EXTREME WIND WAVES WORLDWIDE FROM THE VOS DATA AND THEIR CHANGES OVER THE LAST 50 YEARS

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1. Introduction

Extreme ocean wind waves affect operations of marine carriers and naval architect. Moreover, extreme wind waves serve as an effective indicator of climate variability, because they reflect changes in atmospheric circulation types, responsible for the generation of extreme storms. Long-term time series of characteristics of ocean wind waves are presently available from long-term model hindcasts, satellite altimeter measurements and Voluntary Observing Ship (VOS) data. Hindcasts of Cox and Swail (2001), Wang and Swail (2001, 2002) and Sterl and Caires (2005) based on NCEP/NCAR winds and ERA-40 winds respectively show a growing mean SWH as well as intensification of SWH extremes during the last 40 years. In particular, the 99% extreme of the winter SWH increased in the northeast Atlantic by a maximum of 0.4 m/decade (Wang and Swail 2001, 2002, Caires and Sterl 2005). However, centennial hindcasts for the 21st century, based on the forcing reconstructed from the observed relationships between sea level pressure (SLP) and SWH (Wang et al. 2004, Caires and Sterl, *personal communication*) show different sign of trends in SWH extremes for different scenarios and different seasons. Satellite data provide global times series of wind wave characteristics for the period from 1 to 2 decades. Woolf et al. (2002) reported increasing of significant wave height in the North Atlantic mid latitudes from a 14-year (1988-2002) time series of the merged TOPEX/POSEIDON and ERS-1/2 *Ku*-band altimeter data. However, these data are still short to be extensively applied for climate variability studies.

Wave data available from VOS represent visual estimates of wave parameters, reported by marine officers worldwide starting from 1856 (Worley et al. 2005, Gulev et al. 2003, Gulev and Grigorieva 2004). In comparison to the other data sources these data have the longest records and provide independent estimates of wind sea and swell. Gulev and Grigorieva (2004) using longer time collection developed 120-year long time series of SWH for well sampled areas of the location of major ship routes. These time series were homogenized with respect to the impact of sampling uncertainties on the data. Analysis has shown significantly positive trends in annual mean SWH almost everywhere in the North Pacific, with a maximum upward trend of 8-10 cm/decade (up to 0.5% per year) and weak negative trends along the North Atlantic storm track. During the period 1958-2002 linear trends in annual mean SWH were significantly positive over most midlatitudinal North Atlantic and North Pacific with the largest upward changes of 14 cm/decade. In the recent study Gulev and Grigorieva (2006) demonstrated association of variability in wind sea with the local scalar wind, while swell changes were found to be driven by the variations in the cyclone counts, implying importance of forcing frequency for the resulting changes in significant wave height.

At the same time VOS data are influenced by sampling uncertainties which are time-dependent. Thus, a direct application of the methodologies of estimation of extreme wave characteristics from VOS data is not an easy task. In this work we use the collection of visual wave observations over the Northern Hemisphere for the last 5 decades for statistical estimation of extreme wave parameters and analysis of their decadal variability.

2. Data and methods

We used the latest update of the global climatology of wind wave characteristics (Gulev et al. 2003) covering now 48-year period from 1958 to 2005. This data set is based on the ICOADS (Worley et al. 2005) collection of marine meteorological observations. Comprehensive description of the data processing, coding systems, changes in data formats, *ad-hoc* corrections of biases and estimates of the uncertainties can be found in Gulev et al. (2003). The major biases in wind sea height (h_w), swell height (h_s) and SWH which have been considerably reduced in climatology of Gulev et al. (2003) were the overestimation of small wave heights and poor separation of sea and swell in visual observations. Gulev et al. (2003a) also provided global estimates of random observational errors in h_w and h_s, estimates of day-night differences and estimates of sampling uncertainties. Sampling errors were found to be large in poorly sampled Southern Ocean, where they dominate over the other error sources. The recently incorporated in our data base data for the period 2003-2005 extended the total period up to 48 years.

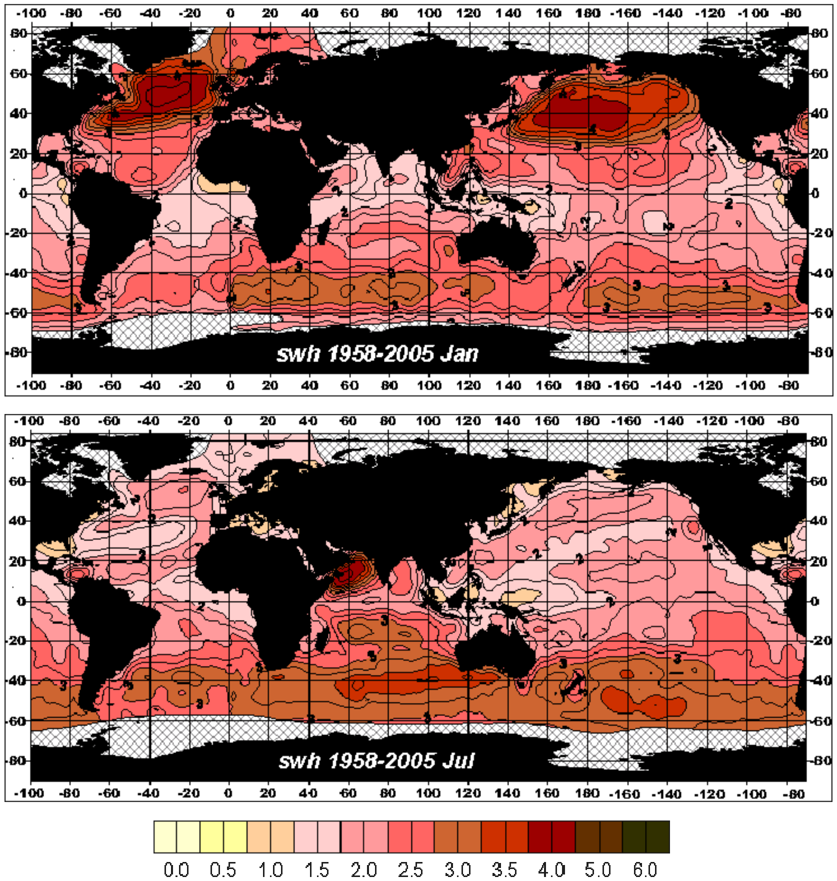

Figure 1. January (upper panel) and July (lower panel) climatologies of SWH over the Global Ocean for the period 1958-2005 from visual wave data.

Figure 1 shows January and July climatology of significant wave height with 2°×2° resolution in space covering the World Ocean from 80°S to 80°N for the period from 1958 to 2005. Spatial distribution of SWH does not significantly differ from the earlier presented in Gulev et al. (2003). The highest SWH of 4.5-5 meters is observed in January in the North Atlantic mid latitudes with the Pacific midlatitudinal values being 10-20% smaller. In the Southern Ocean the highest SWH in July ranges from 3.5 to 4 meters and is identified in the South Indian Ocean and South Pacific. Locally high July values of SWH were observed in the western Arabian Sea, where they amount to 4.5-5 meters. For the further estimation of extreme wave statistics we used the data exclusively over the Northern Hemisphere, were sampling density is high enough to provide accurate application of statistical procedures.

For the further estimation of extreme wave characteristics we used the method of initial value distributions (IVD) and the so-called peak over threshold (POT) method. In IVD method the extreme wave statistics were estimated form the tails of distribution functions fitted to all wave observations for different the 20-degree grid cells. For fitting data we used Weibull distribution whose parameters were estimated from the maximum likelihood method. The choice of 20-degree boxes is justified by the necessity to achieve reasonable sampling size for the further estimation of Weibull probability density function (PDF) and cumulative distribution function (CDF). Alternatively, we applied for the first time to irregularly sampled VOS data the POT method (Caires and Sterl 2005). In this method only storm peak values of wind sea, swell and SWH were considered. First, for every 2-degree box all VOS reports were matched to 6-hourly time steps. In the case when more than one report matches to a given time moment the median value was considered. Unsampled time steps imply the undersampling of the monthly time series. As in the case with altimeter data which are also characterized by undersampling, sparse data do not necessarily record the biggest exceedances at a point. However, the distribution of any exceedance provides the estimation of the probability of the largest one. According to the experience of application of POT to the altimeter data (Challenor and Woolf, *personal communication*) undersampling will lead to an underestimate of the extremes by about 10-15%. Nevertheless, to avoid strong impact of the undersampling onto estimation of extreme wave characteristics, we excluded from the analysis monthly composed time series which covered have less than 40% of month.

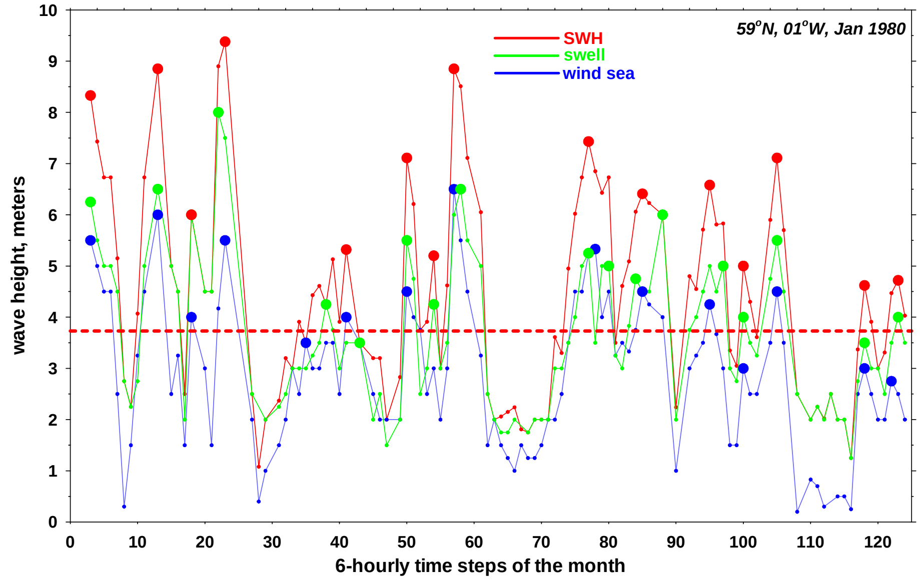

Figure 2. Time series with 6-hourly resolution of wind sea, swell and SWH composed for one 2-degree box in the North Atlantic for January 1980. Bold red dash line shows the first guess threshold for SWH.

The first-guess thresholds were established as 50% exceedance of the monthly time series of wave parameter considered. Then the search between the adjacent time moments was applied to remain in the record only peak values. The search was based on the consideration of storm durations (derived from the analysis of the regularly sampled WAM data) and on the use of filtering procedures. Figure 2 shows an example of the application of POT for identification of the peak storm values for wind sea, swell and SWH for one well sampled box during January 1980 in the North Atlantic. Finally the peak values identified were approximated by the Generalized Pareto Distribution in order to further estimate percentiles and return values of wave parameters. Using both IVD and POT methods we estimated 95%- and 99%-percentiles of wave characteristics as well as 100-year return values. Estimation was performed for individual decades that allowed for the further analysis of the decadal variability of wave statistics.

3. Results

The results obtained using IVD method reported considerably smaller estimates of extreme wave heights in comparison to those reported by altimeter data and WAM model hindcasts. Thus, the highest 100-year return value in the North Atlantic was about 17 meters. In the North Pacific 100-year return value of SWH amounted to 14.8 meters. Considerably smaller 100-year values of SWH were identified for the Southern Ocean, characterized by poor sampling which strongly limits the applicability of the extreme value estimation even for 20-degree boxes. The largest 100-year return value of SWH in July in the Southern Ocean was about 13 meters. Application of the POT method for the North Atlantic and North Pacific resulted in the wave statistics which are quite comparable with those reported from the analysis of the model hindcasts and altimeter data (Caires and Sterl 2005, Wang and Swail 2001, Challenor and Woolf, *personal communication*). Figure 3 shows estimates of 95%-percentiles and 100-year return values of SWH derived for the North Atlantic and North Pacific. The highest 95%-percentile values of SWH range from 8 to 10 meters and are identified in the North Atlantic subpolar latitudes and in the mid latitudes of the central North Pacific. The highest 100-year return values amount to more than 22 meters in both North Atlantic and North Pacific being comparable with those derived from the model hindcasts. The absolute maximum 100-year return value of SWH of 24 meters was identified in the western North Atlantic. Analysis of statistical parameters of wind sea and swell (no figure shown) allowed for the first time to obtain extreme characteristics of wind wave components which are only directly estimated in the VOS data. In the North Atlantic extreme values of wind sea and swell are quite close to each other (about 7 meters) with wind sea being slightly higher. At the same time in the North Pacific for 95% and 99% percentiles as well as for 100-year return values swell demonstrates somewhat larger heights than the wind sea does. Typical differences amount to 0.6-1 meter over the Pacific mid latitudes. Thus, extreme SWH in the Pacific is largely dominated by swell, while in the North Atlantic both wind sea and swell equally contribute to the extreme SWH. Higher extreme swell height in the Pacific can be explained by the relatively longer fetches in the Pacific compared to the North Atlantic.

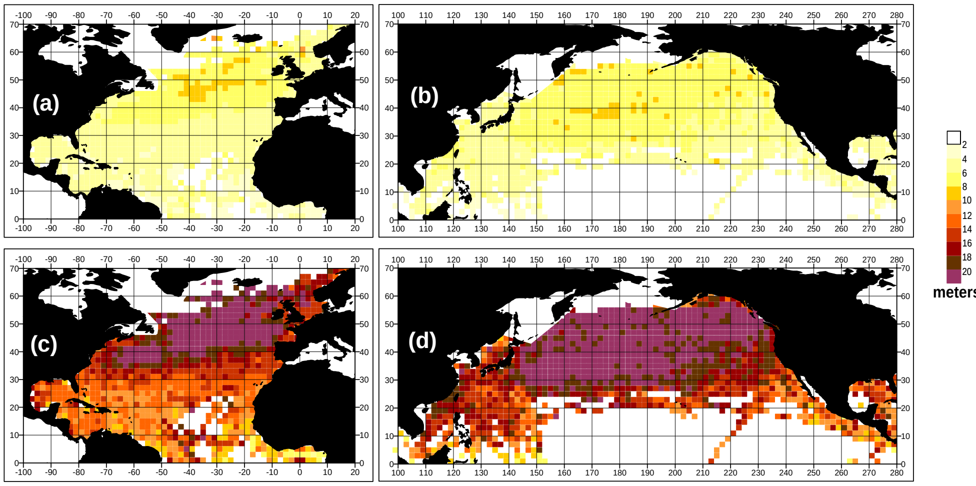

Figure 3. Estimates of 95%-percentiles (a, b) and 100-year return values (c, d) of SWH derived fro the North Atlantic (a, c) and North Pacific (b, d).

Of a special interest is the analysis of climate variability in extreme characteristics of wind waves. On one hand, this analysis shows the extent to that the estimates of wind wave extremes taken from the data for different decades are robust and can be applicable for the naval architect needs. On the other hand, these estimates along with the other extreme characteristics (winds, cyclones) allow for the consideration of the mechanisms of climate change which are believed to impact on the parameters of statistical distributions event to a larger extent than on mean values.

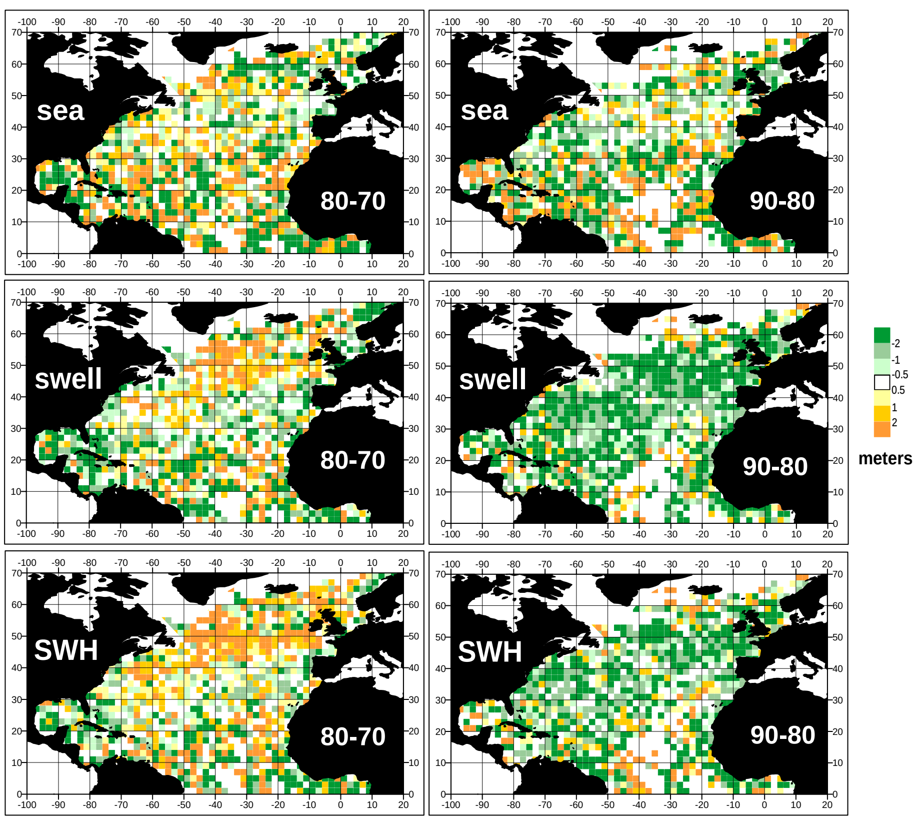

Figure 4. Differences between 100-year return values in wind sea (upper row), swell (middle row) and SWH (bottom row) over the North Atlantic Ocean, estimated for different decades.

We estimated wind wave statistics for different decadal periods over the last 40 years. Figure 4 shows differences in 100-year return values of different wave parameters between different decades for the North Atlantic. Remarkably, wind sea does not show any spatial pattern of the differences. For the decades of 1980s and 1990s one can identify some indication of primarily decreasing extreme seas in the mid latitudinal North Atlantic. Alternatively, swell shows a clear pattern of the increase of 100-year return values from the decade of 1970s to the decade of 1980s with the further decrease in the decade of 1990s. These changes are confirmed by the variability derived for SWH. This is in agreement with the results of Gulev and Grigorieva (2006) showing that changes in the mean seasonal SWH are closely associated with variability of swell. It is interesting to note that similar analysis performed in the North Pacific (not shown) also did not demonstrate any regular patterns of interdecadal differences in the wind sea height. At the same time, tendencies for swell height and SWH between different decades were qualitatively similar to those in the Atlantic.

4. Conclusions

We estimated characteristics of extreme waves from VOS data over the Northern Hemisphere oceans. Application of IVD and POT methods results in quite different estimates of extreme wave statistics with POT giving significantly higher values of extreme waves. Our estimates have shown 100-year return values in significant wave height higher than 22 meters in both North Atlantic and North Pacific that is comparable to the estimates derived from the model simulations. The highest 100-year return value was obtained in the North Atlantic. Extreme wave statistics may experience changes from one decade to another. Particularly, strong differences were identified in the North Atlantic between the decades of 1970s and 1980s (growing extreme SWH) and between 1980s and 1990s (decreasing extreme SWH).

Further analysis will involve comprehensive validation of the results against ERA-40-WAM hindcast which is characterized by regular sampling and may help identify biases in the VOS-based estimates associated with the inhomogeneous sampling in the VOS data. Of a special importance is the testing of alternative probability density distributions used in both IVD and POT methods. For the well sampled coastal areas as well as for major ship routes extreme wave statistics can be provided with much higher resolution matching 0.5 degrees.

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