Assessment of global wave models

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1. INTRODUCTION

This study analyses the performance of two spectral wave models: the European model WAM[1] (Cycle 4.6.2) and the American model WAWEWATCH III[2] (WW3 version 5.16). WAM and WW3 are treated as 'stand-alone' models which were configured to run at global scale (from 80S to 89N) considering atmospheric forcing (10-meter winds and sea-ice cover) from the ERA5 dataset and the analysis of the ECMWF high resolution forecast system (ECHRES). Outputs of wave hindcasts (3-hourly) were generated at spatial resolution of 0.25° by 0.25° and assessed by means of CMEMS near real time in-situ and satellite observations. To further evaluate the consistency and accuracy of the WAM and WW3 outputs, we also intercompared the results with 2 operational systems: the CMEMS global wave analysis and forecast and the ERA5 ocean waves reanalysis.

2. WAM AND WW3 CONFIGURATION

- Global Bathymetry: WAM: from ETOPO2 data; WW3: from ETOPO1 data
- Wave spectrum discretization: 24 directions; 30 frequencies starting from 0.035 Hz
- Forcing:
  - ERA5 (0.25°x0.25°): u&v10m (3-hourly), sea-ice cover (00z)
  - ECHRES (0.125°x0.125°): u&v10m (analysis at 00z, 06z, 12z, 18z), sea-ice cover (00z)
- Gridded output resolution: 0.25°x0.25°
- Source Terms configuration:

Source Term	WAM (cycle 4.6.2)	WW3 (v5.16)
Atmosphere-wave interaction + Dissipation	As in ECWAM CY38R1 (Bidlot[3])	Ardhuin[4]
Non-linear wave-wave interaction	Discrete interaction approximation	
Wave-bottom interactions	Jonswap parameterization	
Depth-induced breaking	Battjes-Jansen parameterization	

List of experiments: WAMera5, WAMechres, WW3era5, WW3echres
The strings "era5" and "echres" identify the forcing used in the experiment

3. WAVE GLOBAL NUMERICAL PRODUCTS AND OBSERVATIONS

Numerical Products

- **CMEMS**
  - Product Type: Global Analysis and Forecast (based on the ECWAM IFS CY38R2 system)
  - Source: ftp://nrt.cmems-du.eu/Core/GLOBAL_ANALYSIS_FORECAST_WAV_001_027
  - Gridded output resolution: 0.083°x0.083°
  - Additional components: data assimilation + surface current forcing (daily update)
- **ECWAM**
  - Product Type: ERA5 ocean waves reanalysis (based on the IFS CY41R2 system)
  - Source: https://cds.climate.copernicus.eu
  - Gridded output resolution: 0.5°x0.5°
  - Additional components: data assimilation + atmosphere-soil-wave coupling

Observations

- **Significant Wave Height (SWH) from In-Situ data (moorings)**
  - Product Type: Global In-situ Near Real Time observations
  - Source: ftp://nrt.cmems-du.eu/Core/INSITU_GLO_NRT_OBSERVATIONS_013_030
- **Significant Wave Height (SWH) from Satellite data (Jason-3)**
  - Product Type: Global L3 Near Real Time observations
  - Source: ftp://nrt.cmems-du.eu/Core/WAVE_GLO_WAV_L3_SWH_NRT_OBSERVATIONS_014_001

6. CONCLUSIONS

As a general outcome of this assessment study, we can state that WAM and WW3 (in the selected configuration as 'stand-alone' models) provide results which are consistent with those generated by operational systems which include additional important components (e.g. data assimilation and coupling) for the analysis and forecasting of waves. Overall, the CMEMS Global Wave System provides the most skilful product and, although the resolution of the model is the lowest, the ECWAM Reanalysis System appears second best. Analysing the results for WAM and WW3 (in the proposed configuration), we can infer 2 main conclusions: a) the ECHRES wind forcing constantly improves the fit of the modelled SWH to observations respect to the case when the ERA5 dataset is used instead; b) WW3 looks more skilful than WAM. We might speculate that conclusion b is mainly due to the Ardhuin physics package. Results presented in this work are confirmed by additional verifications of SWH (not shown here) considering mooring data restricted to other regional areas (e.g. US East/West coast, UK, Hawaii and so on) and global Sentinel-3A observations. We also verified the model wave peak period and the mean wave direction against mooring observations (not shown here) and we found similar results outlined for the significant wave height. However, the impact of the ECHRES forcing in WAM and WW3 is different: the magnitude of the improvement (in terms of reduction of NRMSE) is not as strong as that observed for the SWH and in some regional areas we can find a minor increase in the NRMSE.

4. ASSESSEMENT VS IN-SITU OBSERVATIONS

Figures 1-3 and Tables 1-4 summarize the results of the assessment which was performed considering 3-hourly wave model gridded outputs (CMEMS, ECWAM, WAMera5, WAMechres, WW3era5 and WW3echres) and mooring data from 1 June 2017 to 31 March 2018. Location of the moorings used in this study (a total of 249) is displayed in Figure 1 (and equally in Figure 2).
Method to select model/observation value at mooring location and model time (e.g. 00z, 03z, 06z …):

a. Time and QC check: search for observations within +/- 30 minutes respect to the model time and where the quality flag is "good_data" or "probably_good_data"
b. As observed value: consider the mean of observations selected in a
c. As model value: extract the nearest neighbour at mooring location

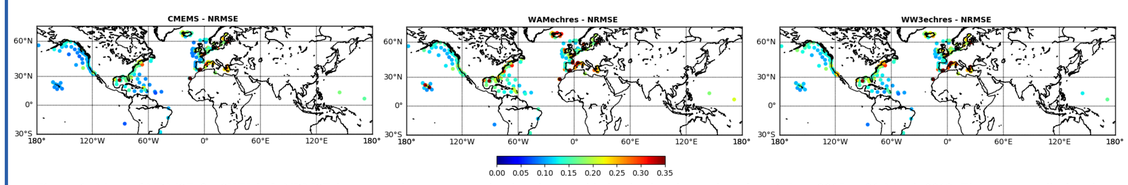

Figure 1: Maps of NRMSE for SWH [m]. NRMSE is computed at every mooring location considering in-situ observations from 1 June 2017 to 31 March 2018. The maps are displayed as follows: CMEMS (left panel), WAM (middle panel) and WW3 (right panel) when ECHRES forcing is used

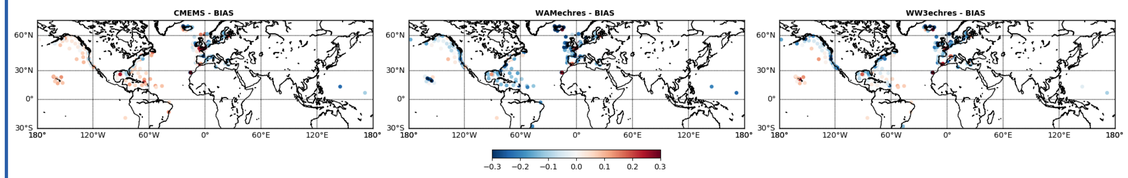

Figure 2: Same as Figure 1, but showing the mean bias of SWH [m]

NRMSE: Normalized RMSE. The RMSE is normalised respect to the root mean square value of the observations
BIAS: Model - Observation

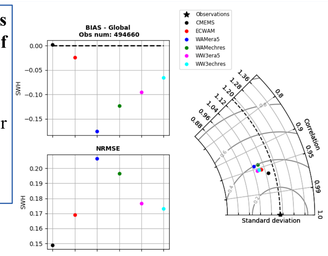

Figure 3: Summary of statistics for the 6 wave models (CMEMS, ECWAM, WAM era5/echres, WW3 era5/echres) considering all the observations of SWH collected by the 249 moorings as those in Figure 1 (a total of 494660 observations): mean bias (top panel), NRMSE (bottom panel), and Taylor diagram (right panel) which shows correlation, standard deviation (std) and centered RMS difference. The black star and the dashed black line in the Taylor diagram indicate the std of the observations

SWH: Difference (%) in NRMSE - Global	WAMechres	WW3echres
CMEMS	24.21%	13.92%
ECWAM	13.99%	2.31%
WAMera5	4.75%	16.13%
WAMechres	-	11.95%
WW3era5	10.17%	1.98%
WW3echres	11.95%	-

Table 1: Difference in NRMSE considering all the observations collected by the 249 moorings (obs num: 494660). Green indicates a reduction, red an increase of NRMSE for WAMechres and WW3echres respect to the models in the first column

SWH - Global Bootstrap 95% Confidence Interval (CI)	CMEMS	WAMechres	WW3echres
Bias	0.0009 -0.0009	0.0011 -0.0010	0.0010 -0.0011
NRMSE	0.0010 -0.0009	0.0009 -0.0009	0.0009 -0.0009

Table 2: Bootstrap 95% CI $[x-\delta_{0.05};x+\delta_{0.95}]$ for the bias and the NRMSE. The bootstrap CI is evaluated from the same sample of data used to calculate statistics shown in Figure 3

SWH: Difference (%) in NRMSE – Europe	WAMechres	WW3echres
CMEMS	23.85%	11.66%
ECWAM	16.89%	3.58%
WAMera5	2.82%	13.80%
WAMechres	-	11.30%
WW3era5	10.58%	0.81%
WW3echres	11.30%	-

Table 3: Same as Table 1, but considering the observations collected in the European region [30<Lat<70;-30<Lon<40] for a total of 94 moorings (obs num: 173009)

SWH: Difference (%) in NRMSE – Gulf of Mexico & Caribbean	WAMechres	WW3echres
CMEMS	16.93%	6.77%
ECWAM	7.64%	3.53%
WAMera5	9.43%	19.30%
WAMechres	-	10.90%
WW3era5	6.53%	4.68%
WW3echres	10.90%	-

Table 4: Same as Table 1, but considering the observations collected in the Gulf of Mexico and the Caribbean region [0<Lat<31;-100<Lon<-45] for a total of 32 moorings (obs num: 62294)

5. ASSESSEMENT VS SATELLITE OBSERVATIONS

Figures 4-6 and Tables 5-6 summarize the results of the assessment which was performed considering 3-hourly wave model gridded outputs (CMEMS, ECWAM, WAMera5, WAMechres, WW3era5 and WW3echres) and Jason-3 observations (J3) from 1 July 2017 to 31 March 2018.
Method to select model/observation value at satellite location and model time (e.g. 00z, 03z, 06z …):

a. As observed values: for a specific model time (e.g. 00z), select all the observations which are within the interval of +/- 45 minutes and then subsample the data considering a time step of 30 seconds
b. As model values: extract the nearest neighbour at the satellite locations selected in a

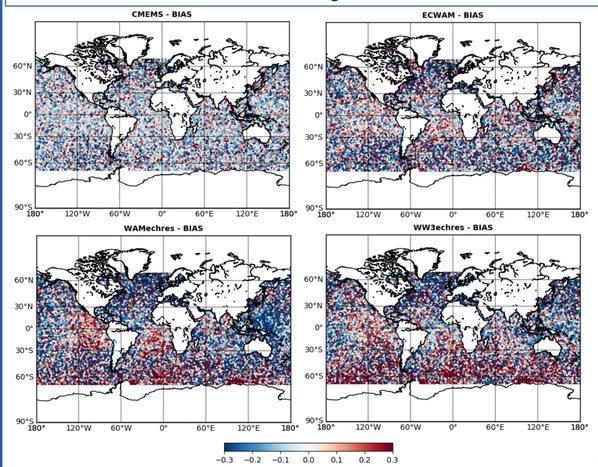

Figure 4: Maps of bias for SWH [m] at every location of J3 observations collected from 1 July 2017 to 31 March 2018. J3 observations (a total of 120961) are selected within +/- 45 minutes respect to the model time (e.g. 00z, 03z, 06z …) and then subsampled considering a time step of 30 seconds. The maps are displayed as follows: CMEMS (top-left panel), ECWAM (top-right panel), WAM (bottom-left panel) and WW3 (bottom-right panel) when ECHRES forcing is used

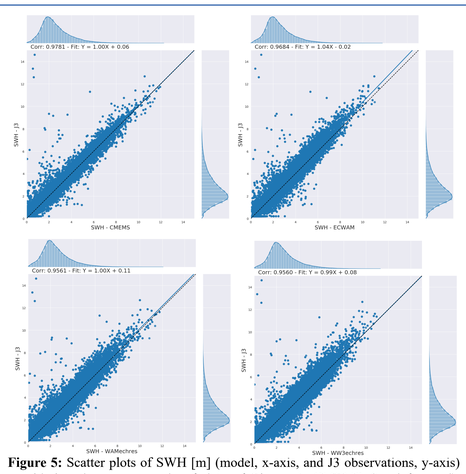

Figure 5: Scatter plots of SWH [m] (model, x-axis, and J3 observations, y-axis) considering the same sample of data of Figure 4: CMEMS (top-left panel), ECWAM (top-right panel), WAM (bottom-left panel) and WW3 (bottom-right panel) when ECHRES forcing is used. In every panel additional details are provided: the model/observation data distribution, the linear fit (blue line) and the reference y=x (black dashed line), the value of the Pearson correlation coefficient and the coefficients of the linear fit

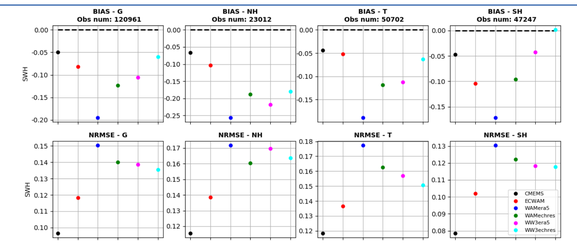

Figure 6: Summary of statistics, mean bias (first row) and NRMSE (second row), for the 6 wave models (CMEMS, ECWAM, WAM era5/echres, WW3 era5/echres) considering the same sample of SWH data (model/observation) of Figure 4, but taking into account different latitude bands: Global [-90<Lat<90], Northern Hemisphere [Lat>30], Tropics [-30<Lat<30] and Southern Hemisphere [-30<Lat]

SWH: Difference (%) in NRMSE – Global	WAMechres	WW3echres
CMEMS	31.00%	28.71%
ECWAM	15.57%	12.77%
WAMera5	6.85%	9.85%
WAMechres	-	3.21%
WW3era5	0.86%	2.38%
WW3echres	3.21%	-

Table 5: Difference in NRMSE considering all the J3 observations as those in Figure 4. Green indicates a reduction, red an increase of NRMSE for WAMechres and WW3echres respect to the models in the first column

SWH - Global Bootstrap 95% Confidence Interval (CI)	CMEMS	WAMechres	WW3echres
Bias	0.0016 -0.0015	0.0022 -0.0022	0.0023 -0.0024
NRMSE	0.0047 -0.0037	0.0034 -0.0026	0.0033 -0.0029

Table 6: Bootstrap 95% CI $[x-\delta_{0.05};x+\delta_{0.95}]$ for the bias and the NRMSE. The bootstrap CI is evaluated from the same sample of data used to calculate statistics shown in Figure 6 (for the global case)

REFERENCES AND ACKNOLEDGEMENTS

1 Thanks to Arno Behrens (Helmholtz-Zentrum Geesthacht) for providing the WAM source code and for the helpful guidance with the configuration
2 The WAVEWATCH III Development Group (WW3DG), 2016: User manual and system documentation of WAVEWATCH III version 5.16
3 Bidlot, J.-R., 2012: Present status of wave forecasting at ECMWF. in Proceedings of ECMWF workshop on ocean wave forecasting
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