

Future behavior of wind wave extremes due to climate change

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Supplementary material

Atmosphere-Ocean General climate model data

This work makes use of a CMIP5-based multi-model ensemble consistent of seven atmosphere-ocean general circulation models (GCMs) (**Supplementary Table 1**). The criterion to select the models is defined by the need of producing hourly time series of H_s to better capture the extremes. Therefore, we look for GCMs that provide surface winds and sea ice coverage fields with the maximum time resolution as possible. All the GCMs provide 3-hourly winds and daily ice coverage fields (except from HadGEM2-ES that provides monthly ice) for the historical and projected periods, both for RCP4.5 and RCP 8.5 greenhouse gas emission scenarios¹. A single run of each GCM is simulated to reduce the storage capacity demanded by the hourly H_s series needed, which is sustained by the low variability between wave projections from runs of the same model². In particular, the r1i1p1 member of each realization ensemble is selected.

In addition to the spatial resolution, the independency of the models is analyzed to ensure the reliability of the ensemble mean results. This issue is addressed on the basis of the classification of GCMs proposed by Knutti et al., in 2013³ in terms of the degree of dissimilarity between pairs of individual models with regard to a multivariate description of the natural variability⁴. The similarity between models is defined using the Kullback-Leibler divergence distance metric considering the seasonal cycle, interannual variations, annual mean climatology and spatial correlation from temperature and precipitation monthly fields, both for the control state period and for the projected changes under RCP8.5 scenario by the end of the century. A hierarchical clustering is applied to define the relationship between members, presenting the results as a dendrogram. HadGEM2-ES and ACCESS1.0 are the closest in the control state, which can be related to sharing the same atmospheric model. Concerning the projected changes, there are no strong enough similarities that may cause a bias in the results, not even for the two models found to be similar in the control period.

<i>GCM</i>	<i>Institution</i>	<i>Country</i>	<i>Atmospheric resolution (lat x lon)</i>
MIROC5	MIROC	Japan	1,40° x 1,40°
IPSL-CM5A-MR	Institut Pierre-Simon Laplace	France	1,25° x 1,25°
GFDL-ESM2G	NOAA Geophysical Fluid Dynamics Laboratory	USA	2,00° x 2,50°
CNRM-CM5	Centre National de Recherches Météorologiques	France	1,40° x 1,40°
CMCC-CM	Centro Euro-Mediterraneo per I Cambiamenti Climatici	Italy	0,75° x 0,75°
ACCESS1.0	CSIRO-BOM	Australia	1,25° x 1,90°
HadGEM2-ES	Met Office Hadley Centre	UK	1,25° x 1,90°

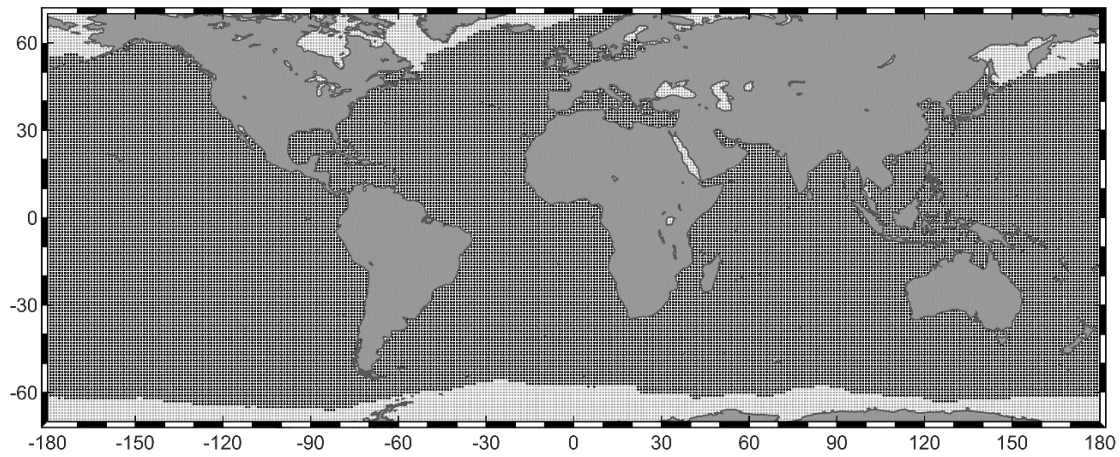
Supplementary Table 1 Main characteristics of the selected Atmosphere-Ocean General Circulation Models.

Dynamical wave projections

A series of global wave projections (GWP_{GCM}) are dynamically simulated considering sea surface wind fields and ice coverage outputs from the ensemble members as inputs of the wave generation model. The third-generation wave model WaveWatchIII (WW3) version 4.18⁵ is used to run the simulations. The main features of the numerical scheme used in this work are summarized below:

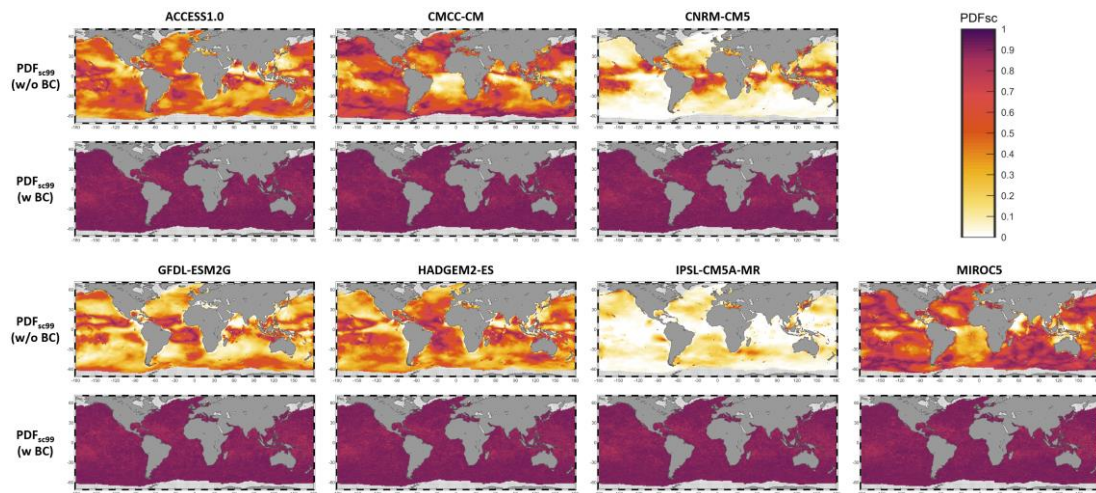
- Parametrization TEST451⁶.
- Continuous ice concentration blocking from 0.25 (no blocking) to 0.75 (total blocking).
- Discrete Interaction Approximation⁷ (DIA)
- Depth-inducing breaking following Battjes and Janssen approach⁸.
- SHOWEX bottom friction formulation⁹.
- Coastal reflexion equal to 0.05.
- Energy flux reduction due to islands or any other coastal obstacles smaller than cell size¹⁰.
- Third-order Ultimate Quickest propagation scheme¹¹.

Significant wave height hourly time series are obtained globally at 1° spatial resolution. Grid nodes with less than 60% of the hourly data due to the presence of ice for any of the GWP_{GCM} are not selected. **Supplementary Figure 1** shows the final 31591 selected grid nodes.



Supplementary Figure 1 Black dots represent the selected grid nodes to study the projected changes in wave height extremes. Figure generated with MATLAB R2020a (<https://es.mathworks.com/products/matlab.html>).

Bias correction (BC)



Supplementary Figure 2 Agreement between the distribution of H_s above the q_{99} before applying the bias correction (w BC panels) and after correcting the bias (w/o BC panels) under RCP8.5 scenario. Figure generated with MATLAB R2020a (<https://es.mathworks.com/products/matlab.html>).

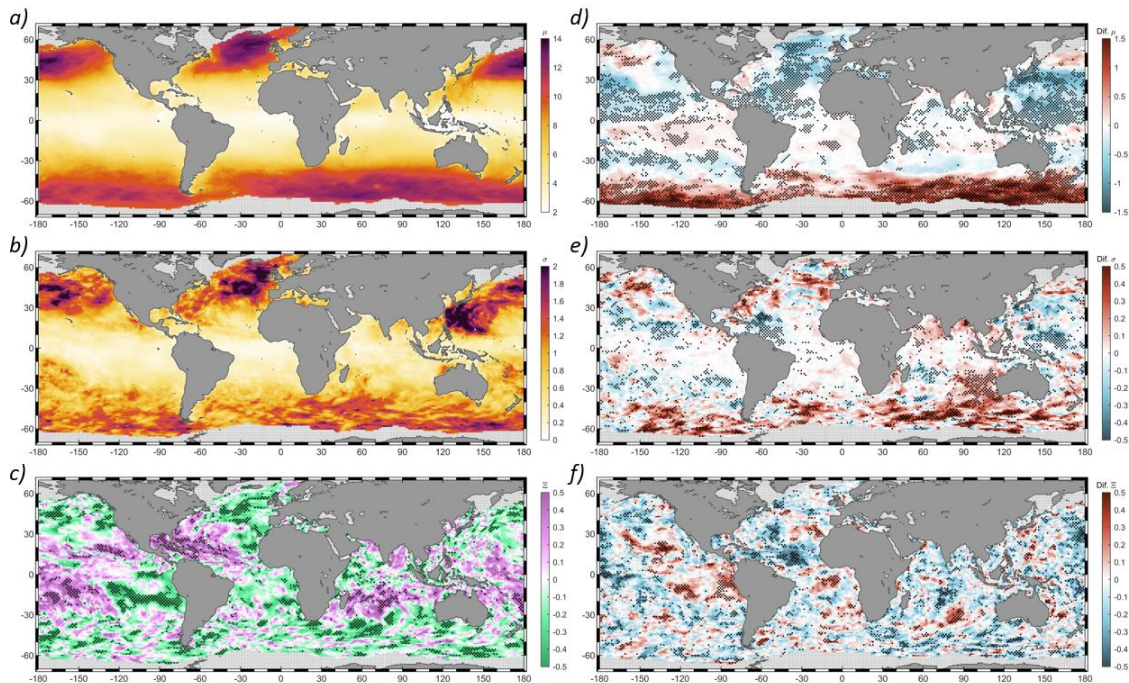
Extreme value analysis

GEV parameters assessment

Global GEV parameters and their projected variation by the end of the century under RCP8.5 scenario are shown in **Supplementary Figure 3**. The location parameter (μ), an indicator of the central values of the extreme distribution, increases with latitude until reaching its highest values in the extratropical region and, in particular, in the North Atlantic Ocean, where μ reaches values close to 14m (**Supplementary Figure 3a**). There is a robust agreement concerning the future decrease in μ in the Northern Hemisphere, showing local decreases close to 1m in the North Atlantic Ocean and around the Japanese Archipelago. The northernmost Pacific Ocean and the northwestern Atlantic are the most remarkable exceptions found within this decreasing pattern (**Supplementary Figure 3d**). A robust projected change is also obtained in the Southern Ocean although with the opposite sign (i.e. increase in μ).

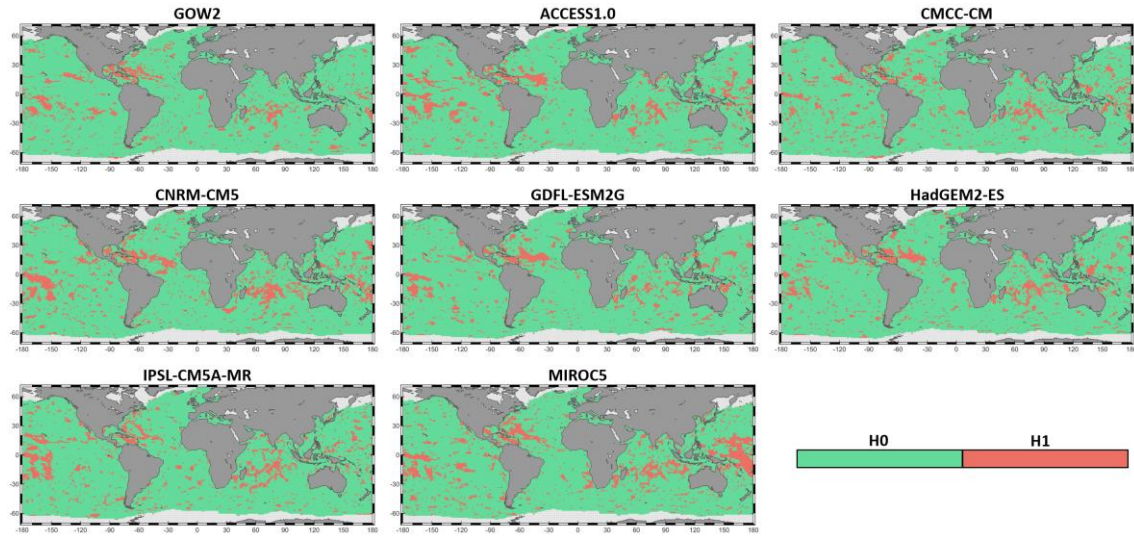
The spatial distribution of the scale parameter (σ) is quite similar to the location's (i.e. higher values at higher latitudes) although showing some relevant differences such as the very high σ values found around Japan (**Supplementary Figure 3b**). Concerning future changes (**Supplementary Figure 3e**), a higher noise in the sign of change with respect to μ can be observed, making it difficult to find other consistent general conclusions beyond an increase in the Southern Ocean. In spite of this, some relevant aspects such as the robust decrease found in the tropical southeastern Indian Ocean and the loss of a clear decreasing change pattern in the North Atlantic Ocean can be pointed out.

The shape parameter (ξ) presents positive values (i.e. heavy-tailed distribution) in tropical cyclone (TC) activity regions and TC-induced swell affecting zones (Caribbean Sea, West Pacific, South-West Indian Ocean; **Supplementary Figure 3c**). Negative values (i.e. bounded upper tail distribution) can be observed throughout the global ocean, being the northeastern Atlantic, southeastern Pacific and south Indian the regions which present the clearest negative patterns.



Supplementary Figure 3 Location (a), scale (b) and shape (c) GEV parameters from GOW2 hindcast. Multi-model ensemble mean change in the location (d), scale (e) and shape (f) parameters by the end of the century (2081-2100 relative to 1986-2005). Stippling in (c) denotes significant fit of the shape parameter at 95% confidence level. Stippling in right panels denotes changes statistically significant at 95% confidence level in at least 50% of the members and an agreement in the sign of change in more than 80% of the members. Figure generated with MATLAB R2020a (<https://es.mathworks.com/products/matlab.html>).

Goodness-of-fit of the extreme model



Supplementary Figure 4 Anderson-Darling test statistic at 95% confidence level ($\alpha=0.05$) for GOW2 and every member of the ensemble under RCP8.5 scenario. Orange grid points indicate where the null hypothesis (H_0) is rejected at 95% confidence level ($\alpha=0.05$) for each GCM. Figure generated with MATLAB R2020a (<https://es.mathworks.com/products/matlab.html>).

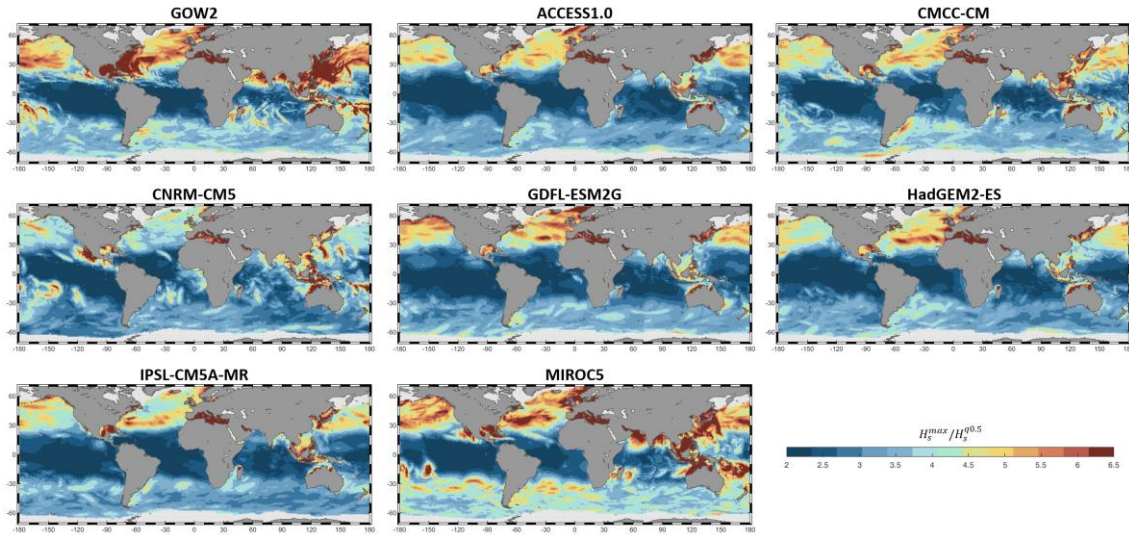
MIROC5	IPSL-CM5A-MR	GFDL-ESM2G	CNRM-CM5	CMCC-CM	ACCESS1	HadGEM2-ES
14.7	11.8	10.4	13.3	11.8	12.1	11.6

Supplementary Table 2 Proportion of the global ocean (%) where the null hypothesis (H_0) is rejected at 95% confidence level ($\alpha=0.05$) for each GCM.

Tropical cyclone representation

The relation between the maximum and the median H_s before the bias correction is calculated globally. The TC simulation performance is assessed comparing the results against the GOW2 wave hindcast, which has already been validated for extreme TC-induced waves¹².

Results show that all members are able to simulate the extreme wave climate induced by TC activity (dark red colors from **Supplementary Figure 5**). However, there is a general underestimation of the magnitude of extremes, existing notable discrepancies between members. For example, MIROC5 is the model that best represent the TCs, showing extreme waves in all the regions affected by TCs. CNRM-CM5 and CMCC-CM also show extreme waves in all these regions, although with a clear underestimation with respect to MIROC5. The rest of the models show a great underestimation of TC-induced extreme wave climate, especially in the westernmost Pacific, the world's region most affected by this kind of events.



Supplementary Figure 5 Relation between the maximum H_s ($H_s^{\max}$) and the median H_s ($H_s^{0.5}$) before applying the bias correction for each GCM and for the reference wave hindcast. Figure generated with MATLAB R2020a (<https://es.mathworks.com/products/matlab.html>).

Regionalization of the global ocean

The global ocean is discretized in ocean regions to better understand the projected changes. Although a division with straight lines is far from the physical reality as ocean basins are not independent units, the assessment of the average changes and their robustness not only at global scale, but also in each of the regions included in the analysis, helps to provide a more detailed and structured description of the projected wave climate changes. The division is based on the regionalization proposed by Alves in 2006¹³ attending to the swell generation criteria, which have been extensively cited in wave climate studies^{14–16}. Thus, at first, each ocean basin (i.e. Pacific, Atlantic and Indian) is divided in four regions: extra-tropical north (above 30°N), tropical north (30°N to equator), tropical south (equator to 30°S) and extra-tropical south (below 30°S). Then, this initial division is modified to better fit with the spatial change pattern found after comparing present and future extreme wave height and to give more accurate aggregate results. First, the latitudinal threshold that separates tropical and extra-tropical regions is risen from 30° to 35°, defining the extra-tropical north Pacific (ETNP) and the extra-tropical north Atlantic (ETNA) regions. Then, all extra-tropical south regions are joint together to constitute the Southern Ocean (SO). The eastern transition between the tropical north Atlantic (TNA) and the tropical south Atlantic (TSA) is also slightly modified. Concerning the Pacific basin, a new wedge-shaped region is introduced in the tropical eastern Pacific (TEP) between tropical north (TNP) and tropical south (TSP) regions. Finally, while tropical north Indian (TNI) remains unaltered, the tropical south Indian Ocean is divided in two regions: tropical southeastern Indian (TSEI) and tropical southwestern Indian (TSWI).

Validation of significant wave height return values

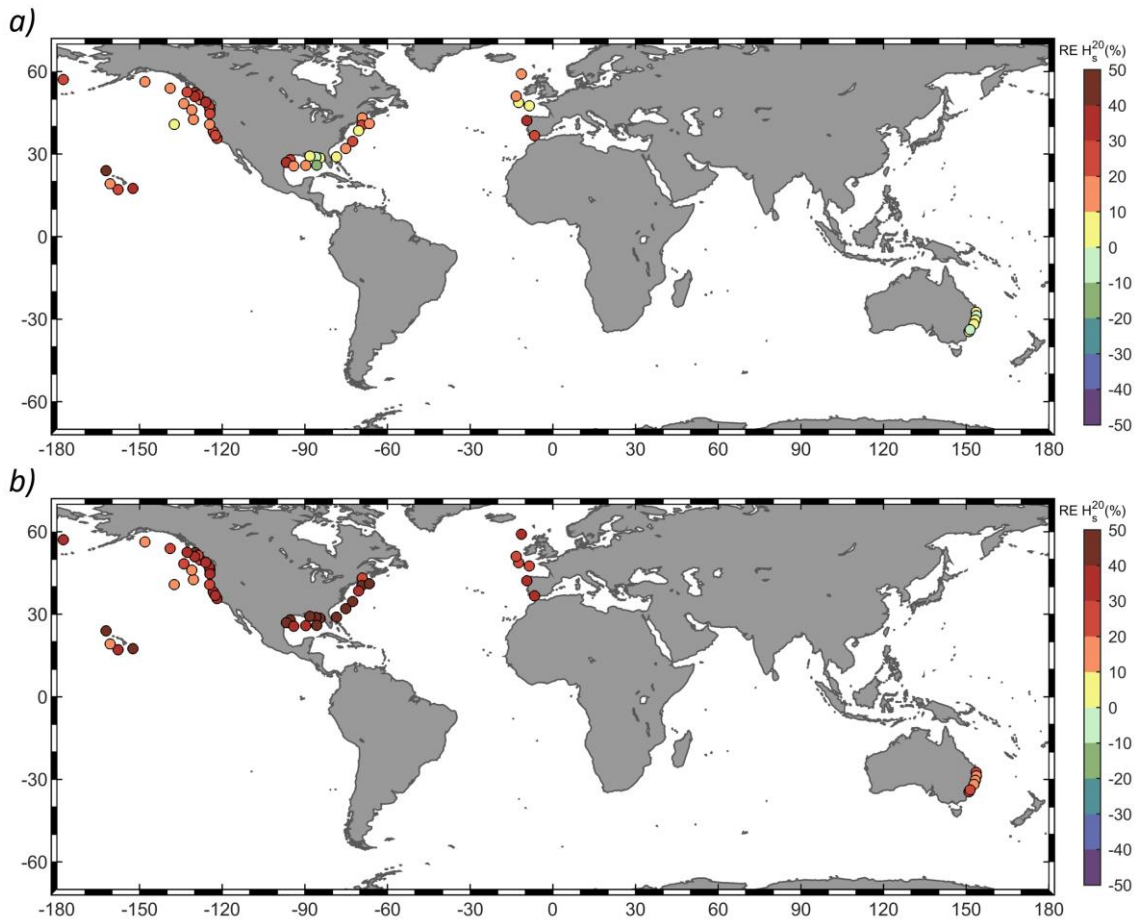
A set of fifty-two buoy records are selected to conduct the validation (**Supplementary Table 3**). **Supplementary Figure 6** and **Supplementary Table 4** summarize the results before and after applying the bias correction. A mean relative error (MRE) lower than 20% is obtained after bias correction for all the return periods. The analysis for the non-bias-corrected H_s return values evidences a clear reduction of the error after the correction.

Name	Lon (°)	Lat (°)	Depth (m)	Name	Lon (°)	Lat (°)	Depth (m)
NDBC-41001	-72.63	34.60	4462	NDBC-46041	-124.74	47.35	131
NDBC-41002	-75.16	32.07	4297	NDBC-46050	-124.51	44.64	127
NDBC-41010	-78.55	28.90	887	NDBC-46132	-127.93	49.74	2047
NDBC-42001	-89.66	25.86	3217	NDBC-46184	-138.86	53.91	3380
NDBC-42002	-94.04	25.63	3125	NDBC-46042	-122.44	36.77	1890
NDBC-42003	-85.65	25.98	3292	NDBC-46185	-129.79	52.42	220
NDBC-42019	-95.35	27.91	83	NDBC-46204	-128.76	51.38	223
NDBC-42020	-96.70	26.96	83	NDBC-46206	-126.00	48.83	119
NDBC-42036	-84.51	28.51	52	NDBC-46207	-129.91	50.87	2088
NDBC-42039	-86.03	28.80	291	NDBC-46208	-132.70	52.51	2922
NDBC-42040	-88.22	29.21	190	NDBC-51001	-162.14	23.94	4869
NDBC-44004	-70.50	38.48	3182	NDBC-51002	-157.75	17.11	5029
NDBC-44005	-69.15	43.19	205	NDBC-51003	-160.65	19.18	4920
NDBC-44008	-69.34	40.50	63	NDBC-51004	-152.40	17.52	5082
NDBC-44011	-66.60	41.11	86	QLD-Brisbane	153.63	-27.49	77
NDBC-46001	-148.02	56.30	4124	Met Office-K1	-12.40	48.70	1871
NDBC-46002	-130.47	42.59	3438	Met Office-K2	-13.30	51.00	1994
NDBC-46005	-131.01	46.07	2721	Met Office-Brittany	-8.50	47.50	2108
NDBC-46006	-137.44	40.79	4294	Met Office-K5	-11.40	59.10	2011
NDBC-46012	-122.88	37.36	206	PdE-Silleiro	-9.40	42.12	301
NDBC-46013	-123.31	38.23	125	PdE-Cadiz	-6.63	36.66	450
NDBC-46022	-124.55	40.74	512	MHL-Byron Bay	153.72	-28.77	65
NDBC-46028	-121.87	35.73	1075	MHL-Coffs Harbour	153.27	-30.35	69
NDBC-46029	-124.51	46.12	137	MHL-Crowdy Head	152.86	-31.82	64
NDBC-46035	-177.67	57.06	3682	MHL-Port Kembla	151.02	-34.47	82
NDBC-46036	-133.93	48.35	3548	MHL-Sydney	151.42	-33.78	97

Supplementary Table 3 Main characteristics of the selected buoys: name, longitude, latitude and depth

		H _s ⁵	H _s ²⁰	H _s ⁵⁰
w BC	Mean relative error (%)	13.1	17.5	19.6
	Interquartile range of relative error (%)	6.9-17.9	9.6-24.0	11.5-26.9
	Mean square error (m)	2.3	7.0	11.9
w/o BC	Mean relative error (%)	28.2	33.2	35.4
	Interquartile range of relative error (%)	18.9-34.9	24.2-41.5	27.3-44.5
	Mean square error (m)	8.0	18.7	28.7

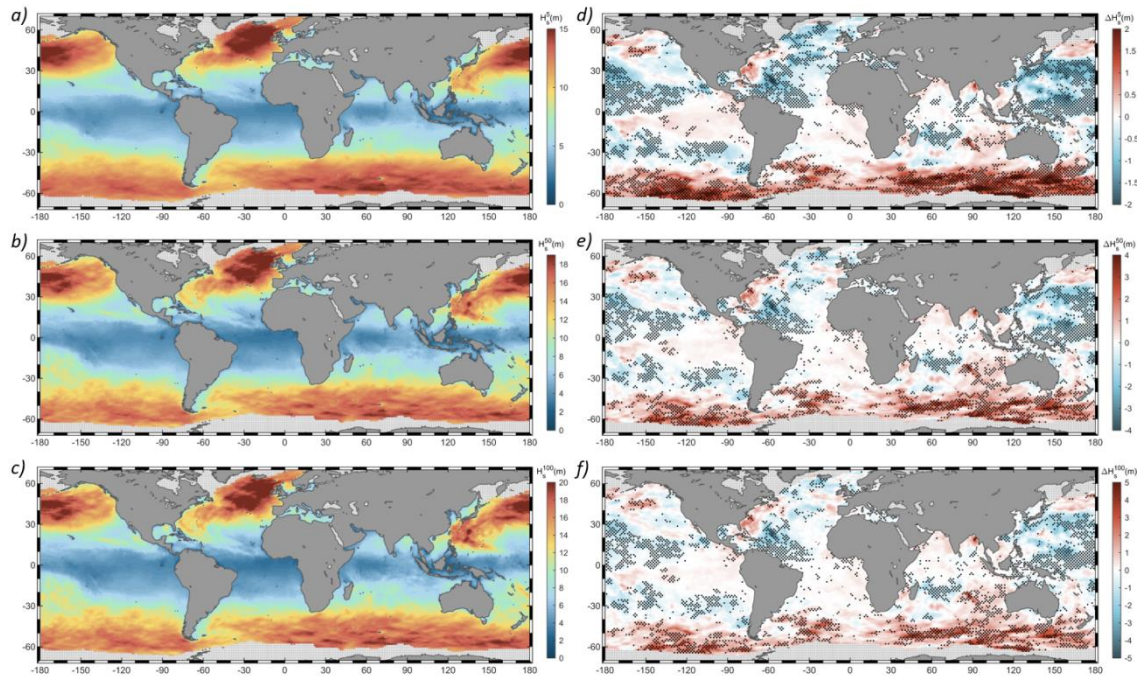
Supplementary Table 4 Relative error (%), interquartile range of relative error and mean-square error in significant wave height return values calculated from the dynamical projections with (w) and without (w/o) BC with respect to return values from buoy records.



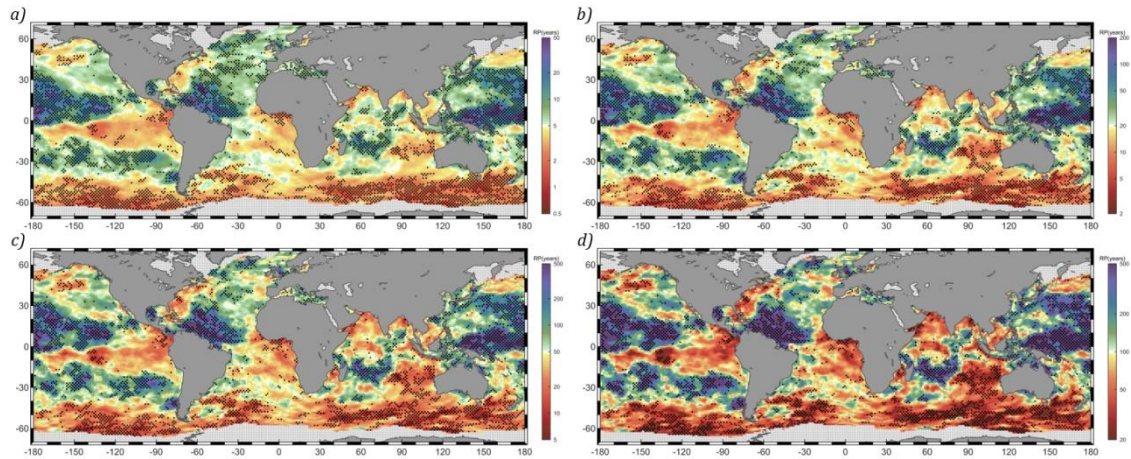
Supplementary Figure 6 Relative error (%) in significant wave height 20-year return values calculated from the dynamical projections with (a) and without (b) BC with respect to return values from buoy records. Figure generated with MATLAB R2020a (<https://es.mathworks.com/products/matlab.html>).

Extreme wave climate future changes under RCP8.5 scenario

In addition to the changes in the 20-year return period H_s extremes (Figure 2c; Table 1), future changes in 5-, 50- and 100-year return period events under RCP8.5 scenario are also studied (Supplementary Figure 7d-f; Table 1). The main conclusions derived from the found spatial change pattern agree with those already explained for H_s^{20} . Concerning the magnitude of the projected changes, the Southern Ocean presents an expected future increase of +0.6m, +0.9m and +0.9m for H_s^5 , H_s^{50} and H_s^{100} , respectively. The Atlantic Ocean exhibit a decreasing pattern in the Northern Hemisphere, especially robust in the tropical region for all return periods (above 28% of the region show robust changes), with projected decreases of -0.3m, -0.4m and -0.4m. On the other hand, the high uncertainty in TSA (10% of robust change for all return periods) precludes the possibility of reaching any strong conclusion. Along the tropical Pacific, a consistent decreasing change pattern can be observed with the only exception of TEP region, where a highly uncertain increase is found (less than 10% of robust change). TNP shows an average projected change of -0.5m, -0.6m and -0.6m for H_s^5 , H_s^{50} and H_s^{100} , and TSP presents an average change of -0.2m, -0.3m and -0.4m for H_s^5 , H_s^{50} and H_s^{100} , respectively. The Indian Ocean is characterized by heterogeneity in the sign of change. Thus, while in TSWI an average decrease of -0.1m for H_s^5 , -0.2m for H_s^{50} and -0.2m for H_s^{100} is obtained, TSEI shows the opposite sign of change with +0.1m, +0.3m and +0.4m, respectively. Again, the high uncertainty found in TNI makes it very difficult to assert a robust conclusion. In addition, the projected change in the return period associated to present-day extreme wave heights by the end of the century is also shown (Supplementary Figure 8).



Supplementary Figure 7 H_s^5 (a), H_s^{50} (b) and H_s^{100} (c) from GOW2 hindcast. Multi-model ensemble mean change in H_s^5 (d), H_s^{50} (e) and H_s^{100} (f) (in meters) under RCP8.5 scenario. Stippling denotes changes statistically significant at 95% confidence level in at least 50% of the members and an agreement in the sign of change in more than 80% of the members. Figure generated with MATLAB R2020a (<https://es.mathworks.com/products/matlab.html>).

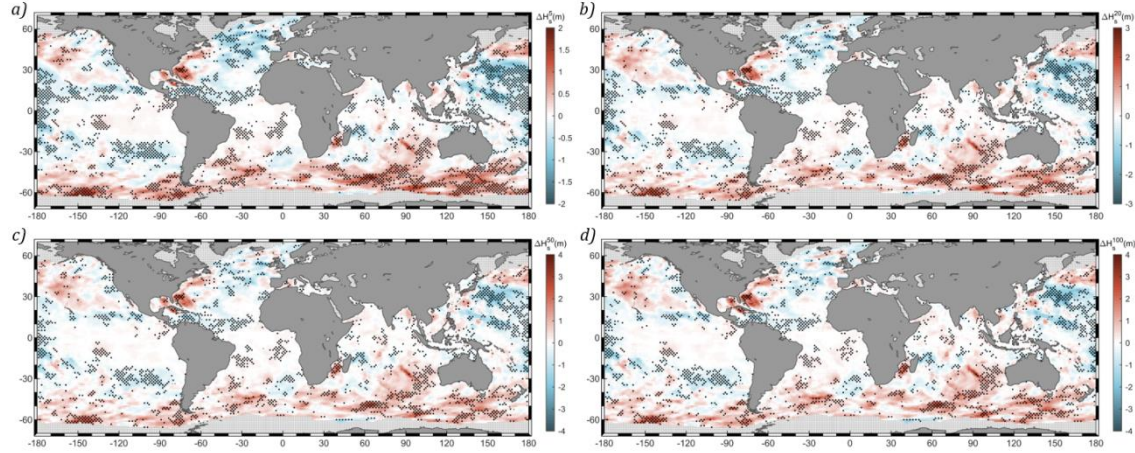


Supplementary Figure 8 Projected return period by 2100 of present-day H_s^5 (a), H_s^{20} (b), H_s^{50} (c) and H_s^{100} (d). Stippling indicates the same as in Sup. Figure 7. Figure generated with MATLAB R2020a (<https://es.mathworks.com/products/matlab.html>).

Extreme wave climate future changes under RCP4.5 scenario

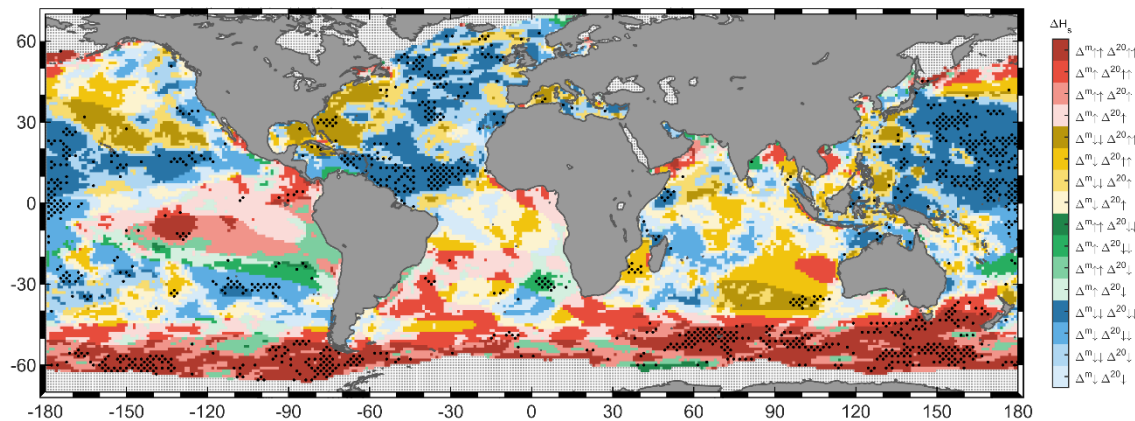
Future changes under RCP4.5 scenario have a very similar spatial pattern for all the analyzed return periods (Supplementary Figure 9; Table 1). Nevertheless, the uncertainty increases for wave extremes with a lower probability of occurrence so that the proportion of the global ocean that shows robust changes reduces from 22% for H_s^5 to 16% for H_s^{100} . Results for H_s^{20} (Supplementary Figure 9b; Table 1) indicate a robust expected decrease in the North Atlantic Ocean excluding the westernmost part of the basin, where a consistent positive change is found. The proportion of the region with a robust decrease is 13% in ETNA and 22% in TNA, with averaged projected changes of -0.2m and -0.0m, respectively. TSA shows a positive change characterized by a 16% of robust changes and an average increase of +0.1m. Concerning the Pacific Ocean, ETNP presents a low-robust increase (12%) with an average change of +0.1m. The tropical region shows a heterogeneous spatial pattern so that

while a decrease is expected in TNP and TSP (average of -0.2m in both regions), a very low-robust positive projected change is expected in TEP (8%). The change pattern in the Indian Ocean is characterized by a high uncertainty in TNI (11%) and heterogeneity in the sign of change in the tropical south region. Thus, while a robust increase can be observed in TSEI (19% and average change of +0.2m), TSWI presents areas with robust projected positive (e.g. Mozambique Channel) and negative (e.g. east of Madagascar) changes, resulting in an average projected change of -0.0m for all return periods. Finally, a consistent increase in the Southern Ocean characterized by a 20% of robust changes and an average of +0.4m is obtained.



Supplementary Figure 9 Multi-model ensemble mean change in H_s^5 (a), H_s^{20} (b), H_s^{50} (c) and H_s^{100} (in meters) under RCP4.5 scenario. Stippling denotes changes statistically significant at 95% confidence level in at least 50% of the members and an agreement in the sign of change in more than 80% of the members. Figure generated with MATLAB R2020a (<https://es.mathworks.com/products/matlab.html>).

In this work we also carry out a comparison between the spatial pattern obtained for projected changes in mean and extreme wave height by the end of the century under RCP4.5 (Supplementary Figure 10) scenario. Despite results exhibit a concordance in the sign of change between both conditions in approximately two thirds of the global ocean, a general great uncertainty can also be observed (only 9% of the area show robust change for mean and extreme wave climate). In this regard, while the Southern Ocean (increase) and the north tropical western Pacific (decrease) are the regions which present the most robust agreement, the extra-tropical north Pacific and tropical southeastern Indian are the areas with the most evident disagreement. Similarly, the North Atlantic Ocean shows a concordance in the sign of change in most of the basin that breaks down due to the positive projected changes obtained for extremes in the westernmost part of the region.



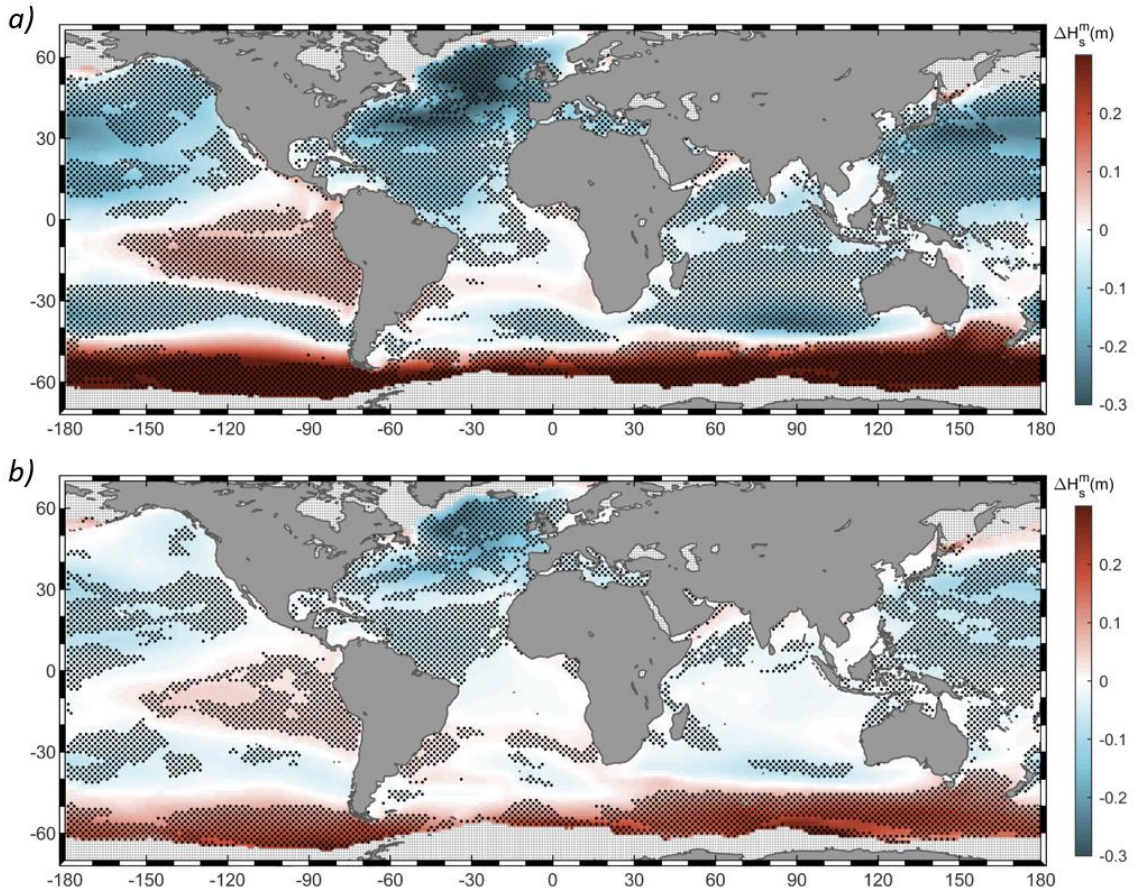
Supplementary Figure 10 Comparison of projected changes in mean (Δ^m) and extreme (Δ^{20}) significant wave height under RCP4.5 scenario by the end of the century (2081-2100 relative to 1986-2005). Colors represent the combinations of sign of change between mean and extreme wave conditions: red indicates an increase in both conditions, blue represent a decrease in both conditions, yellow represent a decrease in mean and an increase in extreme conditions and green represents an increase in mean and a decrease in extreme conditions. For each combination, one arrow indicates a relative change lower than the global median and two arrows indicate relative changes higher than the global median. The global median is obtained as the median of the

relative changes with the same sign as the analyzed variation. Stippling denotes changes statistically significant at 95% confidence level in at least 50% of the members and an agreement in the sign of change in more than 80% of the members for both mean and extreme significant wave height. Figure generated with MATLAB R2020a (<https://es.mathworks.com/products/matlab.html>).

Mean wave climate future changes

Projected changes in annual mean significant wave height (H_s^m) are calculated as the difference between future and present-day H_s^m . The uncertainty assessment follows the same method as for projected changes in extremes (see [Methods](#)).

Changes in H_s^m under RCP8.5 scenario ([Supplementary Figure 11a](#)) exhibit a general decreasing pattern in the Northern Hemisphere. In this regard and in line with previous studies, the North Atlantic and the northwestern Pacific show a robust projected change^{14,17,18}. The northeastern Pacific presents as well a consistent decrease although with a higher uncertainty compared to the previous regions. Concerning the Southern Hemisphere, a heterogenous spatial change pattern can be observed. The Southern Ocean and the tropical eastern Pacific present a robust increase, which agrees with the projected changes found in previous studies^{14,17,18}. Contrarily, a robust negative change can also be observed in the Indian Ocean. Results for the RCP4.5 ([Supplementary Figure 11b](#)) show a pretty similar spatial change pattern with respect to the RCP8.5 scenario although with a notable increase in the uncertainty (from 63% to 46% of the global ocean showing robust changes). Despite the north Atlantic, northwestern Pacific, Southern Ocean and tropical eastern Pacific maintain a robust agreement in the projected changes, there is a remarkable increase in the uncertainty in regions such as the Indian Ocean.



Supplementary Figure 11 a) Multi-model ensemble mean change in H_s^m under RCP8.5 scenario. b) Multi-model ensemble mean change in H_s^m under RCP4.5 scenario. Stippling denotes changes statistically significant at 95% confidence level in at least 50% of the members and an agreement in the sign of change in more than 80% of the members. Figure generated with MATLAB R2020a (<https://es.mathworks.com/products/matlab.html>).

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