.	Sea Level Anomaly	Satellite Sea Level along track data from CMEMS Sea Level TAC product: SEALEVEL_MED_SLA_L3_NRT_OBSERVATIONS_008_019 SEALEVEL_MED_SLA_ASSIM_L3_NRT_OBSERVATIONS_008_021 SEALEVEL_MED_PHY_ASSIM_L3_NRT_OBSERVATIONS_008_048	Time series of Sea level daily RMSs of the difference between model and satellite observations averaged over the qualification testing period (Jan-Dec 2017). This quantity is evaluated on the model analysis. The statistics are defined for all the Mediterranean Sea and 16 selected sub-basins. Together with the time series, the time (2017) average RMSD value is reported in tables.
SST-D-CLASS4-RAD-RMSD-Jan2017-Dec2017	Sea Surface Temperature comparison with SST CMEMS SST TAC L4 (satellite) data for the Mediterranean basin and selected sub-basins.	Sea Surface Temperature	SST satellite data from CMEMS SST TAC L4 product: SST_MED_SST_L4_NRT_OBSERVATIONS_010_004	Time series of Sea surface temperature daily RMSs of the difference between model and satellite observations averaged over the qualification testing period (Jan-Dec 2017). This quantity is evaluated on the model analysis. The statistics are defined for all the Mediterranean Sea and 16 selected sub-basins. Together with the time series, the time (2017) average RMSD value is reported in tables.
SST-D-CLASS4-RAD-BIAS-Jan2017-Dec2017	Sea Surface Temperature comparison with SST CMEMS SST TAC L4 (satellite) data for the Mediterranean basin and selected sub-basins.	Sea Surface Temperature	SST satellite data from CMEMS SST TAC L4 product: SST_MED_SST_L4_NRT_OBSERVATIONS_010_004	Time series of Sea surface temperature daily mean differences between model and satellite observations averaged over the qualification testing period (Jan-Dec 2017). This quantity is evaluated on the model analysis. The statistics are defined for all the Mediterranean Sea and 16 selected sub-basins. Together with the time series, the time (2017) average BIAS value is reported in tables.

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Name	Description	Ocean parameter	Supporting reference dataset	Quantity
NRT evaluation of Med-MFC-Currents using semi-independent data. Weekly comparison of misfits				
T-<X-Y>m-W-CLASS4- PROF-RMSD-MED- Jan2017-Dec2017	Temperature vertical profiles comparison with assimilated CMEMS INSITU TAC data at 5 specified depths.	Temperature	Argo floats and XBT from the CMEMS INSITU TAC products: INSITU_MED_NRT_OBSERVATIONS_013_035	Time series of weekly RMSs of temperature misfits (observation minus model value transformed at the observation location and time). Together with the time series, the average value of weekly RMSs is evaluated over the qualification testing period (2017). The statistics are defined for all the Mediterranean Sea and are evaluated at five different depths: 8, 30, 150, 300 and 600 m.
S-<X-Y>m-W-CLASS4- PROF-RMSD-MED- Jan2017-Dec2017	Salinity vertical profiles comparison with assimilated CMEMS INSITU TAC data at 5 specified depths.	Salinity	Argo floats from the CMEMS INSITU TAC products: INSITU_MED_NRT_OBSERVATIONS_013_035	Time series of weekly RMSs of salinity misfits (observation minus model value transformed at the observation location and time). Together with the time series, the average value of weekly RMSs is evaluated over the qualification testing period (2017). The statistics are defined for all the Mediterranean Sea and are evaluated at five different depths: 8, 30, 150, 300 and 600 m.
SLA-SURF-W-CLASS4- ALT-RMSD-MED- Jan2017-Dec2017	Sea level anomaly comparison with assimilated CMEMS Sea Level TAC satellite along track data for the Mediterranean basin.	Sea Level Anomaly	Satellites (Jason2, Jason2N, Jason3, CryoSat-2, Saral/Altika, Sentinel3) Sea Level along track data from CMEMS Sea Level TAC products: SEALEVEL_MED_SLA_L3_NRT_OBSERVATIONS_008_019 SEALEVEL_MED_SLA_ASSIM_L3_NRT_OBSERVATIONS_008_021 SEALEVEL_MED_PHY_ASSIM_L3_NRT_OBSERVATIONS_008_048	Time series of weekly RMSs of sea level anomaly misfits (observation minus model value transformed at the observation location and time). Together with the time series, the average value of weekly RMSs is evaluated over the qualification testing period (2017). The statistics are defined for all the Mediterranean Sea and are evaluated for the different assimilated satellites.

Table 7: (continued) List of metrics for Med-Currents evaluation using in-situ and satellite observations.

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Name	Description	Ocean parameter	Supporting reference dataset	Quantity
NRT evaluation of Med-MFC-Currents using semi-independent data. Depth-Time Monthly comparison of misfits (Hovmoller diagrams)				
T-<X-Y>m-M-CLASS4- PROF-RMSD-MED- Jan2017-Dec2017-HOV	Temperature depth-time comparison with assimilated CMEMS INSITU TAC between 0 and 900m.	Temperature	Argo floats and XBT from the CMEMS INSITU TAC products: INSITU_MED_NRT_OBSERVATIONS_013_035	Depth-Time (Hovmoller diagram) of monthly RMS temperature misfits (observation minus model value transformed at the observation location and time) evaluated over the qualification testing period (2017). The statistics are averaged over the whole Mediterranean Sea and are defined between 0 and 900m depth.
S-<X-Y>m-M-CLASS4- PROF-RMSD-MED- Jan2017-Dec2017-HOV	Salinity depth-time comparison with assimilated CMEMS INSITU TAC between 0 and 900m.	Salinity	Argo floats from the CMEMS INSITU TAC products: INSITU_MED_NRT_OBSERVATIONS_013_035	Depth-Time (Hovmoller diagram) of monthly RMS salinity misfits (observation minus model value transformed at the observation location and time) evaluated over the qualification testing period (2017). The statistics are averaged over the whole Mediterranean Sea and are defined between 0 and 900m depth.
NRT evaluation of Med-MFC-Currents using semi-independent data. 2D MAPS of Yearly comparison of misfits				
T-<X-Y>m-Y-CLASS4- PROF-RMSD-MED- Jan2017-Dec2017- 2DMAP	Temperature comparison with assimilated CMEMS INSITU TAC data at 5 specified depths.	Temperature	Argo floats and XBT from the CMEMS INSITU TAC products: INSITU_MED_NRT_OBSERVATIONS_013_035	2D MAPS of RMS temperature misfits (observation minus model value transformed at the observation location and time) averaged over the qualification testing period (2017). The statistics are defined for all the Mediterranean Sea and are evaluated at five different depths: 8, 30, 150, 300 and 600 m.
S-<X-Y>m-Y-CLASS4- PROF-RMSD-MED- Jan2017-Dec2017- 2DMAP	Salinity comparison with assimilated CMEMS INSITU TAC data at 5 specified depths.	Salinity	Argo floats from the CMEMS INSITU TAC products: INSITU_MED_NRT_OBSERVATIONS_013_035	2D MAPS of RMS salinity misfits (observation minus model value transformed at the observation location and time) averaged over the qualification testing period (2017). The statistics are defined for all the Mediterranean Sea and are evaluated at five different depths: 8, 30, 150, 300 and 600 m.
SLA-SURF-CLASS4- PROF-RMSD-MED- Jan2017-Dec2017- 2DMAP	Sea Level Anomaly comparison with assimilated CMEMS INSITU TAC.	Sea Level	Satellites (Jason2, Jason2N, Jason3, CryoSat-2, Saral/Altika, S3A) Sea Level along track data: SEALEVEL_MED_SLA_L3_NRT_OBSERVATIONS_008_019; SEALEVEL_MED_SLA_ASSIM_L3_NRT_OBSERVATIONS_008_021	2D MAPS of RMS Sea Level Anomaly misfits (observation minus model value transformed at the observation location and time) averaged over the qualification testing period (2017). The statistics are defined for all the Mediterranean Sea

Table 7: (continued) List of metrics for Med-Currents evaluation using in-situ and satellite observations.

Name	Description	Ocean parameter	Supporting reference dataset	Quantity
NRT evaluation of Med-MFC-Currents using independent data. Daily comparison with moorings				
UV-SURF-D-CLASS2-MOOR-RMSD-Jan2017-Dec2017	Surface currents comparison with CMEMS INSITU TAC	Currents	Moored buoys from CMEMS InSitu TAC products: INSITU_MED_NRT_OBSERVATIONS_013_035	Time series of daily sea surface currents of insitu observations and model outputs evaluated over the qualification testing period. Together with the time series, the average value of daily RMSs is evaluated over the qualification testing period. This quantity is evaluated on the model analysis.
UV-SURF-D-CLASS2-MOOR-BIAS-Jan2017-Dec2017	Surface currents comparison with CMEMS INSITU TAC	Currents	Moored buoys from CMEMS InSitu TAC products: INSITU_MED_NRT_OBSERVATIONS_013_035	Time series of daily sea surface currents of insitu observations and model outputs evaluated over the qualification testing period. Together with the time series, the average value of daily bias is evaluated over the qualification testing period. This quantity is evaluated on the model analysis.
NRT evaluation of Med-MFC-Currents using Climatological dataset				
MLD-D-CLASS1-CLIM-MEAN_M-MED	Mixed Layer Depth comparison with climatology from literature in the Mediterranean Sea	Mixed Layer Depth	Monthly climatology from literature (Houpert et al., 2015)	Comparison of climatological maps form model outputs and a climatological dataset (Houpert et al., 2015)
SBT-D-CLASS4-CLIM-MEAN_M-MED	Bottom Temperature comparison with a climatological dataset in the Mediterranean Sea	Sea Bottom Temperature	SeaDataNet EAS4 climatological datasets	Time series of monthly mean Sea Bottom Temperature from model outputs and SeaDataNetEAS4 climatologies. The time series are presented for the entire basin, for the area with topography < 500m and for the areas with topography < 1500m
SBT-D-CLASS1-CLIM-MEAN_M-MED	Bottom Temperature comparison with a climatological dataset in the Mediterranean Sea	Sea Bottom Temperature	SeaDataNet EAS4 climatological datasets	Comparison of climatological maps form model outputs and SeaDataNetEAS4 climatologies for the area with topography < 1500m

Table 7: (continued) List of metrics for Med-Currents evaluation using in-situ and satellite observations.

VALIDATION RESULTS

III.1 Temperature

In the following table are synthesised the values of the temperature Root Mean Square (RMS) differences and Bias calculated comparing the analysis of MEDSEA_ANALYSIS_FORECAST_PHY_006_013 product with quasi-independent data assimilated by the system (ARGO, CTD, /XBT and Satellite SST). The synthesis is based on 1 year period (2017) validation and provided at 5 depths (8, 30, 150, 300, 600 m) showing that the larger error is achieved at 30 m depth while below it is lower than 0.3°C.

Variables/estimated accuracy:	Metrics		Depth	Observation
SEA SURFACE TEMPERATURE (°C)	RMS Diff	BIAS		
	0.56±0.11	0.21±0.1	0	Satellite SST
TEMPERATURE (°C):	RMS Diff		Depth	Observation
	0.52±0.19		8	Argo
	0.77±0.47		30	Argo
	0.26±0.06		150	Argo
	0.2±0.03		300	Argo
	0.1±0.02		600	Argo
	0.2±0.16		8	XBT
	0.33±0.4		30	XBT
	0.27±0.24		150	XBT
	0.17±0.14		300	XBT
	0.14±0.03		600	XBT

Table 8: Quasi-independent validation. Analysis evaluation based over year 2017.

Figure 3 shows the time series of weekly RMSs of temperature misfits (observation minus model value transformed at the observation location and time before being assimilated) at 5 depths (8, 30, 150, 300, 600 m), T-<X-Y>m-W-CLASS4-PROF-RMSD-MED-Jan2017-Dec2017, for the CMEMS Med-MFC-currents EAS4 system (red line) and the EAS5 system (blue line); the values of the mean RMS difference are reported in the legend of the figures; the number of observed profiles are represented in shaded coloured areas.

The new system presents almost the same temperature skill with respect to EAS4 system. The temperature error is generally higher at depth around 30 m and has a better skill below 150 m. It presents a seasonal variability at first layers with higher values during warm seasons.

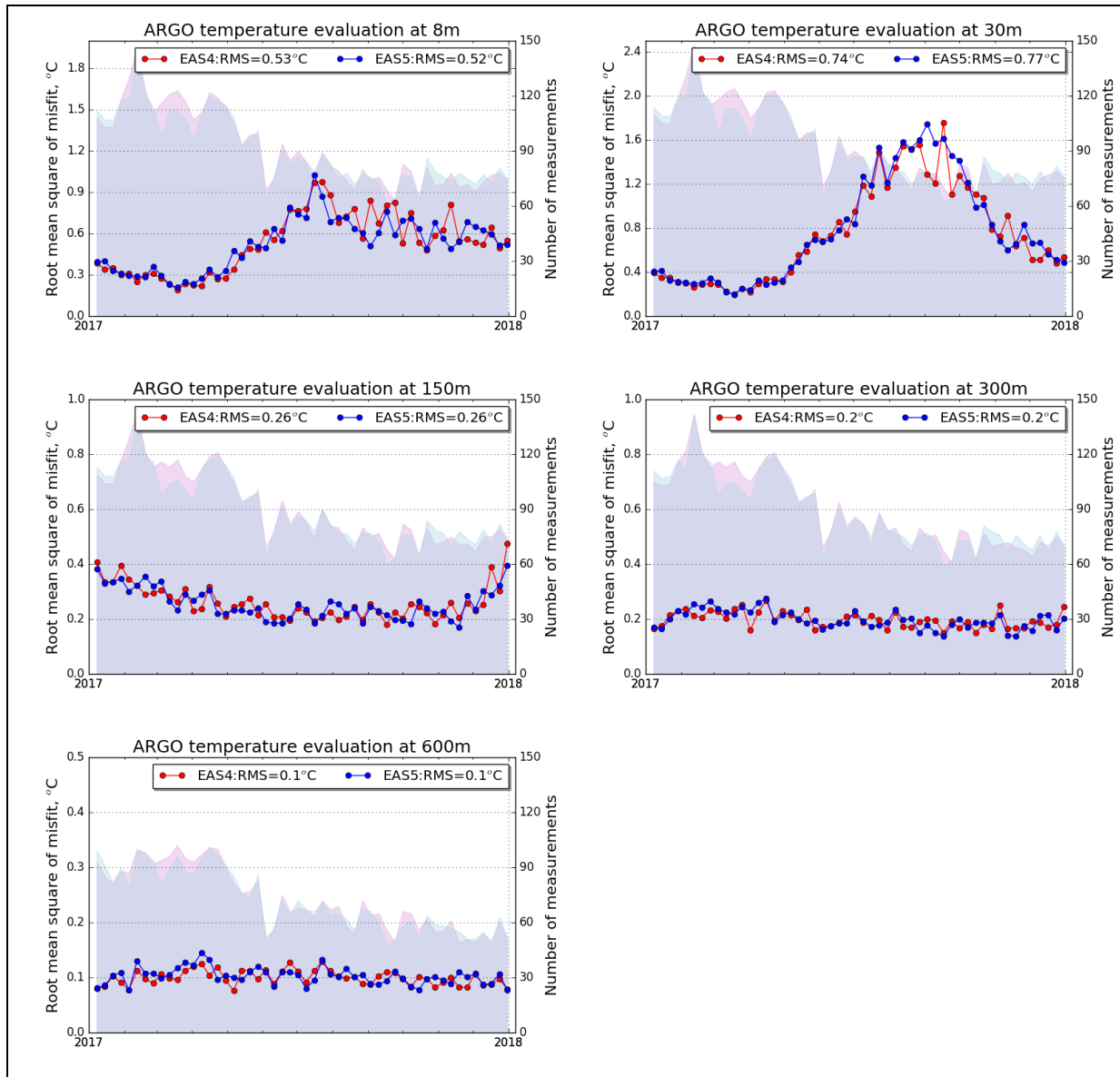


Figure 3: Time series of weekly RMS misfit of temperature (solid lines) and number of observed profiles (shaded area) at 8, 30, 150, 300 and 600 m (T-<X-Y>m-W-CLASS4-PROF-RMS-MED-Jan2017-Dec 2017)

Monthly mean RMS misfits of temperature for EAS4 and EAS5 systems are represented in the following (Depth-Time) Hovmöller diagrams (Figure 4) along the water column between surface and 900 m showing the vertical pattern of the error averaged in the whole Mediterranean Sea. Both systems present higher errors during summer-autumn seasons between 30-60 m depth.

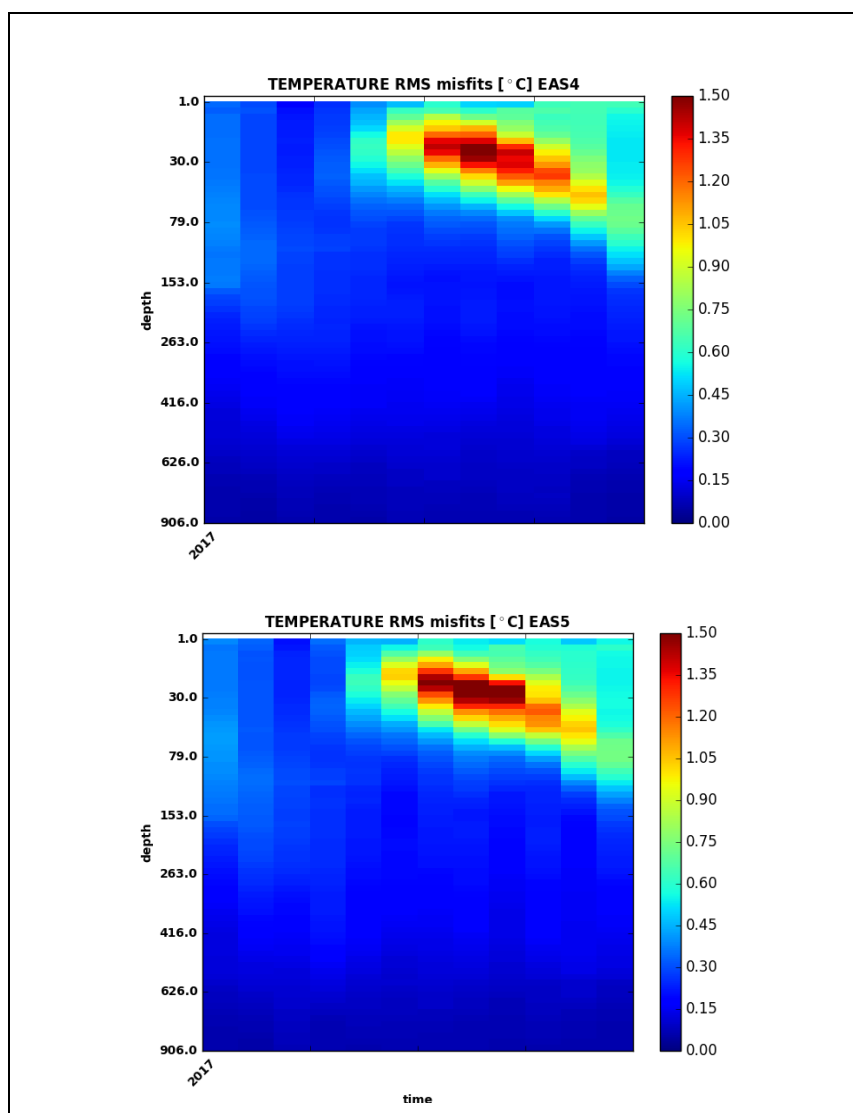


Figure 4: Hovmoller (Depth-Time) diagram of monthly mean RMS misfits of temperature along the water column averaged in the whole Mediterranean Sea during 2017. Top: EAS4; bottom: EAS5 (T-<X-Y>m-M-CLASS4-PROF-RMSD-MED-Jan2017-Dec2017-HOV).

In addition to basin averaged statistics, the following panels in Figure 5 show the spatial pattern of the temperature RMS misfits for EAS5 system averaged over the entire qualification period (2017) at several depths (8, 30, 150, 300 and 600 m) with respect to ARGO data. The bottom right panel shows the number of data used for this analysis.

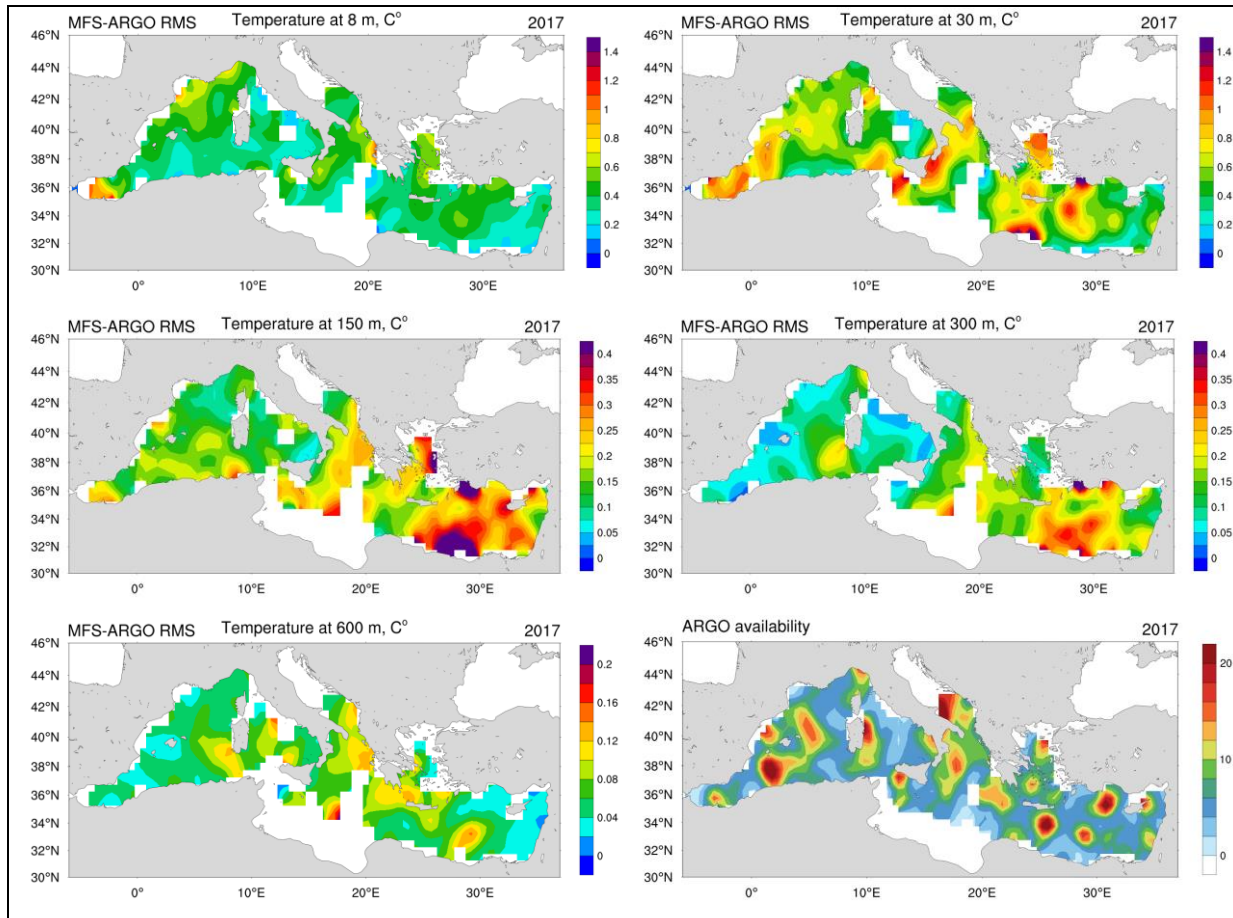


Figure 5: Maps of temperature RMS misfits for EAS5 system averaged in the entire qualification period (2017) at several depths (8, 30, 150, 300 and 600 m) with respect to ARGO data. The bottom right panel shows the number of data used for this analysis (T-<X-Y>m-Y-CLASS4-PROF-RMSD-MED-Jan2017-Dec2017-2DMAP).

The following panels in Figure 6 show the time series of temperature daily RMS differences between model outputs and observations evaluated over the qualification period (2017). The statistics are evaluated for nine different layers (0-10, 10-30, 30-60, 60-100, 100-150, 150-300, 300-600, 600-1000, 1000-2000 m): T-<X-Y>m-D-CLASS4-RMSD-MED-Jan2017-Dec 2017.

The differences between EAS4 and EAS5 systems are negligible. The average value of RMS over the entire period is the one listed in Table 1. The temperature error is generally higher above 100 m and presents a clear seasonal variability with higher values during warm seasons, then the error decreases significantly below 100 m and at lower levels.

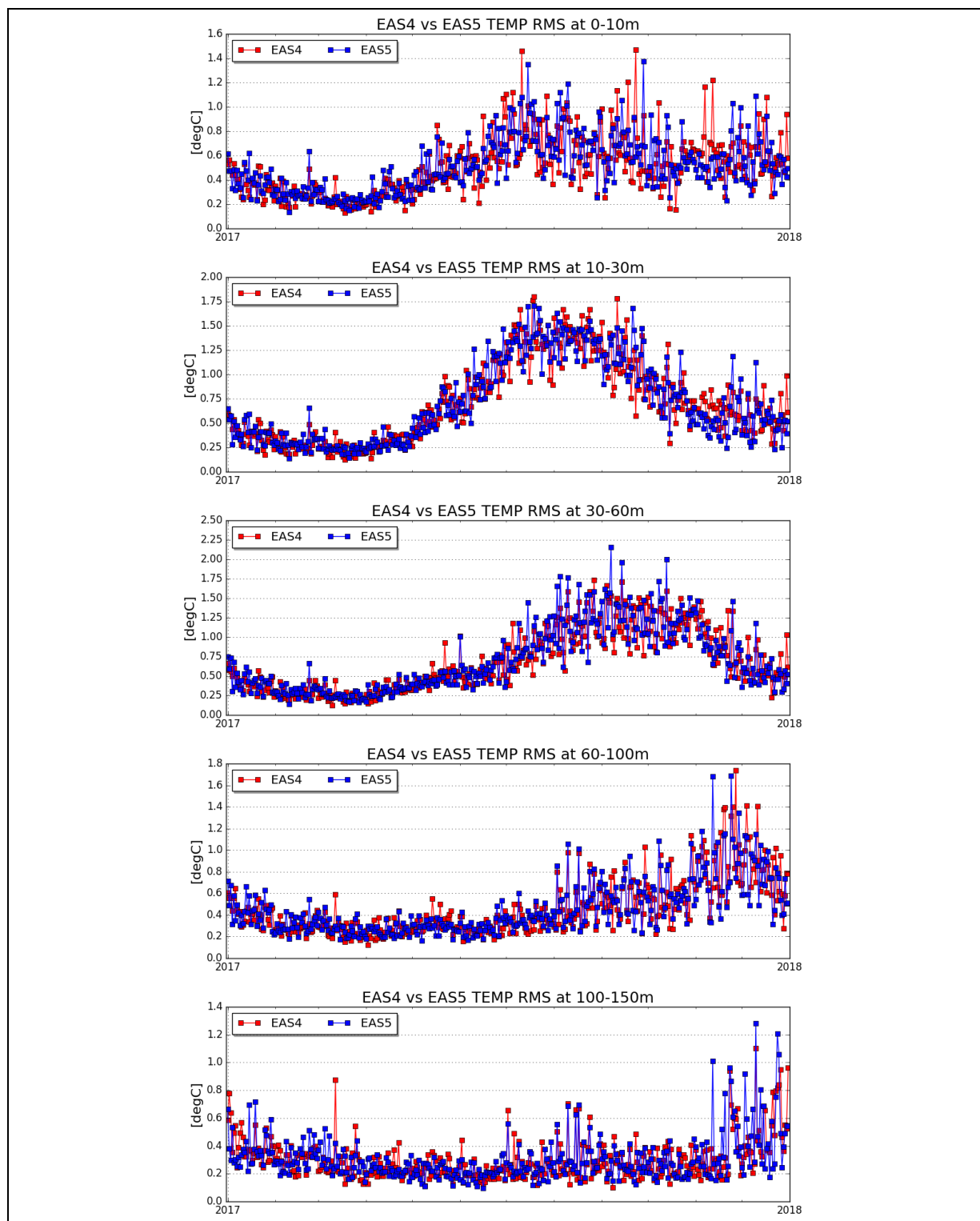


Figure 6: Time series of daily RMS of temperature at different vertical layers for EAS4 (red line) and EAS5 (blue line) systems (T-<X-Y>m-D-CLASS4-RMSD-MED-Jan2017-Dec2017) (continues in next page).

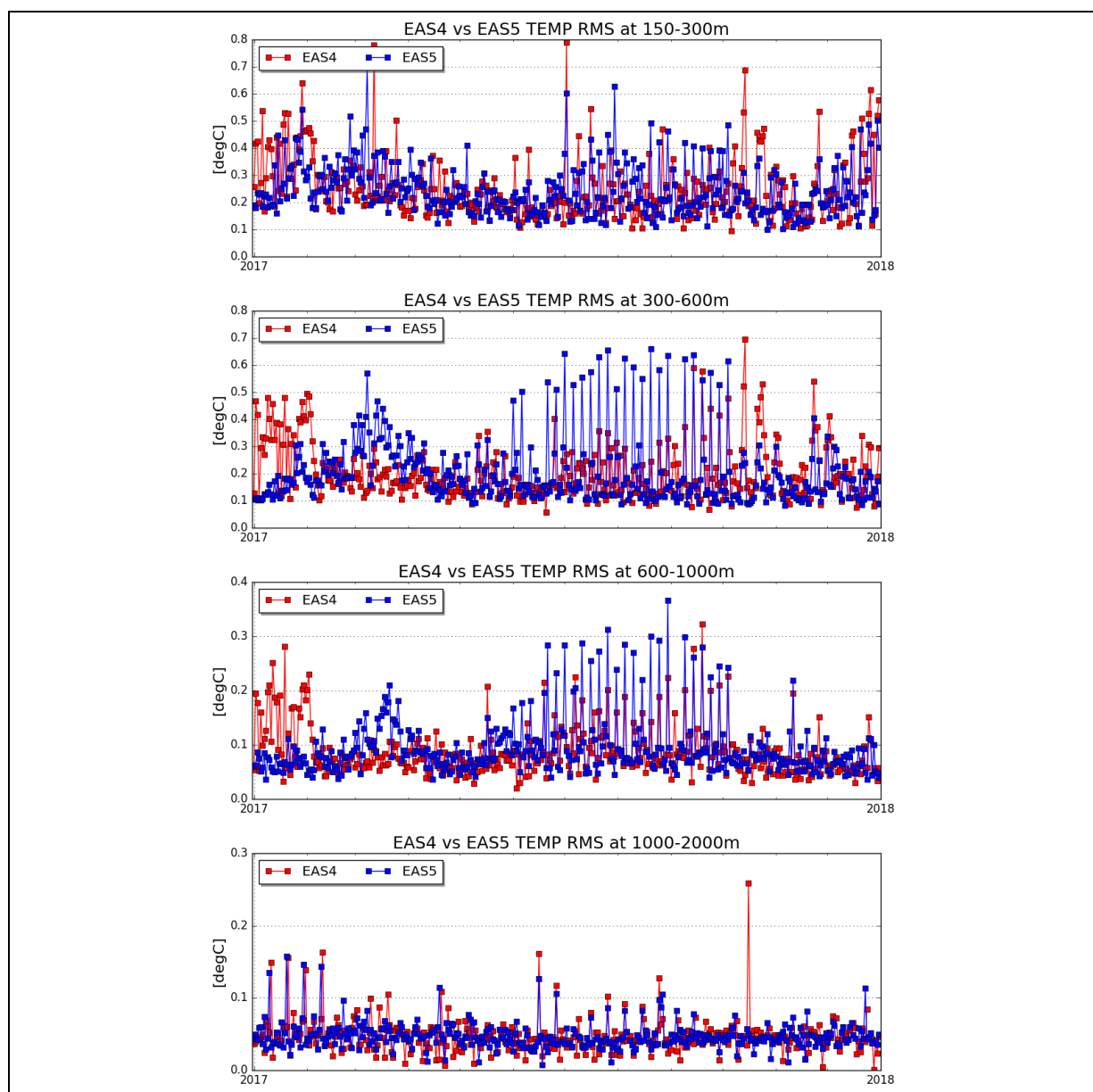


Figure 6: (Continued) Time series of daily RMS of temperature at different vertical layers for EAS4 (red line) and EAS5 (blue line) systems (T-<X-Y>m-D-CLASS4-RMSD-MED-Jan2017-Dec2017).

Figure 7 shows the time series of Sea Surface Temperature daily RMS difference (top) and BIAS (bottom) between daily model outputs and observations (L4 satellite SST at 1/16 degree resolution) evaluated over the qualification testing period (Jan-Dec 2017): SST-D-CLASS4-RAD-RMSD-Jan2017-Dec2017 and SST-D-CLASS4-RAD-BIAS-Jan2017-Dec2017.

The EAS4 and EAS5 systems show similar performances, with a slightly decreased error and bias in the new system. In general, the SST RMS is higher during warm periods and autumn while it decreases in April and the SST Bias is generally positive meaning that the models present higher SST with respect to the observations.

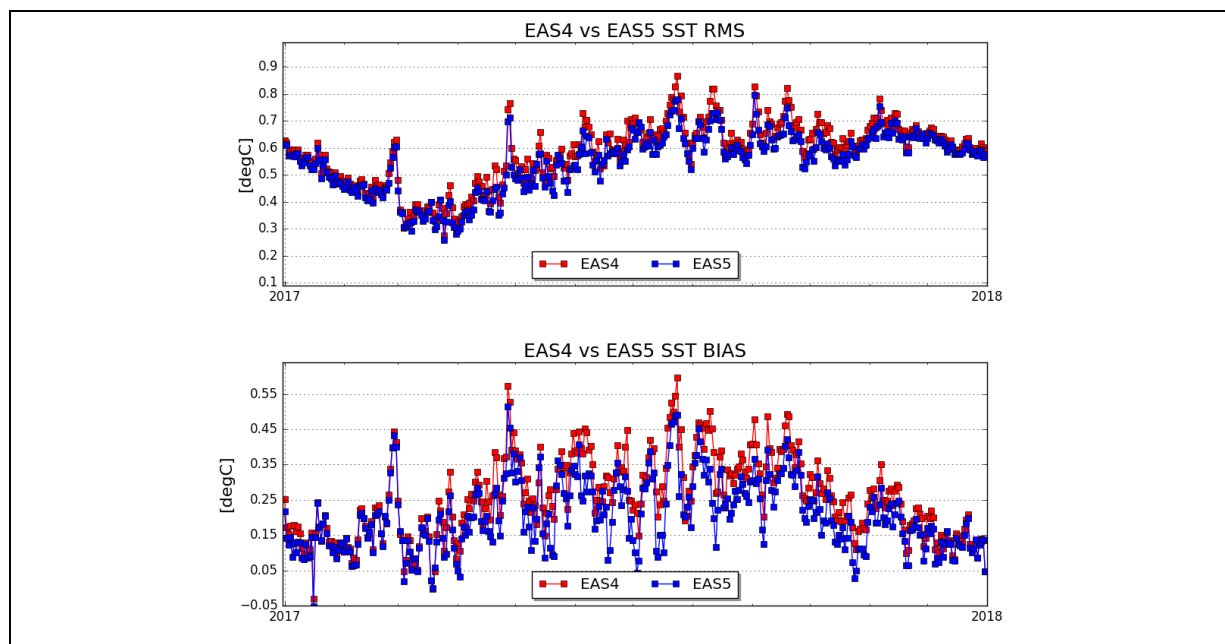


Figure 7: Time series of daily RMS difference (top) and Bias (bottom) of Sea Surface Temperature for EAS4 (red line) and EAS5 (blue line) systems (SST-D-CLASS4-RAD-RMSD-Jan2017-Dec2017, SST-D-CLASS4-RAD-BIAS-Jan2017-Dec2017) with respect to satellite L4 data at 1/16 degree resolution.

III.2 Seabed Temperature

The bottom temperature, that is the temperature of the deepest level of the circulation model, has been compared to SeaDataNet climatology (see Tonani et al., 2013 for more details) for the year 2017.

Figure 8 shows the time series of the monthly climatological dataset (green line), EAS4 system (red line) and EAS5 system (blue line) evaluated as monthly averages for the year 2017. The left panel shows the climatological time series of seabed temperature at depths included between [0-500] m, while the right panel shows the comparison at depths included between [0-1500] m. The 2 systems provide very similar values and are able to reproduce the seasonal variability of the bottom temperature that is generally overestimated by the models with respect to the climatological dataset.

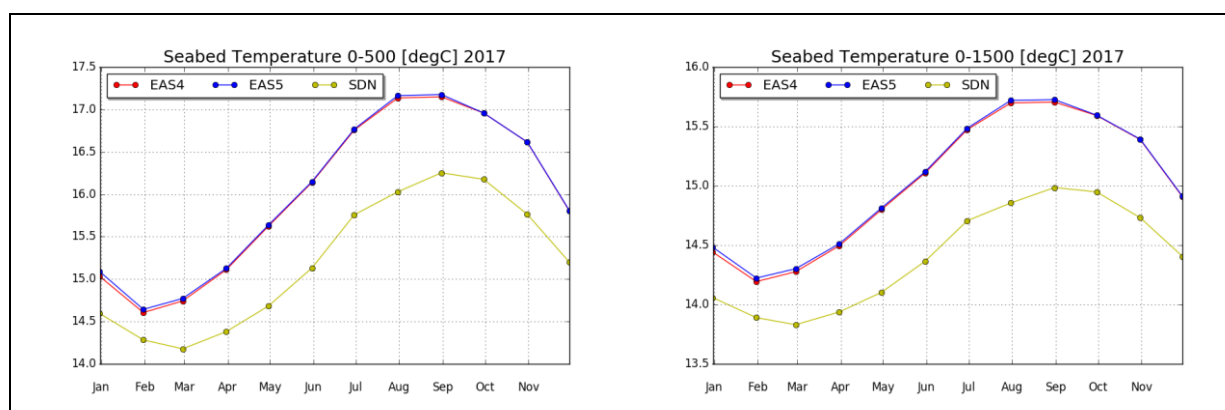


Figure 8: Time series of seabed temperature monthly climatology from SeaDataNet dataset (green line), EAS4 system (red line) and EAS5 system (blue line): SBT-D-CLASS4-CLIM-MEAN_M-MED.

The following figures show the January (Figure 9), April (Figure 10), July (Figure 11) and October (Figure 12) monthly mean seabed temperature in areas with topography included between 0 and 1500 m from SDN dataset (top), and corresponding monthly averages for Med-Currents EAS4 system (bottom-left), Med-Currents EAS5 system (bottom-right) evaluated for the year 2017. The two numerical systems exhibit similar temporal and spatial patterns compared to the climatological datasets. The main differences are related to warmer seabed temperature along the Tunisian and Libyan coasts predicted by the models with respect to the climatological dataset.

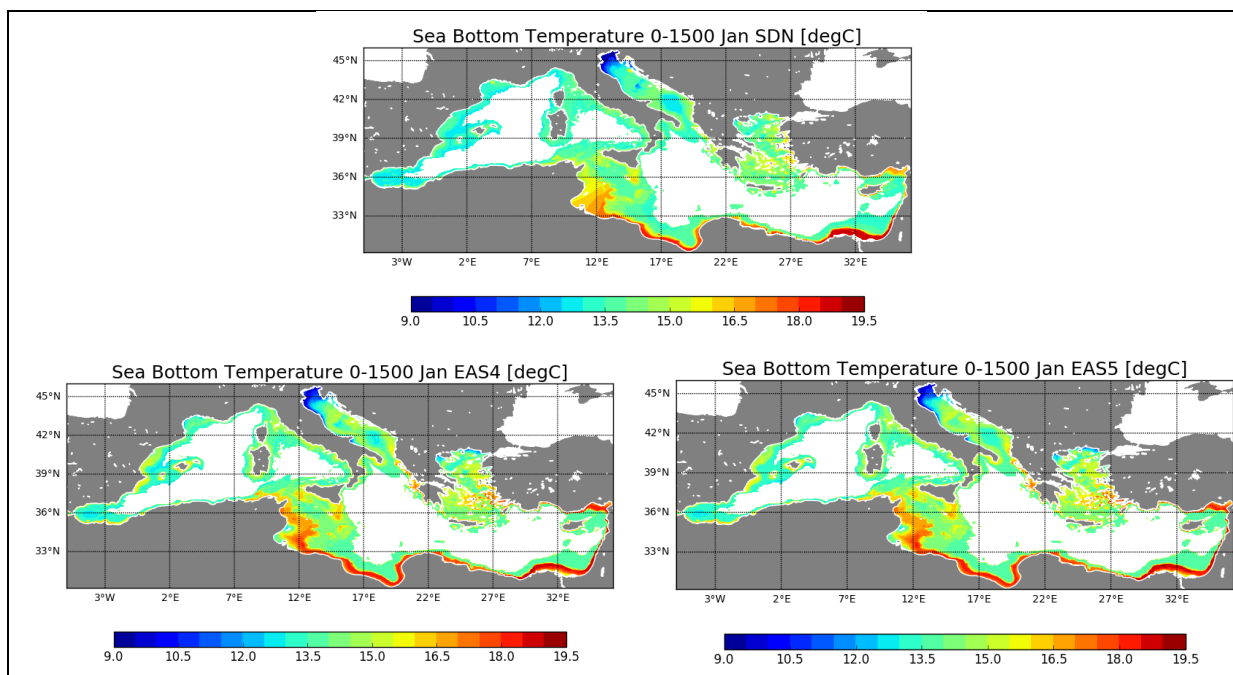


Figure 9: January Seabed temperature 2D maps in areas with topography lower than 1500 m: SDN climatology (top), monthly average Med-Currents EAS4 system (bottom-left), monthly average Med-Currents EAS5 system (bottom-right): SBT-D-CLASS1-CLIM-MEAN_M-MED.

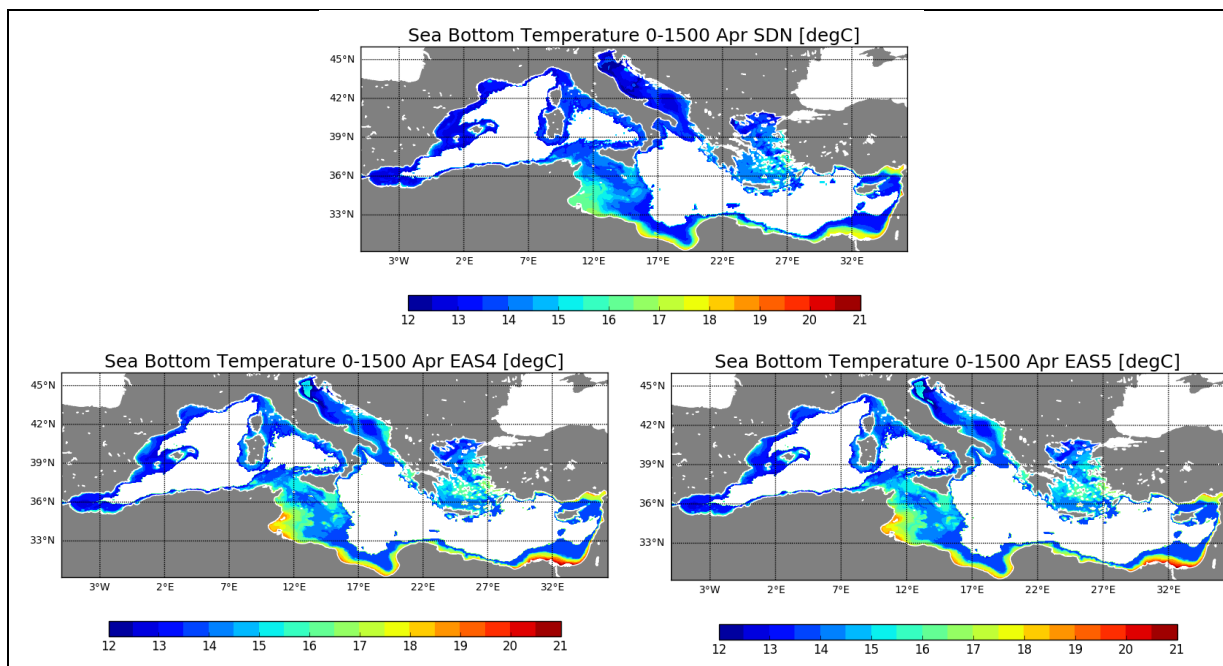


Figure 10: April Seabed temperature 2D maps in areas with topography lower than 1500 m: SDN climatology (top), monthly average Med-Currents EAS4 system (bottom-left), monthly average Med-Currents EAS5 system (bottom-right): SBT-D-CLASS1-CLIM-MEAN_M-MED.

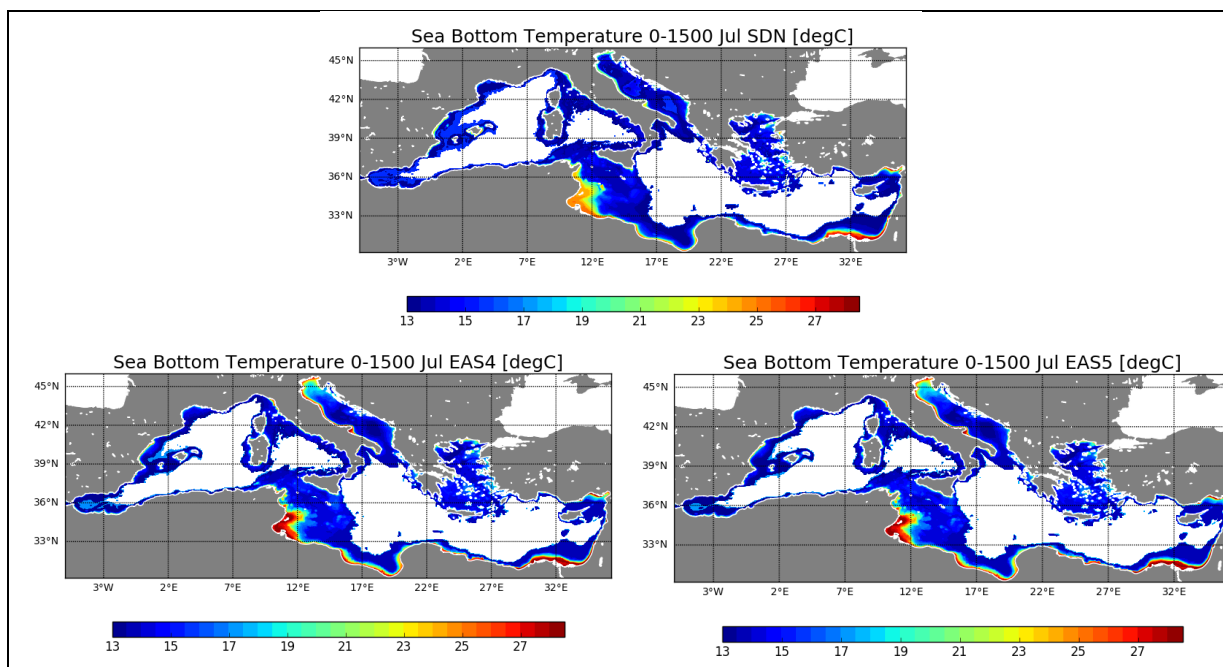


Figure 11: July Seabed temperature 2D maps in areas with topography lower than 1500 m: SDN climatology (top), monthly average Med-Currents EAS4 system (bottom-left), monthly average Med-Currents EAS5 system (bottom-right): SBT-D-CLASS1-CLIM-MEAN_M-MED.

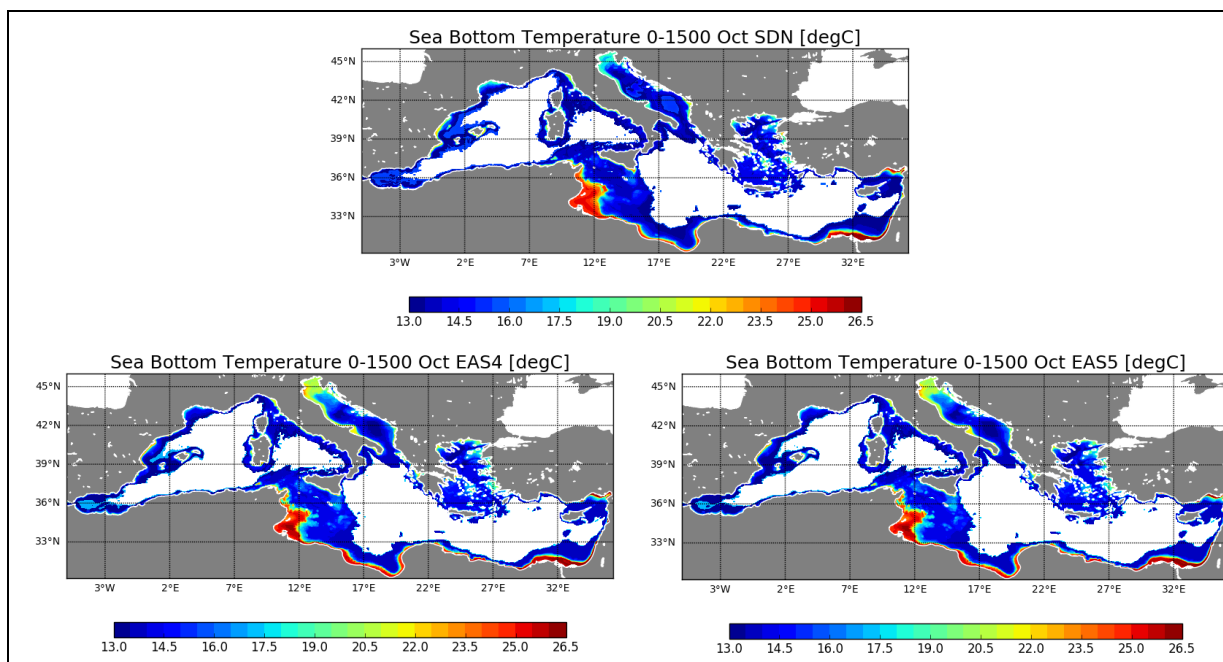


Figure 12: October Seabed temperature 2D maps in areas with topography lower than 1500 m: SDN climatology (top), monthly average Med-Currents EAS4 system (bottom-left), monthly average Med-Currents EAS5 system (bottom-right): SBT-D-CLASS1-CLIM-MEAN_M-MED.

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III.3 Salinity

In the following Table 9 there is a synthesis of the values of the salinity Root Mean Square (RMS) differences calculated comparing the analysis of MEDSEA_ANALYSIS_FORECAST_PHY_006_013 product with quasi-independent data assimilated by the system for salinity (ARGO, CTD).

The synthesis is based on 1 year period (2017) and provided at 5 depths (8, 30, 150, 300, 600 m). The error is always lower than 0.2 PSU and it is higher at surface and decreases significantly below 150 m.

Variables/estimated accuracy:	Metrics	Depth	Observation
SALINITY (psu)	RMS Diff	Depth	Observation
	0.17±0.04	8	Argo
	0.16±0.04	30	Argo
	0.08±0.02	150	Argo
	0.04±0	300	Argo
	0.03±0	600	Argo

Table 9: Quasi-independent validation. Analysis evaluation based over year 2017.

The panels in Figure 13 show the time series of weekly RMS of salinity misfits (observation minus model value transformed at the observation location and time before being assimilated) at 5 depths (8, 30, 150, 300, 600 m), S-<X-Y>m-W-CLASS4-PROF-RMSD-MED-Jan2017-Dec2017, for the CMEMS Med-MFC-currents EAS4 system (red line) and the EAS5 system (blue line); the values of the mean RMS differences are reported in the legend of the figures; the number of observed profiles that have been assimilated are represented as shaded areas.

The new system presents the same performances of the previous system. The salinity error is generally higher above 30 m with values less than 0.2 PSU and better skill below 150 m with values lower than 0.1 PSU. It presents a seasonal variability at first layers with higher values during warm seasons.

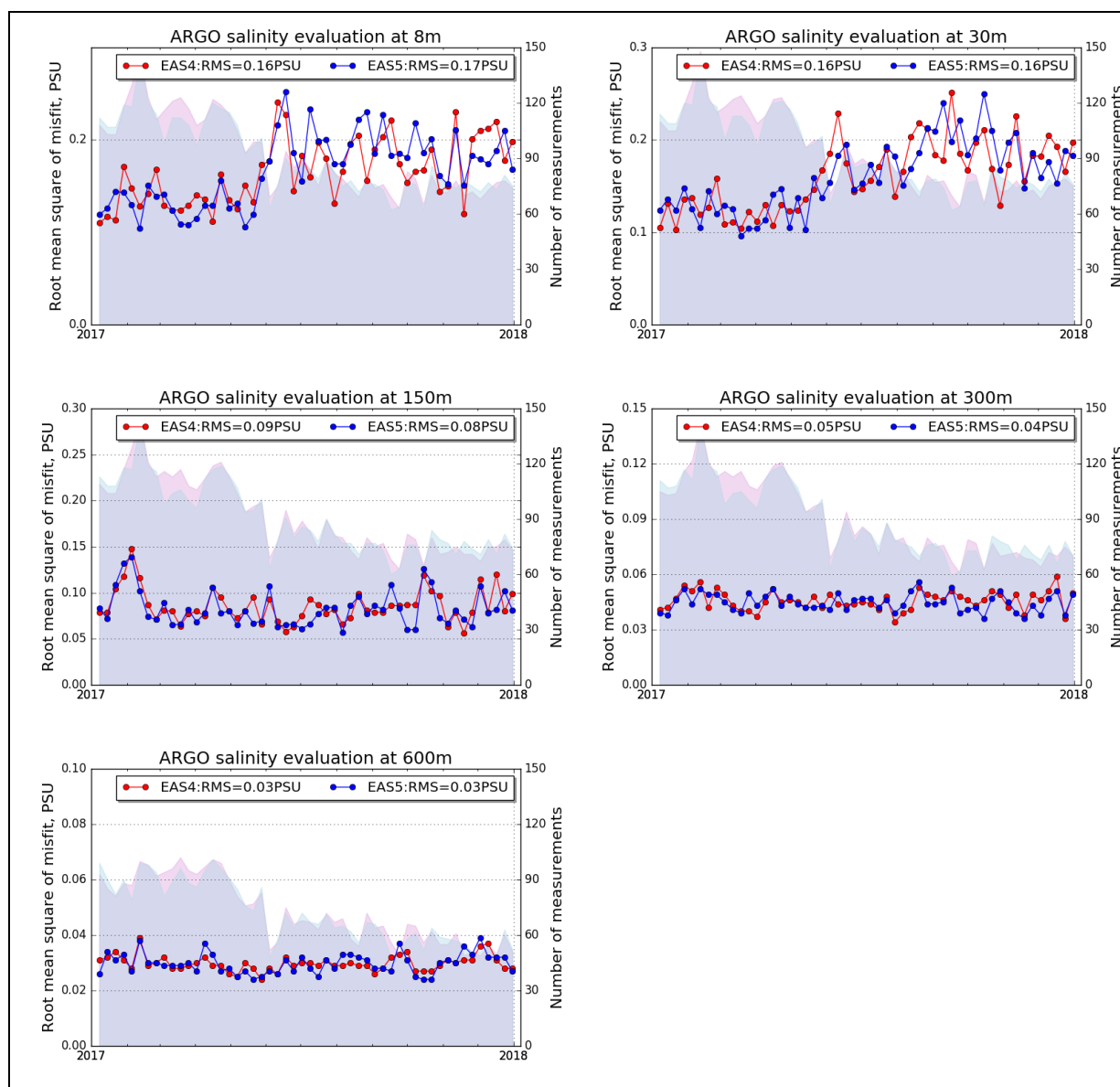


Figure 13: Time series of weekly RMS misfit of salinity ARGO-Model (solid lines) and number of observed profiles (shaded area) at 8, 30, 150, 300 and 600 m (S-<X-Y>m-W-CLASS4-PROF-RMSD-MED-Jan2017-Dec2017).

Monthly mean RMS misfits of salinity for EAS4 and EAS5 systems are represented in the following Figure 14 by means of Hovmoller diagrams (Depth-Time) along the water column between surface and 900 m depth showing the vertical pattern of the error averaged in the whole Mediterranean Sea. Both systems present higher errors in the first layers decreasing below 150 m.

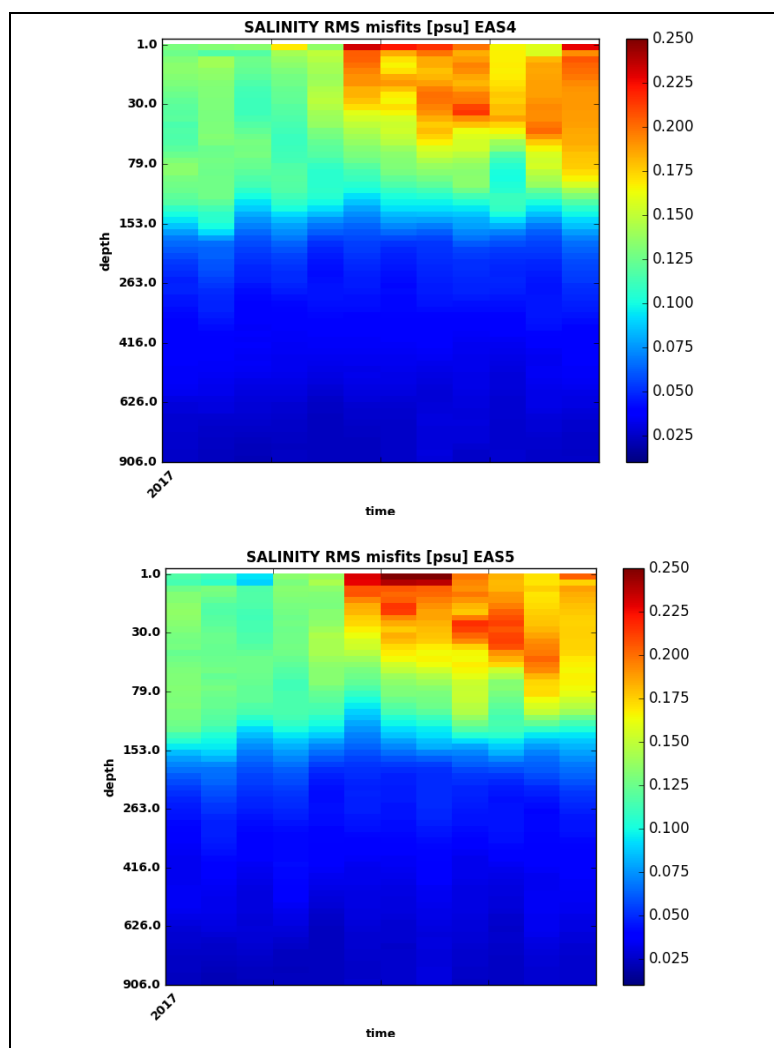


Figure 14: Hovmöller (Depth-Time) diagram of monthly mean RMS misfits of salinity along the water column averaged in the whole Mediterranean Sea. Top: EAS4; bottom: EAS5 system (S-<X-Y>m-M-CLASS4-PROF-RMSD-MED-Jan2017-Dec2017-HOV).

In addition to basin averaged statistics, the following figures (see panels in Figure 15) show the spatial pattern of the salinity RMS misfits for EAS5 system averaged in the entire qualification period (2017) at several depths (8, 30, 150, 300 and 600 m) with respect to ARGO data. The bottom right panel shows the number of data used for this analysis.

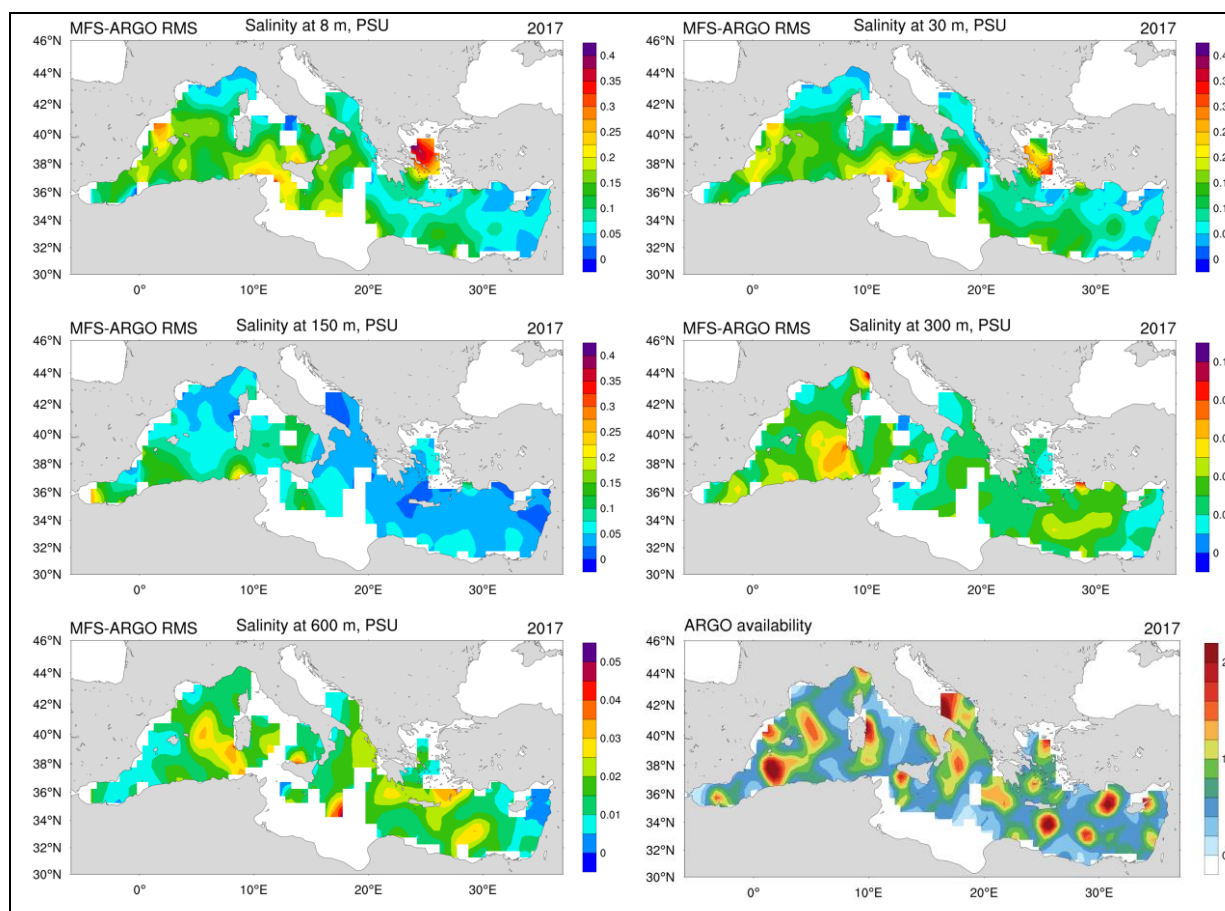


Figure 15: Maps of salinity RMS misfits for EAS5 system averaged in the entire qualification period (2017) at several depths (8, 30, 150, 300 and 600 m) with respect to ARGO data. The bottom right panel shows the number of data used for this analysis (S-<X-Y>m-Y-CLASS4-PROF-RMSD-MED-Jan2017-Dec2017-2DMAP).

The following panels in **Error! Reference source not found.** show the time series of salinity daily RMSs of the difference between model outputs and observations evaluated over the qualification testing period (2017): S-<X-Y>m-D-CLASS4-PROF-RMSD-MED-Jan2017-Dec2017. The statistics are evaluated for nine different layers (0-10, 10-30, 30-60, 60-100, 100-150, 150-300, 300-600, 600-1000, 1000-2000 m).

The differences between EAS5 and EAS4 systems are very small. The two systems present similar errors at all levels. The average value of RMS difference over the entire period is the one listed in Table 3. The salinity error is generally higher above 150 m then the error decreases significantly below 150 m.

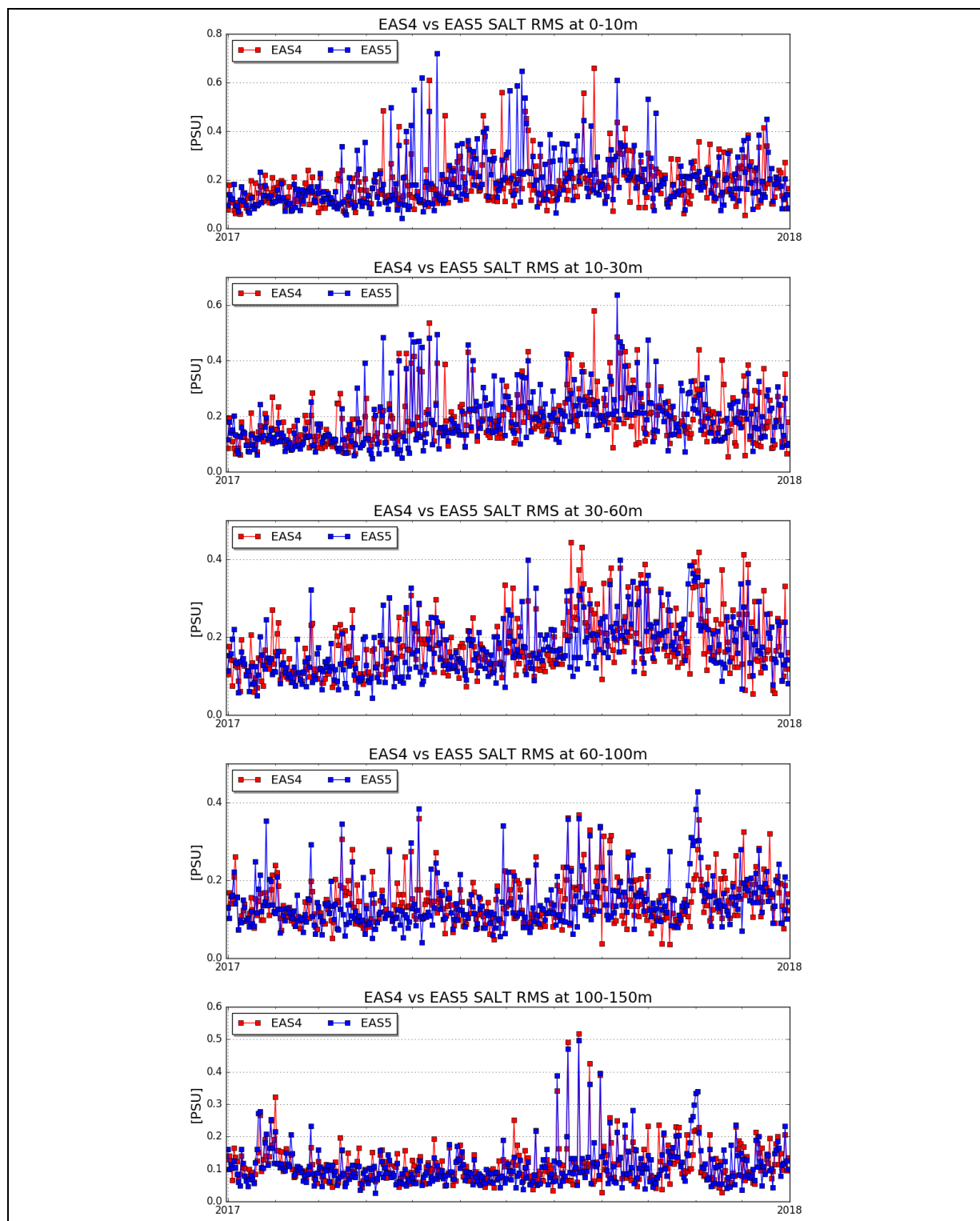


Figure 16: Time series of daily RMS of salinity at different vertical layers for EAS4 (red line) and EAS5 (blue line) systems (S-<X-Y>m-D-CLASS4-PROF-RMSD-MED-Jan2017-Dec2017) (continues in next page).

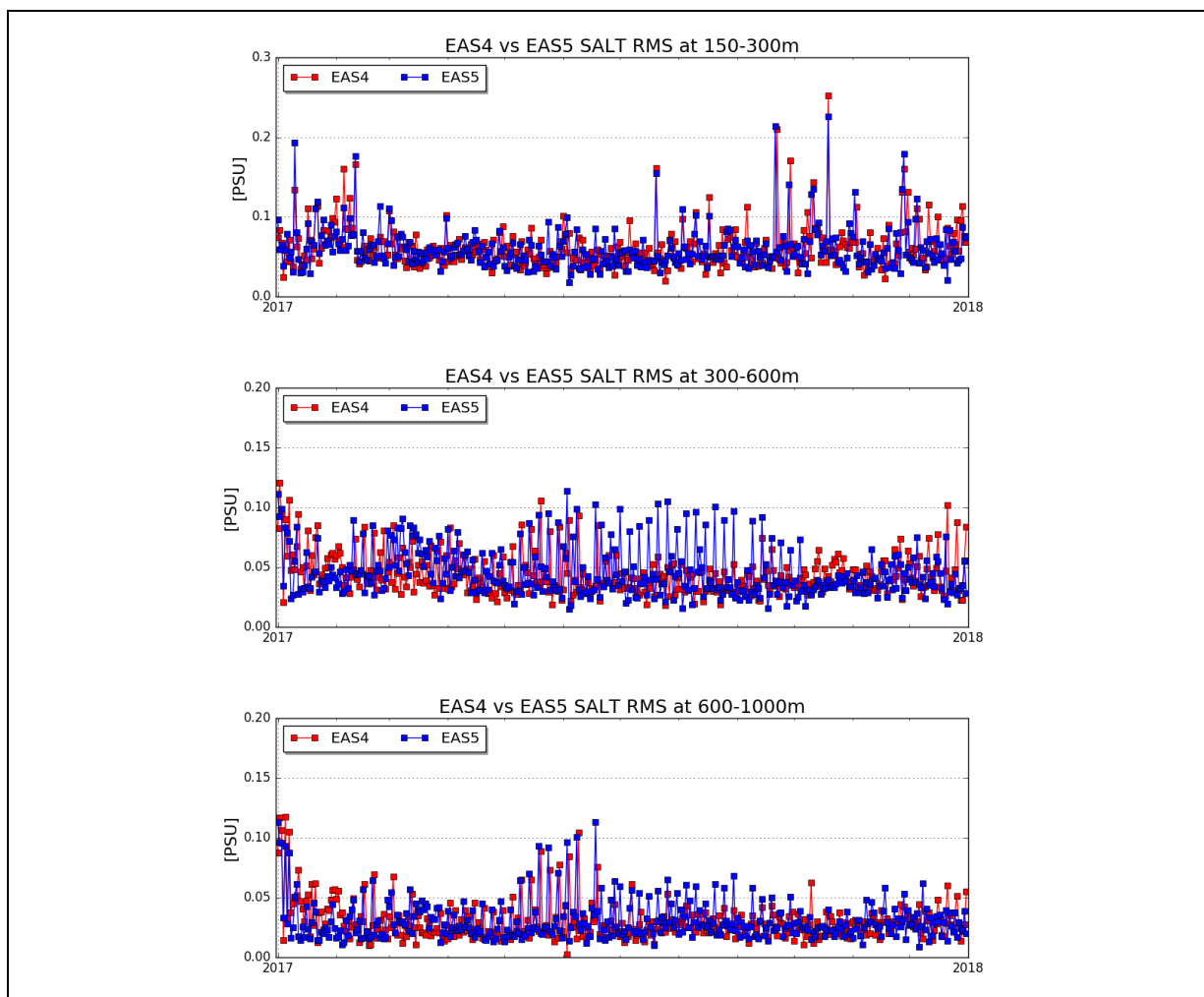


Figure 16: (continued) Time series of daily RMS of salinity at different vertical layers for EAS4 (red line) and EAS5 (blue line) systems (S-<X-Y>m-D-CLASS4-PROF-RMSD-MED-Jan2017-Dec2017).

III.4 Sea Level Anomaly

In Table 10 there are the RMS differences for the Sea Level Anomaly calculated comparing the analysis of MEDSEA_ANALYSIS_FORECAST_PHY_006_013 product with each available satellite (along track observations) from January to December 2017.

SEA LEVEL ANOMALIES (cm)	RMS Diff	Availability
All Satellites	3.6	01/01/2017-31/12/2017
ALTIKA	3.5	01/01/2017-31/12/2017
CRYOSAT	3.6	01/01/2017-31/12/2017
JASON 2N	3.5	01/01/2017-15/03/2017 30/03/2016-17/05/2017
JASON3	3.5	01/01/2017-31/12/2017
SENTINEL3A	3.5	29/03/2017-31/12/2017

Table 10: Analysis evaluation based over 1 year time series (2017) for the Sea Level Anomaly for each available satellite.

The following Figure 17 shows the time series of weekly RMS of sea level anomaly misfits (observation minus model value transformed at the observation location and time before being assimilated), SLA-SURF-W-CLASS4-ALT-RMSD-MED-Jan2017-Dec2017, for the CMEMS Med-Currents EAS4 system (red line) and the EAS5 system (blue line); the number of assimilated data is provided as shaded areas.

The new system presents a similar skill with respect to EAS4 system for each of the available satellite with an overall error of about 3.5 cm in the whole basin.

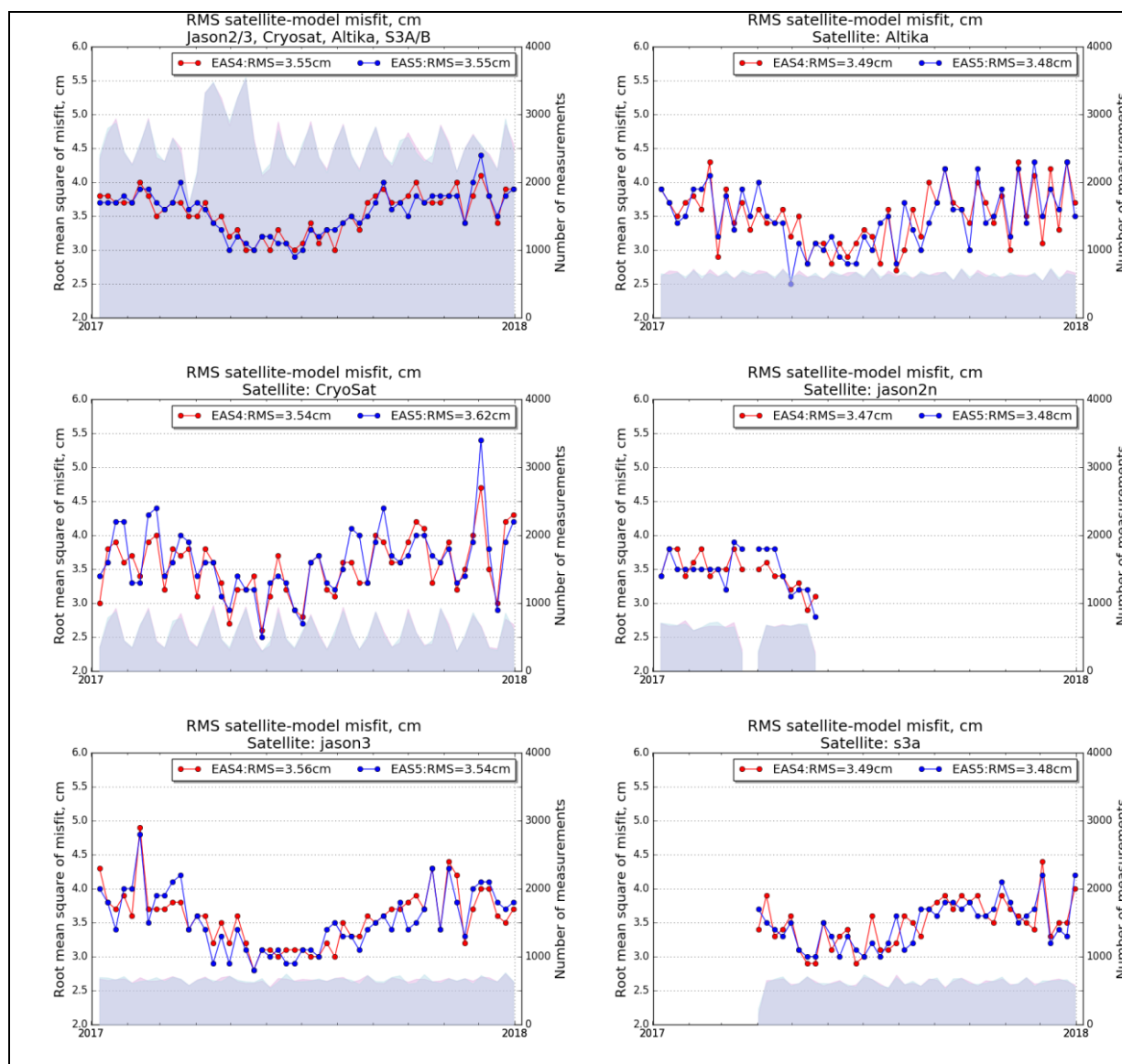


Figure 17 Time series of weekly RMS of satellite-model misfit along SLA data track for all the satellites (top-left panel), Altika (top-right), Cryosat (middle-left), Jason2/N (middle-right), Jason3 (bottom-left) and Sentinel3A (bottom-right) and corresponding number of assimilated data (shaded areas in the figures) for EAS4 (red line) and EAS5 (blue line) (SLA-SURF-W-CLASS4-ALT-RMSD-MED-Jan2017-Dec2017).

In addition to basin averaged statistics, the following figures (Figure 18) show the spatial pattern of the Sea Level Anomaly RMS misfits (top panel) for EAS5 system averaged in the entire qualification period (2017) with respect to SLA tracks and the number of data used for this analysis (bottom panel).

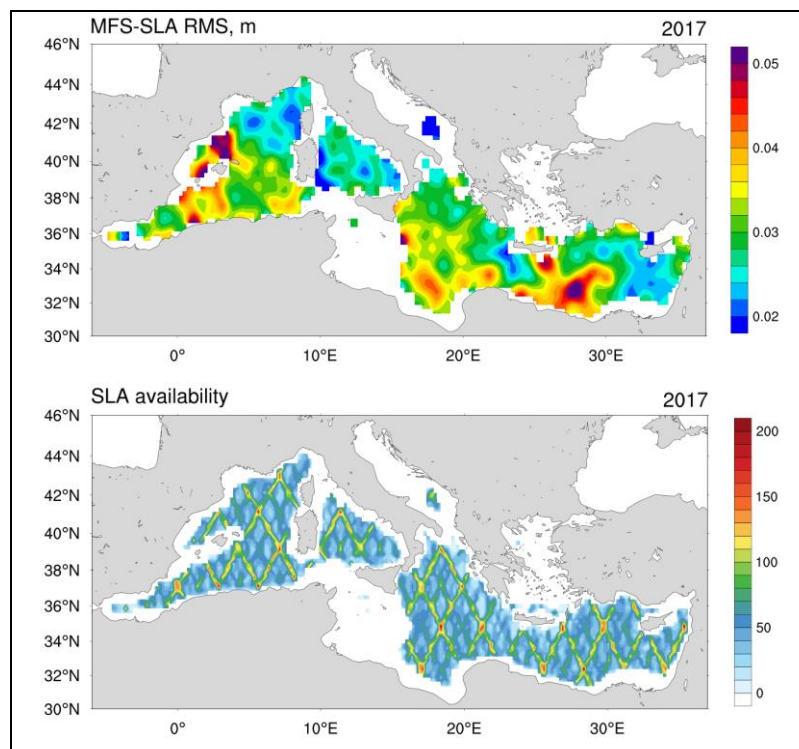


Figure 18: Maps of Sea Level Anomaly RMS misfits (top) for EAS5 system averaged in the entire qualification period (2017) with respect to SLA L3 along track Altimetry data and number of data used for this analysis (bottom) (SLA-SURF-CLASS4-PROF-RMSD-MED-Jan2017-Dec2017-2DMAP).

Figure 19 shows the daily time series of Sea Level Anomaly daily RMS of the difference between model outputs and observations evaluated over the qualification testing period (2017): SLA-SURF-D-CLASS4-RMSD-MED-Jan2017-Dec 2017. The new system (blue line) presents similar skill during all the simulated period if compared to EAS4 system (red line).

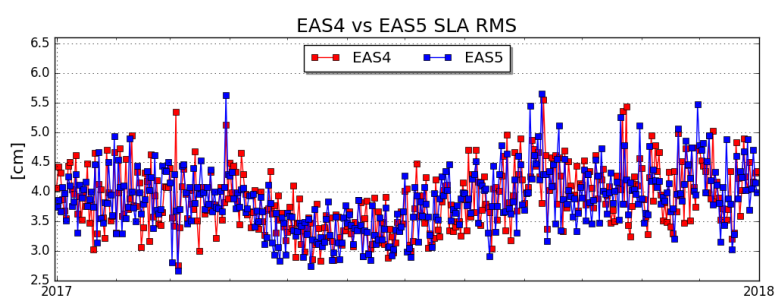


Figure 19: Time series of daily RMS of Sea Level Anomaly for EAS4 and EAS5 systems (SLA-SURF-D-CLASS4-RMSD-MED-Jan2017-Dec 2017)

III.5 Currents

The predicted sea surface currents skill is assessed by means of independent validation through coastal moorings.

Table 11 summarizes the RMS differences and the Bias calculated comparing the analysis of MEDSEA_ANALYSIS_FORECAST_PHY_006_013 product with the independent in-situ data (MB: coastal moored buoys) for the year 2017.

Variables/estimated accuracy:	RMS diff	Bias	Depth	Obs	No. of Obs.
	UV-SURF-D-CLASS2-MOOR-RMSD-Jan2017-Dec2017	UV-SURF-D-CLASS2-MOOR-BIAS-Jan2017-Dec2017			
Current (cm/s) year 2017: EAS5	13.7	3.0	0-3	MB	11

Table 11: Independent observation evaluation based on 1-year time series (2017) of analysis and Moored Buoys observations.

Figure 20 shows an example of daily sea surface currents time series of EAS5 (blue line) model outputs against the Tarragona coastal mooring (green line) for year 2017, the figure presents also the Bias and RMS difference.

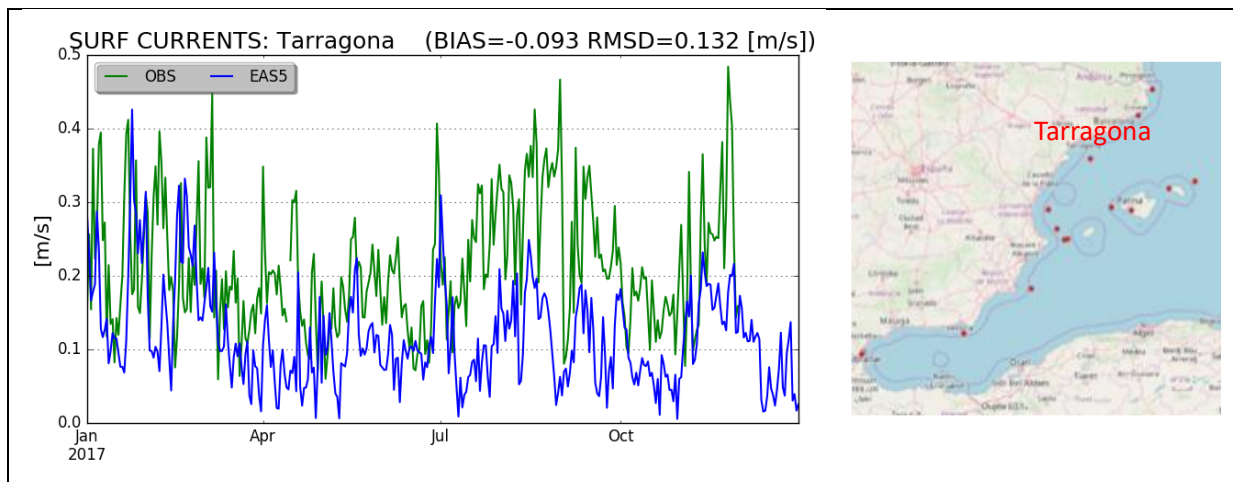


Figure 20: Left: Time series of daily sea surface currents at Tarragona buoy. Comparison between observations (green line) and EAS5 model outputs (blue line). (UV-SURF-D-CLASS2-MOOR-RMSD-Jan2017-Dec2017, UV-SURF-D-CLASS2-MOOR-BIAS-Jan2017-Dec2017). Right: Tarragona Buoy location.

In addition to surface current validation, an assessment of velocity derived variables is provided in terms of transport through the strait of Gibraltar.

In Figure 21 the time series of the mean daily Net flux through the Gibraltar Strait is represented for EAS4 (red line) and EAS5 (blue line) during 2017 showing very similar results for the two systems.

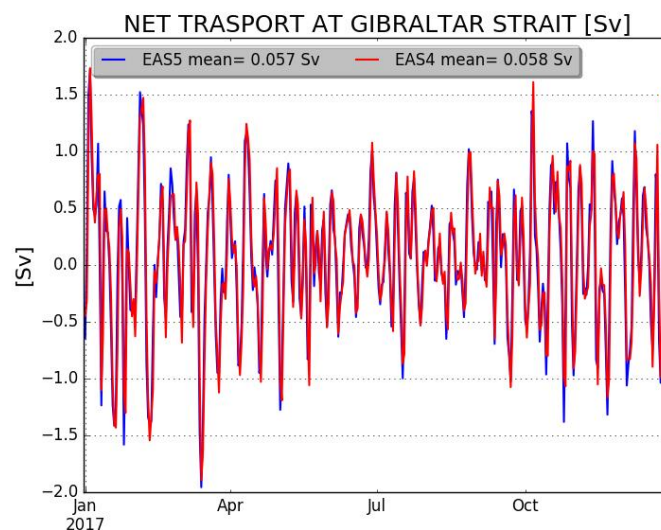


Figure 21: Time series of daily mean Net Flux through the Gibraltar Strait for EAS4 (red line) and EAS45 (blue line) systems.

In Table 12 the comparison of net, eastward and westward transports with respect to literature fluxes (Soto-Navarro et al., 2010) is included showing that the two systems yearly (2017) mean fluxes are very similar and are close to literature values.

Gibraltar Mean Flux [Sv]	EAS4 (2017)	EAS5 (2017)	Soto-Navarro et al., 2010
Net	0.058	0.057	0.038 ± 0.007
Eastward	0.882	0.881	0.81 ± 0.06
Westward	0.825	0.824	0.78 ± 0.05

Table 12: Gibraltar mean fluxes [Sv] from EAS4 and EAS5 systems averaged in the year 2017 compared to literature values.

III.6 Mixed Layer Depth

In order to assess the model ability to reproduce the Mixed Layer Depth (MLD), monthly averaged 2D maps of MLD have been compared to a climatological datasets available from literature (Houpert et al., 2015) providing monthly gridded climatologies produced using MBT, XBT, Profiling floats, Gliders, and ship-based CTD data from different database and carried out in the Mediterranean Sea between 1969 and 2013. Figure 22 to Figure 25 show the 2D maps of climatological MLD from literature (top), monthly averaged MLD from MED-Currents EAS4 (bottom-left) and MED-Currents EAS5 system (bottom-right).

It can be noticed that during March 2017 (Figure 22), the modelled MLD in the Gulf of Lyon is shallower than the climatological value and slightly deeper in the Aegean Sea. During June 2017 (Figure 23) the modelled MLD is in general similar to the climatological one with a slightly deeper MLD in the North Adriatic Sea. During August 2017 (Figure 24) the Med-Currents EAS5 and EAS4 systems are very close to the climatology in the central and eastern basins, while the modelled MLD is deeper in the Western basin with respect to the climatology; in November 2017 (Figure 25) the 2 systems have similar spatial pattern with slightly deeper modelled MLD with respect to the climatology.

In general, it can be noticed that the numerical systems are able to represent the spatial and seasonal distribution of the MLD and the main differences can be due to the low resolution of the climatological dataset that moreover do not cover the whole domain of the Mediterranean Sea as well as on the different period of evaluation.

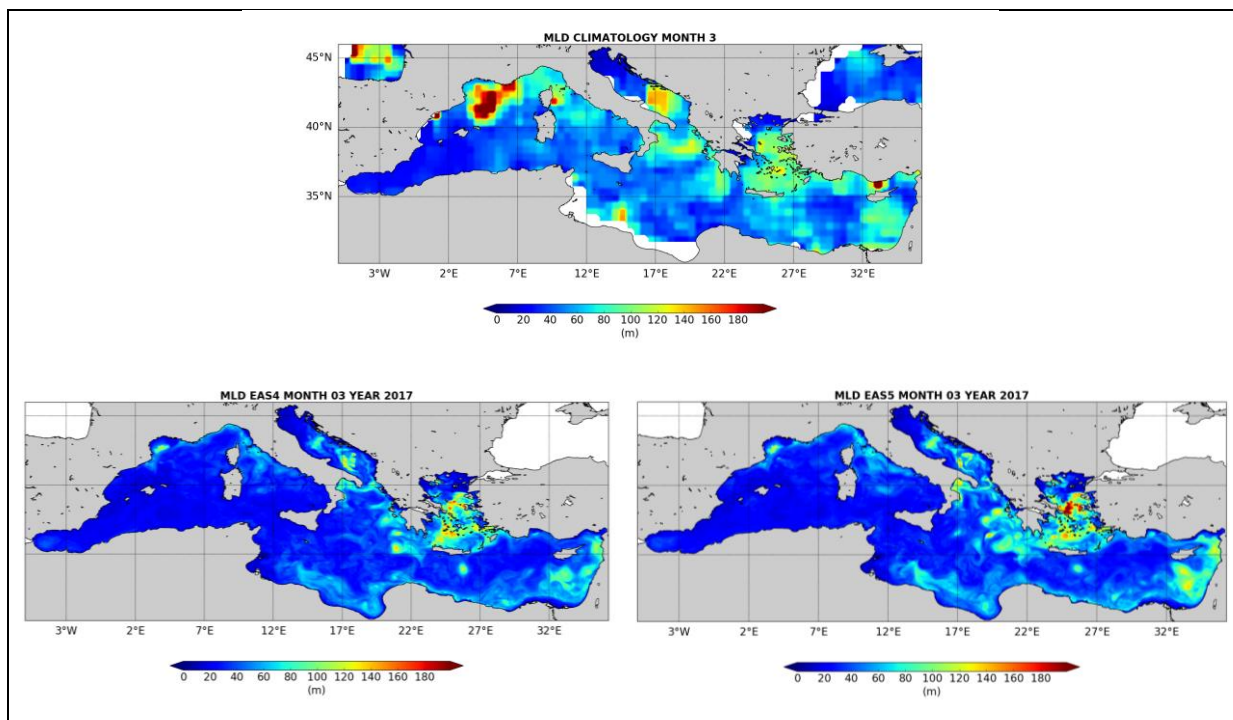


Figure 22: March MLD 2D maps. Top: climatological data from literature; left: March 2017 monthly averaged MLD from MED-Currents EAS4; right: March 2017 monthly averaged MLD from MED-Currents EAS5: MLD-D-CLASS1-CLIM-MEAN_M-MED

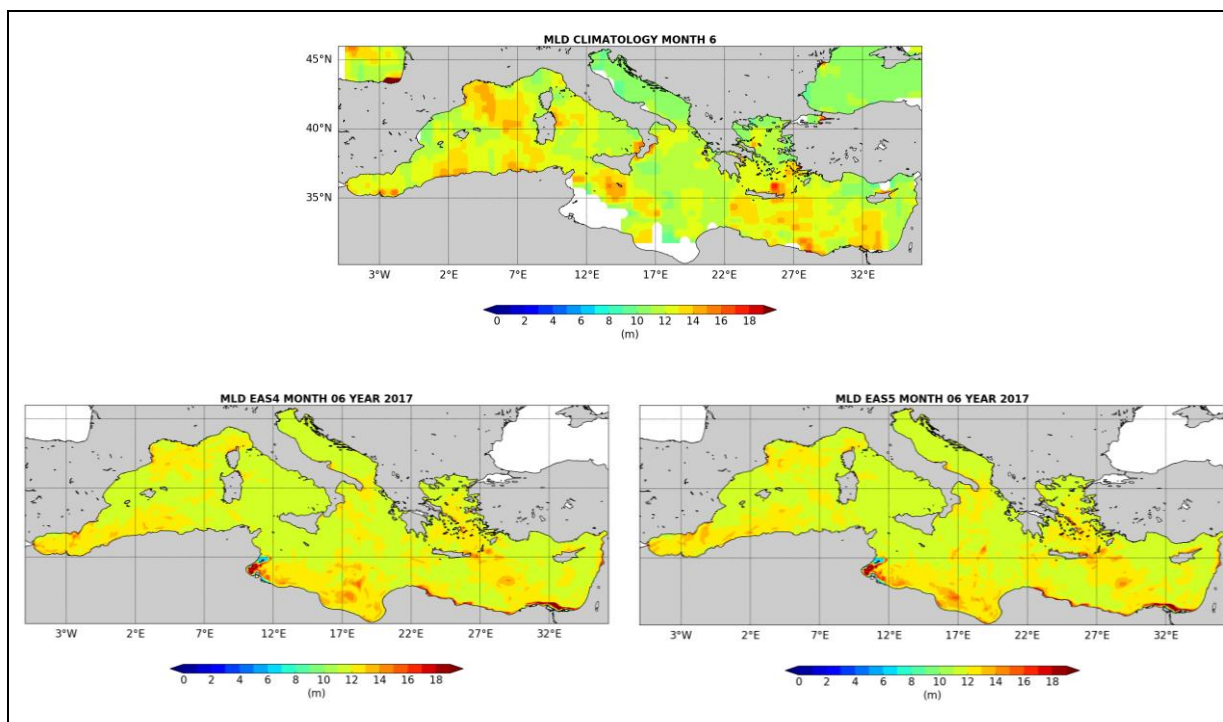


Figure 23: June MLD 2D maps. Top: climatological data from literature; left: June 2017 monthly averaged MLD from MED-Currents EAS4; right: June 2017 monthly averaged MLD from MED-Currents EAS5: MLD-D-CLASS1-CLIM-MEAN_M-MED

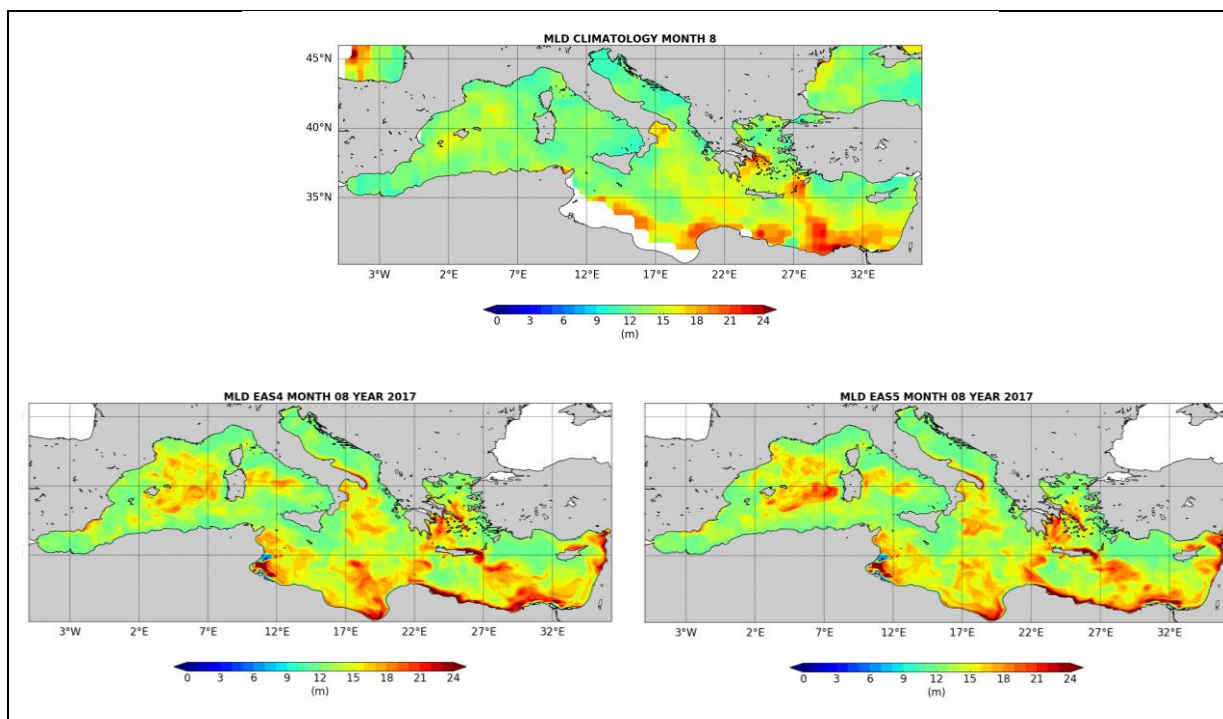


Figure 24: August MLD 2D maps. Top: climatological data from literature; left: September 2017 monthly averaged MLD from MED-Currents EAS4; right: September 2017 monthly averaged MLD from MED-Currents EAS5: MLD-D-CLASS1-CLIM-MEAN_M-MED

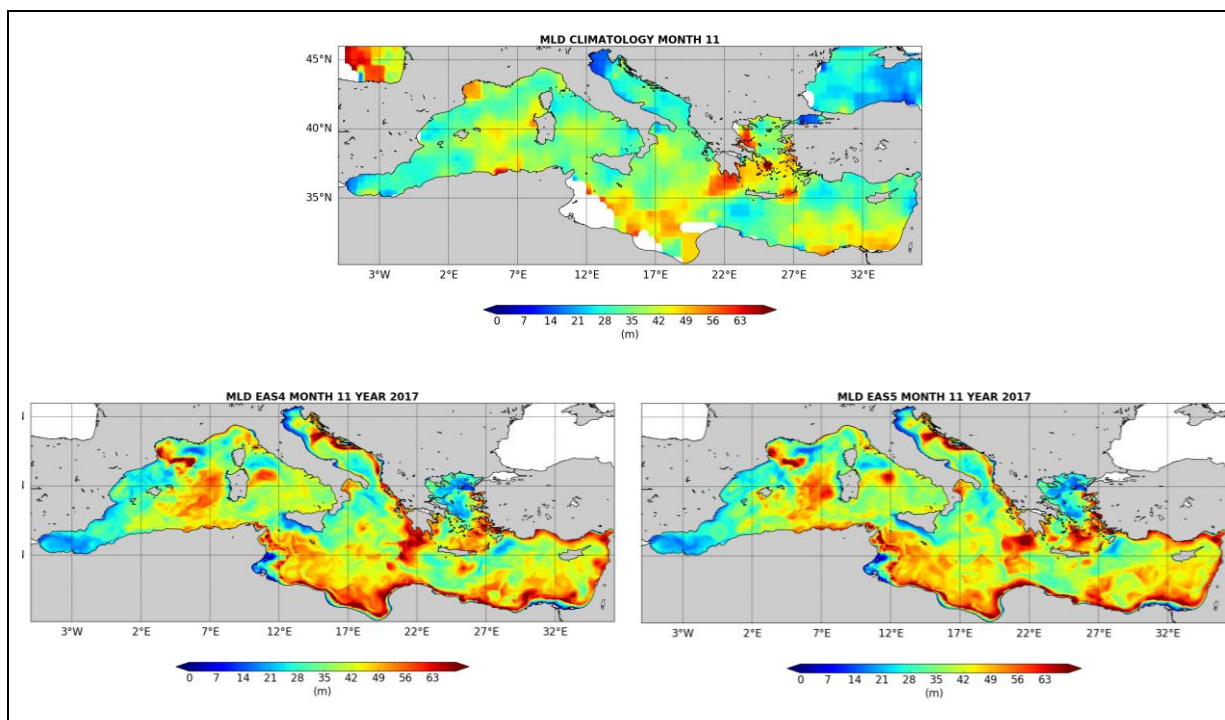


Figure 25: November MLD 2D maps. Top: climatological data from literature; left: November 2017 monthly averaged MLD from MED-Currents EAS4; right: November 2017 monthly averaged MLD from MED-Currents EAS5: MLD-D-CLASS1-CLIM-MEAN_M-MED

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IV SYSTEM'S NOTICEABLE EVENTS, OUTAGES OR CHANGES

Date	Change/Event description	System version	other
8 July 2019 EIS	Updated SST nudging; Included assimilation S3B; Lateral open boundary conditions at the Dardanelles Strait.	EAS4	Time series availability: 01/01/2017 to 30 May 2020
30 March 2020 EIS	Model daily data centred at 12.00 UTC (instead 00:00 UTC).	EAS5	Time series availability: From 01/01/2018
15 Dec 2020 EIS	Upgrade of ECWMF atmospheric forcing to higher spatial and temporal resolution	EAS5	

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V QUALITY CHANGES SINCE PREVIOUS VERSION

March 2019: From EAS4 to EAS5 system (more details in section II.2).

The quality of the product is similar to the one of the previous system.

December 2020: Use of higher spatial and temporal resolution ECMWF atmospheric forcing (more details in section II.2).

The quality assessment of the daily analysis physical fields carried out using the higher resolution atmospheric forcing, has provided no significantly changes with respect to the previous system.

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