EVALUATION OF OCEAN WINDS AND WAVES FROM VOLUNTARY OBSERVING SHIP DATA

Sergey K. Gulev*, Vika Grigorieva, Konstantin Selemenov and Olga Zolina, P.P. Shirshov Institute of Oceanology, RAS, Moscow

ABSTRACT

This paper considers the problem of the accuracy of Voluntary Observing Ship (VOS) wind and wave data, using individual wind and wave reports from the COADS (Comprehensive Ocean-Atmosphere Data Set). Additional information on the accuracy of marine wind and wave observations was available from a pilot questionnaire, SHIPMET, which was distributed among 400 marine officers with the aim of discovering the actual practice of marine meteorological observations onboard merchant vessels. The evaluation of true wind is one of the most important sources of error in wind observations. Estimates of the possible effects of inaccurate evaluation of true wind are presented. An estimation of random observational errors in wave parameters shows that wave fields can be successfully evaluated from the VOS data. Some approaches are recommended to remove systematic biases in visual wave estimates.

1. INTRODUCTION: CURRENT STATUS OF OUR KNOWLEDGE ABOUT VOS WIND AND WAVE OBSERVATIONS

Despite considerable progress in the development of satellite instruments and modelling, Voluntary Observing Ship (VOS) data are still the main source of our knowledge about ocean winds and waves, especially for the decades before the 1980s. During the last two decades these data have been assimilated in the Comprehensive Ocean-Atmosphere Data Set (COADS), which is currently the most complete collection of marine surface observations, assembled from the Global Telecommunication System (GTS) and log books and archived as Compressed Marine Reports (CMR) and Long Marine Reports (LMR) (Woodruff *et al.,* 1998). However, marine meteorological variables derived from COADS contain a number of biases and uncertainties connected with the observational accuracy and should be carefully validated before they are used for the flux fields production. In this context, wind and wave fields are the most ‘questionable’ and problematic VOS observations. Although the other surface variables (SST, SLP, air temperature and humidity) are also influenced by random and systematic observational errors, it is easier to assess their accuracy since they are exclusively instrumental observations. Taking into account the fact that winds and waves can be derived from satellite observations and model hindcasts with a better accuracy than other meteorological variables, we expect that the alternative products of these sea-air interface parameters will appear quite soon for the period covering the last several decades. In this context, it is very important to quantify the accuracy of the VOS winds and waves to provide the best possible VOS data possible for the intercomparison with remotely-sensed and model products. This paper addresses some issues on the accuracy of VOS wind and wave data on the basis of statistical analysis and new information about the actual measurement techniques used onboard merchant vessels which is provided by the questionnaire distributed among a representative population of officers.

(a) Wind observations

There are many uncertainties in VOS wind observations. First of all, a considerable part of wind observations are the visual estimates made by officers of

---

* corresponding author’s address: P.P. Shirshov Institute of Oceanology, RAS, 36 Nakhimovsky ave., 117851, Moscow, Russia, Email: gul@gulev.sio.rssi.ru

merchant ships. The observational accuracy of these observations is reasonably low in comparison to in situ measurements. There are additional uncertainties connected with the systematic biases of different equivalent Beaufort scales in the low and high wind speed ranges. Instrumental wind observations show the mixture of measurements made by hand-held and fixed anemometers. Hand-held anemometer data are crucially affected by the ship's superstructure and sample procedure. Winds recorded by fixed anemometers are also influenced by the ship's superstructure; they are additionally affected by differences in anemometer heights onboard different ships and by the uncertainty of the procedure for evaluating true wind (or drop of it). Altogether, these uncertainties result in a coupled error which is comparable or overestimates the uncertainty of visual observations (Kent *et al.,* 1993). Finally, for the creation of climatologies, data from the fixed anemometers (hand-held anemometers are usually excluded from the analysis) are merged with visual observations. This leads to additional time- and space-dependent uncertainty of monthly averaging of inhomogeneous data.

During the last several decades the issue of the accuracy of wind observations at sea has been addressed in many works. To minimize biases in visual wind observations several alternative Beaufort equivalent scales were developed in addition to the traditionally used WMO Code 1100 scale (Cardone, 1969; WMO, 1973; Kaufeld, 1981; Isemer and Hasse, 1991; da Silva *et al.*, 1995; Lindau, 1995). Kent and Taylor (1997) comprehensively reviewed all these equivalent scales and found the Lindau (1995) scale to be the most unbiased. Considerable progress has been achieved during recent years as regards the problem of adjusting wind observations to a standard height, primarily by merging the WMO *International List of Selected, Supplementary and Auxiliary Ships* (WMO-No. 47) with the LMR available from the COADS collection. By matching the call signs from WMO-No. 47 and LMR, it is possible to get the actual observational heights of fixed anemometers at 30 to 60 per cent of marine carriers (Kent and Taylor 1997) and to adjust the wind to a standard level and neutral stability. During the VOS Special Observing Project in the North Atlantic (VSOP-NA) (Kent *et al.,* 1993), a large set of well documented surface meteorological data was collected in the North Atlantic mid-latitudes for the period from 1989 to 1991. Analysis of this data set makes it possible to quantify the most important biases in ocean wind observations and to implement the corrections. Laboratory and numerical modelling using typical ship superstructures helped to abate the impact of the ship on anemometer measurements (Yelland *et al.,* 1998). However, some biases remain unexplained. In particular, Gulev (1999) compared the high quality instrumental data to COADS winds for the 1980s and early 1990s in the north-west Atlantic, and found an overestimation of the COADS winds in low ranges and underestimation for the strong and moderate winds, i.e. the opposite tendency to that usually expected for such intercomparisons. Since the application of the alternative equivalent Beaufort scales did not remove the bias and made it even more pronounced, it was concluded that such a disagreement results from the incorrect evaluation of true wind. Quantitative inspection of the procedure for evaluating true winds onboard merchant ships and correction of corresponding biases is difficult in contrast to research vessels, for example, whose data are much better documented (Smith *et al.,* 1999).

(b) Visual wave observations

VOS wave observations are exclusively visual estimates of heights, periods and directions of wind sea and swell. For a long time visual wave observations from limited collections were used to produce ocean wave statistics (Hogben and Lumb, 1967) and global wave statistics (Hogben *et al.*, 1986) widely used by sailors and naval engineers. Direct comparisons of wind waves to in situ observations from buoys and the other platforms (e.g. Wilkerson and Earle, 1990) reported about the large random and systematic errors in visual observations. Gulev and Hasse (1998, 1999) updated all visual observations in the North Atlantic from the COADS collection for the last 30 years and quantified many of the errors and uncertainties. Intercomparison of Gulev and Hasse (1998) climatology with the European Centre for Medium Range Weather Forecasts (ECMWF) wave model (WAM) wave hindcast and altimeter measurements in the North Atlantic (Gulev *et al.,* 1998, Cotton *et al.,* 1999) shows a general similarity of spatial patterns and the co-location of local maxima. Although the mid-latitudinal estimates of VOS waves were consistent with WAM hindcast and altimeter measurements, it has been found that overestimation of VOS waves in the tropics and subtropics is systematic. Small waves are relatively poorly resolved in WAM, leading to difficulties in their validation. However, small wave heights in the VOS data are influenced by systematic bias, which will be analysed below.

Considering the validation of the VOS waves over the global ocean, one of the main weaknesses of the VOS data is the inhomogeneity of the data coverage. In general, there is concern that the observational density of wave observations is considerably smaller in comparison to the other variables. Gulev and Hasse (1998) reported that 40 to 60 per cent of the total number of reports for the North Atlantic include wave information. Note that for the 1963-1979 period they used CMR and LMR that were available only from 1980. The inspection of newly updated LMR (Woodruff *et al.,* 1998) shows that the percentage of reports with wave observations closely matches 70 to 80 per cent of reports which contain wind information. Figure 1(a) shows the total number of reports with wave parameters for 2-degree boxes over the Global Ocean during January for a 15-year period from 1979 to 1993. The distribution of the number of wave reports is qualitatively similar to that of the other meteorological variables. Mid-latitudinal and subtropical regions in the northern hemisphere are much better sampled than the southern hemisphere, where high observational density is observed primarily along the major ship routes. The quantitative comparison of the number of wave observations with the observational density of the basic variables (widely used for the creation of global scale climatologies) shows that the estimated 70 to 80 per cent of wind reports derived for the North Atlantic remains valid also for the other oceans. Even in the Southern Ocean, considered to be very poorly sampled, the density of wave observations considerably overestimates the density of humidity observations. In general, we can conclude that the number of observations is large enough for the creation of global scale climatology at least north of 40S.

The main problem with the validation of visual wave observations against instrumental measurements is the evaluation of significant wave height (SWH), which is usually reported in instrumental records. The traditional approach to deriving SWH from separate visual estimates of wind sea and swell is to apply the formula (Hogben *et al.*, 1988):

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

where h_w and h_s are wind sea and swell heights, respectively. The results of intercomparison with instrumental measurements (Gulev and Hasse, 1998) show that Formula (1) overestimates the observed SWH in the majority of cases by several tens of centimeters with a mean deviation of -0.27 m. An alternative estimate of SWH was established by Wilkerson and Earle (1990), who analysed buoys, a majority of which had been deployed in the subtropics, and found that the highest of the two estimates was less biased. However, intercomparison of the measurements in both subtropics and mid-latitudes (Gulev and Hasse, 1998) showed a tendency of frequent underestimation of this SWH estimate. The best estimate of SWH was found to be a combined estimate, computed as recommended by Barratt (1991) (i.e. applying (1) when sea and swell are within the same 45° directional sector, and taking the higher of the two components in all other cases), but the optimal directional sector was found to be 30°. This combined estimate gives the mean ‘buoy minus VOS’ difference of -0.07 m in the Atlantic (Gulev and Hasse, 1998). The combined approach was chosen for the production of new global wave climatology recently developed at IORAS (Gulev *et al.,* 2001). Figure 1(b) shows an example of a climatological chart of January SWH computed using the combined estimate for the 1979-1993 period. It shows reasonable heights in the North Atlantic and North Pacific mid-latitudes. In the

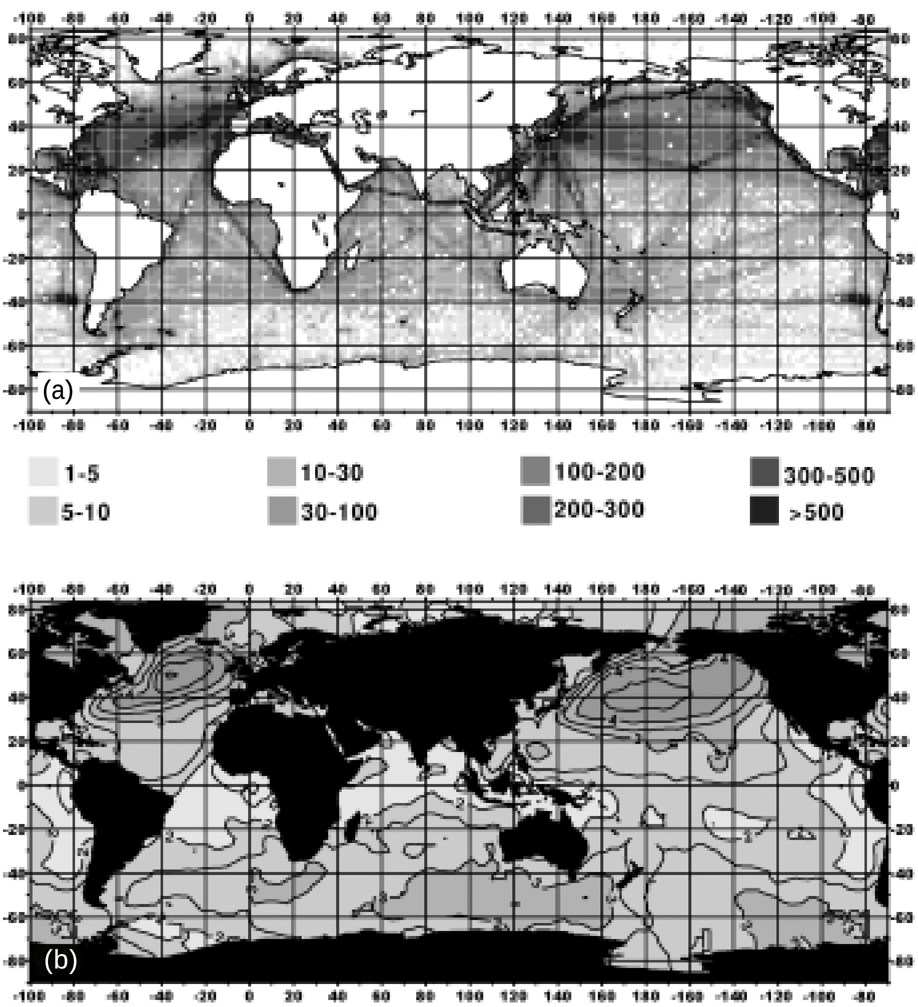

Figure 1—Number of COADS reports with visual wave observations in climatological January for the period from 1979 to 1993 (a), and climatological January significant wave height over the Global Ocean (b).

South Atlantic, where the number of wave observations is considerably smaller, our climatology does not indicate ‘the belt’ of large wave heights as in model hindcasts. This difference results mostly from undersampling and considerable efforts are required to develop new procedures for the optimal interpolation of wave characteristics in poorly sampled areas.

Visual estimates of wave periods were found to be systematically underestimated in the VOS observations. Wilkerson and Earle (1990) reported about 0.2 sec ‘buoy minus VOS’ differences. Gulev and Hasse (1998) found that mean departure is about 0.26 sec with a std. dev. of 0.1 to 0.6 sec. Dacunha *et al.* (1984) and Hogben (1988) reported even larger systematic biases in periods for the Cobb seamount in the North Pacific. To correct biases several methods were developed. Ochi (1978) and Dacunha *et al.* (1984) recommended correcting joint probability distributions of wave heights and periods, making it possibile to obtain the corrected mean periods. Gulev and Hasse (1998) developed a method for the correction of individual observations for periods with an accuracy of 0.12 sec. This method is based on the consideration of joint probability distributions of wave height and period in 17 locations of the North Atlantic. The appplication of this correction to the North Atlantic wave climatology shows that the largest corrections of 0.4 sec for sea periods and 0.8 sec for swell periods were applied in the north-east Atlantic.

Estimation of the observational accuracy of visual VOS wave data (Gulev and Hasse, 1999) shows that the day minus night-time difference in the visual wave estimates is not as large as in wind observations. In the North Atlantic it ranges from several centimetres to 0.2 m and does not have any pronounced spatial pattern. Another possible source of error in visual estimates of ocean waves is a poor separation of seas and swells by the observers. Gulev and Hasse (1999) tested the success of this separation using joint probability distributions of the wave height and wind speed for the wind sea and swell, which were overplotted by the JONSWAP curves, representing wave height as a function of wind speed and duration in the formulation of Carter (1982). Most of the wind sea observations were bracketed by the JONSWAP curves corresponding to the 6- and 18-hour durations. Alternatively, only less than 20 per cent of swell observations were bracketed by the JONSWAP curves. Thus, there is evidence of quite good separation of seas and swells in the VOS wave data. However, as is the case with wind observations, further improvements to the accuracy of VOS wave data requires information on how the observations are actually made by the officers onboard merchant ships.

2.
THE SHIPMET QUESTIONNAIRE

Houmb *et al.* (1978) were probably the first to report on interviewing observers as a method of estimating the observational accuracy of meteorological data. They investigated the effects of changing from meteorological assistants to mates on the visual wave estimates on some Norwegian ships. They found that mates tended to underestimate wave height in comparison to meteorological assistants. Unfortunately, this practice was not widely distributed for assessments of the observational accuracy of winds and waves at sea. To assess the impact of the ‘personal factor’ on the accuracy of VOS wind and wave observations, we designed the SHIPMET questionnaire (Gulev, 1996) and distributed it for a pilot pool among nearly 400 Russian ship officers. Such a population is considered to be very representative for narrow professional questionnaires. The questionnaire contained more than 60 groups of questions about the technical details of different meteorological observations (not only waves and winds) onboard different marine carriers. These questions were assembled according to the requirements of sociological pools. When one question is repeated at least several times in different contexts, it provides the possibility of testing the reliability of the given answers using the answers to the so-called ‘sister questions’. Before the final list of questions was established, 11 officers were interviewed in a free manner. These interviews helped to provide details on the techniques used. Important questions were asked on which operational guide to use as the reference for the survey. In different Russian fleets (merchant, military and fishing) slightly different guides were used. Finally, the guide for the merchant fleet was taken as the reference and it was assumed that all officers were familiar with it. This guide elaborates on most of the details of meteorological observations for different types of meteorological onboard equipment. Some sample questions from the SHIPMET questionnaire which are analysed in this study are given in the Appendix below.

The ‘response function’ of the officers was quite good and more than 2/3 of the questionnaires were answered. After the expertise of the answered questionnaires, aimed at excluding unreliable samples, 211 of them were selected for the statistical analysis. Most sailors who participated in the pool were mid- and high-level officers and had the rank of mates, although approximately 15 per cent of them were sailors, appointed as low-rank officers after a couple of years of sailing experience. Figure 2(a) shows the distribution of officers’ sailing experience. Most officers (63 per cent) have 5 to 15 years experience and this reflects the typical distribution of the experience of officers in most Russian ship companies. Figure 2(b) shows the regions in the North Atlantic where these officers operated. We asked them to mark roughly the most frequent ship routes along which they travelled. Thus, this picture contains some uncertainty. Nevertheless, it correlates well with the typical observational density over the North Atlantic (if the American and Canadian carriers are excluded), and we beieve that we achieved an adequate representation of geographical regions. Most officers travelled along the ship routes that cross the North Atlantic mid-latitudes and subtropics and also the European basin.

Figure 3 displays some pilot results of the statistical analysis of the officers’ answers to the questions concerning the determination of wind speed onboard the vessels. Figure 3(a) shows that most of the officers were quite familiar with the Beaufort scale details. Seventy five per cent of respondents either use a table with the description of the Beaufort scale or know it with varying degrees of accuracy.

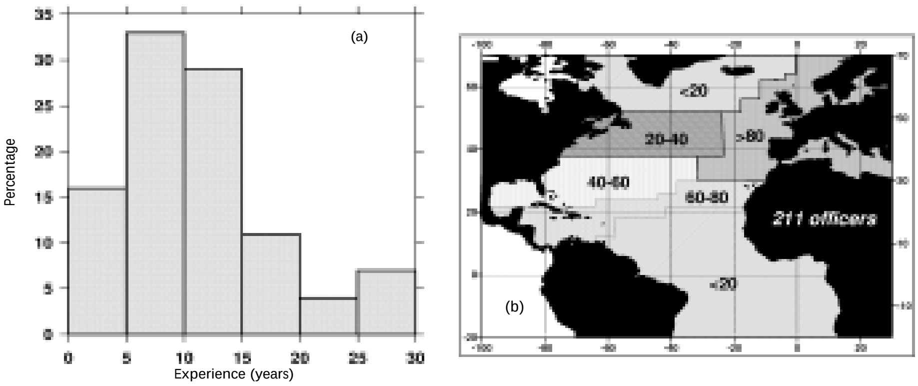

Figure 2—Distribution of experience of respondents of the SHIPMET questionnaire (a) and North Atlantic areas where officers travelled most frequently (b). Numbers indicate the number of officers marked this region.

About 16 per cent of respondents use the reduced tables based on sea state only. However, Figure 3(b) shows that less than 1/3 of all officers account for ship behavior and other factors and estimate the Beaufort number, i.e. sea state remains the highest priority for most officers when determining the Beaufort number. If we assume arbitrarily that poor familiarity with the Beaufort table may result in the error of ±1 Beaufort number for low and moderate winds and of ±2 Beaufort numbers for strong winds, and apply these error estimates to 25 per cent of officers, who were completely or partly unaware of Beaufort scale details, the resulting absolute error of the reported Beaufort numbers will be ±0.25 and ±0.5 respectively.

Figure 3(c) shows results of the analysis of the evaluation procedure of true wind onboard merchant vessels equipped with anemometers. According to the answers of respondents, 19 per cent of officers do not know about the technique for evaluating true wind; 21 per cent know, but do not usually use it; 33 per cent use it either episodically or using the “approximate course and ship velocity”; and only 27 per cent use it correctly. Thus, according to our pool, about 40 per cent of officers omit true wind correction. Assuming roughly that anemometer measurements contribute 30 to 50 per cent of the total number of wind observations, the actual contribution of uncorrected winds is about 12 to 20 per cent of all wind reports. Additionally, considerable uncertainty stems from the 33 per cent of officers who do this correction episodically or using an approximate (i.e. expected, and not reported by the navigation system) ship course. Assuming very tentatively that half of the reports by this 33 per cent of officers can be considered as uncorrected, and using the same estimate of 30 to 50 per cent for the contribution of anemometer winds, we can increase our estimates of the total percentage of uncorrected winds by at least 5 to 8 per cent.

If we consider the determination of wind direction in the absence of an onboard anemometer (Figure 3(d)), nearly 60 per cent of respondents report it from the wave direction, and more than a quarter of sailors do not explain how the direction is derived. In this sense, the recently introduced simplification of the LMRF format (use of wind direction when the wind sea direction is not reported or deviates considerably from the wind direction) seems to be a reasonable step. At the same time, the situation with the evaluation of true wind from the relative wave direction for visual wind estimates (not shown here) is somewhat better than with the correction of anemometer winds. More than 80 per cent of officers ensured that in this case the reported wave and wind directions were absolute and not relative, although different approaches for evaluating the absolute directions were reported. Smith *et al.* (1999) reported on frequent confusions concerning the definition of true wind, used by meteorologists, oceanographers and the merchant marine. However, in our pool, more than 90 per cent of officers among those who are familiar with the technique of true wind correction used the meteorological definition of true wind (i.e. speed referenced to the fixed earth, and direction referenced to true north).

Figure 4 shows the the results of the analysis of the observational techniques of visual wave estimates. Figure 4(a) summarizes how the officers of ships without onboard anemometers follow the recommendations on wave

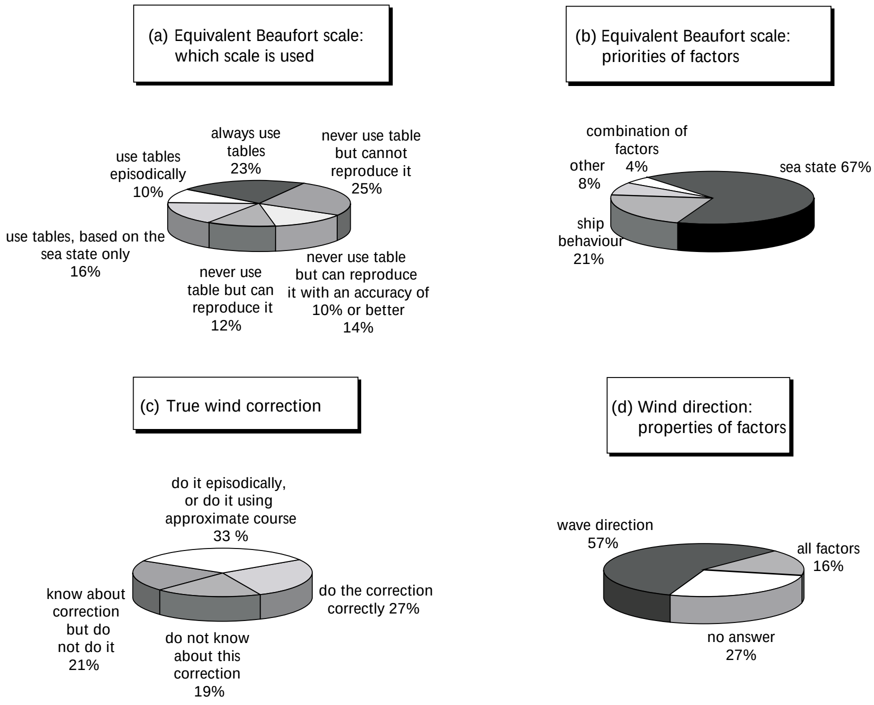

Figure 3—Results of the SHIPMET questionnaire: (a) familiarity with the Beaufort table, (b) priority of factors for Beaufort estimates, (c) approaches used for true wind correction, (d) priorities of factors determining wind direction.

height measurements. These recommendations require the use of a special plane for the measurements of wave height, at least during the daytime. Ideally, the estimates of both wave height and period should be taken as an ensemble average within the parcel of 10 waves. In order to count the parcel, it is recommended to use a buoyant piece of red, yellow or white meterial to mark the reference point. The use of a watch is strongly recommended for the estimation of periods. However, in practice, many approaches are used. Remarkably, 32 per cent of observers do not even leave the bridge to make wave measurements. Although this has to affect the accuracy of visual wave estimates, note that the wind speed estimated by these sailors will be affected to the same degree. Only about 23 per cent of respondents reported that they count the parcel of 10 waves and about 17 per cent use a special plane during the daytime to estimate wave height. Forty-two per cent of observers report waves with intermediate accuracy, i.e. they leave the bridge, watch the sea surface but do not count the parcel of 10 waves, and do not use the plane to estimate wave height. Our questionnaire shows that high uncertainties of visual wave estimates can be

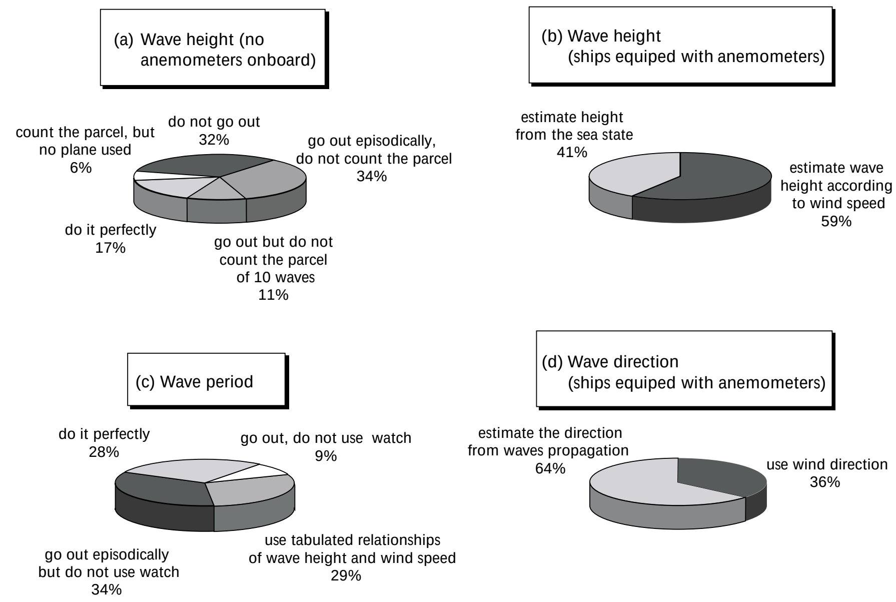

Figure 4—Results of the SHIPMET questionnaire: (a) approaches to determining wave height on ships without anemometers, (b) approaches to determining wave height on ships equipped with anemometers, (c) approaches to determining wave period, (d) approaches to determining wave direction.

associated with reports from vessels equipped with anemometers (Figure 4(b)). Officers onboard these ships consider ocean waves to be a low priority parameter with respect to wind, which is measured by fixed anemometers. Nearly 60 per cent of these sailors either directly use in situ measured wind speed to estimate wave height, or at least take wind measurements into account when they estimate waves. Assuming, as before, that 30 to 50 per cent of vessels are equipped with anemometers, in 15 to 30 per cent of cases we deal with some kind of simplified wave hindcast carried out by observers using wind information. Note that for ships equipped with anemometers 36 per cent of observers directly report wind direction as wind sea direction; and it is clear that many of these reports are affected by an inaccurate evaluation of true wind. Joint consideration of Figures 3(d) and 4(d) shows that the reported wind direction and wind sea directions in the majority of cases are not independent estimates in the VOS observations. Wave periods are perfectly estimated (i.e. a using watch) by just 28 per cent of respondents. In 45 per cent of cases we can expect that the low accuracy of reported wave periods are caused by simplifications of the observational technique. An important lesson is that nearly 30 per cent of observers use tabulated relationships between wind speed and wave height in order to estimate wave periods. Inspection of the tables used (the origin of these tables is always unknown) shows that their application usually results in the systematic underestimation of wave periods, which can partly explain the general underestimation of visual wave period estimates. The correction of these biases in wave periods requires the application of the procedures mentioned above in section 2.

Although the processing of the results of the SHIPMET questionnaire is still under way, the first pilot results show that the actual uncertainties inherent to the VOS collections of marine observations may be considerably larger than we expect from the traditional estimates of random and systematic errors in marine observations. Particularly, some of the reported approaches can result in systematic biases which should be taken into account. First of all, this is an inaccurate evaluation of true wind. There are reasonable questions about the reliability of the results of the SHIPMET questionnaire itself. According to sociological statistics, the random errors of narrow professional questionnaires are even higher than for the typical public pools, and ranged from 5 to 10 per cent. Thus, many of the conclusions based on these questionnaires should be considered more qualitatively rather than quantitatively. The most important question of all is whether we should believe that officers report reality rather than what the questionnaire expects of them (i.e. cite the instructions). The motivation of respondents is different for public relation pools and for professional pools, and this may result in additional uncertainty. An additional problem is connected with the question of whether Russian officers are representative of officers from other parts of the world. We estimated biases in winds and waves reported by the officers of different nations in the North Atlantic (Gulev and Hasse, 1998), using country code in COADS, and did not find any significant climatological biases. However, it is obvious that fleet-to-fleet differences in observational practices can be quite significant, especially if we consider the North Pacific where there is considerable contribution from the Japanese vessels.

3.
ESTIMATION OF OBSERVATIONAL ERRORS IN MARINE WIND AND WAVE OBSERVATIONS

Kent *et al.* (1999) recently estimated random errors in basic meteorological variables reported by VOSs using the semivariagram technique. Random errors of the wind speed in the North Atlantic ranged from 2.0 to 2.3 m/s and did not indicate any significant spatial variability. This random observational error couples many particular uncertainties which affect wind observations at sea, and partly, of course, account for the random part of uncertainty associated with the evaluation of true wind. In general, there is concern that in many regions the problem of true wind evaluation does not seriously affect wind climatology. This is because on major ship routes the underestimation (overestimation) of true wind (if the correction is not done) when travelling in one direction will be compensated by the overestimation (underestimation) of true wind when travelling in the opposite direction. However, this concern is based on several assumptions which may not necessarily apply to all regions. First, it is assumed that the directional steadiness of the dominant winds is quite high and is not affected by synoptic variability, or that the latter exhibits the random process. Secondly, it is assumed that ships always take the same routes travelling in both directions. The first assumption seems to be reasonable, at least for the mid-latitudinal regions, however weather regime changes may play an important role in wind speed and direction variations on weekly time scales. As regards the second assumption, it should be noted that many ships which contribute to the VOSs do not shuttle between two regions, but operate in different regimes. Moreover, marine carriers now use different routes travelling to the west and to the east. For instance, for the Newfoundland basin, the majority of ships, following the recommendations of meteoservices, use the southern routes when travelling from Europe to the USA and cross this region only on the way back. In this case, winds in this region will be slightly underestimated if the true wind evaluation is omitted (Gulev, 1999). Separate consideration of the zonal and meridional components of wind speed for this region shows that zonal wind speed (mostly affected by the 'true wind effect' under the dominant wind directions and ship routes for this region) indicates the larger disagreement between the COADS and high quality instrumental measurements than the meridional component.

We can demonstrate very roughly the possible bias in monthly climatological wind speed, which may result from an inaccurate evaluation of true wind from relative wind. Using the ship course and velocity reported in LMR, we recomputed winds for the North Atlantic assuming that the correction of relative winds was not applied at all. We also applied the reverse convergence to the winds, which were properly corrected. According to the SHIPMET pool, approximately 40 per cent of anemometer winds were not corrected. Thus, after the application of this procedure, approximately 60 per cent of wind observations were converted from true winds to relative winds and 40 per cent were corrected. Figure 5 shows the difference between climatological wind speed computed from the original VOS reports and from the reports after the 'overall' correction. All Beaufort estimates were used in the averaging of both arrays without any correction. The considerable positive difference of 0.5 to 1 m/s in the north-west mid-latitudinal Atlantic shows that the actual increase in the number of uncorrected reports (due to the application of the true wind correction to the already corrected winds, which were assumed to constitute a majority of reports) results in the underestimation of climatological wind in this region. Alternatively, overestimation is observed in the North Atlantic tropics and subtropics.

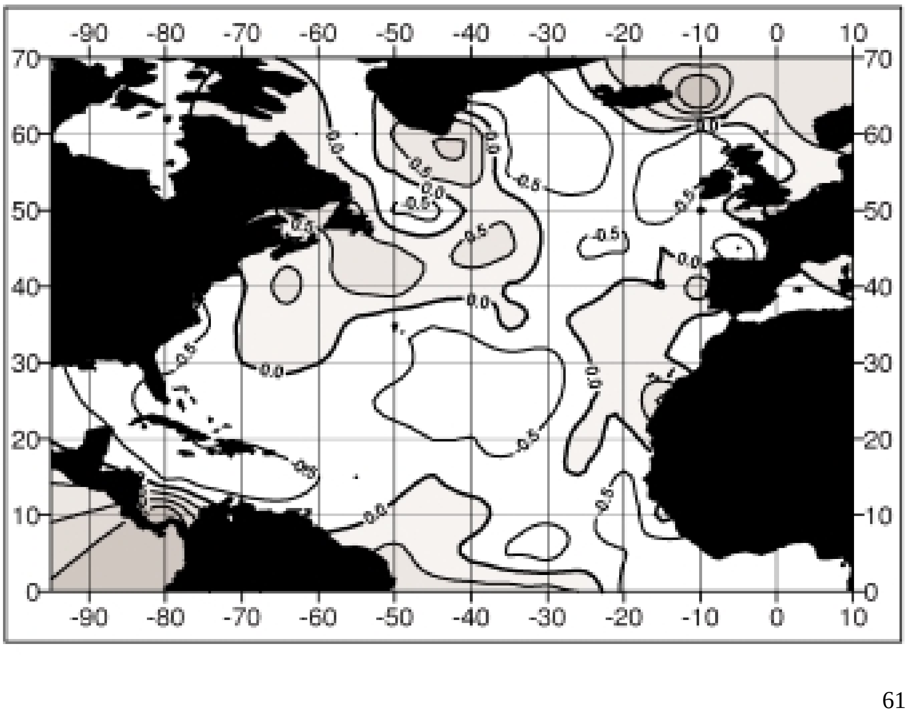

Figure 5—Difference between climatological wind speed in the North Atlantic ocean and wind climatology computed after the application of true wind correction to all anemometer measurements (see explanations in the text).

To estimate random observational errors in the visual wave observations, Gulev and Hasse (1999) used the approach of Lindau (1995) and Kent and Taylor (1997), who recommended computing the differences between simultaneous observations for certain classes of ship-to-ship distances. When the distance is equal to zero, natural variability does not contribute to the total variance, and 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). To arrive at the σ_o^2 estimate, the polynomial extrapolation has to be used. An alternative approach was suggested earlier by Laing (1985), who introduced the dependence of the correlation between the log-transformed wave heights (r) on ship separation (x) as $r(x) = r_o \exp(-kx)$, where estimates r_o are reasonably not influenced by the spatial variability and should characterize the observational error.

Figure 6(a) shows the results of estimation of both ε_m^2 and r_o for significant wave height estimate for the North Atlantic Ocean after Gulev and Hasse (1999). The resulting estimate of r_o gives 0.76 for significant wave height, 0.69 for the wind sea, and 0.73 for the swell height. When we consider the regional correlations for 20-degree areas, the lowest correlation from 0.50 to 0.60 is found in the Western Atlantic subtropics and the highest (of about 0.83) in the North Atlantic mid-latitudes. The polynomial fit for ε_m^2 gives a standard deviation (std.) error of about 0.85 m^2 at Δx=0. However, if we use only classes of distances from 20 to 180 km, this estimate will be lower by about 0.07 m^2. We made an additional estimate for the class 0-10 km only and got ε_m^2, which is a little bit less than 0.8 m^2. Figure 7 shows spatial distributions of the error estimates for wind sea and swell heights over the North Atlantic Ocean, computed by Gulev and Hasse (1999) for 20-degree boxes. The largest observational error of wind sea height of about 0.8 - 0.85 m^2 is obtained in the western subtropics, and the minimum (0.55 - 0.6 m^2) is located in the eastern mid-latitudes. The spatial distribution of the observational error in swell height is quite different from that of the wind sea. The minimum error of around 0.8-0.85 m^2 is observed in the eastern mid-latitudes and the central subtropics and tropics. The largest errors up to 1 m^2 are observed in the western North Atlantic. A similar estimation of the random observational error in the resultant wave periods (after the correction of the wind sea and swell periods) has been carried out by analysing ship pairs and the data from the NDBC buoys in the subtropical Northwest Atlantic (Figure 6(b)). Although there is a disagreement between the two error estimates for large distances, the obtained ε_m^2 is quite comparable for both tests and closely matches 0.6 sec^2. However, this error grows by approximately 50 per cent in the mid-latitudinal North Atlantic. Thus, despite the fact that, according to the SHIPMET pool, less than 30 per cent of officers estimate wave periods perfectly, relative random errors in wave periods are not very high with respect to the observed magnitudes of seasonal and

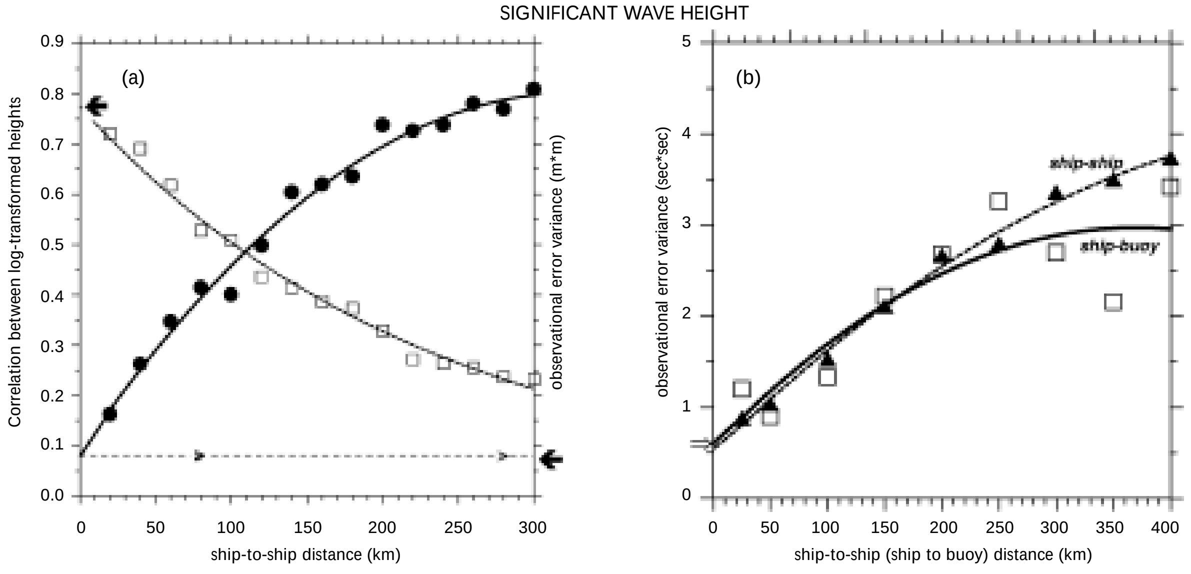

Figure 6—Semivariagram (bold line, solid circles) and correlation (dashed line, boxes) estimates of random observational error in SWH over the North Atlantic (a) and estimates of random observational error in resultant wave period for ship-buoy (solid line, triangles) and ship-ship (dashed line, boxes) pairs (b).

interannual variability (Gulev and Hasse 1998, 1999). Furthermore, we can point out that the uncertainty of observational procedures results primarily in the systematic underestimation of wave periods.

Considering the possible systematic biases in wave height, we have to mention first of all the systematic overestimation of small seas and swells in VOS data. This overestimation results from the usage of the code figure ‘1’ which is applied in COADS LMR to all waves smaller than 0.5 m. Therefore, all sea heights coded as ‘1’ should represent a value that is somewhat lower than 0.5 m. Particularly, Gulev *et al.* (1998) found that the tropical VOS wave heights are slightly lower in comparison to the altimeter data and WAM hindcast. To resolve this problem we considered two-dimensional frequency distributions of wind speed and wave height for small waves, computed using instrumental data from NDBC buoys and from the VOS reports which give ‘1’ as the measure of wave height and were sampled simultaneously with buoy measurements within a radius of 50 km. Buoy records report significant wave height and do not provide separate measurements of sea and swell. Thus, we selected the cases with the absence of swell in the VOS reports for this comparison. We required that the VOS wind speed estimate should not deviate from the wind speed measured at buoy by more than on 1 m. In total, more than 350 pairs of buoy and VOS

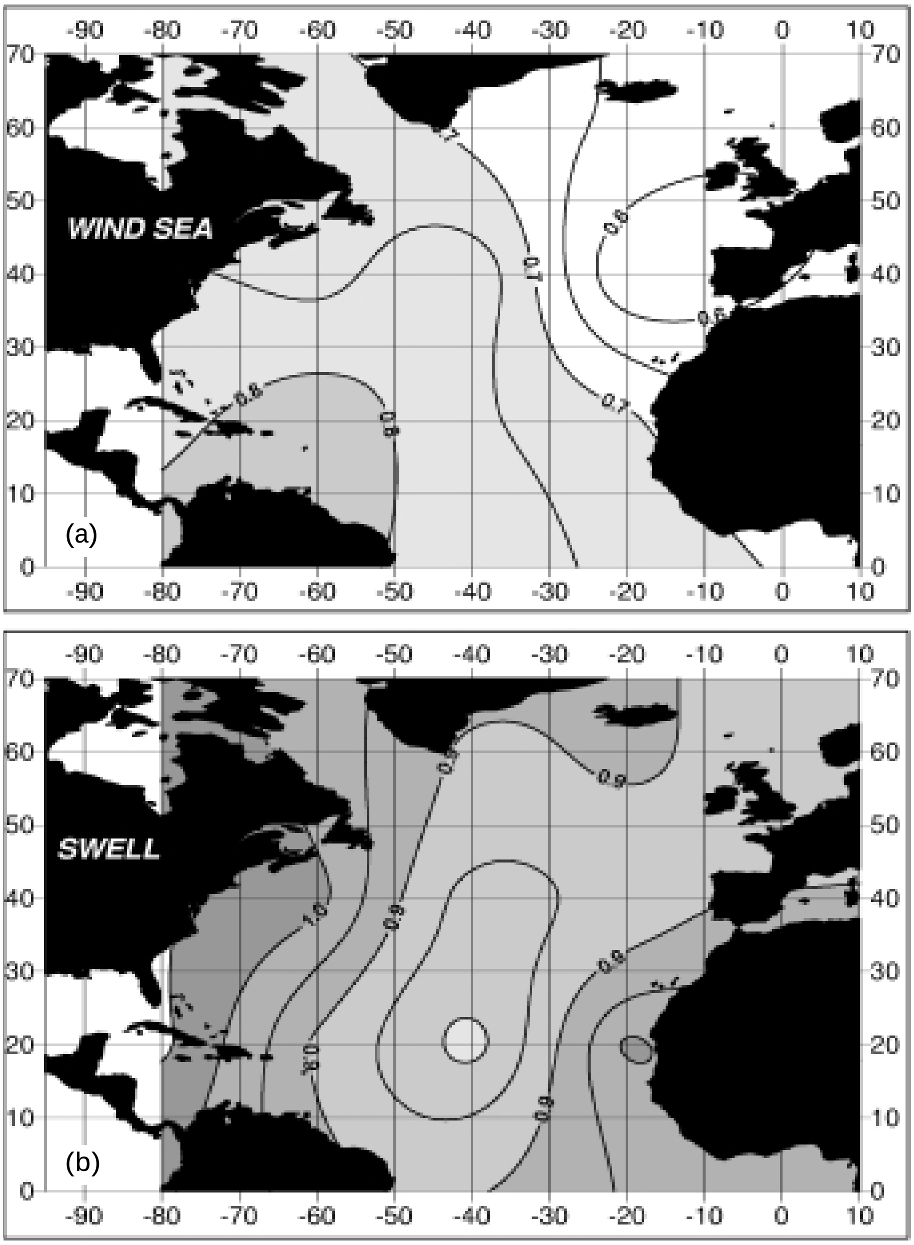

Figure 7—Spatial distribution of the random observational error (m^2) in the wind sea (a) and swell (b) visual estimates over the North Atlantic ocean. Contour interval 0.05 m^2.

measurements of SWH and wind speed were chosen, primarily in the Gulf of Mexico and in the subtropical Atlantic. The analysis of probability functions for the wind speed, derived from the buoys and VOS reports, showed frequency distributions that were very close to each other. Subsequently, the two-dimensional probability density distribution of wind speed and wave height from the buoy measurements was considered for the wind speed range of 1.2 to 6 m/s and wave height of less than 0.5. For this range we derived a simple formula which can be used for correcting VOS wave height. The corrected sea height, reported with the code figure ‘1’, has to be derived as $h_s = 0.5 - \exp(-0.658V)$, where $1.2 \leq V \leq 6$ is a wind speed. This formula makes it possible to correct small sea height with an accuracy of better than 20 per cent. Our attempts to derive the accurate correction of small swells were less successful. However, we can recommend with an accuracy of 30 per cent applying the correction of 0.15 m to all swells reported with the code figure ‘1’. Further details on the evaluation of small waves in COADS are given in Gulev *et al.* (2001).

4. SUMMARY AND CONCLUSIONS

We reviewed the accuracy of the VOS wind and wave observations using traditional statistical estimates together with the results of the questionnaire aimed at shedding light on the observational practices used by marine officers. Our initial experience with the questionnaire distributed among marine officers shows that this was quite a helpful tool for improving our knowledge of the actual uncertainties of winds and waves reported by VOSs. The statistical analysis of the pool results gives a reliable, although primarily qualitative, picture of the main sources of uncertainties inherent to the VOS observations.

It has been shown that the evaluation of true wind remains one of the most important sources of uncertainties in marine wind observations. Using ship course and velocity together with estimates of the percentages of uncorrected reports, which are available from the SHIPMET, it is possible to estimate roughly the possible error associated with the true wind correction, but it is still unclear how to correct the biases. As noted by Kent *et al.* (1993) and Gulev (1999), requirements to report both true and relative wind, or the relative wind only (even if satisfied), may result in additional uncertainty; this can affect the homogeneity of historical data. A remarkable example of this kind was the change of WMO swell period codes in 1968. This change was not simultaneously accepted by all nations and ship companies, and resulted in the biased swell periods for 1968-1969. However, the creation of some high quality regional and time limited subsets of the VOS data (like VSOP-NA) is very important for marine climatologists.

Wave parameters visually observed by marine officers can be successfully derived from the COADS collection of marine meteorological observations. Although the sampling frequency of wave observations is somewhat smaller in comparison to wind and temperature observations, it makes it possible to produce global and basin scale climatologies. However, south of 40S, VOS wave products should be considered with great care owing to the considerable undersampling of this region. It should be noted that VOS climatologies of the other parameters also show large sampling errors in these latitudes. We quantified the accuracy of visual wave observations. Random observational errors ranged from 0.5 to 0.85 m^2 for wind sea, from 0.8 to 1 m^2 for swell and from 0.4 to 0.7 sec^2 for wave periods. Beside the random observational errors, visual wave observations are influenced by some systematic biases. In particular, small waves are overestimated because of the coding system in the COADS, and periods are also underestimated by several tens of seconds. Simple corrections of these biases can be applied. At the same time, systematic biases associated with the differences in observational practices during the day and at night-time were not found.

Results of the SHIPMET questionnaire show that the approaches adopted by the officers affect the wave observations in the same degree as visual wind estimates. In this sense, the relative observational accuracy of wave observations should not be worse than for Beaufort wind estimates. Comparisons of visual wave estimates with instrumental measurements and alternative global data

(Gulev *et al.*, 1998) show a number of systematic biases between the VOS waves and alternative wave products. In particular, there is an evident overestimation of small waves, an underestimation of high waves, and an overall underestimation of wave periods. It should be noted that small and high waves in the model hindcasts and satellite products are also of a low accuracy. In this sense, buoys and the other in situ platforms provide in situ observations of a very high value, but further efforts are needed to obtain reliable estimates of sea and swell from wave recorders. Otherwise, direct comparisons with the VOS data will always be influenced by the uncertainty of evaluation of SWH from visual estimates of sea and swell. To quantify and correct the systematic biases in the VOS wave observations it could be desirable in the future to establish some kind of analog of equivalent Beaufort scale(s) for visual wave estimates.

Results of the SHIPMET questionnaire show that visual estimates of ocean waves and winds are, in fact, largely influenced by each other and are not fully independent. A considerable amount of wave observations are actually simplified local wave hindcasts carried out by sailors on the basis of wind information. The standardization of COADS formats also works in this direction. In this context, it is difficult to use jointly wave and wind information to cross-check the quality of wind and wave parameters. Nevertheless, these checks, if performed for the limited collections of truly independent observations, can help to considerably improve the accuracy of both wind and wave fields.

ACKNOWLEDGEMENTS

We would like to thank David Cotton of SATOBSYS (Godalming), Lutz Hasse of IFM (Kiel), Neil Hogben of BMT Ltd. (Teddington) and Andreas Sterl of KNMI (de Bilt) for the useful discussions. We appreciated the suggestions and criticism of two anonymous reviewers which helped to improve the paper. The COADS data for this study were made available courtesy of Steve Worley of NCAR (Boulder). Special thanks are also given to all marine officers who agreed to participate in the SHIPMET pool. This study was supported by the Russian Ministry of Science and Technology under the ‘World Ocean’ National Programme and EU INTAS grant 96-2089.

REFERENCES

Barratt, M.J., 1991: *Waves in the North East Atlantic*. UK Department of Energy Report OTI 90545, HMSO, London, 16 pp. (with 40 figures).

Cardone, V., 1969: *Specification of the Wind Distribution in the Marine Boundary Layer for Wave Forecasting*. Report TR69-1, New York University, N.Y., 131 pp.

Cotton, P.D., P.G. Challenor, L. Redbourn-Marsh, S.K. Gulev, A. Sterl and R. Bortkovsii, 1999: An intercomparison of in situ, voluntary observing, satellite data, and modelling wind and wave climatologies. *Preprints of the CLIMAR99-WMO Workshop on Advances in Marine Climatology* (Vancouver, Canada, 1999), 110–120.

Carter, D.J.T., 1982: Prediction of wave height and period for a constant wind velocity using the JONSWAP results, *Ocean Engng*., 9, 17-33.

Dacunha, N.M.C., N. Hogben and K.S. Andrews, 1984: Wave climate synthesis worldwide. *Proc. Int. Symp. on Wave and Wind Climate Worldwide*. Royal Inst. Naval Architects, London, 1–11.

da Silva, A.M., C.C. Young, and S. Levitus, 1995: Toward a revised Beaufort equivalent scale. *Proceedings of the International COADS Winds Workshop* (Kiel, Germany, 1994). Ed. H. Diaz and H.-J. Isemer, NOAA-ERL, IFM (Kiel), 270–286.

Gulev, S.K., 1996: *SHIPMET – pilot questionnaire for VOS officers*. Release 1. P.P. Shirshov Inst. of Oceanol., RAS, Internal note, Moscow, 43 pp.

Gulev, S.K., 1999: Comparison of COADS Release 1a winds with instrumental measurements in the north-west Atlantic. *J. Atmos. Oceanic Technology*, 16, 133–145

Gulev, S.K. and L. Hasse, 1998: North Atlantic wind waves and wind stress from voluntary observing data. *J. Phys. Oceanogr*., 28, .1107–1130.

Gulev, S.K., D. Cotton and A. Sterl, 1998: Intercomparison of the North Atlantic wave climatology from voluntary observing ships, satellite data and modelling. *Physics and Chemistry of the Earth*, 23, n.7/8, 587–592.

Gulev, S.K. and L. Hasse, 1999: Changes of wind waves in the North Atlantic over the last 30 years. *Int. J. Climatol.*, 19, 1091–1018.

Gulev, S.K., V. Grigorieva and A. Sterl, 2001: Global climatology of wind waves from voluntary observing ship data. *J. Geophys. Res.*, submitted.

Hogben. N., 1988: Experience from compilation of global wave statistics. *Ocean Engng.*, 15, 1–31.

Hogben, N. and Lumb, 1967: *Ocean Wave Statistics*. The Ministry of Technology, HMSO, London, 263 pp.

Hogben, N., N.M.C. Dacunha and G.F. Oliver, 1986: *Global Wave Statistics*. Unwin Brothers, London, 661 pp.

Houmb, O.G., K. Mo and T. Overvik, 1978: *Reliability Tests of Visual Wave Data and Estimation of Extreme Sea States*. Division of port and ocean engineering. Univ. Trondheim, Norwegian Institute of Technology, Report No. 5, 28 pp with figures and tables.

Isemer, H.-J. and L. Hasse, 1991: The scientific Beaufort equivalent scale: Effects on wind statistics and climatological air-sea flux estimates in the North Atlantic Ocean. *J. Climate*, 4, 819–836.

Kaufeld, L., 1981: The development of a new Beaufort equivalent scale. *Meteor Rundsch.*, 34, 17–23.

Kent, E.C. and P.K. Taylor, 1997: Choice of a Beaufort equivalent scale. *J. Atmos. Oceanic Tech.*, 14, 228–242.

Kent, E.C., P.K. Taylor, B.S. Truscott and J.S. Hopkins, 1993: The accuracy of voluntary observing ships' meteorological observations-results of the VSOP-NA. *J. Atmos. oceanic Tech.*, 14, 591–608.

Kent, E.C., P.G. Challenor and P.K. Taylor, 1999: A statistical determination of the random observational errors present in voluntary observing ships meteorological reports. *J. Atmos. Oceanic Tech.*, 16, 905–914.

Laing, A.K., 1985: An assessment of wave observations from ships in Southern Ocean. *J. Clim. Appl. Meteor.*, 24, 481–494.

Lindau, R., 1995: A new Beaufort equivalent scale. *Proceedings of the International COADS Winds Workshop* (Kiel, Germany, 1994). Ed. H. Diaz and H.-J. Isemer, NOAA-ERL, IFM (Kiel), 232–252.

Ochi, M.K., 1978: Wave statistics for the design of ships and offshore structures. Proc. SNAME, November 1978, New York, N.Y.

Smith, S.R., M.Bourassa and R.J.Sharp, 1999: Establishing more truth in true winds. *J. Atmos. Oceanic Tech.*, 16, 939–952.

Wilkerson, J.C. and M.D. Earle, 1990: A study of differences between environmental reports by ships in the voluntary observing program and measurements from NOAA Buoys. *J.Geophys.Res.*, 95, 3373–3385.

WMO, 1973: Commission for Marine Meteorology. *Abridged Final Report of the Sixth Session*. Geneva, Switzerland, 117 pp.

Woodruff, S.D., H.F. Diaz, J.D. Elms and S.J. Worley, 1998: COADS Release 2 data and Metadata enhancements for improvements of marine surface flux fields. *Physics and Chemistry of the Earth*, 23, 7/8, 517–526.

Yelland, M., B.I. Moat, P.K. Taylor, R.W. Pascal, J. Hutchings and V.C. Cornell, 1998: Wind stress measurements from the open ocean corrected for airflow distortion by ship. *J. Phys. Oceanogr.*, 28, 1511–1526.