THE ACCURACY OF METEOROLOGICAL OBSERVATIONS FROM VOLUNTARY OBSERVING SHIPS - PRESENT STATUS AND FUTURE REQUIREMENTS.

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SUMMARY OF RECOMMENDATIONS

Based on the results summarized in this paper the following recommendations are suggested. They are grouped according to the observed variable and not presented in any order of priority. In general the recommendations fall into two groups: (i) the need for more complete and accurate information in the List of Voluntary Observing Ships (WMO 47); (ii) the need to decrease errors in the ship's weather report. The more general use of computer systems to automatically code the weather report would aid the latter.

A. Wind

A.1 For ship's reporting anemometer winds the ship's officers should be provided with a automated method of calculating the true wind.

A.2 Anemometer readouts should automatically average the winds.

A.3 Hand held wind sensors should not be used.

A.4 The position of anemometer must be documented. This must include height above sea level and also measurements indicating the position of the anemometer with regard to the overall shape of the ship.

A.5 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).

B. Pressure

B.1 The use of a digital Precision Aneroid Barometer (preferably connected to an external static head) is recommended.

B.2 The observers should be urged to ensure that variations in ship's draft are taken into account when correcting to sea level.

B.3 The instrument type and position must be accurately documented.

C. Air Temperature and humidity

C.1 All VOS should be asked to report dew point.

C.2 Hand operated psychrometers are better than manually read thermometer screens.

C.3 If thermometer screens are used they should be of a design that has been shown to be efficient. They should be fixed in a well exposed position - at least two are normally required to ensure proper exposure.

C.4 The instrument type and exposure must be accurately documented.

D. Sea Surface temperature

D.1 Hull contact sensors are the preferred method of measurement.

D.2 The method of measurement should be included with the observation.

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E. Position

E.1 Errors in reporting the ships position (including the quadrant indicator) must be minimized.

1. INTRODUCTION

The initialization of atmospheric forecast models remains an important use of weather reports from Voluntary Observing Ships (VOS). However there is an increasing use of data from satellite borne sensors, for example for determining sea surface temperature (SST), sea waves, or surface wind velocity. These remote sensed data allow coverage of the global oceans but rely on empirical algorithms applied to data from a very limited number of sensors. An important role of the VOS data is to allow the detection of biases in the remote sensed data due to instrument calibration changes or changing atmospheric transmission conditions. For example, the SST analyses produced by NCEP (Reynolds and Smith, 1994) use VOS data to detect and correct biases in the satellite data caused by varying atmospheric aerosol loading.

The VOS data also are being increasingly used for climate analysis and forecasting. Assembled into large data bases (such as the Comprehensive Ocean Atmosphere Data Set, COADS, Woodruff et al., 1993) the observations have been used, for example, to quantify global changes of sea and marine air temperature (Folland and Parker, 1995). Based on such studies, the recommendations of the International Panel on Climate Change (Houghton et al., 1990) have led to politically important international resolutions such as the UN Framework Convention on Climate Change. However the detection of climate trends in the VOS data has only been possible following the careful correction, as far as is possible, for varying observational bias due to the changing methods of observation. For example sea temperature data has different bias errors depending on whether it was obtained using wooden buckets from sailing ships, canvas buckets from small steam ships, or engine room intake thermometers on large container ships.

These relatively new applications for VOS data imply a need to minimize the errors present in the observations. For example, 10 Wm^{-2} is often quoted as a target accuracy for determining the heat fluxes; it is about 10% of the typical interannual variability of the wintertime turbulent heat fluxes in mid to high latitudes. To achieve such accuracy implies that the basic meteorological fields are known to about ±0.2°C for the SST, dry and wet bulb temperatures (or about 0.3 g/kg for specific humidity) and that the winds be estimated to ±10% or better, say about 0.5 m/s (see, for example, Taylor, 1984; Taylor, 1985). These are stringent requirements which we do not expect to be met by an individual VOS observation. Enough observations must be averaged to reduce the errors to the required level. However, the more accurate the individual VOS observations, the less averaging will be needed. Nor is averaging enough; corrections must be applied for the systematic errors in the data set. This requires detailed, accurate documentation on the methods of observation, information which is at least partly provided in the List of Selected Ships (WMO47).

2. RANDOM ERRORS IN VOS DATA

2.1 Method of calculation

The random errors in VOS observations may be determined by comparing observations from pairs of ships and ranking the difference in, say, the reported air temperature value, 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 will represent twice the random error for a single ship observation. Using this method, Kent et al., (1999) analyzed 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 are shown in Table 1 and Figure 1. and will be discussed for each variable.

Table 1 - RMS Error Estimates: from Kent et al. (1999) who calculated mean error estimates for 30° x 30° areas of the global ocean. This table shows the minimum and maximum values for the area means. The mean error is an average of all the error estimates for each box with absent ocean boxes (where there was too little data for analysis) filled by linear interpolation (in the zonal direction only) to give an error weighted for the whole region. The uncertainty quoted in the mean error is derived from the weighted sum of the error variances.

Observed Field	RMS Error:		
	Min.	Max.	Mean
Surface Wind Speed (m/s)	1.3	2.8	2.1 ± 0.2
Pressure (mb)	1.2	7.1	2.3 ± 0.2
Air Temperature (°C)	0.8	3.3	1.4 ± 0.1
Sea Surface Temperature (°C)	0.4	2.8	1.5 ± 0.1
Specific Humidity (g/kg)	0.6	1.8	1.1 ± 0.2

2.2 Wind speed

Kent et al. (1999) found that a typical root mean square (RMS) error for a wind speed observation is 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) 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.

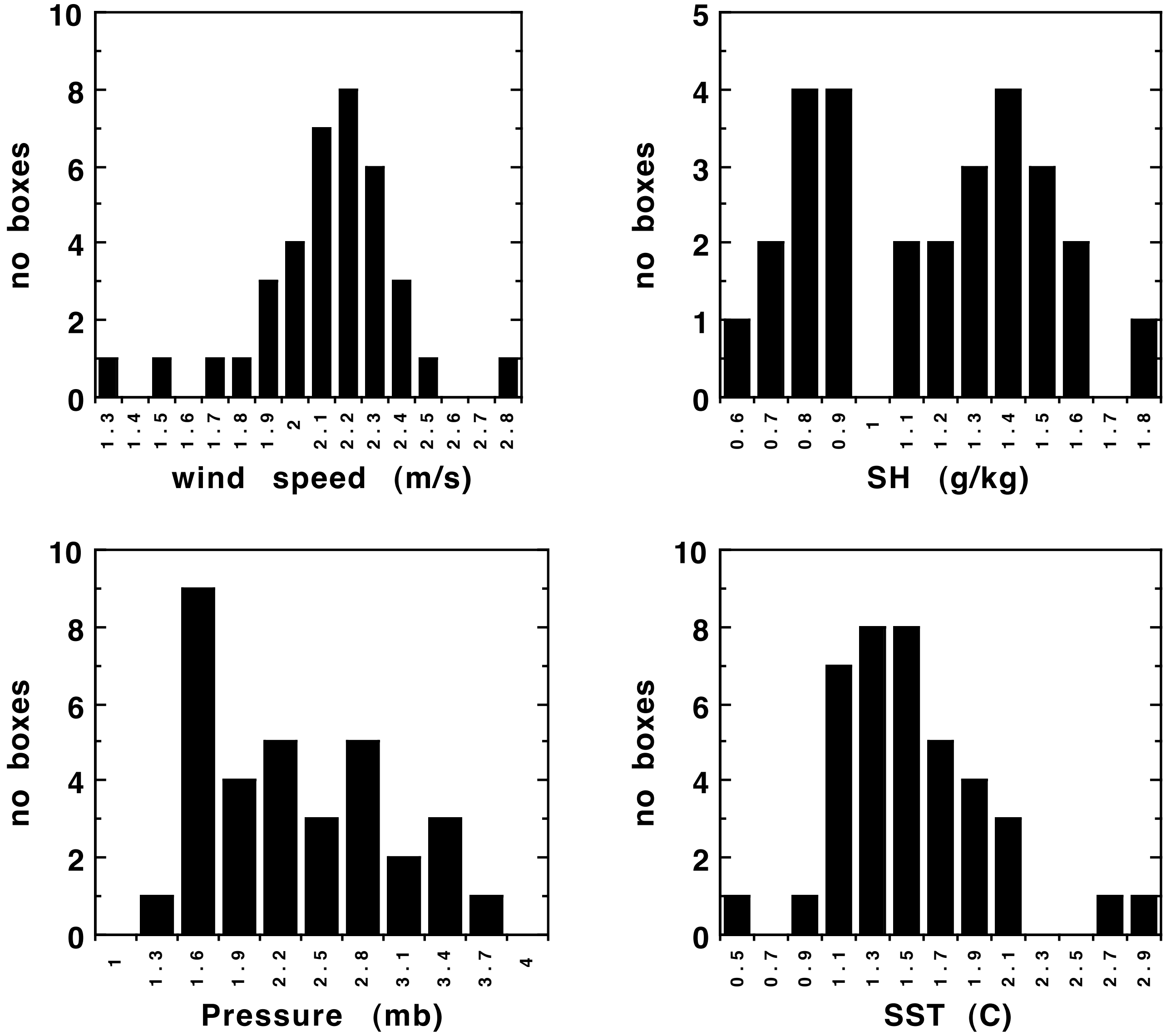
The VOS in the VSOP-NA project reported the anemometer estimated, relative wind speed in addition to the calculated true wind speed. Kent et al., (1991) showed that a major cause of error was the calculation of the true wind speed. Only 50% of the reported winds were within 1 m/s of the correct value, 30% of the reports were more than 2.5 m/s incorrect. For wind direction, only 70% were within ±10° of the correct direction and 13% were outside ±50°. These are large, needless errors which significantly degrade the quality of anemometer winds. A similar conclusion was reached by Gulev (1999). Preliminary results from a questionnaire distributed to 300 ships' officers showed that only 27% of them used the correct method to compute true wind. The problem is not confined to VOS observations. A majority of the wind data sets obtained from research ships during the World Ocean Circulation Experiment showed errors in obtaining true wind values (Smith et al., 1999).

2.3 Air pressure

While Kent et al., (1999) suggested that a typical error for air pressure was 2.3 mb, the histogram (Figure 1b) shows a significant peak at about 1.6 mb representing lower error estimates in tropical regions. Reasons may that pressure changes less rapidly with time and also that the pressure reading is less affected by vertical ship motions in tropical areas.

2.4 Air temperature

Although a typical RMS air temperature error was about 1.4°C, the histogram (Figure 1c) shows a significant number of higher error values representing high latitude coastal regions with mean air temperatures of 10°C or lower. This may indicate a failure to remove spatial variability from the error estimate (for example in the Gulf Stream and Kuroshio areas) or it may be that errors in air temperature observations are greater in cold conditions. For example, psychrometers may not be exposed outside the wheelhouse for a long enough period.



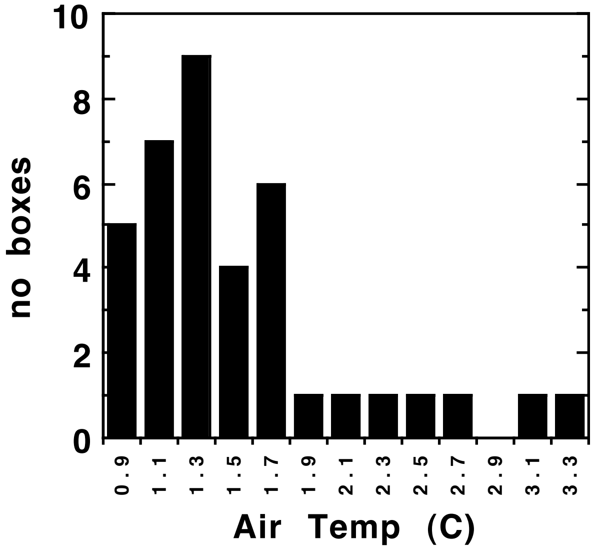


Figure 1 Histograms of the random errors for VOS observations. The number of 30° x 30° ocean areas having a given mean RMS error is shown. (adapted from the data of Kent et al. 1999)

2.5 Sea surface temperature

The RMS errors for SST showed similar features to those for air temperature. The mean error was 1.5°C, the highest values occurred in high latitude coastal regions, higher values occurred in the Gulf Stream and Kuroshio regions than in other areas at the same latitude.

2.6 Specific humidity

Kent et al., (1999) examined errors in specific humidity because that is the humidity variable that is important in calculating the latent heat flux. However the errors in specific humidity reflect the variation of saturation vapour pressure with temperature. Higher errors occur in tropical regions where the air is warm. The ships actually report dew point temperature. Errors for dew point tended to be about 2°C in colder regions and somewhat less, between 1°C and 2°C in warmer regions (Figure 2).

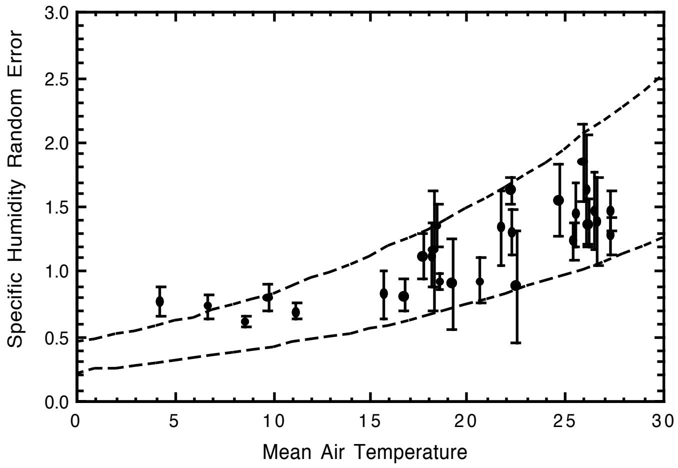


Figure 2. Random observational error in specific humidity (gkg^{-1}) as a function of mean air temperature (°C). Upper line is the error in specific humidity arising from a 2°C error in dew point temperature and the lower from a 1°C error in dew point. A relative humidity of 80% has been assumed in the calculation. (from Kent et al. 1999)

3. SYSTEMATIC ERRORS

3.1 Method of calculation

Determining the systematic errors in VOS observations is more difficult than determining the random errors. The VSOP-NA (Voluntary Observing Ship Special Observing Programme - North Atlantic) project (Kent et al., 1991, 1993a) was designed to 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 analyzed according to instrument type and exposure, ship size and nationality, and other factors. For some variables, correction schemes were devised. Limited verification of the corrected data has been obtained by comparison with research buoy deployments (Josey et al., 1999).

Our own experience of mounting meteorological instrumentation on research ships, weather ships, and meteorological buoys, has shown that for ship mounted instruments a major consideration is the air-flow disturbance caused by the ships' hull and superstructure (Yelland et al., 1998b). The systematic errors in anemometer wind determinations are being investigated by using computational fluid dynamics (CFD) modeling of the airflow (Yelland et al., 1998a).

3.2 Surface Wind Speed

3.2.1 Lack of an absolute standard

Accurate wind data are important because wind stress increases roughly as (wind speed)^3 and mixed layer deepening with (wind speed)$^{4.5}$. However it must be noted that we do not have an error free source of wind data over the ocean. It might be expected that the best data sources would be anemometer measurements from ocean weather ships (OWS), research ships, or meteorological buoys. However there are biases in each of these data types. For example, examining data from the period 1992 to 1994, Taylor et al., (1995) showed that the wind observations from OWS *Cumulus* were not properly corrected for ship motion when the ship was drifting or hove to. This resulted in errors of up to 1.5 m/s. Isemer, (1994) has attempted to evaluate the ocean weather ship wind data more generally. As for any other ship, the wind data from research ships are in error due to the air flow distortion caused by the ship (Yelland et al., 1998b); errors of order 10% are quite possible. 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). Two possible causes are the vertical movement of the buoy through a non-linear near surface wind profile, and the distortion of that profile due to the effect of high waves; again errors of order 10% may be possible.

Satellite scatterometers are empirically calibrated by comparison with in situ data and therefore do not provide an independent standard. However Kent et al. (1998) showed that scatterometer data might be used for quality controlling ship winds on a ship by ship basis.

In the future, measurements of wind stress rather than wind velocity may allow the biases in wind data to be corrected (see section 5). At present our aim must be to obtain a consistent, well documented wind velocity data set so that any future correction procedures may be implemented.

3.2.1 Instrument based estimates

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.

With regard to fixed anemometers we have already noted (section 2.2) that correcting for the height above the sea of the anemometer demonstrably improves the data set. Note that this correction should be done on a ship by ship basis since the average height of anemometers varies both geographically and with time (Table 2).

Taylor et al., (1995) reanalyzed 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 air flow distortion. Using computational fluid dynamics (CFD) to analyze the air flow over typical VOS shapes, Yelland et al., (1998a) showed that there is a plume of accelerated air above the wheelhouse top (Figure 3). The shape of this plume depends on the geometry of the ship's accommodation block. 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, in or above the plume an overestimate will occur.

3.2.2 Beaufort 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. 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).

Table 2. Mean and standard deviation of the distribution of anemometer heights during January of the years 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	North Pacific (30° to 50°N, 180° to 150°W)			North Atlantic (30° to 50°N, 40° to 20°W)		
	Mean Height (m)	Standard deviation (m)	Fraction (%)	Mean Height (m)	Standard deviation (m)	Fraction (%)
1980	28.7	5.9	69	18.4	7.3	35
1986	33.7	6.4	81	21.5	8.9	44
1990	35.2	8.4	82	24.2	10.9	38

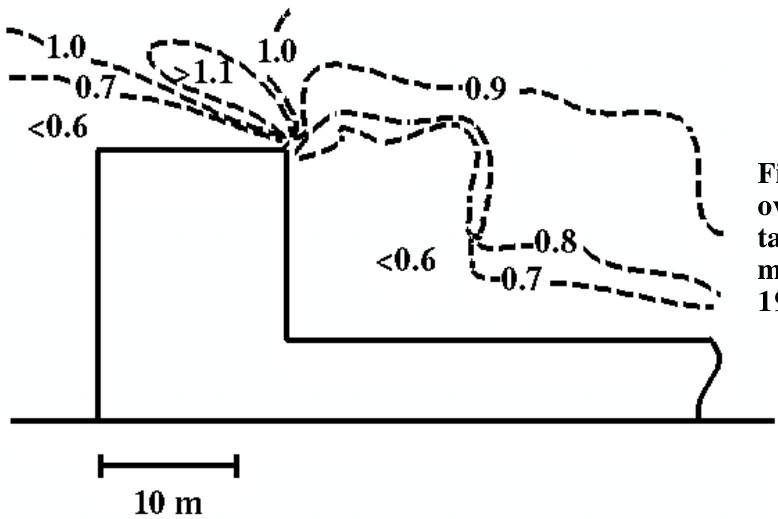


Figure 3. Distortion of the airflow over the stern section of a typical tanker as determined by CFD modelling (after Yelland et al. 1998)

3.3 Pressure

The VSOP-NA results suggested that digital Precision Aneroid Barometers (PAB's) showed less scatter than readings of aneroid barometers. Mean offsets for the PAB's were typically less than 0.5 mb whereas some analogue instruments showed offsets of 1 mb or more. Depending on cargo loading, the VSOP-NA ships showed variations of draft (and hence barometer height) of up to ±5m. There was evidence that the ships' officers normally took these changes into account in correcting the barometer readings provided the changes were more than 1m. However in some cases changes of draft had been ignored.

3.4 Air Temperature

The exposure of thermometer screens on the VOS selected for the VSOP-NA varied from good (e.g. screens hung on stanchions on the outboard rails of either bridge wing) to very bad (e.g. "the screen is made of brown varnished wood and fitted to the side of the wheelhouse in the 'porch' of the bridge wind on the port side"). The effect on the temperature readings is illustrated in Figure 4. This shows the mean difference between the VOS air temperature observations and an atmospheric forecast model for sensor exposure classed as "good", "medium", or "poor". The left part of this figure shows night data plotted against cloud cover and the right part shows day time observations plotted against the solar radiation. The latter was calculated from the ships' position and the reported cloud cover. At night the better exposed sensor recorded lower temperatures than the model suggesting a possible bias in the model. The poorly exposed sensors were about 0.5°C warm. During the day all the sensors showed increasingly warm readings with increasing solar radiation. For the better exposed sensors this bias was up to 2°C; for the poorly exposed sensors the mean bias reached over 4°C.

Data obtained from hand held psychrometers showed solar heating effects similar to the better exposed screens suggesting that the bias represents a heat island effect caused by the ship. The bias in data from better exposed sensors (which constituted the majority of the observations) was found to depend both on the solar heating and the relative wind speed and a correction scheme was devised (Kent et al., 1993b).

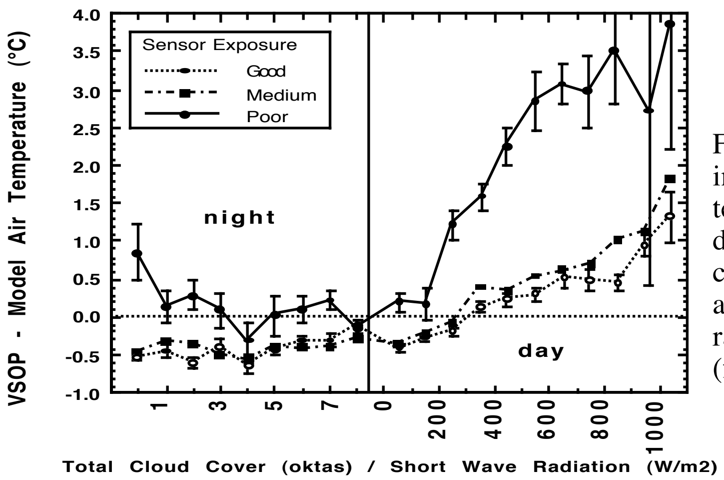


Figure 4. The effect of different instrument exposure on the air temperature observation. Night time data are plotted against total cloud cover, day time data are plotted against the calculated incoming solar radiation. See text for discussion. (from Kent et al. 1991)

3.5 Humidity

The VSOP-NA results showed that psychrometers produced lower (and therefore presumably more accurate) dew point readings compared to screens. Since the ship may often be a source of heat but is rarely a significant source of water vapour, ship board humidity readings may be of better quality than the temperature data (see for example Kent & Taylor, 1996). The humidity data is vital for determining the latent heat flux which, over much of the ocean, represents the major loss of heat to the atmosphere and which tends to dominate the interannual variability of the fluxes. However humidity is at present not reported by a large number of the VOS. Equipping those ships with wet and dry bulb psychrometers and encouraging them to report dew point would represent a major improvement to the VOS data set.

3.6 Sea Surface Temperature

Taylor et al. (1998) have recently re-examined the VSOP-NA results for SST. Using the atmospheric forecast model as a comparison standard (Figure 5a) the bucket and hull sensor data were in reasonable agreement at night, while the engine room intake (ERI) data was comparatively warm. The hull contact data were less scattered than those from other methods. Using the hull contact data as a reference (Figure 5b) showed that the ERI data were on average biased high by between 0.2 and 0.4°C, a typical mean value was 0.35°C but individual ships had mean biases between -0.5°C (too cold) and +2.3°C (too warm). Figure 5b also indicates that the bucket values were possibly about 0.1°C cold at night but became biased warm by up to 0.4°C with increasing solar radiation. This was believed to be due to the bucket having been heated on deck and then not immersed in the sea for a long enough period.

The conclusion was that hull contact sensors are the preferred method of SST determination. The feasibility of installing such sensors on VOS has recently been improved by the demonstration that acoustic methods can be used to transmit data from the hull contact sensor, through the ships hull, to the temperature readout on the bridge (Weller, Woods Hole, pers. comm.). SST buckets are to be preferred for accuracy compared to ERI thermometers, however it is recognized that practical considerations may favour the latter.

It is desirable that, where ships use more than one method (e.g. bucket or ERI), an indication of the method used by included with the observation. However at present only the log book reports contain a flag; there is no indication in the GTS message.

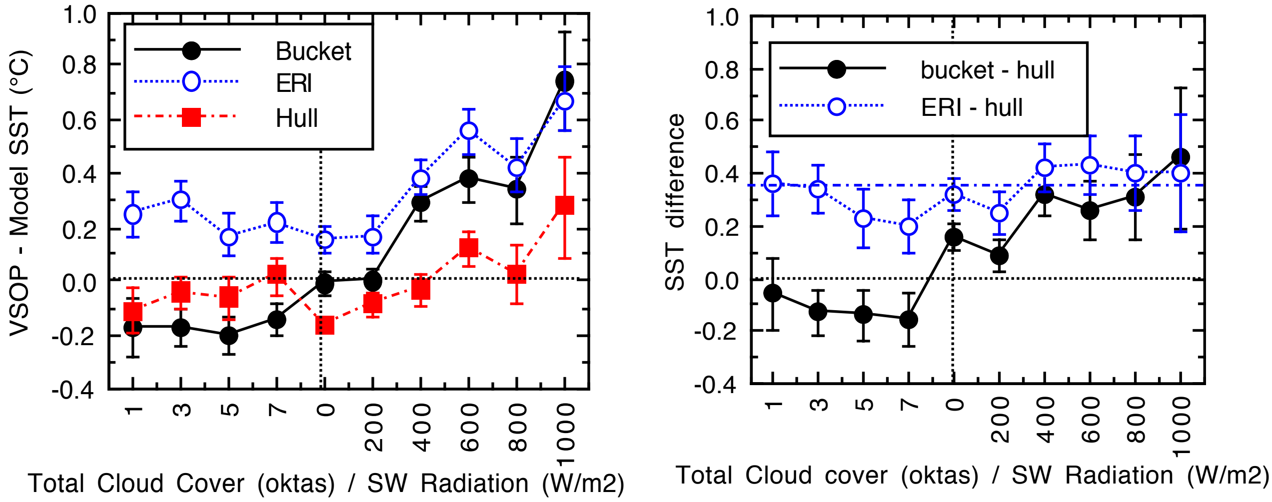


Figure 4. Comparisons of SST data obtained from the VSOP-NA ships using SST buckets, engine room intake thermometers, and hull contact sensors. Night time data is plotted against total cloud amount and day time data against the estimated solar (short wave) radiation (from Taylor et al. 1998)
a. (left) mean difference (ship data - model value)
b. (right) mean difference using the hull contact sensor data as a reference.

4. OTHER ERRORS IN THE VOS DATA

4.1 Position

About 2 to 3% of the VOS weather reports in COADS 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 where the false report may 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. The importance of correctly coding the quadrant code should be stressed.

5. FUTURE DEVELOPMENTS

5.1 Automatic coding

The more extensive use of automatic coding of ship's weather message using a personal computer system and form filling techniques would minimize the occurrence of many errors. Such a system should ensure that position is correctly coded (and is compatible with the last reported position), and automatically compute true wind, dew point, and surface pressure, checking that the results are sensible.

Such a system could 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. A standard PC can be used for data acquisition and display. The present set of IMET modules includes wind speed/direction, air temperature, sea surface temperature, relative humidity, precipitation, incoming short-wave radiation, incoming long-wave radiation, and barometric pressure.

5.2 Air-sea flux determination

Using European Union funding under the MAST programme, the AutoFlux group (1998) 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 (in both laboratory and the field) a 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 minimizes the effects of flow distortion and platform motion. The system is centered around an improved sonic anemometer/thermometer and will feature a specially developed sonic thermometer as well as a dedicated humidiometer and carbon dioxide instrument (employing infra red absorption technique). 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.

5.3 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 and the standard GTS message extracted and transmitted by the land station.

5.4 Quality control

We understand that some forecast centres compare VOS observations to the analysed fields and provide feedback to Port Meteorological Officers concerning ships which are reporting biased values. However, despite that system, the observations from certain ships within the COADS data set show significant biases (e.g. Kent et al. 1998). This suggests that the present system for feedback is not always effective and also illustrates that the feedback is not available to those constructing climate data-sets. We suggest that the VOS data set might be significantly improved by more thorough near-real time quality control (for example by comparing ship and remote sensed data) and more efficient feedback both to the PMO's and to projects such as COADS.

6. REFERENCES

AutoFlux-Group, 1998: AutoFlux - an autonomous system for monitoring air-sea fluxes using the inertial dissipation method and ship mounted instrumentation. http://www.soc.soton.ac.uk/JRD/MET/AUTOFLUX

Folland, C. K. and D. E. Parker, 1995: Correction Of Instrumental Biases In Historical Sea-Surface Temperature Data. Q. J. Roy. Met. Soc., **121**(522), 319 - 367.

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.

Houghton, J. T., G. J. Jenkins and J. J. Ephraums, 1990: Climate Change: The IPCC Scientific Assessment. , Cambridge University Press, pp. 365.

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

Josey, S. A., E. C. Kent and P. K. Taylor, 1999: New insights into the Ocean Heat Budget Closure Problem from analysis of the SOC Air-Sea Flux Climatology. Journal of Climate, (*accepted*).

Kent, E. C., P. Challenor and P. Taylor, 1999: A Statistical Determination of the random errors present in VOS Meteorological reports. Journal of Atmospheric and Oceanic Technology (*accepted*) .

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

Kent, E. C. and P. K. Taylor, 1996: Accuracy of humidity measurements on ships: consideration of solar radiation effects. J. Atmos. & Oceanic Tech., **13**(6), 1317 - 1321.

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, B. S. Truscott and J. A. Hopkins, 1993a: The accuracy of Voluntary Observing Ship’s Meteorological Observations. J. Atmos. & Oceanic Tech., **10**(4), 591 - 608.

Kent, E. C., R. J. Tiddy and P. K. Taylor, 1993b: Correction of marine daytime air temperature observations for radiation effects. J. Atmos. & Oceanic Tech., **10**(6), 900 - 906.

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 Organisation, Geneva, *86 pp*.

Lander, M. A. and M. L. Morrissey, 1987: Unexpected duplicate ship reports in the Comprehensive Ocean-Atmosphere Dataset (COADS). Trop.Ocean-Atmosphere Newsletter, **38**, 13 - 14.

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. Internat. COADS Winds Workshop, Kiel, Germany, 31 May - 2 June 1994, Environmental Research Labs., National Oceanic and Atmospheric Administration, Boulder, Colorado, 232 - 252.

Reynolds, R. W. and T. M. Smith, 1994: Improved global sea surface temperature analyses using optimum interpolation. J. Climatol., **7**, 929 - 948.

Smith, S. R., M. A. Bourassa and R. J. Sharp, 1999: Establishing more truth in true winds. J. Atmos. & Oceanic Tech., (accepted).

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: Mathematical and Physical Sciences: Large-scale oceanographic experiments and satellites, C. Gautier and M. Fieux, Ed., Vol.128, D.Reidel, 223 - 246.

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., E. C. Kent, M. J. Yelland and B. I. Moat, 1995: The Accuracy of Wind Observations from Ships. Proc. Internat. COADS Winds Workshop, Kiel, Germany, 31 May - 2 June, 1994, Environmental Research Labs., National Oceanic and Atmospheric Administration, Boulder, Colorado, 132 - 155.

Taylor, P. K., E. C. Kent and S. A. Josey, 1998: The accuracy of sea surface temperature data from Voluntary Observing Ships. *GCOS Workshop on Global SST*, International Research Institute for Climate prediction, Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY, USA, 2-4 November 1998, (in press).

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 Symposium on Integrated Observing Systems, Dallas, Texas, January, 1999, American Meteorological Society.

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 report for AES and BIO , *Southampton Oceanography Centre*.

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.