Project information	
Project full title	EuroSea: Improving and Integrating European Ocean Observing and Forecasting Systems for Sustainable use of the Oceans
Project acronym	**EuroSea**
Grant agreement number	862626
Project start date and duration	1 November 2019, 50 months
Project website	https://www.eurosea.eu

Deliverable information	
Deliverable number	D4.9
Deliverable title	**Intercomparison of glider assimilation in the different analysis and forecasting systems**
Description	Intercomparison of skill scores of forecast and analyses for the two different assimilation and model systems in the Med Sea
Work Package number	4
Work Package title	Data integration, Assimilation, and Forecasting
Lead beneficiary	SOCIB
Lead authors	Jaime Hernandez-Lasheras, Ali Aydogdu, Baptiste Mourre
Contributors	Carolina Amadio, Gianpiero Cossarini, Jenny Pistoia, Romain Escudier, Elisabeth Remy
Due date	30 April 2023
Submission date	28 April 2023
Comments	

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 862626.

https://doi.org/10.3289/eurosea_d4.9

Table of contents

Executive summary 1
1. Introduction 1
2. Experiment setup 2
   2.1. Glider observation availability 2
   2.2. Pre-processing glider observations for data assimilation 3
   2.3. System description 4
   2.4. Experiments 5
3. Model assessment 6
   3.1. SOCIB WMOP 6
   3.1.1. Sea level anomaly 6
   3.1.2. Sea surface temperature (SST) 7
   3.1.3. Vertical profiles 8
   3.2. MedFS 11
4. Model intercomparison 15
   4.1. Seasonal error profiles 16
   4.2. Evaluation of Balearic Sea eddy 18
5. Interfaces with other tasks and WPs 20
6. Conclusions 21
7. Future perspectives 21
References 23

Executive summary

The present deliverable is a continuation of deliverable D4.2[1], in which we presented the first steps in the design and preparation of different reanalysis simulations assimilating glider data. We here show the assessment and intercomparison of CMCC MedFS and SOCIB WMOP systems experiments. We have performed, for each system, three different experiments, running a one-year simulation during 2017. We compare a free-run simulation without data assimilation (FREE) and two reanalyses including assimilation: one considering only the generic data sources included in each operational system (NOGLID) and another one adding glider observations to the previous dataset (GLIDER).

The models are assessed and inter compared to each other, focusing on the performance to represent the observed 3D structure of the ocean and on their capacity to recreate physical processes, as an anticyclonic eddy structure present in the Balearic sea. Results show how in both systems the use of glider observations can help to further improve the results obtained when using data assimilation, helping to an enhancement of the forecasting capabilities.

1. Introduction

WP4 of the EuroSea project aims to improve marine forecasting systems by increasing the quality and quantity of observations for better analysis and more skilful forecasts. One of the main objectives of task 4.2[2] is to ingest glider observations in two different ocean analysis and forecasting systems in the western Mediterranean Sea and evaluate their impact in a long-term simulation.

Gliders are becoming an increasingly important tool for ocean observation due to their high spatial and temporal resolution. However, incorporating glider data into ocean models is not straightforward. Their high-resolution observations cannot be considered independent from each other, and their errors are often assumed to be uncorrelated in assimilation systems. This study assessed different strategies for using glider data in two completely different systems.

CMCC's Copernicus Marine MED-MFC physical system (MedFS) and SOCIB's WMOP model have been evaluated and intercompared, performing different one-year-long simulations with and without glider observations to evaluate the impact in the models. The intercomparison has been performed for the year 2017. It was selected as it was the year with the largest number of available glider observations in the Western Mediterranean. Furthermore, MedFS will also be used in task 4.2 to force the biogeochemical system in which BGC-Argo and glider data are assimilated. This evaluation is not addressed in this deliverable but in deliverable D4.10[3].

[1] https://doi.org/10.3289/eurosea_d4.2

[2] EuroSea task 4.2: Assimilation in the Mediterranean Sea Copernicus Marine modelling system and analysis/forecast quality assessment

[3] https://doi.org/10.3289/eurosea_d4.10

2. Experiment setup

2.1. Glider observation availability

The availability of glider observations in the Copernicus Marine repository was a big issue that needed to be addressed before running the simulations, as was extensively discussed in the previous deliverable D4.2. Briefly, a preliminary research showed a significant mismatch between the glider missions from SOCIB's glider fleet, stored at the institutional repository, and those in the Copernicus Marine in-situ catalogue. These represent the most significant part of all the glider observations in the region during 2017, as reported in Table 1. Thus, a joint effort needed to be made in order to merge both datasets. For 2017, more than 25000 glider profiles are available in Copernicus Marine[4] portal. The data are all L2, i.e., profiles are collocated vertically and have been quality controlled and flagged by Coriolis, which is the Production Unit integrating ocean glider data in Copernicus Marine Service.

Table 1. Number of glider observations in three years provided by different institutions shown in Figure 1 and their annual sum in the central and western Mediterranean.

	SOCIB	**OGS**	**IFREMER**	**INSU**	**ENSTA**	**CMRE**	**OC-UCY**	***Total***
2017	14386	76	666	6937	373	3149	260	25847

Seven institutions provided glider observations, as identified in the file metadata information in the central and western Mediterranean in 2017. Figure 1 shows the spatial distribution of the data from each provider, which are marked in different colours (see the legend). The largest volume of glider observations is located in the western Mediterranean. There are some gliders operated in the Adriatic Sea delivered by OGS, in the Sicily Strait by INSU and by OC-UCY in the Levantine basin. The temporal distribution of the observations in the different sub-basins of the Western Mediterranean is shown in Figure 2. In 2017 most of the observations were provided by SOCIB. In the Ibiza channel, an endurance line provides almost continuous monitoring of the area, and from the Balearic Islands towards Corsica and towards the Algerian basin there were several missions. Some observations cover the area between the Gulf of Lion and the Ligurian Sea provided by CMRE, IFREMER, ENSTA and INSU. Table 1 summarises the number of observations per provider (see also the legend in Figure 1) and their annual sum. We refer to D4.2 for a complete discussion on the observation availability and efforts to achieve the best practices to access the broadest coverage via a joint workshop organised by the Task 4.2 team.

[4] INSITU_MED_NRT_OBSERVATIONS_013_035

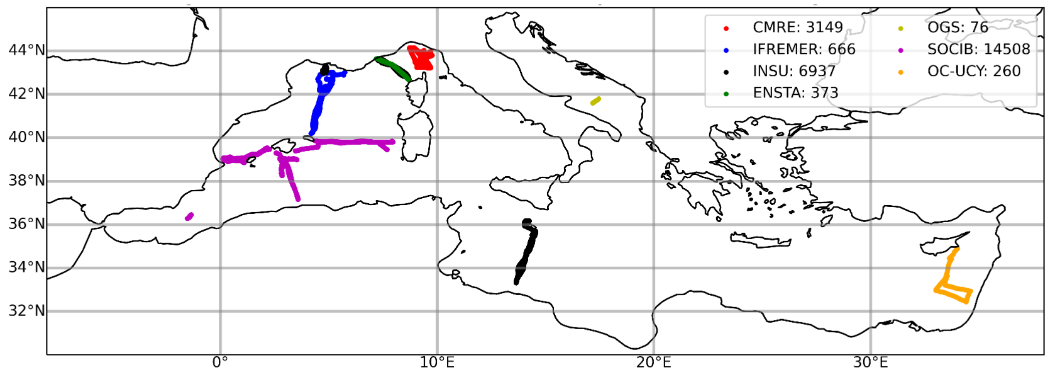


Figure 1. Distribution of glider observations in 2017 provided by six institutions: CMRE (red), IFREMER (blue), INSU (black), ENSTA (green), OGS (yellow) and SOCIB (purple). Data retrieved from CMEMS repository "monthly" catalogue on 10 October 2021.

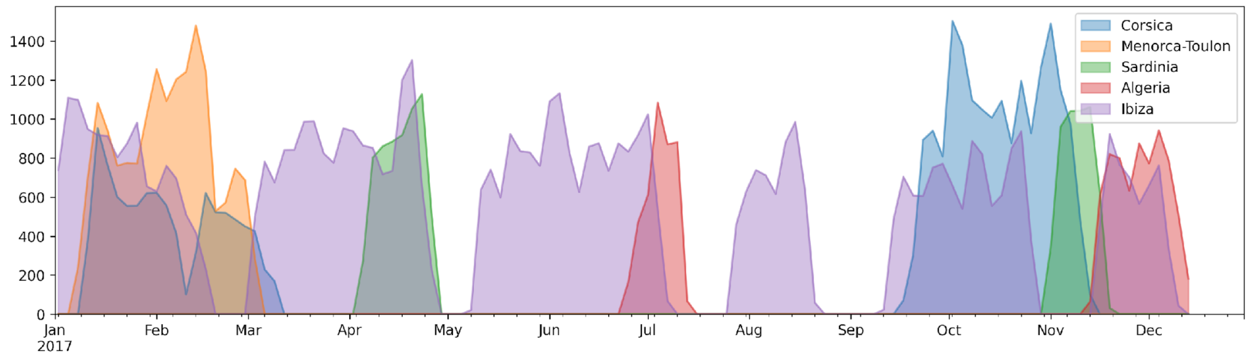


Figure 2. Temporal distribution of glider observations in the different sub-basins of the WesternMed during 2017.

2.2. Pre-processing glider observations for data assimilation

Glider data assimilation is not straightforward, and data should be analysed carefully before ingestion in the model. Several pre-processing techniques have been discussed and analysed for this intercomparison experiment, as described in deliverable D4.2. The optimal pre-processing strongly depends on the model used, the type of assimilation scheme, the temporal window or the kind of observational errors considered. Here, as in most state-of-the-art works, we will consider the observation errors uncorrelated for technical and computational reasons. Given the differences between the modelling systems, and the fact that this optimal pre-processing approach is not unique, we decided not to follow a common strategy for both models but a "best as possible" method. Thus, each team decided on the pre-processing procedure that best suits their system, which minimises the errors in the analysis most.

SOCIB WMOP uses a super-obbin dataset. All up and down-cast profiles from the CMEMS L2 product are considered from bottom to surface. For each grid cell, a single observation is considered. Profiles are binned vertically to have one observation in each vertical level. Then all the observations from the different profiles are averaged to provide a single value. The variance of all the observations in the cell is added to the representation error.

In MedFS, several strategies are tested to assimilate glider observations. These include choosing all ascending and descending profiles if they sample the first 10 m of the water column to avoid constraining the surface with the deep observations. Another approach was to vertically subsample all ascending profiles on the model layers to avoid the correlations in the assimilated observations. Finally, what we present here is an experiment with all ascending profiles without any vertical subsampling. This choice is done partially considering that we assign an increased observation error to the gliders in the R matrix, but also, we do not see a major increase in the computational cost in the minimisation of the cost function.

2.3. System description

In Task 4.2 we have employed MedFS and WMOP systems, whose modelling domains are shown in Figure 3. The MedFS system (Clementi et al. 2021, Coppini et al. 2023) is a NEMO configuration that covers the entire Mediterranean Sea, with a horizontal resolution of 1/24° and 141 vertical levels, and also includes an Atlantic box. On the other hand, the WMOP system (Juza et al. 2016, Moure et al. 2018) is a ROMS configuration for the western Mediterranean Sea, spanning from the Gibraltar Strait in the west to Corsica/Sardinia Island in the east, with a high horizontal resolution of 1/50° and 32 vertical sigma-levels. For the data assimilation, MedFS employs a 3D variational scheme (OceanVar), while WMOP uses an EnOI ensemble-based method (Hernandez-Lasheras and Mourre 2018). Table 2 provides additional differences between MedFS and WMOP. Both systems are configured to assimilate glider observations, with observation operators implemented and updated in each system. The OceanVar at CMCC uses the observation operator from Storto et al., (2016), updated over time for temperature and salinity observations. In the past, the WMOP data assimilation system has successfully assimilated data from up to 8 simultaneous gliders, as demonstrated in Hernandez-Lasheras and Mourre (2018). It was also used to evaluate the impact of high-frequency radar (HFR) surface currents (Hernandez-Lasheras et al. 2021).

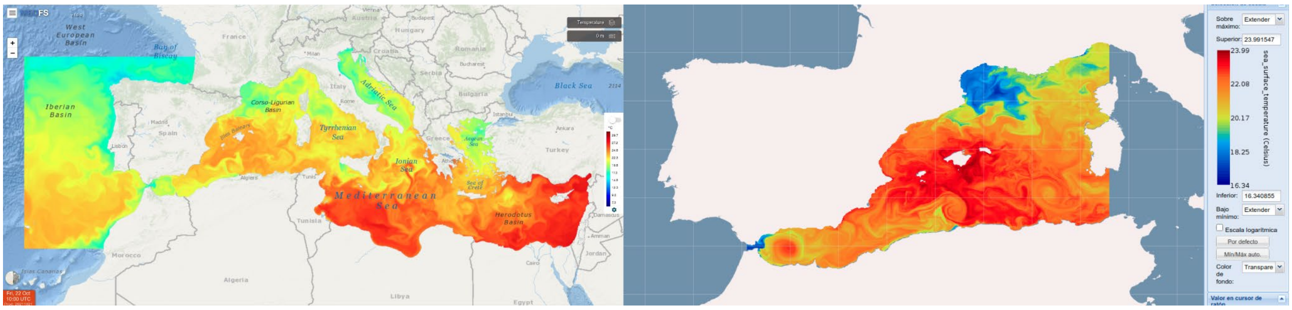


Figure 3. Left: MedFS systems domain including the Atlantic box. Right: WMOP system domain in the western Mediterranean. Both maps are coloured by sea surface temperature. Last access 19/10/2021 from https://medfs.cmcc.it and https://socib.es/?seccion=modelling&facility=lw4nc , respectively.

Table 2. Main configuration

	MedFS (CMCC)	WMOP (SOCIB)
Domain	Mediterranean Sea (+ Atlantic box)	Western Med. Gibraltar to Corsica- Sardinia
Resolution	1/24° degree (~4.5km) 141 z* vertical levels	~1/50° degree (2km) 32 vertical sigma-levels
Numerical model	NEMO v3.6 < - > WW3 v3.14	ROMS v3.4
Time step	240 sec (Barotropic step 2.4sec)	120 sec (Barotropic step 6sec)
Parameterizations	Tides, atmospheric pressure	No tides, No atm. pressure
	climatological inputs from 39 rivers.	climatological inputs from 6 major rivers.
	Richardson number-dependent vertical diffusion	Generic model of two-equations GLS turbulent closure.

	MedFS (CMCC)	WMOP (SOCIB)
	Flather for barotropic currents and SSH. Orlanski for baroclinic currents	Flather for 2-D momentum. Chapman for surface elevation. Mixed radiation-nudging for 3-D equations.
Atmospheric forcing	ECMWF HR 10km, 6hr resolution	AEMET (Spanish meteorological agency) HARMONIE 2.5km 1hr
Lateral open boundary condition	From Copernicus Marine GLO-MFC NRT system	From Copernicus Marine MED-MFC
Data Assimilation	OceanVar: SLA along tracks, ARGO vertical T/S profiles. SST relaxation to gridded product in NEMO	EnOI: SLA along-track, ARGO vertical T/S profiles, SST L4 satellite product, HF-Radar (Ibiza Channel)

2.4. Experiments

For each system, three different simulations have been run to evaluate the impact of glider observations. First, a free run simulation without data assimilation that has been used as control (FREE). Second, a simulation that in each case uses the actual configuration of the model which is used operationally (NOGLID). This simulation assimilates satellite altimetry and sea surface temperature and Argo floats temperature and salinity profiles. Additionally, the SOCIB model also assimilates surface current observations from the HFR system in the Ibiza Channel. Finally, the third simulation that in addition to the observations from NOGLID also includes glider temperature and salinity profiles (GLIDER). Figure 4 illustrates the amount of observations from each data source that are assimilated in the WMOP system during the whole period for GLIDER simulation. Note that there is a gap in SST observations during March for this particular experiment. For three consecutive analyses dates there was an issue downloading the observations from the server, which we noted a posteriori. However, this gap does not appear to impact the results in our assessments and we decided not to run the whole simulation again.

Table 3. Simulation name list with the data observations being assimilated in each one.

	FREE	NOGLID	GLIDER
MedFS	no assimilation	SLA, SST, Argo (T-S)	SLA, SST, Argo (T-S) + **Gliders**
WMOP	no assimilation	SLA, SST, Argo (T-S), HFR	SLA, SST, Argo (T-S), HFR + **Gliders**

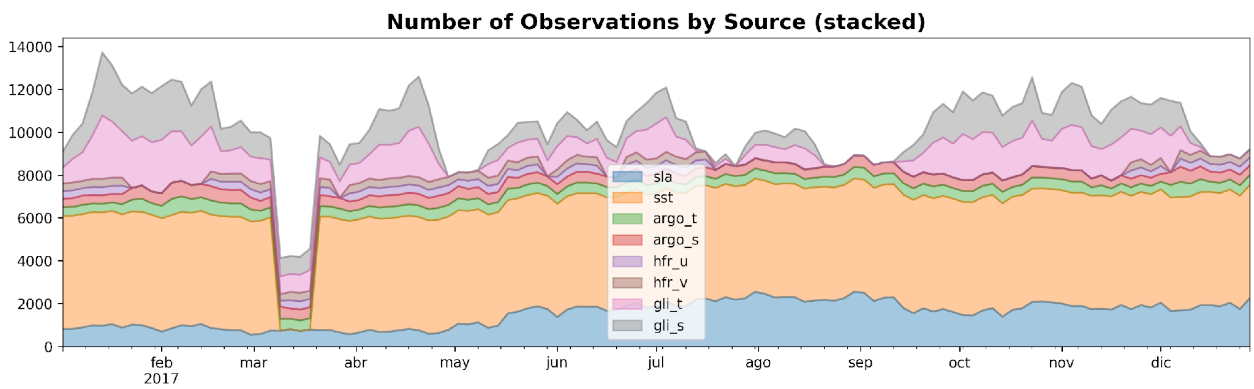


Figure 4. Timeline of the number of observations by each source for WMOP GLIDER simulation.

3. Model assessment

First, each model has been assessed individually to evaluate the performance of the data assimilation system and the impact of each observation source in the different fields. Here, each partner has performed its own assessment using its own tools and metrics.

3.1. SOCIB WMOP

3.1.1. Sea level anomaly

Model sea level anomaly has been compared against L4 satellite products. As it can be seen in Figure 5, the correlation between satellite observations and the model presents a significant improvement. While FREE simulation has low correlation (mean value of 0.2), especially between March and August, the simulations using DA increase the correlation, with values between 0.5 and 0.8 for most part of the year. Both simulations present a similar behaviour, with one simulation slightly outperforming the other depending on the time of the year, with a mean value of 0.66 for GLIDER and 0.69 for NOGLID.

In terms of RMSD, the improvement is moderate (5-10%) when using data assimilation. However, this is also due to the increase in the BIAS (mean error). This is an effect that is common in many data assimilation systems when including altimetry observations due to the different mean sea level. For this, we prefer to focus on the centred RMSD (cRMSD), that does not take into account the mean deviation. As we can observe in Table 4, the cRMSD is reduced by 42% for NOGLID simulation and 38% for GLIDER. This decrease is steady along the year and similar for both simulations assimilating data.

Table 4. Assessment metrics comparing the sea level anomaly L4 maps from satellite against SOCIB WMOP model.

	RMSD	cRMSD	Corr	BIAS	RMSD-Norm	cRMSD-Norm
FREE	0.10	0.06	0.20	-0.07	1.00	1.00
NOGLID	0.09	0.04	0.69	-0.08	0.89	0.58
GLIDER	0.10	0.04	0.66	-0.09	0.96	0.62

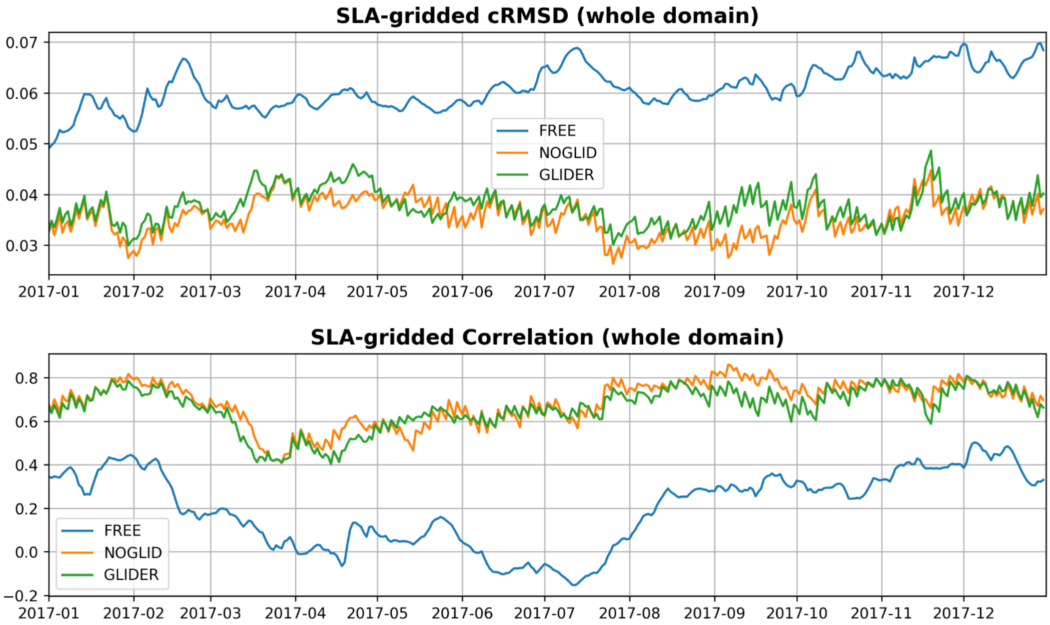


Figure 5. Sea level anomaly centred RMSD (top) and correlation (bottom) evolution along the 2017 year of satellite L4 observations against the three different WMOP simulations.

3.1.2. Sea surface temperature (SST)

For SST we employ the Copernicus Marine L4 UHR (ultra-high resolution) for the Mediterranean Sea. This is a blended product which uses several different satellites providing 1 km resolution observations. For our validation we subsample the satellite daily observations taking one observation every 10 km grid and compare it against the mean field of the model at that date. Data assimilation has a big impact reducing the RMSD error around 20% and increasing the correlation, as summarised in Table 5. NOGLID and GLIDER simulations have similar results during the whole simulation period, obtaining a significantly better performance than FREE, mainly from the end of August to beginning of February, coinciding with the half of the year where the ocean is cooling down (Figure 6).

Table 5. Assessment metrics comparing the sea surface temperature L4 UHR maps from satellite against SOCIB WMOP model.

	RMSD	cRMSD	Corr	BIAS	RMSD-Norm	cRMSD-Norm
FREE	0.73	0.65	0.84	-0.26	1.00	1.00
NOGLID	0.60	0.48	0.91	-0.32	0.81	0.73
GLIDER	0.60	0.49	0.90	-0.32	0.81	0.75

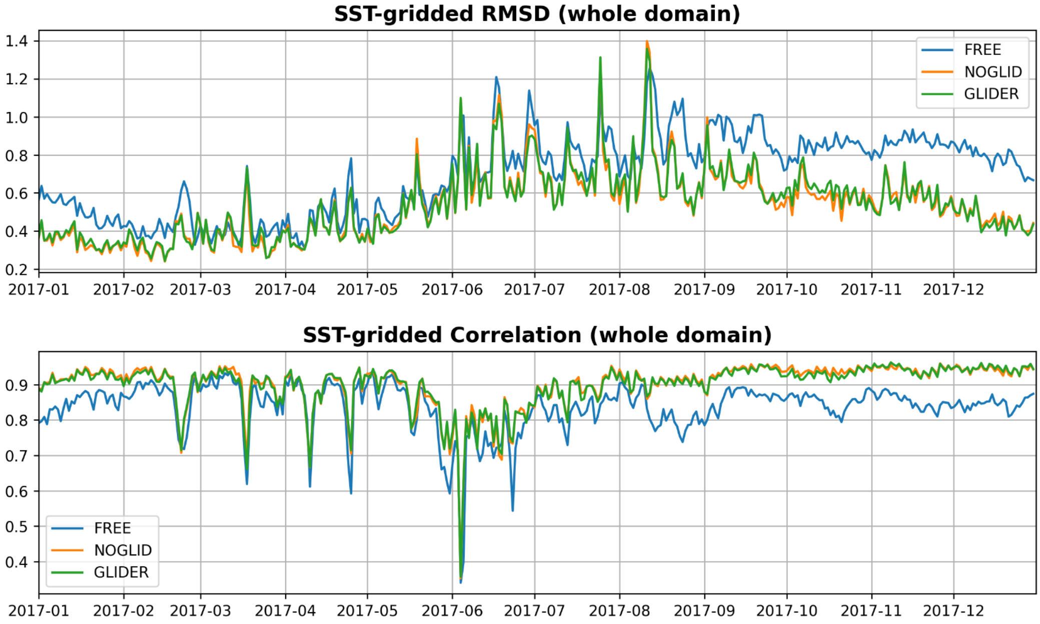


Figure 6. Sea surface temperature RMSD (top) and correlation (bottom) evolution along the 2017 year of satellite L4 observations against the three different WMOP simulations.

3.1.3. Vertical profiles

We have used all the Argo and glider observations in the model domain during the whole year to validate. Note that this is not an independent validation, since all these floats have been assimilated into the model. We have first analysed the mean RMSD averaging in all depths and binning by longitude and latitude to have an estimation of the regions where the model has a higher error with respect to observations, as illustrated in Figure 7.

As it can be seen, the RMSD in the temperature profiles highly decreases when using data assimilation. NOGLID simulation reduces these discrepancies all over the domain, with the exception of the Ibiza channel, where results are similar to FREE. When including glider data in the system, we observe that GLIDER simulation is able to reduce this error also in the Ibiza channel, while having a similar average performance as NOGLID in the rest of the domain.

For the salinity fields we can observe a similar behaviour. FREE has a higher error, especially in the southern part of the domain which is corrected in NOGLID, with the exception of the Ibiza channel area. From the RMSD salinity map for NOGLID, it can be also observed how the error is slightly higher over the other glider lines, since these observations have not been ingested in the system. Again, the GLIDER simulation has a low and homogeneous error in all the domain outperforming FREE and NOGLID.

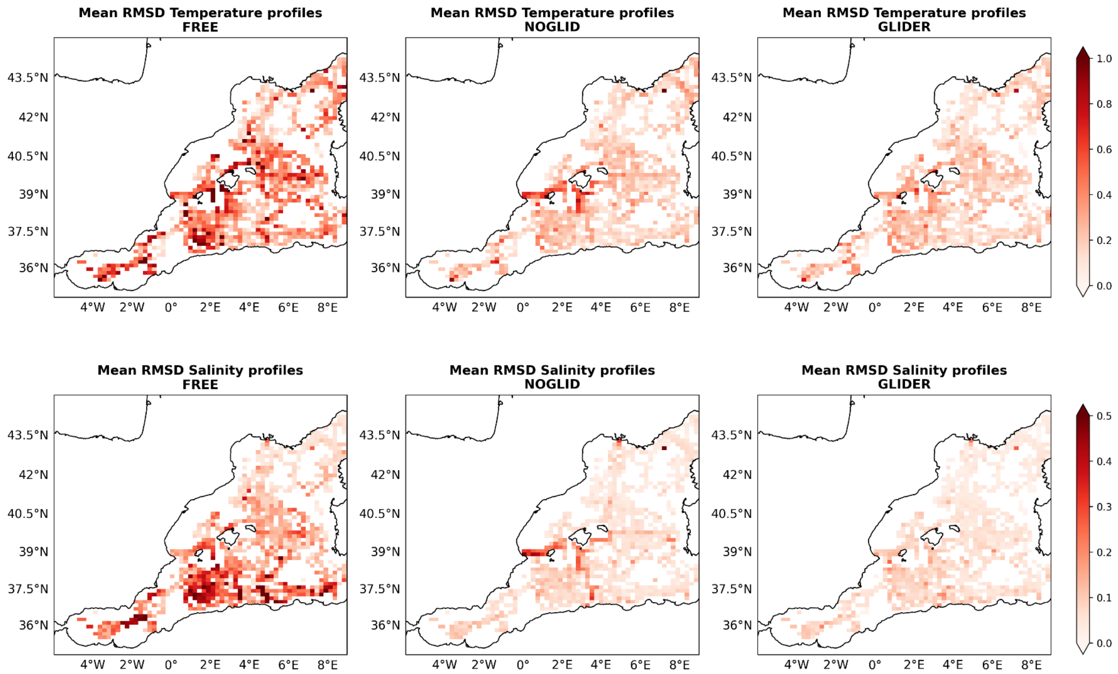


Figure 7. Spatial representation of the RMSD for temperature and salinity profiles averaged in all depths.

Argo

Scatter plots below show Argo temperature (Figure 8) and salinity (Figure 9) observation against its model equivalents for the three different simulations. Each panel depicts also the metrics in each case. It can be seen how the model fits the observations when these are assimilated, reducing the RMSD by 39% and 65% and increasing the correlation compared to FREE, for temperature and salinity respectively.

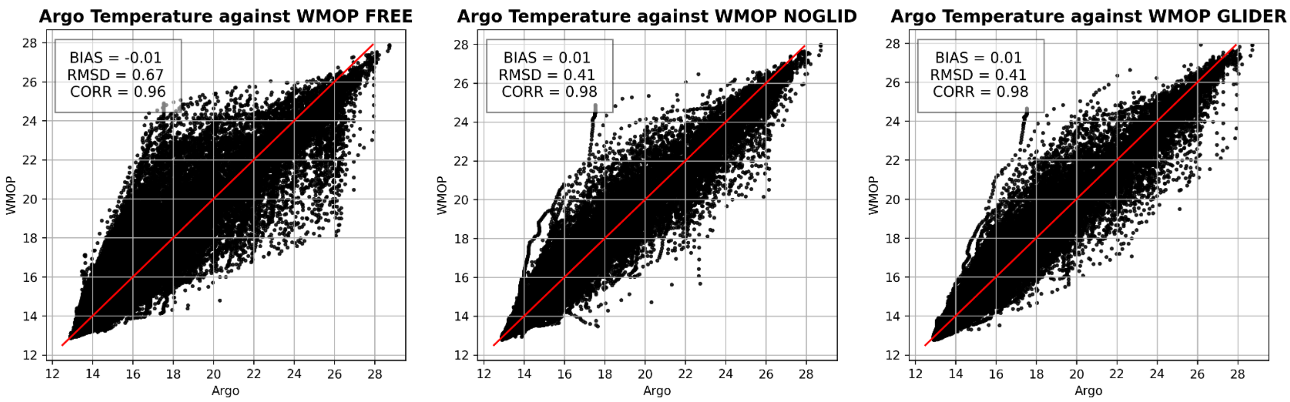


Figure 8. Scatter plot of all Argo temperature observations in 2017 against the three WMOP simulations. Metrics (BIAS, RMSD and Correlation) from each simulation are shown in the correspondent panel.

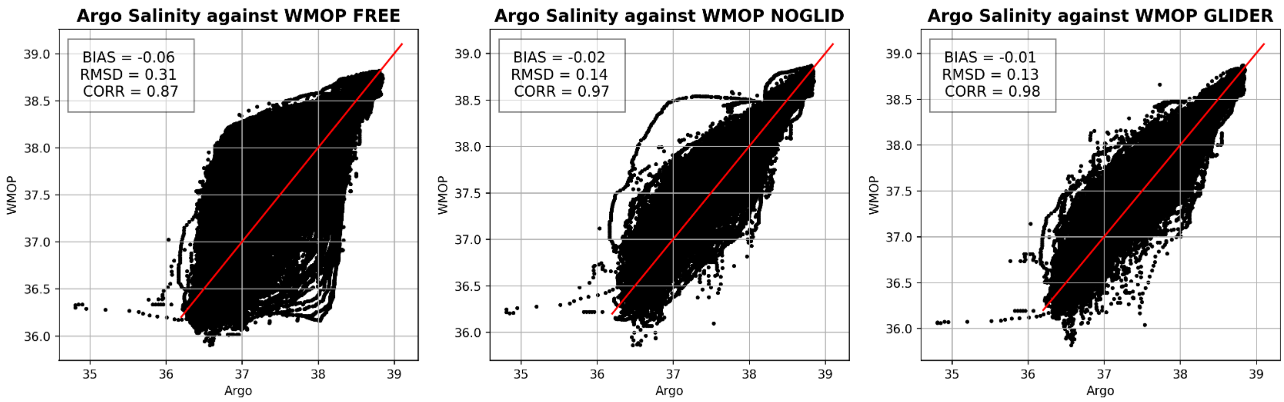


Figure 9. Scatter plot of all Argo temperature observations in 2017 against the three WMOP simulations. Metrics (BIAS, RMSD and Correlation) from each simulation are shown in the correspondent panel.

Gliders

The glider observations have also been compared against their model equivalents, and metrics have been calculated independently from the other in-situ profile observations (Argo).

In Figure 10 it can be observed that in all three simulations the RMSD is higher during the second half of the year, in relation with the increased stratification of the water column. Especially in temperature the discrepancies between the model and the observations are higher from May onwards, with the higher error in the most surface layers, that tends to be slightly deeper towards the end of the year, where the maximum can be found around 80 m depth. The temporal increase in the second half of the year is also observed in the salinity observations. Regarding the differences between simulations, NOGLID does not show an improvement with respect to FREE. While in temperature the error is slightly reduced in the surface layers (above 100 m), this is not consistent along the year, and below 100 m NOGLID degrades FREE simulation. This decrease in the performance below 100 m is more evident in the salinity profiles, leading to a total 4% increment in the average RMSD in the whole water column for all the year.

The assimilation of glider data helps to reduce the error between model and observations. GLIDER simulation shows a decrease in the RMSD during the whole year, both in temperature and in salinity. Although there can be observed a slight increase in the temperature RMSD in depth (400-800 m) during the summer, the rest of the year GLIDER clearly outperforms NOGLID and FREE simulations, leading to a 40% and 50% total error reduction in temperature and salinity respectively, with respect to FREE simulation.

An important point to highlight is the lower performance of NOGLID simulation with respect to what could be expected. Theoretically, the assimilation of SLA, SST and Argo should help to reduce the error everywhere. Note that these metrics are highly impacted by results in the Ibiza channel area. Given the amount of observations there, its weight in the metrics is very significant. The complex dynamics in the area could generate some ensemble correlations that may introduce stronger vertical corrections leading to a representation of the water masses that is not fully satisfactory. This is partially corrected when using glider observations. As we can observe, the spatiotemporal RMSD is reduced for the GLIDER simulation. This representation of deep water masses remains to be analysed in detail to improve model results.

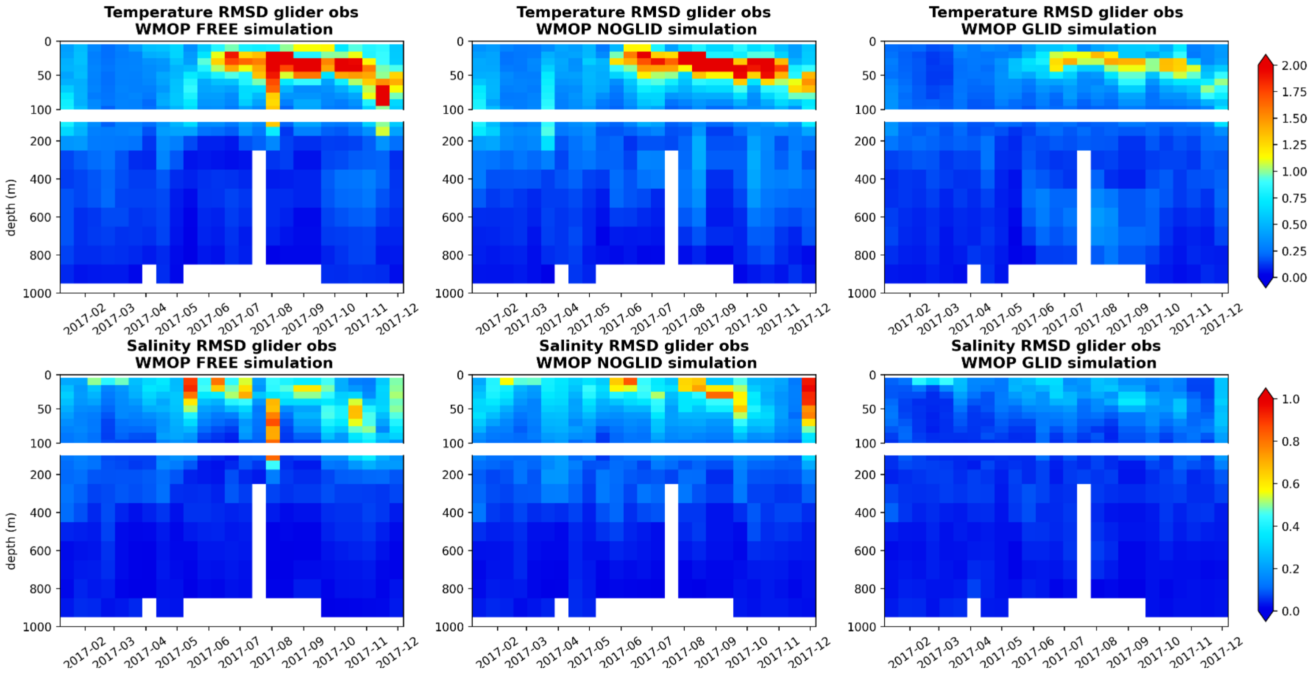


Figure 10. Temporal evolution of the biweekly RMSD profile until 1000m along the simulation period. Temperature is plotted at the top, and Salinity at the bottom panels. Each simulation is shown in one column: FREE (left), NOGLID (centre), GLIDER (right).

3.2. MedFS

Experiments in MedFS are evaluated in terms of estimated accuracy numbers (EAN) using the all observations from ARGO and glider profilers for the temperature and salinity. EAN in this section are performed in the entire Mediterranean Sea for in-situ observations, unless explicitly stated.

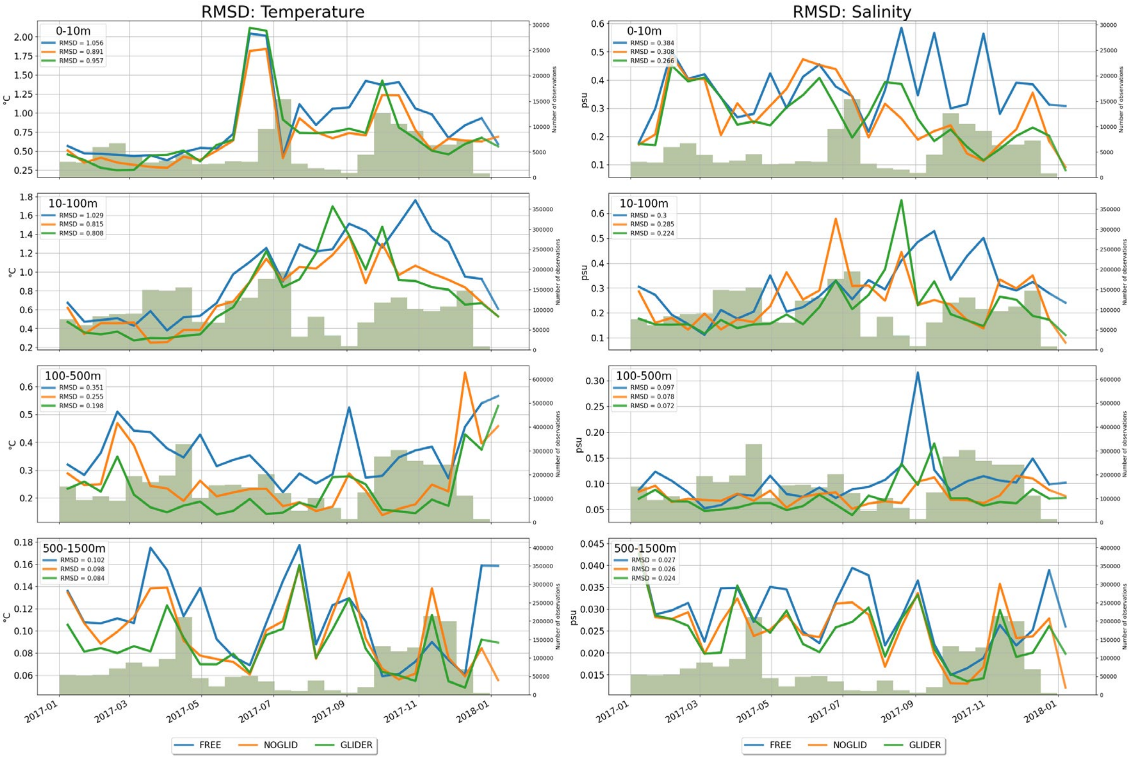


Figure 11. Biweekly time series of RMS of temperature (left) and salinity (right) difference for depth layers 0-10 m, 10-100 m, 100-500 m, 500-1500 m, from top to bottom. The annual mean RMSD are printed in the legend of each panel. The experiment without assimilation (FREE), with assimilation without gliders (NOGLID), with assimilation with gliders (GLIDER) are depicted in blue, orange and green colours, respectively. We refer to Table 3 for the information on each experiment.

Table 6. Summary of mean RMS of temperature and salinity difference between the observations and model at each depth layer 0-10 m, 10-100 m, 100-500 m, 500-1500 m in 2017.

		RMSD Temperature (ºC)	**RMSD Salinity**
0 - 10 M	FREE	1.06	0.38
	NOGLID	0.90	0.31
	GLIDER	0.96	0.27
10 - 100 m	FREE	1.03	0.30
	NOGLID	0.82	0.29
	GLIDER	0.81	0.22
100 – 500m	FREE	0.35	0.10
	NOGLID	0.26	0.08
	GLIDER	0.20	0.07
500 - 1500	FREE	0.10	0.03
	NOGLID	0.10	0.03
	GLIDER	0.08	0.02

In Figure 11, biweekly time-series of RMSD of temperature and salinity for 0-10 m, 10-100 m, 100-500 m, 500-1500 m are shown while their mean RMSD are outlined in Table 6. With respect to FREE run without any data assimilation, GLIDER with all observations always has improved RMSD of temperature and salinity at each depth layer. We note a degradation of temperature in the upper 10 m. against NOGLID, however, the rest of the water column on average is improved when the glider observations are assimilated. In some periods in the timeseries, for example, August - September at 10-100 m there is a degradation with respect to NOGLID. Although the reason is not very clear, it may be related to the strong stratification in the water column that may not be well represented in the background and observation error covariances, it should be noted that in this specific period the number of observations are quite low. It can be better seen if we compare NOGLID and GLIDER experiments via their Hovmoller diagrams of temperature and salinity RMSD (Figure 12).

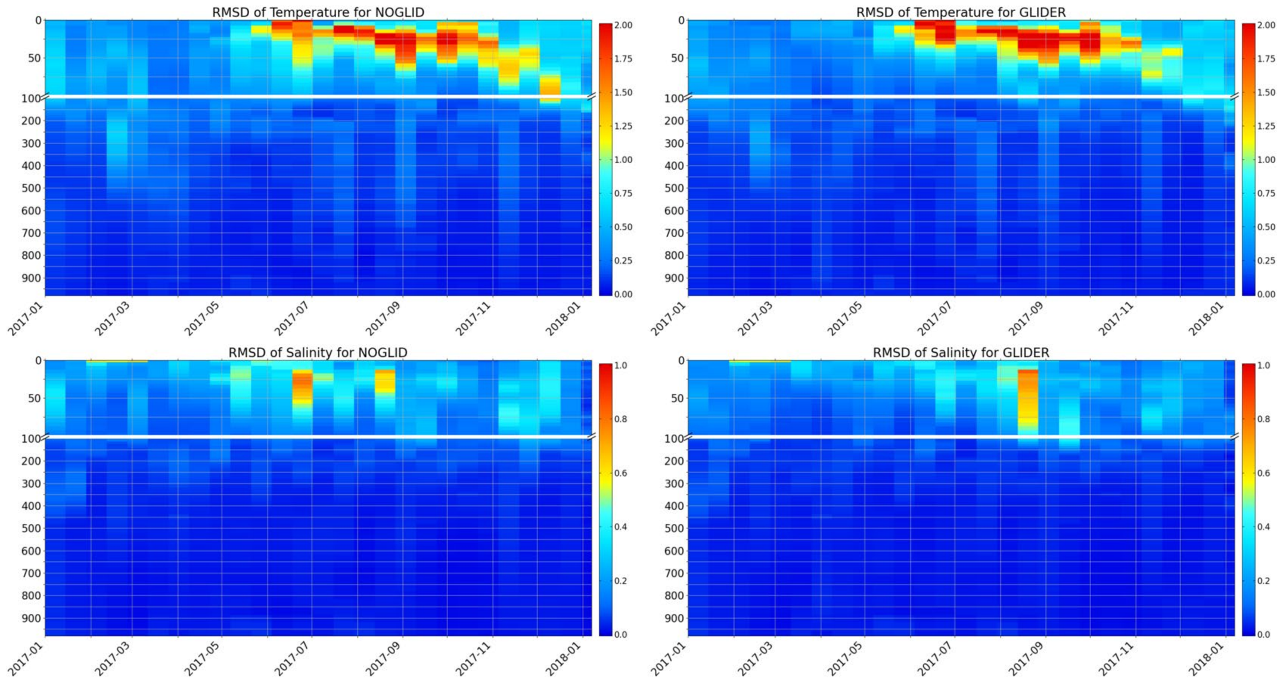


Figure 12. Hovmoller diagrams of RMS of temperature (top) and salinity (bottom) difference until 1000 m. We show only NOGLID (left) and GLIDER (right) experiments to compare the impact of glider assimilation in all depths.

Figure 12, the evolution of temperature RMSD in NOGLID and GLIDER experiments in the first 1000 m are shown, respectively, in the upper left and upper right panels. The ones for salinity instead are depicted in the bottom row. In salinity, the general improvement can be noticed easily, except last week of August between 50-100 m. For temperature, a general improvement below 100 m is seen between July - September while larger RMSD are found in the first 100 m. While before July and after September, in the entire water column the errors are reduced.

In Figure 13, we show the spatial distribution of the RMSD (top) and BIAS (mid) of temperature in different seasons for NOGLID and the number of in-situ observations at the bottom row. We note the large observation density on the glider path over all seasons is noticeable. The errors are larger in summer and fall season as expected due to the seasonal stratification but also due to the dynamic mesoscale structures in areas such as south of Crete where there resides the quasi-permanent Iera-Petra eddy. Larger RMSD are present in the eastern basin in winter and spring, especially western Levantine and Aegean Seas. RMSD and bias are seen also in the Ionian Sea especially in the south of Sicily. There is a warm bias around Rhodes gyre in winter and cold bias in the south of Crete for the rest of the year which are improved in GLIDER (Figure 14).

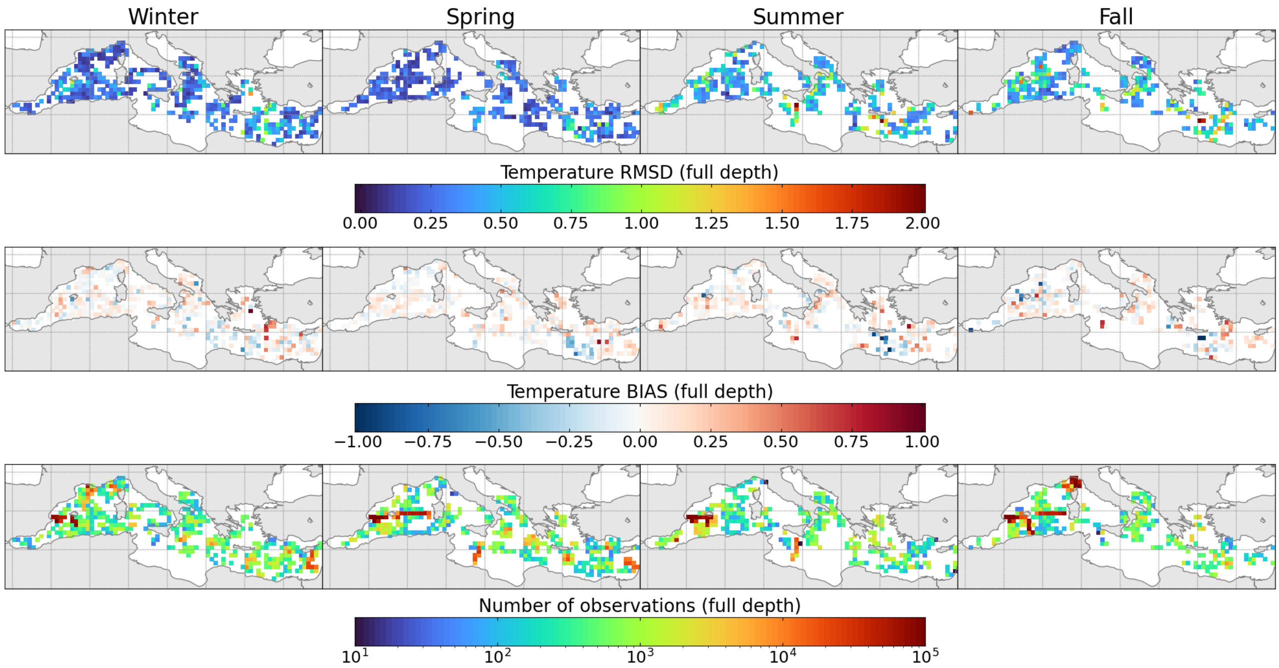


Figure 13. RMSD (top) and BIAS (mid) of temperature in the entire Mediterranean Sea for different seasons in all depths binned on a 0.5° resolution grid for NOGLID. Bottom row shows the number of observations in which the glider observations can be noticed from their density on their tracks.

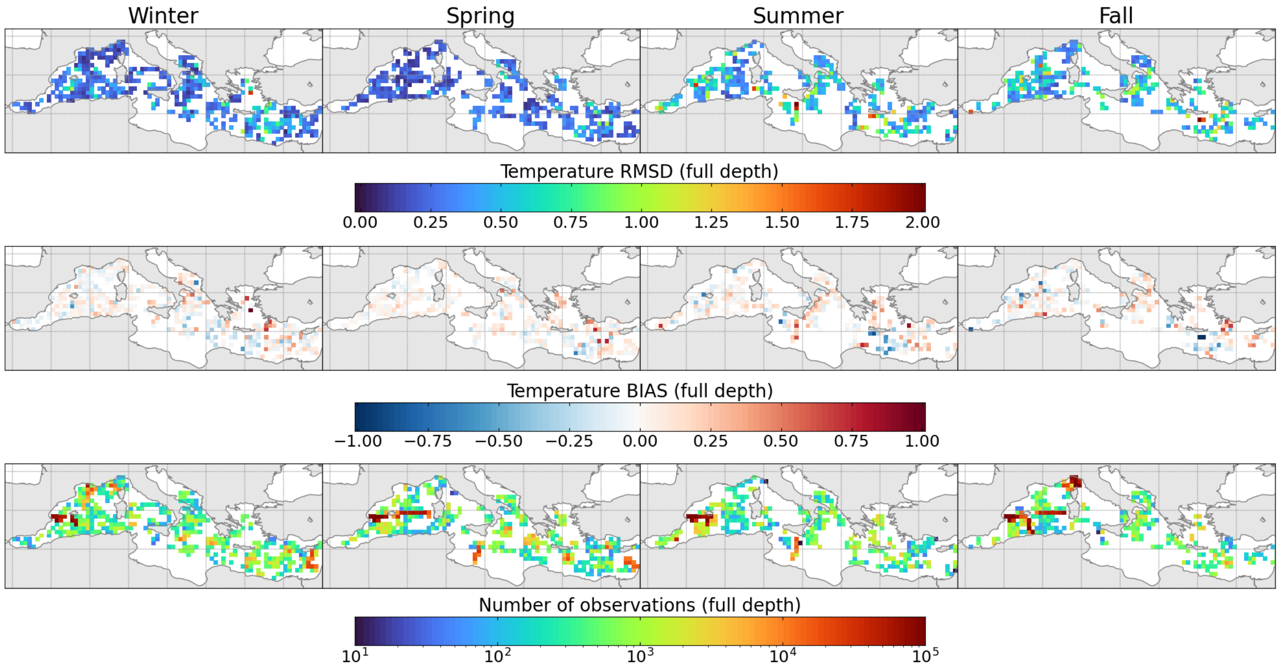


Figure 14. Same as Figure 13 but for GLIDER

For salinity instead (Figure 15 for NOGLID) larger errors are seen in the western basin in almost all seasons and in the central one in spring and summer. RMSD of salinity are particularly larger along the southern coast of the western basin and around Sicily Island. Even though they persist, the RMSD improved in GLIDER (Figure 16) in summer around Balearic Islands and south of Sicily. The bias is reduced noticeably in the same areas.

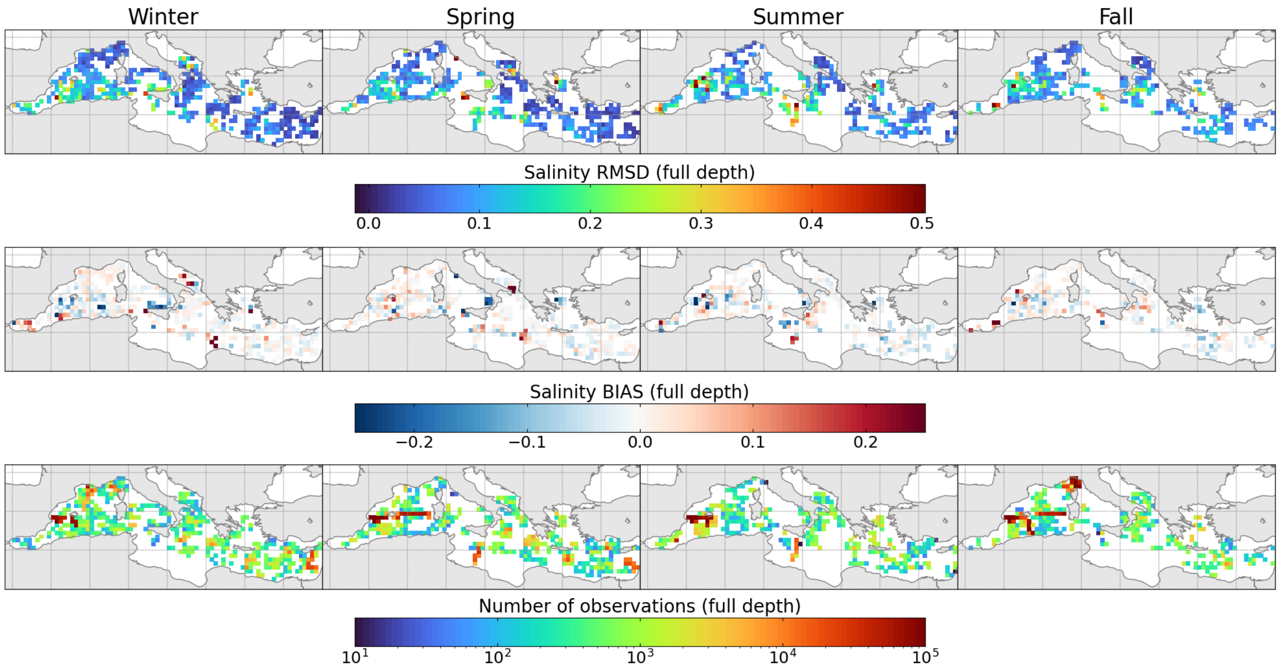


Figure 15. Same as Figure 13 but for salinity in NOGLID.

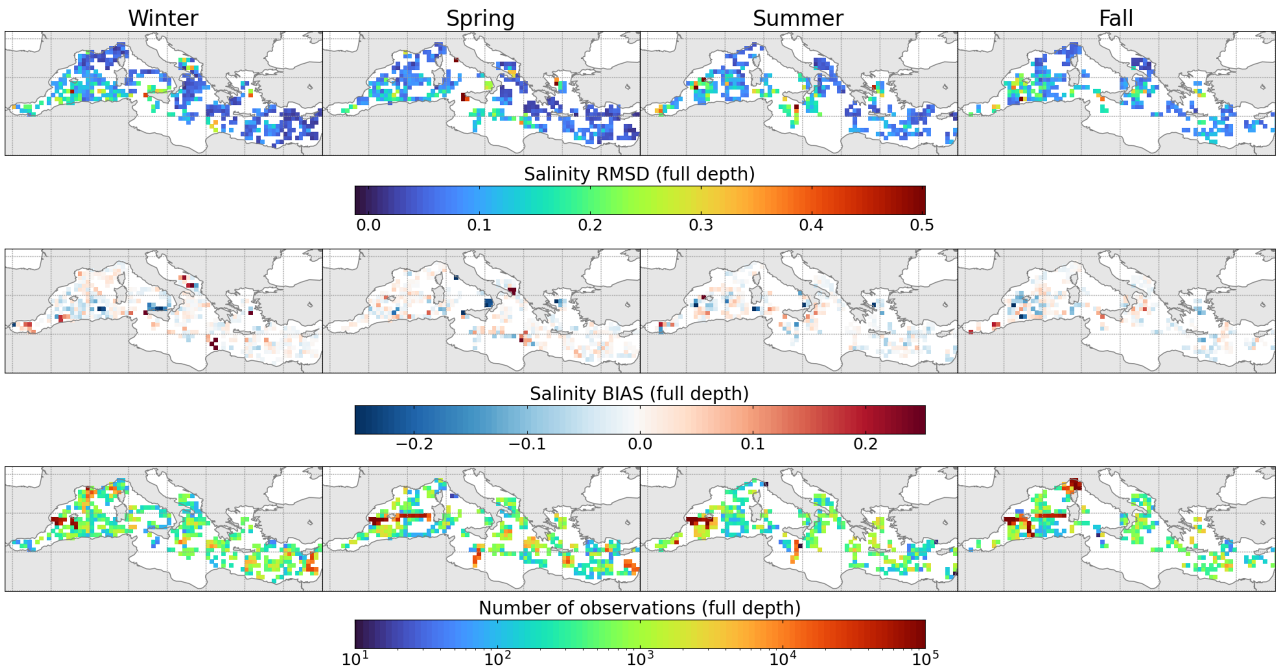


Figure 16. Same as Figure 15 but for GLIDER.

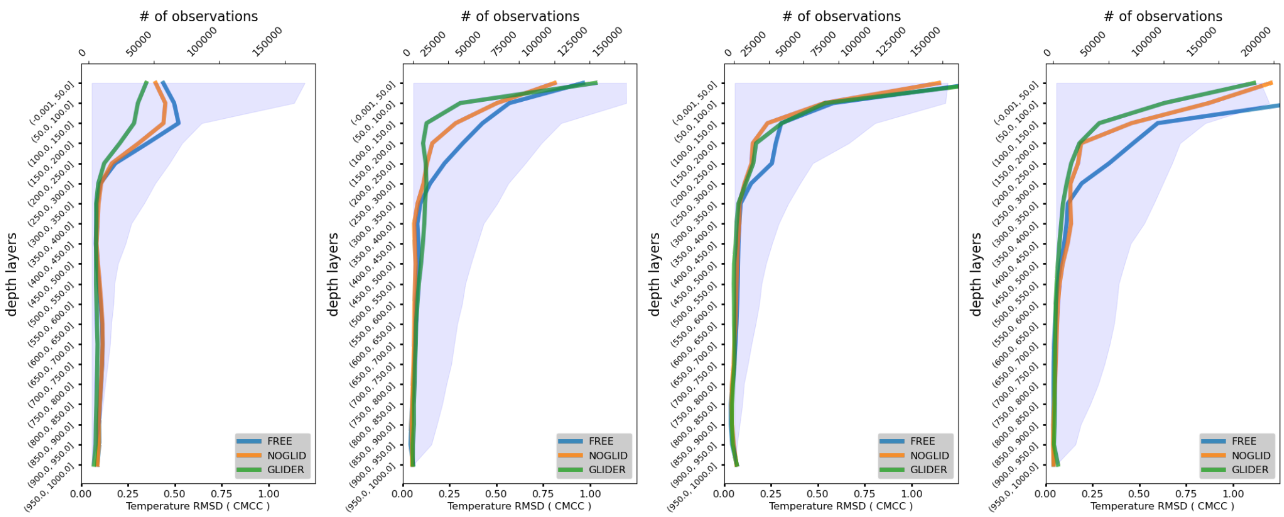
4. Model intercomparison

We performed a model intercomparison based on several aspects. Quantitative intercomparisons are necessary but may be misleading, as for example, a mean error averaged in time and/or in depth could be not showing the real performance of a simulation and may be hiding some negative aspect or, on the other side, highlighting an issue where there is not so. Point-wise metrics can also be affected by small positional discrepancies in the spatial representation of a frontal structure or an eddy. A model could be representing such circulation reasonably well but slightly displaced, which may lead to a higher error than other model that may not be representing the presence of any frontal structure, for instance. For these reasons, we have also performed an intercomparison based on more physical aspects, as the capacity of the models to improve the water mass transport across the Ibiza Channel or the representation of an anticyclonic eddy developed in the Balearic sea during the autumn and winter of 2017, as revealed in the satellite products, and whose presence and formation processes have been studied by Aguiar et al. (2021).

4.1. Seasonal error profiles

The RMSD profile has been calculated by season for all the glider profiles in the Balearic sea region. Figures 17 and 18 show the RMSD profiles of temperature and salinity respectively for both systems together with the number of available observations (see upper y-axis in plots) to which the models have been compared at each layer depth. Note that the number of glider observations used for the evaluation are the same and the differences are due to other in-situ profilers ingested in different systems. The MedFS configuration significantly reduces the temperature RMSD in the first 300 m with respect to FREE. Results show how the model benefits from the assimilation of glider data, reducing more the error in GLIDER with respect to NOGLID. Below 300 m the three experiments have similar results. Similar results are obtained for the salinity profiles, for which NOGLID outperforms FREE simulation, especially at surface, and with GLIDER further reducing the error. During the summer season, there is an increase in errors between 50-150 m depth in salinity in GLIDER simulation. This error increment is not present in NOGLID, however is not exactly understood.

On the other hand, the WMOP configuration presents worse results for NOGLID than for FREE both in temperature and salinity. Although for salinity the RMSD is slightly lower for NOGLID in the first 100 m, downwards FREE simulation gives better results. The ingestion of glider observation is able to partially correct the degradation obtained in NOGLID, with GLIDER simulation reducing the error both in temperature and in salinity also compared against FREE. Note that the errors in depth are very low and close to the instrumental error. The error is higher during the summer in layers below 150 m, possibly due to the stratification, where, although GLIDER has a lower error than NOGLID it is not able to outperform FREE.



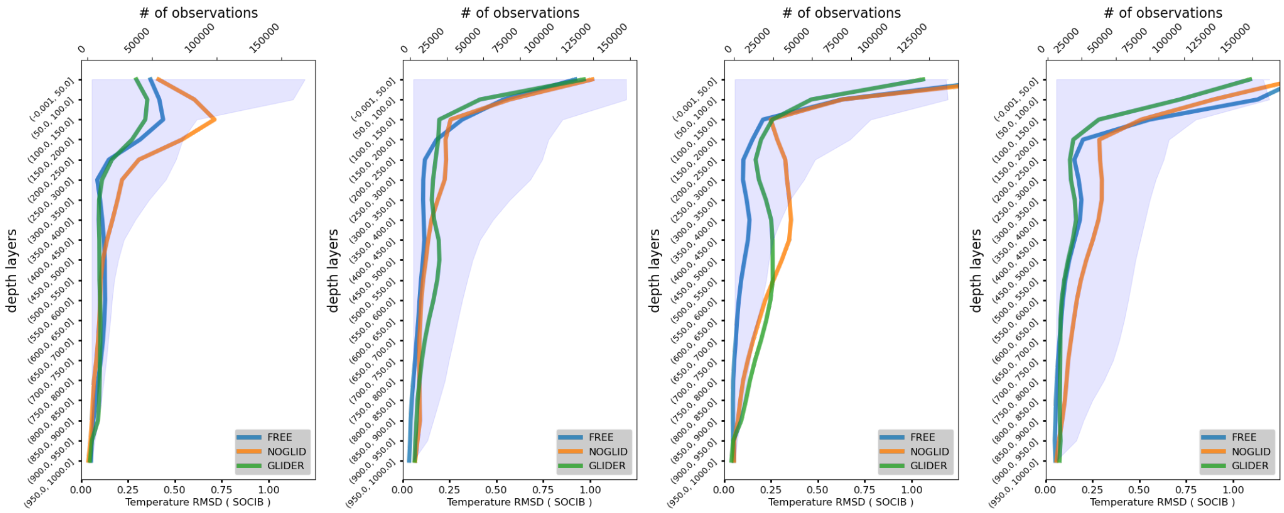
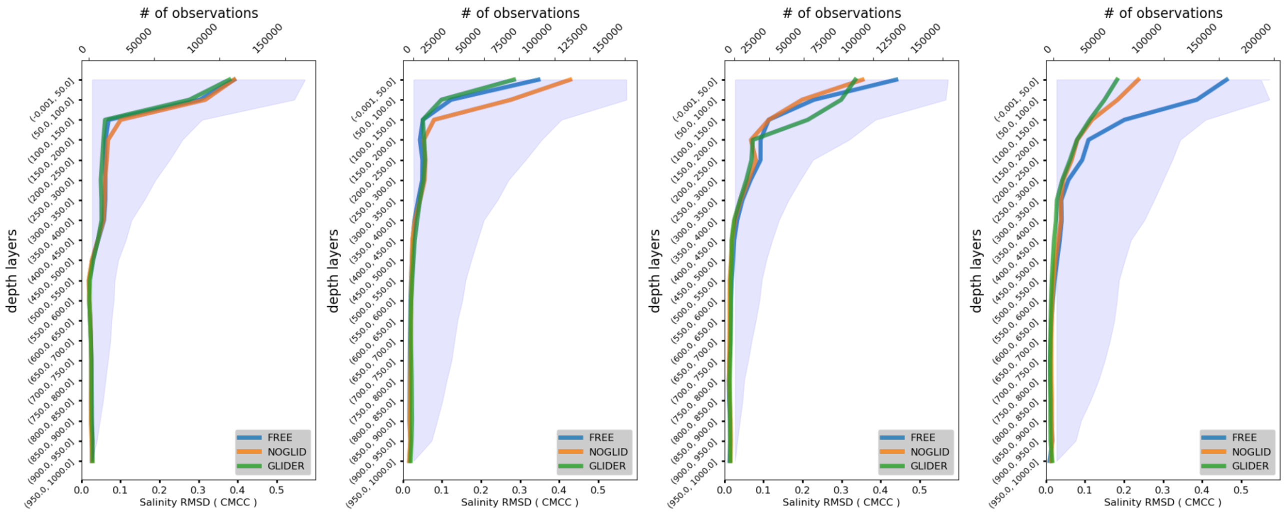


Figure 17. Seasonal RMSD profiles of temperature for CMCC MedFS (top) and SOCIB WMOP (bottom) models in the Balearic Sea. Left to right three month periods: JFM, AMJ, JAS, OND representing seasons. FREE (blue), NOGLID (orange) and GLIDER (green) differences with observations are binned every 50 m. down to 1000 m. Number of observations used in evaluation are shaded.



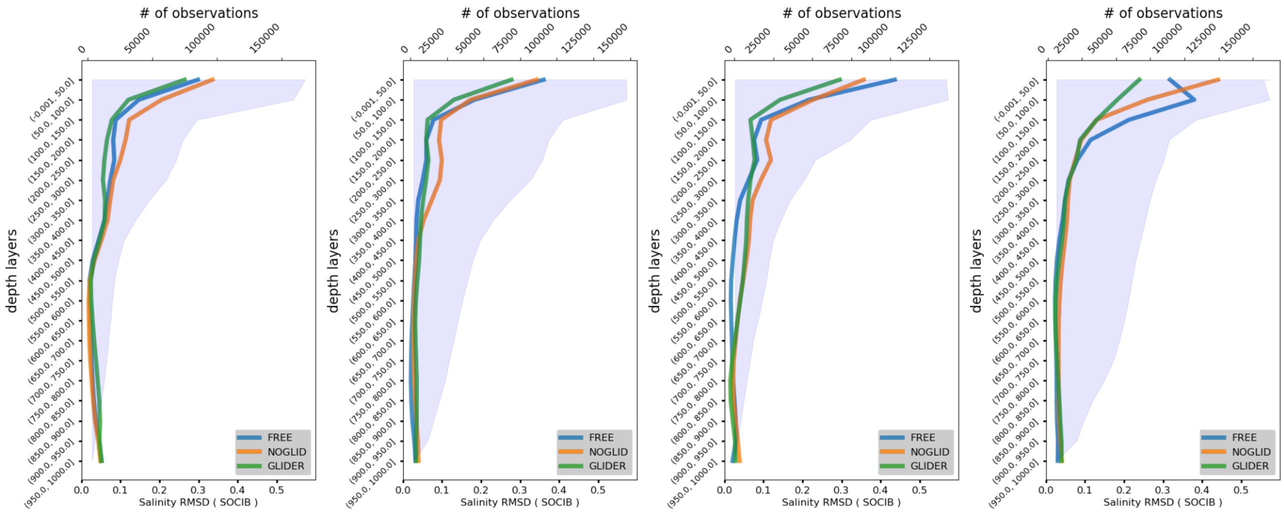


Figure 18. Same as Fig. 17 but for salinity.

4.2. Evaluation of Balearic Sea eddy

We studied the capacity of the models to represent the anticyclonic eddy present in the Balearic sea in the autumn of 2017. The eddy had a signature in the sea surface height and in temperature, as evidenced in the satellite observations, and started forming in August and lasted until December. We have calculated the mean error (bias), centred RMSD and correlation between the satellite sea surface height and temperature measurements and the model fields in the region. The area where this has been computed is highlighted in a blue square in Figure 19. For this, we have interpolated both models and the satellite observations to the same grid to perform a fair comparison.

During December, the eddy is fully developed and we can observe how both models represent its presence. Notice that in the Figure 19, the colorbar of the satellite observations is centred around the spatial average keeping the same range, in order to appreciate the structures and the gradients present in the surface height both from satellite and models. CMCC MedFS is able to represent the eddy even in the FREE simulation. This structure is more accurately represented in GLIDER, leading to an increment of the correlation and a decrease of the centred RMSD compared to NOGLID and FREE, particularly during December, as evidenced in Figure 20.

In the SOCIB WMOP model the improvement when using data assimilation is more evident, given that FREE has a higher error and lower correlation than in MedFS that is improved when assimilating data. Note that both models obtain similar metrics, during the analysed period, with SOCIB performing slightly better, mostly in terms of centred RMSD.

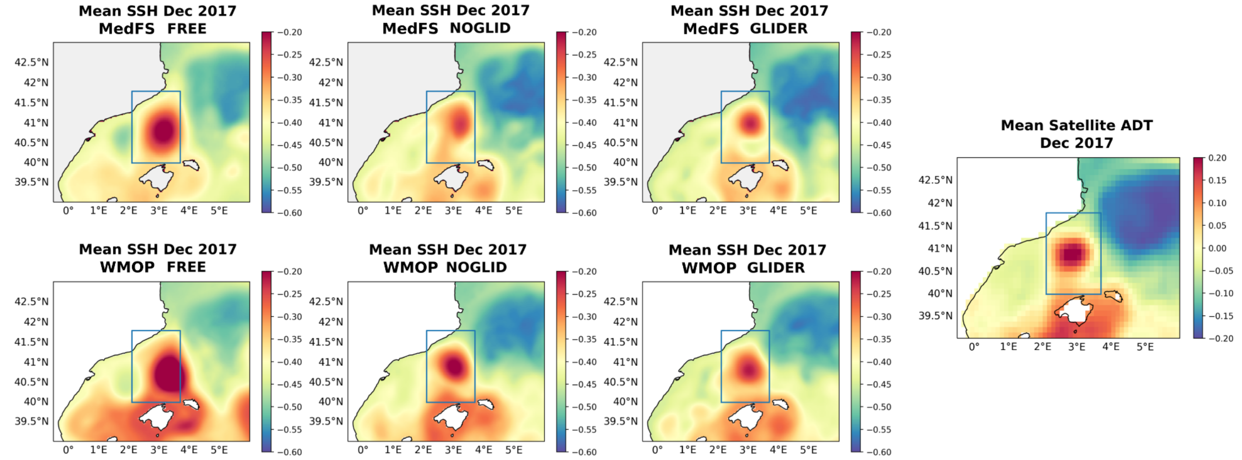


Figure 19. SSH mean fields during December in the Balearic Sea as represented by MedFS (top), WMOP (bottom) models, and from satellite altimetry (most right panel). For the models, each column is for a different experiment: FREE (left), NOGLID (centre), GLIDER (right).

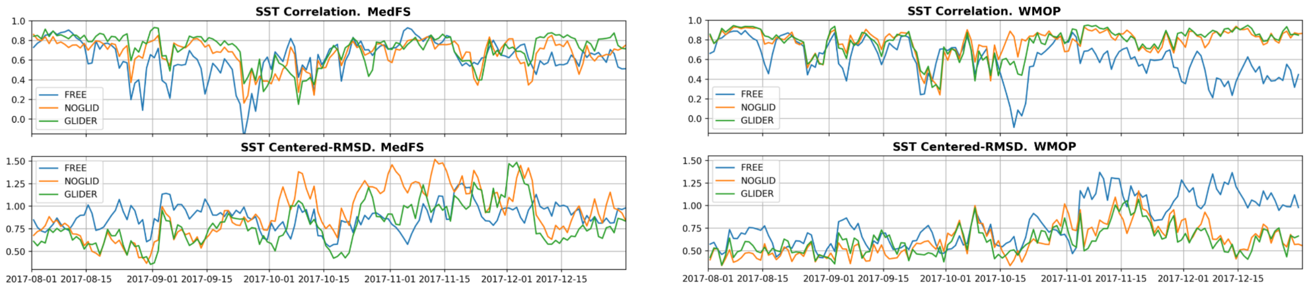


Figure 20. SSH correlations (top) and centred-RMSD (bottom), computed from August to December 2017 in the eddy region in the Balearic Sea, for MedFS (left), WMOP (right) models.

For SST we can observe (Figure 21) how in MedFS the eddy is present in FREE, but it is not well positioned and the model also depicts a dipole of warmer-colder structures that is not present in the satellite observations. Assimilation helps to improve this, by positioning correctly the warmer eddy structure and weakening the colder water mass present in FREE. It also helps to better represent the colder water mass of the north-east part and the gradients between both regions. The glider observations further improve the shape and position, leading to an increase of the correlation and a decrease of the centred RMSD in GLIDER with respect to NOGLID, especially during December, as can be observed in Figure 22.

WMOP model behaves in a similar way. The dipole structure present in MedFS can also be observed in this case, although the centre of the structure appears to be better located. Employment of data assimilation leads to a significant improvement in terms of correlation and decrease of centred RMSD of more than 30% during December, as shown in FIgure 22. GLIDER performs slightly better than NOGLID according to the metrics, although qualitatively it can be observed how GLIDER better represents the eddy structure both in location and in shape.

Both models show the best results for GLIDER simulation.

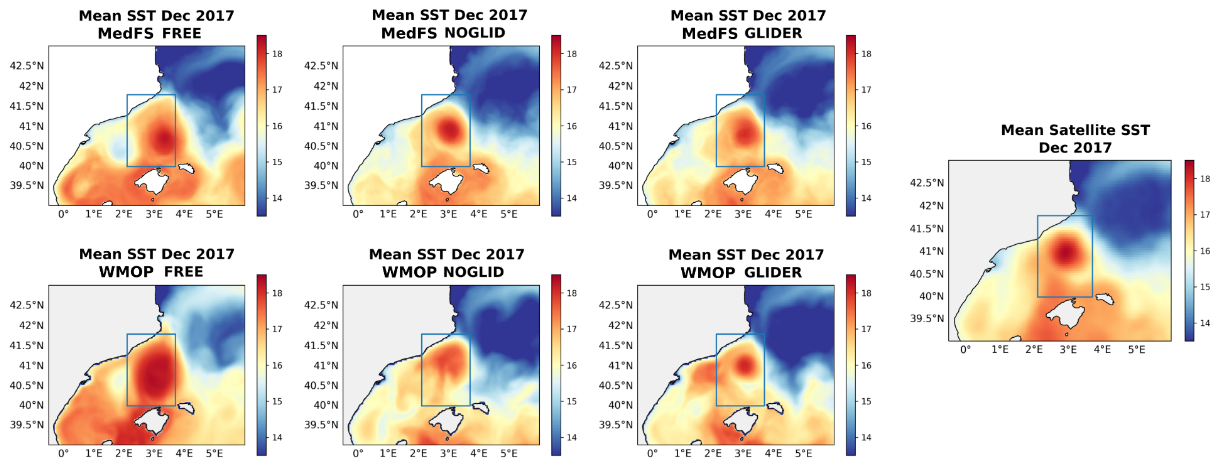


Figure 21. SST mean fields during December in the Balearic Sea as represented by MedFS (top), WMOP (bottom) models, and from satellite products (most right panel). For the models, each column is for a different experiment: FREE (left), NOGLID (centre), GLIDER (right).

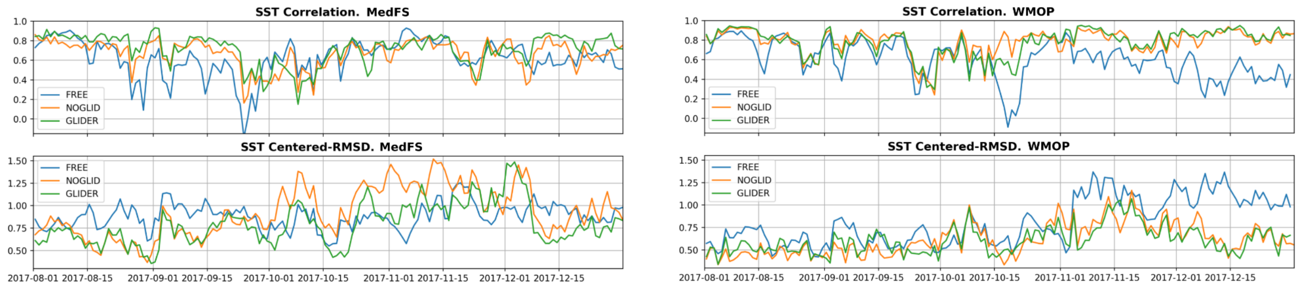


Figure 22. SST correlations (top) and centred-RMSD (bottom), computed from August to December 2017 in the eddy region in the Balearic Sea, for MedFS (left), WMOP (right) models.

5. Interfaces with other tasks and WPs

The task intercomparison duties have all been performed in collaboration with colleagues from Mercator Ocean working on Task 4.1[5]. Although the initial grant agreement did not include the collaboration, Task 4.1 also included the assessment of the impact of glider data assimilation in the CMEMS-IBI model, but in the Atlantic Ocean. The coverage of the CMEMS-IBI includes most of the WesternMed, and overlaps the SOCIB WMOP domain. Mercator Ocean colleagues decided therefore to include the Mediterranean Sea gliders in their analyses and interact together with Task 4.2, collaborating actively in the duties described in this deliverable. The interaction has been very fruitful for all partners and has led to very interesting results, which will help to improve the ocean forecasting systems in the Mediterranean Sea.

Besides, the modelling outputs generated from Task 4.2 experiments, with and without glider assimilation, are planned to be exchanged with WP5 partners for initialization of Taranto/Barcelona coastal downscaling. The feasibility of these outputs for their purposes still needs to be explored.

[5] EuroSea Task 4.1: Assimilation in the global and North East Atlantic (IBI) Copernicus Marine modelling system and analysis/forecast quality assessment

6. Conclusions

This deliverable reports the results of several experiments providing an intercomparison of CMCC MedFS and SOCIB WMOP systems. The intercomparison is focused on the capability of both systems to ingest glider observations and the impacts that these have in the analysis results.

WMOP model has demonstrated to benefit from the data assimilation, improving the representation of surface fields and profiles at the location of Argo observations. Overall, no significant differences between the simulations with or without gliders data have been found when comparing against surface observations in the whole domain. However, when focusing on the model capability to recreate a certain event, i.e., the formation of an anticyclonic eddy in the Balearic sea during autumn, the ingestion of glider data leads to model improvement. GLIDER simulation outperforms NOGLID, leading to a better representation of the eddy signature both in SSH and SST.

On the other hand, comparison against glider data evidence a degradation of the fields in NOGLID, compared to FREE. This degradation is partially corrected when including glider data in the reanalysis. GLIDER shows the best metrics, reducing the RMSD and increasing the correlation against temperature and salinity glider observations.

The reasons for degradation of temperature and salinity fields in depth with the generic data assimilation are being explored. The impact of sea level anomaly and the background error covariances is being analysed as a possible source of error. This would lead to an improvement of the SOCIB system, based on the results of the intercomparison process developed in this task.

Regarding MedFS, the system without data assimilation appears to already give a good representation of the ocean circulation. This is further improved by data assimilation step-wise. NOGLID shows how the assimilation of SLA, SST and Argo observations leads to an improvement in the model performance, with a reduction in the error at all depths. The performance is further increased when including glider data, with GLIDER improving the metrics for NOGLID. RMSD is reduced both in salinity and temperature at all depths, leading to a better representation of the 3D structure of the ocean.

Moreover, we have shown how the assimilation of glider data can help to represent a specific eddy structure, even without observations in its vicinity. The models seem to benefit from a better representation of the water masses, whose improvement spreads in time and space. The mechanisms behind this improvement still need to be further explored. Furthermore, this improvement can also be appreciated in the representation of the BGC structures as described in D4.10.

7. Future perspectives

The work realised during Task 4.2 has helped to the development of CMCC MedFS and SOCIB WMOP systems and to a better understanding of the effect of continuous glider data assimilation. It has not only led to a fruitful collaboration of the different teams involved in the task, but also with the glider observation community.

The work presented in this deliverable is to be continued. The collaboration done with the MERCATOR team should lead to the submission of an article analysing the intercomparison of the three systems before the end of the EuroSea project. Besides, the intercomparison intends to include the analysis of the water mass transport in the Ibiza Channel, comparing the model data against geostrophic currents inferred from the dynamic height computed from glider observations. Additionally, independent CTD observations from diverse research vessel campaigns will be used for validation.

References

Aguiar, E., Mourre, B., Revélard, A., Juza, M., Alvera-Azcárate, A., Pascual, A., Mason, E. and Tintoré, J., (2021), April. Strong long-lived anticyclonic mesoscale eddies in the Balearic Sea: formation and intensification mechanisms. In EGU General Assembly Conference Abstracts (pp. EGU21-8742).

Clementi, E., Aydogdu, A., Goglio, A. C., Pistoia, J., Escudier, R., Drudi, M., Grandi, A., Mariani, A., Lyubartsev, V., Lecci, R., Cretí, S., Coppini, G., Masina, S., and Pinardi, N., (2021). Mediterranean Sea Physical Analysis and Forecast (CMEMS MED-Currents, EAS6 system) (Version 1) set. Copernicus Monitoring Environment Marine Service (CMEMS).

Coppini, G., Clementi, E., Cossarini, G., Salon, S., Korres, G., Ravdas, M., Lecci, R., Pistoia, J., Goglio, A. C., Drudi, M., Grandi, A., Aydogdu, A., Escudier, R., Cipollone, A., Lyubartsev, V., Mariani, A., Cretì, S., Palermo, F., Scuro, M., Masina, S., Pinardi, N., Navarra, A., Delrosso, D., Teruzzi, A., Di Biagio, V., Bolzon, G., Feudale, L., Coidessa, G., Amadio, C., Brosich, A., Miró, A., Alvarez, E., Lazzari, P., Solidoro, C., Oikonomou, C., and Zacharioudaki, A.: The Mediterranean forecasting system. Part I: evolution and performance, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2022-1337, 2023.

Hernandez-Lasheras, J. and Mourre, B., (2018). Dense CTD survey versus glider fleet sampling: comparing data assimilation performance in a regional ocean model west of Sardinia, Ocean Sci., 14, 1069–1084, DOI: os-14-1069-2018.

Hernandez-Lasheras, J., Mourre, B., Orfila, A., Santana, A., Reyes, E., & Tintoré, J. (2021). Evaluating high-frequency radar data assimilation impact in coastal ocean operational modelling. Ocean Science, 17(4), 1157-1175.

Juza M., Mourre, B., Renault, L., Gómara, S., Sebastián, K., Lora, S., Beltran, J.P., Frontera, B., Garau, B., Troupin, C., Torner, M., Heslop, E., Casas, B., Escudier, R., Vizoso, G. and Tintoré J., (2016). SOCIB operational ocean forecasting system and multi-platform validation in the western Mediterranean Sea, J. Oper. Oceanogr., 9 :sup1, s155-s166, doi:10.1080/1755876X.2015.1117764

Mourre B., Aguiar, E., Juza, M., Hernandez-Lasheras, J., Reyes, E., Heslop, E., Escudier, R., Cutolo, E., Ruiz, S., Mason, E., Pascual, A., and Tintoré, J., (2018). Assessment of high-resolution regional ocean prediction systems using multi-platform observations: illustrations in the Western Mediterranean Sea. In “New Frontiers in Operational Oceanography”, E. Chassignet, A. Pascual, J. Tintoré and J. Verron, Eds, GODAE Ocean View, 663-694, doi: 10.17125/gov2018.ch24.

Storto, A., Masina, S., & Navarra, A. (2016). Evaluation of the CMCC eddy-permitting global ocean physical reanalysis system (C-GLORS, 1982–2012) and its assimilation components. *Quarterly Journal of the Royal Meteorological Society*, *142*(695), 738-758.