IMPROVING GLOBAL FLUX CLIMATOLOGY: THE ROLE OF METADATA

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1. INTRODUCTION

This paper will describe the use of metadata in the development of the Southampton Oceanography Centre (SOC) Surface Flux Climatology (Josey *et al.*, 1999). The data source for the climatology was the merchant ship weather reports within the Comprehensive Ocean-Atmosphere Data Set (COADS) Release 1a (Woodruff *et al.*, 1993). Although the quality of reports from the merchant ships, the Voluntary Observing Ships (VOSs), is known to be variable, the reports are a valuable source of data over the oceans. The metadata we shall use are collected by Port Meteorological Officers around the world and in the period up until 1994 were published annually by WMO (WMO-No. 47 e.g. WMO, 1994). Metadata for later years can be found on the WMO web site. COADS also contains data from other sources, such as moored and drifting buoys and oil platforms, but metadata for these data sources have not been collated in the same way as for the VOS data. Buoy metadata were therefore not used in the SOC climatology but should prove useful in future.

The information contained in the WMO-No. 47 metadata allows the identification of instrument types and heights for most VOS weather reports from COADS Release 1a for the 1980-1993 period. Using this information we can apply the results of the VOS Special Observing Project - North Atlantic (VSOP-NA) which identified errors in merchant ship weather observations. The importance of external sources of metadata is well recognized and the next version of COADS, Release 2 (Woodruff *et al.,* 1998), will contain metadata enhancements.

Climatological estimates of the ocean surface heat balance can be calculated from COADS individual weather reports. Bulk formulae (e.g. Smith, 1980; 1988) are used to calculate heat and momentum fluxes from the meteorological variables reported by the ships. In past climatologies, global adjustments have been made to the resulting flux fields to balance the global heat budget. Authors have justified these modifications as potentially compensating for the effect of ship measurement errors on the fluxes, and for uncertainties in the bulk formulae used to calculated the surface fluxes from the VOS reports. The approach taken to balance the heat budget has been to appeal to external information to constrain the fluxes. For example, da Silva *et al.* (1994) used inverse analysis to simultaneously tune COADS-based heat and fresh water fluxes to conform with oceanographic estimates of meridional heat and fresh water transports. This resulted in a 13 per cent increase in the latent heat flux (with a compensatory increase in the precipitation to balance the fresh water transport) and an 8 per cent decrease in the incoming solar flux. The sensible heat flux and the longwave flux were changed by smaller amounts. Even larger adjustments have been made in other studies that are hard to justify (Kent and Taylor, 1995).

Following the identification of sources of error in VOS data in the VSOP-NA project we were able to test whether the heat imbalance (about 30 Wm^{-2} excess heating of the ocean) found in VOS-derived flux climatologies is due to errors in the data. If the VSOP-NA corrections applied to the COADS data are similar in size to the global adjustments used by da Silva *et al.* (1994) then we might assume that the latter can be justified on the grounds of ship errors. If not, we will have to look for other methods of balancing the heat budget.

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2. CORRECTING THE VOS DATA

2.1 THE CORRECTIONS

The VSOP-NA (Kent *et al.*, 1991, Kent and Taylor, 1991) consisted of the detailed analysis of two years of meteorological reports from 46 ships selected because they reported regularly in the North Atlantic. Port Meteorological Officers gathered detailed information about the ships and the instruments carried. Photographs or plans of the ships and of the instrumentation sites were collected where possible along with information on observing practices. In addition, extra fields were added to the ships' weather log to identify the conditions at the time of the observations. Deutscher Wetterdienst, Hamburg, keyed the information from the logbooks (over 33 000 records) into ASCII format. The reports were then merged with the output of a numerical weather prediction model by the UK Met Office. The model was used to provide a consistent standard to allow ship reports separated in space and time to be compared. Figure 1 shows one of the ships that took part in the VSOP-NA project which is typical of many of the ships providing weather reports in the North Atlantic.

An example of the VSOP-NA results for sea surface temperature (SST) is shown in Figure 2. The ships in the VSOP-NA project used three different methods of measuring the SST (Kent and Taylor, 1991). Ships recruited by Germany and the Netherlands used insulated buckets to collect samples of surface seawater and measured the temperature of the water on deck with a thermometer. Ships from France and the United States measured the temperature of seawater pumped aboard to cool the ships engines (engine room intake, ERI). Ships recruited by the UK used a combination of methods but some were fitted with a dedicated SST sensor attached to the ships hull, a hull contact sensor.

Using the model as a comparison standard (Figure 2(a)) the bucket and hull sensor data were in reasonable agreement at night, while the 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 2(b)) 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 2(b) 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.

These and other results from the VSOP-NA suggested that:

1. Sea surface temperature (SST) measurements made using engine intake thermometers were biased warm (Kent *et al.*, 1993*a*). This correction could be applied for the logbook reports which contain the method of SST measurement, but for reports received by radio during this period the method of SST measurement needed to be found from the WMO-No. 47 metadata.
2. Air temperature measurements were affected by solar radiation. The warm bias caused by the solar heating of the ship superstructure could be removed on average using a formula depending on the incoming solar radiation and

Figure 1—The Nedlloyd Zeelandia, one of the 46 VSOP-NA ships.

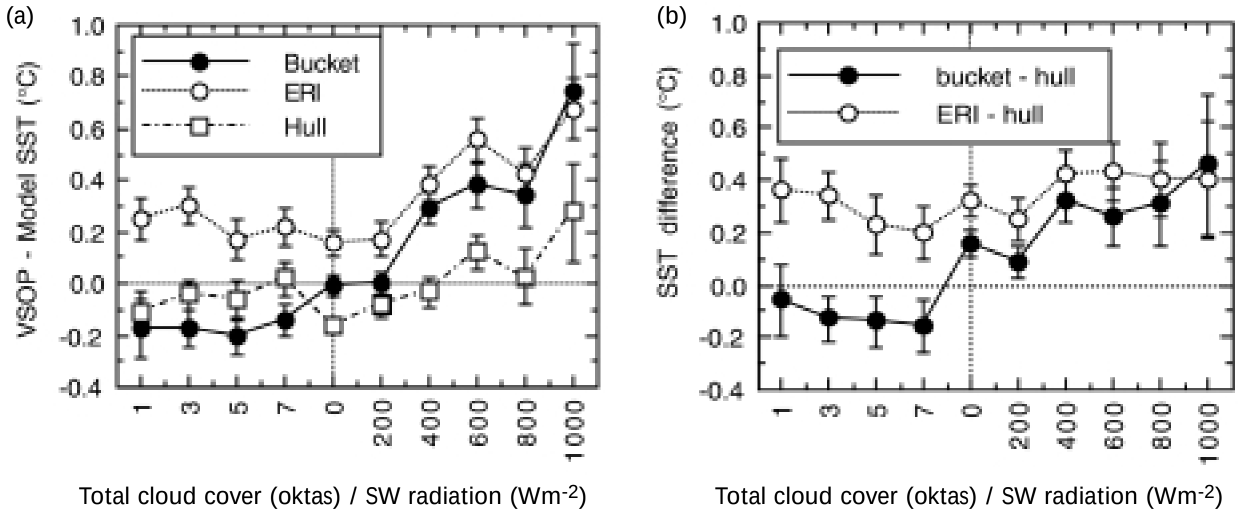

Figure 2—Comparisons of SST data obtained from the VSOP-NA ships using SST buckets, engine room intake (ERI) thermometers and hull contact sensors. Night - time data is plotted against total cloud amount and daytime data against the estimated solar radiation.
(a) mean difference (ship data - model value)
(b) mean difference using the hull contact sensor data as a reference. (from Taylor et al., 1998).

the relative wind speed (Kent *et al.*, 1993*b*). Both these parameters can be calculated from information in the normal weather report; no external metadata are required.

3. Humidity measurements from both screens and psychrometers were unaffected on average by solar heating (Kent and Taylor, 1996).
4. Humidity measurements from screens were biased high when compared with those from psychrometers, presumably due to their poorer ventilation. This bias could be removed on average by reducing the humidity from screens using an empirical formula (Kent *et al.*, 1993*a*). The method of humidity measurement needs to be found from WMO-No. 47 metadata.
5. Height correction of instrument-based wind speed measurements to 10 m should be carried out to homogenize the wind data (Kent *et al.*, 1993*a*). The height of the anemometer is contained in the WMO-No. 47 metadata. It should be noted that some recent wind reports are adjusted to 10 m height on board ships by software such as TurboWin. At present there is no way of telling which reports have already been adjusted and, therefore, height adjustment has been made for all anemometer measured reports. As more ships start to use such automated software, the number of reports that do not require further adjustment will increase. An extension to the wind speed indicator (iw in the Ship Code) or other data flag to indicate which reports have been adjusted to 10 m height would be necessary to allow this correction to be applied with confidence in the future.

Additionally, visual estimates of sea state need to be converted to a wind speed using a Beaufort equivalent scale. This conversion is made on board the ship by the observer using a conversion code that is now thought to introduce biases into the data (WMO, 1970). Many alternative Beaufort equivalent scales have been suggested in the literature. Kent and Taylor (1997) found that adjusting visually observed winds to conform to the Beaufort equivalent scale of Lindau (1995) gave the best agreement between one-degree monthly mean wind speeds derived from anemometers and those derived from visual observations. The method of wind measurement, visual or by anemometer, is contained within COADS and no external metadata are required to make this adjustment.

2.2
THE METADATA

The metadata for merchant ships in the Voluntary Observing Fleet have been published annually by WMO since the 1950s (e.g. WMO, 1994) and are available in electronic format for 1973 onwards. For each ship the metadata consists of the ship's name and call sign followed by a coded list of instrument types and heights. The instrument types for pressure, air and sea temperature and humidity are listed along with information about more specialized instrumentation installed on the ship. Anemometer heights are listed for those ships carrying anemometers (although some ships with anemometers still report winds from visual observations of sea state if national observing practices so dictate) along with the height of the observing platform which we have used as a proxy for the height of air temperature and humidity measurement.

The ASCII version of the metadata for 1973 to 1994 which was reformatted as part of the SOC flux climatology project can now be found on the internet via the COADS web site: http://www.cdc.noaa.gov/coads/.

Updates to WMO-No. 47 can be found on the WMO web site: http://www.wmo.ch/web/ddbs/ddbs.html.

2.3 COMBINING DATA AND METADATA

The link between the COADS data and the WMO-No. 47 metadata is made using the ship's call sign, which is at present in both data sets. Since a given call sign can be transferred from one ship to another, and because changes may occur in the metadata, the matching must be done on a year-by-year basis. For each ship's meteorological report in COADS, the WMO-No. 47 database was searched to find the metadata for the ship with the appropriate call sign in that particular year. About 10 per cent extra reports were matched if reports that were unmatched with the correct year were checked with metadata for the following year, indicating that there is sometimes a time lag between a ship being recruited to make weather reports and its details being collected for WMO-No. 47. Figure 3 shows the success rate for matching a report in COADS with the ship metadata. This figure shows that although the number of reports in COADS has increased slightly over the 1980–1993 period, the number of reports from ships has declined. The deficit is made up from reports from fixed platforms and moored and drifting buoys. The composition of COADS is therefore very different towards the end of this 14-year period than at the beginning. This also leads to reduced spatial coverage since the data from platforms and buoys are usually restricted to fixed locations near the coast. The matching rate increased from less than half the ship reports at the beginning of the period, largely due to the lack of call sign information in COADS, to more than 80 per cent by the end of 1992. The step increase in the match rate in 1982 is due to the inclusion of ship call signs in the WMO format for the exchange of ship logbook data at that time.

3. RESULTS

3.1 EFFECT OF THE VSOP-NA CORRECTIONS

The effect of the corrections described in section 2.1 on the flux fields can now be determined (for a full description of the corrected climatological fields see Josey *et al.*, 1999). As an example we shall take the latent heat flux. Figure 4 shows the effect of the VSOP-NA corrections, the individual height corrections (as opposed to a single assumed height of 25 m for anemometer winds) and the visual scale of Lindau (1995) on the latent heat flux in January 1990.

The latent heat flux is reduced in the North Pacific, in some regions by more than 15 Wm^{-2}. This is due to the correction to SST from engine intakes. The SST

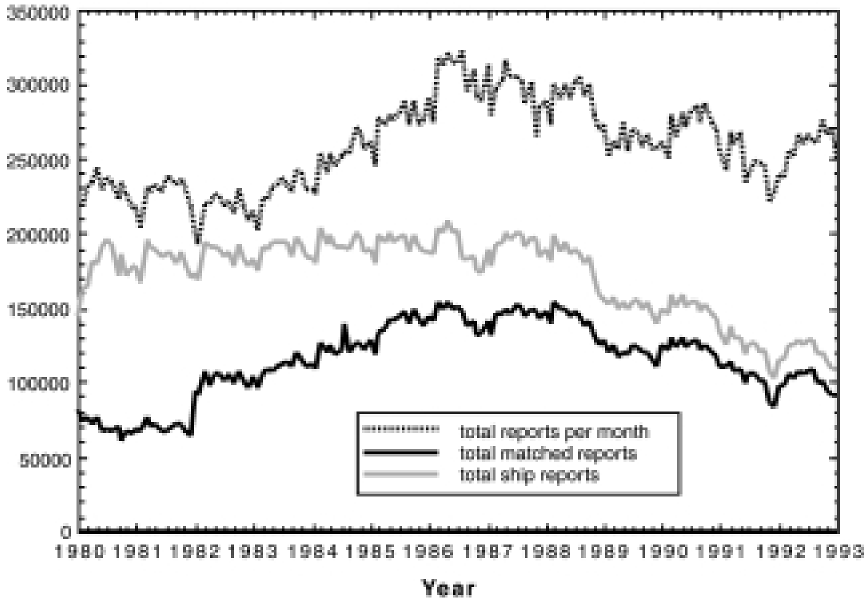

Figure 3—The number of reports per month in COADS Release 1a (top dotted line). The number of reports from ships (centre line). The number of reports for which metadata were found in WMO-No. 47 (lower dark line).

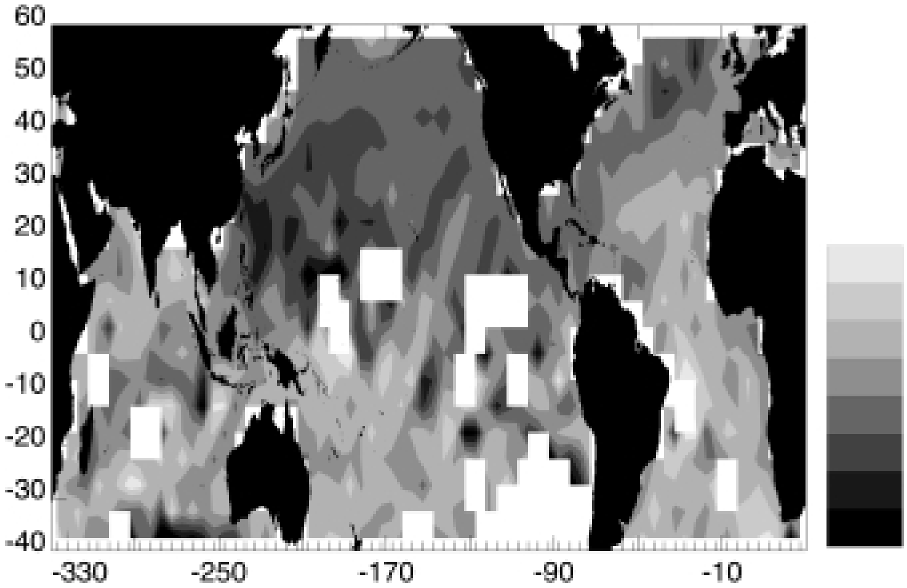

Figure 4—The effect of VSOP-NA corrections applied to the VOS data on the latent heat flux. Differences are plotted in Wm^{-2} and a negative difference represents a decrease in the heat loss from the ocean due to the corrections.

is reduced in these cases, which reduces the saturation humidity at the sea surface and hence the sea-air humidity difference results in a decrease in the latent heat flux. An additional, but smaller, decrease in the latent heat flux in this region arises from the use of individual anemometer heights. In contrast, the correction to the screen humidities decreases the air humidity, hence increasing the sea-air humidity difference and leading to an increase in the latent heat flux. It is largely this effect which leads to the increased latent heat flux values over the subtropical and South Atlantic where most of the screen-measured humidities are reported. In the North Atlantic, particularly in the north-west, the effect of the individual anemometer heights causes a decrease in the latent heat flux. The effect of the solar radiation correction to the air temperature only affects the calculation of stability and the effects on the latent heat flux are therefore small. A larger effect of this correction is seen in the sensible heat flux field (not shown). The overall effect of the individual height corrections and the Lindau (1995) scale is patchy. The effect of ship corrections on the latent heat flux is thus complex and regional and has little correlation with the magnitude of the latent heat flux. This implies that a global increase of latent heat flux in order to match the fluxes with the ocean heat transport estimates cannot be justified on the grounds of errors in the ship data.

The use of metadata has shown us that the latent heat flux errors are regional in nature. This suggests that for a regional study, globally adjusted latent heat fluxes may not be the best to use. This is investigated further in the next section.

3.2 EXAMPLE OF HEAT FLUX VALIDATION

The surface fluxes in the climatology require validation against independent data. An example of this is shown in Figure 5, in which the net heat flux data from IMET research buoys (Weller *et al.*, 1998) are compared with data from the climatology (Weller and Taylor, 1999). The IMET buoys produced high-quality flux data in the subtropical Atlantic, the Arabian Sea and the tropical Pacific. The buoy and climatology agree to within 25 Wm^{-2}. If the flux components are adjusted in a manner similar to da Silva *et al.* (1994) then the agreement between the buoys and the climatology worsens (open squares in Figure 5). In addition, White and da Silva (1999) find that zonal mean net heat flux estimates from the da Silva *et al.* (1994) unadjusted fluxes compare better with the output of reanalysis models than the globally balanced fluxes in well sampled mid-latitude regions. This again suggests that regional, and not global, corrections are required.

3.3 EFFECT OF METADATA ON RANDOM ERRORS

The use of metadata with COADS data can reduce the random errors present in the data set, which will impact on the accuracy of monthly mean values, particularly in poorly sampled regions. An example of this was demonstrated by Kent *et al.* (1999) who used the semivariogram technique following Lindau (1995) to

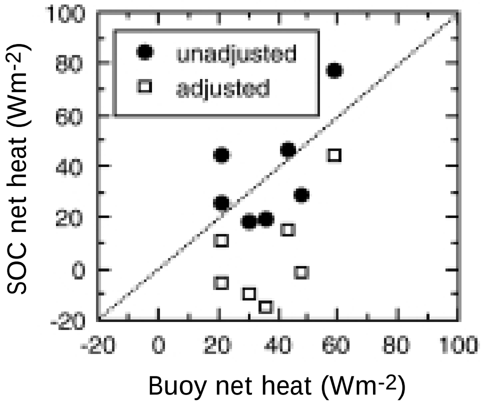

Figure 5—Comparison of the net heat flux calculated from the SOC climatology and from IMET buoy data. The open symbols show the effect of globally adjusting the SOC fluxes to balance the heat budget.

determine the random errors in merchant ship observations using the same meta data enhanced version of COADS as Josey *et al.* (1999). The semivariogram technique is used to extrapolate the mean square differences of many pairs of ship reports to estimate the root mean square (rms) error expected if the ships were in the same position. The spatial element of variability in the ship reports is thus removed giving a better estimate of the true random error. Figure 6 shows the mean square SST and wind speed differences for pairs of ships in January 1980 in the North Pacific averaged in 50 km ranges of ship separation. The spatial element of the mean square difference increases nearly linearly for ships less than 300 km apart and can be extrapolated to zero separation to give the observational component of the mean square difference.

Kent *et al.* (1999) found that using the individual anemometer heights from WMO-No. 47 to correct the data to the standard level of 10 m above sea level, rather than assuming an average of 25 m anemometer height, reduced their random error estimates by about 15 per cent. Figure 7 shows the random observational errors derived for wind speed after applying the individual height correction to the data. If error estimates are required for uncorrected wind speed estimates these values should be increased by 15 per cent. It is worth noting that a random error in wind speed will cause a systematic error in the wind stress. Hence the reduction of wind speed random errors, even in well-sampled regions, will improve the quality of wind stress data sets.

Although the method of calculation employed by Kent *et al.* (1999) precluded any estimate of the changes to random errors in other variables due to the metadata-derived corrections, there was an indication that air temperature random errors were reduced by the corrections applied.

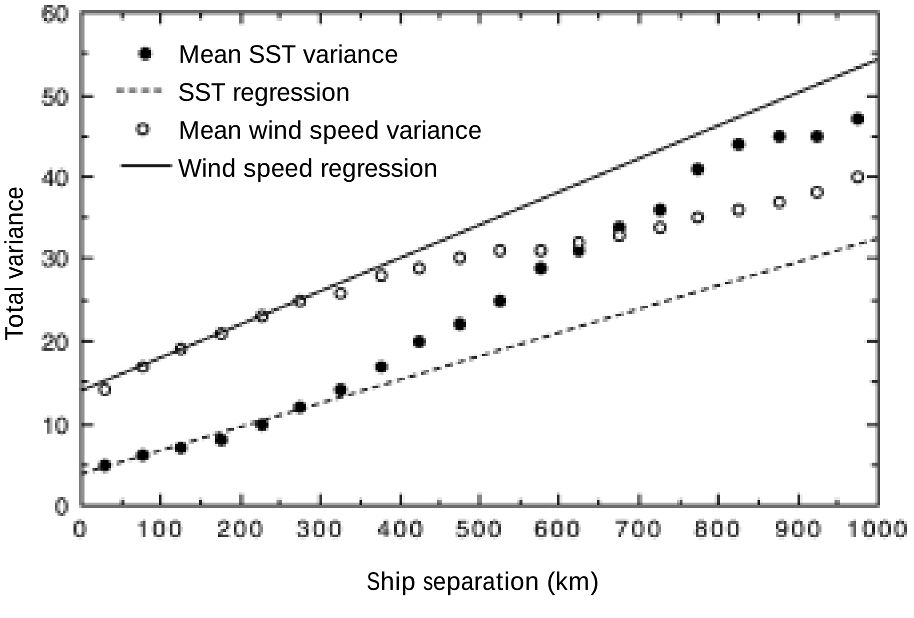

Figure 6—Examples of semivariograms for SST and 10 m corrected wind speed in the North Pacific for January 1980. The dark circles are the SST mean variance ($^{\circ}C^2$) and the open circles the wind speed mean variance (m^2s^{-2}) in 50 km ranges for ship pair separations below 1000 km. The lines are a regression on the individual points for data pairs up to 300 km separation. The intercept of the plot is twice the error variance. The regression lines are:
SST $y = 0.029 (\pm 0.001) x + 3.65 (\pm 0.1)$
Wind $y = 0.040 (\pm 0.001) x + 13.9 (\pm 0.3)$.

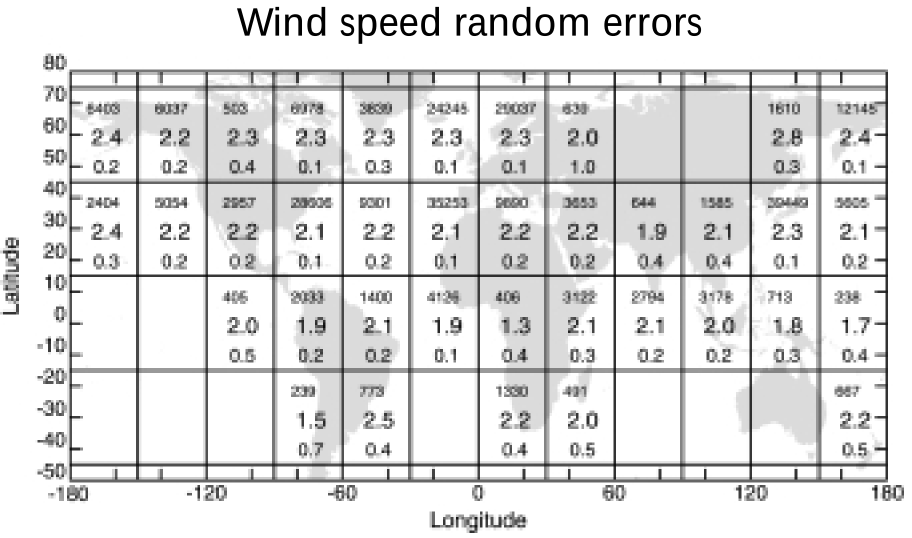

Figure 7— Wind speed random observational errors derived from COADS. The upper figure is the number of report pairs used to make the error estimate, the large central figure is the rms error (ms^{-1}) for that particular 30° region and the lower figure is the estimated uncertainty in the rms error estimate.

3.4 FUTURE USE OF METADATA

As computing and data storage capacity increase, the use of metadata with data sets such as COADS becomes easier. Although the results of the VSOP-NA suggested corrections that might be applied to merchant ship observations, these were derived from a limited subset of large merchant ships operating in the North Atlantic. Josey *et al.* (1999) applied these corrections to data from other regions in the absence of other information. The metadata-enhanced version of COADS and COADS Release 2 will allow the extension of the study of biases to other ocean basins. The semivariogram technique could be extended to look at mean differences as well as rms differences. The metadata allow the mean differences between data measured using different methods to be determined and the study of these differences under different environmental conditions. Thus, the results of the VSOP-NA could be tested for a wider range of ships and extended to other regions.

4. SUMMARY AND CONCLUSIONS

Surface flux climatologies calculated from VOS reports typically show a 30 Wm^{-2} global heat imbalance which is often removed by scaling the flux components using inverse techniques. This has been justified by appealing to errors in the VOS data. Surface fluxes calculated from the metadata-enhanced COADS showed regional and seasonal differences from those calculated without bias correction. The differences depended on the types of instruments used by ships in a particular region and are therefore affected by the choice of instrument type made by local meteorological agencies. The resulting bias corrections are not simply related to the magnitude of the flux, which suggests that global adjustments scaling the fluxes will not give a correct regional picture of the surface fluxes. This is confirmed by comparing the SOC climatology with high-quality research buoy data in the limited regions where it is available. In most cases global adjustments to the latent and shortwave fluxes typical of those required to remove the heat imbalance worsen the local agreement of the ship-derived and buoy heat fluxes. The global heat flux imbalance is, however, little affected by the corrections to the fluxes, which increase the fluxes in some regions and decrease them in others.

We cannot currently appeal to models to determine the correct fluxes. Unconstrained models can show even larger global heat imbalances and worse agreement with the research quality buoy data.

The VSOP-NA project used reports from a small subset of ships in the North Atlantic which were compared with model output. The large increase in computing resources since the project means that different types of analyses are now possible. Computationally intensive statistical techniques have been used to quantify the random errors in COADS ship reports, which will prove valuable to those wishing to apply advanced interpolation and smoothing techniques to VOS data sets. These statistical methods can be extended to examine biases between instrument types in a metadata-enhanced data set. This would extend the results of the VSOP-NA beyond the North Atlantic, examine data from countries that did not participate in the VSOP-NA and include a wider range of ship types.

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