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ASSESSMENT OF GLOBAL WAVE DATASETS FOR LONG TERM RESPONSE OF SHIPS

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ABSTRACT

Ship structure design process begins with the evaluation of environmental conditions a ship is expected to withstand. This paper deals with wave data, and more specifically with global wave dataset that can be used to evaluate waves encountered by a ship along its lifetime track. Benchmark of existing global hindcast datasets is performed, having in mind its use to assess extreme ship response. The presented comparison is thus not limited to the mean and standard deviation but includes also extreme significant wave height. Wave period that can significantly modify ship behaviour is also investigated. Five different hindcast datasets are selected for the present analysis and compared with buoy and altimeter data. Area of interest is region far from the coast, and more specifically the North-Atlantic, which is currently considered the most severe for sailing ships. In such area, the global wave models are expected to provide decent results (as opposed to near shore area where a local mesh would be required). Two datasets are provided by ECMWF (ERA5 and ERA-Interim) that uses WAM model, two others are from NOAA/NCEP and Ifremer and use WaveWatchIII, finally WAVERYS dataset is provided by the Copernicus program, and uses MFWAM. Some differences are observed in the wave parameters projected by different models, especially on extremes. Reasons for this scatter are briefly discussed, but more emphasis is put on the consequence for ship response. This work has been performed within IACS (International Association of Classification Societies) framework.

Nomenclature and notation

IFORM :	Inverse First Order Reliability Method
H_s :	Significant wave height
T_z :	Mean up-crossing period ($= T_{02}$)
RP :	Return period

INTRODUCTION

Current standard for wave statistics to be accounted for in ship design is defined in IACS Recommendation 34 [1]. Those statistics are based on visual observations collected on-boards of sailing ships [2]. Since then, big progresses have been achieved in wave modelling, and in development of global numerical wave datasets; today room for improvement of the IACS standard is quite likely. Around 2010, before the development of "Common Structural Rules for Bulk Carriers and Oil Tankers" (CSR BC&OT, [3]), the relevance of an update of the IACS wave standard was investigated. A benchmark of several datasets was performed, but the scatter in the results was such that it was decided that the update of wave data should wait a few years for more mature hindcast data [4] (see also [5]). Ten years later, hindcast models have been further improved, and additional comparisons have been performed (see for instance [6]). This paper aims at complementing those existing comparisons, with an application to shipping perspective. Five modern datasets are thus evaluated, compared with each other as well as with buoy and altimeter measurements. Finally, the effect of using one dataset or the other with regard to ship response is investigated.

1 WAVE HINDCAST DATA

"Hindcast" refers to reanalysis of past weather by numerical means. Compared to observed data, the key feature is the wider coverage (temporal and spatial), necessary to statistics (especially for large return period). Five hindcast datasets, (that are to the authors knowledge, the most recent ones, publicly available, with a global coverage in both space and time) are here investigated. Two datasets are from ECMWF, based on WAM wave model. The first one ERA-INTERIM [7], has been released in 2006 and cover the whole globe for about 39 years. The second one, its successor, ERA5, is currently being released. Two other datasets are based on the WaveWatchIII wave model, the NOAA dataset ("phase 2" [8]) has been released in 2017 and covers about 30 years, from 1979 to 2009. The Ifremer dataset (called IOWAGA) exists in two versions using either CFSR or ECMWF wind forcing. In the present study, only the CFSR wind version is used (cover a longer time). The fifth dataset is called WAVERYS and is provided by the European Copernicus program [9]. WAVERYS uses MFWAM, a Meteo-France version of WAM. Compared to ERA5, higher resolution is used, as well as current forcing (effect of current on waves).

While the fundamentals of the WAM and WaveWatchIII models are similar (spectral model, third generation), many differences exist: in the physical parametrization, in the numerics and in the strategy with regard to measurement. For instance ERA5 assimilates altimeter data to correct the model results at each time step, while in IOWAGA, altimeter is used for calibration [10]. Besides, a good wind field input is of paramount importance. The datasets' properties are listed in Table 1.

In the first part of the paper, significant wave height of the five datasets will be compared to altimeters. Then, buoys data will be added to allow validation of periods.

Dataset	ERA5	ERA-INTERIM	IOWAGA	NOAA	WAVERYS
Provider	ECMWF	ECMWF	IFREMER	NOAA	Copernicus
Software	WAM	WAM	WWIII	WWIII	MFWAM
Release date	2018	2006	2016	2017	2019
Wind forcing	ERA5	ERA-Interim	CFSR*	CFSR	ERA5
Resolution (grid)	0.36°	0.75°	0.5°	0.5°	0.2°
Time step	1h	6h	3h	3h	3h
Full spectra	Yes	Yes	Some	Some	No
Range	1950-2019**	1979-2018	1990-2016*	1979-2009	1993-2018
Data access	API	API	FTP	FTP	FTP
Altimeter	Assimilation	N/A	Calibration	N/A	Assimilation

TABLE 1: Datasets features
*2007-2018 with ECMWF forcing
** from 1979 at the date of writing

2 COMPARISON TO ALTIMETERS

Altimeter is generally considered as a reference for significant wave height. Thus, the five datasets are compared with altimeter measurements. The altimeter data used are corrected from bias thanks to buoys and cross comparison [11].

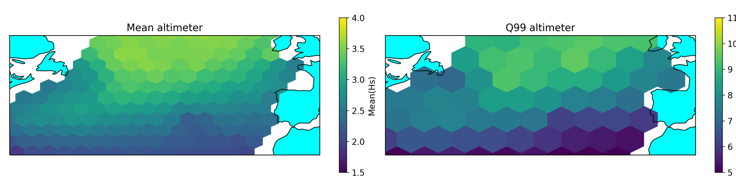
Here, it is important to note that most hindcast models use altimeter data, more or less directly. ERA5 assimilates them (i.e. correct the model results at each time step to better match with measurement). Comparison still makes sense, as observed data are not assimilated 100%. With a different approach, IOWAGA uses altimeters for calibration of model coefficients (more specifically, the wind wave growth parameter [10]).

The comparison of the five datasets is performed in North-Atlantic, on the period 2000-2009 (included in all datasets).

2.1 Mean map and standard deviation maps

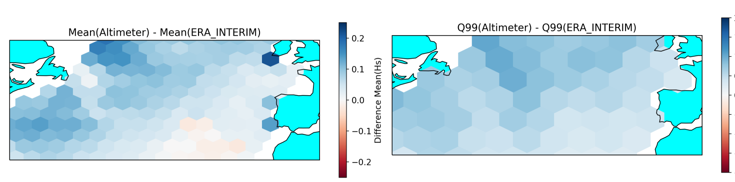
To get a rapid and global overview of the models performance, the mean H_s and the 99% percentile are plotted on the North-Atlantic area (Figure 1). Difference maps shown in Figure 2 to 6 show fairly good agreement to the altimeter mean H_s, for the 5 datasets used.

Looking at 99% percentile, more representative and relevant indicator for extreme ship loading than the mean, it seems that the IOWAGA dataset matches better to altimeter data. Extremes are slightly underestimated by ERA5 and WAVERYS, and more severely by ERA-INTERIM and NOAA.



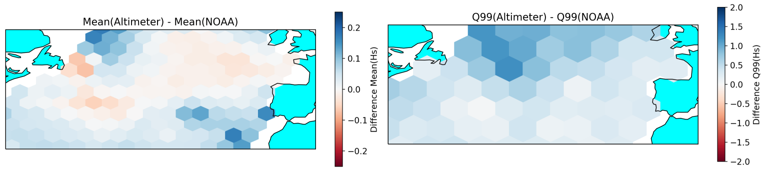
(a) $\mathbb{E}(H_s^{altimeter})$ (b) $Q99(H_s^{altimeter})$

FIGURE 1: Altimeter H_s mean and 99% percentile (2000-2009)



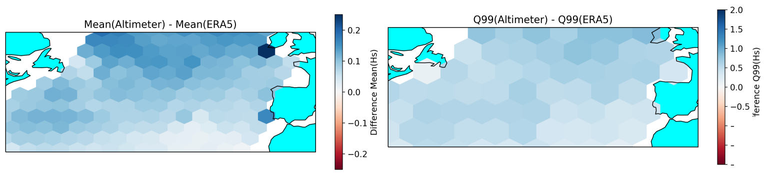
(a) $\mathbb{E}(H_s^{altimeter}) - \mathbb{E}(H_s^{model})$ (b) $Q99(H_s^{altimeter}) - Q99(H_s^{model})$

FIGURE 2: ERA-INTERIM - Comparison with altimeter (2000-2009)



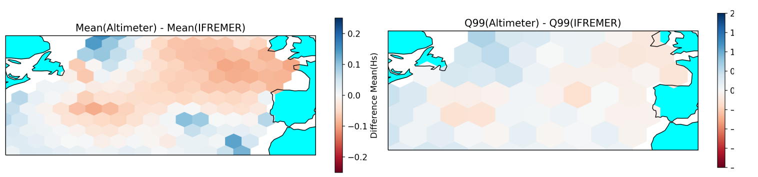
(a) $\mathbb{E}(H_s^{altimeter}) - \mathbb{E}(H_s^{model})$ (b) $Q99(H_s^{altimeter}) - Q99(H_s^{model})$

FIGURE 3: NOAA - Comparison with altimeter (2000-2009)



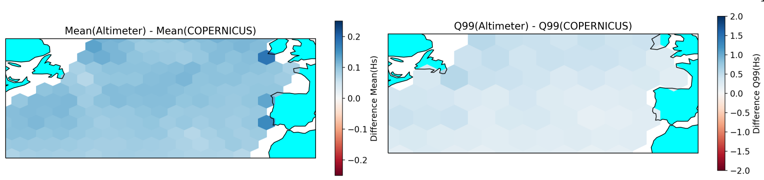
(a) $\mathbb{E}(H_s^{altimeter}) - \mathbb{E}(H_s^{model})$ (b) $Q99(H_s^{altimeter}) - Q99(H_s^{model})$

FIGURE 4: ERA5 - Comparison with altimeter (2000-2009)



(a) $\mathbb{E}(H_s^{altimeter}) - \mathbb{E}(H_s^{model})$ (b) $Q99(H_s^{altimeter}) - Q99(H_s^{model})$

FIGURE 5: IOWAGA - Comparison with altimeter (2000-2009)



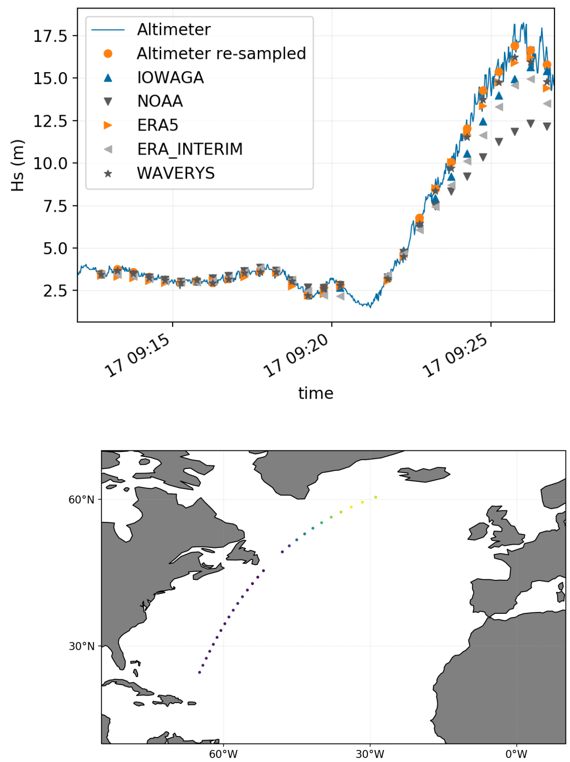
(a) $\mathbb{E}(H_s^{altimeter}) - \mathbb{E}(H_s^{model})$ (b) $Q99(H_s^{altimeter}) - Q99(H_s^{model})$

FIGURE 6: WAVERYS - Comparison with altimeter (2000-2009)

Note : Size of bins for 99% percentile has been increased to ensure that enough data are collected in each bin.

2.2 Synchronized comparison plots

For a more detailed, synchronized comparison, the H_s is recorded along satellite track and compared to H_s from hindcast (linearly interpolated). As the satellite data shows a bit of noise, and is oversampled for the current purpose, the altimeter H_s is re-sampled with moving average (window of 30s). An example of time series thus obtained is shown in Figure 7.

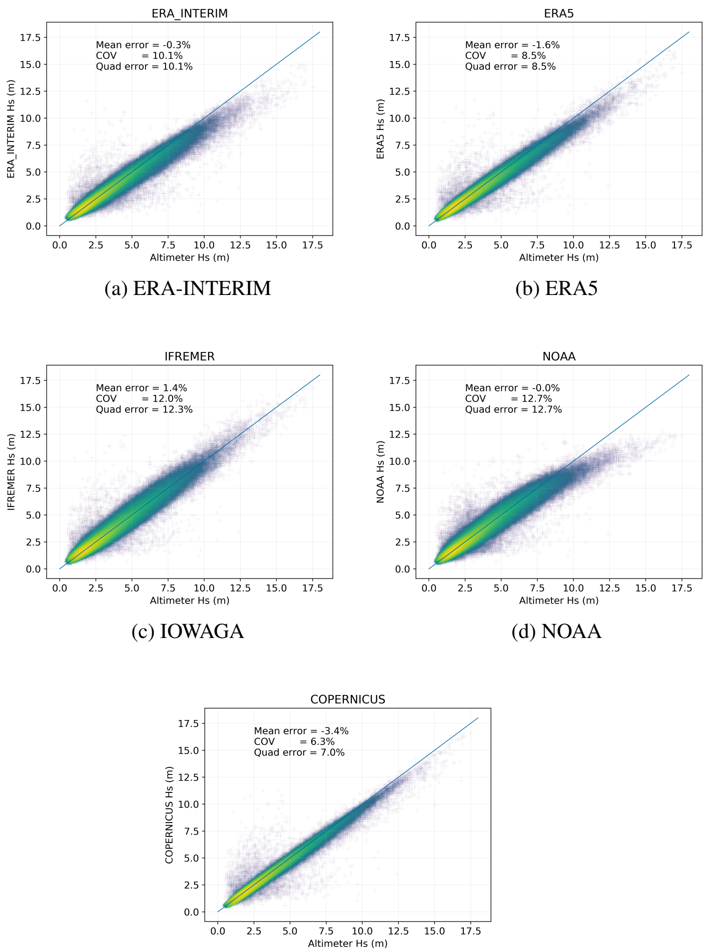


(b) Satellite position, coloured by measured H_s

FIGURE 7: H_s along satellite track TOPEX satellite, on 17/01/2005

Scatter plots comparing altimeter to hindcast (in the North-Atlantic area) are then derived and plotted on Figure 8. From those results, it appears that the mean error and COV (Coefficient of Variation) are acceptable for all datasets. However, while mean H_s is, possibly, a good indicator for fatigue life of ships, it is not relevant for extreme loading. Regarding extreme H_s values, a clear and significant bias is observed for the NOAA and ERA-INTERIM dataset. The error metrics displayed on graphs are defined by equation 1.

$$\begin{cases} \varepsilon_{rel} = \frac{model}{reference} \\ \text{Mean error} = Mean(\varepsilon_{rel}) - 1 \\ \text{COV} = \frac{Standard\ deviation(\varepsilon_{rel})}{Mean(\varepsilon_{rel})} \\ \text{Quad error} = \sqrt{Mean((\varepsilon_{rel}-1)^2))} \end{cases} \tag{1}$$



(a) ERA-INTERIM

(b) ERA5

(c) IOWAGA

(d) NOAA

(e) WAVERYS

FIGURE 8: Scatter plots : Hindcast vs Altimeter
Coloured by density (log(1+x) scale)

	Mean(Hs>8m)	Mean	Quad	COV
IOWAGA	-2.3%	1.4%	12.3%	12.0%
NOAA	-11.2%	-0.0%	12.7%	12.7%
ERA5	-8.6%	-1.6%	8.5%	8.5%
ERA_INTERIM	-10.5%	-0.3%	10.1%	10.1%
WAVERYS	-4.9%	-3.4%	7.0%	6.3%

TABLE 2: Error compared to altimeter

It should be noted that the error statistics like the mean, COV and the quadratic error are mainly driven by relatively small sea-states ($H_s < 3m$), which are the most probable. For structure design with regard to extreme H_s, those sea-states are not the relevant ones. For extreme responses, the bias for $H_s > 8m$, displayed in Table 2, is a better indicator.

Another way to present the data is to compare probability distribution. This emphasis the difference of high H_s by NOAA and ERA-INTERIM, and to a lesser extent, of ERA5 and WAVERYS.

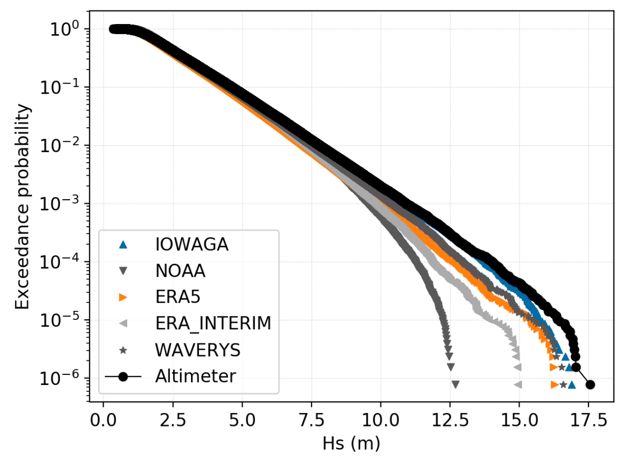


FIGURE 9: H_s distribution over altimeters track in North-Atlantic (2000-2009)

2.3 Altimeter calibration

One possible bias of the above presented results is the fact that the reference is considered as the altimeter calibrated by Ifremer, which are also those used for the IOWAGA hindcast calibration. On the other hand, the assimilated results in ERA5 are differently calibrated. In each calibration, the main idea is the same : buoys data collocated with altimeter measurements are used to make regressions. Cross-validation is also used to ensure the consistence of the various satellite missions. However, some details can be handled differently, resulting in slightly different calibrations.

Hence, this section aims at comparing the different altimeter calibrations ([12] and [11]). Figure 10 shows the H_s distribution along the satellites tracks, in North-Atlantic. The calibration shows rather moderate effect on H_s distribution, and the different estimates lead to similar results. This comforts the observation made in previous sections.

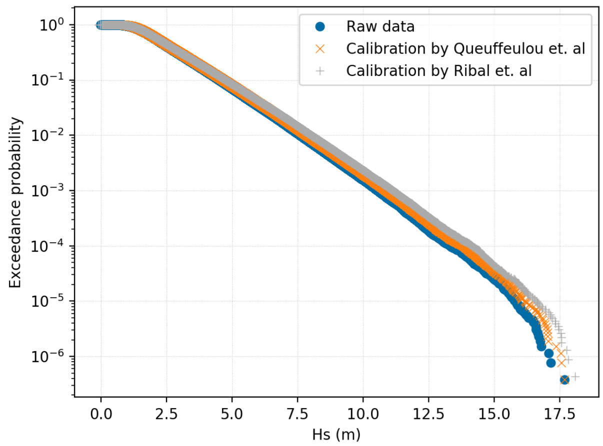


FIGURE 10: H_s distribution over altimeters track in North-Atlantic (1990-2016)

3 COMPARISON WITH BUOY DATA

Significant wave height is not the only relevant parameter for ship response. The wave period, and more generally the wave spectrum shape are also of importance. Those are not measured by altimeter, but are available thanks to wave buoys. Additionally, buoys data are not assimilated by hindcast model and thus provide a more independent reference. Unfortunately, most of existing buoys are close to the coast, while the current interest is rather on more remote locations, where higher waves can intersect ship routes. Besides, global wave datasets are not meant to be accurate in near shore area. In those coastal area, an accurate wave prediction would require a more detailed topology together with a finer mesh. The locations chosen for the current investigation are selected for their relatively remote location and are presented by the round dots in Figure 11. ERA5 and IOWAGA datasets only are used for this comparison.

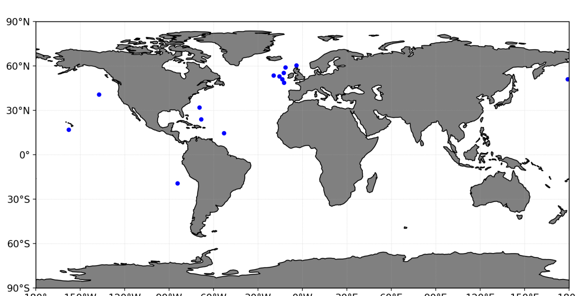
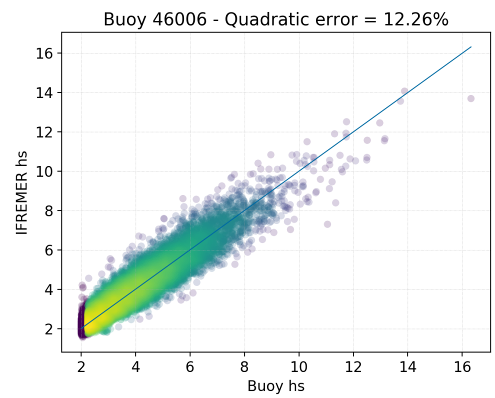


FIGURE 11: Test locations

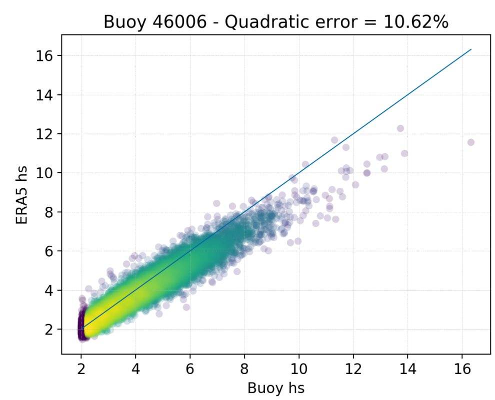
The wave period used is the mean up-crossing one (often noted T_{02} or T_z). While this period is not considered as the most relevant one for ship response (T_{01} or T_{0m1} would be preferred) this is unfortunately, today, the only one available on some buoys.

Overall, the comparison of the hindcast data to buoy data is quite satisfactory: mean errors are below 10% and COV under 15%. Graphs for the buoy 46006 (east of Pacific ocean) are shown in Figure 12 to 14. This example is chosen for its severe wave climate, and its buoy data quality (unfortunately, wave buoys in east part of North-Atlantic only provide a 1 second resolution for wave period).

Synthesized results for all buoys are listed in Table 3. Regarding H_s, it confirms the results obtained from altimeter data : ERA5 is, in average, slightly more accurate than IOWAGA, but IOWAGA seems to perform significantly better for extremes.



(a) Iowaga

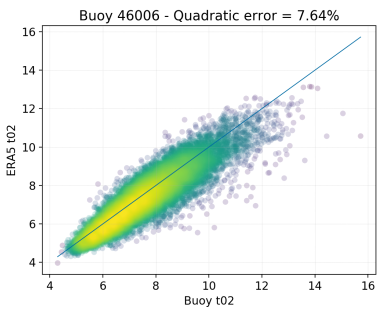


(b) ERA5

FIGURE 12: H_s scatter plot
Coloured by density (2D histogram, log(1+x) scale)

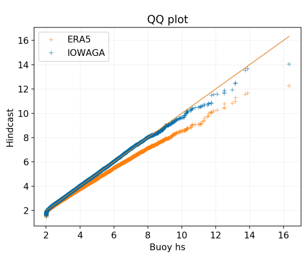
Regarding wave periods (at least the zero-crossing period T_{02}) a quite satisfactory agreement is found with buoy data, with a slight bias towards shorter period in hindcast data (for both ERA5 and IOWAGA).

(a) IOWAGA

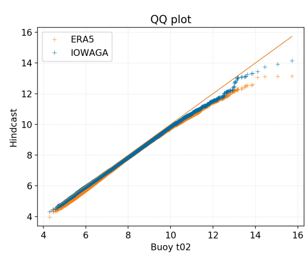


(b) ERA5

FIGURE 13: T_z scatter plot
Coloured by density (log(1+x) scale)



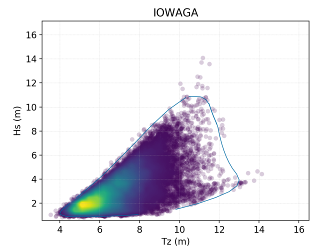
(a) H_s



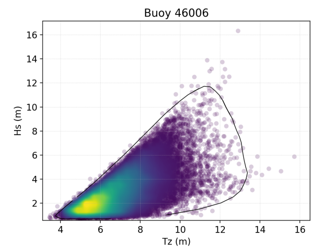
(b) T_z

FIGURE 14: Quantile-Quantile plot, buoy 46006

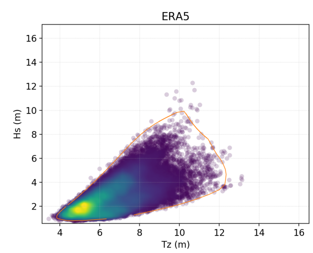
One thing is to get correct marginal distribution of height and period separately, but what actually matters for long-term ship response is the joint-distribution. To compare this in a pragmatic way, the environmental contour is calculated at buoy location, using either measurements or model data. The H_s-T_z contour is calculated considering a return period of 1 year and a sea-state duration of 1 hour. The Direct-IFORM method is used to calculated the contour [13]. Direct-IFORM is here used for its ability to capture accurately the steepness limit (upper left part of the contour), which can be easily smoothed out by standard contour methods that relies on a joint probability model. Results for buoy 46006 are displayed on Figure 15. On this particular buoy, the steepness provided by both models match fairly well with measurements, with a very slight over-estimation by ERA5.



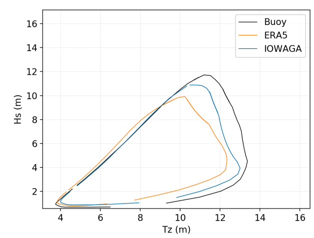
(a) IOWAGA



(b) Buoy



(c) ERA5



(d) Comparison

FIGURE 15: H_s-T_z 1 year contour, buoy 46006

buoy	dataset	Mean(Hs>8m)	Mean	Quad	COV
46006	ERA5	-15.2%	-4.9%	10.6%	9.9%
	IOWAGA	-5.9%	1.2%	12.3%	12.1%
46071	ERA5	-16.8%	-3.8%	15.8%	16.0%
	IOWAGA	-11.0%	-3.7%	15.8%	15.9%
62021	ERA5	-8.3%	-4.1%	11.0%	10.6%
	IOWAGA	1.7%	1.8%	12.6%	12.2%
62029	ERA5	-10.0%	-5.2%	10.5%	9.6%
	IOWAGA	0.0%	0.9%	11.2%	11.0%
62095	ERA5	-7.1%	-2.5%	9.4%	9.3%
	IOWAGA	2.3%	2.6%	11.2%	10.6%
62105	ERA5	-7.6%	-3.1%	10.3%	10.1%
	IOWAGA	2.2%	2.1%	11.8%	11.4%
62108	ERA5	-8.9%	-4.3%	11.9%	11.6%
	IOWAGA	-0.1%	1.7%	13.4%	13.1%
64045	ERA5	-8.6%	-4.6%	10.3%	9.7%
	IOWAGA	0.2%	-0.7%	11.3%	11.3%
64046	ERA5	-10.8%	-3.8%	12.3%	12.1%
	IOWAGA	-2.2%	-0.0%	13.5%	13.5%

TABLE 3: H_s error compared to buoy

4 EFFECT ON SHIP RESPONSE

After satisfactory comparison of the ERA5 and IOWAGA data with buoys' and altimeters' data, in this section, the effect of a choice of a dataset for ship response calculations is investigated. To get a roughly realistic input about ship position, a density map (figure 16) is defined from ICOADS data [14]. Weighted scatter diagrams are then defined for both IOWAGA and ERA5 dataset. Scatter diagram are compared in Figure 17. It is to be noted that this data does not include bad weather avoidance.

FIGURE 16: Ship density map in the North-Atlantic

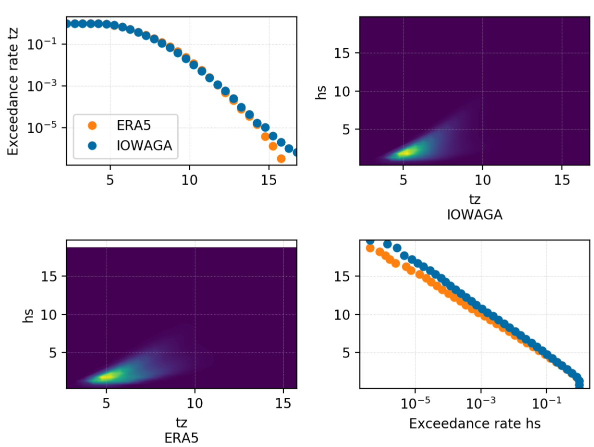


FIGURE 17: Scatter diagram comparison

Overall, the two scatter diagrams are very similar. It can be noticed on the H_s distribution that extreme wave heights by ERA5 are slightly smaller than those from IOWAGA.

To get a more synthetic comparison, a joint distribution of H_s and T_{02} is fitted to the data. IFORM environmental contour is calculated for both datasets [15]. The joint distribution used is a conditional model, as described in [16] (3-parameter Weibull distribution for H_s, and conditional log-normal for T_z). Both contours (Figure 18) can be considered as rather similar, the difference lies in the upper-right part of the contours, where higher sea-states are predicted by IOWAGA. Both models present the same steepness limit : the higher sea-states predicted by IOWAGA also present longer wave periods.

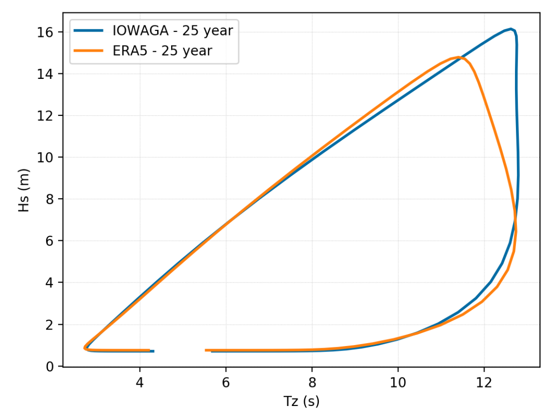


FIGURE 18: Contour comparison

Going further towards ship response, the wave parameter [17] is computed for both datasets. Indeed, the wave parameter allows to directly compare ship response in different wave environments, simply knowing the ship length and a single coefficient α. This α depends only on the response transfer function, and quantifies if a load responds at low or high frequency : transfer function presenting significant response at low frequency are associated to small α, and inversely, response at high frequency are associated to higher α. To provide order of magnitude, for a container-ship, typical value of α for wave vertical bending moment is around 0.8, for horizontal bending moment, about 1.5. More details on wave parameter can be found in [17].

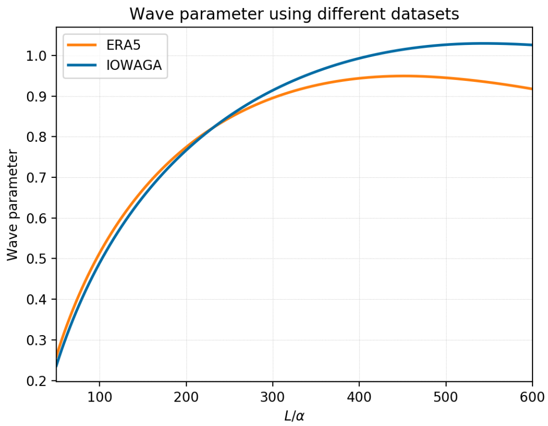


FIGURE 19: Wave parameter comparison

From wave parameter plotted in Figure 19, it is clearly seen that for small to medium ship, using one dataset or the other does not matter much. On the other hand, the observed underestimation of extreme H_s by ERA5, will lead to lower ship response for longer ships.

With regard to ship response, H_s and T_z are not the only variable of interest, spectrum and spreading shape are also important. In figure 19, a Pierson-Moskowitz spectrum together with a cos^2 spreading is used, as recommended by [1]. While using full spectra for long term statistics is currently out of reach (data exists, but not the method to extrapolate to long return period), better calibration of those parameters could be used. This could affect significantly the wave parameter, but not so much the relative comparison between ERA5 and IOWAGA scatter diagram.

CONCLUSION

The 5 different wave datasets benchmarked, while providing a quite decent agreement to measurements, show some discrepancies when extremes are investigated. The extreme significant wave heights by NOAA and ERA-INTERIM datasets are significantly lower than those by altimeters. From literature, the main reason for the underestimation of extreme waves is the wind-fields. As shown in [10] and [18], the extreme winds (both ECMWF and CFSR) are underestimated. This quite straightforwardly leads to underestimated extreme waves. In IOWAGA this issue is addressed by calibrating the ”wave growth parameter”. In ERA5 and WAVERYS, the problem is very likely mitigated by assimilation of altimeter wave measurements.

WAVERYS, ERA5 and IOWAGA datasets compared generally well. ERA5 and WAVERYS shows slightly better COV for H_s, but looking at extremes, IOWAGA achieves a better match with altimeter measurement. Those conclusions are confirmed by wave buoys’ data.

Regarding application to ship response in the North-Atlantic, ERA5 and IOWAGA data result in very similar environmental contour : the extreme wave height is slightly lower for ERA5 (as expected from the comparison with the altimeter data); the zero-crossing wave periods, as well as the wave steepness limit are very close for both datasets.

Thus, since previous IACS investigations on wave datasets, it can be said that large progress has been made. At least, the two datasets considered herein, ERA5 and IOWAGA, give quite consistent results and agree fairly well with measurements. Application of these datasets for ship design seems possible today. This would be a significant step forward compared to the wave data currently used.

ACKNOWLEDGMENT

This work has been performed within IACS (International Association of Classification Societies) framework.

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