# GLOBAL-SCALE WAVE OBSERVATIONS FROM VOLUNTARY OBSERVING SHIPS: ASSESSMENT OF RELIABILITY AND POTENTIALITIES FOR GLOBAL AND OFF-SHORE REGIONS STUDIES

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## 1. INTRODUCTION

Although during the last two decades modelling and satellite missions became the main sources of the global wave information (e.g. Sterl et al. 1998, Cox and Swail 2001, Cotton and Carter 1994, Young and Holland 1996, Young 1999, others), voluntary observing ship (VOS) data still remain very valuable source of alternative information about ocean wind waves worldwide. Wave observations available from VOS are taken visually by marine officers over many years. Limited collections of visual data were used to derive wave statistics for the use of marine officers and naval engineers (Hogben and Lumb 1967, Hogben et al. 1986) and to produce climate summaries on a global scale, such as the U.S. Navy Marine Climatic Atlas of the World (hereafter MCA) (Naval Oceanography Command Detachment 1981) and for selected basins (Paskausky et al. 1984, Korevaar 1990). Gulev and Hasse (1998) first derived wind waves from the Comprehensive Ocean-Atmosphere Data Set (COADS) (Woodruff et al. 1998) and produced a North Atlantic climatology of the basic wave parameters for the period 1964-1993. This product has been used for the analysis of secular changes in the North Atlantic waves (Gulev and Hasse 1999). Gulev et al. (1998) validated visual estimates of surface waves against altimeter data and WAM hindcast. Despite a general similarity of spatial patterns, they also identified systematic biases, especially for small and high waves.

Pessimism concerning the reliability of the VOS wave data in comparison to the satellite and model products is based on the general concern about their low accuracy, insufficient sampling, and relatively difficult (in comparison to the other parameters) procedures of pre-processing and corrections of biases. However, VOS wave data still have the longest continuity and provide separate estimates of sea and swell parameters, as well as periods, which are hardly available from satellites. Thus, it is very important to quantify the accuracy of these data and to determine quantitatively where and for which purposes they can be used. The aim of this work is to quantitatively assess different uncertainties in VOS wave data by validating a Global climatology of ocean waves based on VOS observations (1958-1997). We will describe the data processing, quantify the accuracy of visual wave data, and intercompare the climatology with alternative wave products in order to determine the extend to which VOS wave data can be used for the description of global wind wave fields.

## 2. DATA

The global climatology of ocean waves is based on the newly updated COADS, which cover the period 1950-1997 (Woodruff et al. 1998). All individual observations are stored in the COADS archive as long marine reports (LMRF6). In contrast to the old TDF-11 format used in former COADS releases, this format already contains decoded wave variables. This implies some differences in the pre-processing of wave data with respect to Gulev and Hasse (1998). For instance, in the earlier releases periods of sea and swell were duplicated is code figures and in seconds, giving the possibility to control suspicious values. In LMRF6 periods are reported in seconds only and there is no way of knowing which estimate has been taken (NCAR 1999). This may particularly affect swell periods, whose codes were changed in 1968, but this change was not accepted simultaneously by all nations and owners of marine carriers, resulting in an overestimation of swell periods for 1969. From the LMRF6 reports we extracted the basic meteorological variables as well as visually observed heights, periods, directions of wind sea and swell. The coding precisions are 0.5 m for heights, 1 sec for periods and 10 deg for the directions.

Global distribution of sampling density for wind wave observations is quite typical for the other basic meteorological variables (e.g., da Silva et al. 1994, Josey et al. 1999). The highest sampling density is associated with the main shipping routes. The most poorly sampled regions are located in the Southern Ocean, where there are boxes having less than 5 observations per month during the 48-year period. According to Gulev and Hasse (1998) the visible presence of wave information in COADS appears in 1963. However, the re-processed COADS (Woodruff et al. 1998) shows a considerable increase of the number of wave data for the earlier years. In comparison to the earlier releases there is a 20 to 40% increase of the number of observations for the period from the 1960s to the 1990s and a nearly doubling in the late 1950s. If we compare the number of wave observations with the other VOS parameters, wave observational density is 10 to 30% higher than that for surface humidity, which is one of the least frequently parameters observed, and just 20% smaller than that for wind speed. Thus, at least from the viewpoint of sampling density, a global analysis of wave parameters from VOS has the same level of uncertainty as for the other basic meteorological variables.

## 3. METHODS OF DATA PRE-PROCESSING AND CORRECTIONS OF BIASES

Visual wave observations available from VOS are influenced by a number of random and systematic uncertainties which arise from the inaccuracy of observational techniques and the coding system. Thus, visual wave estimates have to be carefully pre-processed and validated before further climatological assessments. In order to validate visual estimates against instrumental measurements, which usually report estimates of significant wave height (SWH), SWH has to be derived from sea and swell heights, reported separately in VOS. Traditionally, SWH is derived from estimates of wind sea and swell using the formula of Hogben (1988), which follows from the definition of SWH:

$$SWH = (h_w^2 + h_s^2)^{1/2}, \qquad (1)$$

where $h_w$ and $h_s$ are the wind sea and swell heights respectively. However, comparisons with instrumental measurements (Wilkerson and Earle 1990, Gulev and Hasse 1998) show that it tends to overestimate the observed SWH by several tens of centimeters. Wilkerson and Earle (1990) recommended to use the higher of the two estimates as an alternative estimate of SWH:

$$SWH = max\,[h_w, h_s\,]\cdot \qquad (2)$$

Although this formula does not have a strong theoretical background, it gives the least biased results in the subtropics and in offshore regions. This may be explained by a possible overestimation of sea and swell heights by the observers in the case when sea and swell propagate in considerably different directions. However, an intercomparison with measurements in mid latitudes showed a tendency of (2) to underestimate SWH. Barratt (1991) proposed a combined approach, suggesting to apply (1) when sea and swell are within the same 45° directional sector, and (2) in all other cases. Analysing different directional sectors, Gulev and Hasse (1998, 1999) found that the optimal directional sector is 30°. Thus, the formulation for SWH applied in this study is:

$$SWH = \left\{ \begin{array}{ll} (h_w^2 + h_s^2)^{1/2}, & [dir_{sea}, dir_{swell}] \in 30^\circ sector \\ max[h_w, h_s], & [dir_{sea}, dir_{swell}] \notin 30^\circ sector \end{array} \right\}. \qquad (3)$$

Estimates of climatological differences between different SWH estimates, computed for the period 1958-1997 (not shown), indicate that the largest negative deviations of estimate (3) from (1) as well as the largest positive deviations between (1) and (2) occur in mid latitudes, where the absolute magnitudes of the deviations range from 0.2 to 0.4 m in January. The largest absolute differences for July are observed in the Southern Ocean (from 0.1 to 0.3 m).

A systematic overestimation of small waves in VOS results from the use of the code figure "1" for coding all waves smaller than 0.5 m in COADS. All wave heights coded as "1" in fact range between 0 and 0.5 m, but in the COADS LMR they are decoded as a single height of 0.5 m. We used instrumental data from NDBC buoys to compute 2-dimensional frequency distributions of the wind speed and wave height for small waves (Gulev et al. 2002). For the comparison we selected more than 350 VOS data which reported a wave height of 0.5 m (i.e., were coded as “1”) and were sampled simultaneously with buoy measurements within a radius of 50 km. They are primarily located in the Gulf of Mexico and in the subtropical Atlantic. Analysis of the 2-dimensional probability density distributions of wind speed and wave height from the buoy measurements for the wind speed allowed us to derive a correction procedure. The corrected sea height, reported with the code figure “1”, reads:

$$\boldsymbol{h_s = 0.5 - \exp(-0.658V),} \qquad (4)$$

where $1.2 \leq \boldsymbol{V} \leq 6$ m/s is the wind speed. This formula allows us to correct small sea heights with an accuracy better than 20%.

Separation between sea and swell in VOS observations has been tested according the method of Gulev and Hasse (1999), who computed joint probability distributions of wave height and wind speed for both wind sea and swell and overplotted these distributions by the JONSWAP curves, representing wave height as a function of wind speed and duration (Carter 1982). We computed joint distributions of wave height and wind speed for different regions and excluded all wind seas which were not captured by the JONSWAP curve corresponding to 24 hours duration, and all swells which were captured by the JONSWAP curve of 4 hours. The portion of the omitted reports varies from 0.1 to 3% of the wave reports. Local maxima occurred in the North Atlantic and North Pacific mid latitudes and in the Southern Ocean, where sea and swell directions are close to each other. The retained data were analysed with respect to the wave age, resulting in the elimination of an additional 0.05 to 1.5% of the observations.

Wave periods are known to be systematically underestimated in visual VOS data. One of the reasons for this underestimation is that it is difficult to distinguish periods when sea and swell propagate in the same direction, especially if the observational techniques are not properly applied (Gulev et al. 2002). Another possible reason is an improper computation of the true wave period and direction from the relative estimates (Gulev 1999, Gulev et al. 2001). Following the definition of zero-up-crossing period (Skorosz and Challenor 1987) we estimated the resultant period as the period reported for the higher of the two components (wind sea and swell). *Gulev and Hasse* [1998], fitting the distributions of SWH and dominant periods ($h|p$) for the locations of NDBC buoys and ship recorders in the North Atlantic, developed an empirical method for the correction of *individual* observations of periods. This method was applied to correct sea and swell periods in this study. The corrections range from 0.4 s to 1.5 s with maxima of 0.9 to 1.5 s in subtropical regions. In the mid latitudes of the North Atlantic and North Pacific the corrections are between 0.4 and 0.9 s in winter and 10-20% higher in summer.

## 4. A GLOBAL CLIMATOLOGY OF WAVE PARAMETERS

The pre-processed and corrected individual visual wave observations were used for the production of a wave climatology. Monthly fields of sea and swell heights and periods as well as of SWH, resultant period and characteristics of directional steadiness were computed for the 40-year period 1958 to 1997 on a global 2° by 2° grid, including all marginal and semi-enclosed seas. For 2-degree monthly averaging we applied $4.5\sigma$ limits for the trimming of wave parameters. For the spatial interpolation into unsampled locations we used the modified method of local procedures (Akima 1970) in combination with 2-dimensional Lanczos filtering (Lanczos 1956, Duchon 1979). The whole climatology, including all wave parameters, can be found on our web-site at *http://www.sail.msk.ru/projects/waves/ATLAS_CD/Index.htm*. Here we present only most important features in order to provide background for the further validation.

Figure 1 shows charts of climatological significant wave height for January and July. In January, the highest SWH of 4.2 to 4.5 m is observed in the midlatitudinal North Atlantic. The smallest SWH (less than 1.5 m) is observed in the western Atlantic and western Pacific equatorial regions and in the Indonesian Seas. In July a considerable increase of SWH up to 4-4.5 m is observed in the South Atlantic and South Indian Ocean. The local maximum in the Arabian Sea shows values of 4.5 m. In the South Pacific SWH grows to 3.5-4 m between 35°S and 40°S, but does not indicate a significant increase south of 40S°. The highest January dominant periods (not shown) in the Northern Hemisphere mid latitudes range from 9 to 10 s. In the South Atlantic and South Indian

Ocean the highest January dominant periods are from 7 to 9 s. In July there is an increase of the period values in the South Hemisphere to 9-10 s with local maxima in the Indian Ocean, southeast Atlantic and southwest Pacific.

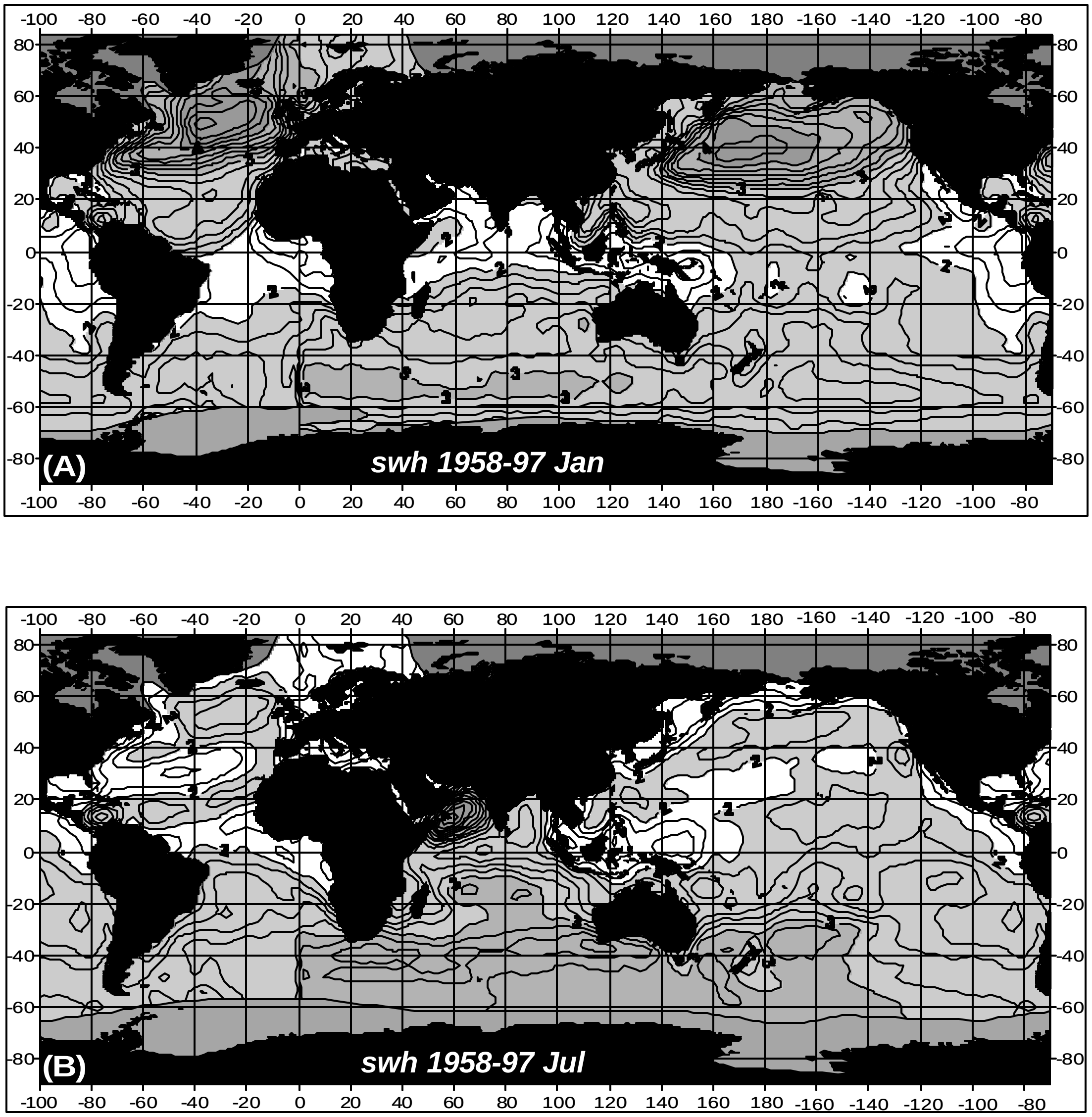


**Figure 1**. Climatological charts of the heights (m) of SWH in January (AC) and July (B).

## 5. VALIDATION OF CLIMATOLOGY AND ESTIMATION OF ERRORS AND UNCERTAINTIES

Random observational errors of wave variables were estimated using the semi-variagram approach (Kent et al. 1999, Lindau 1995). In this method the differences between measurements taken simultaneously on different ships is considered as a function of ship-to-ship distance. It is then extrapolated to zero distance, at which natural variability does not contribute to the total variance. Therefore, the latter should represent only the error variance

$\sigma_b^2$, which has to be divided by two to get the squared measurement error $\varepsilon_m^2 = \sigma_b^2/2$ [*Lindau* 1995]. A polynomial fit is used to extrapolate the error to zero distance.

Figures 2,3 show random observational errors in heights of sea and swell for 20°×20° boxes for the World Ocean for different months of the year. For wind sea observational errors range from 5 to 20% of the mean values and vary from several centimeters to several decimeters. The highest values of 0.8 to 1 m are found in the north and south mid latitudes of the Atlantic and Pacific in winter. For swell height the largest observational errors exceed 1.5 m in the mid latitudes of the South Indian Ocean and South Pacific, where the absolute maximum of 2.06 m is found. The smallest errors of less than 0.5 m are observed in the tropics and equatorial area. For most locations random observational uncertainties of the wind sea periods (not shown) vary from 1 to 2 s (20 to 35% of the mean values). Typical observational errors of the swell periods (not shown) are from 2 to 2.5 s, that is usually less than 30% of the mean values. The largest errors in the swell and dominant periods are observed in the Southern Ocean, where they exceed 3 s. Thus, random observational errors in basic wave variables are usually smaller than 20-30% of the mean values, except for some poorly sampled areas, where the relative error can reach 50%.

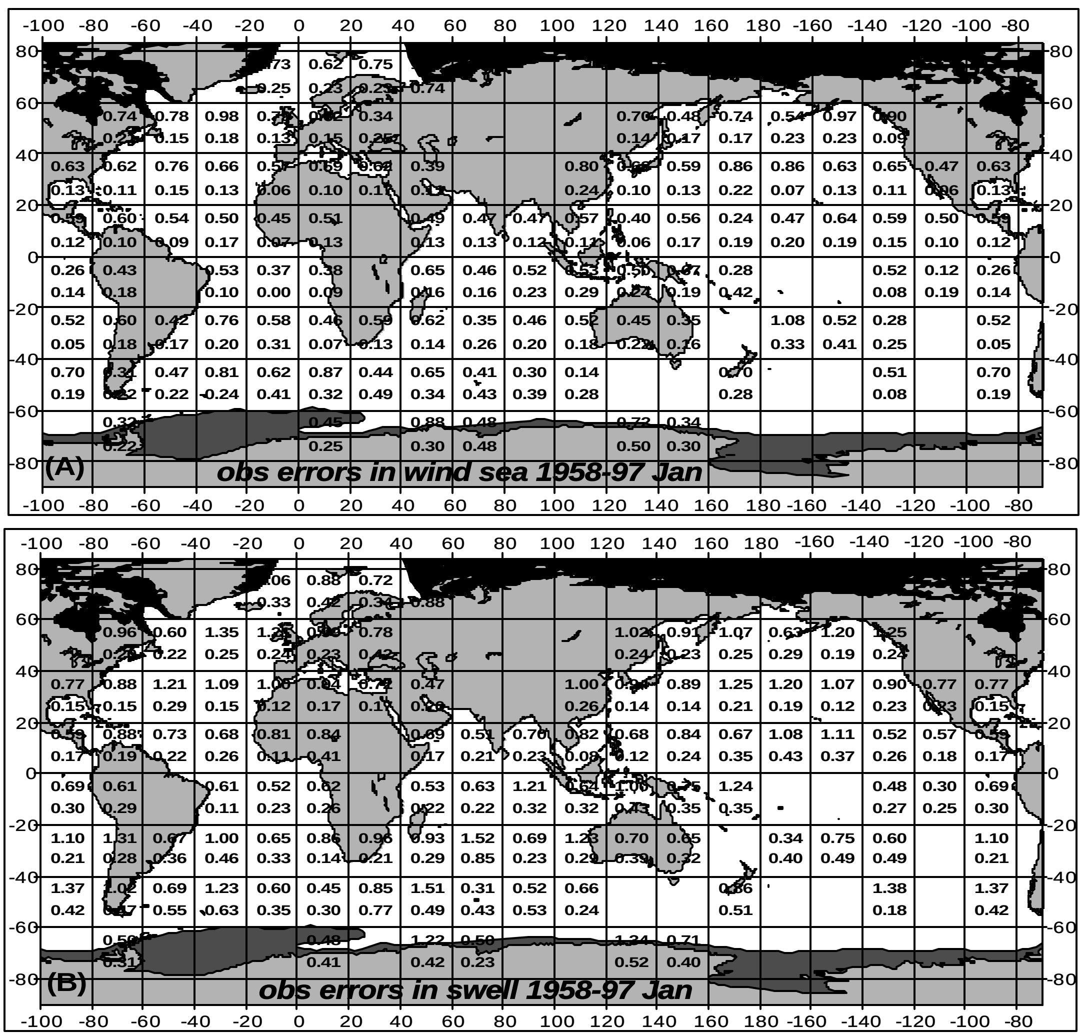


**Figure 2**. Random observational errors (upper numbers) and uncertainties in random observational errors (lower numbers) (m) in wind sea height (A) and swell height (B) in January.

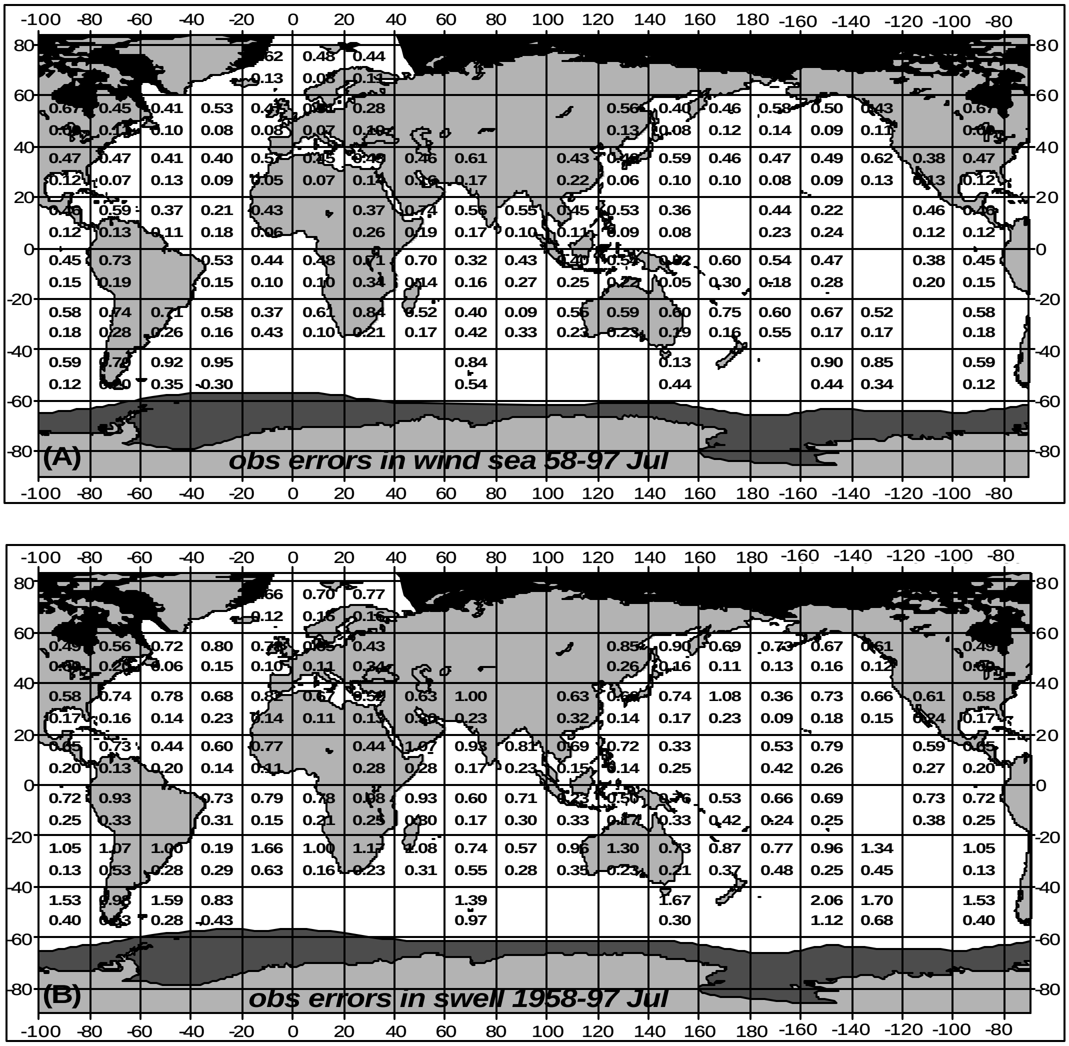


**Figure 3**. Random observational errors (upper numbers) and uncertainties in random observational errors (lower numbers) (m) in wind sea height (A) and swell height (B) in July.

The random observational uncertainties of *monthly means* can be derived from the random observational errors in *individual visual observations*. For normally distributed random errors the overall random uncertainty of a mean of $n$ observations is $n^{1/2}$ times the individual errors (Taylor 1982). We estimated the random observational errors of 2-degree monthly averages of basic wave parameters for January and July (not shown). The smallest random uncertainties in monthly means are observed in well sampled Northern Hemisphere mid latitudes and along the major shipping routes. The largest random observational uncertainties occur in the poorly sampled areas of the Southern Ocean. Thus, in July random uncertainties of monthly means in the Southern Ocean increase to 0.9-1 m for sea and to 1.2 m for swell. Monthly mean sea periods indicate random observational errors from 0.2 s in the mid latitudes of the Northern Hemisphere to more than 2 s during July in the Southern Ocean. For swell periods the largest errors are higher than 2 s. Thus, random observational uncertainties in monthly means are smaller than 10% of the mean monthly values for the areas of good and moderate sampling. However, in poorly sampled regions they can reach 25 to 40% of the mean monthly values.

Traditionally, the accuracy of night-time observations is considered to be lower than those taken during day time. However, it is uncertain whether night time observations tend to underestimate or to overestimate the true sea state. In order to quantify this, we separated all observations into two subsets, corresponding to the presence or absence of day light. The latter was determined using the solar declinations derived from the actual coordinates, the Julian day and UTC time. For different regions the percentage of night time reports varies from a minimum of 30% to a maximum of 60%.

In general, there is no indication that night time estimates have higher observational errors than those taken during day time. For the well sampled regions day time errors are even higher. For instance, random errors in the wind sea height in the northwest Pacific during day time are on average 10 to 20% higher than during night. This can be explained by the observational practice during day time and night time. Assuming that at night time officers less frequently go out of bridge and estimate wave parameters on the basis of wind measurements (*Gulev et al*. 2001), night time estimates may have reasonably less scatter in comparison to those taken during day time. Wave periods (not shown) demonstrate the same relationship between the random errors for day time and night time observations, which differ from each other within a range of 10 to 20%.

For the wave heights day minus night differences show primarily random patterns in all ocean basins for all seasons. For roughly half of the 2-degree boxes, the climatological differences are small, falling within ±0.1 m. Only in July one can observe a systematic overestimation of day time estimates over the night time estimates in the off-shore regions of the east coast of South America and in the Arabian Sea. For wave periods day time estimates are slightly higher in the tropics and subtropics and smaller in the mid latitudes with the highest absolute differences ranging from 1 to 2 seconds. Thus, for wave height there is no systematic difference between day time and night time measurements. For periods night time observations report slightly higher values in mid latitudes and smaller values in the tropics.

## 6. ESTIMATION OF SAMPLING BIASES USING WAM WAVE HINDCAST

In order to estimate sampling biases and their possible impact on our climatology we used a 15-year wave hindcast performed with the WAM model, forced by ERA-15 winds (Sterl et al. 1998). For the comparison with the WAM model we re-processed the climatology for the period of the WAM hindcast (1979-1993). COADS provides between zero and several thousand of samples per month in a $2^{\circ}$x$2^{\circ}$ box, while the WAM always gives 120 samples for a 30-day month. In order to quantify sampling biases, we simulated a VOS-like sampling of the WAM data. The WAM individual data were interpolated in space and time onto the VOS reports. If several VOS reports were available for the same time, the corresponding WAM wave parameters were repeated. Figure 4 shows differences between the regularly sampled and "undersampled" WAM climatology of SWH for January and July 1993, giving an estimate of biases associated with inadequate sampling. The largest differences between the "undersampled" and original WAM wave fields occur in the Southern Ocean, where the VOS sampling density is poor. Thus, SWH shows pronounced negative differences of 1.2 in the Southern Ocean and in the subpolar North Atlantic. July differences between the regularly sampled and "undersampled" WAM wave height show a remarkable underestimation of the VOS-like sampled SWH in the Southern Ocean with the largest differences of 0.8-1.3.

Figure 4 results from two effects of sampling on wind wave climatology. On one hand, it accounts for the random sampling error, which is associated with the actual number of samples used to derive the monthly mean. This so-called representativeness error has a *random* nature. On the other hand, this effect includes the *fair weather bias*, which is *not random*, and in general acts to decrease the wave heights, because ships tend to avoid stormy conditions. We also simulated VOS-like sampling density in WAM, using a random generator. For each month and $2^{\circ}\times2^{\circ}$ box we randomly choose $n$ model results, $n$ being the number of VOS observations for that box and month. This process was repeated 20 times, yielding 20 estimates of differences $\delta_i$, $i$=1,…20, between monthly means from the full and the VOS-like *randomly* sampled WAM, respectively. The value $\langle d_i^2 \rangle^{1/2}$, $\langle\rangle$ being the averaging operator, gives an estimate of the monthly random sampling error. The random sampling errors for SWH, are smaller than those for wind sea. This results from swell having smaller short period synoptic and subsynoptic variability than does wind sea. In other words, adequate monthly averaging requires a smaller number of samples than it does for sea.

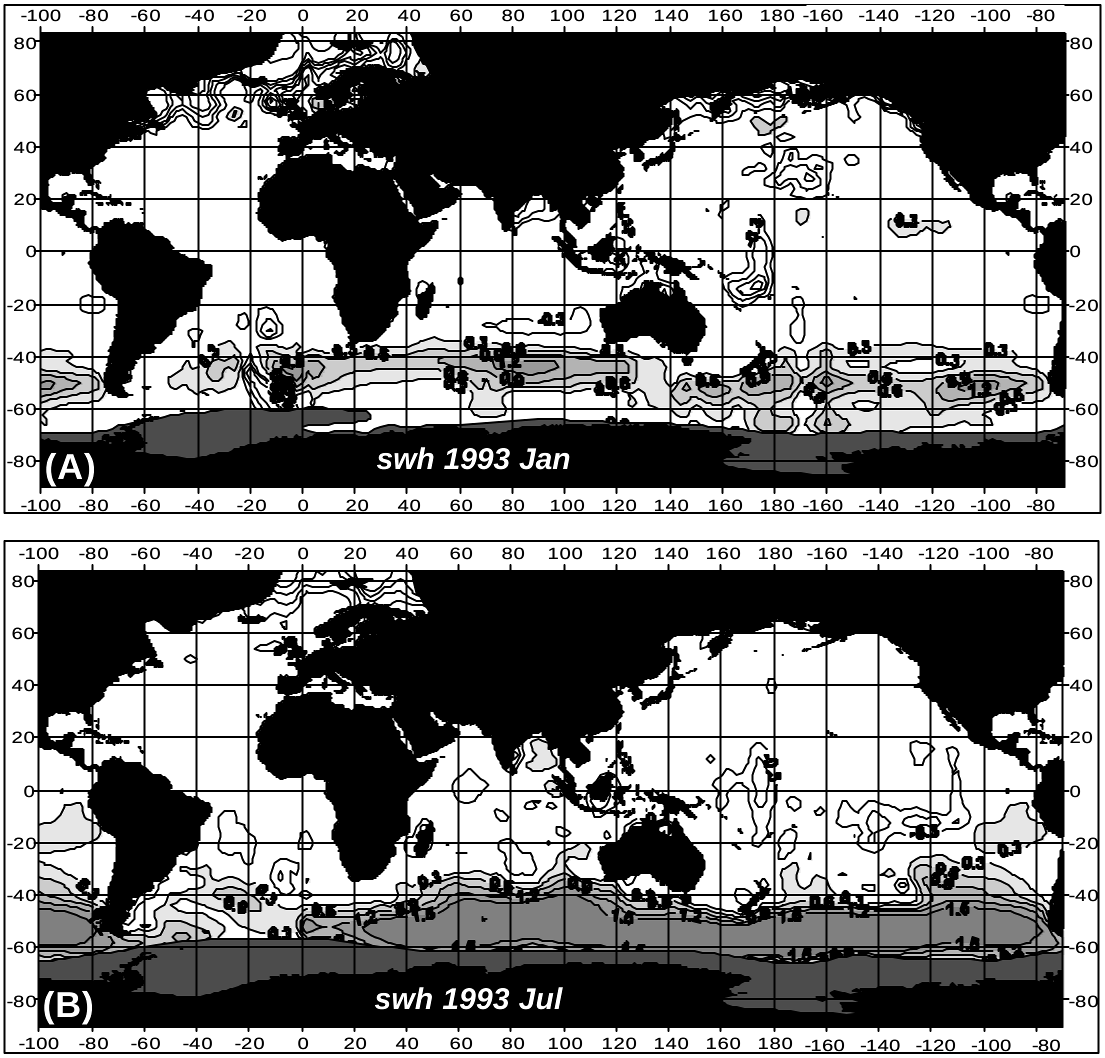


**Figure 4**. Differences (m) between original and VOS-like sampled WAM SWH in January 1993 (A) and July 1993 (B).

7. COMPARISON OF VOS CLIMATOLOGY WITH SATELLITE DATA

Cotton and Carter (1994) calibrated the data from three *Ku*-band altimeters on GEOSAT, TOPEX/POSEIDON and ERS-1 against NDBC buoys and produced a global (from 72°N to 63°S) climatology of SWH, that now spans a period of more than fifteen years, beginning in 1985 with some gaps in 1989-1990. This product considerably less suffers from the sampling problems than the VOS data. Sampling is much higher than for VOS data, and the measurements are independent of other data sources. They may, however, be influenced by the uncertainties in the retrieval algorithms used. In order to intercompare our climatology with this product, we re-processed the fields of SWH for the period 1985-1997, excluding the months which were not provided with altimeter data in 1989-1990. In general, altimeter SWHs are higher than those from VOS in areas of high waves and smaller in areas of low to moderate waves. In January altimeter SWH, is higher in the eastern subpolar and midlatitudinal North Atlantic and North Pacific and over the most of the Southern Ocean. Positive differences (VOS SWH is higher) are observed over most of the Northern Hemisphere in July and in the south tropics and subtropics in January. The magnitude of differences ranges within ±1 m for most regions. In the Southern Ocean the comparison should be considered with caution, because of the sampling uncertainty in the VOS data. As also the altimeter data contain sampling errors, it is difficult to estimate the sampling uncertainty in the VOS data with respect to the sampling provided by satellite altimeters in the same manner as we did for the model data. However, we can safely assume that in the Southern Ocean sampling density in satellite data is considerably better than in VOS, so that sampling is largely responsible for the "VOS minus altimeter" differences in this region.

## 8. SUMMARY AND CONCLUSIONS

A global climatology of wave parameters for the period 1958-1997 has been derived from the visual wave data that are present in the COADS collection. A careful quality control has been performed, and known biases, resulting from the coding system and the observational practice, have been removed from the data. The least biased estimate of SWH from separate observations of wind sea and swell appears to be a combined estimate in which the square root of the sum of the squares of seas and swells is used when both are propagating approximately in the same direction, and the higher of the two components is used in all other cases. Random observational uncertainties have been estimated to be within 10-20% of the monthly mean values for most places. This allows to quantitatively discuss the climatology produced at least north of 40°S. Wave heights in our climatology are not influenced by the day-night bias. At the same time, wave periods show an overestimation of day time estimates in the tropics and subtropics and an underestimation in the mid latitudes, especially for the swell periods. Biases associated with inadequate sampling were quantified using WAM data. The highest sampling biases are found in the Southern Ocean, where wave heights are underestimated by 1-1.5 m due to the poor sampling density.

Our climatology represents the state of the art of VOS wave data analysis. In comparison to satellite products, the advantages of the VOS data are their long duration and the presence of independent estimates of sea and swell characteristics. In the mid latitudes and subtropics of the Northern Hemisphere our climatology is in good agreement with model and satellite-derived ones. In many areas of the Southern Ocean, however, our climatological fields are influenced by large random uncertainties and sampling errors, which result in high spatial noise and a general underestimation of wave parameters. This is especially true during the Southern Hemisphere winter, when the number of observations typically decreases by about 20-30%. Estimates of wave periods in the Southern Hemisphere are influenced by the sampling problem to a higher degree than the wave heights. Thus, all results based on VOS wave data for the Southern Ocean should be considered with great caution. This is a general problem of all climatologies of surface parameters and fluxes that are based on VOS observations (e.g., *da Silva et al*. 1994, *Josey et al*. 1999). In addition to the random observational and sampling uncertainties, wave periods suffer from systematic biases, which partly originate from the improper evaluation of the true period from the relative period.

Our climatology of wave parameters can be used for many purposes. It is useful for the assessments of climate variability in surface wave parameters in the Northern Hemisphere. VOS data allow to analyse variability in sea and swell separately and investigate the mechanisms of this variability. We have to note, that sampling biases can also affect patterns of interannual variability, especially for the regions where there were changes in sampling density over time. We are going to use our climatology for the computations of a new generation of wave statistics for the global ocean, that is important for marine carriers, naval architects and insurance companies. The currently used "Global wave statistics" of Hogben et al. (1986) is based on a limited amount of marine observations, and can be considerably improved using the present climatology. Estimates of climatological changes in different wave statistics can be particularly added.

*Acknowledgements*. We greatly appreciate discussions with Eva Bauer of PIK (Potsdam), Bernard Barnier of LEGI (Grenoble), Jean Bidlot of ECMWF (Reading), Roman Bortkovsky of MGO (St. Ptersburg), Vincent Cardone of Ocean Weather Inc. (Cos Cob), David Cotton, Peter Challenor of SOC (Southampton), Fred Dobson of BIO (Darthmouth), Lutz Hasse of IFM (Kiel), Andrew Laing of NIWA (Wellington), Val Swail of Environment Canada (Toronto). Individual COADS reports were made available by courtesy of Steve Worley of NCAR (Boulder) and Scott Woodruff of NOAA CDC (Boulder). We thank them both them for providing long-term reliable feedback in data management. This study is supported by the EU-INTAS grant 01-2206 and by Russian Ministry of Science and Technology under the "World Ocean National Programme".

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