



Mediterranean Production Centre MEDSEA_ANALYSISFORECAST_WAV_006_017

Issue: 2.1

Contributors: Anna Zacharioudaki, Michalis Ravdas, Gerasimos Korres

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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
1.2	January 2019	All	Release of the new version (MEDWAM3) of the Med-waves analysis and forecast product at 1/24 ^h resolution. Upgrades since previous version (Q2/2018) include: i) upgrade of WAM model version from V4.5.4 to V4.6.2, ii) inclusion of non-linear wave-wave interactions for shallow water, iii) tuning of WAM input and dissipation source terms, and iv) tuning of spectral steepness.	Anna Zacharioudaki	Vladyslav Lyubartsev (PQ Responsible)
1.3	December 2019	I.3, II.1, II.2, V, VI	Updates of the new version Q1/2020 with respect to the previous version Q1/2019 include: i) daily forecast cycle starting at 00:00 UTC instead of 12:00 UTC. This is a technical change with no changes in product quality, and ii) additional assimilation of SENTINEL-3B observations. Quality changes are marginal and are described in Section VI.	Anna Zacharioudaki	Vladyslav Lyubartsev (PQ Responsible)
2.0	January 2021	All	New Product (Q2/2021), including the following updates with respect to the previous version (Q1/2020): i) one-way coupling with hourly currents and sea level from Med-PHY ii) additional assimilation of CFOSAT and HAIYANG-2B observations, and iii) inclusion of a 2 nd forecast cycle	Anna Zacharioudaki	Emanuela Clementi (Med-MFC Deputy)

2.1	September 2021	II, V, VI	Updates of the new version (Q4/2021) with respect to the previous version (Q2/2021) include the following upstream data changes (Q4/2021): i) nesting with GLO-waves ii) use of higher spatial (1/10°) and temporal resolution ECMWF winds Quality changes are marginal and are described in Section VI.	Anna Zacharioudaki	Emanuela Clementi (Med-MFC Deputy)
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I EXECUTIVE SUMMARY

I.1 Products covered by this document

This document describes the quality of the analysis and forecast nominal product of the wave component of the Mediterranean Sea: MEDSEA_ANALYSISFORECAST_WAV_006_017. The product includes the following 2D 1-hourly analysis and forecast instantaneous fields of:

- VHMO: spectral significant wave height (Hm0);
- VTM10: spectral moments (-1,0) wave period (Tm-10);
- VTM02: spectral moments (0,2) wave period (Tm02);
- VTPK: wave period at spectral peak / peak period (Tp);
- VMDR: mean wave direction from (Mdir);
- VPED: wave principal direction at spectral peak;
- VSDX: stokes drift U;
- VSDY: stokes drift V;
- VHMO_WW: spectral significant wind wave height;
- VTM01_WW: spectral moments (0,1) wind wave period;
- VMDR_SW1: mean wind wave direction from;
- VHMO_SW1: spectral significant primary swell wave height;
- VTM01_SW1: spectral moments (0,1) primary swell wave period;
- VMDR_SW1: mean primary swell wave direction from;
- VHMO_SW2: spectral significant secondary swell wave height;
- VTM01_SW2: spectral moments (0,1) secondary swell wave period; and
- VMDR_SW2: mean secondary swell wave direction from.

Output data are produced at 1/24° horizontal resolution.

I.2 Summary of the results

The quality of the MED-MFC-waves system of analysis and forecast is assessed over a 1 year period (July 2019 - July 2020) by comparison with in-situ and satellite observations.

The main results of the MEDSEA_ANALYSISFORECAST_WAV_006_017 product quality assessment are summarized below:

Spectral Significant Wave Height (Hm0): Overall, the significant wave height is accurately simulated by the model. Considering the Mediterranean Sea as a whole, the typical difference with observations (RMSD) is 0.21 m with a bias of 0.01 m (2%) and -0.05 m (4%) and a Scatter Index (SI) of 0.24 and 0.15 against in-situ and satellite observations respectively. In general, the model somewhat underestimates or converges to the observations for wave heights smaller than about 3-4 m, depending on the reference dataset, whilst it mostly overestimates or converges to the observations for higher waves. Its performance is better in winter when the wave conditions are well-defined. Spatially, the model performs optimally at offshore wave buoy locations and well-exposed Mediterranean sub-regions. Within enclosed basins and near the coast, unresolved topography by the wind and wave models and fetch limitations cause the wave model performance to deteriorate.

Spectral moments (0,2) wave period (Tm02): The mean wave period is reasonably well simulated by the model. The typical difference with observations (RMSD) is 0.63 s and is mainly caused by model bias which has a value of -0.38 s (10%). In general, the model underestimates the observed mean wave period and exhibits greater variability than the observations. A relatively larger model underestimate is found for mean wave periods below 4.5 s. Over the high MWP range the model tends to converge or even overestimate the observed values. Model performance is a little better in winter when wave conditions are well-defined. Similarly to the wave height, the model performance is best at well-exposed offshore locations and deteriorates near the shore mainly due to fetch limitations.

Other variables: No observations are available for all other variables except for the wave period at spectral peak / peak period (Tp) and the mean wave direction from (Mdir). In contrast to Tm02 variation, which is smooth in the Mediterranean Sea, Tp variation is particularly spiky. As a result, validation of the latter wave parameter is thought to be less reliable and has not been considered herein despite data availability. On the other hand, qualification of Mdir will be considered in the future. Generally, wave height variables are expected to be of similar quality to Hm0 and wave period variables to Tm02. Stokes drift quality is expected to be a function of both Hm0 and Tm02.

I.3 Estimated Accuracy Numbers

Estimated Accuracy Numbers (EANs), that are the mean and the RMS of the differences (RMSD) between the model and in-situ or satellite reference observations, are provided in Table 1 and Table 2 below.

EANs are computed for:

- Significant Wave Height (SWH): refers to the "spectral significant wave height (Hm0)"
- Mean Wave Period (MWP): refers to the "spectral moments (0,2) wave period (Tm02)"

The observations used are:

- independent in-situ observations from moored wave buoys obtained from the CMEMS INSITU_MED_NRT_OBSERVATIONS_013_035 dataset, available through the CMEMS In Situ Thematic Assemble Centre (INS-TAC)
- quasi-independent satellite altimeter observations obtained from the CMEMS WAVE_GLO_WAV_L3_SWH_NRT_OBSERVATIONS_014_001 dataset, available through the CMEMS Wave Thematic Assemble Centre (WAV TAC)

Q1/2020

Q2/2021

Model vs. in-situ observations: full MED	Mean	RMS	Mean	RMS	Units
SWH	0.007	0.209	0.014	0.209	m
MWP	-0.398	0.648	-0.377	0.631	s

Table 1: EANs of SWH and MWP evaluated for a period of 1 year (Jul 2019 - Jul 2020) for the full Mediterranean Sea: SWH-H-CLASS4-MOOR-<STAT>-MED, MWP-H-CLASS4-MOOR-<STAT>-MED in Table 5, Section III.

	Q1/2020		Q2/2021		
Model SWH vs. satellite observations: full MED and sub-regions	Mean	RMS	Mean	RMS	Units
MED	-0.057	0.220	-0.049	0.213	m
atl	0.021	0.191	0.017	0.193	
alb	0.017	0.252	0.014	0.241	
swm1	-0.056	0.221	-0.047	0.214	
swm2	-0.053	0.241	-0.047	0.235	
nwm	-0.061	0.252	-0.056	0.245	
tyr1	-0.071	0.239	-0.068	0.237	
tyr2	-0.044	0.232	-0.040	0.227	
ion1	-0.036	0.191	-0.030	0.185	
ion2	-0.069	0.200	-0.058	0.193	
ion3	-0.082	0.226	-0.070	0.219	
adr1	-0.052	0.247	-0.048	0.244	
adr2	-0.083	0.254	-0.075	0.248	
lev1	-0.053	0.202	-0.041	0.193	
lev2	-0.062	0.195	-0.053	0.187	
lev3	-0.062	0.182	-0.051	0.174	
lev4	-0.075	0.206	-0.062	0.199	
aeg	-0.033	0.250	-0.025	0.240	

Table 2: EANs of SWH evaluated for a period of 1 year (Jul 2019 - Jul 2020) for the full Mediterranean Sea and the different sub-regions shown in Figure 1: SWH-H-CLASS4-ALT-<STAT>-MED, SWH-H-CLASS4-ALT-<STAT>-<REGION> in Table 5, Section III.

The computed EANs are based on the simulation of the system in analysis or first-guess mode, depending on the reference data used, for a period of 1 year from 16 July 2019 to 15 July 2020. They are computed for the Mediterranean Sea as a whole and for 17 sub-regions from which 1 is in the Atlantic Ocean and 16 in the Mediterranean Sea (Figure 1): (atl) Atlantic, (alb) Alboran Sea, (swm1) West South-West Med, (swm2) East South-West Med, (nwm) North West Med, (tyr1) North Tyrrhenian Sea, (tyr2) South Tyrrhenian Sea, (adr1) North Adriatic Sea, (adr2) South Adriatic Sea, (ion1) South-West Ionian Sea, (ion2) South-East Ionian Sea, (ion3) North Ionian 3, (aeg) Aegean Sea, (lev1) West Levantine, (lev2) North-Central Levantine, (lev3) South-Central Levantine, (lev4) East Levantine.

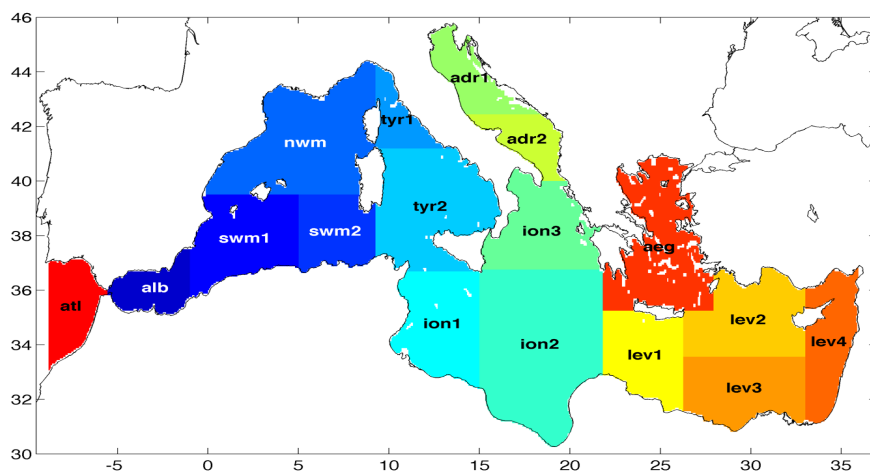


Figure 1: Mediterranean Sea sub-regions for qualification metrics

II PRODUCTION SYSTEM DESCRIPTION

II.1 Production centre details

PU: HCMR, Greece

Production chain: Med-waves

External product (2D): spectral significant wave height (Hm0), spectral moments (-1,0) wave period (Tm-10), spectral moments (0,2) wave period (Tm02), wave period at spectral peak / peak period (Tp), mean wave direction from (Mdir), wave principal direction at spectral peak, stokes drift U, stokes drift V, spectral significant wind wave height, spectral moments (0,1) wind wave period, mean wind wave direction from, spectral significant primary swell wave height, spectral moments (0,1) primary swell wave period, mean primary swell wave direction from, spectral significant secondary swell wave height, spectral moments (0,1) secondary swell wave period, mean secondary swell wave direction from.

Frequency of model output: 1-hourly analysis and forecast (instantaneous)

Geographical coverage: 18.125°W → 36.2917°E; 30.1875°N → 45.9792°N

Horizontal resolution: 1/24°

Vertical coverage: Surface

Length of forecast: 10 days

Frequency of forecast release: Twice per day

Analyses: Yes

Frequency of analysis release: Twice per day

The wave analyses and forecasts for the Mediterranean Sea are produced by the HCMR Production Unit by means of the WAM wave model (described below).

The Med-waves system integration is composed of several steps:

1. Upstream Data Acquisition, Pre-Processing and Control of: ECMWF (European Centre for Medium-Range Weather Forecasts) NWP (Numerical Weather Prediction) atmospheric forcing, CMEMS Med MFC and Global MFC currents and CMEMS WAVE TAC SWH satellite NRT observations.
2. Analysis/Forecast: The Med-waves prediction system runs two cycles per day (starting at 00:00 UTC and 12:00 UTC). Each cycle produces 12 hours in the past (analysis) assimilating SWH satellite observations available from the CMEMS WAVE TAC and 10 days (240 hours) into the future (forecast mode). A schematic of the Med-waves operational cycle is shown in Figure 2.
3. Post processing: the model output is processed in order to obtain the products for the CMEMS catalogue.
4. Output delivery.

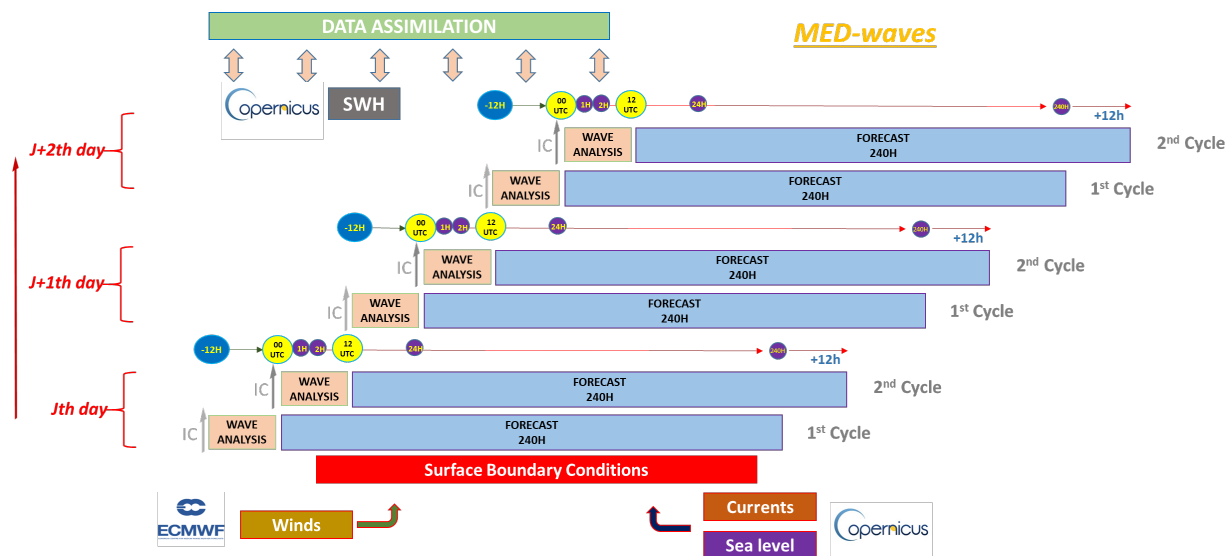


Figure 2: Schematic of the Med-waves production chain at Q4/2021. Each cycle simulates 252 hours: 12 hours in the past (wave analysis) and 240 hours into the future (wave forecasts).

II.2 Description of the Med-waves modelling system

The wave component of the Mediterranean Forecasting Centre (Med-waves) is providing analyses and short-term wave forecasts (10 days) for the Mediterranean Sea at $1/24^\circ$ horizontal resolution.

The Med-waves modelling system consists of a wave model grid implemented over the whole Mediterranean Sea at $1/24^\circ$ horizontal resolution, one-way nested with lateral boundary conditions supplied from the CMEMS Global wave model (Figure 3). The nested fine grid domain covers the Mediterranean Sea from 18.125°W to 36.2917°E and from 30.1875°N to 45.9792°N .

Med-waves is based on the state-of-the-art third-generation wave model WAM Cycle 4.6.2 which is a modernized and improved version of the well-known and extensively used WAM Cycle 4 wave model (WAMDI Group, 1988; Komen et al., 1994), also including different depth scaling (deep – shallow) allowing for the calculation of the nonlinear wave-wave interactions.

WAM solves the wave transport equation explicitly without any presumption on the shape of the wave spectrum. Its source terms include the wind input, whitecapping dissipation, nonlinear transfer and bottom friction. The wind input term is adopted from Snyder et al. (1981). The whitecapping dissipation term is based on Hasselmann (1974) whitecapping theory. The wind input and whitecapping dissipation source terms of the present cycle of the wave model are a further development based on Janssen's quasi-linear theory of wind-wave generation (Janssen, 1989; Janssen, 1991). The nonlinear transfer term is a parameterization of the exact nonlinear interactions as proposed by Hasselmann and Hasselmann (1985) and Hasselmann et al., (1985). Lastly, the bottom friction term is based on the empirical JONSWAP model of Hasselmann et al. (1973).

The bathymetric map has been constructed using the GEBCO bathymetric data set (GEBCO, 2016). Mapping on the model grid was done using bi-linear interpolation accompanied by some degree of isotropic laplacian smoothing.

The Mediterranean Sea model receives full wave spectrum at 3-hourly intervals at its Atlantic Ocean open boundary. The wave spectrum is discretized using 32 frequencies, which cover a logarithmically scaled frequency band from 0.04177 Hz to 0.8018 Hz (covering wave periods ranging from approximately 1 s to 24 s) at intervals of $df/f = 0.1$, and 24 equally spaced directions (15 degrees bin).

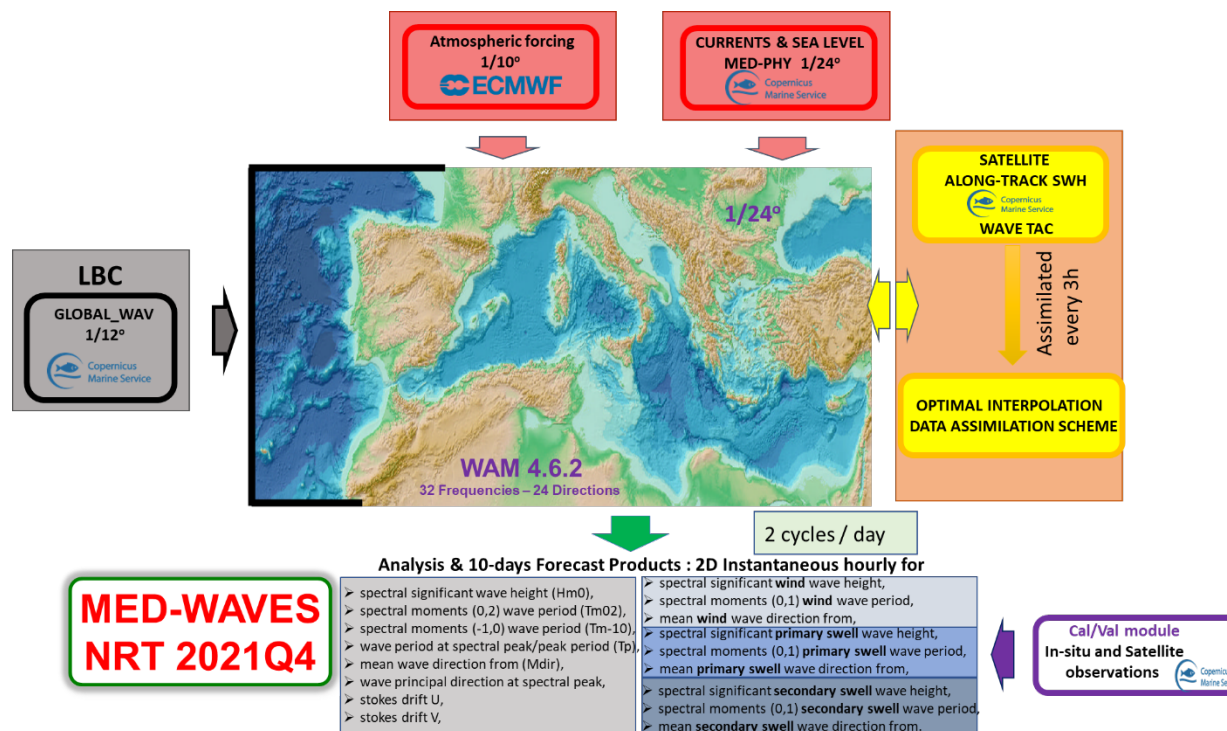


Figure 3: Schematic of the Med-waves system at Q4/2021 (MEDWAM3).

The wave model runs in shallow water mode considering wave refraction due to depth and currents in addition to depth induced wave breaking. Modifications from default values have also been performed in the input source functions. Specifically, the value of the wave age parameter (z_{alp}) has been set to 0.011 (0.008 is the default). In addition, the imposition of a limitation to the high frequency part of the wave spectrum corresponding to the latest version of the ECMWF wave forecasting system (ECMWF, 2016) has been applied in order to reduce the wave steepness at very high wind speeds.

At Q4/2021 the system is forced with 10 m above sea surface wind fields obtained from the ECMWF Integrated Forecasting System (IFS) at 1/10° dissemination resolution (upgrade with respect to the use of 1/8° winds at Q2/2021), at hourly intervals for forecast days 1-3, 3-hourly intervals for day 4 to day 6 and at 6-hourly intervals for days 7-10. Wind is bi-linearly interpolated onto the model grids. With respect to currents forcing, the Mediterranean Sea model is forced by hourly averaged surface currents and sea level obtained from CMEMS Med MFC at 1/24° resolution. These are the Med MFC surface currents products operational at the time this Med-waves system version is released. A schematic of the Med-waves system is shown in Figure 3. Also, Table 3 summarizes the Med-waves modelling characteristics.

Med-waves generates hourly wave fields over the Mediterranean Sea at 1/24° horizontal resolution. These wave fields correspond either to wave parameters computed by integration of the total wave spectrum or to wave parameters computed using wave spectrum partitioning. In the latter case the complex wave spectrum is partitioned into wind sea, primary and secondary swell. Wind sea is defined as those wave components that are subject to wind forcing while the remaining part of the spectrum is termed swell. Wave components are considered to be subject to wind forcing when

$$c \leq 1.2 \times 28 u_* \cos(\theta - \varphi)$$

where c is the phase speed of the wave component, u_* is the friction velocity, θ is the direction of wave propagation and ϕ is the wind direction. As the swell part of the wave spectrum can be made up of different swell systems with quite distinct characteristics it is further partitioned into the two most energetic wave systems, the so called primary and secondary swell. Swell partitioning is done following the method proposed by Gerling (1992) which finds the lowest energy threshold value at which upper parts of the spectrum get disconnected with the process repeated until primary and secondary swell is detected.

The assimilation module

The assimilation system of Med-waves is based on the inherent data assimilation scheme of WAM Cycle 4.6.2 which consists of performing an optimal interpolation (O.I.) on the along-track SWH observations retrieved by the altimeters and then re-adjusting the wave spectrum at each grid point accordingly. This assimilation approach was initially developed by Lionello et al. (1992) and consists of two steps.

First, a best guess (analysed) field of significant wave height is determined by optimum interpolation with appropriate assumptions regarding the error covariance matrix. Based on the prejudice that the wind is the main contributor to the wave model error and that the form of the spectra is essentially correct, the aim is to obtain the spectrum that the model would have if the correct forcing was used. One of the key issues of the optimal interpolation approach is the specification of the errors of the assimilating system. Especially, the specification of the background error covariance matrix, P , and the observation error covariance matrix, R , are important since the computation of the gain matrix K depends largely on the structure of these matrices. The Med-waves assimilation module, uses the default expressions of WAM for the background error covariance matrix

$$P = \exp\left(\frac{d_{ij}}{l_c}\right)$$

and the observation error covariance matrix

$$R = \frac{\sigma_o^2}{\sigma_b^2}$$

where i and j are, respectively, the model grid points, d is the distance from the observation location to the grid point, l_c is the correlation length, while σ_o and σ_b stand for the observation and model errors, respectively. In the above expressions the error is considered as homogeneous and isotropic.

We set the ratio between errors of observations and model (background) equal to 1 and the correlation length l_c which controls the width of exponential bell equal to 3 deg (~300 km).

Finally, the weights assigned to the observations are the elements of the gain matrix K :

$$K = PH^T[HPH^T + R]^{-1}$$

where H is the observation operator that projects the model solution to the observation location.

The above O.I. analysis procedure applies to significant wave height and 10 m wind speed, U10, observations that fall within the model domain. For the current version of Med-waves, it has been applied to altimeter along-track SWH measurements only. No assimilation of U10 measurements is performed because of a lack of readily available data. It has been shown, through sensitivity testing, that omitting U10 assimilation in the Mediterranean Sea has negligible effect on output quality.

During the second step, the analysed significant wave height field is used to retrieve the full dimensional wave spectrum from a first-guess spectrum provided by the model itself, introducing additional assumptions to transform the information of a single wave height spectrum into separate corrections

for the wind sea and swell components of the spectrum. Two-dimensional wave spectra are regarded either as wind sea spectra, if the wind sea energy is larger than 3/4 times the total energy, or, if this condition is not satisfied, as swell. If the first-guess spectrum is mainly wind-sea, the spectrum is updated using empirical energy growth curves from the model. Additionally, if 10 m winds observations are available the local forcing wind speed is updated. In case of swell, the spectrum is updated assuming the average wave steepness provided by the first-guess spectrum is correct but the wind is not updated. A problem arises when both wind-sea and swell are present. In this situation the update is done depending on which is the dominant process, which is a limitation of the method.

Prior to assimilation all altimeter SWH observations are subject to quality control procedure. The primary purpose of the quality control system is to identify observations that are obviously erroneous, as well as the more difficult process of identifying measurements that fall within valid and reasonable ranges but nevertheless are erroneous. Accepting this erroneous data can cause an incorrect analysis, while rejecting extreme, but valid, data can miss important events. The procedure takes into account thresholds of significant wave height and wind speed (upon availability) observations and root mean square differences between the model first-guess and the observed SWH.

The wave prediction system runs two cycles per day (starting at 00:00 UTC and 12:00 UTC respectively). Each cycle is scheduled to simulate 252 hours: 12 hours in the past (analysis) blending through data assimilation model results with available SWH satellite observations available from CMEMS WAVE TAC and 10 days (240 hours) into the future (forecast mode). The assimilation step adopted in this scheme equals to 3 hours. At the end of the analysis mode, a restart file is written that forms the basis (initial conditions) for the next cycle.

For every day J, the available time series (hourly fields) of the product start from 2 years back, up to the day J+10. The last ten days of the time series are forecast fields, while the remaining days of the archive are analysis.

	Mediterranean Sea model
Model	WAM Cycle 4.6.2
Model Domain	18.125°W 36.291°E; 30.1875°N 45.9792°N
Horizontal Resolution	1/24° x 1/24°
Frequency Bins	32 (logarithmically spaced) 0.04177-0.80818 Hz
Direction Bins	24 (equally spaced)
Propagation Time-Step	60 s
Forcing (10m winds)	1/10° x 1/10° ECMWF operational analysis & 10-days forecasts
Data assimilation	SWH along-track NRT observations (JASON-3, SENTINEL-3A, SENTINEL-3B, CRYOSAT2, SARAL, CFOSAT, HAIYANG-2B) from CMEMS WAVE TAC
Surface Currents	CMEMS MED MFC (1/24° x 1/24°)
Open Boundary Conditions	CMEMS GLOBAL MFC
Sea Level	CMEMS MED MFC (1/24° x 1/24°)

Table 3 Med-waves modelling characteristics at Q4/2021

II.3 Upstream data and boundary condition of the WAM model

The CMEMS Med-waves system uses the following upstream data:

1. Atmospheric forcing: NWP 6-h operational analysis and forecast fields at 1/10° spatial resolution (at hourly intervals for forecast days 1-3, at 3-hourly intervals for forecast days 4-6 and at 6-hourly intervals from forecast day 7 to 10) from ECMWF, distributed by the Italian National Meteo Service (USAM/CNMA)
2. Data assimilation: WAVE_GLO_WAV_L3_SWH_NRT_OBSERVATIONS_014_001 inter calibrated along track SWH observations from JASON-3, SENTINEL-3A, SENTINEL-3B, SARAL/Altika, CRYOSAT-2, CFOSAT and HAIYANG-2B satellite missions, distributed by the CMEMS WAVE TAC
3. Surface currents forcing: MEDSEA_ANALYSISFORECAST_PHY_006_013 hourly averages at 1/24° (Mediterranean model grid forcing) from the CMEMS Mediterranean MFC Analysis and Forecast System.
4. Sea Level: MEDSEA_ANALYSISFORECAST_PHY_006_013 hourly averages at 1/24° from the CMEMS Mediterranean MFC Analysis and Forecast System.
5. Wave spectra from GLO-WAV for Open Boundary Conditions: GLOBAL_ANALYSIS_FORECAST_WAV_001_027

III VALIDATION FRAMEWORK

In order to evaluate and assure the quality of the MEDSEA_ANALYSISFORECAST_WAV_006_017 product of the CMEMS Med-MFC analysis and forecast released in Q2/2021, analysis and first-guess wave parameters were compared to independent and quasi-independent observations respectively over the period of 1 year, July 2019 - July 2020, focusing on model output quality in the Mediterranean Sea. It is noted that all the observations that are assimilated into the system are considered as quasi-independent. In this situation, to assure some level of independency, qualification metrics are calculated before the assimilation of data (i.e. first-guess output).

The wave parameters that have been qualified through their comparison with observations include:

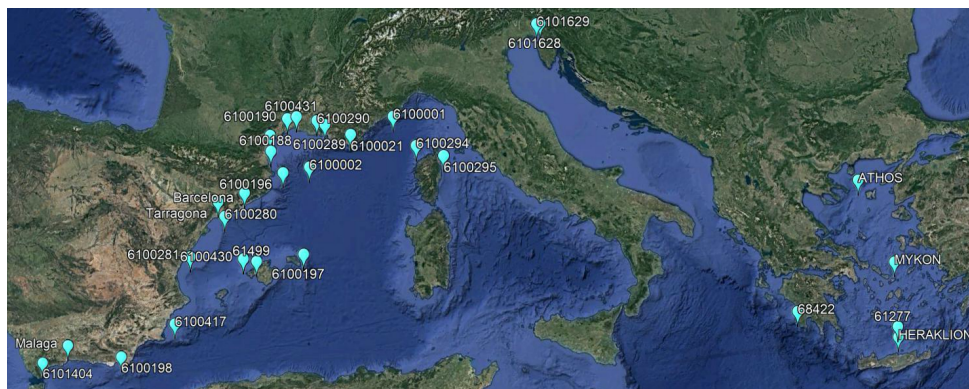
- ✓ spectral significant wave height (Hm0) [SWH]
- ✓ spectral moments (0,2) wave period (Tm02) [MWP]

The remaining wave parameters included in the CMEMS Med-waves product are not qualified against observational data. This is mainly because there are no relevant observations or because the existing observations are not suited for a robust validation either because of limited data availability or because of data ambiguities (e.g. highly spiky variation). In most of the cases, the quality of these wave parameters is inferred from the quality of those parameters that are thoroughly compared with observations. A valid range, based on climatology and/or expert knowledge, is assigned to each wave parameter.

The observations against which modelled wave parameters are compared to include:

- independent in-situ observations from moored wave buoys obtained from the CMEMS INSITU_MED_NRT_OBSERVATIONS_013_035 dataset, available through the CMEMS In Situ Thematic Assemble Centre (INS-TAC)
- quasi-independent satellite altimeter observations from the WAVE_GLO_WAV_L3_SWH_NRT_OBSERVATIONS_014_001 dataset, available through the CMEMS WAV-TAC

In-situ SWH measurements come from 30 wave buoys in the Mediterranean Sea. Figure 4 depicts their location and unique ID code. MWP measurements were available from 25 of the depicted buoys (see *Figure 11*). In order to collocate model output and buoy measurements in space, model output was taken at the grid point nearest to the buoy location. In time, buoy measurements within a time window of ± 1 h from model output times at 3-h intervals (0, 3, 6, ..., etc) were averaged. Prior to model-buoy collocation, the in-situ observations were filtered so as to remove those values accompanied by a bad quality flag (Quality Flags included in the data files provided by the INS-TAC). After collocation, visual inspection of the data was carried out, which led to some further filtering of spurious data points. In addition, MWP data below 2 s were omitted from the statistical analysis, since 0.5 Hz ($T = 2$ s) is a typical cut-off frequency for wave buoys. Metrics have been obtained for individual wave buoys and aggregations of them. In addition to the full Mediterranean Sea domain, the wave buoy groups that have been generated by merging wave buoy observations over regions with similar characteristics are presented in Table 4.



Group Name	Wave buoys
ES offshore	61198, 61417, 61281, 61280, 61430, 61197, 61196
ES coastal	6101404, Malaga, Tarragona, Barcelona
FR offshore	6100002, 6100001
FR coastal	6100188, 6100191, 6100190, 6100431, 6100290, 6100289
GR Aegean	ATHOS, MYKON, 61277, HERAKLION

Table 4: Wave buoy groups: ES = Spanish, FR = French, GR = Greek.

Satellite observations of SWH are from 7 satellite missions: Cryosat-2, SARAL, Jason-3, Sentinel-3a, Sentinel-3b, CFOSAT, HaiYang2B (H2B). Satellite observations of wind speed, U10, used to validate the forcing wind fields, come from 5 of these missions (no winds from SARAL and CFOSAT). All satellite SWH and U10 observations have been cross-calibrated and filtered (Taburet et al., 2019). To collocate model output and satellite observations the former were interpolated in time and space to the individual satellite tracks. For each track, corresponding to one satellite pass, along-track pairs of satellite measurements and interpolated model output were averaged over ~ 16 km grid cells. This averaging is intended to break any spatial correlation present in successive 1 Hz (~ 7 km) observations and/or in neighbouring model grid output. After collocation, visual inspection of the data was carried out, which led to some further filtering of spurious data points. In addition, $U10 < 2$ m/s and $SWH < 0.5$ m were omitted from the statistical analysis, since a lesser confidence pertains to altimeter measurements in this range (Rosmorduc et al., 2018). Metrics have been obtained for individual satellites and aggregations of them, for the full Mediterranean Sea and for the individual sub-regions defined in Figure 1.

Metrics that are commonly applied to assess numerical model skill and are in alignment with the recommendations of the EU FP7 project MyWave (A pan-European concerted and integrated approach to operational wave modelling and forecasting – a complement to GMES MyOcean services, 2012-2014) have been used to qualify the Med-waves system within the Mediterranean Sea. These include the RMSD, BIAS, Scatter Index (SI), Pearson Correlation Coefficient (CORR), and the Linear Regression Slope (LR_SLOPE). The SI, defined here as the standard deviation of model-observation differences relative to the observed mean, being dimensionless, is more appropriate to evaluate the relative closeness of the model output to the observations at different locations compared with the RMSD which is representative of the size of a ‘typical’ model-observation difference. For the same reason, Relative BIAS and Relative RMSD, i.e. BIAS and RMSD relative to the observed mean, are also used in the analysis to

compare model output quality over different regions and/or time periods. The LR_SLOPE corresponds to a best-fit line forced through the origins (zero intercept). In addition to the aforementioned core metrics, merged Density Scatter and Quantile-Quantile (QQ) plots are provided. The slope as well as the intercept of a linear regression line is included in these plots. The full set of metrics used in the qualification of the Med-waves system is defined in Table 5.

Name	Description	Wave parameter	Supporting reference dataset	Quantity
Evaluation of Med-waves using independent in-situ observations (Full MED)				
SWH-H-CLASS4-MOOR-<STAT>-MED	Comparison to wave buoy significant wave height	Spectral significant wave height (Hm0)	INSITU_MED_NRT_OBSERVATIONS_013_035	RMSD, SI, BIAS, CORR, LR_SLOPE between observations and analysis, for all Med, for 1-year period and seasonally
MWP-H-CLASS4-MOOR-<STAT>-MED	Comparison to wave buoy mean wave period	Spectral moments (0,2) wave period (Tm02)	INSITU_MED_NRT_OBSERVATIONS_013_035	RMSD, SI, BIAS, CORR, LR_SLOPE between observations and analysis, for all Med, for 1-year period and seasonally
SWH-H-CLASS4-MOOR-QQ-MED SWH-H-CLASS4-MOOR-SCATTER-MED	Comparison to wave buoy significant wave height	Spectral significant wave height (Hm0)	INSITU_MED_NRT_OBSERVATIONS_013_035	Merged Quantile-Quantile and Scatter plots between observations and analysis, for all Med, for 1-year period
MWP-H-CLASS4-MOOR-QQ-MED MWP-H-CLASS4-MOOR-SCATTER-MED	Comparison to wave buoy mean wave period	Spectral moments (0,2) wave period (Tm02)	INSITU_MED_NRT_OBSERVATIONS_013_035	Merged Quantile-Quantile and Scatter plots between observations and analysis, for all Med, for 1-year period
Evaluation of Med-waves using independent in-situ observations (at buoy locations or for wave buoy groups)				
SWH-H-CLASS2-MOOR-<STAT>-<MOORING ID>	Comparison to wave buoy significant wave height	Spectral significant wave height (Hm0)	INSITU_MED_NRT_OBSERVATIONS_013_035	RMSD, SI, BIAS, CORR, LR_SLOPE between observations and analysis, for each wave buoy separately, for 1-year period
MWP-H-CLASS2-MOOR-<STAT>-<MOORING ID>	Comparison to wave buoy mean wave period	Spectral moments (0,2) wave period (Tm02)	INSITU_MED_NRT_OBSERVATIONS_013_035	RMSD, SI, BIAS, CORR, LR_SLOPE between observations and analysis, for each wave buoy separately, for 1-year period
SWH-H-CLASS2-MOOR-QQ-<MOORING ID> SWH-H-CLASS2-MOOR-SCATTER-<MOORING ID>	Comparison to wave buoy significant wave height	Spectral significant wave height (Hm0)	INSITU_MED_NRT_OBSERVATIONS_013_035	Merged Quantile-Quantile and Scatter plots between observations and analysis, for each wave buoy separately, for 1-year period
MWP-H-CLASS2-MOOR-QQ-<MOORING ID> MWP-H-CLASS2-MOOR-SCATTER-<MOORING ID>	Comparison to wave buoy mean wave period	Spectral moments (0,2) wave period (Tm02)	INSITU_MED_NRT_OBSERVATIONS_013_035	Merged Quantile-Quantile and Scatter plots between observations and analysis, for each wave buoy separately, for 1-year period
Equivalent metrics are produced for individual wave buoy groups (e.g. SWH-H-CLASS4-MOOR-<STAT>-<MOORINGS GROUP ID>)				

Table 5: List of metrics for Med-waves evaluation using in-situ and satellite observations (continues in next page).

Name	Description	Wave parameter	Supporting reference dataset	Quantity
Evaluation of Med-waves using quasi-independent satellite observations (full MED)				
SWH-H-CLASS4-ALT-<STAT>-MED	Comparison to altimeter significant wave height	Spectral significant wave height (Hm0)	WAVE_GLO_WAV_L3_SWH_NRT_OBSERVATIONS_014_001	RMSD, SI, BIAS, CORR, LR_SLOPE between observations and first-guess, for all Med, for 1-year period and seasonally
SWH-H-CLASS4-ALT-QQ-MED SWH-H-CLASS4-ALT-SCATTER-MED	Comparison to altimeter significant wave height	Spectral significant wave height (Hm0)	WAVE_GLO_WAV_L3_SWH_NRT_OBSERVATIONS_014_001	Merged Quantile-Quantile and Scatter plots between observations and first-guess, for all Med, for 1-year period
Equivalent metrics are produced for individual satellite missions				
Evaluation of Med-waves using quasi-independent satellite observations (MED sub-regions)				
SWH-H-CLASS4-ALT-<STAT>-<REGION>	Comparison to altimeter significant wave height	Spectral significant wave height (Hm0)	WAVE_GLO_WAV_L3_SWH_NRT_OBSERVATIONS_014_001	RMSD, SI, BIAS, CORR, LR_SLOPE between observations and first-guess, for Med sub-basins, for 1-year period
SWH-H-CLASS4-ALT-QQ-<REGION> SWH-H-CLASS4-ALT-SCATTER-<REGION>	Comparison to altimeter significant wave height	Spectral significant wave height (Hm0)	WAVE_GLO_WAV_L3_SWH_NRT_OBSERVATIONS_014_001	Merged Quantile-Quantile and Scatter plots between observations and first-guess, for Med sub-basins, for 1-year period
Equivalent metrics are produced for individual satellite missions				

Table 5: (continued) List of metrics for Med-waves evaluation using in-situ and satellite observations

IV VALIDATION RESULTS

IV.1 Significant wave height

Comparison with in-situ observations

Table 6 shows results of the comparison between analysis SWH (model data) and in-situ observations (reference data), for the Mediterranean Sea as a whole, for the entire year (Jul 2019 - Jul 2020) and seasonally. In the table, "Entries" refers to the number of model-buoy collocation pairs, i.e. to the sample size available for the computation of the relevant statistics, $\bar{R}$ is the mean reference value, $\bar{M}$ is the mean model value, STD R and STD M are the standard deviations of the reference and model data respectively. The remaining quantities are the qualification metrics defined in the previous section. *Figure 5* is the respective merged QQ-Scatter plot for the full 1-year period. In the figure, the QQ-plot is depicted with black crosses. Also shown are the best fit line with intercept (red solid line) and the 45° reference line (red dashed line).

MED	ENTRIES	$\bar{R}$ (m)	$\bar{M}$ (m)	STD R (m)	STD M (m)	RMSD (m)	SI	BIAS (m)	CORR	LR_SLOPE
Whole Year	68061	0.88	0.89	0.74	0.74	0.21	0.24	0.01	0.96	1.00
Winter	16362	1.07	1.08	0.96	0.98	0.26	0.24	0.01	0.97	1.00
Spring	16738	0.88	0.89	0.68	0.67	0.20	0.22	0.02	0.96	0.99
Summer	17196	0.66	0.69	0.47	0.49	0.17	0.25	0.02	0.94	1.02
Autumn	17765	0.92	0.92	0.71	0.71	0.21	0.23	0.00	0.96	0.98

Table 6: Med-waves SWH evaluation against wave buoys' SWH, for the full Mediterranean Sea, for 1 year period and seasonally. Relevant metrics from Table 5: SWH-H-CLASS4-MOOR-<STAT>-MED.

Table 6 shows that the typical difference (RMSD) varies from 0.17 m in summer to 0.26 m in winter. However, the scatter in summer (0.25) is a little higher than the scatter in winter (0.24) whilst the lowest correlation coefficient (0.94) is associated with the former season and the highest (0.97) with the latter. This suggests that the model follows better the observations in winter which is associated with more well-defined patterns and higher waves than in summer. A similar conclusion has been derived by other studies (Cavaleri and Sclavo, 2006; Ardhuin et al., 2007; Bertotti et al., 2013) with respects to wind and wave modelling performance in the Mediterranean Sea. Spring and autumn present similar statistics with SI values (0.22-0.23) being the best of all seasons and a correlation (0.96) that is between winter and summer correlation. Small positive BIAS is obtained for all season with the highest positive value found in summer (4% relative to the observed mean) and the lowest in autumn (0%). Also, summer has an LR_SLOPE which is above 1, whilst the other seasons have LR_SLOPEs equal or very close to 1. These values indicate a possible model overestimate which is enhanced in summer. Indeed, the relevant QQ-Scatter plots (not shown) revealed that the model mostly overestimates the observations in summer, especially over the higher SWH range. A smaller overestimate, except at very low waves, was also observed in winter whilst spring and autumn have scatters that are more uniform along the 45° reference line.

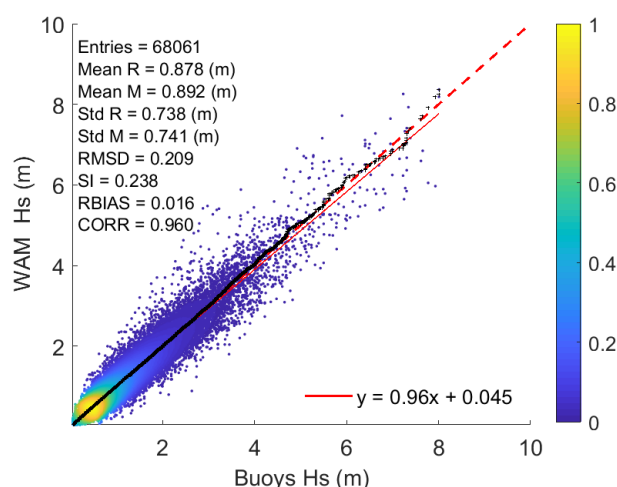


Figure 5: QQ-Scatter plots of Med-waves output SWH (H_s) versus wave buoys' observations, for the full Mediterranean Sea, for 1 year period: QQ-plot (black crosses), 45° reference line (dashed red line), least-squares best fit line (red line). Relevant metrics from Table 5: SWH-H-CLASS4-MOOR-QQ-MED, SWH-H-CLASS4-MOOR-SCATTER-MED.

Figure 5 depicts the pattern of the agreement between analysis and observed SWH for different SWH value ranges, for the full Mediterranean Sea. The figure reveals that the model approximates very well the observations with a small model overestimation of the observed SWH dominating for waves above about 3 m.

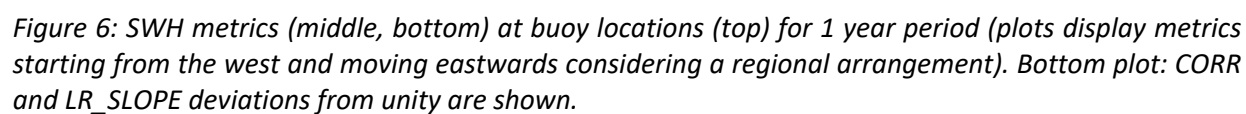
Table 7 shows results of the comparison between analysis SWH and in-situ observations for each of the wave buoys depicted in Figure 4. The qualification metrics for the different buoy locations are also plotted in Figure 6 in order to facilitate the visualization and interpretation of the relative performance of the wave model at the different locations. To be able to readily compare the pattern of variation of the different metrics at the different locations the absolute BIAS and the CORR and LR_SLOPE deviations from unity are plotted in the bottom plot of Figure 6. The values of BIAS and LR_SLOPE as given in Table 7 are shown in the middle plot. For convenience, a map of the wave buoy locations is included in the figure (top).

Table 7 and Figure 6 reveal that the typical difference (RMSD) at the different buoy locations varies from 0.13 m to 0.4 m. The Scatter Index (SI) varies from 0.17 at the offshore buoys 6100417 and 6100002, in the western Mediterranean Sea, to 0.41 and 0.53 at the coastal buoys 6101629 and 6101628 respectively in the Gulf of Trieste, in the North Adriatic Sea. In general, SI values above the mean value for the whole Mediterranean Sea (0.24) are obtained at wave buoys located near the coast (e.g. coastal Spanish buoys), particularly if these are sheltered by land masses on their north-northwest (e.g. western French coastline), and/or within enclosed basins characterized by a complex topography (e.g. ATHOS in the Aegean Sea). As explained in several studies (e.g. Cavaleri and Sclavo, 2006; Bertotti et al., 2013; Zacharioudaki et al., 2015), in these cases, the spatial resolution of the wave model is often not adequate to resolve the fine bathymetric features whilst the spatial resolution of the forcing wind model is incapable to reproduce the fine orographic effects, introducing errors to the wave analysis. The correlation coefficient (CORR) mostly follows the pattern of variation of the SI. It ranges from 0.78 at buoy 6101628 in the North Adriatic Sea to 0.98 at deep water buoy 6100002, offshore from France, and buoy 6100294, west of Corsica, which are well exposed to the prevailing north-westerly winds in the region. Nevertheless, despite a high correlation, buoy 6100294 has the largest negative BIAS of -0.18 m

whilst the largest positive BIAS of 0.18 m is found at buoy 6100021, offshore the eastern exit of the Gulf of Lion, France. Both locations are associated with islands and/or promontories in their vicinity that might not be well resolved by the model. The sign of BIAS varies, with positive and negative values computed at almost the same number of locations respectively. In agreement with BIAS, the LR_SLOPE varies between 0.84 at buoy 6100294 to 1.13 at buoy 6100021. In most of the cases, when BIAS is negative an LR_SLOPE below unity is obtained, pointing to a prevalence of model underestimation of the observed SWH, and vice versa. Nevertheless, there are cases when BIAS and LR_SLOPE do not show towards the same direction. This pattern is indicative of a differential model performance over the different wave height ranges.

Buoy ID	ENTRIES	$\bar{R}$ (m)	$\bar{M}$ (m)	STD R (m)	STD M (m)	RMSD (m)	SI	BIAS (m)	CORR	LR_SLOPE
6101404	2179	0.54	0.53	0.30	0.38	0.18	0.34	-0.01	0.88	1.02
Malaga	2828	0.46	0.46	0.33	0.36	0.15	0.33	0.00	0.91	0.99
Tarragona	2920	0.55	0.58	0.39	0.47	0.19	0.34	0.03	0.93	1.08
Barcelona	2798	0.75	0.69	0.54	0.49	0.17	0.21	-0.07	0.96	0.90
6100198	2725	1.01	1.10	0.70	0.75	0.23	0.21	0.09	0.96	1.07
6100417	2935	1.02	1.04	0.68	0.68	0.17	0.17	0.01	0.97	1.00
6100281	2910	0.83	0.82	0.68	0.68	0.18	0.22	0.00	0.97	0.98
6100280	2936	0.93	0.94	0.77	0.78	0.20	0.21	0.01	0.97	1.00
6100430	2916	1.04	1.03	0.82	0.75	0.21	0.20	-0.01	0.97	0.95
6100197	1899	1.34	1.30	1.07	1.01	0.26	0.19	-0.04	0.97	0.95
6100196	2924	1.21	1.27	0.98	0.94	0.24	0.20	0.06	0.97	1.00
61499	2050	0.44	0.44	0.39	0.48	0.16	0.36	0.01	0.96	1.08
6100002	2900	1.39	1.43	1.01	1.04	0.23	0.17	0.04	0.98	1.02
6100001	2920	1.04	1.09	0.74	0.84	0.22	0.20	0.05	0.97	1.07
6100188	2905	0.66	0.64	0.62	0.57	0.18	0.27	-0.03	0.96	0.92
6100191	2906	0.68	0.70	0.58	0.56	0.17	0.25	0.03	0.96	0.99
6100190	2897	0.63	0.71	0.56	0.55	0.19	0.27	0.08	0.96	1.04
6100431	2826	0.71	0.69	0.55	0.50	0.18	0.24	-0.03	0.95	0.93
6100290	2681	0.72	0.81	0.50	0.54	0.20	0.25	0.09	0.94	1.08
6100289	2812	0.90	0.88	0.60	0.58	0.19	0.21	-0.02	0.95	0.96
6100021	1519	1.23	1.40	0.80	0.95	0.40	0.29	0.18	0.93	1.13
6100294	2361	1.18	1.00	0.96	0.82	0.30	0.21	-0.18	0.98	0.84
6100295	2496	0.65	0.62	0.51	0.48	0.17	0.25	-0.03	0.95	0.93
6101628	786	0.25	0.25	0.17	0.21	0.13	0.53	0.01	0.78	1.00
6101629	911	0.37	0.35	0.27	0.29	0.15	0.41	-0.02	0.85	0.93
68422	502	0.74	0.77	0.49	0.47	0.15	0.19	0.03	0.96	1.00
HERAKLION	1854	0.73	0.80	0.57	0.58	0.16	0.20	0.06	0.97	1.05
61277	2117	1.02	1.06	0.72	0.73	0.20	0.19	0.04	0.96	1.02
MYKON	2726	1.04	1.14	0.83	0.91	0.25	0.22	0.10	0.97	1.08
ATHOS	1669	0.77	0.71	0.70	0.64	0.22	0.28	-0.06	0.95	0.90

Table 7: Med-waves SWH evaluation against wave buoys' SWH, for each individual buoy location, for 1 year period. Relevant metrics from Table 5: SWH-H-CLASS2-MOOR-<STAT>-<MOORING ID> .



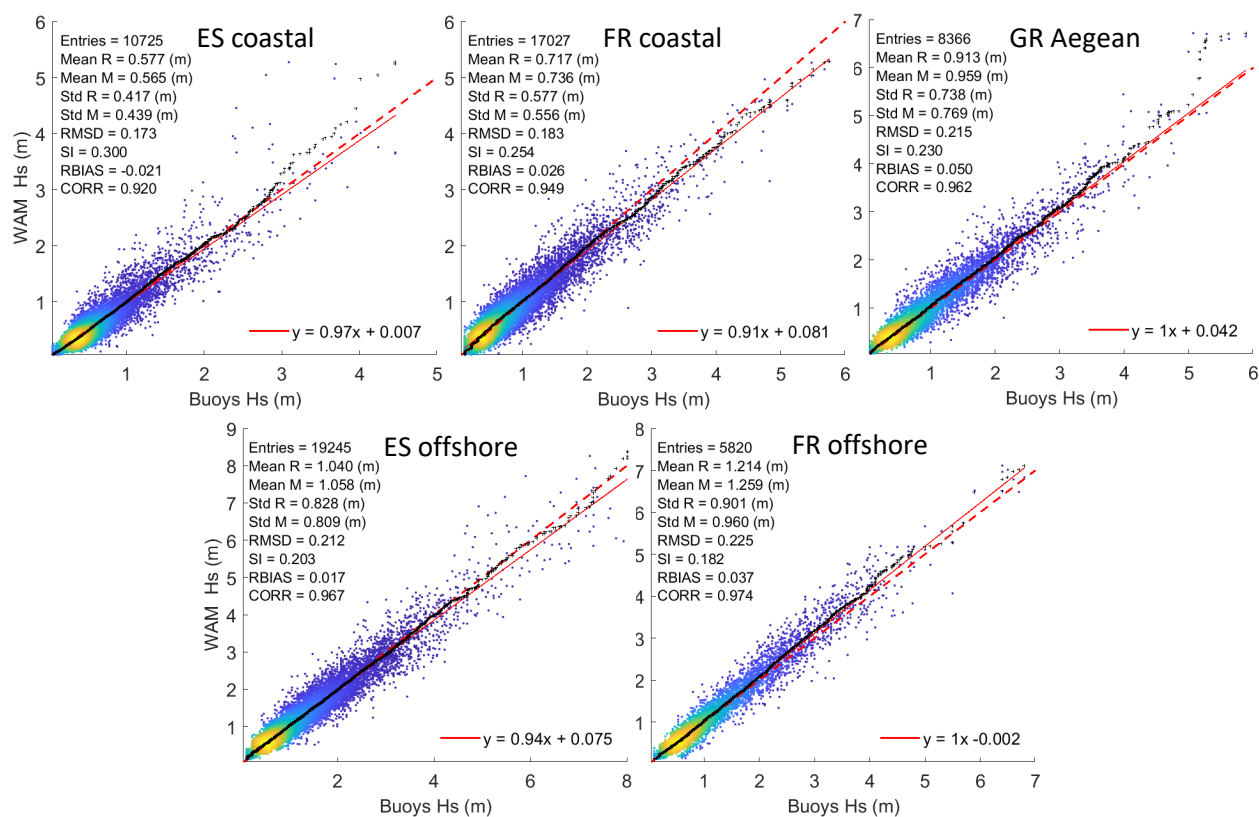


Figure 7: QQ-Scatter plots of Med-waves analysis SWH (Hs) versus wave buoy observations for each of the wave buoy groups defined in Table 4, for 1 year period: QQ-plot (black crosses), 45° reference line (dashed red line), least-squares best fit line (red line). Relevant metrics from Table 5: SWH-H-CLASS4-MOOR-QQ-<MOORINGS GROUP ID>, SWH-H-CLASS4-MOOR-SCATTER-<MOORINGS GROUP ID>.

Figure 7 shows QQ-Scatter plots for each of the wave buoy groups defined in Table 4, exhibiting model performance over the different wave height ranges. It shows that, as expected, the best overall statistics are obtained for the offshore wave buoy group of France (Relative RMSD = 0.14) which contains relatively well exposed deep water wave buoys. Nevertheless, a widespread model overestimation of the observed SWH is seen for heights above about 1 m, which is exacerbated over the high wave height range. It is noted that this model overestimation is small for buoy 6100002 which is the most exposed of the two buoys in the group. The behaviour of the model for this group is expected to be representative of its performance at well-exposed deep water sites. Model performance is second best (Relative RMSD = 0.16) for the offshore wave buoy group of Spain whose wave buoys are located closer to the coast compared to the previous group. Here, the QQ-plot crosses lay close to the reference line and the positive BIAS seems to be mainly due to a small model overestimation over low wave heights. For waves above about 3 m, a variable pattern of model-observations agreement is seen with small model underestimation or convergence towards the observations being the most frequent patterns along the SWH range. Nevertheless, at the wave buoys located near the Gibraltar Strait (61198, 61417), the model overestimates the observations over most or all of the SWH range. This is most probably related to a general model overestimation in the Alboran Sea, as it will be seen later in the comparison with the satellites. Model overestimation throughout the SWH range is also seen in the Aegean Sea (Relative RMSD = 0.24). This is the case for all the individual buoys in the group, especially for those located closer to the coastline, except for ATHOS where model underestimation is dominant. The poorest model

performance is obtained for the coastal wave buoy groups of France (Relative RMSD = 0.26) and Spain (Relative RMSD = 0.3). For the coastal wave buoys of France, except for buoy 6100290, the typical scatter distribution is similar to the one shown for the wave buoy group as a whole. Thus, convergence or small model overestimation of the observations is seen over the lower SWH range while a small model underestimation is found over the higher SWH range. At buoy 6100290, which is located near complex topography, a widespread model overestimation is observed. Generalizing, non-trivial model overestimation of the observed SWH is not uncommon at wave buoys associated with unresolved bathymetric features in their surrounding (e.g. 6100021, 61499, 6101628) as also seen in the validation of the Med-waves multi-year product (Zacharioudaki et al., 2021). Model overestimation of SWH observations above about 0.5-1 m is also obtained at most of the coastal wave buoys of Spain, as also indicated by the QQ-Scatter plot of this group. Only at Barcelona buoy, a widespread model underestimation is observed. Model underestimation is also the dominant mode at buoys 6100294, 6100295 (not included in a group), located on either side of Corsica island.

Comparison with satellite observations

This sub-section starts with the comparison of the ECMWF forcing wind speeds, U10, and Med-waves first-guess SWH, with satellite observations of U10 and SWH respectively, separately for each satellite. For U10, altimeter observations from CMEMS WAV TAC are available since 2020, therefore, the U10 validation corresponds to a shorter period of about half a year (1 Jan 2020 – 15 Jul 2020) compared to the SWH validation which spans a full year (16 Jul 2019 – 15 Jul 2020). Figure 8 shows relevant metrics for the full Mediterranean Sea (top plots) and for the individual sub-regions shown in Figure 1 (bottom plot).

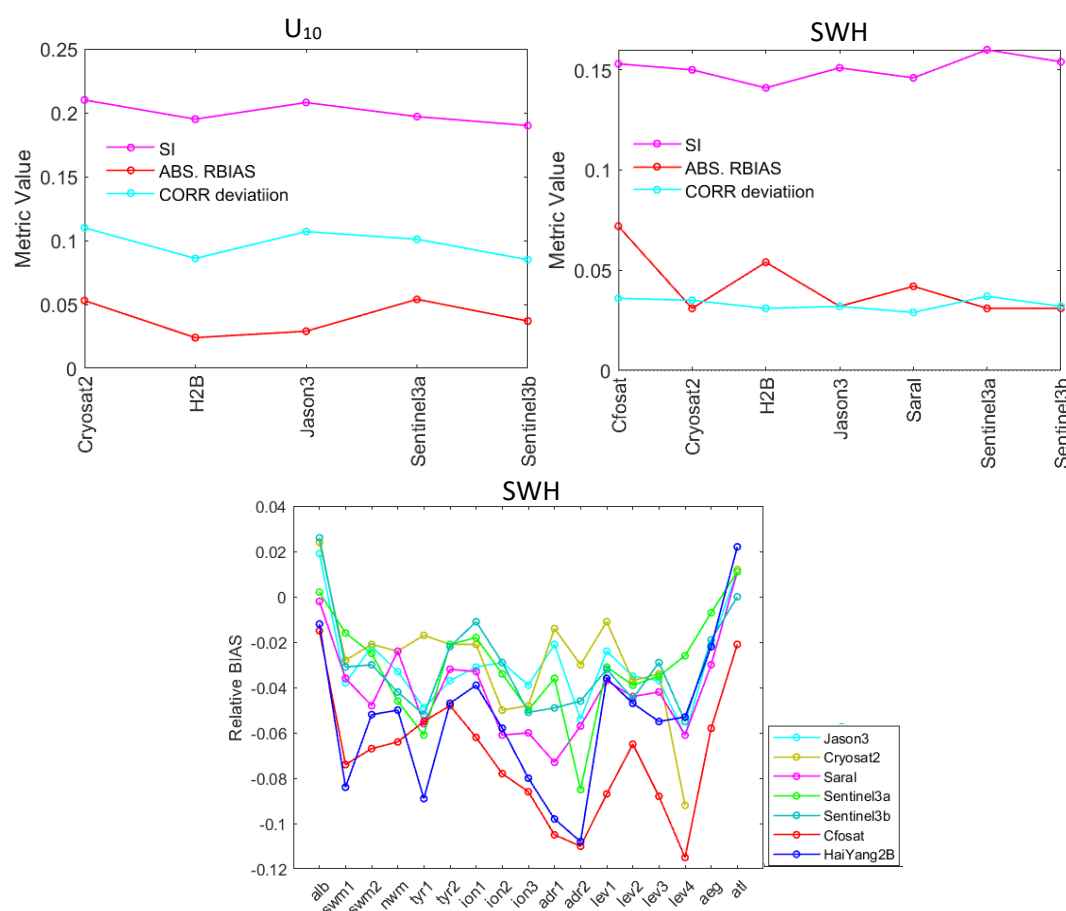


Figure 8: (top plots) ECMWF analysis U10 and Med-waves first-guess SWH evaluation against satellite U10 and SWH respectively, for each satellite, for the full Mediterranean Sea and for the periods Jan 2020 - Jul 2020 and Jul 2019 - Jul 2020 respectively. (bottom plot) As top right plot but for the individual sub-regions defined in Figure 1. Relevant metrics from Table 5: SWH-CLASS4-ALT-<STAT>-MED, SWH-H-CLASS4-ALT-<STAT>-<REGION> for individual altimeters.

An apparent feature in Figure 8 is a differentiation in model-satellite Relative BIAS found for CFOSAT with respects to SWH. This is seen for the full Mediterranean Sea and for the individual sub-regions, especially over the eastern Mediterranean basin. In particular, SWH model-CFOSAT Relative BIAS are found to be different by 2-4% compared to the values computed for the other model-satellite pairs. In addition, many spikes have been detected in the CFOSAT dataset. SWH model-H2B comparisons are also producing increased negative model BIAS, however, to a lesser degree compared to model-CFOSAT

results. No spikes were found in the H2B dataset. Otherwise, the model-satellite comparison behaves similarly for the different satellites with the Med-waves model exhibiting its best overall performance when compared to the observations of SARAL, which are known from literature (e.g. Sepulveda et al., 2015; Queffeulou et al., 2016) to be of very high quality, better than most satellites. As a result, in this study, model-SARAL SWH metrics' values are considered as a benchmark and satellites leading to considerably different results may be excluded from the validation analysis. Herein, the CFOSAT observations were omitted from the validation because of the numerous spikes in the dataset and of the increased model BIAS associated with the model-CFOSAT comparisons.

After excluding CFOSAT and merging all other satellite data, Table 8 shows statistics from the comparison of the Med-waves first-guess SWH and satellite observations of SWH, for the full Mediterranean Sea, for 1-year period and seasonally. Figure 9 (right) shows the corresponding QQ-Scatter plot for 1-year period, for the full Mediterranean Sea. Figure 9 (left) shows an equivalent QQ-Scatter for the ECMWF analysis U10 (Jan 2020 – Jul 2020).

MED	ENTRIES	$\bar{R}$ (m)	$\bar{M}$ (m)	STD R (m)	STD M (m)	RMSD (m)	SI	BIAS (m)	CORR	LR_SLOPE
Whole Year	197654	1.37	1.32	0.81	0.81	0.21	0.15	-0.05	0.97	0.96
Winter	53847	1.68	1.63	1.03	1.05	0.25	0.14	-0.05	0.97	0.98
Spring	54434	1.35	1.29	0.73	0.71	0.21	0.15	-0.05	0.96	0.95
Summer	44513	1.07	1.03	0.49	0.48	0.17	0.15	-0.04	0.94	0.95
Autumn	44859	1.32	1.27	0.74	0.72	0.21	0.15	-0.05	0.96	0.96

Table 8: Med-waves SWH evaluation against satellite SWH, for the full Mediterranean Sea, for 1 year period and seasonally. Relevant metrics from Table 5: SWH-H-CLASS4-ALT-<STAT>-MED.

Figure 9 (left) shows that the ECMWF forcing wind model overestimates observed U10 below about 14 m/s and underestimates it above that value. An overall model overestimation of 3.6% (relative to the observed mean) associated with a linear regression slope of 0.92 have been computed. On the contrary, Figure 9 (right) shows an overall Med-waves model underestimation of the observed SWH by 3.6% associated with a linear regression slope of 0.96. Nevertheless, in this case the model better approximates the observations along the SWH range with small model underestimation mainly observed for SWHs below 4 m. Over high winds and waves, an offset of the wind model negative BIAS is achieved by the wave model. This result is consistent with previous CMEMS validation activities and is related to the tuning of the dissipation coefficients in WAM. On the whole, Figure 9 shows that the performance of Med-waves at offshore locations in the Mediterranean Sea (satellite records near the coast are mostly filtered out as unreliable) is very good. Comparing to similar results obtained from the model-buoy comparison (Figure 5), a smaller scatter and a BIAS of different sign is associated with the model-satellite comparison. SI values are in better agreement at the more exposed waves buoys in the Mediterranean Sea. At this point, it should be kept in mind that the omission of any SWH < 0.5 m from the model-satellite comparisons does lead to somewhat improved SI and BIAS values compared to the values that would have been obtained by including very small waves as is the case for the model-buoy comparisons (SWH > 0.05 m used).

Table 8 shows the seasonal variation of the Med-waves model performance. The typical difference with observations (RMSD) varies from 0.17 m in summer to 0.25 m in winter. SI has a very small variation with its value being lower in winter (0.14) than in other seasons (0.15). Accordingly, the correlation coefficient is the highest in winter (0.97). Summer correlation (0.94) is lower than in autumn and spring

(0.96). In general, as explained in the previous sub-section, a lower scatter with a higher correlation is expected the more well-defined the weather conditions are. BIAS is negative in all seasons. Like SI, Relative BIAS has a small variation between seasons. Its best value (3%) is computed for winter for which model overestimation of SWH > 3.5 m dominates the scatter distribution. For the other seasons, a Relative BIAS of about 4% is obtained with model underestimation being the dominant mode. In accordance, LR_SLOPE is always below unity (0.95) reaching close to unity in winter (0.98).

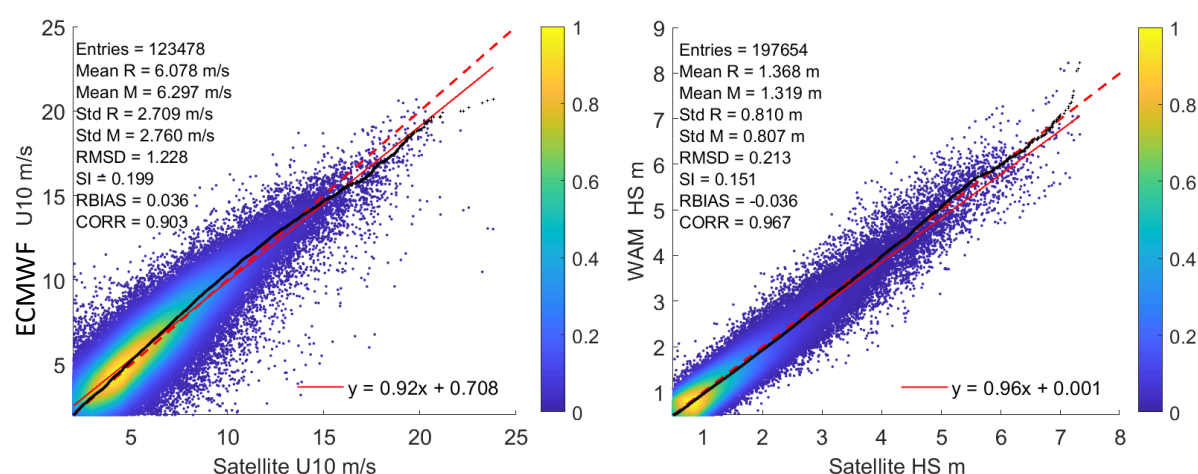


Figure 9: QQ-Scatter plots of: (left) ECMWF forcing wind speed U10 versus satellite U10; (right) Med-waves first-guess SWH (Hs) versus satellite SWH, for the full Mediterranean Sea, for 1 year period: QQ-plot (black crosses), 45° reference line (dashed red line), least-squares best fit line (red line). Relevant metrics from Table 5: SWH-H-CLASS4-ALT-QQ-MED and SWH-H-CLASS4-ALT-SCATTER-MED.

Table 9 shows the statistics of the comparison of the Med-waves first-guess SWH and satellite observations of SWH for the different sub-regions of the Mediterranean Sea defined in Figure 1. For visualization purposes, Figure 10 (right column) maps the statistics shown in Table 9. In addition, equivalent statistics are mapped for the ECMWF - satellite comparison of U10 (left column). It is highlighted that the model-satellite wind results span half a year less than the model-satellite wave results. Thus, the relative performance of the wind and wave models should be interpreted with caution.

Figure 10 (right column) shows that the highest values of SI are obtained for the Adriatic Sea (0.20-0.21) followed by the Alboran (0.19) and the Aegean Sea (0.18). The North Tyrrhenian Sea and the East Levantine have also relatively high SI values (0.17). Otherwise, SI is 0.12-0.16, with the lowest values observed over the south-eastern Mediterranean Sea, which is the most open part of the Mediterranean basin, free of topographic obstacles. SI and CORR have a similar pattern of variation. In accordance with these results, Ratsimandresy et al. (2008), examining model-satellite agreement over coastal locations of the western Mediterranean Sea, found the worst correlations in the Alboran Sea and east of Corsica Island. Bertotti et al. (2013), in a comparison of high resolution wind and wave model output with satellite data over different sub-regions of the Mediterranean Sea, also found the largest scatter and lowest correlations in the Adriatic Sea, followed by the Aegean Sea. In agreement, Zacharioudaki et al. (2015), focusing on the Greek Seas, have shown a considerably larger scatter in the Aegean Sea than in the surrounding seas, when model output was compared to satellite observations.

Satellite	ENTRIES	$\bar{R}$ (m)	$\bar{M}$ (m)	STD R (m)	STD M (m)	RMSD (m)	SI	BIAS (m)	CORR	LR_SLOPE
atl	9885	1.73	1.75	0.76	0.74	0.19	0.11	0.02	0.97	1.00
alb	4720	1.29	1.31	0.69	0.72	0.24	0.19	0.01	0.94	1.00
swm1	14616	1.35	1.31	0.77	0.75	0.21	0.15	-0.05	0.96	0.96
swm2	9423	1.56	1.51	0.99	0.98	0.24	0.15	-0.05	0.97	0.97
nwm	23123	1.57	1.52	1.02	1.00	0.25	0.15	-0.06	0.97	0.96
tyr1	3356	1.32	1.25	0.68	0.69	0.24	0.17	-0.07	0.95	0.95
tyr2	16463	1.39	1.35	0.79	0.82	0.23	0.16	-0.04	0.96	0.98
ion1	13698	1.27	1.24	0.69	0.69	0.19	0.14	-0.03	0.97	0.97
lon2	33072	1.41	1.35	0.86	0.84	0.19	0.13	-0.06	0.98	0.96
ion3	11004	1.33	1.26	0.81	0.81	0.22	0.16	-0.07	0.97	0.95
adr1	3358	1.12	1.07	0.57	0.59	0.24	0.21	-0.05	0.92	0.95
adr2	4052	1.20	1.13	0.61	0.63	0.25	0.20	-0.08	0.93	0.94
lev1	11543	1.40	1.36	0.75	0.75	0.19	0.14	-0.04	0.97	0.97
lev2	14664	1.29	1.24	0.70	0.71	0.19	0.14	-0.05	0.97	0.96
lev3	14365	1.35	1.30	0.76	0.74	0.17	0.12	-0.05	0.98	0.96
lev4	9033	1.11	1.04	0.63	0.62	0.20	0.17	-0.06	0.95	0.94
aeg	11144	1.30	1.27	0.69	0.73	0.24	0.18	-0.03	0.95	0.99

Table 9: Med-waves SWH evaluation against satellite SWH, for each individual Mediterranean Sea sub-region shown in Figure 1, for 1 year period. Relevant metrics from Table 5: SWH-H-CLASS4-ALT-<STAT>-<REGION>.

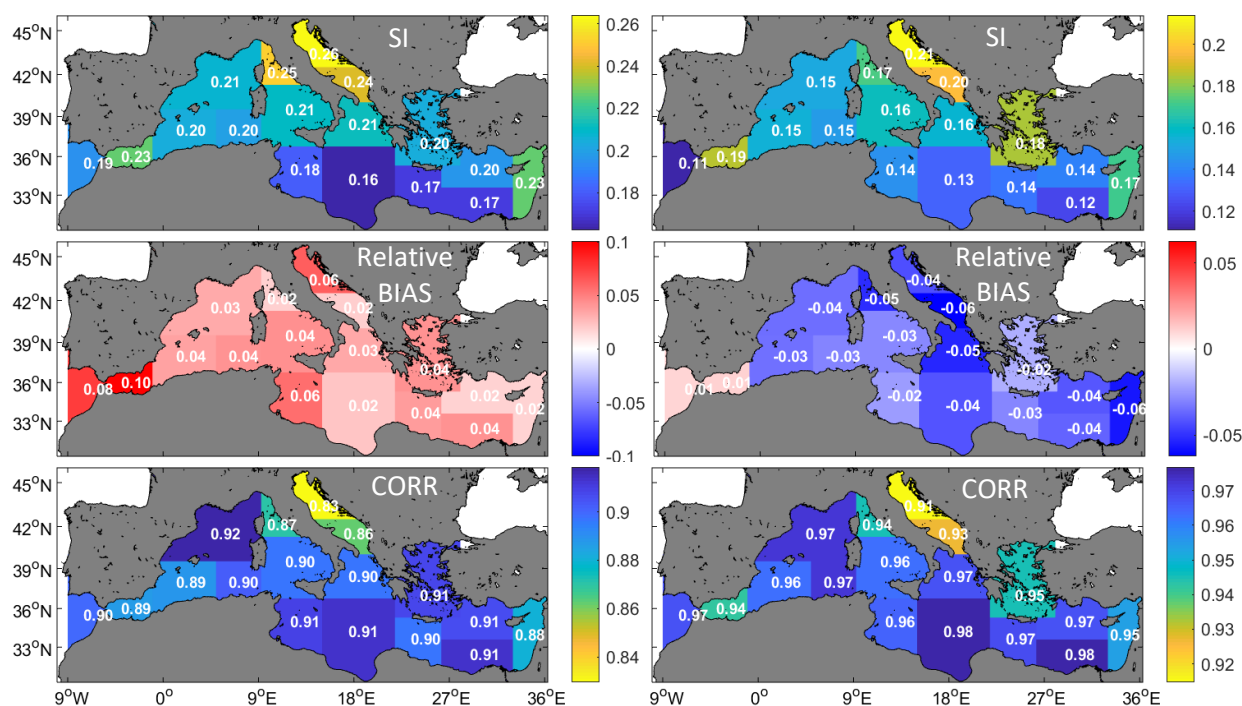


Figure 10: ECMWF U10 (left column) and Med-waves first-guess SWH (right column) evaluation against satellite U10 (Jan 2020 – Jul 2020) and satellite SWH (Jul 2019 – Jul 2020) respectively: maps of metric values over the Mediterranean Sea sub-regions shown in Figure 1, for 1 year period.

As explained in the previous sub-section (model-buoy comparison), it is the difficulties of wind models to properly reproduce orographic effects and/or local sea breezes and the difficulties of wave models to appropriately resolve complicated bathymetry that introduce errors in these fetch-limited, enclosed regions, often characterized by a complex topography. Indeed, comparison with the equivalent results for the ECMWF wind speeds confirms these difficulties. For example, the pattern of SI and CORR variation for U10 and SWH have similarities, corroborating the conclusion of many studies that errors in wave height simulations by sophisticated wave models are mainly caused by errors in the generating wind fields (e.g. Komen et al., 1994; Ardhuin et al., 2007). Nevertheless, differences do exist. For instance, the SWH SI in the Aegean Sea is relatively higher than the corresponding U10 SI. This is most probably because in this region of highly complicated bathymetry with many little islands the error of the wave model increases in relation to the error of the wind model. This is a result that has been consistent across CMEMS validations of different Med-waves versions. Negative BIAS is the case in all sub-regions except for the Atlantic and Alboran Sea sub-regions, where a small positive BIAS (1% relative to the observed mean) is obtained. Otherwise, Relative BIAS is negative by 2-6% with the most negative values observed in the South Adriatic and East Levantine Sea (6%), followed by the North Ionian and the North Tyrrhenian Sea (5%), and the lowest negative values seen in the Aegean and the West Ionian Sea (2%). The low negative BIAS and high scatter in the Aegean Sea could be related to unresolved topography by the wave model, as explained above, as well as in the section of model-buoy comparisons. In the Mediterranean Sea, QQ-Scatter plots for the individual sub-regions (not shown) have revealed, that, in all cases but in the Alboran Sea, the model underestimates the observations over the lower SWH range. In the Alboran Sea, the model converges to the observations. Over the middle SWH range, model underestimates the observations in most of the cases except again in the Alboran Sea as well as in the Aegean Sea where overestimate is widespread except at low waves. Over the high SWH range, the model converges to or even overestimates the observations in most of the cases. Only in the North West Mediterranean a more uniform pattern of model underestimate is seen. LR_SLOPE generally varies according to the BIAS, except in the Tyrrhenian and Aegean Sea, where a higher LR_SLOPE in relation to BIAS is connected to a more severe overestimation of high waves in the first case and a more widespread overestimation except at low waves in the second. Comparing with the respective results obtained for the ECMWF U10, a prominent discrepancy between winds and waves is the different sign of BIAS in the different sub-regions, except in the Atlantic and the Alboran Sea. This discrepancy did not change when the SWH validation over the same time period as the U10 validation was examined. By and large, the more positive the U10 RBIAS the least negative the SWH RBIAS. The Aegean Sea is the most obvious exception.

IV.2 Mean Wave Period

Comparison with in-situ observations

Table 10 presents the statistics of the comparison between the Med-waves analysis mean wave period, MWP, and in-situ observations of mean wave period, for the full Mediterranean Sea, for 1 year period and seasonally. Figure 11 shows the corresponding QQ-Scatter plot for the year-long statistics. It is shown that the model exhibits greater variability than the observations (STD in Table 10). The RMSD varies from 0.61 s in summer to 0.65 s in winter while Relative RMSD is about 15-17%, with winter, spring and autumn being at the low end of this range and summer at the high. SI is invariant (0.13). The non-trivial deviation of SI from Relative RMSD indicates that a substantial part of the model-observation difference is caused by BIAS. CORR has its minimum value (0.82) in summer and its maximum (0.9) in winter. These results indicate that the model wave period, like the model wave height, better follows the observations in well-defined wave conditions of higher waves and larger periods. The BIAS is negative. Relative BIAS is about 9% in all seasons but in summer when it reaches 11%. LR_SLOPE varies accordingly. In agreement, the seasonal QQ-Scatter plots (not shown) show a general tendency of the model to underestimate wave periods except over the higher percentiles where the model converges to the observations. Seasonal QQ-Scatter plots agree well with the year-long QQ-Scatter plot of Figure 11 which shows that the wave model underestimates the observations for MWP < 6 s, especially so for MWP < 4.5 s. Model underestimation is also seen at very high MWP values (winter values).

MED	ENTRIES	$\bar{R}$ (m)	$\bar{M}$ (m)	STD R (m)	STD M (m)	RMSD (m)	SI	BIAS (m)	CORR	LR_SLOPE
Whole Year	54575	3.98	3.61	0.94	1.06	0.63	0.13	-0.38	0.88	0.91
Winter	13013	4.19	3.82	1.09	1.23	0.65	0.13	-0.37	0.90	0.92
Spring	13446	4.06	3.69	0.91	1.03	0.63	0.13	-0.37	0.87	0.91
Summer	13743	3.68	3.29	0.71	0.80	0.61	0.13	-0.39	0.82	0.89
Autumn	14373	4.02	3.65	0.93	1.06	0.63	0.13	-0.37	0.88	0.91

Table 10: Med-waves MWP evaluation against wave buoys' MWP, for the full Mediterranean Sea, for 1 year period and seasonally. Relevant metrics from Table 5: MWP-H-CLASS4-MOOR-<STAT>-MED.

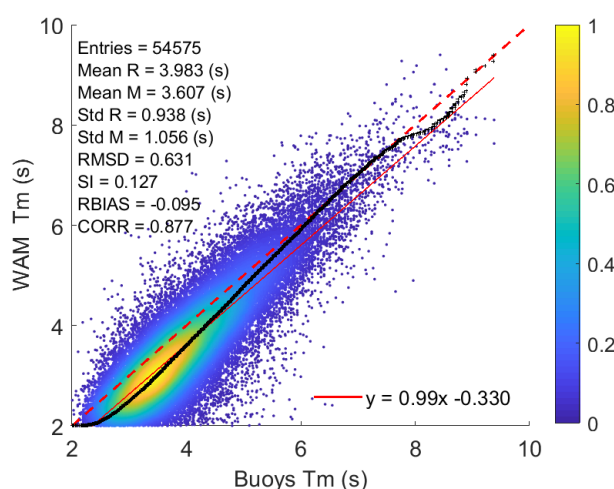


Figure 11: QQ-Scatter plots of Med-waves output MWP (T_m) versus wave buoys' observations, for the full Mediterranean Sea, for 1 year period. Relevant metrics from Table 5: MWP-H-CLASS4-MOOR-QQ-MED and MWP-H-CLASS4-MOOR-SCATTER-MED

Buoy ID	ENTRIES	$\bar{R}$ (m)	$\bar{M}$ (m)	STD R (m)	STD M (m)	RMSD (m)	SI	BIAS (m)	CORR	LR_SLOPE
6101404	1573	3.70	3.44	0.81	1.06	0.76	0.19	-0.27	0.74	0.93
Malaga	2597	3.58	3.40	0.77	0.96	0.62	0.17	-0.18	0.79	0.95
Tarragona	2885	3.98	3.68	0.89	1.04	0.73	0.17	-0.30	0.78	0.92
Barcelona	2777	3.96	3.74	0.82	0.97	0.58	0.14	-0.22	0.83	0.95
6100198	2713	4.24	3.77	0.83	0.90	0.65	0.11	-0.47	0.87	0.89
6100417	2920	4.28	3.87	0.88	0.97	0.58	0.09	-0.41	0.91	0.91
6100281	2896	3.99	3.58	0.83	1.00	0.61	0.12	-0.41	0.89	0.91
6100280	2929	4.19	3.70	0.90	0.97	0.66	0.10	-0.49	0.90	0.89
6100430	2912	4.50	4.03	0.97	1.12	0.65	0.10	-0.46	0.91	0.90
6100197	1897	4.66	4.31	1.09	1.28	0.57	0.10	-0.36	0.94	0.93
6100196	2922	4.42	3.96	0.92	1.03	0.61	0.09	-0.46	0.92	0.90
6100188	2720	3.69	3.30	0.93	1.01	0.66	0.15	-0.39	0.85	0.90
6100191	2561	3.47	3.08	0.99	1.04	0.63	0.14	-0.38	0.88	0.89
6100190	2694	3.52	3.12	0.96	0.99	0.63	0.14	-0.41	0.88	0.89
6100431	2638	3.60	3.10	0.85	0.93	0.69	0.13	-0.51	0.87	0.86
6100289	2757	3.80	3.41	0.74	0.84	0.63	0.13	-0.39	0.81	0.90
6100021	1514	4.40	4.15	0.94	1.06	0.53	0.11	-0.25	0.90	0.95
6100294	2342	4.26	4.04	1.08	1.30	0.55	0.12	-0.21	0.92	0.96
6100295	2431	3.71	3.45	0.78	0.95	0.59	0.14	-0.26	0.83	0.93
6101628	206	3.03	2.35	0.31	0.25	0.75	0.10	-0.68	0.39	0.77
6101629	419	3.14	2.48	0.39	0.35	0.72	0.09	-0.66	0.70	0.79
68422	502	3.92	3.61	0.78	0.94	0.58	0.13	-0.30	0.86	0.93
HERAKLION	1827	3.84	3.52	0.67	0.83	0.55	0.12	-0.32	0.85	0.92
61277	2104	4.04	3.67	0.77	0.88	0.54	0.10	-0.37	0.89	0.91
ATHOS	1464	3.80	3.03	0.74	0.75	0.85	0.10	-0.77	0.88	0.80

Table 11: Med-waves MWP evaluation against wave buoys' MWP, for each individual buoy location, for 1 year period. Relevant metrics from Table 5: MWP-H-CLASS2-MOOR-<STAT>-<MOORING ID>.

Table 11 gives the statistics of the model-buoy comparison at individual wave buoy locations. Figure 12, like Figure 6 for SWH, plots those statistics to facilitate their visualization and interpretation. Table 11 and Figure 12 show that the typical model-observation difference (RMSD) varies from 0.53 s to 0.85 s. In terms of Relative RMSD, this variation corresponds to a percentage range of 12% (6100021, 6100197) - 23% (6101629). It is evident that this difference is mainly caused by BIAS, which has a variation of -0.77 to -0.18 s, with Relative BIAS (not shown) varying from 5% at Malaga coastal buoy, near Gibraltar, and buoy 6100294, west of Corsica, to 20-21% at ATHOS buoy in the Aegean Sea and buoy 6101629 in the Gulf of Trieste, in the North Adriatic Sea. LR_SLOPE follows the variation of BIAS with LR_SLOPE values from 0.79 (6101629) to 0.96 (6100294). CORR varies from 0.7 at buoy 6101629 to 0.94 at the offshore location 61197, southeast of Minorca. Generally, in agreement with the wave height results, the lowest correlations are found at coastal locations affected by fetch differences between model and reality due to a complex surrounding topography. On the other hand, the highest correlations are obtained at the most exposed locations in Figure 12 (top). The variation of SI is relatively small compared to the variation of CORR and its values are relatively small compared to the equivalent results for SWH. It varies from 0.09 (6100196, 6100197) to 0.19 (6101404). In the case of MWP, because of the presence of strong biases, SI becomes a less determinant metric in model performance evaluation. It is noted that the metrics at buoy 6101628 are not included in the aforementioned variations because they are often far

(e.g. CORR = 0.39) from the values obtained at the rest of the locations, indicating the inability of the wave model to simulate MWP at this very difficult coastal location. A similar situation has been seen for SWH metrics at the two wave buoys located in the Gulf of Trieste, in the North Adriatic Sea.

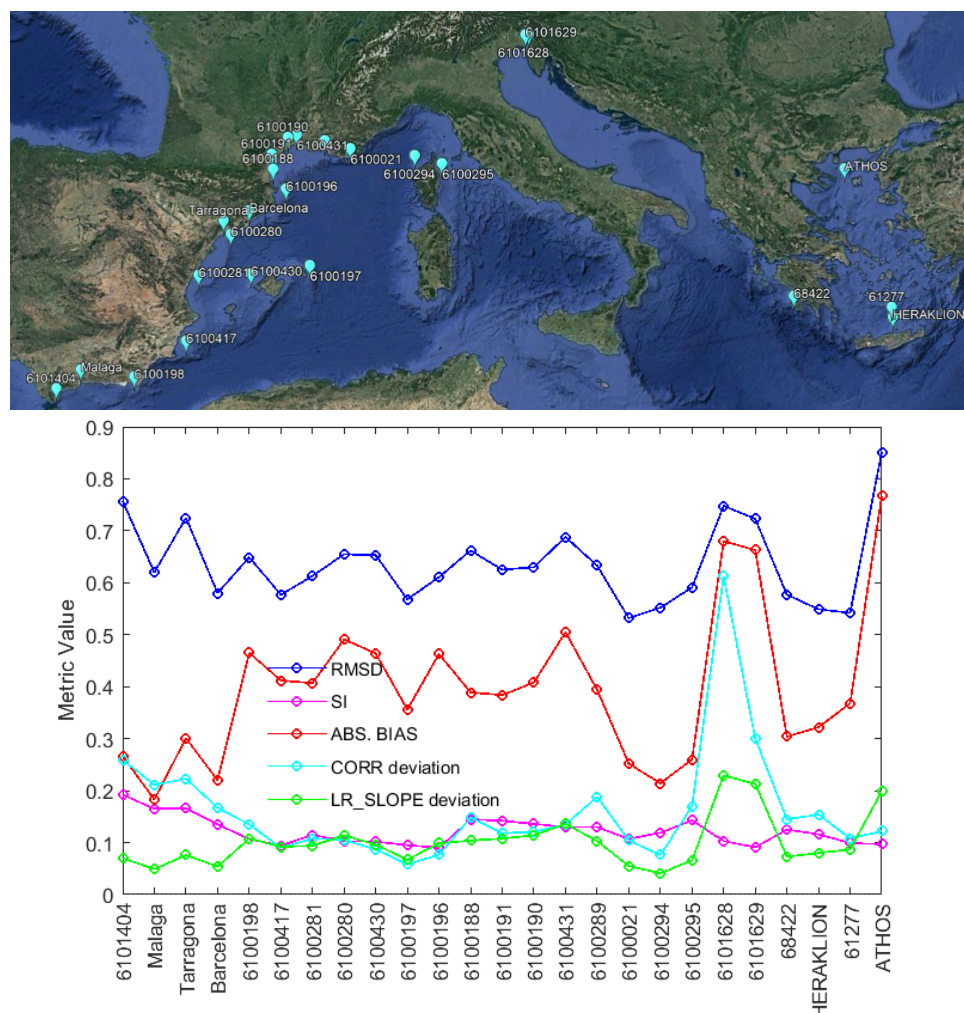


Figure 12: MWP metrics (bottom) at buoy locations (top) for 1 year period (plots display metrics starting from the west and moving eastwards considering a regional arrangement). CORR and LR_SLOPE deviations from unity are shown.

Figure 13, like Figure 7 for SWH, shows QQ-Scatter plots for each of the wave buoy groups defined in Table 4 (except FR offshore that has no MWP measurements), exhibiting model performance over the different mean wave period ranges. As expected, the best overall model performance is seen for the offshore wave buoy group of Spain (Relative RMSD = 0.15) which contains relatively well exposed wave buoys. The wave buoy group of the Aegean Sea follows (Relative RMSD = 0.16) whilst the worst model performance is obtained for the coastal wave buoy groups of Spain (Relative RMSD = 0.17) and France (Relative RMSD = 0.18). Regarding BIAS, in agreement with Figure 11, a model underestimation of the observations is seen over the lower MWP range and a model convergence towards the observations over the higher MWP range whilst model overestimation of MWP > 5 s is the case for the coastal wave buoy group of Spain. Model underestimation is relatively more severe in the Aegean Sea and the coast

of France. In general, a close examination of the QQ-Scatter plots of individual buoys (not shown) has revealed that the model underestimates lower MWP at all locations and converges towards high MWPs at most locations, occasionally overestimating the observed MWP. Model overestimation along higher MWPs is more noticeable at all coastal buoys of Spain and at buoy 6100294 west of Corsica island. Nevertheless, at few locations, a more uniform and persistent model underestimation of the observed MWP is obtained. These include the offshore buoy ATHOS in the Aegean Sea, buoys 6100190 and 6100431 at the coast of France, and the offshore buoy 6100198 in the Alboran Sea. Also, model underestimation is significant along the entire MWP range at the two wave buoys located in the North Adriatic Sea. Lastly, a density scatter plot that appears to have two peaks, indicative of a double peaked frequency spectrum, has been obtained at buoy 6100021, offshore from eastern France, and 6100198 in the Alboran Sea.

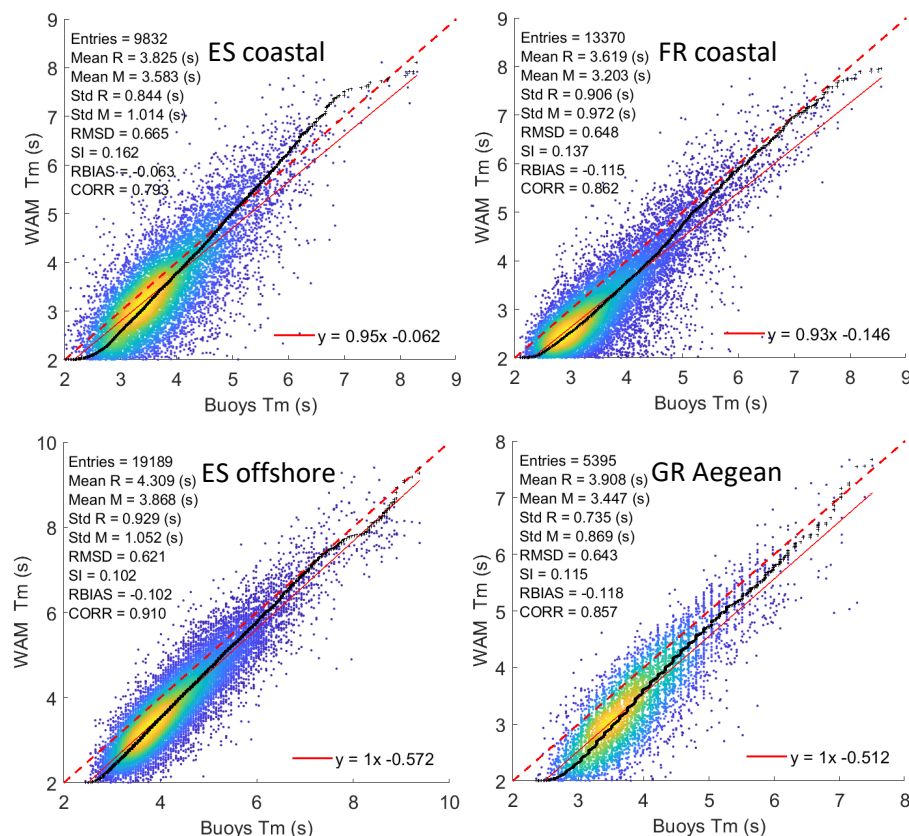


Figure 13: QQ-Scatter plots of Med-waves output MWP (Tm) versus wave buoy observations for each of the wave groups defined in Table 4 containing MWP measurements, for 1 year period: QQ-plot (black crosses), 45° reference line (dashed red line), least-squares best fit line (red line). Relevant metrics from Table 5: SWH-H-CLASS4-MOOR-QQ-<MOORINGS GROUP ID> and SWH-H-CLASS4-MOOR-SCATTER-<MOORINGS GROUP ID>

V SYSTEM'S NOTICEABLE EVENTS, OUTAGES OR CHANGES

V.1 Q2/2021 to Q4/2021

The new version of the CMEMS Med-waves NRT system (Q4/2021) compared to the previous version (Q2/2021) includes the following upstream data changes:

- i) nesting with GLOBAL waves system
- ii) use of higher spatial (1/10°) and temporal resolution ECMWF winds

VI QUALITY CHANGES SINCE PREVIOUS VERSION

For each of the two upstream data changes of version Q4/2021 (use of higher spatial and temporal resolution ECMWF winds and nesting with GLO-WAV), 2-month period experiments are performed in order to assess the difference in product quality since the previous version (Q2/2021) as shown in Table 12. Validation is performed using first-guess SWH of the Med-waves system collocated with along track satellite observations for the same 2-month period (May 2021 – June 2021).

EXP	Winds	OBC	Period
Control	As of Q2/2021	As of Q2/2021	May 2021 – Jun 2021
ECMWF10	Higher spatial and temporal resolution ECMWF winds	As of Q2/2021	May 2021 – Jun 2021
GLO-WAV	As of Q2/2021	From Global Waves	May 2021 – Jun 2021

Table 12: Experiments performed for Q4/2021 system validation

Quality changes with respect to the control run (version Q2/2021) are found to be marginal, as presented in figures 14-16. Run with the 1/10° ECMWF winds shows an improvement of SWH BIAS for all lead times (up to +96h) while the RMSD improves slightly until +48h (Figure 14). As regards the nesting with the GLO-WAV system, the Mediterranean Sea statistics are identical with the two types of nesting. Outside the Mediterranean the solution is practically the same with the control run (Q2/2021) being only slightly better in the north-western corner of the model domain (Figure 15-16).

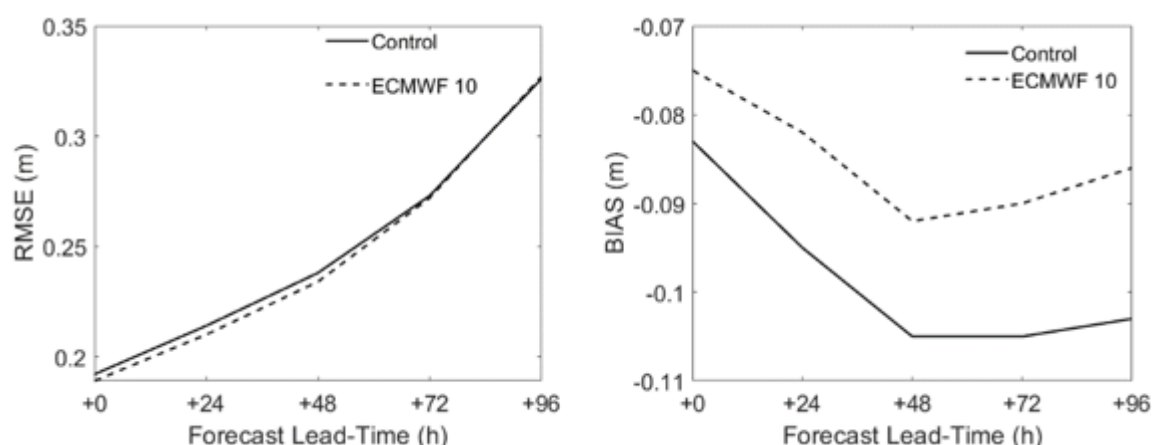


Figure 14: RMS difference (left) and bias (right) with respect to satellite SWH observations at different lead times corresponding to control (system at Q2/2021) and ECMWF10 run (May 2021 – June 2021) of the system. In both cases, the intercomparison is done using first-guess SWH of the Med-waves system.

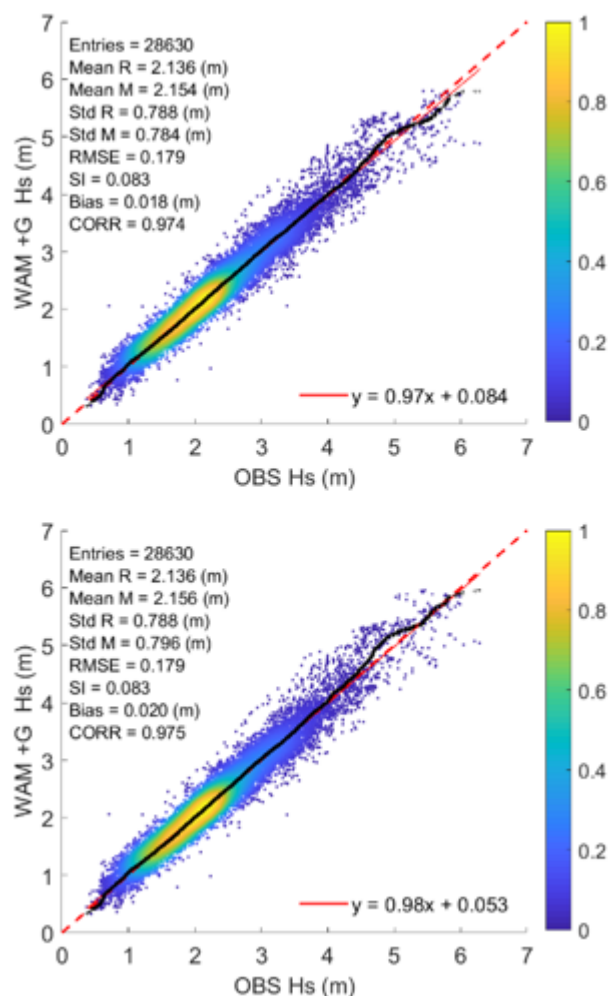


Figure 15: QQ-Scatter plots of the Med-waves first-guess SWH (Hs) versus satellite SWH, for the area west of 7° W (Atlantic region) and the period May 2021 – June 2021. Top panel corresponds to the control run while lower panel corresponds to nesting with the GLO-WAV system (GLO-WAV experiment).

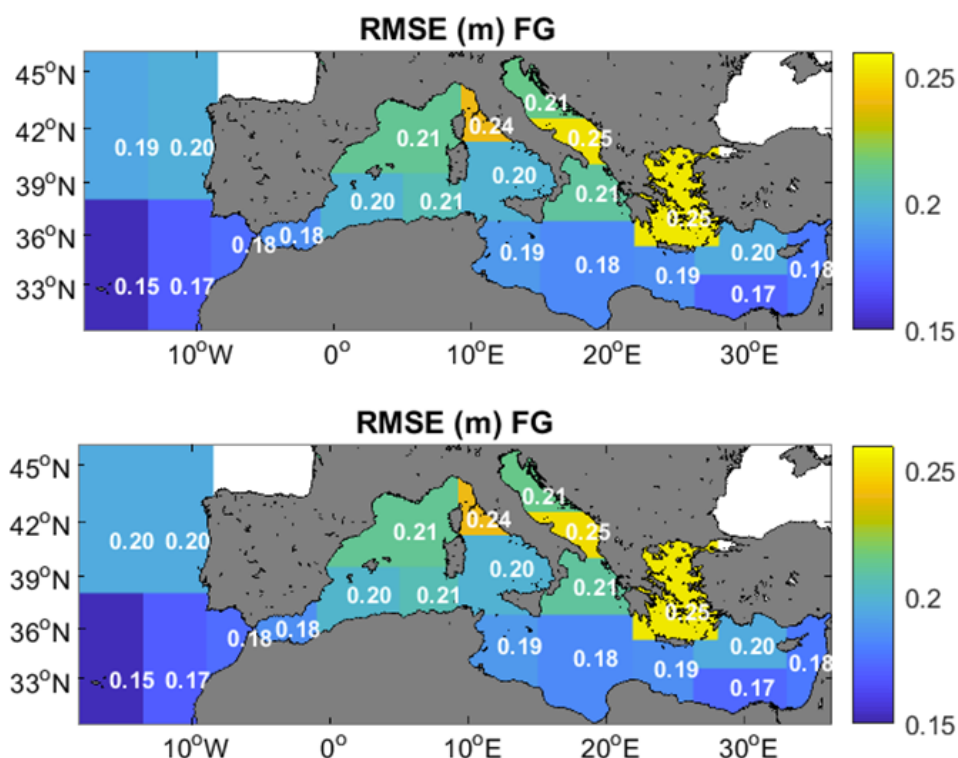


Figure 16: Med-waves first-guess SWH evaluated against satellite SWH observations (May 2021 – June 2021). Top panel: RMS difference corresponding to control run; Bottom panel: system run nested with the Global Wave CMEMS solution (GLO-WAV experiment).

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