The Accuracy Of Marine Surface Winds From Ships And Buoys

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1. INTRODUCTION

In this paper we will review progress in determining the accuracy of marine wind observations since the International COADS Winds Workshop, held in Kiel in 1994 (Diaz and Isemer, 1995). Accurate marine wind data are important because, since the sea surface roughness increases with wind speed, wind stress increases roughly as (wind speed)$^{2.7}$ and mixed layer deepening with (wind speed)^{4}. However a major problem is that that we do not have an error free source of wind data over the ocean. Whilst it might be expected that the best data sources would be anemometer measurements from research ships, ocean weather ships (OWS), research ships, or meteorological buoys, we shall demonstrate in Section 2 that there are potential biases in each of these data types. In Section 3 we will discuss the methods of wind determination used by the VOS, and then consider random errors (Section 4), and systematic errors (Section 5). We will show that quantitative knowledge of the errors is vital in order, for example, to compare ship and satellite winds. We shall consider how future developments may improve the accuracy of VOS winds (Section 7) before summarising our conclusions and providing some recommendations (Section 8).

2. LACK OF AN ABSOLUTE STANDARD

2.1 Research ships

It should not be assumed that anemometer measurements on research ships are necessarily accurate. For example, before the World Ocean Circulation Experiment (WOCE) Taylor and Weller, (1991) carefully specified the required underway meteorological measurements. Despite that, only one in five of the vessels recorded all the parameters needed to compute true wind and for less than one ship in seven was that calculation correctly applied (Smith *et al.*, 1999). On ships like research ships which are frequently moving slowly, possibly sideways or backwards, it is particularly important to separately log both the ships head and the ships course; this is not always appreciated.

Many research ships have a ship's anemometer which is permanently mounted, often over the wheelhouse, to give an indication of the meteorological conditions. Only for specific air-sea interaction experiments might they be equipped with accurately calibrated research anemometers, usually mounted on a special mast in the bow. Like all ships, research ships disturb the wind flow and the effect varies with location. Results of a wind tunnel study using a model of a small research ship, CSS Dawson (Thiebaux, 1990), are shown in Figure 1. At the ship's mainmast anemometer site the airflow is generally accelerated by 5 to 10% except when the wind is from starboard (when it is in the wake of part of the mast) or from astern. Results from a Computational Fluid Dynamics (CFD) study for bow on flow were in reasonable quantitative agreement and showed (Figure 2) that there is a large region of accelerated flow over the main accommodation block - this is typical of ships in general (Section 5.3).

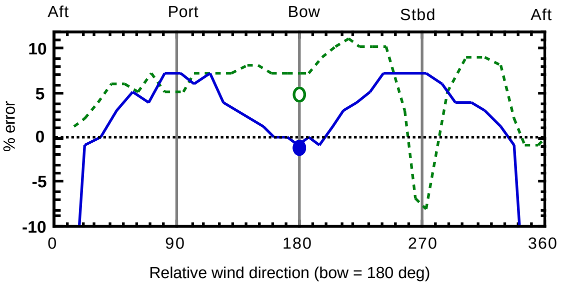

Fig. 1. Wind speed errors at the bow (solid lines) and main mast (dashed lines) anemometer sites as measured in wind tunnel studies of the CSS Dawson (Thiebaux, 1990). CFD model results are shown as a shaded circle for the bow anemometer site and a open circle for the main mast site (adapted from Yelland *et al.*, 1998b).

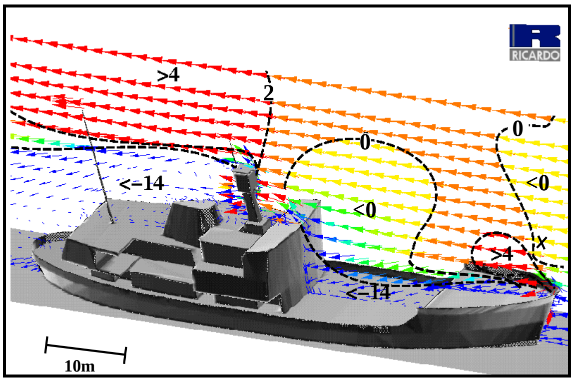

Fig. 2. CFD calculations for bow-on flow over the CSS Dawson. The shading indicates wind speed error, as a percentage of the undisturbed value, on a vertical fore-aft plane through the bow-mast anemometer position (shown by a cross). The numbers indicate the percentage error in each region.

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At the bow anemometer site the wind speed was close to the free stream value when the ship was pointed into the wind. However for wind from either beam the wind would have been over-estimated and for winds from astern the anemometer was in the wake of the accommodation block. Had this anemometer been mounted lower, it would have measured accelerated flow. On many ships the accommodation is nearer the bow and in that case the bow anemometer would be in a region of decelerated flow.

Further examples of the computed flow around research ships are given by Yelland *et al.* (1998b). It is clear that obtaining accurate measurements of the mean wind takes considerable care and that almost all ship wind data will be biased unless the airflow disturbance is allowed for.

2.2 Ocean Weather Ships

Ocean Weather Ships were of similar size to research ships. Typically they maintained their station by drifting beam on to the wind until the limit of their station "box" was reached when they would steam back into the windward limit. In higher winds they would be hove to, i.e. heading into the wind at a speed just sufficient to maintain steerage way. These different operating modes would cause varying wind flow errors at the anemometer sites which were, in any case, not necessarily ideal. For example on the OWS Cumulus (studied by Taylor *et al.* 1995) the aft mast was used. This was considered acceptable because the ship's main purpose was weather observation for forecasting purposes (and now-casting and navigation for aviation) rather than to provide a climatological wind standard.

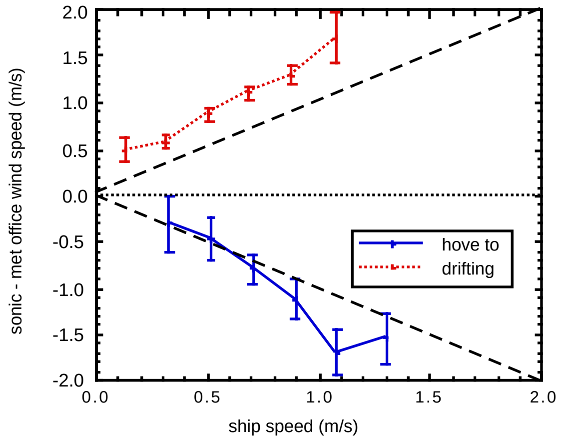

Figure 3. Average difference between wind speeds measured by research instrumentation (sonic anemometer plus GPS navigation package) and the standard WMO reports from the OWS Cumulus plotted against the ship speed from the navigation package. Cases where the ship was hove-to or drifting are shown separately, the diagonal lines indicate agreement between the wind speed error and the ship's speed (from Taylor *et al.* 1995).

For the same reason it is likely that corrections were not applied for the ship's velocity through the water unless the ship was actually steaming. Taylor *et al.*, (1995) used a sonic anemometer and GPS system on the OWS Cumulus to show that, with the ship drifting the reported wind speed was too low by slightly more than the expected amount - possibly due to flow distortion (Figure 3). When the ship was hove-to the wind speeds were over-estimated by approximately the expected amount. The difficulty of constructing a time series of weather ship data has been well illustrated by Isemer (1994); careful consideration of the history of observation at the OWS sites has resulted in a data set which is more consistent through time compared to VOS data (Isemer, 1995) but within which there are significant discontinuities at some sites.

2.3 Buoy data

Wind speeds from meteorological buoys are believed to be biased low in strong winds (Large *et al.*, 1995; Weller and Taylor, 1998; Zeng and Brown, 1998). During the Storm Wind Study 2 experiment, SWS-2 (Dobson *et al.*, 1999; Taylor *et al.*, 1999) 10m neutral equivalent winds were estimated using sonic anemometers on a buoy (at 4.5m) and a nearby research ship (at 17.5m). The comparison of the measured wind speed values is shown in Figure 4. The data are very scattered, but on average the buoy appears to under estimate the wind by about 5%. There are two possible mechanisms. Firstly, assuming that the mean wind profile is logarithmic, an instrument being moved up and down vertically by the

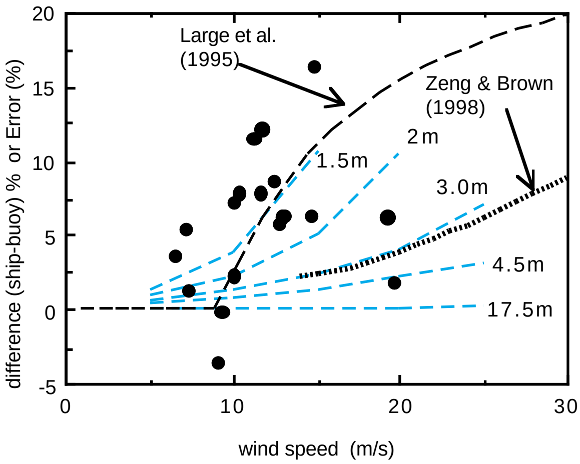

Figure 4. The difference (closed circles: (ship - buoy) %) between values of the 10m neutral wind from buoy and ship data during the SWS-2 experiment for cases where the separation was less than 10 km (anemometer heights 4.5m and 17.5m respectively). Also shown are the calculated effect of vertical movement through a logarithmic wind profiles for instruments at heights between 1.5m and 17.5m (light dashed lines); the mean error curve reported by Large *et al.* (1995) and the polynomial of Zeng and Brown (1998).

waves will measure an average wind which is less than the wind at the mean measurement height. Using the observed wave height to wind relationship for SWS-2, this effect has been crudely estimated for different anemometer heights (light dashed lines on Figure 4). Zeng and Brown, (1998) noted that there were a lack of high wind speed data in buoy observations used for scatterometer calibration. They used surface air pressure data to infer a low bias for buoy winds at higher wind speeds. Their polynomial relationship (Figure 4) appears very similar to what might be expected due to the logarithmic averaging for a 3m anemometer height - not an unreasonable mean anemometer height for the mix of buoy data which they used.

The second mechanism is that the instrument may enter regions where the vertical wind profile is distorted due to the sheltering effect of the waves. Large *et al.* (1995) have suggested that the effect is to significantly bias buoy wind data for wind speeds above some threshold. Their predicted error for a 5m anemometer height is also shown on Figure 4, it is much greater than that predicted by Zeng and Brown (1998). The preliminary SWS-2 results shown on Figure 4. appear to be of similar order to the Large *et al.* (1995) prediction, however the measured friction velocity values suggested the wind error in the 20 to 25 m/s region was 3% to 5% (similar to Zeng and Brown) rather than 15% or more. Very recently the high frequency (2 Hz) data logged on the SWS-2 buoy have become available. These include buoy motions and wind velocities and hopefully will bring more under standing to the problems of wind measurement by buoys.

2.4 Satellite data

The physics of radar backscatter or microwave emission is not well enough known to allow a absolute calibration of satellite instruments so they are calibrated and verified against buoy data. Thus if, as discussed above, the buoy data is biased the satellite retrievals will also be biased (e.g. Zeng and Brown, 1998).

3 METHOD OF OBSERVATION FOR VOS WINDS

VOS winds are either visually estimated or determined using an anemometer. In the Pacific most reports are anemometer based (Table 1). The fraction of anemometer measurements has increased with time as has the average height of the anemometer. Because of the preference of some European meteorological agencies for visually estimated winds, the fraction of anemometer reports is significantly less in the North Atlantic and the anemometers are on average mounted lower. As might be expected the anemometer height tends to be higher in the trans-oceanic shipping routes and lower in coastal regions (Kent and Taylor, 1997).

Table 1. Mean and standard deviation of the distribution of anemometer heights during January of each year indicated for the North Pacific and the North Atlantic. Also shown is the fraction of wind observations which were measured by anemometer. (after Kent and Taylor, 1997)

Year	Mean Height (m)	Standard deviation (m)	Fraction (%)
North Pacific (30° to 50°N, 180° to 150°W)			
1980	28.7	5.9	69
1986	33.7	6.4	81
1990	35.2	8.4	82
North Atlantic (30° to 50°N, 40° to 20°W)			
1980	18.4	7.3	35
1986	21.5	8.9	44
1990	24.2	10.9	38

4. RANDOM ERRORS IN VOS WINDS

4.1 Method of determination

The random errors in VOS observations may be determined by the semivariogram technique which has been described at this conference by (Kent *et al.*, 1999b). Observations from pairs of ships are compared and the squared differences in the reported wind value ranked according to the distance separating the ships. If enough observations are available, then the mean difference at zero separation may be determined by extrapolation. This represents twice the random error variance for a single ship observation.

4.2 Typical error values

Kent *et al.*, (1999) analysed VOS observations from four months (January and July 1980 and 1993) which they assumed to be typical of the period 1980 to 1993 (the large computing resources needed for the calculations prevented more months being examined). The results for wind speed are shown in Figures 5. and 6. A typical root mean square (RMS) error for a single wind speed observation was about 2.2 m/s. However this was after instrumental observations had been corrected for the height of the anemometer above the sea surface (using the WMO47 data, Kent *et al.*, 1999b) and visual observations corrected using the Lindau, (1995) version of the Beaufort scale. For the observations as reported, the errors were about 15% greater - about 2.5 m/s. This demonstrates that, despite the varying effects of air flow distortion around the ship, correcting the data for anemometer height does reduce the errors. The RMS wind speed errors appeared to be lower than average in tropical regions, however no significant dependence on wind speed was found.

4.3 Position errors

About 2 to 3% of the VOS weather reports in the Comprehensive Ocean Atmosphere Data Set (COADS, Woodruff *et al.*, 1993) collection of VOS weather reports can be identified as having incorrect position information. Typically the position is incorrect by 10° or is in the wrong quadrant. Often these data exist in COADS as a duplicates, one report having the correct position (Lander and Morrissey, 1987). Position errors are detected in operational forecast centres by tracking individual ships, but this is rarely done for climate studies. However position errors are potentially very serious because the ship might be erroneously placed away from the shipping lanes in a data sparse region. Such a report may thus be given undue weight. For example in January, 1984, ship reports from near Iceland appeared as a group of erroneous duplicates in the COADS data set, positioned near Antarctica.

5. SYSTEMATIC ERRORS IN VOS WINDS

5.1 Method of determination

Because of the lack of an absolute standard, determining the systematic errors in VOS observations is difficult. The VSOP-NA (Voluntary Observing Ship Special Observing Programme - North Atlantic) project (Kent *et al.*, 1991, 1993) was designed to identify, and if possible quantify, systematic errors in the VOS data. A subset of 46 VOS was chosen, the instrumentation used on each of the participating ships documented (Kent and Taylor, 1991), and extra information was obtained with each report, for example the relative wind at the time of observation. The output from an atmospheric forecast model was used to compare one ship observation against another. The results were then analysed according to instrument type and exposure, ship size and nationality, and other factors.

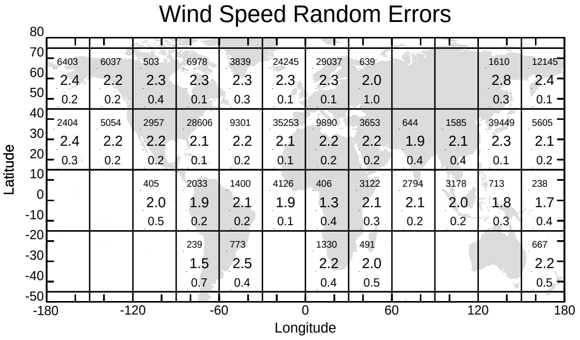

Figure 5. Random observation errors for VOS wind speed reports. The upper figure is the number of report pairs used to make the estimate, the central figure is the rms error (m/s) for each 30° region, and the lower figure is the estimated uncertainty in the rms error estimate (from Kent *et al.* 1999).

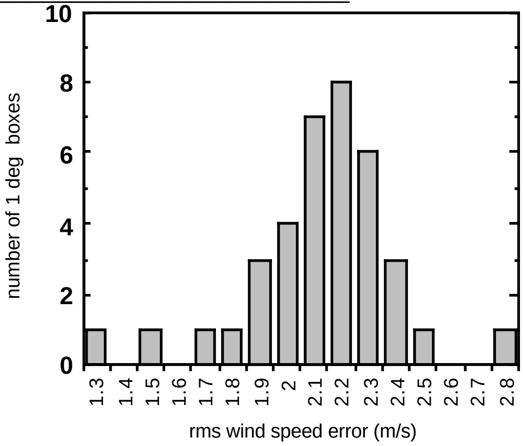

Figure 6. Histogram of the rms error estimates shown in Figure 5.

5.2. Accuracy of anemometer winds

The VSOP-NA results showed that speed estimates from hand held anemometers were very scattered at wind speeds above about 7m/s and that there was also a larger scatter in the direction estimates compared to other methods. The use of hand held anemometers was therefore to be discouraged.

The VOS in the VSOP-NA project reported the anemometer estimated, relative wind speed in addition to the calculated true wind speed (only the latter is transmitted in the standard ships weather observation). Kent *et al.*, (1991) showed that a major cause of error was the calculation of the true wind speed. Only 50% of the reported winds were within 1 m/s of the correct value, 30% of the reports were more than 2.5 m/s incorrect (Figure 7). For wind direction, only 70% were within ±10° of the correct direction and 13 percent were outside ±50°. These are large, needless errors which significantly degrade the quality of anemometer winds. A similar conclusion was reached by Gulev (1999). Results from a questionnaire distributed to 300 ships' officers showed that only 27% of them used the correct method to compute true wind, 19% did not know how to do the calculation, 21% usually did not do the calculation and 33% did it either episodically or approximately. This is perhaps not surprising given the problems in obtaining accurate true wind data from research ships (Smith *et al.*, 1999; see Section 2.1 above).

We have already noted (section 4.2) that correcting for the height above the sea of the anemometer demonstrably improved the data set. This correction should be done on a ship by ship basis since the average height of anemometers varies both geographically and with time (Section 3).

For a 10 m/s wind and neutral stratification an anemometer at 35m will read about 10% higher than

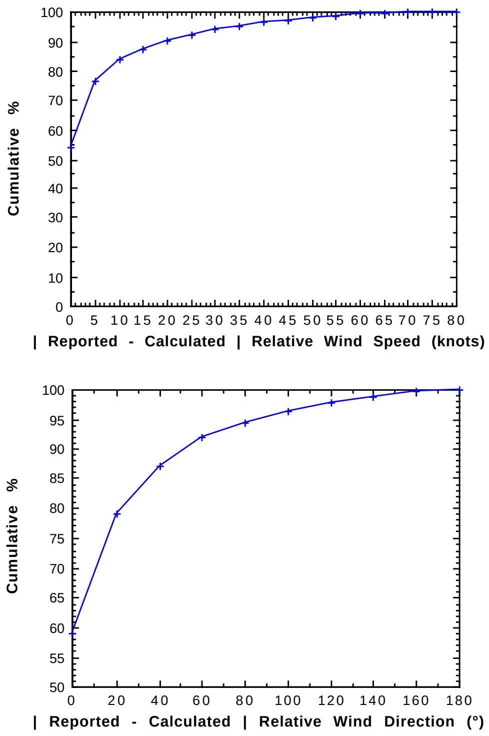

Figure 7. Cumulative histograms of the difference between the value calculated by the ship's officers and the correct value for (top) true wind speed; (bottom) True wind direction (From Kent *et al.* 1991)

one mounted at 20m. For unstable conditions this ratio decreases. For very stable conditions one or both anemometers may be outside the near surface boundary layer in which case the error would be indeterminate. Fortunately very stable conditions are relatively rare over most of the ocean. For the VSOP-NA ships which used anemometers, the mean difference between the ship and model wind speed estimates increased with anemometer height even more than might have been expected due to the vertical wind profile (Figure 8).

Taylor *et al.*, (1995) reanalysed the VSOP-NA results for wind speed. They found that, having corrected OWS Cumulus data for ship motion and corrected the VOS data for anemometer height, there appeared to be agreement between the OWS and VOS data for winds below 10 m/s. For higher wind speeds the VOS winds were biased high - by about 1.5m/s to 2 m/s at 20 m/s wind speed. If this bias is real, the reasons might include mis-reading of the anemometer dial (gust values rather than mean winds being reported) and the air flow distortion caused by the ship.

5.3 CFD studies of airflow distortion for VOS

We have noted above (Section 2.1) that for ship mounted anemometers a major consideration is the air-flow disturbance caused by the ships' hull and superstructure and shown that this may be determined using CFD simulation. The CFD results have been verified for wind speeds within 30° of the bow by comparison with data from an array of anemometers on the research ships RRS Darwin and RRS Discovery. Both ships had been instrumented with up to 10 anemometers located at various sites around the ships, including some regions of high flow distortion. These comparisons showed good agreement between the ships data and the CFD results in all cases except where the anemometers were in the wake of an upstream obstruction - a situation where the CFD code is expected to perform poorly.

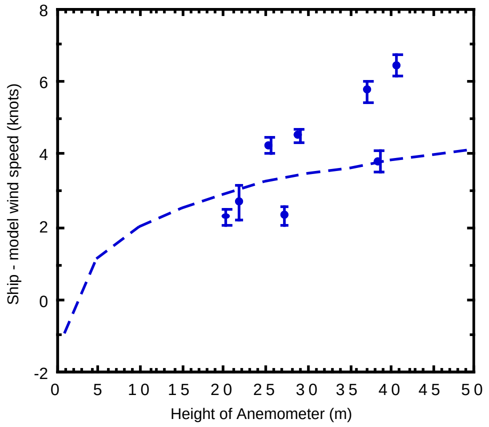

Figure 8. Mean difference between the ship and model wind speed estimates for those VSOP-NA ships which used anemometers plotted against the anemometer height. Also shown is the expected variation of wind speed with height for a neutral boundary layer. This has been offset by the estimated mean error in the model winds (2 knots).

Table 2. Dimensions (metres) for the three tanker/bulk carrier models used in the CFD studies.

Tanker model number =	(1)	(2)	(3)
Length Overall	170	250	330
Beam	27	42	62
Freeboard	6	8	10
Deck to Bridge top (D)	14	16	18
Bridge length	14	15	23

The obvious problem in applying CFD modelling to the VOS is the almost infinite variety of merchant ships sizes and shapes. However two ship types, container ships, and tankers (the results of which may also be applicable to Oil Bulk Ore, or “OBO” ships) are believed to account for around 70% of the deep-ocean merchant fleet. Since the effective shape and roughness for container ships will vary with the degree of loading, we have chosen first to study the flow over tankers. Based on a sample of 36 tankers and 8 bulk carriers, three representative models were created (Table 2 and Figure 9). Tanker 1 was modelled with a close mesh to resolved the accelerated "plume" region above the bridge; for tankers 2 and 3 a coarser mesh was used for computational efficiency.

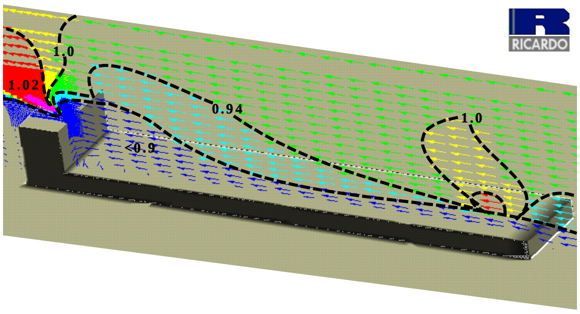

Figure 9. A three dimensional view of a simple “two block” tanker model. Model results of the wind speed error, expressed as the wind speed at a point divided by the free stream (undistorted) wind speed, are shown for a vertical plane intersecting the ship (Moat *et al.*, 1998).

Using the fluid dynamics analogy of flow past a rectangular block we would expect the bridge-to-deck height, D, to be an important scaling factor. For example comparison of tanker 2 and tanker 3 showed a similar pattern of wind speed error for heights less than about 8m, but the magnitude of the decelerations differed by up to 20% in profiles obtained near (i.e. within 5m of) the front edge of the bridge. When distances were scaled by the bridge-to-deck height these differences reduced to around 5%. Indeed, all three models showed that at a height above the wheelhouse top greater than 0.5D where any anemometer site would give an over-estimate of the wind speed by up to 5% (Figure 10). This held for all sites up to 10m back from the front edge of the bridge (Figure 11), and would not vary with a moderate displacement to port or starboard of the centre line of the bridge.

Below a height above the wheelhouse top of 0.5D the results vary with both anemometer position and with the mesh density used in the model. The tanker 1 model (fine mesh) shows a "plume" of accelerated flow, with a maximum acceleration of around 13% at a height of about 4m above the bridge (and about 4m from the bridge front), and large decelerations below this height (Figures 11 and 12). The other two tankers do not resolve the plume and both show decelerations at heights of less then 5 or 6 m. Here we have used dimensions in metres to emphasise that an anemometer mounted above the wheelhouse may be below, in, or above the plume maximum depending on how high and how far aft it is mounted. Below the plume the wind will be significantly underestimated, above the plume an overestimate will occur. If the anemometer is in the plume the over estimate may be significant and vary rapidly with relative wind direction.

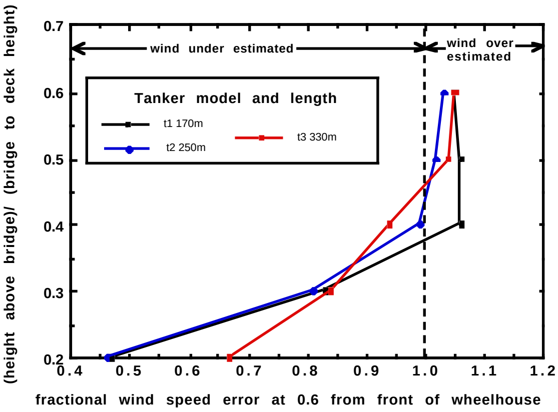

Figure 10. The fractional wind speed error for each of the three tanker models at a distance x from the front of the wheelhouse where x/D = 0.6. The vertical scale is z/D where z is the height of the anemometer above the wheelhouse. D is the height of the bridge top above the deck.

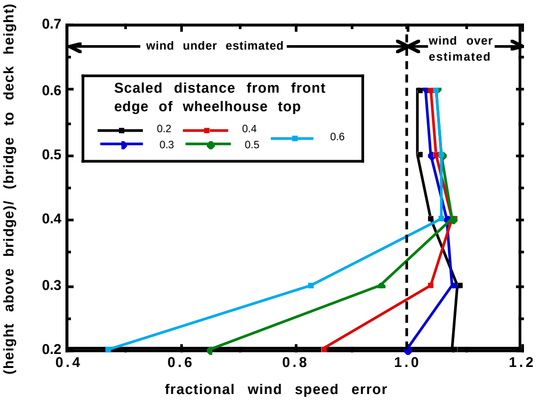

Figure 11 As Figure 10 but for tanker (1) at different scaled distances from the front of the wheelhouse, x/D.

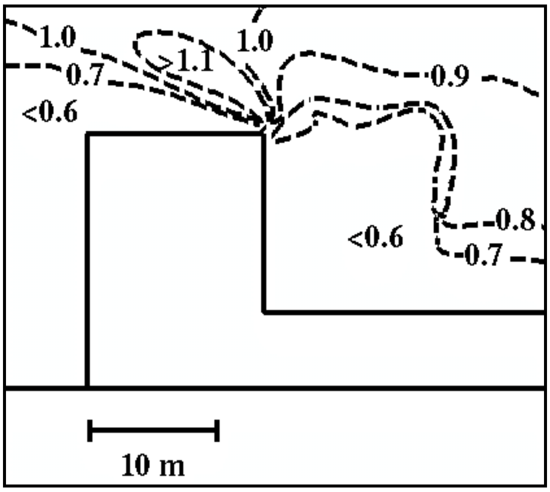

Figure 12. Detailed view showing airflow distortion over the stern section of a typical tanker as determined by CFD modelling (after Yelland *et al.*, 1998a). The wind is blowing from right to left.

5.2 Accuracy of visual wind estimates

Kent and Taylor (1997) reviewed the various Beaufort Equivalent Scales and found that that of Lindau (1995) was most effective at giving similar wind speed distributions for both anemometer estimated and visual monthly mean wind data. They also confirmed Lindau's suggestion that the characteristic biases of the earlier Beaufort scales could be explained by the statistical method by which they were derived. The UWM scale (da Silva *et al.*, 1995) which is similar to the Lindau scale, also performed well. It should be noted that the Lindau scale is more similar to the WMO1100 scale used for the observations than the so called "scientific scale" recommended by CMMIV (see WMO, 1970).

However Gulev (1999) showed that use of the Lindau scale degrades the agreement between VOS winds and a data set of Russian Research Ship winds. The reason is that the Lindau and UWM scales are calculated to bring VOS visual and VOS anemometer winds into agreement. The anemometer winds from the Russian research ships used by Gulev were similar in magnitude to unadjusted VOS visual winds and significantly higher in magnitude compared to VOS anemometer reports. Thus converting the VOS winds to the Lindau scale decreased the stronger wind values, improving the comparison with the VOS anemometer data as expected, but degrading the agreement with the Research Ship data.

If Gulev's research vessel data is correct then the implication is that VOS winds are on average under-estimated. However Isemer (1994) noted that when weather station "C" began to be manned by ships of the type which provided Gulev's data set, there appeared to be an increase in the measured winds. This does not prove that the Russian winds are necessarily too high; we repeat that, in our view, there is not an absolute standard for wind measurement.

Finally, in discussing visual winds we would stress that it is important that the ships' officers do not change from the present "WMO 1100" scale. Any adjustment should be left to those preparing climatological data sets.

6 COMPARISON WITH SATELLITE DATA

6.1 Importance of correct error treatment

Kent *et al.* (1998; henceforth K98) compared VOS winds with winds measured by the scatterometer on ERS-1. The VOS winds had been quality controlled and corrected for anemometer height, or adjusted to the Lindau scale, as appropriate. The study demonstrated very clearly the importance of properly accounting for the observation errors in each of the data sets which are compared. Thus Figure 12 shows the results of different comparison strategies. If the (satellite-ship) differences were averaged as a function of the ship winds it appeared that, compared to the ships, the scatterometer was biased high at low wind speeds and high at high wind speeds. Similar plots showing similar apparent bias can often be found in the literature (e.g. Liu, 1984; Offiler, 1994; Boutin and Etcheto, 1996).

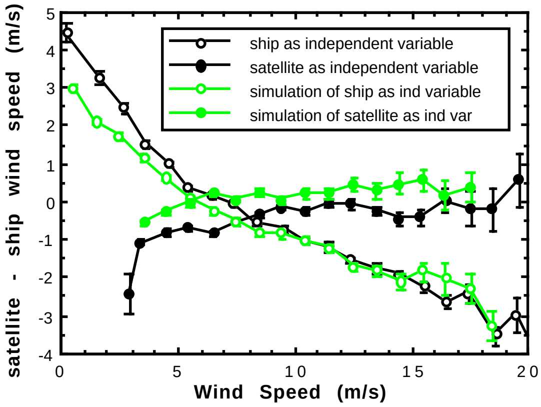

Figure 12. Comparison of the ERS-1 scatterometer with ship wind speeds showing different results depending on which data set is used as the independent variable. Also shown (lighter lines) are the results of the simulated comparison described in the text (from Kent *et al.* 1998).

However if the same differences were binned using the satellite data as the independent variable then the conclusions appeared different. The satellite data were apparently low at lower winds but in agreement with the ship data over much of the wind speed range. K98 demonstrated that this was due to the different variance for the two data sets, a problem that has been recently discussed by Tolman (1998; see also Kent & Taylor, 1999).

To simulate the effect, K98 used a single wind speed data set obtained from a moored buoy. The simulated data sets were calculated by adding to the buoy wind data random errors, normally distributed with an rms of 2.0 m/s to represent the ship winds, and 0.5 m/s to represent the scatterometer winds. These rms values had previously been obtained by semivariogram analysis. The two simulated data sets were then analysed in a similar manner to the actual data sets. Apart from a small offset when using the simulated satellite data as the independent variable, the results of the simulation (also shown on Figure 12) showed the same behaviour as the real data. K98 proceeded to demonstrate that the same effect could result in a stability dependent bias being erroneously ascribed to the scatterometer data.

Using a correct regression method (e.g. Graybill, 1961) K98 showed that the ship winds were slightly higher than those from the scatterometer:

$$U_{10n}(ship) = 1.025U_{10n}(scat) + 0.255 \qquad (1)$$

A much different result than would be obtained by regressing the satellite winds on the ship winds without considering the errors. The ship values are about 0.5 m/s higher at 10 m/s and 1 m/s higher at 30 m/s. This could be due to the buoy measured winds, used to develop the scatterometer algorithm, underestimating the wind speed; it may be due to airflow disturbance biasing the ship winds; we do not know if either is the more correct.

6.2 Quality control of VOS data

K98 also showed that the scatterometer data could be used to identify ships whose wind reports showed large biases or error variability. Thus Figure 13(a) shows the distribution of satellite-ship comparisons for two ships reporting reliable winds. The rms scatter is typical of the overall data set from the ships and the mean bias is similar to that predicted by (1). In contrast Figure 13(b) shows the distribution for two ships whose wind estimates were less reliable. Although both histograms showed a number of observations close to the scatterometer values, secondary peaks occurred at about 4 m/s difference. Since these ships were reporting visual winds, correction to true wind should not have been a problem. Rather it suggests that a Beaufort force two intervals away from the true value was sometimes chosen.

7. FUTURE DEVELOPMENTS

7.1 Automatic coding

The use of automatic coding of ship's weather message using a personal computer system and form filling techniques is becoming more common. A popular system is "TurboWin" developed at KNMI in the Netherlands. Such a system should ensure that position is correctly coded (and is compatible with the last reported position), and by automatically computing true wind remove a major source of error.

7.2 Automatic data acquisition

Computer based systems can also be used to automate the data acquisition. For example the Improved Meteorological System (IMET) has been installed on a number of the U.S. Research Vessels and is now being placed on U. S. VOS (Weller and Taylor, 1998). IMET uses sensors chosen (based on laboratory and field studies) for accuracy, reliability, low power consumption, and their ability to stay in calibration during unattended operation. The sensors are combined with front end, digital electronics to make a module that is digitally addressable (RS-232 or RS-485), stores its calibration information, and provides either raw data or data in meteorological units. The present set of IMET modules includes wind velocity and most other meteorological variables.

7.3 Air-sea flux determination

Using European Union funding under the MAST programme, the AutoFlux-Group (1997) are developing an autonomous system for monitoring air-sea fluxes using the inertial dissipation method and ship mounted instrumentation. They aim to develop and test a prototype system, "AutoFlux", which will measure surface stress, sensible and latent heat flux and also carbon dioxide flux. The system is aimed primarily towards unattended use on Voluntary Observation Ship (VOS) and on unmanned buoys. The fluxes are derived from the turbulence spectra using the "inertial dissipation" method. This technique minimises the effects of flow distortion and platform motion. The system software will manage the data conversion, storage and transmission including the necessary navigational information. The present project should be regarded as "proof of concept" but if successful, AutoFlux type systems might be being installed on selected VOS in a few years time. Transmitting flux data over the GTS will require a new code format.

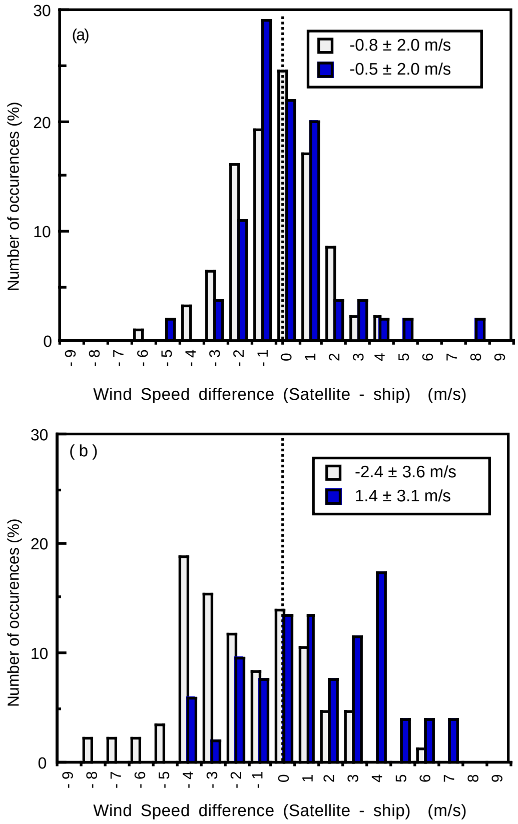

Figure 13. Comparison of satellite-ship wind speed differences for individual ships: (a) two "good" ships (one anemometer, one visual); (b) two "bad" ships (both visual).

7.4 Satellite transmission

The recent introduction of relatively inexpensive global data transmission systems via satellites suggests the possibility of transmitting a more comprehensive weather observation message including information such as the method of SST measurement, the relative wind observation, etc. The full message could be archived for use in climate studies and the standard GTS message extracted and transmitted by the land station for weather prediction purposes.

7.5 A improved subset of the VOS

While these various improvements to VOS observations are highly desirable, systems such as IMET or AutoFlux are much more expensive, and require more shore-side support, compared to the instrumentation typically provided to the VOS. It will not be practicably to supply such instrumentation to a substantial fraction of the VOS fleet. However establishment of an improved subset of VOS would provide a verification standard which would allow the biases in the standard VOS data to be quantified. As a result all VOS observations would be improved in value. A subset of about 100 to 300 chosen VOS could provide a significant contribution (e.g. Taylor, 1984).

8. SUMMARY

We have emphasised the lack of an absolute calibration standard for marine wind measurements. Wind data obtained from ships is affected by the air flow distortion around the ship. This is true for all practicable anemometer sites. Positions can be found where for some relative wind directions the disturbed wind speed matches the free stream wind speed but this is unlikely to hold for all wind directions. We have demonstrated success at correcting these errors using CFD or wind tunnel data but there are very few data sets for which this has been done. Data from buoys is suspect at higher wind speeds because of the sheltering effect of waves. The error in buoy winds may have also caused bias in scatterometer data.

The fraction of anemometer based winds has increased with time, particularly in the Pacific. The average height of anemometers is higher in the Pacifica compared to the Atlantic. Correcting for anemometer height (on a ship by ship basis) and adjusting winds to the Lindau scale reduces the rms scatter in the wind speed data set by about 15%.

A major error source in anemometer derived winds is the calculation of true wind speed and direction from the measured wind speed; an automatic method of calculation is required. CFD studies on the airflow over simple generic tanker models shows that it is important that the anemometer be mounted above the plume of accelerated air which occurs over the wheelhouse top.

In comparing ship and scatterometer data we have emphasised the importance of taking into account the different error characteristics. If that is done then it appears that the ships are biased high compared to the scatterometer by around 4%; we do not know which is the more correct. The scatterometer data can be used to determine ships whose wind reports are less reliable.

In the future it is expected that VOS meteorological reports will be increasingly automated, removing the errors in calculating true winds or in coding the ship's position. An improved subset of the VOS would be valuable as a standard for improving the VOS data set as a whole.

Finally we make the following recommendations:

- For ship's reporting anemometer winds the ship's officers should be provided with a automated method of calculating the true wind.
- Anemometer readouts should automatically average the winds.
- Hand held wind sensors should not be used.
- The position of the anemometer must be documented. This must include height above sea level and also measurements indicating the location of the anemometer with regard to the overall shape of the ship. In future this will allow average CFD corrections to be calculated for typical VOS.
- Visual wind observations should continue to be based on the WMO 1100 scale. For scientific analysis the Lindau scale is to be preferred over other versions (such as CMM IV).
- That a high quality subset of the VOS be developed and used to verify the data from the VOS fleet as a whole.

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REFERENCES

AutoFlux, 1997: AutoFlux: an autonomous system for monitoring air-sea fluxes using the inertial dissipation method and ship mounted instrumentation (MAST Project) http://www.soc.soton.ac.uk/JRD/MET/AUTOFLUX

Boutin, J. and J. Etcheto, 1996: Consistency of Geosat, SSM/I, and ERS-1 Global Surface Wind Speeds - Comparison with in situ data. *J. Atmos. & Oceanic Tech.*, **13**, 183 - 197.

da Silva, A. M., C.C.Young and S. Levitus, 1995: Towards a revised Beaufort equivalent scale. *in* Diaz & Isemer (1995), 270 - 286.

Diaz, H. F. and H.-J. Isemer (ed.), 1995: *Proc. Internat. COADS Winds Workshop, Kiel, Germany 31 May - 2 June 1994.* NOAA/ERL Boulder, Colorado & Institit für Meereskunde, Kiel., 301 pp.

Dobson, F. W., R. J. Anderson, P. K. Taylor and M. J. Yelland, 1999: Storm Wind Study II: Open Ocean Wind and Sea State Measurements. *Air Sea Interface Symposium*, Sydney, Australia, 11-15 January 1999.

Graybill, F., 1961: *An introduction to linear statistical models, Volume 1*, New York: McGraw-Hill, 463 pp.

Gulev, S. K., 1999: Comparison of COADS Release 1a winds with instrumental measurements in the NorthWest Atlantic. *J. Atmos. & Oceanic Tech.*, **16**(1), 133 - 145.

Isemer, H.-J., 1994: On the homogeneity of Surface Wind Speed records from Ocean Weather Stations, Inst. für Meereskunde, Kiel, Germany, 43 pp. + figs.

Isemer, H.-J., 1995: Trends in Marine Surface Wind Speed: Ocean Weather Stations versus Voluntary Observing Ships, *in* Diaz & Isemer (1995), 68 - 84.

Kent, E. C. and P. K. Taylor, 1999: Accounting for random errors in linear regression: A practical guide. *Q. J. Roy. Met. Soc.*, (accepted).

Kent, E. C. and P. K. Taylor, 1997: Choice of a Beaufort Equivalent Scale. *J. Atmos. & Oceanic Tech.*, **14**(2), 228 - 242.

Kent, E. C., P. K. Taylor and P. Challenor, 1998: A Comparison of Ship and Scatterometer-Derived Wind Speed Data in Open ocean and coastal areas. *Int.J.Remote Sensing*, **19**(17), 3361 - 3381.

Kent, E. C., P. Challenor and P. Taylor, 1999a: A Statistical Determination of the random observational errors present in VOS Meteorological reports. *J. Atmos. & Oceanic Tech.* (accepted), 16(7), 905 - 914.

Kent, E. C., P. K. Taylor and S. A. Josey, 1999b: Improving Global Flux Climatology: The Role of Metadata. *CLIMAR 99, WMO Workshop on Advances in Marine Climatology*, Vancouver, 8 - 15 Sept. 1999.

Kent, E. C., P. K. Taylor, B. S. Truscott and J. A. Hopkins, 1993: The accuracy of Voluntary Observing Ship's Meteorological Observations. *J. Atmos. & Oceanic Tech.*, **10**(4), 591 - 608.

Kent, E. C., B. S. Truscott, J. S. Hopkins and P. K. Taylor, 1991: *The accuracy of ship's meteorological observation - results of the VSOP-NA.* Marine Meteorology and Related Oceanographic Activities 26, WMO, Geneva, 86pp.

Large, W. G., J. Morzel and G. B. Crawford, 1995: Accounting for Surface Wave Distortion of the Marine Wind Profile in Low-Level Ocean Storms Wind Measurements. J. Phys. Oceanogr., 25, 2959 - 2971.

Lindau, R., 1995: A new Beaufort equivalent scale, *in* Diaz & Isemer (1995), 232 - 252.

Liu, W. T., 1984: The effects of the variation in sea surface temperature and atmospheric stability in the estimation of average wind speed by Seasat-SASS. *J. Phys. Oceanogr.*, **14**, 392-401.

Moat, B. I., M. J. Yelland and P. K. Taylor, 1998: The impact of airflow distortion on in situ meteorological wind speed measurements. *Proc. 23rd European Geophysical Society General Assembly*, Nice, 20-24th April, 1998, Annales Geophysicae, C646.

Offiler, D., 1994: The calibration of ERS-1 satellite scatterometer winds. *J. Atmos. & Oceanic Tech.*, **11**, 1002 - 1017.

Smith, S. R., M. A. Bourassa and R. J. Sharp, 1999: Establishing more truth in true winds. *J. Atmos. & Oceanic Tech.*, **16**(7), 939-952.

Taylor, P. K., 1984: The determination of surface fluxes of heat and water by satellite microwave radiometry and in situ measurements. *NATO ASI, Series C: Math. and Phys. Sci.*: *Large-scale oceanographic experiments and satellites*, C. Gautier and M. Fieux, Ed., *Vol.128*, D.Reidel, 223 - 246.

Taylor, P. K. and E. C. Kent, 1999: The Accuracy Of Meteorological Observations From Voluntary Observing Ships - Present Status And Future Requirements. *First Session of the CMM Subgroup on Voluntary Observing Ships*, Athens, 8 - 12 March, 1999., (to be published by WMO)

Taylor, P. K., E. C. Kent, M. J. Yelland and B. I. Moat, 1995: The Accuracy of Wind Observations from Ships. *in* Diaz & Isemer (1995), 132 - 155.

Taylor, P. K. and R. A. Weller, 1991: *Meteorological measurements from WOCE research ships.* WOCE Operations Manual, Vol 3: Section 3: Underway Measurements WHPO 91-1, WOCE Report 68/91, WOCE, Woods Hole, Mass. USA, 26pp.

Taylor, P. K., M. J. Yelland, F. W. Dobson and R. J. Anderson, 1999: Storm Wind Study II: Wind Stress Estimates from Buoy and Ship. *Air Sea Interface Symposium*, Sydney, Australia, 11-15 January 1999.

Thiebaux, M. L., 1990: Wind tunnel experiments to determine correction functions for shipborne anemometers. *Canadian Contractor Rep. Hydrog. & Ocean Sci. 36*, BIO, Dartmouth, Nova Scotia, 57 pp.

Tolman, H. L., 1998: Effects of observational errors in linear regression and bin-average analysis. *Q. J. Roy. Met. Soc.*, **124**(547), 897 - 917.

WMO, 1970: *The Beaufort scale of wind force (technical and operational aspects),* World Meteorological Organisation, Geneva, 22 pp.

Weller, R. A. and P. K. Taylor, 1998: A Strategy for Marine Meteorological and Air-Sea Flux Observation. *Preprint volume: 3rd Symp. on Integrated Observing Systems*, Dallas, Texas, Jan., 1999, AMS, Boston.

Woodruff, S. D., S. J. Lubker, K. Wolter, S. J. Worley and J. D. Elms, 1993: Comprehensive Ocean-Atmosphere Data Set (COADS) release 1a: 1980-92. *Earth System Monitor*, **4**(1), 4 - 8

Yelland, M. J., B. I. Moat and P. K. Taylor, 1998a: Air-flow distortion around voluntary observing ships. May 1998 Progress report. *Contract rep. for AES and BIO.*

Yelland, M. J., B. I. Moat, P. K. Taylor, R. W. Pascal, J. Hutchings and V. C. Cornell, 1998b: Measurements of the open ocean drag coefficient corrected for air flow disturbance by the ship. *J. Phys. Oceanogr.*, **28**(7), 1511 - 1526.

Zeng, L. X. and R. A. Brown, 1998: Scatterometer observations at high wind speeds. *J. Appl. Meteorol.*, 37(11), 1412 - 1420.