The Accuracy of Wind Observations from Ships

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Introduction

Wind observations from voluntary Observing Ships (VOS) are either visual "Beaufort Scale" estimates or obtained by using an anemometer. Although the fraction of reports from each method varies from one ocean area to another, in all areas the percentage of anemometer derived reports has increased with time. Neither method necessarily gives an unbiased estimate of the wind velocity; visual wind estimates depend on calibration against anemometer values, and there are several possible sources of significant, systematic biases in anemometer observations. Given this situation, the aim must be to produce a consistent data set of wind observations in which anemometer and visual derived observations give rise to the same wind speed distributions. Such a data set should eliminate spurious "climatic" trends such as an apparent wind speed increase due to the increased use of anemometers (e.g. Cardone et al. 1990).

In this paper we will present the results of work at the James Rennell Centre on the accuracy of ship winds, occasionally reviewing other work which, having been published in reports, may not be readily available. Considering sampling issues, we shall briefly review evidence on the percentage mix of visual and anemometer winds and comment with regard to the possibility of "fair weather bias" in the VOS wind observations. Since Ocean Weather Ships have frequently been used to verify VOS wind estimates we shall report our results from Ocean Weather Station Lima. Results from the VOS Special Observing Programme - North Atlantic (VSOP-NA) will be used to compare visual winds (corrected to various Beaufort Scales) to observations from ships equipped with anemometers. We will then discuss the accuracy of anemometer wind estimates from ships.

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Sampling Issues

Percentage of visual and anemometer winds

Although it is known to contain inaccuracies, Kent et al. (1993) used the List of Selected Ships (WMO, 1990) to estimate that, at about that time, 70% of the global VOS fleet provided visual estimates, 22% used fixed anemometers, and 8% used hand-held anemometers. Which method was used depended principally on which country's meteorological agency had recruited the VOS, for example Germany and the UK advocate visual estimates whereas Japan and the USA use fixed anemometers and France supplies hand-held instruments. Thus, although many VOS operate world-wide, the mix of wind observation methods can be expected to vary from one ocean area to another. This is confirmed in the maps of the percentage of anemometer wind reports in the UK Meteorological Office marine data bank, presented by Ive (1987) for each 5 year period from 1960 to 1979; typical values are shown in Fig. 1. Cardone et al. (1990) also give the numbers of measured and visual observations for 3 areas, values estimated from their graphs are also shown in Fig. 1 together with values from (Ramage, 1987) which, although attributed to the global VOS fleet, are presumed to relate to the South China Sea.

Several features are apparent from Fig. 1. The number of anemometer derived winds has increased more rapidly in the Pacific compared to other ocean areas. Most of the winds from the Atlantic are visual. In the Southern Ocean there are a significant number of anemometer reports, probably from research ships and Antarctic supply vessels. There are problems with the data. Ive (1987) notes that all USA VOS reports for 1975 to 1981 were flagged as visual and this error also appears to be evident in the data of Cardone et al. (1990) for the North Pacific and South China Sea. The rapid increase in numbers of anemometer winds from the North Atlantic shown by the latter authors also looks suspicious compared to the previous trends.

Figure 1 clearly shows that, unless visual and anemometer winds can be shown to be equivalent, there is the potential for introducing spurious spatial and temporal variations in the calculated wind climate.

Sampling by merchant ships -fair weather bias

The possible existence of fair weather bias must be considered when evaluating visual winds. For example if a Beaufort conversion scale has been derived by comparison of weather ship anemometer and VOS visual wind speed distributions, any fair-weather bias may have been effectively removed from the visual data. Kent and Taylor (1994) noted that the VSOP-NA data set contained fewer observations at high latitudes during the winter months. However this need not have resulted in a bias provided that those observations which were available were randomly distributed with respect to the weather conditions. They tested this possibility by comparing two distributions of wind reports to determine whether the VOS sampled the wind climate at ocean station LIMA (57°N 20°W) in the same way as the weather ship CUMULUS which occupies that station. The first distribution was the full set of wind speeds reported by the OWS CUMULUS. The second distribution was the subset of OWS CUMULUS wind speed reports corresponding to times at which there was a VOS meteorological observation from the 5° by 5° area surrounding LIMA. If more than one VOS report had been received at the same time, the CUMULUS report was included in the distribution the appropriate number of times. Figure 2 shows the resulting distributions of wind speed occurrences. Using a χ^2-test the data sets were found to be the same to within 97.5% confidence limits.

Kent and Taylor (1994) therefore concluded that there did not appear to be a significant re-routing of ships during periods of high wind speed in the area around LIMA. Presumably those VSOP-NA ships which traveled further south in winter did so because it was winter rather than because it was rough at the time of their voyage; those that traveled north did so whatever the weather.

Accuracy of Ocean Weather Ship Wind Reports

Background

Wind reports from Ocean Weather Ships have been used for comparison with VOS wind reports by Quayle (1980), Graham (1982) and others, and data from the OWS Cumulus will be used in evaluating the VSOP-NA results (Section 4, below). However the weather ship meteorological observations are generally made to the standard required for weather forecasting rather than climate research. In this section we will therefore report the results of Taylor et al. (1994) which compare research quality wind measurements from the Cumulus with the standard weather ship observations. Both sets of observations were derived from anemometers and may therefore contain some of the errors which will be discussed in more detail in section 5.

The Data

The research quality wind data were obtained during the period April, 1992 to January, 1994, from a sonic anemometer mounted on the port side of the foremast platform. Ten minute averaged “horizontal” wind components and a vector averaged total wind vector were available 4 times per hour. There was negligible difference between these two estimates of the relative wind. The ships motion was recorded from a GPS navigation system, and the ship’s head from a flux gate compass, at 2 minute intervals. These data were used to calculate true wind values.

The standard hourly WMO wind observations are obtained by a meteorological officer reading an analog dial. There are two cup-anemometer and wind vanes mounted to either side of the aft mast platform; the windward one is read. The ship speed is obtained from the ship’s officer on the bridge, the ship’s head from a compass repeater. The true wind is calculated using a hand calculator.

Ship operating characteristics

Figure 3 illustrates the recorded behavior of the OWS Cumulus in response to the wind speed climate at Lima. The most likely wind speed is about 10 m/s. For winds up to about 15 m/s the ship usually drifts (sideways with the wind about 10 degrees forward of the port beam) until the edge of the operating area is reached, whereupon the ship steams back to the upwind side of the area. If the wind or sea state is too high (normally above 15 m/s wind speed), the ship heads bow into the wind at slow speed (“hove to”). Note that, while the UK Met. Office anemometers are well exposed when the ship is drifting, they are situated some distance downwind of the ship’s bow when steaming or hove to. The anemometers are, however, at a high level compared to the ships superstructure.

The ship’s speed when drifting or hove to is shown in Fig. 4. As the wind increases the ship drifts downwind faster. When hove-to the engines are kept at a constant setting; as the wind increases the forward motion decreases.

Comparison of wind estimates

Wind estimates were compared for relative wind directions from 60° to starboard to 100° to port; this included most of the observations, and ensured that the sonic anemometer had reasonable exposure. Figure 5(a) shows the averaged wind speed difference (Sonic - WMO) as a function of the true wind speed determined from the sonic data. The sonic and WMO difference was variable but not significantly different from zero when the ship was steaming. The sonic read relatively high when the ship was drifting, and relatively low when the ship was hove-to, compared to the WMO values. This behaviour would be qualitatively explained if the ship’s speed were neglected in reporting the true wind. This appears to be confirmed by Fig. 5(b) which shows that, when the ship is hove to, the difference between sonic and WMO values corresponds well with the ship speed. When drifting, the difference corresponds to the ship speed plus 0.4 m/s.

Correction for Cumulus WMO wind observations

Assuming that the sonic anemometer values are correct, Fig. 6 shows the correction to be added to the reported winds from Cumulus. Below 10 m/s the reports must be increased by about 0.8 m/s. Above 15 m/s, a decrease of about 0.8 m/s is required. Correcting the data in this way will introduce error into the relatively small number of observations obtained when the ship is steaming.

Accuracy of Voluntary Observing Ship Visual Winds - the VSOP-NA Project

Background

Previous studies have compared weather ship data with nearby visual winds (Quayle, 1980, Kaufeld, 1981 and Graham, 1982), compared visual and measured winds from the same ship (Cardone, 1969), or compared wind speed distributions (Quayle, 1980). In analyzing the data from the VOS Special Observing Programme - North Atlantic, Kent et al. (1991, 1993) adopted a different method. Each observation from the 46 ships participating in the two year project was matched with the output from a weather forecast model. By using the model as a comparison standard it was not necessary to restrict comparisons to geographically close pairs of observations. Thus it was possible to use all the reports in the VSOP-NA data. The method of wind estimation for each VSOP-NA ship was known, including the position and exposure of any anemometer carried (Kent and Taylor, 1991), and the VSOP-NA ships reported both relative and true wind values.

Summary of VSOP results

Kent et al. (1993) noted that, for the VSOP-NA ships which used anemometers, the difference of the reported wind from the model value was greater for ships on which the anemometer was situated at a greater height (Fig. 7). Having corrected the anemometer winds to 10m, their analysis suggested that the Cumulus winds were biased low at lower wind speeds and also that the model being used as a comparison standard probably underestimated the wind speed by about 1 to 2 m/s (Fig. 8). They suggested that visual winds adjusted to the CMM scale are more compatible with anemometer winds than the original estimates based on the Code 1100 scale.

Kent et al., (1991) showed that visual wind observations above 8 m/s were under estimated at night (compared to daytime observations) unless the ship also carried a fixed anemometer. This suggests that the best Beaufort conversion scale would have different values for day and night. However, where a fixed anemometer was carried but visual winds reported, both day and night time values showed similar characteristics to the day time visual winds from ships which did not carry an anemometer. It appeared that the ships officers were not relying solely on the anemometer at night, but rather using it to ensure consistency in their visual wind estimates. The differences (Fig. 9) are of the same order as the difference between the Code 1100 and CMM wind scales.

Re-analysis of the VSOP-NA results

For this paper the VSOP-NA results have been re-analyzed with all wind estimates (anemometer and visual) corrected to the equivalent 10 m neutral wind. Height correction was based on the Smith (1988) roughness lengths with the standard Businger-Dyer stability corrections using the observed values of sea surface temperature, air temperature and dew point. For visual winds the Code 1100 estimates represent the 10 m wind, the CMM and Kaufeld scales have been corrected from 18 m and 25 m to 10 m respectively. In addition the OWS Cumulus wind estimates have been corrected for the ship motion as discussed in Section 3. Figure 10 shows that the effect of correcting the anemometer wind values was to bring them into closer agreement with the reported Cumulus wind observations. Applying the correction to the Cumulus winds results in close agreement up to about 10 m/s, but increases the difference above about 15 m/s.

The different wind conversion scales are compared to the anemometer wind values in Fig. 11a and to the corrected Cumulus reports in Fig. 11b. In each case the value is calculated by:

$$(Average\ \ visual\ \ wind - model) - (Average\ \ anemometer\ \ wind - model)$$

and plotted against model wind speed. In each case the results confirm that, at most wind speeds, the CMM values are to be preferred to the Code 1100 values. For winds below 10 m/s, the CMM scale appears to give better agreement with the anemometer winds than the Kaufeld scale. At higher wind values there is little significant difference between the two scales. Note however that a different conclusion might result if only the night time observations were compared.

Errors for Anemometer Wind Measurements on Ships

Background

The previous section has shown that, on average, the use of the CMM scale gives better agreement with anemometer wind observations than the use of the Code 1100 scale. However this does not necessarily imply that the CMM scale represents more closely the actual wind speed since anemometer winds may be affected by systematic errors. There are several possible sources of error for anemometer winds measurements. It is not known how well the increasing number of anemometers being deployed have been calibrated or what, if any, measures are taken to ensure that the instruments remain within calibration. In use, the anemometer is exposed to a turbulent flow which fluctuates as the ship rolls and pitches and the anemometer may not be "vertical" with respect to the mean flow. The reported wind is an estimate of the average reading of a fluctuating analog dial made by the ship's officer. It is not based on 2 minutes, and certainly not on 10 minutes, of observation; 5 seconds seems more likely. Errors are then made in converting to true wind velocity. The following sections will first summarize results from the VSOP-NA experiment concerning anemometer winds, and then consider the errors likely from ship motion and the airflow disturbance by the ship. A method of establishing an absolute wind speed calibration will then be suggested.

Results from VSOP-NA -- Instrument exposure and calibration

The most likely height of an anemometer on a VSOP-NA ship (Fig. 12) was about 30m, considerably more than that shown in WMO (1990) for the VOS fleet as a whole. This may be because the VSOP-NA ships carrying anemometers tended to be large container ships. For each ship the anemometer exposure was estimated on a scale from 0 (poorly exposed) to 9 (well exposed) for winds on the bow, beam, and stem. The most likely ship speed at the time of observation was 16 to 18 knots, similar to the most likely wind speed. As a result the relative wind for 73% of observations was from ±45° of the bow and for 97% it was within ±135° from the bow. Thus an anemometer mounted forward of a mast structure would have been shielded for less than 3% of the observations, and 63% of observations achieved the top exposure rating. This does not mean that the anemometer was situated in an undisturbed air flow, for example Fig. 13 shows the situation of the anemometer on one of the larger VSOP-NA ships.

It will be shown below that possible mean errors from airflow disturbance by the ship may well be of order 10% or more. In analyzing the VSOP-NA results it was not possible to separate these instrument exposure errors from anemometer calibration errors, and the absolute accuracy was difficult to determine. Perhaps the best comparison standard were the OWS Cumulus winds from station Lima. Unfortunately Lima is north of most of the ship routes and it was necessary to assume that the UK Met. Office model was effective in providing a good comparison standard for observations from different areas[2]. With that proviso, and using the wind observations as reported, Kent et al. (1991) found that the VSOP-NA ship reports were about 1 m/s higher than the Cumulus values. Correcting the VSOP-NA ship winds for the height of the anemometer, the observations were on average about 0.8 m/s higher than the reported Cumulus winds (see Fig. 10 and discussion above). Correcting the Cumulus reports for the ship's motion resulted in agreement with the anemometer winds up to about 10 m/s; at higher winds the corrected Cumulus values were lower by something under 10%. Thus even with all corrections applied, the VSOP-NA ships appeared to overestimate the winds compared to the Cumulus.

The VSOP-NA results showed that wind speed estimates obtained using hand-held anemometers were different in character to those from fixed instruments. Below about 7 m/s,

[2] This may have not been the case since the OWS Cumulus wind observations would have been given greater weight when assimilated into the model; however tests suggested this was not a significant factor.

wind speeds from hand-held anemometers gave similar results to the visual wind observations based on the Code 1100 scale. At higher wind speeds few observations were obtained, and these showed large scatter.

Concerning wind direction, the mean differences from the model values were within ±5° for most ships with no obvious bias. Mean difference for ships using wind vanes were similar to and sometimes larger than the values for ships using visual estimates.

Calculation of true wind

The VSOP-NA results showed that a significant and unnecessary error was introduced because officers on ships using anemometers must perform the vector subtraction of the ships velocity from the measured relative wind. Since the most frequently occurring wind speed values were similar to or less than the ships' speeds, large errors could result if this calculation was not performed correctly. The VSOP-NA ships had been requested to report ships speed and head, and the relative wind speed and direction, in addition to the true wind values. Thus, this calculation could be tested for about 2500 anemometer based reports. The method used was to calculate the value of the relative wind implied by the true wind report together with the ship's speed and head at the time of observation. This was compared to the relative wind reported. Only about 50% of the reported winds corresponded to calculated relative winds within ±1 m/s of the observed value. A large fraction of the reports (about 25%) were more than ± 2.5m/s different. For wind direction only 70% were within ±10°, and 13% were outside ±50°.

Errors sources for anemometer winds -- Errors due to ship roll and pitch

Ramstorf (1988) assessed the likely anemometer errors due to ships roll because of (i) "anemometer pumping" (ii) the tilt of the anemometer, and (iii) the variation of height in the near surface wind gradient, and demonstrated that only the first of these has the potential to contribute an error significantly above 1%. The wind error due to anemometer pumping is a function of:

$$\frac{\text{anemometer height above roll axis) x (roll angle)}}{\text{(roll period)}}$$

Thus Fig. 15 shows the percentage wind speed error for three cases for which possible combinations of anemometer height, roll angle, and roll period are shown in Table 1. The errors are largest for case (c) which might represent a research vessel with a cup anemometer at 20 m rolling through 10° with 5 second period. VOS are perhaps more likely to be represented by cases (a) or (b), for example an anemometer at 40 m on a ship with a 20 second roll through 5°. In these cases the errors remain small under most conditions and negligible compared to probable air-flow disturbance effects.

Errors due to airflow disturbance

Attempts to determine the wind error at anemometer sites on research ships due to the airflow i disturbance due to the ship were summarized by Taylor (1985). Based on comparisons with meteorological buoys (Augstein et al., 1974; Large and Pond, 1982), or with bow boom anemometers (Ching, 1976; Kidwell and Seguin, 1978), he concluded that for relative winds within ±45° of the bow, ±5% was a reasonable accuracy estimate. For winds from other directions significantly different errors might occur. More recently, wind tunnel studies have been reported by Blanc (1986; 1987) for two naval ships, and Surry et al. (1989) and Thiebaux (1990) for Canadian research ships.

Although referring to a guided missile cruiser, the study of Blanc (1987) is perhaps closest in terms of ship shape and size to a VOS. The errors in speed at the anemometer (Fig. 16) show the effects of the main mast which is directly downwind of the anemometer for a relative wind direction of about 100°, and the wake of a smaller obstruction at 90° relative wind. However these effects appear to be super-imposed on an overall wind increase of about 9% which presumably represents the combined effects of the ship's superstructure and of a large radar antenna near the anemometer location. For comparison Fig. 17 shows wind errors calculated using the model of Wucknitz (1977). The wind tunnel results for three Canadian survey ships (Thiebaux, 1990) also show an increased wind speed at the main mast site of typically 5 to 10% for most relative wind directions.

Increased wind speeds of this magnitude at typical anemometer heights above the ships accommodation block have also been predicted by numerical modelling. Kahma and Lepparanta (1981) used a potential flow model to predict errors of about 15% at the mast anemometer site on a small research vessel, the RN Aranda. Dupuis (1994) has used a two-dimensional turbulent flow model to predict a wind speed increase of about 20% at the main mast anemometer site on the research ship le Suroit. The use of three-dimensional computational fluid dynamics (CFD) to model the airflow over a ship is being evaluated at the James Rennell Center. Initially the aim is to simulate the wind tunnel results of Thiebaux (1990) (and field results of Anderson, 1993) for the survey ship CSS Dawson. The preliminary results (Ricardo, 1994), Fig. 18, have been calculated for winds on the bow and have reproduced the wind tunnel results for two anemometer sites to within about 2%.

In summary, for research ships and similar vessels, most studies show that an anemometer positioned on a mast above the accommodation is likely to over-read to order 10% or so. This applies for all wind directions except where the anemometer is in the wake of the mast. The only studies showing a significant underestimate are comparisons with a bow boom by Ching (1976), and comparisons with a buoy (Augstein et al., 1974), in both cases when the wind was on the beam. The Ching (1976) result could be due to errors in the bow boom data. The Augstem et al. (1974) results seem harder to explain; for the same ship Ramstorf (1988) found an over-estimate of order 10% for beam winds. Whether an anemometer on a VOS (see for example, Fig. 13), would under-read or over-read is not known. Numerical simulations of typical VOS shapes would give some indication but we know of no such studies in progress or planned. The evidence presented in section 4.3 (Fig. 10) suggests that, after correction for the instrument height, VOS anemometers may read high compared to the OWS Cumulus, at least for wind speeds above 10 m/s.

Toward an absolute wind calibration

Given the difficulty of obtaining accurate wind measurements even from an ocean weather ship or research ship, an alternative standard for wind speed measurements must be sought. Meteorological buoys do not present the air-flow disturbance seen on ships. However it is difficult to ensure that the anemometer remains well calibrated over an extended period of time, and care is necessary in allowing for buoy motion and in the correction for the very low instrument height. If we assume that the quantity that is really required is the wind stress, then an alternative calibration method is suggested by the results of Yelland et al. (1994). By comparing different anemometers mounted on the foremast of a research ship, they concluded that, whereas wind stress could be estimated to a consistency of about 5% using the inertial dissipation method, stress estimates based on the mean wind and the bulk aerodynamic formula are likely to have errors of order 20 to 30%. By equipping a subset of VOS with instrumentation to make inertial dissipation estimates of the wind stress, a wind velocity climatology could be produced using a specified drag coefficient formulation. Wind observations which were adjusted to be consistent with this climatology would then automatically produce the correct wind stress value. Suitable automatic instrumentation is available for wind stress estimation but the cost of the fast response anemometers and processing systems needed would be large compared to the cost of standard VOS instrumentation.

Summary

The percentage of anemometer derived wind reports has increased with time to a varying extent in different ocean areas. To prevent spurious temporal or spatial variations in the marine wind climate it is important that anemometer and visually estimated winds are compatible. Ocean weather ships might be expected to provide an accurate wind velocity estimate with which to calibrate VOS winds. However, by operating a sonic anemometer and GPS navigation system on the OWS Cumulus we have detected systematic errors in the wind reports of order 1 m/s. These appear to be caused by the neglect of the correction for the, relatively small, ship speed when drifting or hove to. Using the Cumulus wind observations and the sampling frequency achieved by the VOS, we can detect no fair weather bias in the wind reports from the area around ocean station Lima.

The accuracy of VOS wind reports was examined in the VSOP-NA project. All the visual wind scales examined (Code 1100, CMM IV, and Kaufeld) showed wind difference trends when compared with both OWS CUMULUS data and with VOS anemometer data. Code 1100 gives significantly larger wind values at higher wind speeds. The closest agreement between VOS visual wind estimates, and VOS or Ocean Weather Ship anemometer derived winds, was obtained using the CMM IV scale. Visual winds at night underestimated the higher wind speed ranges; this should be investigated further.

For anemometer derived winds from the VSOP-NA ships, significant errors were introduced during the calculation of the true wind speed from the observed relative wind. Correcting for the height of the anemometers improved the consistency of the data set. Having applied all corrections, the VOS anemometer derived winds agreed with the OWS Cumulus winds at wind speeds below about 10 m/s; at higher wind speeds the VOS winds appeared to be stronger. The anemometers on the VSOP-NA ships were generally well exposed and it is unlikely that the roll and pitch of the ship resulted in significant error. However field calibrations, wind tunnel studies, and numerical models suggest that, for research ships, an anemometer situated on the main mast is likely to be in error by order 10%. Usually the wind speed is overestimated. The magnitude and sign of this airflow disturbance error for a typical VOS ship is not known. It could be estimated using computer modelling techniques of the sort we are developing for research ships.

At present we have no absolute calibration for marine winds. Estimates of the wind stress using the inertial dissipation method could be used to calibrate marine winds. However the cost of the instrumentation systems would be significant.

References

Anderson, R. J., 1993: A study of wind stress and heat flux over the open ocean by the inertial dissipation method. *J. Phys Oceanogr*., 23 (10), 215 3 - 216 1.

Augstein, E., H. Hoeber and L. Kruegermeyer, 1974: Fehler bei Temperatur-, Feuchteund Windmessungen auf Schiffen in tropischen Breiten. *Meteor Forschungsergebnisse* B9, 1 - 10.

Blanc, T.V., 1986: Superstructure flow distortion corrections for wind speed and direction measurements made from Tarwa Class (LHA I -LHA5) ships. NRL Report 9005, Naval Research Laboratory, Washington, D.C., 20 pp.

Blanc, T. V.,1987: Superstructure flow distortion corrections for wind speed and direction measurements made from Virginia Class (CGN38-CGN41) ships. Report 9026, Naval Research Laboratory, Washington, D.C., 24 pp.

Cardone, V. J., 1969: Specification of the wind distribution in the marine boundary layer for wave forecasting., New York University.

Cardone, V. J., J. G. Greenwood and M. A. Cane, 1990: On trends in historical marine wind data. *J. Climate*, 3, 113 - 127.

Ching, J. K. S., 1976: Ship's influence on wind measurements determined from BOMEX mast and boom data. *J. Appl Meteorol*, 15(l), 102 - 106.

Dupuis, H., 1994: Wind speed errors for the research ship le Suroit. (personal communication).

Graham, A. E., 1982: Winds estimated by the Voluntary Observing Fleet compared with instrumental measurements at fixed positions. *Meteorol. Mag*., 111, 312-327.

Ive, D. S., 1987: A comparison of numbers of visually estimated and instrumentally measured wind data, Marine Technical Note No. 2, Revised February 1987, UK Meteorological Office, Bracknell, 43pp.

Kahma, K. K. and M. Lepparanta, 1981: On errors in wind speed observations on R/V Aranda. *Geophysica*, 17(1-2), 155-165.

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

Kent, E.C. and P.K. Taylor, 1991: Ships observing marine climate: a catalogue of the Voluntary Observing Ships Participating in the VSOP-NA. Marine Meteorology and Relate Oceanographic Activities 25, World Meteorological Organization, Geneva, 123 pp.

Kent, E. C. and P. K. Taylor, 1994: A comparison of heat flux estimates for the North Atlantic Ocean. *J. Phys. Oceanogr*., (submitted).

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), S91 - 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, World Meteorological Organization, Geneva, 86 pp.

Kidwell, K. B. and W. R. Seguin, 1978: Comparison of mast and boom wind speed and direction measurements on US GATE B-Scale Ships. NOAA Tech. Rep. EDS 28, CEDDA, Washington, D.C.

Large, W. G. and S. Pond, 1982: Sensible and Latent Heat Flux Measurements over the Ocean. *J. Phys. Oceanogr*., 12, 464-482.

Quayle, R. G., 1980: Climatic Comparisons of Estimated and Measured Winds from Ships. *J. Appl. Meteorol*., 19, 142-156.

Ramstorf, S., 1988: Wind observations from RV/Rapuhia. Physics Section report (Internal Report 88/2), Division of Marine & Freshwater Science, DSIR, Wellington, New Zealand, 12 pp.

Ricardo, 1994: CFD analysis of airflow over the CSS Dawson. (unpublished report), Ricardo Consulting Engineers Ltd., Shoreham, U.K.

Smith, S. D., 1988: Coefficients for Sea Surface Wind Stress, Heat Flux and Wind Profiles as a Function of Wind Speed and Temperature. *J. Geophys, Res*., 93, 15467-15474.

Surry, D., R. T. Edey and 1. S. Murley, 1989: Speed and direction correction factors for ship borne anemometers. Engineering Science Research Report BLWT-SS9-89, Univ. of Western Ontario, London, Ontario, 83 pp.

Taylor, P. K., 1985: TOGA surface fluxes of sensible and latent heat by in situ measurement and microwave radiometry. Third session of the JSC/CCCO TOGA Scientific Steering Group, Scripps Institution of Oceanography, La Jolla, Ca., WMO, Geneva, 30pp. & figs.

Taylor, P.K., Kent, E.C. and Yelland, M.J. 1994: The accuracy of meteorological measurements from an ocean weather ship (in preparation)

Thiebaux, M. L.,1990: Wind tunnel experiments to determine correction functions for shipborne anemometers. Canadian Contractor Report of Hydrography and Ocean sciences 36, Bedford Inst. Oceanography, Dartmouth, Nova Scotia, 57 pp.

WMO, 1990: International list of selected, supplementary and auxiliary ships., World Meteorological Organization, Geneva.

Wucknitz, J., 1977: Flow distortion by supporting structures.: Air sea interaction: Instruments and methods, F. Dobson, L. Hasse and R. Davis, Ed., Plenum Press, 605-626.

Yelland, M. J., P. K. Taylor, I. E. Consterdine and M. H. Smith, 1994: The use of the inertial dissipation technique for shipboard wind stress determination. (accepted by *J. Atmospheric Ocean Technology*)

Table 1: Possible combinations of anemometer height above roll axis(m), roll amplitude (degrees) and roll period (seconds) for the three cases shown in Fig. 15.

Anemometer Ht	Case (a)		Case (b)		Case (c)	
(m)	Roll (°)	Period (sec)	Roll (°)	Period (sec)	Roll (°)	Period (sec)
10	5	5	10	5	16	4
20	5	10	10	10	10	4
30	5	20	10	20	10	10

Figure 1: Percentage of anemometer wind reports for different ocean areas for year periods from 1960 to 1985. The values have been roughly estimated from [C] Cardone et al., (1990), [I] Ive, (1987), [R] Ramage, (1987). The areas shown are (a) North Atlantic, (b) Indian and southern hemisphere oceans, (c) North Pacific regions.

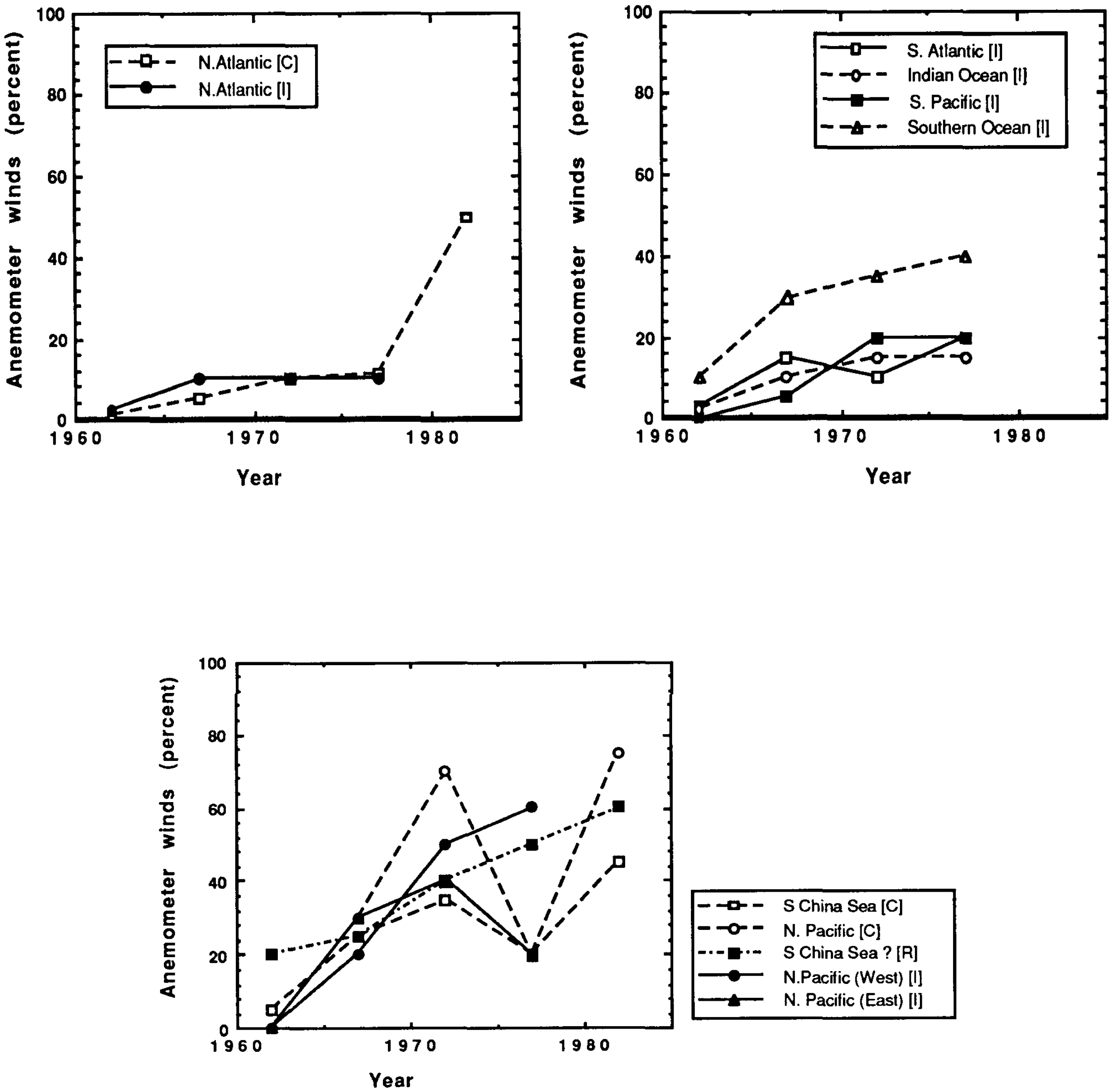


Figure 2: Cumulative percentage distribution of OWs Cumulus wind data and VOS wind data as a function of OWS Cumulus wind speed (m/s) at the time of the VOs observation.

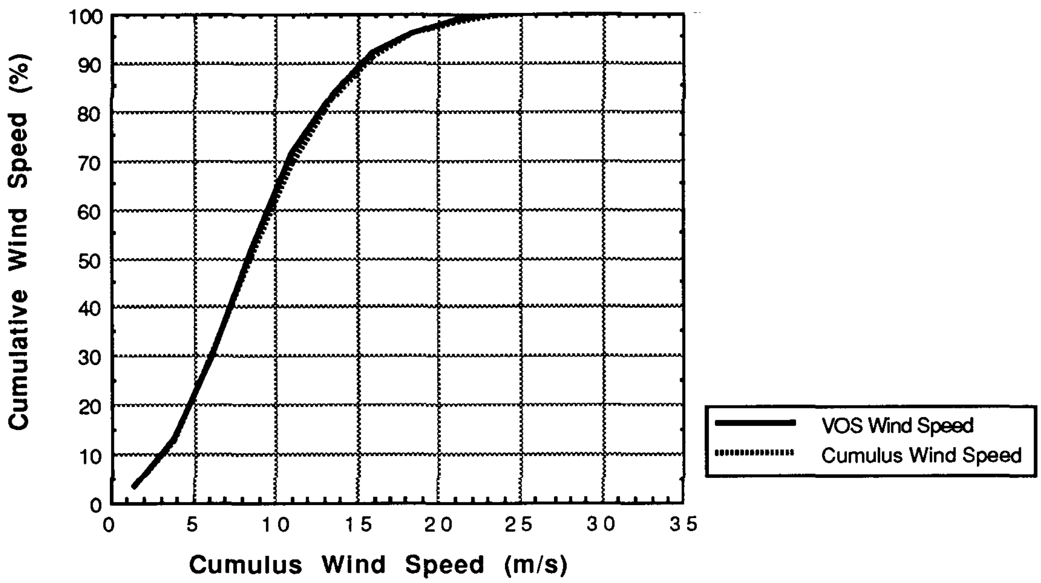


Figure 3: Area plot of wind speed occurrences from the Sonic anemometer data from OWS Cumulus. The number of occurrences is shown for each 2 m/s interval. The shaded area represents the contribution to the total number of cases obtained at each wind speed when the ship was drifting, steaming, or hove to.

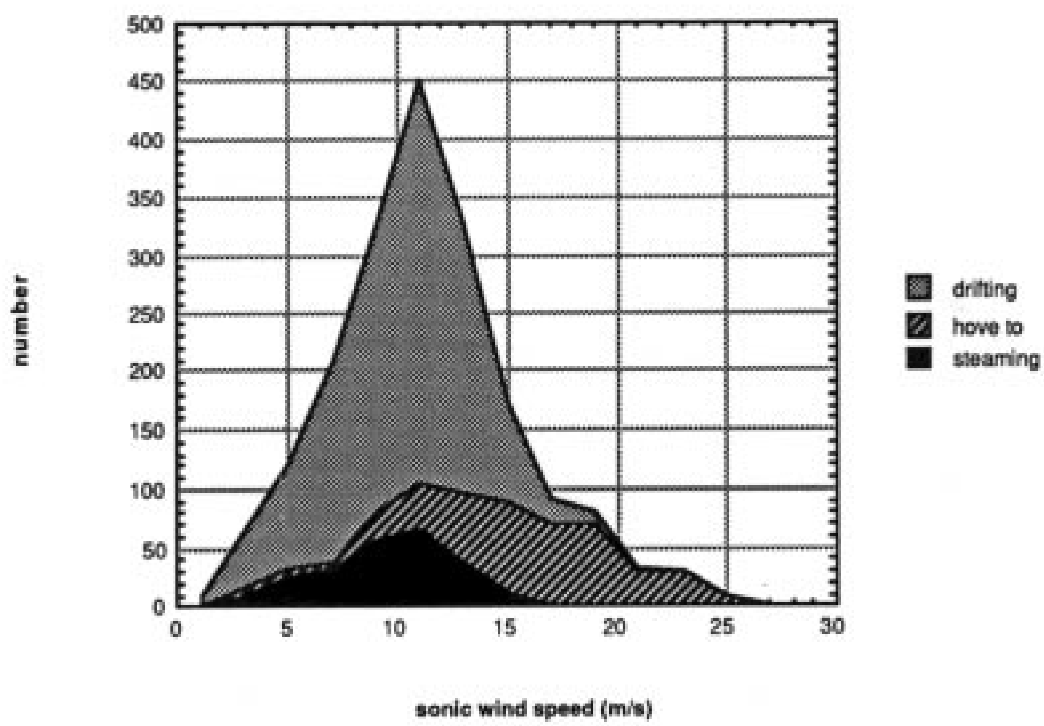


Figure 4: Mean ship speed (m/s) when drifting or hove-to plotted against the true wind speed derived from the sonic anemometer and GPS data.

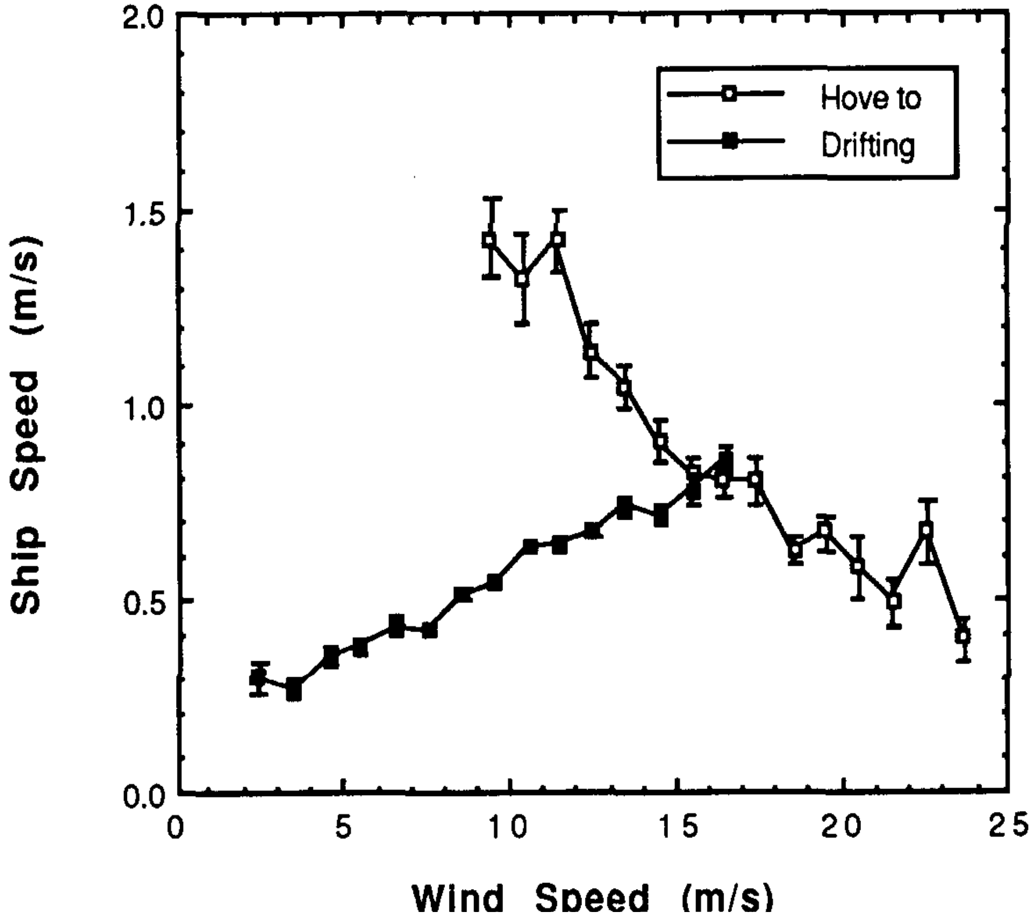
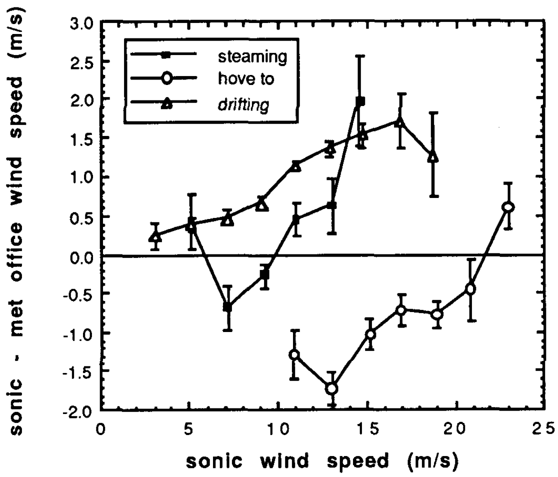


Figure 5: (a) Averaged difference between the wind speed reports, (Sonic - WMO), plotted against the true wind speed derived from the sonic anemometer and GPS data. (b) Averaged difference between the wind speed reports, (Sonic - WMO) when ship is hove-to or drifting plotted against the ship speed.



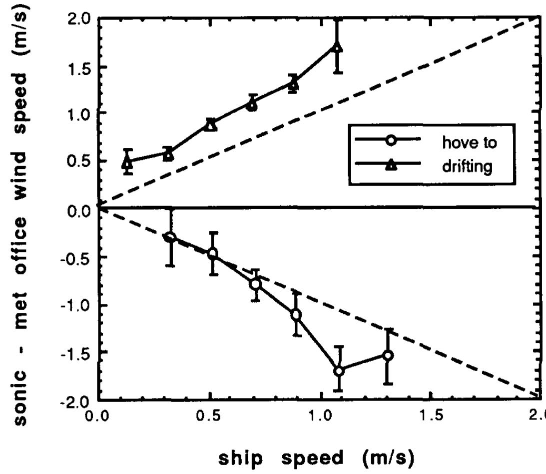


Figure 6: Correction to be added to Cumulus WMO wind observations calculated as a function of the uncorrected WMO observation.

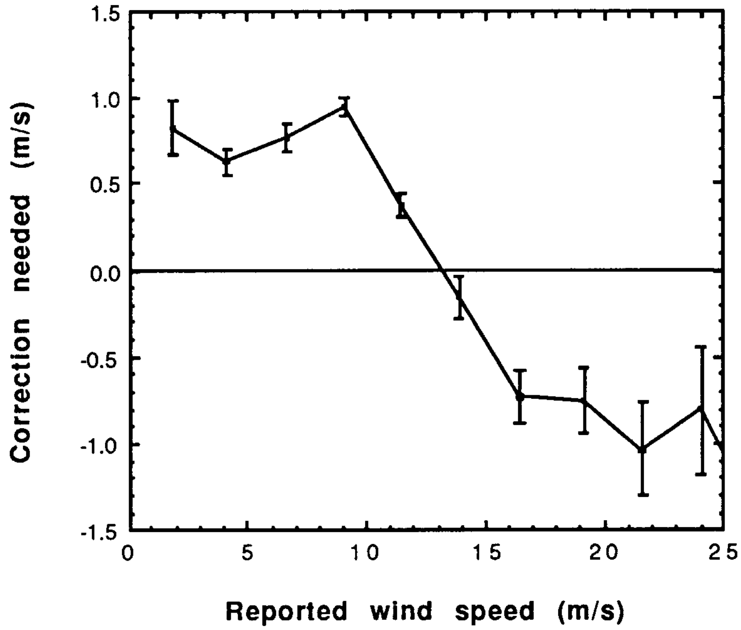


Figure 7: Average difference between the reported wind and the mode value for VSOP-NA ships which used fixed anemometers plotted against the height of the anemometer (adapted from Kent et al., 1993).

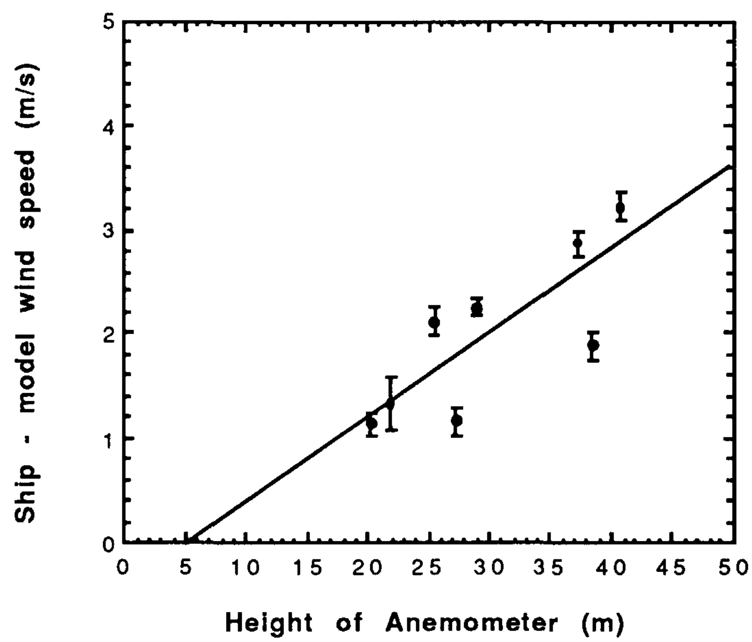


Figure 8: The mean difference in wind speed measurements (VSOP-NA ship minus model value, m/s) plotted against the model wind speed value. The results from fixed anemometers have been corrected for the anemometer height. The visual estimates have been corrected to the CMM Beaufort scale. (The dashed line represents the visual values using the Code 1100 scale). Also shown are the anemometer data for the Ocean Weather Ship Cumulus. (From Kent et al., 1993).

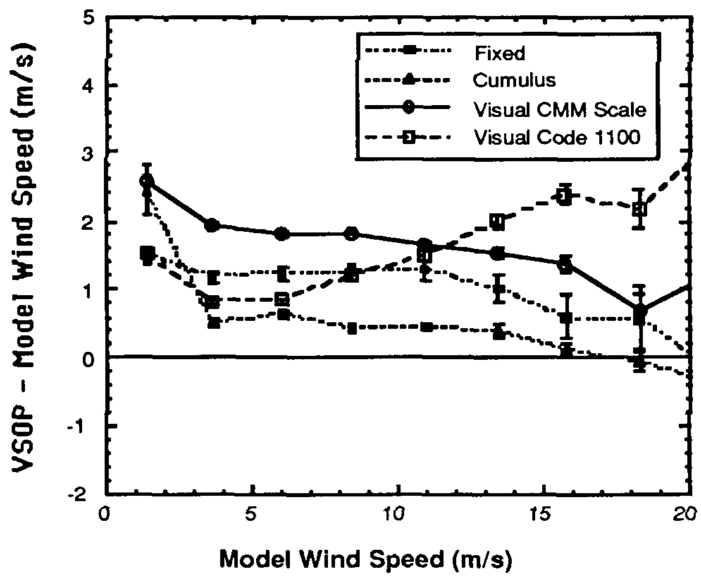


Figure 9: VSOP measured wind speed (m/s) binned on model wind speed (m/s) separately for visual winds reported on ships with and without fixed anemometers and for day and night observations. (From Kent et al., 1993).

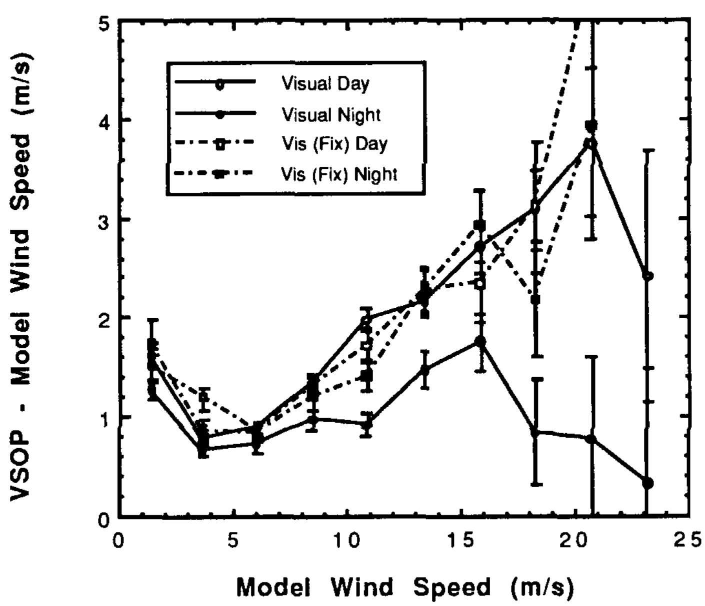


Figure 10: Average difference between the reported wind and the model value for VSOP-NA ships which used anemometers both before and after correcting to the 10 m neutral wind values also shown are the difference for the Cumulus, corrected to 10 m height, both before and after correction for ship motion. Uncorrected values are joined by broken lines, corrected values by full lines.

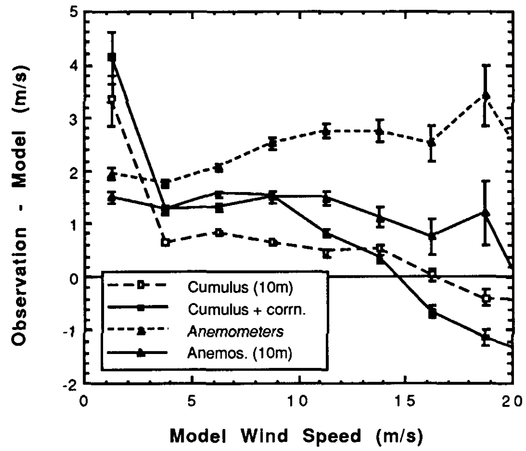


Figure 11: Average difference between 10 m neutral values for visual winds corrected to different conversion scales and anemometer derived values. (a) Anemometer values from the VSOP-NA ships. (b) Anemometer wind estimates from the OWS Cumulus (corrected for ship motion.)

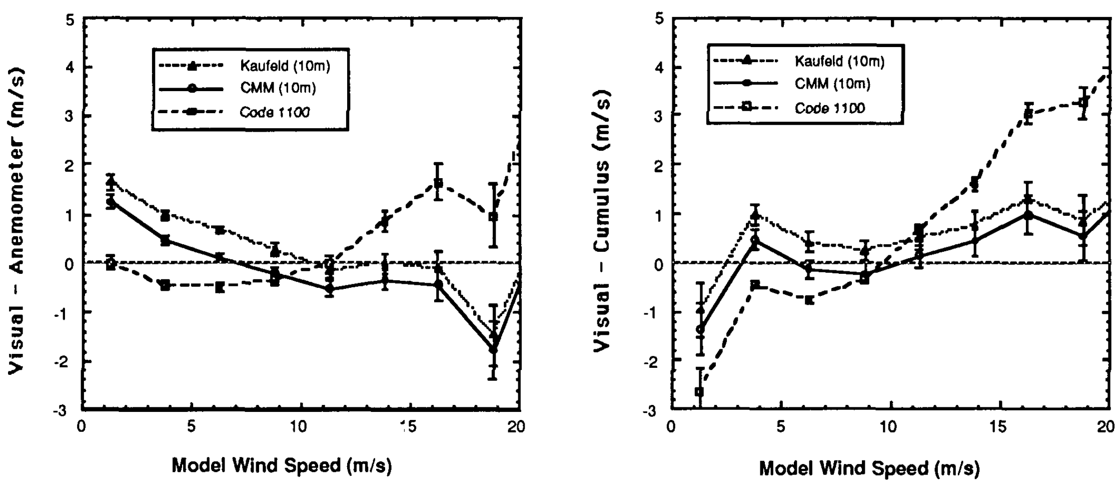


Figure 12: Anemometer heights for the VSOP-NA ships and for the whole VOs fleet. (from Kent and Taylor, 1991).

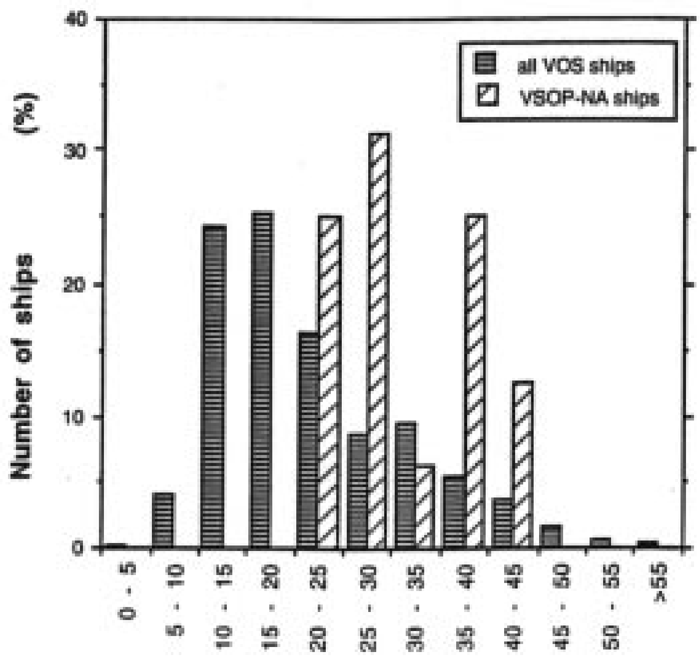


Figure 13: Situation of anemometer on one of the VSOP-NA ships, the Atlantic Cartier. The anemometer was about 40 m above sea level.

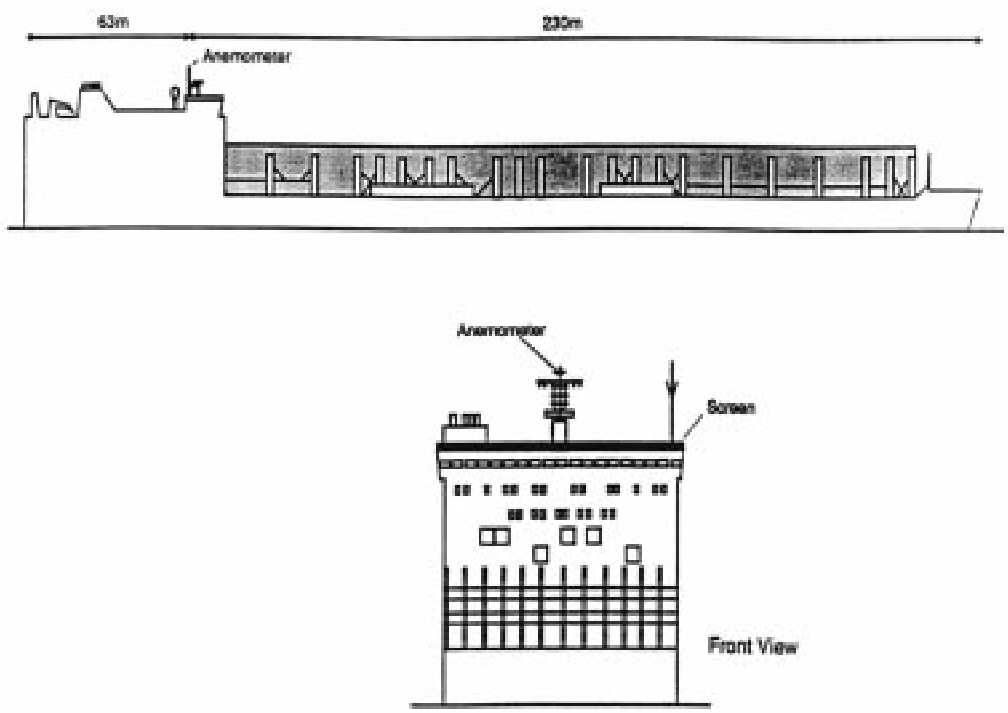
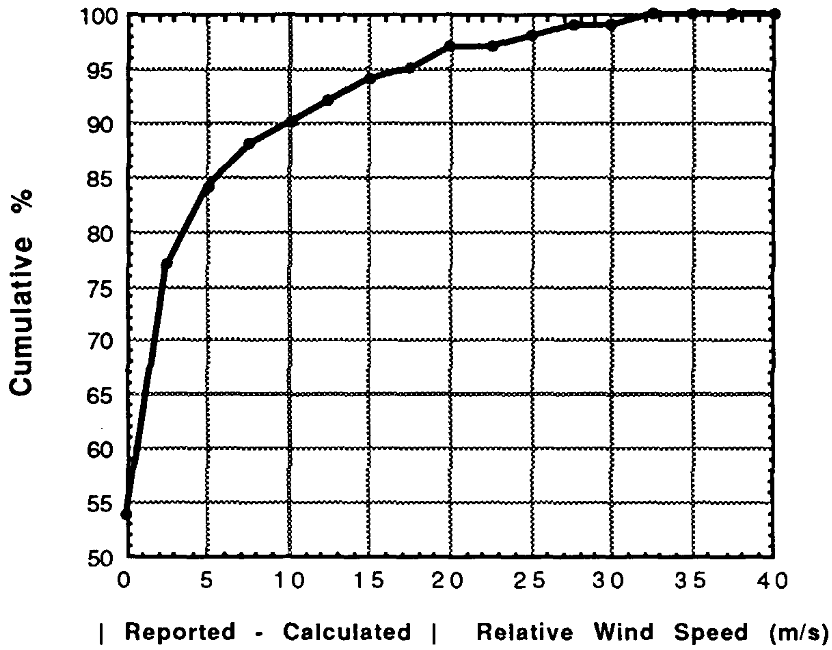


Figure 14: Cumulative percentage plot of the difference in the relative wind reported by the VSOP-NA ship and the relative wind calculated from the reported true wind velocity together with the ship's heading and speed at the time of the observation. (a) wind speed; (b) wind direction.



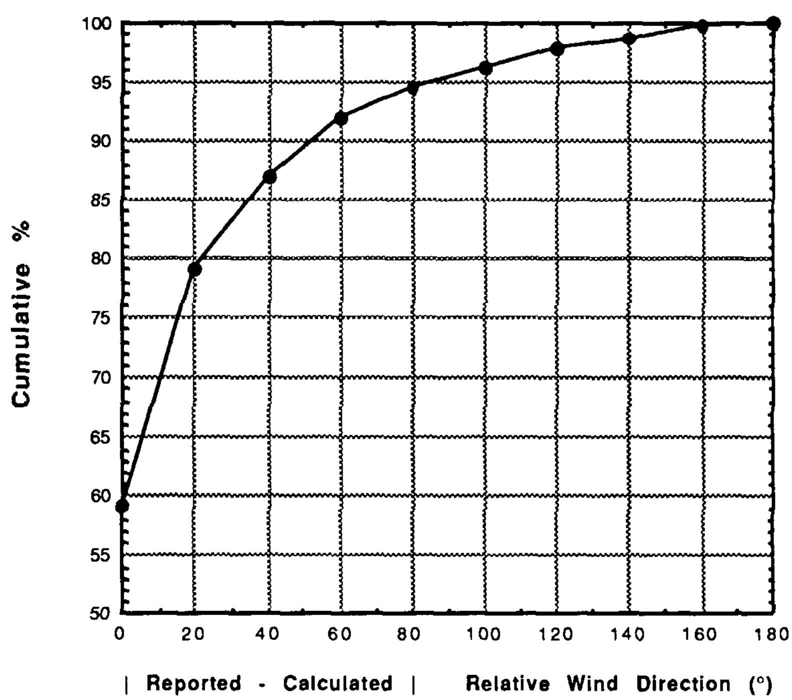


Figure 15: Percentage wind speed error due to anemometer pumping by the ship's roll for three cases (see text).

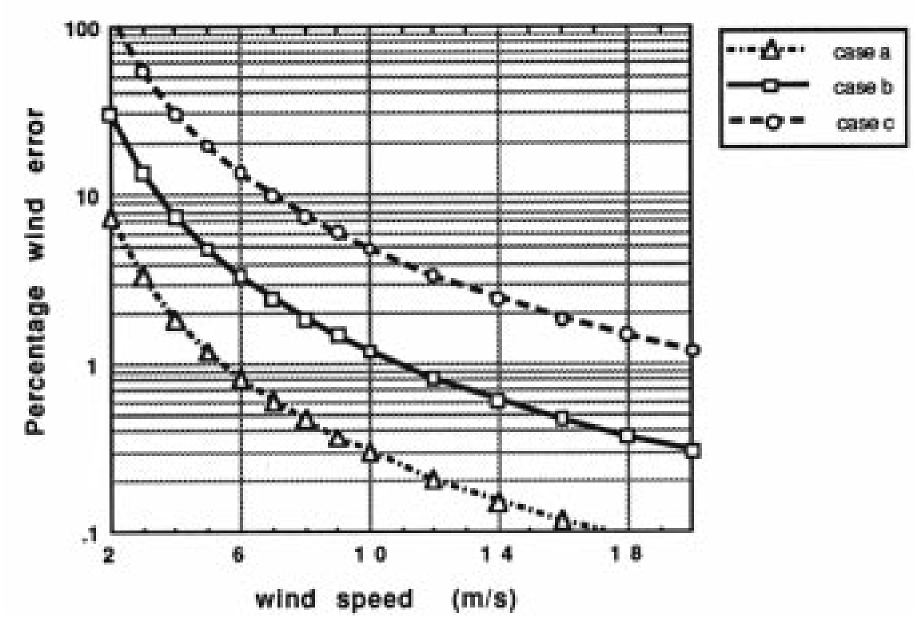


Figure 16: Percentage wind error from the wind tunnel study of Blanc (1987). The data from the port anemometer has been plotted as if the anemometer were situated in the starboard anemometer position.

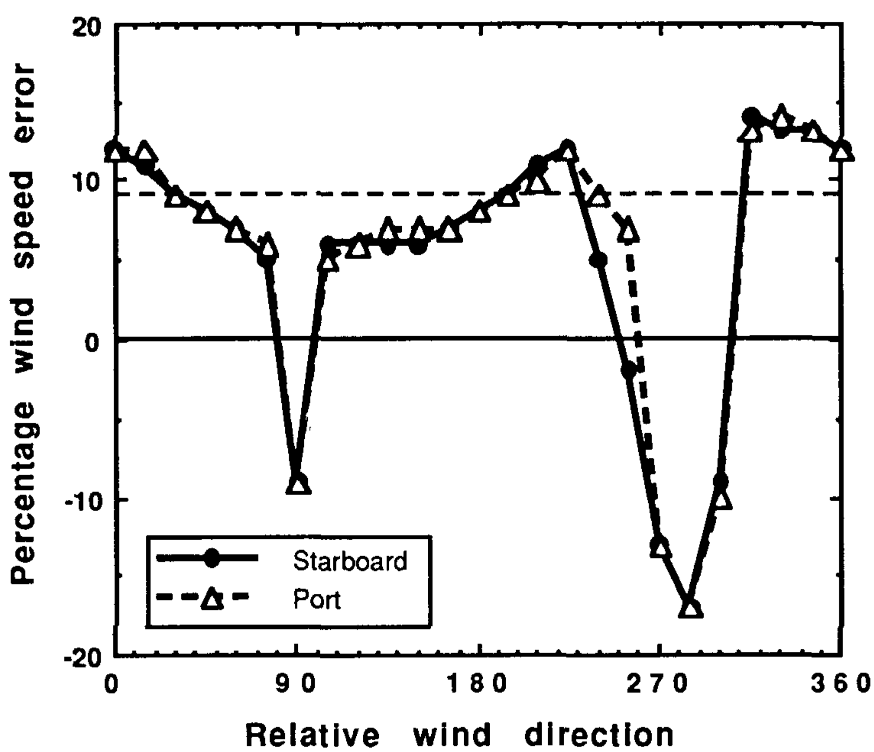
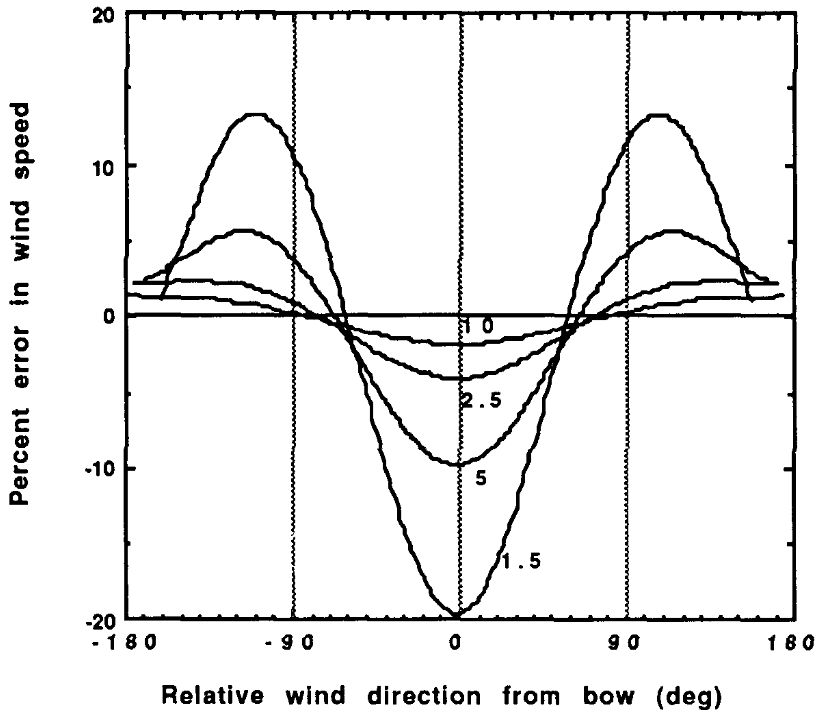


Figure 17: Errors in (a) wind speed), and (b) wind direction (degrees) at positions 1.5, 2.5, 5, and 10 mast diameters away from a circular mast, calculated using model of Wucknitz, (1977).



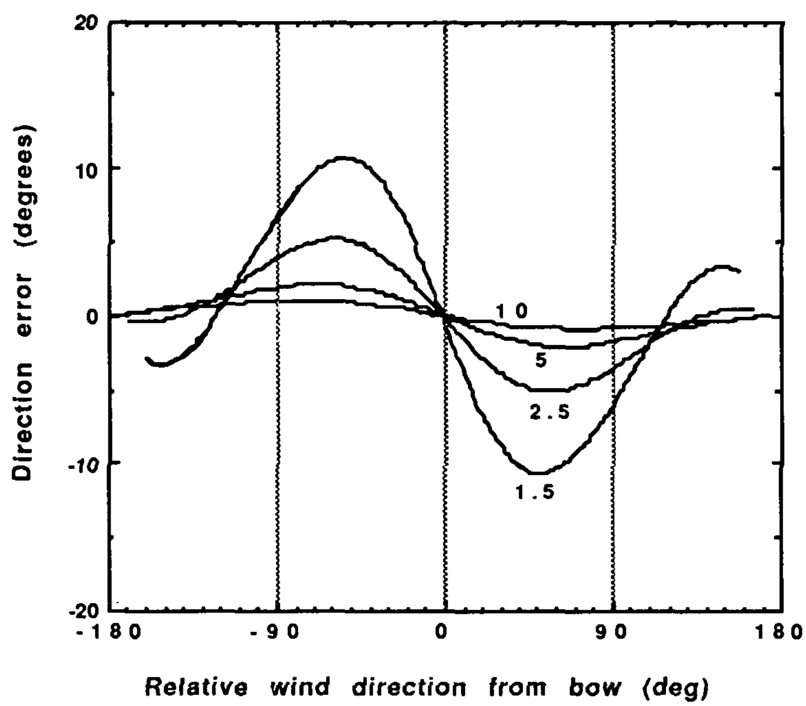


Figure 18: Flow over the CSS Dawson determined by CFD modelling (Ricardo, 1994). Regions of positive and negative wind speed error are marked.