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Assessment of the reliability of wave observations from voluntary observing ships: Insights from the validation of a global wind wave climatology based on voluntary observing ship data

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[1] This paper describes development and validation of a global climatology of basic wave parameters based on the voluntary observing ship (VOS) data from the Comprehensive Ocean-Atmosphere Data Set collection. Climatology covers the period 1958–1997 and presents heights and periods for the wind sea, swell, and significant wave height (SWH) over the global ocean on $2^\circ \times 2^\circ$ spatial resolution. Significant wave height has been derived from separate sea and swell estimates by taking square root of the sum of squares for the seas and swells propagating approximately in the same direction and assuming SWH to be equal to the higher of the two components in all other cases. Special algorithms of corrections were applied to minimize some biases, inherent in visual wave data. Particularly, we corrected overestimation of small seas, corrected underestimation of periods, and analyzed separation between sea and swell. Validation included estimation of random observational errors, observation of sampling errors, and comparison with the alternative wave data. Estimates of random observational errors show that for the majority of locations, observational uncertainties are within 20% of mean values, which allows us to discuss quantitatively the produced climatology. Biases associated with inadequate sampling were quantified using the data from high-resolution WAM hindcast for the period 1979–1993. The highest sampling biases are observed in the South Ocean, where wave height may be underestimated by 1–1.5 m because of poor sampling, primarily associated with a fair weather bias of ship routing and observation. Comparison to the other VOS-based products shows in general higher SWH in our climatology, especially in the midlatitudes. However, comparison with the altimeter data shows that even for well-sampled regions, high waves are still underestimated in VOS, suggesting a ubiquitous fair weather bias. Further ways of improving VOS-based wave climatologies and possible applications are discussed. *INDEX TERMS:* 3384 Meteorology and Atmospheric Dynamics: Waves and tides; 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); *KEYWORDS:* wind waves, climatology, world ocean, observational errors

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1. Introduction

[2] Reliable information about ocean surface waves is very important for many scientific and practical needs. First of all, waves may serve as effective indicators of climate changes in winds, in particular associated with the North Atlantic Oscillation (NAO) [*Bacon and Carter*, 1991, 1993; *Kushnir et al.*, 1997; *The WASA Group*, 1998; *Gulev and Hasse*, 1999; *Wang and Swail*, 2001; *Allan and Komar*, 2000]. Second, waves can strongly affect the transfer of momentum and heat at the sea surface [*Donelan et al.*, 1993; *Janssen*, 1989, 1991; *Janssen et al.*, 1987; *Geernaert*, 1990; *Smith*, 1991; *Smith et al.*, 1992; *Bourassa et al.*, 1999; *Taylor and Yelland*, 2001], that should be accounted for in parameterizations of the atmospheric and oceanic

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boundary layers. Thirdly, accurate knowledge of wind waves is crucially important for ocean forecasting and nowcasting, operations of marine carriers and naval architecture.

[3] Nowadays, modelling and satellite missions are the main sources of global wave information. Model wave hindcasts performed with Wave Model (WAM) [*Komen et al.*, 1994] and similar models [e.g., *U.S. Navy*, 1983; *Sterl et al.*, 1998; *Bauer and Staabs*, 1998; *Cardone et al.*, 1999; *Cox and Swail*, 2001] provide global wave information for periods from several years to several decades. However, in validating model hindcasts, it is difficult to distinguish between the effects of model performance and of winds used as forcing function. Global-scale satellite wave products are currently available from the altimeters of Geosat, TOPEX/Poseidon and the Active Microwave Unit (AMU) in Synthetic Aperture Radar (SAR) mode of ERS-1/2 [*Mognard et al.*, 1983; *Chelton et al.*, 1990; *Tournadre and Ezraty*, 1990; *Campbell et al.*, 1994; *Bruning et al.*, 1994; *Cotton and Carter*, 1994; *Young and Holland*, 1996; *Katsaros*, 1996; *Young*, 1999]. These data span periods ranging from several months to several years. However, the accuracy of remotely sensed wave products strongly depends on the retrieval algorithms used and satellite wave climatologies still have to be intercompared to each other and calibrated against alternative information.

[4] The longest records of in situ wave measurements are available from NDBC (National Data Buoy Center) and JMA (Japan Meteorological Agency) buoys [e.g., *Wilkerson and Earle*, 1990; *Gilhousen*, 1999], some Ocean Weather Stations (OWS) and lightvessels [e.g., *Bacon and Carter*, 1989, 1991]. This information is very valuable for the validation of the model and remotely sensed data, but cannot be used to produce reliable climatological wave fields. It should be mentioned here that buoy data may also suffer from systematic biases and random errors. Thus there is a requirement for alternative global-scale wave information for intercomparison with model and satellite products.

[5] Voluntary observing ships (VOS) provide wave estimates 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* [*Naval Oceanography Command Detachment*, 1981] (hereinafter referred to as MCA) and for selected basins [*Paskausky et al.*, 1984; *Korevaar*, 1990]. Limited subsets of visual wave observations at OWSs for the period 1950–1970 were used to analyze the variability of surface waves [*Walden et al.*, 1970; *Rodewald*, 1972; *Rye*, 1976]. Many works estimated the accuracy of these data and found many sources of errors of both random and systematic nature [*Houmb et al.*, 1978; *Jardine*, 1979; *Dacunha et al.*, 1984; *Laing*, 1985; *Soares*, 1986; *Hogben et al.*, 1983; *Hogben*, 1988; *Wilkerson and Earle*, 1990; *Hogben and Tucker*, 1994]. *Gulev and Hasse* [1998] used wind wave reports 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.

[6] There is a general concern that VOS wave data are less reliable than satellite and model products because of their low accuracy, insufficient sampling, and relatively difficult (in comparison to the other parameters) procedures of preprocessing and bias corrections. However, VOS wave data still have the longest continuity. Moreover, these data provide separate estimates of sea and swell parameters, although the separation is done on a subjective basis by officers. Significant wave height (SWH) is a key parameter for many assessments of wave climate. At the same time, separate estimates of wind sea, associated with the local wind, and swell, which is not dependent on local wind, are also valuable for many purposes. For instance, estimation of the sea state-dependent wind stress requires the knowledge of the parameters of wind sea. Analysis of separate estimates of wind sea and swell can provide a better understanding of the mechanisms of climate variability in the wave fields. Wind sea reflects the variations in the local wind only, while the variability in swell height represents changes in wind forcing magnitude and frequency over a larger domain [e.g., *Hogben*, 1995; *Gulev and Hasse*, 1999]. Finally, VOS wave observations provide periods, which at best can only be inferred indirectly 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 extent to which VOS data can be used for the description of global wind wave fields.

2. Data

[7] The global climatology of ocean waves is based on the newly updated COADS Releases 1a and 1b, which respectively cover the periods 1980–1997 and 1950–1979 [*Woodruff et al.*, 1998]. All individual observations are stored in the COADS archive as long marine reports (LMRF6). 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. 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 preprocessing of wave data with respect to *Gulev and Hasse* [1998]. For instance, in the earlier releases periods of sea and swell were duplicated in code figures and in seconds, giving the possibility to control suspicious values. In LMRF6 periods are reported in seconds only, together with a wind wave period indicator and a swell period indicator, indicating when the periods were known to be converted from code into whole seconds [*National Center for Atmospheric Research* (*NCAR*), 1999]. However,

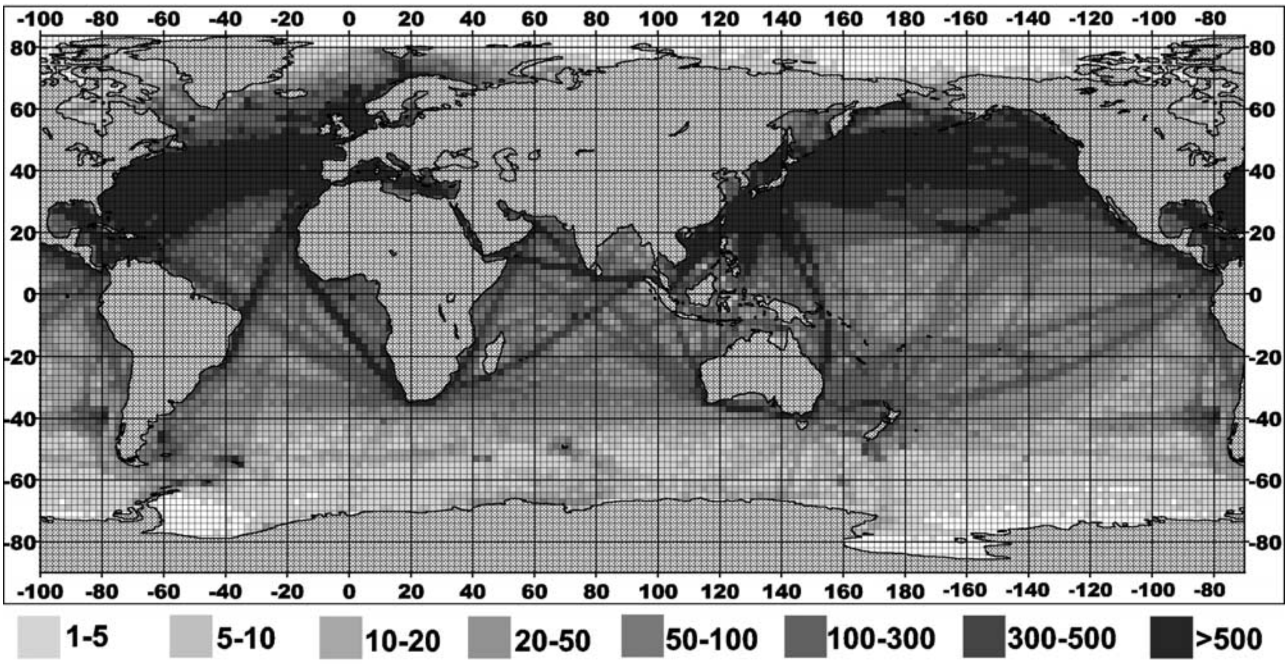

Figure 1. Average number of wave observations per 2° × 2° box per climatological month during the period 1950–1997.

these indicators are available for a small portion of reports only, and mainly for the period prior 1970. One particular problem is the processing of swell periods, the codes of which were changed in 1968. However, this change was not accepted simultaneously by all nations and owners of marine carriers, resulting in an overestimation of swell periods for 1969 and early 1970.

[8] The map of the average number of reports containing wave observations per climatological month per 2° box (Figure 1) represents the typical distribution of VOS observations and is similar to those for 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. *Gulev and Hasse* [1998] reported that wave information in COADS actually started to appear in 1963. However, the reprocessed COADS [*Woodruff et al.*, 1998] shows a considerable increase of the number of wave data for the earlier years (Figure 2). 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. Note here, that the contribution of buoy measurements to the total number of wave reports in COADS grows from 0.1% in mid 1980s to 1.5% in late 1990s. These data were excluded from the analysis and only visual observations were analysed. Relative contributions of different nations to the wave observations are somewhat different from that for the total number of COADS reports as shown by *Woodruff et al.* [1999]. In particular, the contribution of German and Japanese ships to wave observations is only about half that of the total number of observations. Figure 2 shows that at least for wind sea (the most frequently reported parameter) the sampling during the late 1950s and early 1960s is comparable to that for the 1980s and 1990s. From the late 1960s to the late 1970s the number of wind sea reports is twice as large as those containing the other wave variables. However, for the 1980s and early 1990s the number of wind sea reports is higher by only 10 to 20%. During the last four years the number of wind sea reports considerably grows in comparison to the previous years and becomes much higher with respect to the number of reports containing other wave parameters. This increase is much higher than the increase of the total number of reports in COADS for these years, which is primarily due to the contribution of reports from drifting and moored buoys [*Woodruff et al.*, 1999]. Although we do not have a clear explanation of this increase presently, we can hypothesize that it may partly be explained by the fact that for the most recent years the

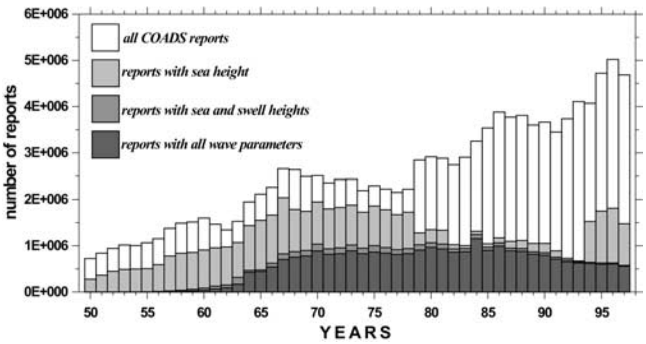

Figure 2. Temporal distribution of the number of VOS reports containing different visually observed wave parameters. The number of "all COADS reports" is given for all platforms available, while the number of reports with wave observations corresponds to visual observations only.

COADS collection is primarily based on Global Telecommunication System (GTS) data, while a considerable amount of wave reports is contributed by log books, which are incorporated into COADS after a lag of several years (S. Worley, personal communication).

[9] The percentage of reports containing wave observations (Figure 2) varies from 30 to more than 80% for the wind sea height and from 10 to 40% for the other wave variables. This is somewhat smaller than the typical values of about 60% reported by *Gulev and Hasse* [1998] for the North Atlantic. However, this relative observational density is 10 to 30% higher than that for surface humidity, which is the least frequently observed parameter, and just 20% smaller than that for wind speed. Thus from the viewpoint of sampling density, a global analysis of wave parameters from VOS has a similar level of uncertainty as for the other basic meteorological variables and fluxes.

3. Developing a Global Climatology of Wind Wave Parameters

3.1. Present Knowledge About the Accuracy of Visual Wave Estimates

[10] Random and systematic uncertainties of visual wave data in the VOS collections arise from the inaccuracy of observational techniques and the coding system. During the past 50 years a number of attempts have been made to assess these uncertainties [e.g., *Brooks and Jasper*, 1957; *Bretschneider*, 1962; *Hogben and Lumb*, 1967; *Quayle*, 1974; *Hoffman and Miles*, 1976; *Jardine*, 1979; *Laing*, 1985; *Soares*, 1986; *Hogben*, 1988; *Wilkerson and Earle*, 1990; *Hogben and Tucker*, 1994; *Gulev and Hasse*, 1998]. However, in most cases only limited subsets of observations were used to quantify the uncertainties. Most validations were carried out at the locations of OWSs, where estimates were taken by either professional or at least well-trained observers. Thus the conclusions about the accuracy of visual observations taken at OWSs may not necessarily be valid for the VOS data in general. Visual observations at OWSs were calibrated against VOS observations onboard of ships passing them [*Hogben and Lumb*, 1967; *Soares*, 1986; *Gulev and Hasse*, 1998]. *Hogben and Lumb* [1967] reported an underestimation of VOS wave height with respect to that reported by OWSs by 5 to 40%. *Soares* [1986] gives smaller biases than *Hogben and Lumb* [1986]. *Gulev and Hasse* [1998] reported an underestimation of climatological means of VOS waves of up to 0.4 m for five of the seven North Atlantic OWSs and in the Newfoundland basin, where SECTIONS data [*Gulev*, 1994, 1999] were used. At OWSs E and M they found a slight overestimation of the VOS waves.

[11] Some qualitative estimates of the accuracy of visual wave observations can be obtained by interviewing the observers. *Houmb et al.* [1978] investigated the effect of the change of meteorological assistants to mates on some Norwegian ships and found that mates tended to underestimate wave height in comparison to the assistants. Recently, *Gulev et al.* [2001] reported the pilot results of the questionnaire SHIPMET [*Gulev*, 1996], distributed among nearly 400 Russian ship officers. SHIPMET shows that only 20 to 50% of respondents strictly follow the observational guidelines. Moreover, many observers tend to use wind information to estimate wave parameters and vice versa. In other words, in the existing observational practice visual wave and wind observations are not fully independent of each other. Some differences in the observational approaches were reported for the day and nighttime [*Gulev et al.*, 2001]. Thus visual wave estimates have to be carefully preprocessed and validated before further climatological assessments.

3.2. General Quality Checks

[12] Visual wave observations used in this study were subject to a number of quality checks. We excluded all swell periods for 1968 and 1969 as they were influenced by the change of the coding system. An initial quality control was based on the COADS quality flags. Then we removed duplicate and wrongly positioned (coordinates with the wrong sign) reports. For instance, a number of observations taken in the subpolar North Atlantic were reported as being from the South Atlantic. Some observations taken in the Baltic Sea in the 1960s and 1970s were translated into the northeast Atlantic because of the wrongly reported sign of longitude. In the latter case SST analysis helps to effectively identify the malpositioned samples, especially during winter. We applied a seasonal ice mask based on the NCEP/NCAR ice cover data, and excluded all wave reports from ice-covered regions. Some quality checks were based on the joint consideration of different wave parameters and basic meteorological variables. All reports indicating nonzero wave heights but zero periods were omitted. Also all cases with a sharp disagreement between wave periods and heights were excluded from the analysis. A further analysis involves wave age and will be presented in Section 3.5.

3.3. Computation of Significant Wave Height

[13] Visual wave observations report sea and swell parameters separately. 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. SWH is defined in terms of spectral moments as SWH = $4\sqrt{m_0}$, where m_0 is the zeroth moment of the spectrum, which is equal to the sea surface variance [e.g., *Srokosz and Challenor*, 1987]. Traditionally, SWH is derived from estimates of wind sea and swell using the formula of *Hogben* [1988], which follows from the definition of SWH:

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

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. *Gulev and Hasse* [1998] reported a mean difference of −0.27 m. An alternative estimate of SWH was established by *Wilkerson and Earle* [1990], who recommended using the higher of the two estimates:

$$SWH = max[h_w, h_s]. \tag{2}$$

Although this formula does not have a strong theoretical background, it gives the least biased results in the subtropics

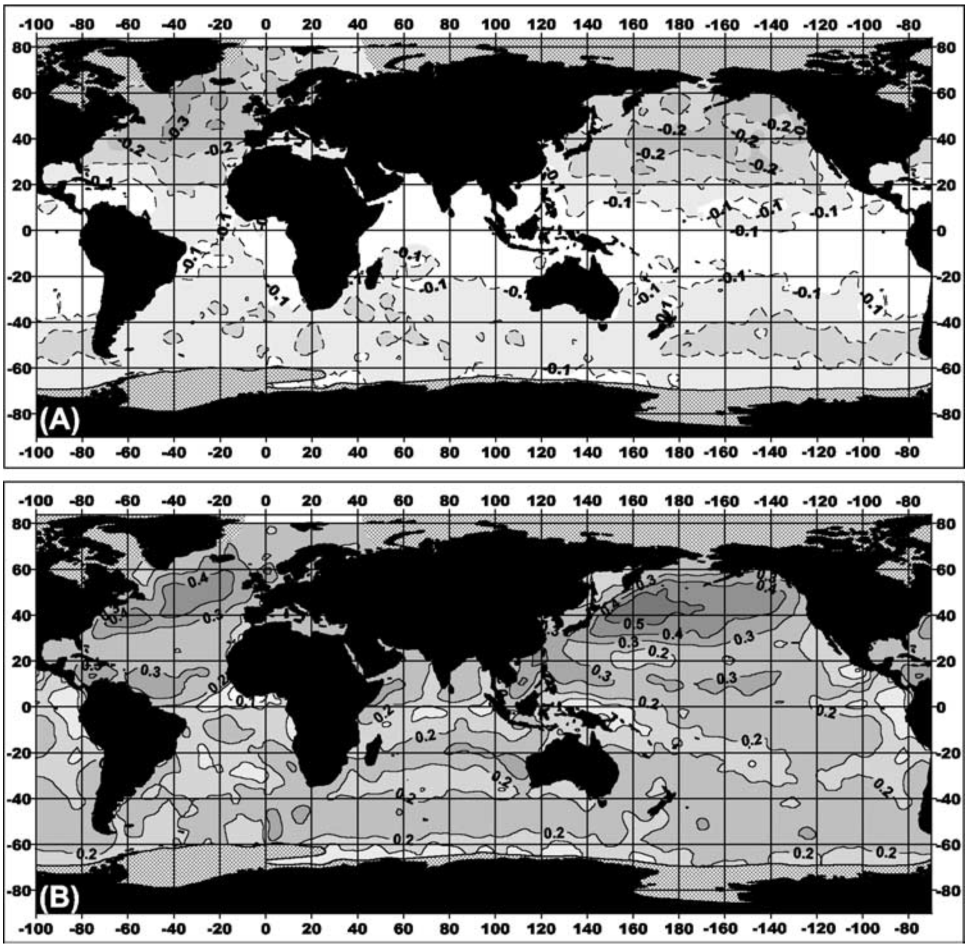

Figure 3. Climatological January difference (m) between SWH estimates from (a) equations (3) and (1) and (b) equations (3) and (2).

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 midlatitudes showed a tendency of equation (2) to underestimate SWH. *Barratt* [1991] proposed a combined approach, suggesting application of equation (1) when sea and swell are within the same 45° directional sector and equation (2) in all other cases. Analyzing different directional sectors, *Gulev and Hasse* [1998, 1999] found that the optimal cut off is 30°. Thus the formulation for SWH applied in this study is:

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

The choice of the algorithm for the computation of SWH may introduce regional biases, especially outside the westerly wind belts. In the tropics sea and swell directions deviate from each other by more than 30° in 50–70% of the cases, while in the midlatitudes they are within a 30° directional sector in 70 to 80% of the cases. Figure 3a shows that the negative climatological winter differences between SWH estimates (3) and (1) range from one centimeter in the tropics to −0.26 m in midlatitudes. At the same time, the largest positive deviations of estimate (3) from equation (2) range from 0.2 to 0.45 m in January and occur in the midlatitudes (Figure 3b). Thus biases between estimate of SWH (equation (3)) used here and traditional estimate of SWH (equation (1)) are smaller than 0.3 m everywhere.

3.4. Correction of Small Wave Heights

[14] Visual estimates of wave height are reported in code figures, corresponding to half meters. According to *World Meteorological Organization* (*WMO*) [1995] the height of waves from 0.25 m to less than 0.75 m should be coded as "01". COADS LMRF6 returns a nominal of 0.5 m for all code figures "01". However, observers in general tend to overestimate small wave heights. Moreover, *Hogben and Lumb* [1967] reported that in practice observers frequently apply code 01 to the wave heights less than 0.25 m, which should be coded "00" according to *WMO* [1995]. This results in a slight systematic overestimation of small waves in VOS. *Hogben and Lumb* [1967] used an estimate of 0.25 m for all wave heights coded as "01". However, this leads to a systematic underestimation of small wave heights. We used instrumental data from NDBC buoys to compute 2-D frequency distributions of the wind speed and wave height for small waves. For the comparison we selected VOS data, which report a wave height code "01" and were sampled simultaneously with buoy measurements within a

radius of 50 km. Since buoys report SWH and not separate sea and swell measurements, we selected cases with no swell in the VOS reports. The VOS-reported wind speed for these cases was corrected following the recommendations of *Josey et al.* [1999]. All visual wind speed estimates were converted from the old WMO1100 scale [*WMO*, 1970] to the *Lindau* [1995] equivalent scale. Then, using the metadata from WMO47 "International list of selected, supplementary and auxiliary ships" [*WMO*, 1973], all anemometer winds were adjusted to neutral stability and 8 m observational height, which is the typical height of the wind speed sensors on buoys. If no information about the actual height of wind speed measurements (call signs of COADS reports do not match WMO47 list) was available, defaults of 20 m were applied. We required that the corrected VOS wind speed estimate should not deviate from the wind speed measured at the buoy by more than 1 m/s. In total, more than 350 pairs of buoy and VOS measurements were chosen, primarily in the Gulf of Mexico and in the subtropical Atlantic. Probability density distributions of the wind speed measured at buoys and reported by VOS (after the correction) were very close to each other. Then we analyzed the 2-D probability density distribution of wind speed and wave height from the buoy measurements for the wind speed range from 1.2 to 6 m/s and wave height returned as 0.5 m in LMRF (Figure 4). Note that the distribution of the wind speed in Figure 4 is affected by the procedure of the selection of pairs, and may deviate from a typical distribution of wind speed. For this range we derived a simple formula, which can be used to correct VOS wave heights. The corrected sea height, reported with the code figure "01", reads:

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

where $1.2 \leq V \leq 6$ m/s is the wind speed. The accuracy of equation (4) has been quantified analyzing rms errors in the used subset of observations and was better than 20%. As by definition swell is not related to the local wind, this procedure cannot be applied to correct small swells. Instead, we applied a correction, subtracting 0.15 m from all swells reported with the code figure "01". The accuracy of this correction, estimated as the standard deviation of the corrected VOS buoy swell difference, is about 30 to 40%.

3.5. Separation of Sea and Swell in Visual Estimates

[15] One possible source of uncertainties in visual wave estimates is a poor separation between sea and swell. This problem appears when well-developed seas are reported as swell and when small swell is reported as sea, and leads to biases in both sea and swell climatologies. We note here, that in general sea and swell as reported by VOS represent to some degree an artificial concept of the wave spectrum. For the northeast Atlantic *Gulev and Hasse* [1999] 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]. This analysis showed that in the northeast Atlantic most of the wind sea observations were bracketed by the JONSWAP curves corresponding to 6 and 18 hours duration. Swell observations, which do not depend on the local wind, showed very large scatter, and only 20% of them were captured by the JONSWAP curves. Taking into account that waves in the northeast Atlantic are spatially correlated with the winds in the central and western Atlantic, *Gulev and Hasse* [1999] concluded that sea and swell are well separated in the COADS marine reports.

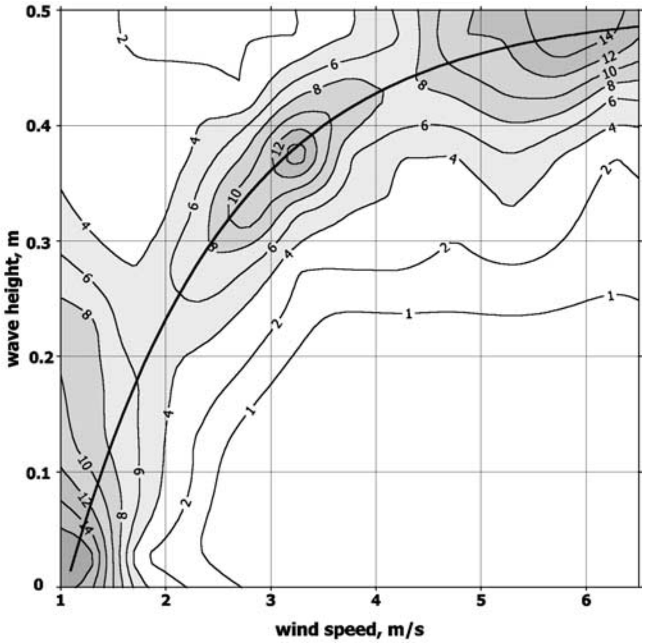

Figure 4. Joint probability distribution of the wind speed and wave height for small seas, coded as "01", where winds ranged from 1.2 to 6 m/s, derived from NDBC buoy measurements.

[16] We computed joint distributions of wave height and wind speed for $20^\circ \times 20^\circ$ regions over the World Ocean and excluded all reports with wind seas which were not captured by the JONSWAP curve corresponding to 24 hours duration. The portion of the omitted reports varies from 0.1 to 3% of the wave reports. Analysis of wave directions shows that 88% of the omitted reports are for cases where swell and sea propagate within the same 60° directional sector, and more than 75% of the omitted reports are for sea and swell propagation within a 30° sector. This agrees with the assumption that the observers tend to poorly separate sea and swell propagating in the close directions. Local maxima occurred in the North Atlantic and North Pacific midlatitudes and in the Southern Ocean, where reported sea and swell directions are often close to each other.

[17] The data retained were analyzed with respect to the wave age, given by [e.g., *Smith*, 1991]:

$$a = C_P / V_{ef}, \tag{5}$$

where C_P is the deep water phase speed at spectral peak, which is derived from the peak wave period p_w as

$$C_P = (g/2\pi)p_w. \tag{6}$$

Here g is the gravitational acceleration, $V_{ef} = V_{10} \cos\theta$ is the component of the wind in the wave direction, θ is the angle between wave and wind directions, V_{10} is the wind speed at 10 m anemometer height and neutral stability. In general, for $a < 1$ waves can be regarded as sea, while for $a > 1$, they should be considered as swell [*Smith et al.*, 1992]. Following *Dobson et al.* [1994], we eliminated wind sea observations for which $a > 1.2$. This check resulted in the elimination of an additional 0.05 to 1.5% of the observations. The highest percentage of totally omitted reports (up to 5%) is observed in the northern midlatitudes and in the Southern Ocean, where sampling density is poor. *Gulev and Hasse* [1998] also analyzed effective wind and eliminated reports for which $|\theta| > 30°$ (less than 5% of reports). However, wind sea direction is no longer part of WMO SHIP code starting from 1968 [*NCAR*, 1999]. In the old TDF-11 format, used by *Gulev and Hasse* [1998], wind direction had been substituted into missing wind sea direction. This practice was discontinued for COADS processing. Thus, to avoid time-dependent biases, we omitted this quality check in our preprocessing.

3.6. Correction of the Wave Periods and Computation of the Dominant Period

[18] Wave periods are known to be systematically underestimated in visual VOS data. To be compared with buoy measurements VOS dominant periods have to be derived from separate estimates of sea and swell periods. Following *Srokosz and Challenor* [1987] we estimated the dominant period as the period reported for the higher of the two components (wind sea and swell). Using data from NDBC buoys, *Wilkerson and Earle* [1990] found a mean underestimation of VOS wave periods of about 0.2 s. One of the reasons for this underestimation is that it is difficult to distinguish periods if sea and swell propagate in the same direction, especially if the observational techniques are not properly applied [*Gulev et al.*, 2001]. Another possible reason is an improper computation of the true wave period and direction from the apparent period. This problem is of the same nature as the evaluation of the true wind from the apparent wind. According to *Gulev* [1999] and *Gulev et al.* [2001] only 27% of marine officers apply this procedure correctly for the wind and about 40% usually do not apply it at all. The situation for wave observations is certainly not better than that for wind observations. Taking into account that under stormy conditions ships tend to be headed into the wind (and waves), omission of the correction will systematically result in an underestimation of the period. More generally, inaccurate evaluation of the true wave period and direction can result in a systematic bias.

[19] *Ochi* [1978] and *Dacunha et al.* [1984] recommended correcting biases in mean VOS wave periods by matching the joint probability distributions of wave heights and periods from VOS and from buoys. *Gulev and Hasse* [1998], fitting the distributions of SWH and dominant periods, p_d, (SWH|p_d) 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. Their relationships between the corrected and uncorrected sea and swell periods involve wind sea height and a number of empirical coefficients, which are different for the cases of sea and swell propagation within and outside of the same directional sector, as well as for $h_w > h_s$ and $h_s > h_w$ and are given by *Gulev and Hasse* [1998]. 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 midlatitudes 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.

3.7. A Global Climatology of Wave Parameters

[20] The preprocessed 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 semienclosed seas. The choice of 2° spatial resolution instead of 1°, used in the global climatologies of basic meteorological variables and sea air fluxes [*da Silva et al.*, 1994; *Josey et al.*, 1999; *Lindau*, 2000], is justified by considerable undersampling, especially in the Southern Ocean. *Kent et al.* [2000] analyzing the impact of interpolation procedures on the SOC climatology, stated that approximately 90% of all gridded monthly values in the SOC climatology effectively have spatial resolution of 3 to 5 degrees, and that the actual resolution is 1 degree for less than 1% of points. Estimates of sampling biases will be given in Section 4.3 below. For 2° monthly averaging we applied 4.5σ limits for the estimation of monthly mean wave parameters. This is more reasonable than the use of 3.5σ limits [*Wolter*, 1997], which considerably underestimate anomalies of different variables for some key regions of the World Ocean. For the spatial interpolation into unsampled locations we used the modified method of local procedures [*Akima*, 1970] in combination with 2-D Lanczos filtering [*Lanczos*, 1956; *Duchon*, 1979]. First, the fields were interpolated on a half-degree grid and then the elliptic Lanczos filter has been applied for 36 directions and the cutoff radius varying from 173 to 485 km. 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.

[21] Figure 5 shows charts of annual mean sea and swell heights and periods. Significant wave height and dominant period for January and July are shown in Figure 6. The highest seas and swells of respectively 1.5–2 m and 3–3.5 m are found in the mid latitudinal regions of both hemispheres. The spatial patterns of climatological swell height in the midlatitudes of the Northern Hemisphere are slightly shifted eastward with respect to those of wind sea. Winter maxima (not shown) exceed 2.5–3 m for wind sea and 4 m for swell. The seasonal cycle in swell height is less pronounced in the Southern Ocean than it is in the Northern Hemisphere. The longest climatological periods are observed in the westerly wind belts, varying from 4 to 4.5 sec for wind sea and from 8 to 8.5 sec for swell. In winter the longest periods in midlatitudes (not shown) exceed 5–6 s for the wind sea and 9 s for swell. In January, the highest SWH (Figures 6a) of 4.5 m is observed in the midlatitudinal North Atlantic. In July (Figure 6b) SWH has

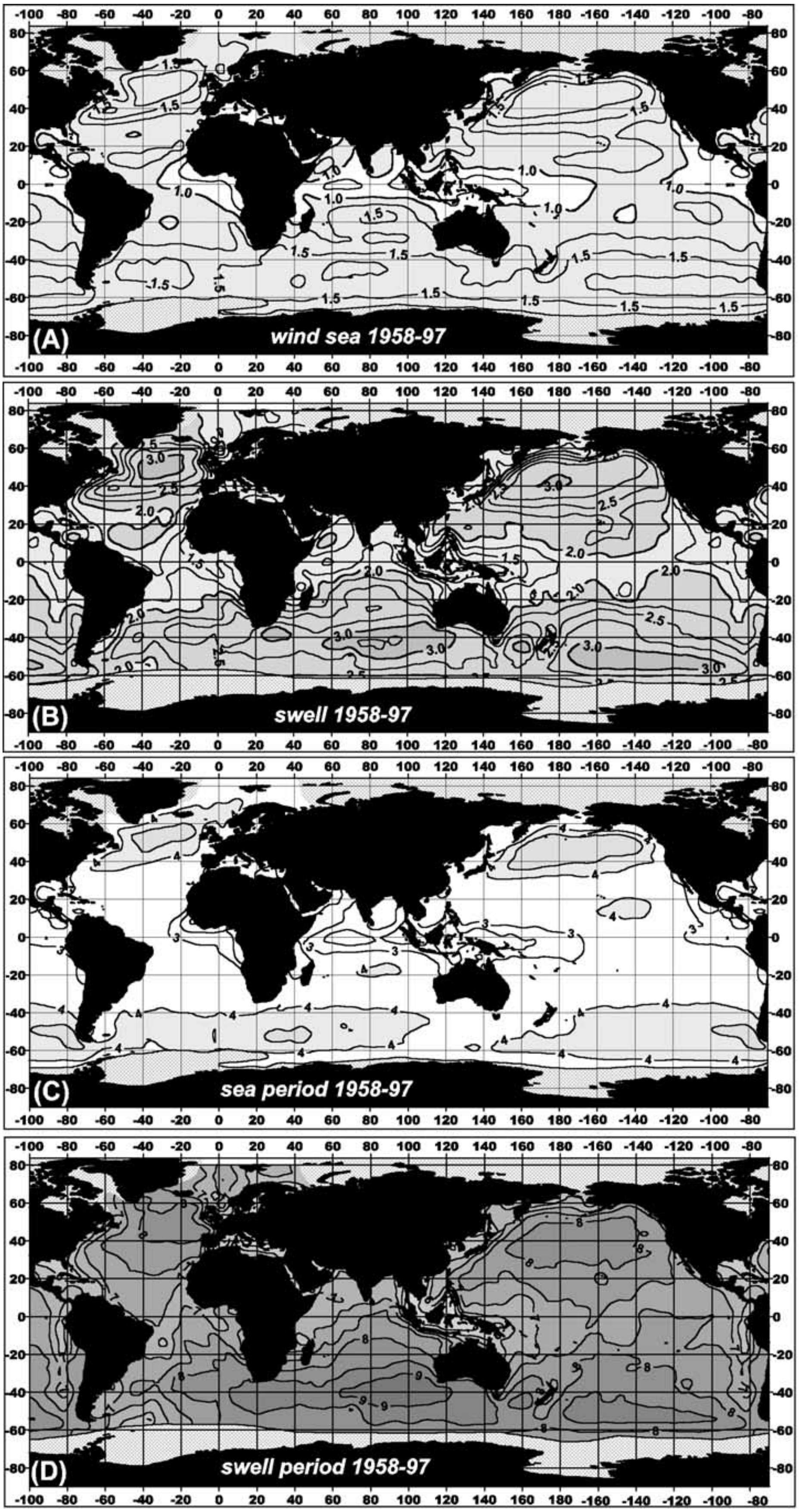

Figure 5. Climatological annual charts of the (a) wind sea and (b) swell heights (m), as well of the (c) wind sea and (d) swell periods (s). Ice-covered regions are hatched.

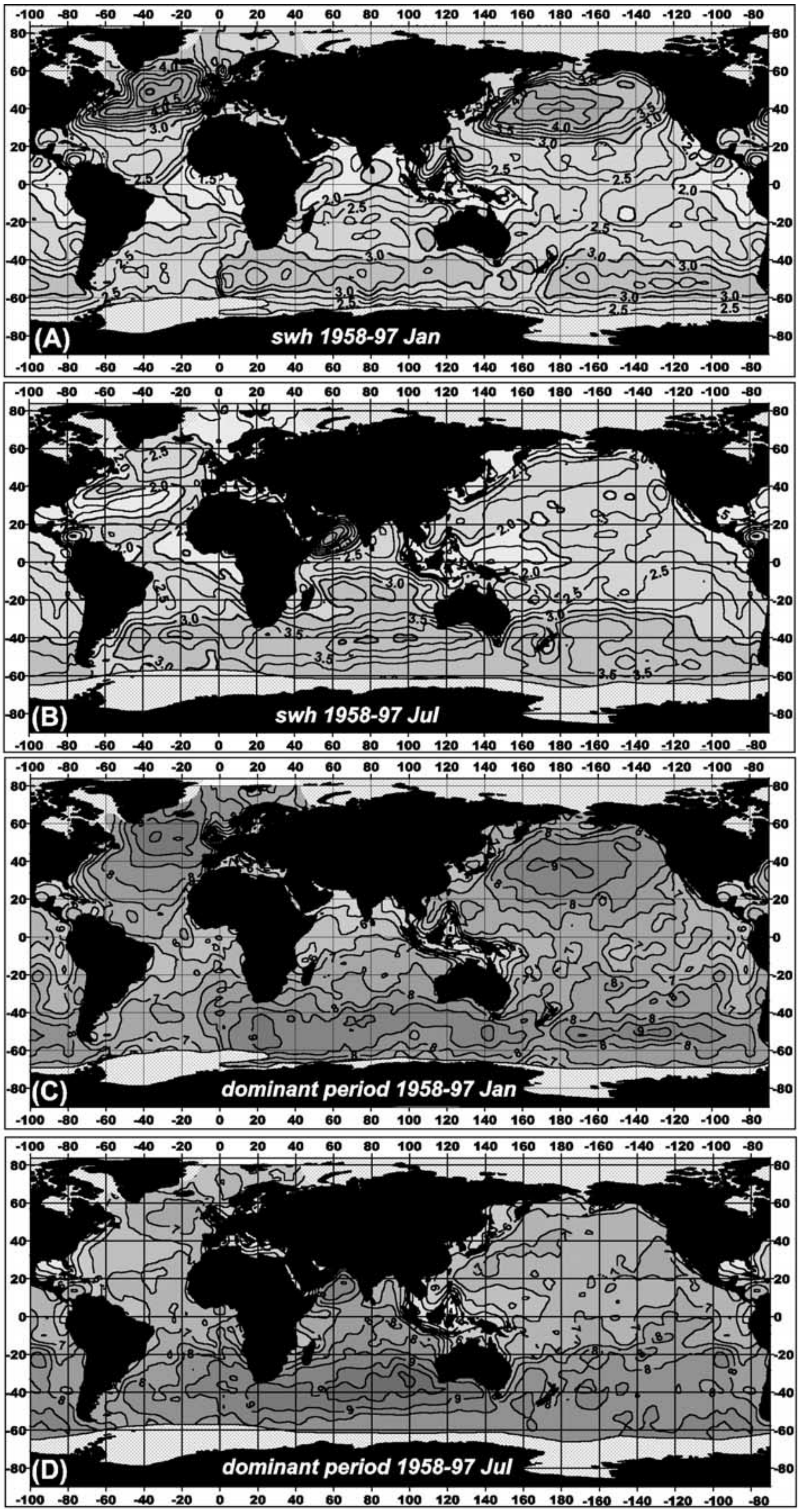

Figure 6. Climatological charts of (a) and (b) SWH (m) and (c) and (d) dominant periods (s) in January (Figures 6a and 6c) and July (Figures 6b and 6d). Ice-covered regions are hatched.

Table 1. Systematic and Random "Buoys Minus Ship" Biases in SWH (meters) and Dominant Period (Seconds) Estimated for January and July at NDBC Buoys (41001–46027), JMA buoys (21002–22001), NDBC Coastal Marine Automated Network Platform (CHLV2), Seven Stones Light Vessel (SSLV), and OWS L

		January					July				
			Systematic Bias		Random Bias			Systematic Bias		Random Bias	
Buoys	Latitude, Longitude	Number of Pairs	SWH	Period	SWH	Period	Number of Pairs	SWH	Period	SWH	Period
				Atlantic NDBC Buoys							
41001	34.7°N, 72.7°W	412	−0.19	−0.16	0.75	1.22	394	−.54	0.27	0.44	1.35
41002	32.3°N, 75.2°W	285	−0.26	−0.04	0.80	1.98	328	−0.38	0.36	0.35	0.97
41006	29.3°N, 77.4°W	161	−0.17	0.04	0.52	1.84	263	−0.08	−0.12	0.23	1.14
41010	28.9°N, 78.5°W	368	0.12	0.14	0.38	2.14	429	0.23	−0.24	0.43	1.76
42001	25.9°N, 89.7°W	553	0.07	−0.35	0.41	2.32	441	0.29	−0.14	0.22	2.12
42003	25.9°N, 85.9°W	421	−0.45	−0.39	0.56	1.36	394	−0.59	0.48	0.79	1.53
				JMA Buoys							
21002	37.9°N, 134.5°W	398	0.44	0.29	0.67	1.04	691	0.39	0.17	0.54	1.03
21004	29.0°N, 135.0°W	701	−0.12	−0.38	0.32	0.79	498	0.22	−0.09	0.560	0.794
22001	28.2°N, 126.3°W	425	−0.24	0.11	0.57	0.84	513	−0.31	−0.43	0.40	1.22
				Pacific NDBC Buoys							
46001	56.2°N, 148.2°W	336	0.22	0.13	0.31	1.83	311	0.26	0.19	0.42	1.43
46002	42.4°N, 130.3°W	239	−0.16	−0.31	0.29	2.47	198	0.27	−0.33	0.39	1.84
46003	51.9°N, 155.5°W	311	0.22	0.18	0.69	2.34	267	0.11	0.38	0.87	1.91
46005	46.2°N, 131.3°W	678	0.07	0.20	1.00	2.97	521	−0.21	0.22	0.39	1.64
46006	40.5°N, 137.4°W	653	−0.03	0.44	0.41	2.08	502	−0.35	0.37	0.47	2.23
46010	46.3°N, 124.7°W	234	−0.14	−0.45	0.52	1.86	336	−0.35	−0.10	0.31	2.02
46011	35.0°N, 121.2°W	330	−0.17	0.51	0.26	2.58	486	−0.98	0.16	1.43	2.87
46012	37.2°N, 122.9°W	193	0.21	0.19	0.46	2.38	298	−0.56	0.53	1.09	3.14
46013	38.1°N, 123.2°W	389	0.09	−0.34	0.66	2.61	586	−0.45	−0.14	0.72	1.56
46014	39.0°N, 123.9°W	602	0.03	0.63	0.74	1.79	646	−0.71	−0.14	1.03	1.38
46022	41.2°N, 124.6°W	213	0.05	0.27	0.97	2.52	310	−0.51	0.35	0.88	2.35
46023	34.2°N, 121.8°W	310	0.54	1.51	0.75	2.14	528	−0.72	−0.08	1.12	2.91
46024	32.8°N, 119.2°W	178	0.80	1.92	0.71	2.35	371	0.15	1.66	0.32	1.84
46025	33.8°N, 119.0°W	730	−0.02	1.49	0.40	1.87	576	−0.34	1.45	0.43	1.26
46026	37.5°N, 127.7°W	240	−0.21	1.39	0.72	1.73	330	−0.79	0.41	0.87	1.44
46027	41.0°N, 124.6°W	147	−0.15	0.33	1.08	1.44	275	−0.46	0.37	0.77	1.79
				Other							
CHLV2	36.9°N, 75.9°W	572	−0.53	1.45	0.71	1.36	647	−0.44	1.90	0.33	1.58
SSLV	50.0°N, 06.0°W	837	−0.09	0.26	0.79	1.52	911	0.03	0.34	0.28	1.21
OWS L	57.0°N, 20.0°W	521	−0.11	0.31	0.47	1.38	603	0.14	0.22	0.37	1.46

pronounced maxima in the Southern Ocean and in the Arabian Sea. The highest January dominant periods in the Northern Hemisphere midlatitudes exceed 9 s (Figure 6c). In July, the longest periods of 8 to 10 s are observed in the Southern Hemisphere.

4. Validation of Climatology and Estimation of Errors and Uncertainties

4.1. Comparison With Buoy Measurements

[22] The results presented have to be considered in the context of the uncertainties inherent in visual wave data. We compared our results with in situ measurements at NDBC and JMA buoys, NDBC Coastal Marine Automated Network platform (CHLV2), OWS L, and Seven Stone light vessel (SSLV) in the North Atlantic and North Pacific. Most NDBC buoys cover a period from the early 1970s onward and report hourly SWH and dominant period. We selected VOS data sampled simultaneously with buoy measurements within 50 km of the buoy location. *Wilkerson and Earle* [1990] used a radius of 100 km, but they found some differences when varying the criterion from 25 to 100 km. Table 1 shows the number of buoy-ship pairs selected for January and July, and estimates of systematic and random biases in SWH and dominant period. The systematic bias was estimated as the mean difference between buoy and VOS observations. Then the systematic bias was removed; that is, both VOS and buoy measurements were adjusted to the same climatological mean, and random uncertainties were estimated as standard deviations of "buoy minus VOS" difference.

[23] In winter, SWH shows systematic differences of both signs ranging from −0.53 to 0.8 m. A smaller buoy SWH is observed in the Atlantic and subtropical Pacific. At the same time, in the midlatitudinal northeast Pacific, buoys show higher SWH than do VOS. In July, SWH measured by buoys is smaller than reported by the VOS data for most of the locations. Considering periods, buoy measurements in comparison to the visual data show deviations of both signs in the Atlantic and primarily longer periods in the Pacific, where the largest observed differences ranges from 1 to 2 seconds s. Random errors in SWH are up to 1 m with an average of about 0.6 m. Random errors for the periods range from 1 to 2.5 sec for most locations. These random errors are a combination of random observational errors in VOS estimates and buoy measurements on one hand, and of the natural spatial variability of wave characteristics within 50 kilometers from the buoy. The latter is not necessarily negligible, especially near the coast. Thus

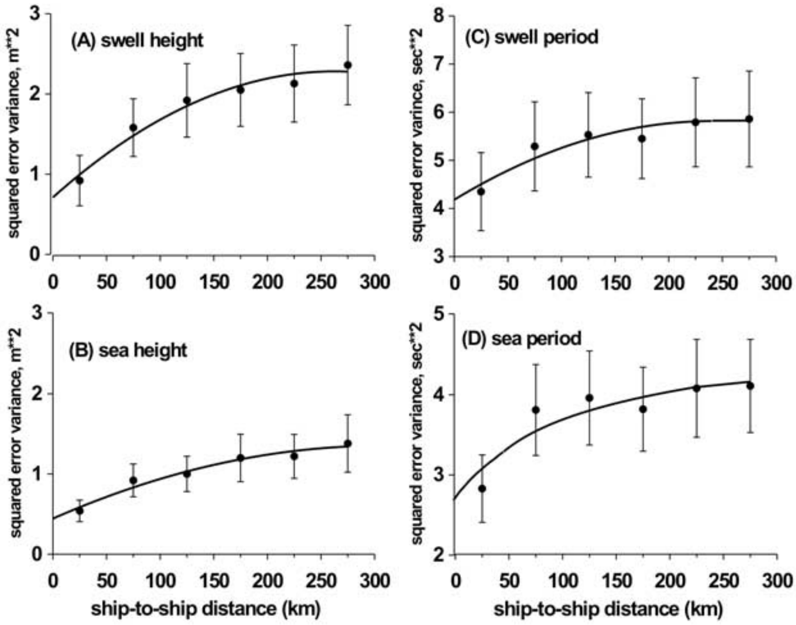

Figure 7. Semivariagrams for (a) swell height, (b) wind sea height, (c) swell period, and (d) wind sea period computed for the region 40°N–60°N, 160°W–180°W in the Pacific. Error bars correspond to the standard deviations of error variances for individual classes.

random observational errors of visual VOS wave data have to be estimated independently.

4.2. Random Observational Errors

[24] In order to estimate random observational errors of wave variables, we used the semivariagram approach. *Kent et al.* [1999] used this technique to estimate random observational errors in basic meteorological variables. In this method the difference between measurements taken simultaneously on different ships is considered as a function of ship-to-ship distance. It is then extrapolated to zero distance, where spatial variability does not contribute to the total variance. Therefore the latter should represent only the error variance σ_o^2, which has to be divided by two to get the squared measurement error $\varepsilon_m^2 = \sigma_o^2/2$ [*Lindau*, 1995]. A polynomial fit is used to extrapolate the error to zero distance. *Kent et al.* [1999] used finite linear functions, however, they had to eliminate some classes of relatively large ship-to-ship distances.

[25] We estimated random observational errors for 20° × 20° boxes for the World Ocean for different months of the year. For most areas the spatial resolution of 20° provides enough pairs for further statistical processing, except for some poorly sampled regions in the Southern Ocean. The analysis was performed for 50-km classes of ship-to-ship distances, *l*, with a maximum of 350 km. Figure 7 shows the dependence of the error variance for different wave parameters on ship-to-ship distance for the region 40°–60°N, 160°–180°W in the Pacific. It shows that the polynomial functions are quite effective for the approximation of the dependencies $\varepsilon_m^2(l)$. Error bars correspond to the standard deviations of error variances for individual classes. Figure 8 shows January and July estimates of random observational errors of wave height. 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 midlatitudes of the Atlantic and Pacific in winter. For swell height the largest observational errors exceed 1.5 m in the midlatitudes of the Southern Indian Ocean and South Pacific, where an 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. Observational errors in SWH (not shown) represent the coupled effect of the uncertainties in the swell and sea height. For most regions they are within 10 to 30% of the mean values. The highest values (1.5–1.8 78m) are observed in the South Pacific.

[26] At most locations, random observational uncertainties of the wind sea periods (Figure 9) vary from 1 to 2 s (20 to 35% of the mean values). Typical observational errors of the swell periods are from 2 to 2.5 s, which is usually less than 30% of the mean values. The largest errors in both swell periods and dominant periods (no figure shown) 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%. Uncertainties in the estimation of random observational errors (Figures 8 and 9) were estimated from the rms errors of polynomial fits for every 20° × 20° box. Uncertainties in random observational errors vary from 10 to 40% of the mean error estimates, which is comparable to the results of *Kent et al.* [1999]. We analyzed the impact of data points at high separations (more than 200 km) on the estimates of uncertainties in observational errors. Elimination of these data results in increase of uncertainties by 5 to 15%. When we compare our error estimates with the random errors for other basic variables computed using a similar technique [*Kent et al.*, 1999], observational errors in wave variables are of the same order of magnitude (relative to the mean values and their seasonal and interannual variability) as for the other parameters. For instance,

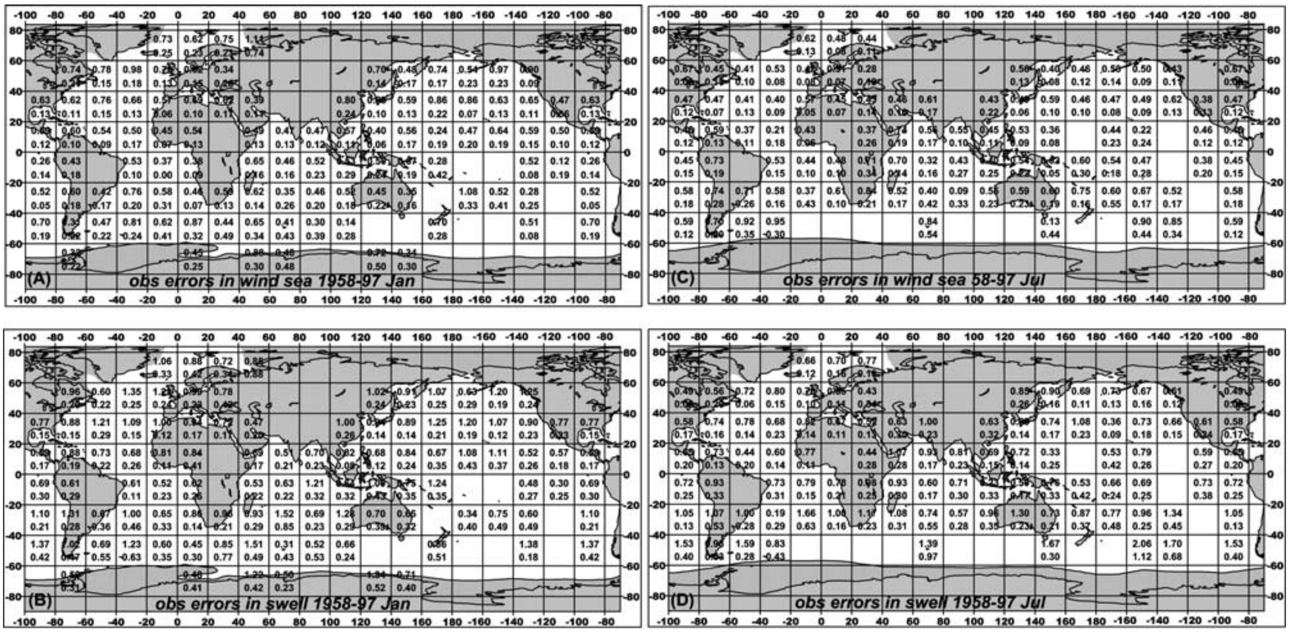

Figure 8. Random observational errors (upper numbers) and uncertainties in random observational errors (lower numbers) (m) in (a) and (c) wind sea height and (b) and (d) swell height in January (Figures 8a and 8b) and July (Figures 8c and 8d). For the blank boxes, errors were not estimated because of an insufficient number of pairs.

random observational errors in the wind speed [*Kent et al.*, 1999] vary from 1.3 to 2.8 m/s. This agrees with the qualitative assumption of *Gulev et al.* [2001] that the accuracy of visual wave observations is not worse than the accuracy of Beaufort estimates of wind speed. Estimating the Beaufort force, sailors primarily use characteristics of the sea state. Pilot results of the SHIPMET [*Gulev et al.*, 2001] show that in estimating the Beaufort force less than 1/3 of officers account for ship behavior and other factors; that is, sea state remains the highest priority in determining the Beaufort number.

[27] The random observational uncertainties of monthly means can be derived from the random observational errors in individual observations (Figures 8 and 9). According to

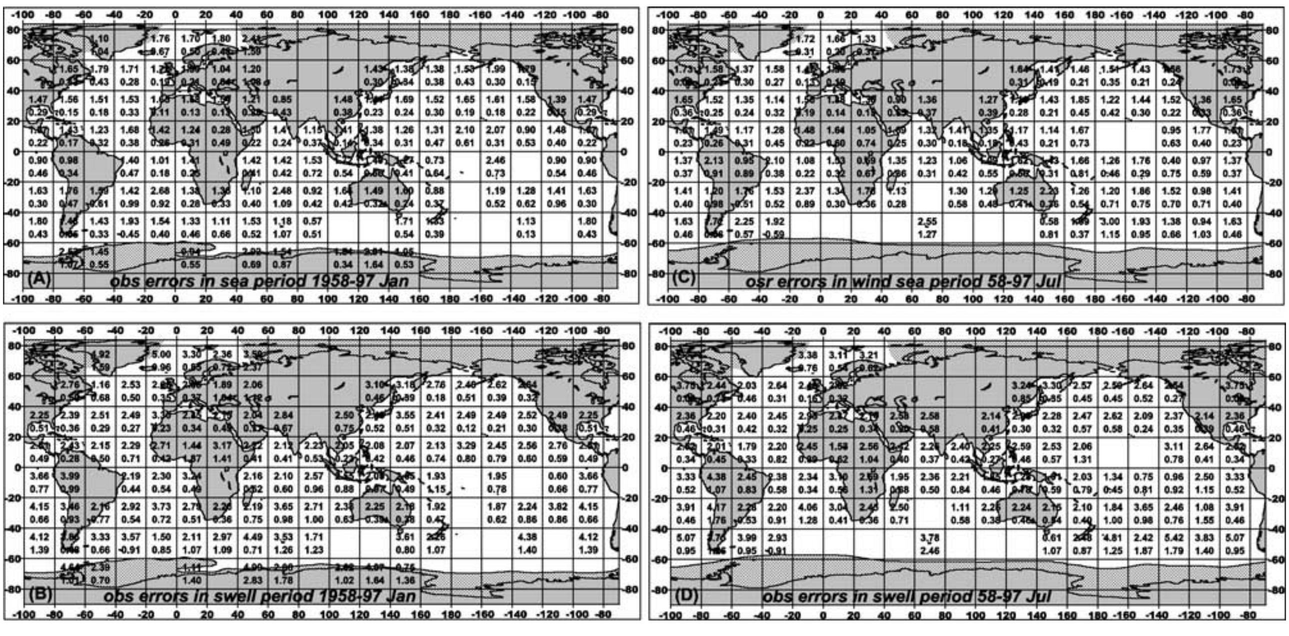

Figure 9. Random observational errors (upper numbers) and uncertainties in random observational errors (lower numbers) (s) in (a) and (c) wind sea period and (b) and (d) swell period in January (Figures 9a and 9b) and July (Figures 9c and 9d). For the blank boxes, errors were not estimated because of insufficient number of pairs.

the Central Limit Theorem for normally distributed random errors the uncertainty of the mean of n observations will be the individual random error reduced by a factor of $n^{1/2}$, where n is the number of observations [e.g., *Taylor*, 1982]. This approach was used by *Gleckler and Weare* [1997] to estimate the uncertainties in surface fluxes. The individual random observational errors were estimated for 20° × 20° boxes, and we are interested in estimating random uncertainties for 2° × 2° cells. We therefore assumed that the estimate derived for 20° × 20° boxes is valid for all 2° cells within a 20° × 20° box. Then we scaled the estimates of random errors with the square root of the average number of samples for each 2° × 2° box per individual month (Figure 1). Thus our estimates of random errors are given for individual monthly means rather than for climatological monthly means, for which they will be smaller because of the averaging over a number of years.

[28] Figure 10 shows the random observational errors of 2° monthly averages of basic wave parameters for January and July. The results reflect the combined effect of individual random observational errors and the number of observations. The smallest random uncertainties in monthly means (less than 0.2 m) for sea and swell are observed in the well-sampled Northern Hemisphere midlatitudes and along the major shipping routes. The largest random observational uncertainties occur in the poorly sampled areas of the Southern Ocean, where the maxima are 0.8 m in January and 1 m in July for the wind sea and approximately 10% higher for swell. Monthly mean sea periods have random observational errors (Figure 10c) ranging from 0.2 s in the midlatitudes of the Northern Hemisphere to more than 2 s during July in the Southern Ocean. The largest errors in swell periods are slightly higher than 2 s and are found in the Southern Ocean. 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. Estimates of periods in the Southern Ocean are very doubtful in the eastern midlatitudinal regions.

[29] Traditionally, the accuracy of nighttime observations is considered to be lower than those taken during daytime. On one hand, daylight provides much better conditions to estimate the sea state. On the other hand, during nighttime sailors sometimes do not strictly follow the observational guidelines, and even do not necessarily go out of the bridge to make the observations. *Kent et al.* [1993] found that moderate and strong winds can be underestimated at nighttime by 10 to 20%. Results of the SHIPMET [*Gulev et al.*, 2001] in general imply a lower accuracy of the nighttime observations. However, it is uncertain whether nighttime 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 daylight. 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 nighttime reports varies from a minimum of 30% to a maximum of 60%.

[30] Figure 11 shows estimates of the random observational errors in wind sea and swell heights, derived for nighttime and daytime observations. In general, there is no indication that nighttime estimates have higher observational errors than those taken during daytime. For the well-sampled regions daytime errors are even higher. For instance, random errors in the wind sea height in the northwest Pacific during daytime are on average 10 to 20% higher than during night. This can be explained by the observational practice during daytime and nighttime. Assuming that at nighttime officers go less frequently outside of the bridge and estimate wave parameters on the basis of wind measurements [*Gulev et al.*, 2001], nighttime estimates may be less scattered than those taken during daytime. Wave periods (not shown) demonstrate the same relationship between the random errors for daytime and nighttime observations, and differ by 10 to 20%.

[31] The difference between nighttime and daytime estimates of wave parameters is a possible source of systematic uncertainties. Climatological differences between the wave height computed from the daytime and the nighttime subsets (no figure shown) show an apparently random patterns in all ocean basins for all seasons with a typical magnitude of differences of ±0.2 m. A systematic overestimation of daytime estimates over the nighttime estimates is found near the east coast of South America and in the Arabian Sea. For wave periods daytime estimates are slightly higher in the tropics and subtropics and smaller in the midlatitudes with the highest absolute differences ranging from 1 to 2 seconds s.

4.3. Comparison With ERA-WAM Hindcast and Estimation of Sampling Biases

[32] 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 [*Sterl et al.*, 1998]. In this run the WAM was driven by ERA-15 (European Reanalysis) winds for the period from January 1979 to February 1994. The WAM covers the globe from 81S to 81N with a resolution of 1.5° × 1.5° and computes wave spectra in 12 directions and at 25 frequencies. Results are output every 6 hours, giving, among other quantities, heights and periods of sea, swell, and SWH. A comparison of the WAM SWH with NDBC buoys generally showed an underestimation of large waves and an overestimation of the low waves by the model [*Sterl et al.*, 1998]. *Gulev et al.* [1998] compared WAM SWH with the VOS SWH estimated according to equation (3) from uncorrected COADS wave data [*Gulev and Hasse*, 1998]. They found that the VOS SWH is systematically higher than the WAM SWH over the North Atlantic by 0.2 to 0.6 m with the largest "VOS minus WAM" differences in the western subtropics, in the regions close to the North American coast, and in the high latitudes. The best agreement was in the northeast Atlantic where the departure of the WAM values from VOS was less than 0.2 m.

[33] For the comparison with the WAM model, we reprocessed the climatology for the period of the WAM hindcast (1979–1993). Because of the regular and high sampling (112 to 124 snapshots per month) the spatial distributions of basic wave variables from the WAM model generally show a smoother picture than the VOS data. Climatological differences between our climatology and the WAM hindcast for SWH are shown in Figures 12a and 12b for January and July. In general, the VOS waves are higher than those for WAM in areas of high waves and

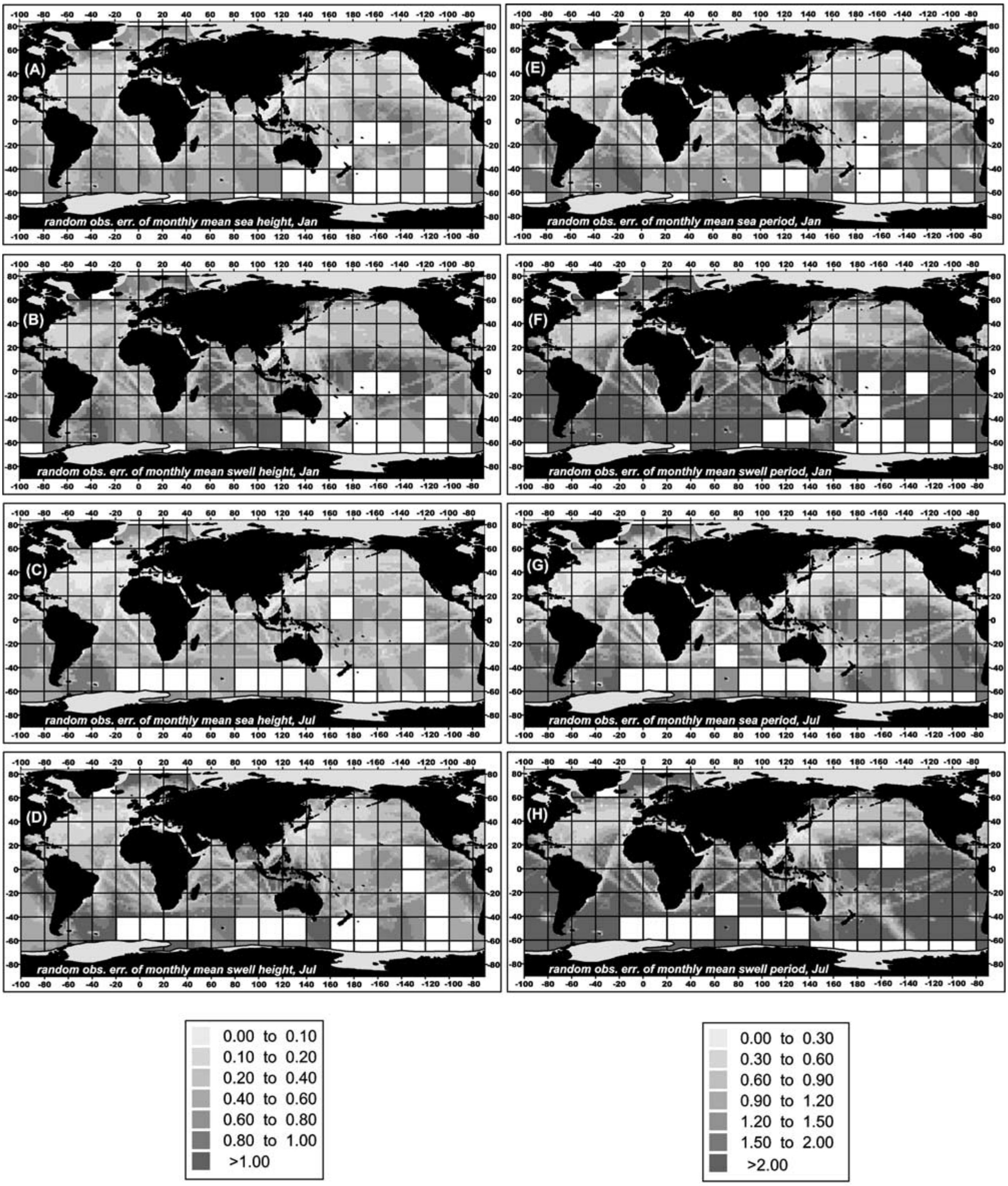

Figure 10. Random observational errors of the monthly mean (a) and (c) wind sea height (m), (b) and (d) swell height (m), (e) and (g) wind sea period (s), and (f) and (h) swell period (s) for January (Figures 10a, 10b, 10e, and 10f) and July (Figures 10c, 10d, 10g, and 10h). For the blank boxes, errors were not estimated because of insufficient number of pairs.

lower in areas of low waves. The largest negative "VOS minus WAM" differences of SWH are found in the mid latitudinal North Atlantic and in the Southern Ocean, where they range from -0.5 to -1.0 m in January rising to -2 m in July. "VOS minus WAM" difference in wind sea (not shown) is positive in the subtropics and tropics and is negative in the Southern Ocean, exceeding -1 m in the Southern Indian Ocean in July. VOS swells are lower than

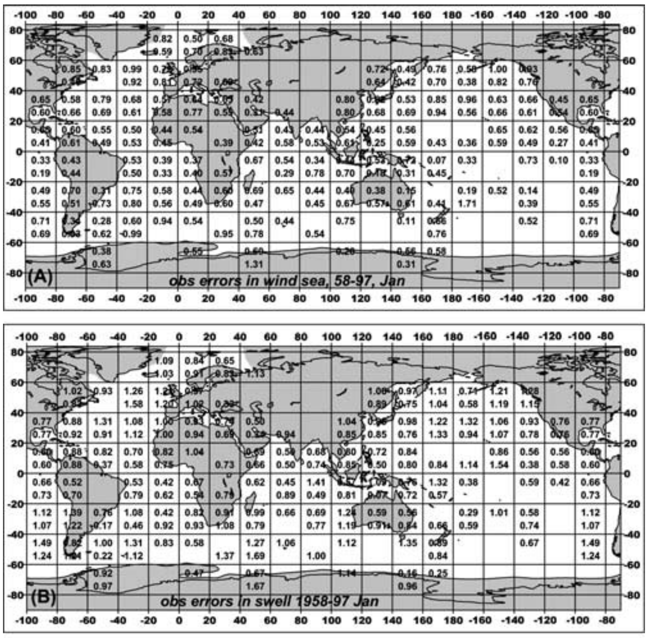

Figure 11. Random observational errors (m) for the nighttime (upper numbers) and daytime (lower numbers) (m) in (a) wind sea height and (b) swell height in January. For the blank boxes, errors were not estimated because of insufficient number of pairs.

those from WAM (no figure shown) in the subpolar regions of both Hemispheres and in the Southern ocean, where July "VOS minus WAM" differences can reach -1.8 m. Locally, large positive "VOS minus WAM" differences in swell are found in the marginal and semienclosed seas, such as the Mediterranean and the Japan Seas.

[34] In principal, the comparisons between WAM and VOS estimates for sea and swell heights should be considered with caution. In WAM sea and swell partitioning is based on the analysis of an objective criterion, namely wave age estimated as $a_1 = u^*/C_p$, where u^* is the friction velocity [*Bidlot et al.*, 2001]. This definition of wave age differs from equation (5), but has similar patterns [*Gulev and Hasse*, 1998]. In the VOS data the partitioning is done by eye and may therefore differ from that in WAM. To test whether the separation of sea and swell in VOS and in WAM are equivalent we applied the limits as established in WAM [*Bidlot et al.*, 2001]. After the applications of the tests described in Section 3.5, only few (less than 0.1%) seas were identified as swells and vice versa. We therefore conclude that the separation in WAM and in VOS are equivalent.

[35] "VOS minus WAM" differences as shown in Figures 12a and 12b result from the performance of WAM, particularly from the quality of ERA winds, and from an inadequate sampling of the VOS data. In order to quantify sampling biases, we simulated a VOS-like sampling of the WAM data. The individual WAM data were interpolated in space and time onto the VOS reports. If several VOS reports were available for the same instance, the corresponding WAM wave parameters were repeated. Figures 12c and 12d show differences between the regularly sampled and "undersampled" WAM climatology ("WAM minus VOS-like WAM") for 1993, illustrating the biases associated with inadequate sampling. The largest underestimation of the "undersampled" WAM wave fields occurs in the Southern Ocean, where the VOS sampling density is poor. SWH shows pronounced positive "WAM minus VOS-like WAM" differences in the Southern Ocean with a maximum of 1.2 m. July differences between the regularly sampled and "undersampled" WAM SWH (Figure 12d) show a remarkable underestimation of the VOS-like sampled waves in the Southern Ocean with the largest differences exceeding 1 m. Patterns of "WAM minus VOS-like WAM" differences for sea and swell heights (not shown) are qualitatively similar to those for SWH and show the largest underestimation of the "undersampled" WAM wave height of 1–1.5 m for wind sea and somewhat smaller (0.5–1 m) for swell in July. Swell demonstrates smaller synoptic variability than sea, and its climatology is less affected by undersampling. Ships seek to avoid storms and large wind seas, but not necessarily high swells. Outside of the Southern Ocean "WAM minus VOS-like WAM" differences in SWH show negative values in the subpolar North Atlantic. This pattern, however, is influenced by differences in swell and not in the wind sea (not shown).

[36] Now the comparison of the original VOS and the "undersampled" WAM ("VOS minus VOS-like WAM") waves (Figures 12e and 12f) allows us to identify that part of the difference between VOS and WAM climatologies that is not influenced by sampling effects. In the South Atlantic and Southern Indian Ocean, as well as in the Northern Hemisphere midlatitudes, VOS SWH exceeds VOS-like WAM SWH by 0.5 to 1 m. Thus sampling effects can significantly modify the observed differences between WAM and VOS wave climatologies, especially in the Southern Ocean. The magnitude of the sampling bias is of the same order as the "VOS minus WAM" differences that are not associated with sampling effects. It should be noted, however, that the ERA-WAM hindcast is also not free from the impact of poor sampling of VOS data, since VOS reports were assimilated into ERA. In areas of poor sampling (e.g., Southern Hemisphere) ERA wind analyses are largely determined by the model and are not constrained by observations. This may partly explain the underestimation of winds and waves by ERA in the Southern Ocean that is visible in Figures 12e and 12f.

[37] The impact of inadequate sampling on wave climatology is quite complicated. On one hand, undersampling leads to a nonrandom error, which is associated with the fair weather bias. In general it acts to decrease the wave heights, because ships tend to avoid stormy conditions. On the other hand, undersampling results in the so-called representativeness error which is associated with the actual number of samples and has a random nature. In order to assess this random error, associated with the lack of representativeness, we simulated VOS-like sampling density in WAM, using a random generator. For each month and $2^\circ \times 2^\circ$ 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 δ_i, $i = 1,\ldots 20$, between monthly means from the full and the VOS-like randomly sampled WAM, respectively. The value $\langle \delta_i^2 \rangle^{1/2}$, $\langle\rangle$ being the averaging operator, gives an estimate of the monthly random sampling error. Maps of this error for

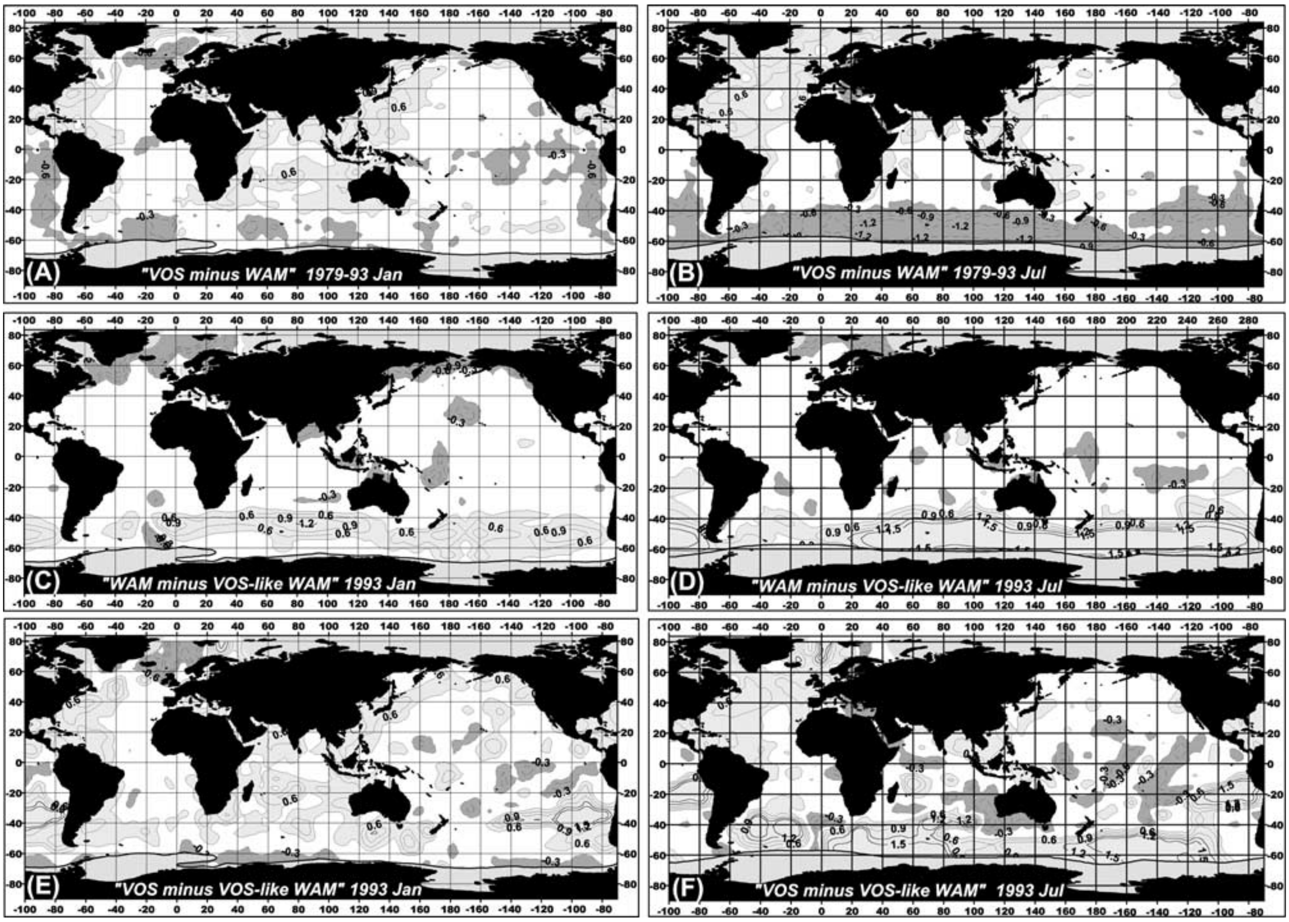

Figure 12. Differences in SWH (m) (a) and (b) between VOS and WAM (“VOS minus WAM”), (c) and (d) between original and VOS-like sampled WAM (“WAM minus VOS-like WAM”), and (e) and (f) between VOS and VOS-like sampled WAM (“VOS minus VOS-like WAM”) for January (Figures 12a, 12c, and 12e) and July (Figures 12b, 12d, and 12f).

1993 are shown in Figure 13. In January, the largest random sampling error is observed in the subpolar North Atlantic (up to 1 m for wind sea and about 0.6 m for swell). In the Southern Ocean, the largest random sampling errors in wind sea are up to 1 m in January and up to 1.8 m in July. The random sampling errors for swell and, therefore for SWH, are smaller than those for wind sea. This can be explained by smaller synoptic and subsynoptic variability of swell in comparison to the wind sea. In other words, adequate monthly averaging for swell requires a smaller number of samples than for wind sea.

5. Comparisons With the Other VOS Climatologies and Satellite Data

5.1. Comparisons With VOS-Derived Climatologies

[38] Our results can be compared with previous climatologies of wave parameters that were derived from VOS observations [*Gulev and Hasse*, 1998; *Hogben et al.*, 1986] and with products based on alternative data sources. In order to ensure comparability, we recomputed climatological distributions for the periods covered by different VOS products: 1963–1993 [*Gulev and Hasse*, 1998], 1950–1978 (MCA) and 1950–1982 [*Hogben et al.*, 1986]. For MCA the actual source of observations is specified as all the historical collection for more than 120 years until 1978. However, we used the data from 1950, taking into account that for the earlier period only a few wave reports are available. The better spatial resolution and the improved preprocessing allows us to depict several features of the spatial distribution of wave parameters, which are not present in the *Gulev and Hasse* [1998] regional climatology, particularly to better resolve the subtropical minimum in sea height. The correction of small waves and the elimination of poorly separated seas and swells resulted in 0.1–0.2 m smaller wind sea heights, especially in the North Atlantic tropics. Estimates of swell heights and SWH are in a good agreement for all seasons though midlatitude swells in the northeast Atlantic are 0.05 to 0.15 m higher in the present study. The MCA and *Hogben et al.* [1986] climatologies exhibit smaller SWH than our data by typically 10 to 20%. The highest differences are obtained in the midlatitudinal North Pacific, where the winter SWH from MCA is 0.4–0.7 m smaller than ours. MCA shows that the local maximum of SWH in the Arabian Sea is lower by 0.2–0.4 during summer. In well-sampled regions of the Southern Ocean, the wave heights of MCA are also generally lower than ours. Unlike that given by MCA, our climatology does not show a consistent latitudinal belt of high waves between 40°S and

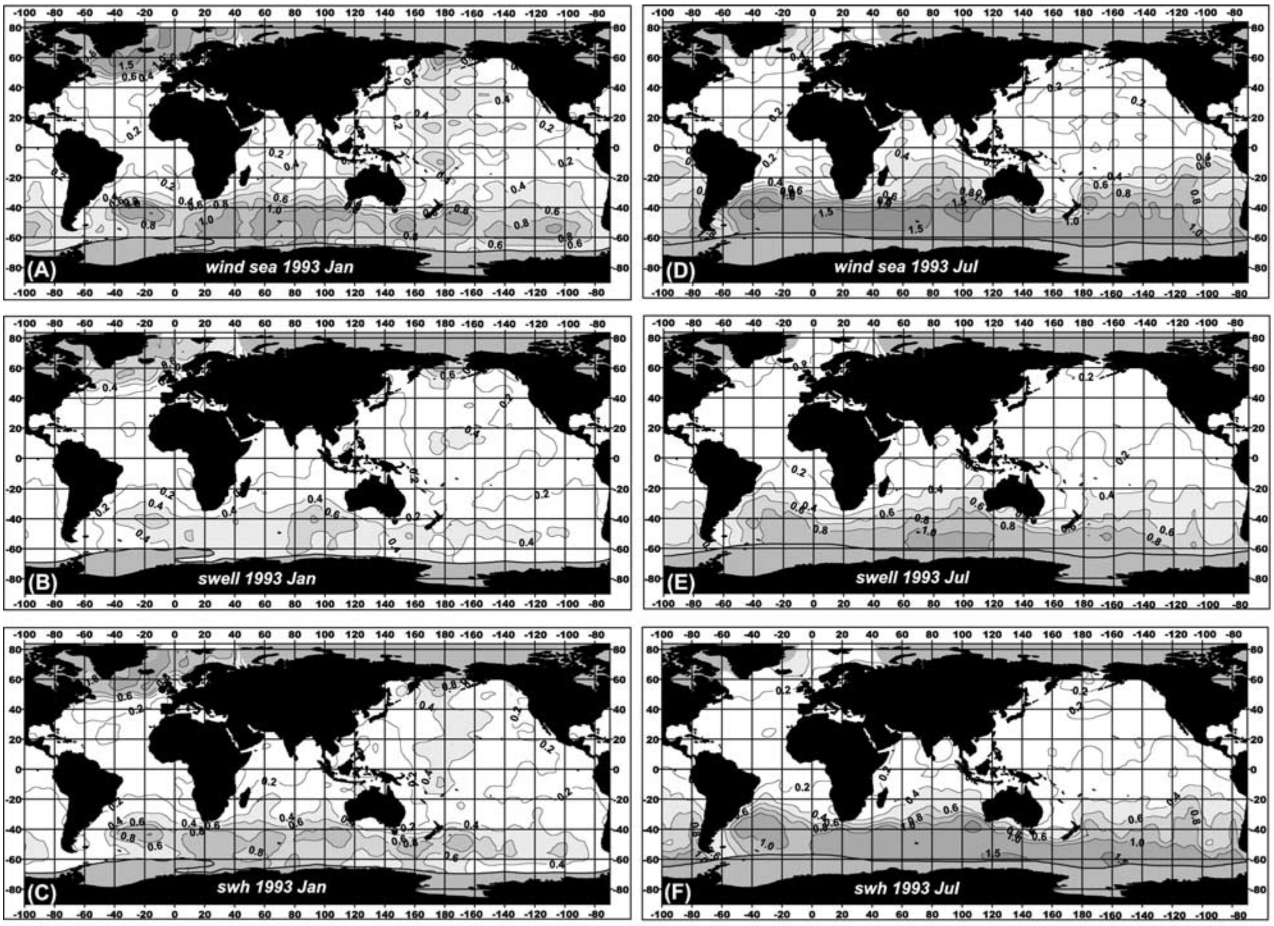

Figure 13. Random sampling errors (m) in (a) and (d) wind sea height, (b) and (e) swell height, and (c) and (f) SWH in January 1993 (Figures 13a, 13b, and 13c) and July 1993 (Figures 13d, 13e, and 13f).

50°S. However, the number of reports used by MCA was much smaller than that used here; and the hand contouring applied by MCA will have affected the appearance of this spatial pattern.

[39] Regarding sampling density, the most uncertain estimates of wave parameters are expected to be in the South Pacific. *Laing and Reid* [1999] assembled a collection of weather reports in the Southwest Pacific for the period 1986–1998. We extracted a subset of our COADS data for the area of the Tasman Sea and the time period analyzed by *Laing and Reid* [1999]. For this particular region, they typically have 5–20% more reports than are available from COADS (Figure 14). It is unclear how large an overlap exists between these two collections. The *Laing and Reid* [1999] regional climatology (Figure 14) in general shows systematically lower estimates of swell, especially in austral winter, than does our study. Wind sea of *Laing and Reid* [1999] is higher than in the present study in the austral winter, but somewhat smaller than our wind sea from august to December. Significant wave height in our climatology is higher during austral spring. Note that *Laing and Reid* [1999] applied formula (1) to estimate SWH, implying 10–20 cm higher values than according to equation (3), which was used in our study. Thus the actual difference in SWH (if the same method of estimation is used) should be even greater. However, our estimates are closer to the altimeter measurements of SWH that were also derived by *Laing and Reid* [1999] using several satellites (Figure 14).

5.2. Comparisons With Altimeter Wave Heights

[40] *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 suffers less from the sampling problems than the VOS data. The sampling by altimeter is fairly sparse, but relatively uniform and there is no significant danger of a "fair weather bias" (satellites certainly do not avoid storms, and there are few problems retrieving data except in the most extreme conditions (e.g., very heavy rain)). Satellite data represent an independent source of global wave measurements. There are, however, remaining uncertainties associated with inaccuracy of retrieval algorithms (and/or calibration). Uncertainties in satellite wave climatologies have been estimated by *Woolf and Challenor* [2002]. In order to intercompare our climatology with this product, we reprocessed the fields of SWH for the period 1985–1997, excluding the months missing altimeter data in 1989–1990. Figure 15 shows January and July differences in SWH, estimated from the VOS data and from the altimeter data. In general, altimeter SWHs are higher than those from VOS in areas of high waves and

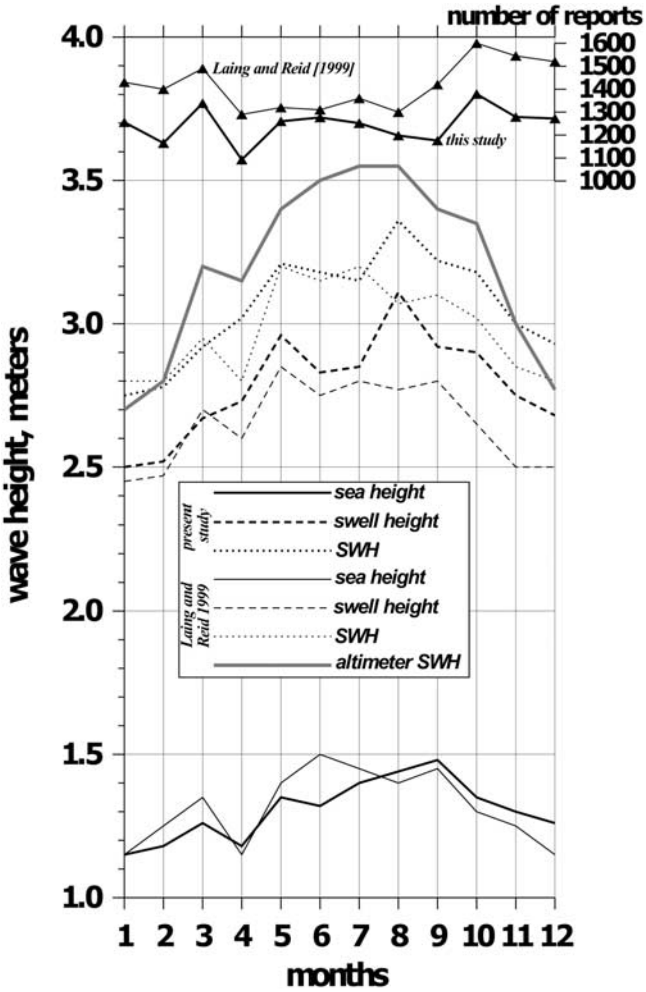

Figure 14. Comparison of the number of reports, wind sea, swell heights, and SWH, for the Tasman Sea in the present study and in the regional climatology of *Laing and Reid* [1999].

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. SWH has been derived from separate observations of wind sea and swell as 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 is sufficient to quantitatively discuss the climatology produced at least north of 40°S. Wave heights in our climatology in most places are not significantly influenced by day-night bias, although some regional biases may exist. Daytime estimates of swell periods are higher than nighttime estimates in the tropics and subtropics and lower in the midlatitudes. 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 because of poor sampling.

[42] Our climatology represents a state of the art of VOS wave data analysis. In comparison to satellite products, VOS data have longer continuity of records and provide independent estimates of sea and swell characteristics. In the midlatitudes 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% and fair weather bias may be a great problem. Comparison with altimeter climatologies implies that VOS underestimates mean SWH wherever wave heights are large, smaller in areas of low to moderate waves. In January, altimeter SWH is greater than VOS SWH in the eastern subpolar and midlatitudinal North Atlantic and North Pacific and over the most of the Southern Ocean. Positive differences (VOS SWH is greater) are observed over most of the Northern Hemisphere in July and in the southern tropics and subtropics in January. The magnitude of the differences ranges within ±1 m. In the Southern Ocean the results are undoubtedly influenced by the very poor VOS sampling. As the altimeter data also contain sampling errors, it is difficult to estimate the effect of VOS-like sampling on "VOS minus altimeter" values by the procedure described in Section 4.3. However, we do know that in the Southern Ocean altimeter sampling is superior to VOS, and "VOS minus altimeter" differences may reasonably be attributed to VOS sampling in this region. For the well-sampled regions comparisons with altimeter data (Figures 14 and 15) show that VOS tends to underestimate high waves.

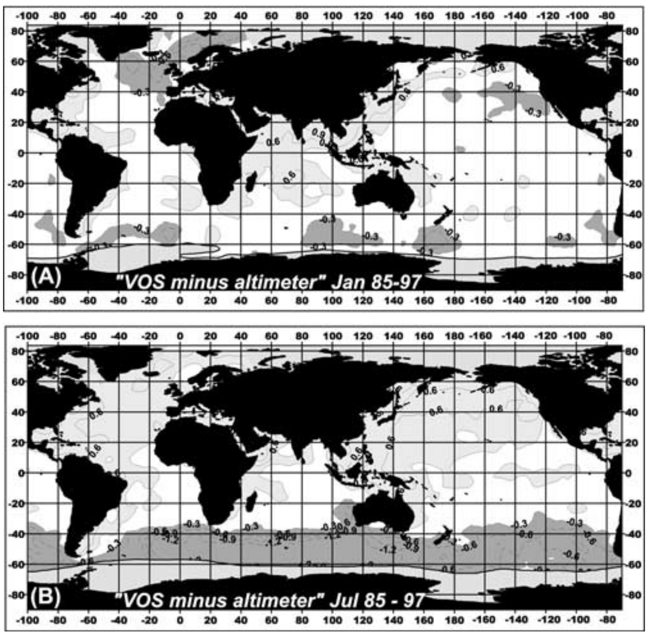

Figure 15. Differences (m) between VOS and altimeter SWH for (a) January and (b) July.

6. Summary and Discussion

[41] A global climatology of wave parameters for the period 1958–1997 has been derived from visual wave data

even if the sampling density is high. This suggests that a fair weather bias (ships avoiding stormy conditions) is a ubiquitous problem. Estimates of wave periods in the Southern Hemisphere are more influenced by the sampling problem than wave heights. Thus all results based on VOS wave data for the Southern Ocean should be considered with great caution. Note, that sampling biases in our climatology may be time-dependent for some areas, affecting patterns of interannual variability. This effect has been recently explored for the sea-air flux parameters [*Sterl*, 2001; S. K. Gulev et al., Assessment of the North Atlantic sea-air heat fluxes from voluntary observing ship data and NCEP/NCAR reanalysis, submitted to *Journal of Physical Oceanography*, 2002]. 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]. Surface humidity, for instance, is characterized by an even poorer sampling density than wave parameters, implying considerable sampling errors in surface fluxes. 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. A comparison with buoy data (Table 1) and estimates of *Young* [1999] show that in the Southern Hemisphere VOS-derived periods can be underestimated by 1–3 s. Further validation efforts can be associated with the recently obtained 40-year model hindcast [*Cox and Swail*, 2001] and new WAM hindcast under ERA-40 project, which provide long-term model time series for comparison.

[43] To further improve our climatology an analysis and minimization of uncertainties associated with observational techniques is needed. The evaluation of the true wave direction and period from the relative wave propagation characteristics is one of the main sources of both random and systematic biases in the wave periods. At the moment it is unclear how to quantify and correct this bias, because there is no way of knowing whether the purely arithmetic operation computing the true wave direction was really applied. Although this problem has the same nature as evaluation of the true wind from the relative wind, its importance for the accuracy of wave periods is even higher than for the wind speed, which is affected by this factor only in the case of anemometer measurements. Beaufort estimates (50 to 70% of the total number of reports), are not influenced by the procedure of the evaluation of the true wind, although wind directions reported with Beaufort estimates can be affected. For wave observations, all estimates of wave periods can be biased because of inaccurate application of the true wave period correction.

[44] New data archaeology efforts can improve the sampling of wave parameters in the VOS collections. Regional subsets, such as *Laing and Reid* [1999] should be analyzed with respect to their overlap with COADS collection. Although this overlap is expected to be quite large, since the sources of data (log books and GTS) are the same, these subsets can provide some useful additions to COADS. The update of wave data from the Japanese Kobe Marine Observatory collection of ship data (under continuing digitization now) [*Manabe*, 1999] and other subsets that were not transmitted by GTS (e.g., SECTIONS [*Gulev*, 1994, 1999]) will be a very valuable step.

[45] Despite the uncertainties, our climatology of wave parameters can be used for many purposes. In the well-sampled midlatitudinal regions of the Northern Hemisphere, our climatology can provide an assessment of climate variability in surface wave parameters. This problem has been widely discussed in the scientific literature since the mid 1980s [*Neu*, 1984; *Carter and Draper*, 1988; *Bacon and Carter*, 1991, 1993; *Schmidt and von Storch*, 1993; *von Storch et al.*, 1993; *Hogben*, 1995; *Bouws et al.*, 1996; *Kushnir et al.*, 1997; *Sterl et al.*, 1998; *Gulev and Hasse*, 1999; *Allan and Komar*, 2000; *Cox and Swail*, 2001; *Wang and Swail*, 2001; *Woolf et al.*, 2002]. VOS data allow analysis of variability in sea and swell separately and allow us to investigate the mechanisms of this variability, in particular describing changes in sea associated with the local wind and variations in swell, which integrate the wind effect over larger scales. We will use our climatology to compute a new generation of wave statistics for the global ocean, which 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 upon using the present climatology. In particular, estimates of climatological changes in different wave statistics can be studied. Global visual wave data can be used for the development of the VOS-based climatologies of surface wind stress, caused by surface waves. *Gulev and Hasse* [1998] estimated these effects using the simple parameterizations of *Smith* [1991], *Smith et al.* [1992], and *Geernaert* [1990], based primarily on wave age. Recently *Bourassa et al.* [1999] and *Taylor and Yelland* [2001] developed new parameterizations, taking into account wave steepness, which can be applied using our data set.

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