Last century changes in ocean wind wave height from global visual wave data

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[1] Centennial time series of visually observed wave height were derived from the International Comprehensive Ocean-Atmosphere Data Set along the major ship routes in the World Ocean and homogenized. They demonstrate positive trends in significant wave height over the North Pacific with a maximum of 8–10 cm/decade in the northeast Pacific. In the North Atlantic and other basins significant upward changes (up to 14 cm/decade) are observed only for the last 50 years and not for centennial records. Long-term changes in wind wave height are closely associated with the North Atlantic Oscillation in the Atlantic and with North Pacific Oscillation and El-Niño–Southern Oscillation in the Pacific. *INDEX TERMS:* 4560 Oceanography: Physical: Surface waves and tides (1255); 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 1635 Global Change: Oceans (4203). **Citation:** Gulev, S. K., and V. Grigorieva (2004), Last century changes in ocean wind wave height from global visual wave data, *Geophys. Res. Lett.*, *31*, L24302, doi:10.1029/2004GL021040.

1. Introduction

[2] Linear trends in surface wind speed derived from Voluntary Observing Ship (VOS) data (up to 40 cm/s per decade) are not supported by the evidence from pressure gradient data [*Ward*, 1992] and alternative observations [*The WASA Group*, 1998]. The artificial nature of these trends is associated with the changing ratio between the anemometer measurements and Beaufort wind estimates [*Cardone et al.*, 1990; *Lindau et al.*, 1990] and the inaccurate evaluation of the true wind speed from the relative wind speed. Ship recorders and buoys in the northeast Atlantic and northeast Pacific [*Bacon and Carter*, 1991; *Allan and Komar*, 2000; *Gower*, 2002] report an increasing significant wave height (H_s) of 1 to 2 cm/year. This trend is partly supported by model hindcasts [*Sterl et al.*, 1998; *Wang and Swail*, 2001] and satellite data [*Woolf et al.*, 2002]. However, hindcasts are influenced by the inhomogeneity of winds used to force the models. Satellite time series are still too short to depict long-term trends. In this light, the visual VOS wave data [*Worley et al.*, 2005] provide an excellent possibility for the analysis of trends in wave height. Although changes in the coding system have occurred, these data have been less affected by changes in observational practice than marine winds.

2. Data and Their Homogenization

[3] Visual wave data were taken from the ICOADS (International Comprehensive Ocean-Atmosphere Data Set) [*Worley et al.*, 2005], covering the period 1784–2002. Details of the pre-processing are given by *Gulev et al.* [2003]. Global data coverage is provided for the period starting from 1950. During earlier decades, wave data are available only for the major ship routes, which have been classified into 63 regions that have adequate sampling. For these regions we derived monthly time series for the analysis of secular trends. Visual data provide separate estimates of the wind sea and swell only for the period after 1950. In the decades prior to 1950, officers reported the highest wave component. Thus, during 1950–2002 H_s was estimated by taking the maximum of sea and swell. The classical definition of H_s is the square root of the sum of

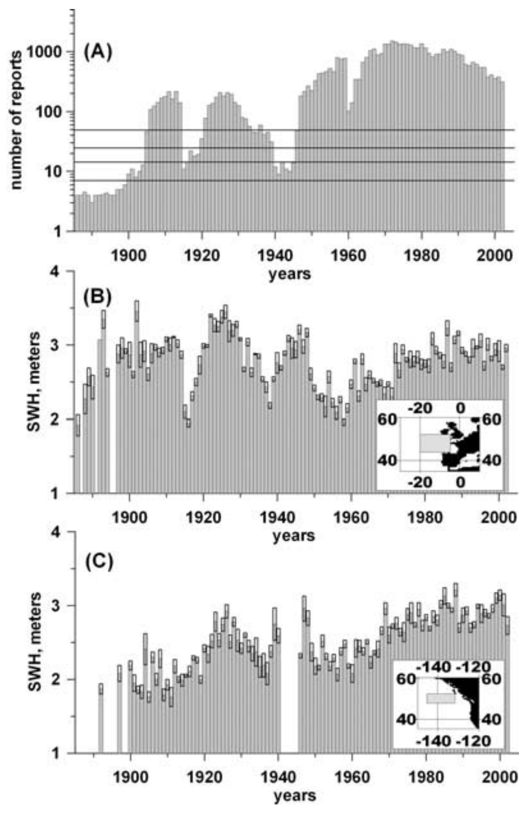

Figure 1. Number of samples per calendar month averaged over all regions (a). Horizontal lines correspond to the limits of 7, 15, 25, 50 reports. Time series of annual mean SWH for the regions in the Northwest Atlantic (44N–52N, 6E–20E) (b) and northeast Pacific (48N–52N, 132W–146W), (c) derived from the sub-sampled time series for 15 reports per month per box. Error bars in Figures 1b and 1c represent the variation derived from all possible differences between the four time series.

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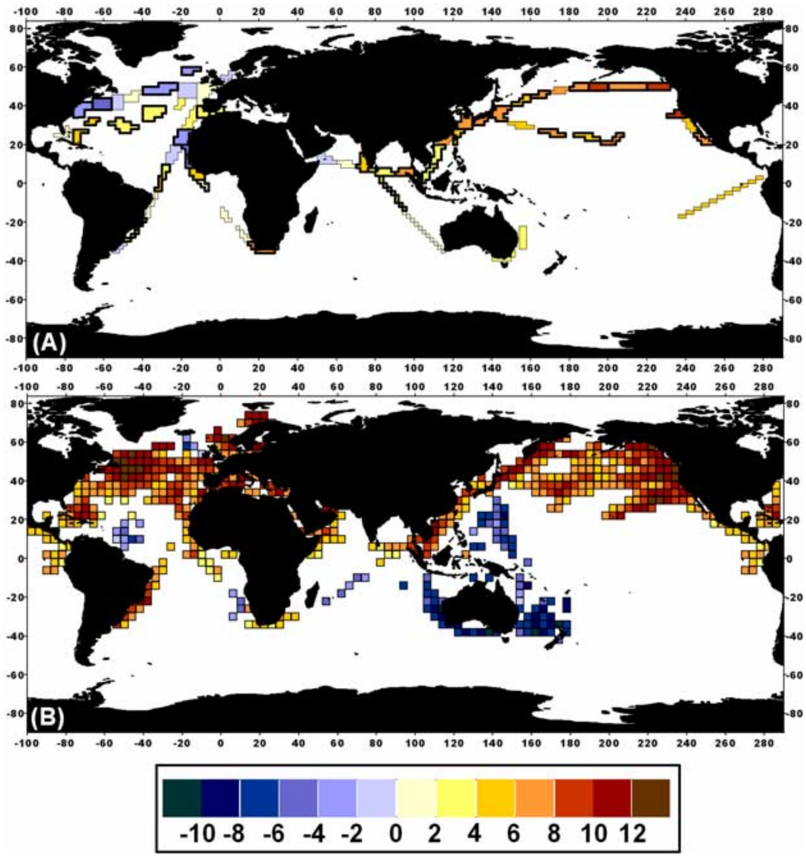

Figure 2. Linear trends in H_s (cm/decade) for the major ship routes for the period 1900–2002 (a) and for the Global Ocean for the period 1950–2002 (b). In Figure 2a regions where trends are significant, are bounded by bold lines. In Figure 2b trends are only shown for the locations, where they are significant.

squares of sea and swell. H_s estimates using different methods are very closely correlated and typically deviate from each other by less than 0.2 m [*Gulev et al.*, 2003].

[4] The number of observations varies from 15–20 per region per month in the late 19th century to several thousands during 1960–2000 (Figure 1a), implying a time-dependent sampling error. In order to homogenize the time series, each monthly mean H_s for the period 1900–2002 was computed from sub-sets of randomly sampled 7, 15, 25, 50 observations for every region from all available observations (Figure 1a). This procedure homogenizes the random sampling errors [*Gulev et al.*, 2003], although the resulting time series may still be influenced by the fair weather bias because ships tend to avoid stormy conditions. Time series for different sampling densities are highly correlated with a correlation being higher than 0.9. All H_s time series presented use a sub-sampling of 15 reports per month.

3. Results

[5] The annual mean H_s visual time series in the northeastern Atlantic and northeastern Pacific show a pronounced increase of wave height starting from 1950 (Figures 1b and 1c). However, for the period 1885–2002 there is no secular trend in H_s in the Atlantic. The upward trend in the Pacific for this period, while statistically significant, becomes considerably weaker than for the period 1950–2002. In the Pacific the highest annual H_s during the period from 1900 to 1950 is comparable with that for recent decades. In the Atlantic it is even higher than during the last 5 decades by 10–15 cm.

[6] Figure 2a shows linear trends for the period 1900–2002 obtained from the box-averaged time series. Statistical significance has been estimated according to a Student *t*-test, Wilcoxon test and tested by the *Hayashi* [1982] reliability ratio ($\boldsymbol{H}$) which considers the confidence intervals of the statistical significance. If $|\boldsymbol{H}| \gg 1$, the true value is close to its estimate. When $|\boldsymbol{H}| \leq 1$, confident intervals can be quite high, even if the *t*-test is satisfied. We also required that the trends computed from the sub-sampled time series for 7, 15, 25 and 50 reports must not be different at the 90% significance level. Error bars (Figures 1b and 1c) represent the variation derived from all possible differences between the four time series. They vary within ±0.1 m, implying very close comparability of the sub-sampled time series. Only the trends which are significant at 95% level according to both *t*-test and Wilcoxon test, have $|\boldsymbol{H}| > 3$ and do not differ from each other for the four sampling densities are considered below.

[7] Trends in Figure 2a are significantly positive almost everywhere in the North Pacific, with a maximum of 8–10 cm/decade (up to 0.5% per year). Centennial time series show weak statistically significant negative trends along the North Atlantic storm track (−5.2 cm/decade or 0.25% per year in the western Atlantic). Weak, but statistically signif-

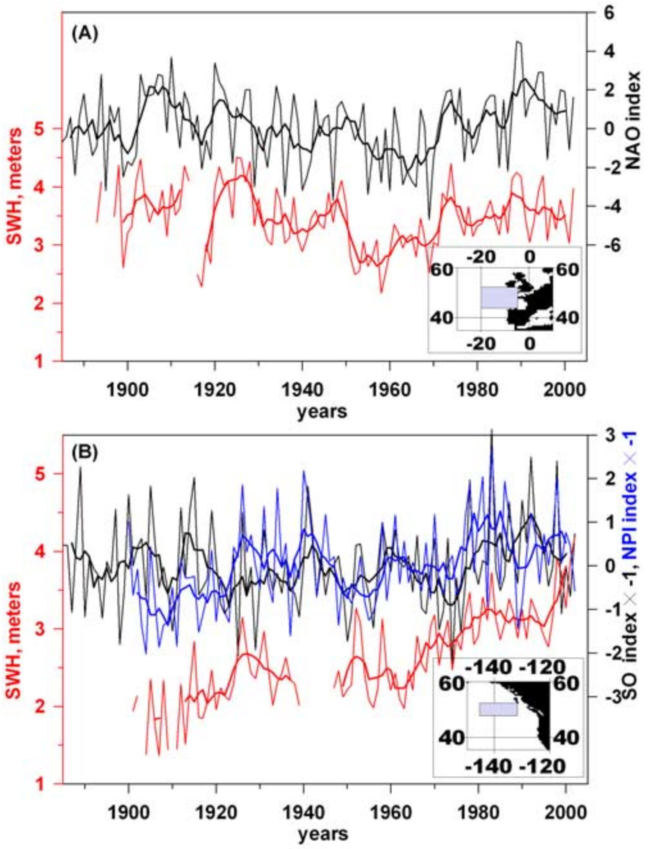

Figure 3. (a) Winter (JFM) time series of SWH in the northeast Atlantic (44N–52N, 6E–20E) (red) together with the NAO index (black). (b) Winter (JFM) time series of SWH in the northeast Pacific (48N–52N, 132W–146W) (red) together with the Southern Oscillation index (black) and the NPI anomaly normalized by standard deviation (blue), multiplied by −1. Bold lines show SWH, NAO, NPI and SO indices, smoothed with a 5-yr running mean.

icant positive trends of 4.6 cm/decade (0.3% per year) are observed off Gibraltar. Statistically significant positive trends are found in the Bay of Bengal and South China Sea (0.34–0.39% per year), as well as the region off the South African coast (0.32% per year).

[8] Linear trends for the period 1958–2002 were obtained for all 4-degree boxes with sufficient data coverage. They are significantly positive over most of the midlatitudinal North Atlantic and North Pacific, as well as the western subtropical South Atlantic, the eastern equatorial Indian Ocean and the East China and South China Seas (Figure 2b). The largest upward trends of 14 cm/decade in the northeast Pacific qualitatively agree with the 25-year buoy records of *Allan and Komar* [2000]. For the buoy off Southern California *Allan and Komar* [2000] found a downward trend in maximum H_s during 1983–1999. Our data for this region show no significant changes during 1983–99. For the Ocean Weather Station L, *Bacon and Carter* [1991] reported annual H_s increasing by 1% a year during 1976–1988. Our data show here downward trends over the entire 45-yr period, but upward changes for 1976–1988 of about 0.6% a year. Statistically significant negative trends are observed in the western Pacific tropics, the eastern Indian Ocean, in the Tasman Sea, and in the south Indian Ocean (11 cm/decade).

[9] Changes in the annual mean H_s are largely determined by winter variability. Correlation coefficients (r) of winter H_s with annual values are 0.81 in the Atlantic and 0.75 in the Pacific. Winter storminess in the North Atlantic is driven by the strength of westerlies that can be deduced from the North Atlantic Oscillation (NAO) index [*Hurrell*, 1995]. Instrumental [*Bacon and Carter*, 1993], visually observed [*Gulev and Hasse*, 1999], model [*Wang and Swail*, 2001] and altimeter [*Woolf et al.*, 2002] time series of H_s show a close correlation with the NAO index on interannual time scale. Correlation of centennial winter (JFM) time series of visual H_s in the northeast Atlantic with the NAO index gives r = 0.64 (Figure 3a). The maxima of H_s in the first part of the 20th century were associated with the high NAO indices, comparable with H_s during the mid-1970s and early 1990s. Neither H_s nor NAO index show any significant secular trend during the last century.

[10] The strength of the northeast Pacific westerlies can be characterized by the North Pacific Index (NPI) [*Trenberth and Hurrell*, 1994]. Correlation of winter H_s in the northeast Pacific with the normalized NPI anomaly gives $r = -0.61$ for the last 100 years (Figure 3b). The intensity of the extratropical circulation in the Pacific can be influenced by the Southern Oscillation (SO) [*Ropelewski and Jones*, 1987] through the mechanism of the ''atmospheric bridge'' [*Alexander et al.*, 2002]. Winter H_s in the northeast Pacific shows statistically significant negative correlation with the South Oscillation Index (SOI) of −0.43 (Figure 3b). Severe wave conditions in the northeast Pacific were associated with most of the strong ENSO events during the last century.

4. Discussion

[11] Our trends in the annual mean H_s are smaller than those reported by *Gower* [2002] for the northeast Pacific buoys (0.012 to 0.027 m/yr) and *Allan and Komar* [2000] who reported trends of 0.042 m/yr and 0.031 m/yr respectively for the Washington and Oregon buoys for winter months (October–March) during 1978–1999. The trends in VOS H_s are smaller and give 0.029 m/yr for the 4-degree box that includes Washington buoy and 0.021 m/yr for the 4-degree box, including the Oregon buoy. These differences can be attributed to the box spatial averaging and sampling differences in VOS and buoy observations.

[12] Careful inspection of the VOS wind speed time series is required as they are influenced by historical changes in observational practices. The exclusive use of Beaufort scale winds abates time dependent biases [*Lindau et al.*, 1990]. Alternatively long-term estimates of storminess can be derived from the tide gauge residuals [*Bromirski et al.*, 2003]. Besides using wind speed estimates, observed changes in wind waves can be compared with the number of cyclones. These have been growing during the last 50 years in both North Atlantic and North Pacific [*Gulev et al.*, 2001; *Graham and Diaz*, 2001]. Recently *Weisse et al.* [2004] reported a growing number of independent storms in the northeast Atlantic. However, the reliability of cyclone tracking for the first part of the 20th century is questionable

due to the quality of surface analyses [*The WASA Group*, 1998]. Furthermore cyclone counts rely on complicated mechanism to arrive at changes in wave height. Any comprehensive analysis requires a separate consideration of wind sea and swell data which are only available for the last 40–50 years. Thus, centennial wave height time series can stand as an independent indicator of the intensity of the westerlies over the midlatitudinal oceans.

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