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Global trends in wind speed and wave height

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Studies of climate change typically consider measurements or predictions of temperature over extended periods of time. Climate, however, is much more than temperature. Over the oceans, changes in wind speed and the surface gravity waves generated by such winds, play an important role. We use a 23-year data base of calibrated and validated satellite altimeter measurements to investigate global changes in oceanic wind speed and wave height over this period. We find a general global trend of increasing values of wind speed and, to a lesser degree, wave height, over this period. The rate of increase is greater for extreme events compared to the mean condition.

Oceanic wind speed and wave height help to control the flux of energy from the atmosphere to the ocean *(1)* and upper ocean mixing *(2).* Thus, they significantly influence the mechanisms of air-sea interaction *(3).* Previous attempts to investigate trends in oceanic wind speed and wave height have used ship observations *(4-8),* point measurements *(9),* numerical modelling *(10-15)* or satellite observations *(16).* Almost all of these studies are regional rather than global. Although there are a range of results, many studies show an increasing trend in significant wave height, particularly in the North Atlantic and North Pacific, often correlated with inter-annual variations such as the North Atlantic Oscillation. Careful ship observations *(4-6)* also show wind-sea and swell behaving quite differently and that there exist quite different trends in wind speed and wave height. The present analysis uses recently developed satellite altimeter data sets to carefully investigate such trends on a global scale.

Satellite-based systems provide an alternative to visual or in-situ measurements of oceanic wind speed and wave height, with a variety of instruments including the altimeter, scatterometer and synthetic aperture radar providing global coverage of wind and/or waves.

Of these instruments, the radar altimeter provides by far the longest duration record. Since the launch of GEOSAT in 1985, there exists an almost continuous (break in 1990 - 1991) record of measures from a total of seven different altimeter missions. Numerous calibrations of these altimeters have shown that the instruments can be used to measure significant wave height, $H_s = 4\sqrt{E}$, where E is the total energy of the wave field, with an rms error less than 0.2m *(17)* and the wind speed, U_{10} with an rms error less than 1.5m/s *(17-21).* Data from altimeter missions have been used to investigate mean ocean wind and wave climatology *(21, 22)*, on a global scale. Recently, Zieger et al. *(20)* carried out systematic calibrations and cross-platform validations of all altimeter measurements over the full 23 years for which data are available. This study provided a consistent data set over this extended period. As the data set spans multiple satellite platforms, consistent calibration and validation is critical when investigating long term trends. In the present study, we use this data set to investigate whether there have been systematic changes in the ocean wind and wave climate over this period. As the seasonal cycle typically is large, care must be exercised in determining trend information from the data set [supporting online material (SOM)].

We aim here to determine if there is a statistically significant trend [where trend is defined as a linear increase/decrease in the mean *(23,24)*] within the time series of monthly mean, 90th and 99th percentile values of wind speed and wave height for $2^o \times 2^o$ regions covering the globe. In the analysis, we take particular care to ensure that the trend can be separated from the seasonal component (SOM).

The trend was quantified as a linear function over the duration of the time series. The analysis revealed that 90th and 99th percentile wind speed data from the GEOSAT altimeter were of questionable quality (SOM). Therefore these data were excluded from the analysis. As a result, the wave height analysis considers the period 1985-2008, whereas wind speed is analysed for the shorter period 1991-2008. The trend was expressed for each $2^{o} \times 2^{o}$ region, as the annual percentage increase/decrease relative to the mean condition and in absolute terms. The monthly mean, 90th and 99th percentile trend values for both wind speed and wave height are shown in Figs. 1, 2 and 3 (percentage increase/decrease) and Figs. S7, S8 and S9 (SOM) (absolute increase/decrease), respectively.

There is a clear global increase in wind speed for all three statistics. The mean and 90th percentile wind speed trends are relatively similar, with the magnitude of the increase being larger for the 99th percentile. Such a result indicates that the intensity of extreme events is increasing at a faster rate than the mean conditions. At the mean and 90th percentile, wind speeds over the majority of the world's oceans have increased by at least 0.25% to 0.5% per annum (5-10% net increase over the past 20 years). The trend is stronger in the southern hemisphere than the north. The only significant exception to this positive trend is the central north Pacific, where there are smaller localized increases in wind speed of approximately 0.25% per annum and some areas where there is a weak negative trend.

Also shown (Figs. 1-3) are regions of the globe where the calculated trend is statistically significant at the 95% level (SOM). The calculated wind speed trend for the majority of the globe is statistically significant, the exceptions being the areas of weak positive trend noted above, particularly in the north Pacific.

At the 99th percentile the wind speed trend becomes more positive, indicating that extreme wind speeds are increasing over the majority of the world's oceans by at least 0.75% per annum. The region in the central north Pacific, which showed a weak increasing trend for the mean and 90th percentile now shows a stronger trend of approximately 0.50% per annum, this trend now being statistically significant.

The mean wave height trend (Fig. 1) shows a relatively neutral condition. Large regions of the north Pacific and north Atlantic show a weak negative trend (0.25% per annum), as does much of the equatorial regions of all oceanic basins. However, the southern hemisphere has a consistent weak positive trend of approximately 0.25% per annum. In almost none of these regions, however, is the trend statistically significant (SOM). The 90th percentile (Fig. 2) and the 99th percentile (Fig. 3) wave height trends are progressively more positive, with the higher latitudes (greater than $\pm 35^{\circ}$) of both the hemispheres showing positive trends of approximately 0.25% per annum at the 90th percentile and 0.50% at the 99th percentile. The equatorial and tropical regions of all oceanic basins show a neutral trend for wave height in both cases. The wave height trend becomes more positive moving from the mean to the 99th percentile (i.e. moving to more extreme conditions). It should be noted that the areas of weak trends observed for the mean and 90th percentile are largely not statistically significant. For the 99th percentile wave height, the stronger positive trends at high latitudes are statistically significant, whereas the weaker trends in the equatorial regions are not. Averaged over the full globe, the following percentage of points produced trends which were statistically significant at the 90% / 95% confidence levels, respectively: wind speed – 48% / 36% (mean), 53% / 40% (90th percentile), 68% / 55% (99th percentile); wave height – 15% / 8% (mean), 20% / 12% (90th percentile), 60% / 47% (99th percentile).

In order to validate the trends observed in the altimeter data, the same analysis was applied to the 12 deep-water buoys used by Zieger et al. *(20)*. The results are shown in Table 1, together with the corresponding altimeter values for $2^{\circ} \times 2^{\circ}$ regions centred on each of the buoy locations. It is clear that there is variability between buoys in the same geographic region and between buoy and corresponding altimeter trend values. However, the same general features observed in the altimeter trends are repeated in the buoy data. At every buoy location, the wind speed trend is positive for each of the monthly mean, 90^{th} and 99^{th} percentile time series. The magnitude of the trend also increases at extreme values, consistent with the altimeter results. As for the altimeter observations, there is no clear trend for mean monthly wave height across the buoys. However, the buoys produce a more positive trend for wave height at extreme values, this trend being weaker than for wind speed, again consistent with the altimeter results.

A further validation check was performed by comparing the altimeter global trend values with numerical model results. Fig. S6 (SOM) shows the trend in mean monthly wind speed calculated from NCEP (National Centre for Environmental Protection) global reanalysis results *(25).* This result is qualitatively consistent with Fig. 1.

The present analysis cannot absolutely determine why there is a stronger trend in wind speed than wave height or the underlying physical processes responsible for the observed positive trends in both quantities at extreme values. Observations of local wave generation *(26, 27)* indicate that for wind generated waves, significant wave height is approximately proportional to wind speed. Hence, one might initially expect that the spatial patterns for wind speed and wave height would be similar. However, the situation is more complex in that wave height in the open ocean is a mix of locally generated wind sea and remotely generated swell. Although trends in wind-sea will be correlated with trends in the local wind speed, it has been shown that swell is influenced by not only the intensity of generating meteorological systems but also their frequency *(4, 6)*. Hence, differing trends in wind-sea (a proxy for wind speed) and swell are plausible.

The present results do show causal relationships between the trends in wind speed and wave height. The Southern Ocean is dominated by strong westerly winds blowing across large oceanic fetches. As expected, in this region, there are well correlated positive trends in both wind speed and wave height. The same is true in the high latitudes of the northern hemisphere. In contract, the wave climate in tropical regions is dominated by remotely-generated swell and the results show little correlation between wind speed and wave height trends for these areas. For extreme conditions (eg. 99th percentile), waves tend to be generated by local storm events and hence one would expect a stronger correlation between wind speed and wave height. The present results (Fig. 3 and Fig. S9) are consistent with this hypothesis, with wind speed and wave height showing similar positive trends for 99th percentile conditions.

A detailed analysis of the observed trends would require information on the distribution of wind-sea and swell together with swell propagation direction and a basin-specific analysis. Such data are not directly available from the altimeter.

The present analysis is aimed at determining whether there is a linear trend over the period of the observations (approx. 23 years). It does not necessarily follow that the observed trends are a result of, for instance, global warming. Indeed, interannual to decadal variations of the high latitude wind belts have been observed, and Hemer et al. *(28)* have shown that the wave climate in the Southern Hemisphere is influenced by the Southern Annular Mode. A regression analysis between the monthly mean altimeter significant wave height and the

Southern Annual Mode Index (SAMI) showed a weak correlation, with a correlation coefficient up to 0.4 across large areas of the Southern Ocean. Similar, interannual variations have also been shown to be correlated with wave heights in the North Atlantic *(5, 10, 11, 13, 14).* Hence, it is highly likely that such long term oscillations will significantly influence the global ocean wind and wave climate. As the present data set is only two decades long, it is not possible to distinguish between a steadily increasing or accelerating trend, which could be extrapolated into the future or simply the upward portion of a multi-decadal oscillation. Only a longer data set will be able to separate these possibilities.

The present analysis does, however, indicate that over the past two decades there has been a consistent trend towards increasing wind speeds. For wave height, the results are more complex, with no clear statistically significant trend for mean monthly values. At more extreme conditions there is a clear statistically significant trend of increasing wave height at high latitudes and more neutral conditions in equatorial regions.

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Figure 1: Colour contour plots of mean trend (% per annum). Wind speed is shown at the top and wave height at the bottom. Points which are statistically significant according to the Seasonal Kendall test are shown with dots.

Figure 2: Colour contour plots of the 90th percentile trend (% per annum). Wind speed is shown at the top and wave height at the bottom. Points which are statistically significant according to the Seasonal Kendall test are shown with dots.

Figure 3: Colour contour plots of the 99th percentile trend (% per annum). Wind speed is shown at the top and wave height at the bottom. Points which are statistically significant according to the Seasonal Kendall test are shown with dots.

Region	Buoy No.	Lat. (ºN)	Long. (ºW)	Buoy Trend (cm/s/yr)			Altimeter Trend (cm/s/yr)		
				Mean	90th	99th	Mean	90th	99th
Gulf of Mexico	42001	25.9	89.7	1.79	**3.00**	**4.53**	0.57	**4.50**	**10.11**
	42002	25.8	93.7	1.88	**3.07**	**6.29**	1.13	0.00	0.69
North Atlantic	44004	38.5	70.4	**4.01**	**4.42**	**7.34**	0.57	2.41	**10.94**
	44011	41.1	66.6	0.48	2.46	4.63	0.51	2.16	**13.03**
	41002	32.4	75.4	**3.66**	**7.50**	**12.99**	-0.47	2.21	**10.73**
North Pacific	46001	53.3	148.0	**2.90**	**4.93**	**7.56**	**5.33**	**7.46**	**10.54**
	46002	42.6	130.5	1.99	2.14	2.83	3.24	**5.25**	**10.42**
	46005	46.1	131.0	**4.02**	**6.43**	**8.89**	**4.26**	**5.50**	**13.76**
	46006	40.9	137.5	**3.52**	**4.15**	**12.70**	**2.45**	**3.33**	**10.04**
	46035	57.1	177.8	**5.62**	**10.00**	**9.08**	1.06	-0.61	0.02
Hawaii	51001	23.5	162.3	2.86	**3.59**	**4.42**	**3.99**	2.77	**4.96**
	51002	17.1	157.8	2.12	1.40	0.92	2.90	3.63	**6.43**

Region	Buoy No.	Lat. (ºN)	Long. (ºW)	Buoy Trend (cm/yr)			Altimeter Trend (cm/yr)		
				Mean	90th	99th	Mean	90th	99th
Gulf of Mexico	42001	25.9	89.7	0.24	0.00	**1.42**	-0.41	0.43	**2.41**
	42002	25.8	93.7	**0.55**	0.50	**1.00**	-0.44	0.24	**1.46**
North Atlantic	44004	38.5	70.4	0.14	0.40	1.27	-0.54	0.51	**2.74**
	44011	41.1	66.6	**0.42**	**1.11**	**1.47**	0.34	**1.64**	**5.20**
	41002	32.4	75.4	-0.05	0.00	0.54	-0.41	-0.02	**2.82**
North Pacific	46001	53.3	148.0	-0.45	0.00	0.50	0.08	1.24	**3.03**
	46002	42.6	130.5	0.06	0.00	-0.06	0.01	0.58	**2.59**
	46005	46.1	131.0	0.36	0.00	1.84	0.42	**1.67**	**4.50**
	46006	40.9	137.5	**0.98**	**1.25**	1.61	-0.21	0.24	**2.64**
	46035	57.1	177.8	-0.31	**-0.95**	**-2.54**	-0.36	0.84	2.59
Hawaii	51001	23.5	162.3	**-0.71**	**-0.71**	-0.65	-0.88	**-0.95**	-0.06
	51002	17.1	157.8	0.02	0.00	-0.51	-0.16	0.27	0.66

Table 1: Comparison of trend estimates for buoy and altimeter data. The top panel shows wind speed and the bottom panel wave height, with the locations grouped by geographic region. Shaded (bold) values are statistically significant at the 95% level (dark shading) and at the 90% level (light shading); where two significance tests were passed (the normal distribution and the homogeneity test) (SOM).