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METHODS TO HOMOGENIZE WIND SPEEDS FROM SHIPS AND BUOYS

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ABSTRACT

Marine winds reported by Voluntary Observing Ships (VOS) and moored buoys require adjustment to provide a homogeneous record of the marine climate. Known sources of inhomogeneity arise from differences in measurement height and method, averaging method and atmospheric stability; methods are available to correct for these. However, significant differences remain in a paired dataset of ship and buoy winds. Regression methods to remove this remaining inconsistency are discussed, and a ranked regression method chosen as most appropriate to adjust ship wind speeds to yield a similar distribution. We show the factors, such as vessel type, that affect the regression results. The corrections, derived from a high-quality paired dataset with rigorous quality control, are effective at reducing inhomogeneity in monthly mean wind speed distributions derived from the International Comprehensive Ocean–Atmosphere Data Set. Copyright © 2005 Environment Canada. Published by John Wiley & Sons, Ltd.

KEY WORDS: wind speed; buoy; VOS; bias; ranked regression

1. INTRODUCTION

Long-term homogeneous datasets of marine surface winds are required for climate analysis. Presently, both satellite winds and model data contain inconsistencies (e.g. Chen, 2004). Long-term marine wind speed records are only available from ship data archived in, for example, the International Comprehensive Ocean–Atmosphere Data Set (ICOADS; Woodruff *et al*., 1998; Diaz *et al*., 2002). However, significant temporal changes in the size and type of observing platform (including the introduction of moored buoys in the 1970s) and in measurement methods have introduced inhomogeneities to databases of archived marine winds. Inhomogeneities occur for many reasons, including: different observing methods (Quayle, 1980; Peterson and Hasse, 1987; Cardone *et al*., 1990; Wilkerson and Earle, 1990; Kent *et al*., 1993, 1998; Lindau 1995a;); systematic changes in measurement height (Cardone *et al*., 1990); airflow distortion over the ship (Dobson, 1981; Yelland *et al*., 2002; Moat *et al*., 2005); different averaging times and methods (Dobson, 1981; Pierson, 1983; Gilhousen 1987; Taylor *et al*., 2002); and the effect of environmental conditions (Dobson, 1981; Kent *et al*., 1993). Other sources of observational error include: differences from nominal observing time; the anemometer type, calibration, and location; errors in calculation of true wind from the relative wind (Kent *et al*., 1993; Gulev, 1999; Smith *et al*., 1999); rounding artefacts; and for Beaufort winds, the stage of development of the waves. Researchers have studied the relationship between Voluntary Observing Ship (VOS) winds and pressures and have concluded that in some cases the pressure and wind trends are consistent (Inoue and Bigg, 1995) and in some cases inconsistent (Posmentier *et al*., 1989; Ward and Hoskins, 1996). It is important, therefore, to correct marine wind data to account for inhomogeneities for which we have

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correction techniques, such as for measurement height and atmospheric stability (Dobson, 1981; Smith, 1988; Walmsley, 1988) and for the Beaufort equivalent scale used to convert from observations of sea state to a wind speed (Lindau, 1995a). The effect of waves, including breaking waves, on near-surface airflow (Hare *et al.*, 1997; Janssen, 1999) and on the buoy motion (Taylor *et al.*, 2002) can also add a bias or increase uncertainty. Buoy winds have limited spatial and temporal coverage; however, moored buoy winds have smaller random observational error than ship winds (Gilhousen, 1987; Kent and Berry, 2005). Buoys report hourly, and are considered to be more reliable for validation of numerical model and remotely sensed data (e.g. Gower, 1996; Ebuchi *et al.*, 2002).

We used wind data from weather buoys moored in Canadian waters of the northeast Pacific and northwest Atlantic, and data from ships passing near these buoys. These regions exhibit differences in the types of ship, their operations, observing preferences, and in climate, which may affect the wind error characteristics.

Our goal is to develop a methodology to adjust both moored buoy and ship wind speeds for known and quantifiable sources of inhomogeneity, then quantify and remove the residual inhomogeneity of unknown source. We describe sources of ship and buoy data, metadata, processing, and quality control in Section 2, adjustments based on physical models in Section 3, and assessment of measurement error and the choice of regression method in Section 4. In Section 5 we describe the results of applying the different adjustment and regression methods to the development dataset and to ICOADS. Discussion follows in Section 6, with conclusions in Section 7.

2. DATA

2.1. Moored buoy data

The Canadian Marine Environmental Data Service (MEDS) provided data from 1980 to 1995 from three offshore moored NOMAD buoys in the northeast Pacific and six in the northwest Atlantic (referred to as the west and east coasts respectively; Figure 1). With the exception of data from buoy 46 004 from 1980 to mid 1988, when it was operated by the US National Data Buoy Center, the rest of the reports analysed were from Canadian buoys originally deployed between 1987 and 1990. The MEDS archived buoy data were used to derive the homogenization methodology described in Sections 3 and 4.

Data transmitted by the buoy as raw buoy messages were coded into World Meteorological Organization (WMO) synoptic ship code format (FM-13) messages. The raw messages were archived by MEDS and the FM-13 reports were archived by ICOADS. The buoy data in ICOADS between 1980 and 2002 were used to demonstrate the application of the homogeneity methods in Section 5.4. The buoy wind speed data in ICOADS have been discretized due to rounding and units conversion (Dischel and Pierson, 1986) and are at a resolution of 2 knots or whole metres per second, depending on period.

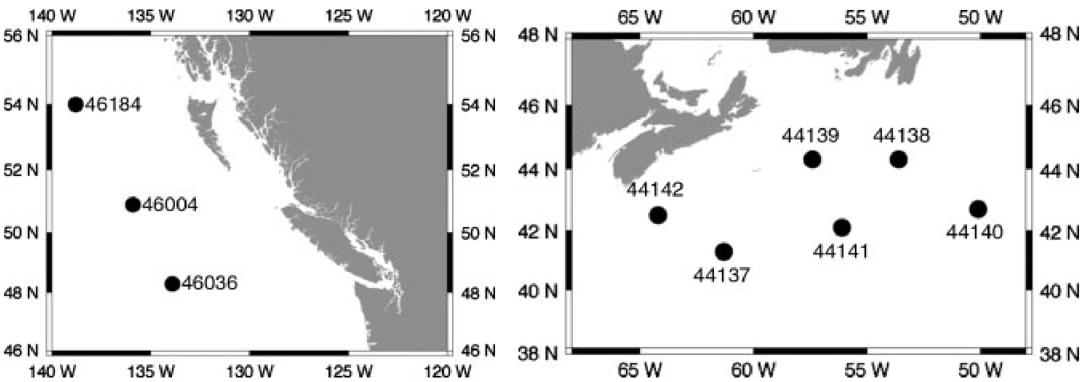

Figure 1. Maps showing locations of buoys used in this study: west coast (left) and east coast (right). The east coast map represents the buoy positions up to the summer of 1995, when three of the buoys were repositioned by up to 125 km. Note that in June 2003 (after the end of this study period) buoys 44 137 and 44 141 were repositioned further to the northwest

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The Canadian-operated buoys had two RM Young propeller-vane anemometers installed at 5.25 and 4.45 m above sea level, duplicate barometers, and single air and sea temperature sensors and a wave accelerometer (Axys Environmental Consulting Ltd, 1996). For duplicate sensors, one was designated as primary, and this designation was switched if the first failed. The primary sensors were used in the FM-13 messages and output from a failed sensor was suppressed from ship-format messages, once the problem was noted. Canadian-operated buoys reported 10 min vector mean winds in the ship-format messages until mid 1997; subsequently, they reported 10 min scalar means. The US-operated buoy reported 8.5 min vector means. The data in MEDS from the US-operated buoy were from a quality-controlled US archive.

2.2. *ICOADS ship data and metadata*

Individual VOS reports came from ICOADS Release 1a, obtained from the GTS, ship log books, and other archives. ICOADS contains observed meteorological parameters and quality assurance flags based on comparison with monthly climatology.

Anemometer heights and other metadata came primarily from yearly electronic files of WMO Publication 47 (e.g. WMO, 1980), supplemented with additional metadata for Canadian-recruited ships and information on ship type from the International Telecommunications Union. The metadata were matched by callsign to the ship report. WMO Publication 47 gives ship name, recruiting country, sensor types and heights. To estimate thermometer height we used the barometer height or platform height plus 1 m. In some cases, unavailable anemometer heights were inferred from platform heights by adding the average difference between anemometer and platform heights for that location (about 9 m). Typical anemometer heights are between 30 and 40 m on the west coast offshore, near shipping lanes. There is more variation near each buoy location on the east coast, with heights typically between 30 and 40 m, near 25 m, and between 10 and 15 m.

2.3. *Collocated dataset and quality assurance*

We created a dataset of pairs of ship and buoy reports made close in time and space with a maximum separation of 1 h and 120 km. The spatial limit was chosen to limit synoptic scale differences. Using smaller distances reduced the number of matches substantially. Since buoys report hourly, it was usually possible to get a match to the nearest hour.

The MEDS archive does not include quality assurance (QA) flags for the meteorological fields. Therefore, we applied a QA process to buoy and ship reports, flagging ship reports with wind speeds differing greatly from those of neighbouring ships, individual ships whose wind speeds differed from those of neighbouring buoys in an inconsistent way, and individual ships with few reports in the database. We assessed buoy wind directions based on comparison with neighbouring ships; if the buoy wind direction was judged to be erroneous then we did not use the vector mean winds. From 1989 onward, when MEDS began archiving both wind speeds, the winds were used only when both anemometers were functioning and in good agreement.

On both coasts the proportion of measured to estimated wind ship reports is about 2 : 1 over the whole period; however, the proportion increased over time. The proportions of different vessel types varied with location. Proportions of reports from different types were, for measured ship winds, for the west coast: 40% tankers, 40% unidentified (mostly Japanese); for the east coast: 50% government vessels (GVs; research or coastguard), 25% unidentified, 25% general cargo and container vessels. Proportions for estimated ship winds were: for the west Coast, 65% tankers, 35% unidentified; for the east coast, 50% general cargo and container, 35% unidentified.

3. ADJUSTMENT METHODS FOR A PRIORI KNOWN INHOMOGENEITIES

3.1. *Adjustment of measured winds for measurement height and atmospheric stability*

The vertical profile of winds in the marine surface layer is described by Monin–Obukov similarity theory (e.g. Stull, 1988), which includes modification of the vertical profile by atmospheric stability. Ship and buoy

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anemometers are generally within the marine surface layer. Exceptions will be anemometers on very large ships and drilling and production platforms. In very stable conditions the surface layer can be shallow and height correction cannot be confidently applied to any wind reports. The theory is also not applicable in highly unstable conditions (Walmsley, 1988). Following Kent and Taylor (1997), we used a valid range of z/L between -2.5 and 1.0, excluding some lighter winds and the most stable and unstable flow regimes.

Buoy and measured ship wind speeds U were adjusted to a reference level of 10 m and effective neutral conditions (U_{10N}) following Walmsley (1988). The greatest change usually comes in the adjustment from U to U_{10}; the difference between U_{10} and U_{10N} generally is much smaller. Atmospheric stability is estimated using air and sea temperatures, neglecting the smaller contribution of humidity. Walmsley (1988) is similar to Smith (1988), but with improvements in the computational scheme. Where temperatures were unavailable the height adjustment used the log profile from KNMI's TurboWin software (Benschop, 1996):

$$U_{10} = U_z \quad ln(10/0.0016)/ln(z/0.0016) = U_z 8.7403/ln(z/0.0016) \tag{1}$$

where z (m) is observation height, U_z is average wind speed, and U_{10} is the average 10 m wind speed.

3.2. Adjustment of measured winds for averaging method

The averaging method affects the value of the buoy mean wind speed and has changed over the period of buoy deployment, as the data logging system changed. The buoy wind speeds available up to mid 1994 were vector means U_V; subsequently, scalar means U_S became available. There was a period of about 4 years, between 1994 and 1998, when the Canadian-operated buoys reported both means in the raw data; after about 1998, calculation of U_V ceased. The changes occurred at somewhat different times at each buoy as it was serviced and the new onboard processor was installed. All the FM-13 reports contained U_V prior to 28 July, 1997, when the coding software was changed, and U_S from then onward.

For these short averaging times the buoy U_S and U_V should be similar. However, U_V is sensitive to wind direction errors, due, for example, to compass errors or sampling in the 'dead band' of the anemometer potentiometer causing a low bias in U_V. This bias can be large when, in the absence of currents, the buoy aligns with the wind with the dead band into the wind (Taylor *et al*., 2002). The 'dead band' problem was corrected sometime during the analysis period (M. Blasecki, Axys, personal communication), but U_V remains sensitive to wind direction errors. U_S is, therefore, more robust and is used in the present study. However, U_S may be biased high by about 1–3% due to wave-induced cross-wind movement of the buoy (Taylor *et al*., 2002). Thomas and Swail (1999) analysed quality-controlled hourly reports for the 4 year period when Canadian buoys reported both U_V and U_S, and found an average difference of 3%. Therefore, we used U_S when available and otherwise increased U_V by 3%.

WMO guidelines for ship wind speed measurements (WMO, 1983) specify a 10 min average, as recommended in Dobson (1981). However, in practice the observer may watch an analogue dial for a 1 or 2 min average (Dischel and Pierson, 1986). Automated weather equipment on ships typically reports a true 10 min mean, but there were relatively few automated reports before 1995. A shorter averaging interval would add variability to the observation, but not necessarily a bias, unless observers tend to report gusts. However, we do not have enough information to adjust for any effects explicitly.

3.3. Adjustment of estimated ship winds

The operational Beaufort equivalent wind scale (WMO, 1970) relates the ship observer's estimate of the condition of the sea to an effective U_{10N} based on a visual estimate of the waves, assuming fully developed seas. At night, or in restricted visibility, observers may also use other methods to estimate the wind, such as the effects on the ship or the sound of the relative wind. On ships carrying anemometers where national guidelines recommend visual observation, it is possible that the measured wind may be used to guide, or even replace, the visual observation.

We use the Beaufort equivalent scale developed from open-ocean data by Lindau (1995a, 2003), to adjust estimated ship winds. Kent and Taylor (1997) showed that this scale resulted in estimated wind speeds much closer to measured ship winds than the operational scale or other scales from the literature. The Lindau scale is non-linear and relates the midpoints of estimated Beaufort values and measured ship U_{10N}. We applied the conversion from estimated ship wind speed U_E to the Lindau-adjusted wind speed U_{EL} using a third-order polynomial, which fits the points on the Lindau scale quite closely:

$$U_{EL} = 0.0161 + 1.1888U_E - 0.0221U_E^2 + 0.0004U_E^3 \tag{2}$$

4. ANALYSIS METHOD FOR REMAINING INHOMOGENEITIES

4.1. Introduction

Our aim is to develop a regression equation to relate buoy and ship winds which have been adjusted for known sources of inhomogeneity. Application of such a regression equation would give a ship wind dataset with similar statistical characteristics to the buoy wind dataset. Isobe *et al.* (1990) review a variety of bivariate regression methods whose use depends on the purpose and the characteristics of the data.

We use the following notation. For n observed pairs $(x_1, y_1), \ldots, (x_n, y_n)$ we define the sample means $\overline{x} = 1/n \sum_{i=1}^{n} x_i$ and $\overline{y} = 1/n \sum_{i=1}^{n} y_i$. The sample variances s_x^2 and s_y^2 are denoted s_{xx} and s_{yy}, and the covariance is s_{xy}: as

$$s_{xx} = 1/(n-1) \sum_{i=1}^{n} (x_i - \overline{x})^2$$

$$s_{yy} = 1/(n-1) \sum_{i=1}^{n} (y_i - \overline{y})^2$$

$$s_{xy} = 1/(n-1) \sum_{i=1}^{n} (x_i - \overline{x})(y_i - \overline{y})$$

The standard deviations are denoted $s_x = \sqrt{s_{xx}}$ and $s_y = \sqrt{s_{yy}}$. The correlation coefficient r is defined as $r = s_{xy}/s_x s_y$. Estimators of real variables, such as the slope of the regression line for a given sample, will be marked with a caret (e.g. $\hat{\beta}_j$ for β_j). For each estimator β_j of the slope, the corresponding intercept is given by $\hat{\alpha}_j = \overline{y} - \hat{\beta}_j \overline{x}$, and the lines intersect at $(\overline{x}, \overline{y})$. If the true functional relationship between two variables is $Y = \alpha + \beta X$, then we denote the measured quantities, with measurement error, as $x_i = X_i + \delta_{xi}$ and $y_i = Y_i + \delta_{yi}$. The ratio of measurement error variances of dependent over independent variables is defined to be $\lambda = \sigma^2(\delta_{yi})/\sigma^2(\delta_{xi})$.

4.2. Ordinary least-squares regression

The most commonly used linear regression method is an ordinary least-squares (OLS) regression of Y (the dependent variable) on X (the independent variable), which we denote OLS($Y|X$). This gives a predictive relationship of the mean Y for a given X and is the true functional relationship only if X has no observational error. The OLS regression line minimizes the sum of squared vertical deviations of the observed points from that line. The inverse regression of X on Y (denoted OLS($X|Y$)) minimizes the sum of squared horizontal deviations of the observed data points from the regression line. Because of errors in the measurements, an OLS regression line, or an equivalent bin-average analysis (Tolman, 1998), based on the measured values will be biased and will differ from the functional line expected between true values. The OLS regression is not symmetrical, and the expressions for the slope of the regression line in each case are given by

$$\text{OLS}(Y|X): \qquad \hat{\beta}_1 = \frac{s_{xy}}{s_{xx}} \tag{3}$$

$$\text{OLS}(X|Y): \qquad \hat{\beta}_2 = \left(\frac{s_{xy}}{s_{yy}}\right)^{-1} = \frac{s_{yy}}{s_{xy}} \tag{4}$$

In our dataset, neither the random observational error variance (ROEV) of the ship wind speed X nor of the buoy wind speed Y can be neglected, so use of the OLS regression will lead to biased estimates of the regression parameters.

4.3. 'Errors-in-variables' least-squares regression

The 'errors-in-variables' (EV) linear regression method accounts for errors in both the X and Y variables (Lindley, 1947). It uses the ratio of the ROEV of X and Y to correct the conventional regression parameters. With the assumption that this ratio is a constant c, there is a non-iterative solution to the slope of the regression line. This is a simplification of the more general case where c can vary (Ripley and Thompson, 1987). The EV model uses a single 'bulk' estimate of c and the regression line minimizes the mean square deviations between the line and observed points at an angle given by c. The OLS$(Y|X)$ and the OLS$(X|Y)$ and orthogonal regression are special cases of EV. If the independent variable has zero error, then EV gives the same result as OLS$(Y|X)$; if the dependent variable has zero error, then EV is equivalent to OLS$(X|Y)$. The regression estimates from OLS$(Y|X)$ and OLS$(X|Y)$, therefore, form upper and lower bounds respectively of the slope of the EV regression line. The orthogonal regression is the special case for which the ROEVs are equal and $c = 1$. The EV regression solution gives the functional relationship between the true values of X and Y, correcting for the measurement errors that bias the OLS regression result. The EV model will give a result close to the line of equality if the two measurements are of the same quantity but contain different random errors. The EV regression estimate is given by

$$\hat{\beta}_3 = \frac{(s_{yy} - cs_{xx}) + \sqrt{(cs_{xx} - s_{yy})^2 + 4cs_{xy}^2}}{2s_{xy}} \qquad \text{where } c = \sigma^2(\delta_y)/\sigma^2(\delta_x) \tag{5}$$

We use the semivariogram method (Lindau, 1995a; Kent and Taylor, 1997; Kent and Berry, 2005) to determine the ROEV for measured and estimated ship wind speeds. However, to prevent systematic differences from being included in the estimates of the ROEV, we worked with variances of differences rather than the mean of squared differences. We obtained an estimate of ROEV of 2.1 m^2 s^{-2} for buoy U_{10N} and 4.3 m^2 s^{-2} for measured ship U_{10N} (west coast), (Table I), yielding a ratio $c = 0.46$. Values of ROEV for estimated ship winds were larger. Gilhousen (1987) found wind speed variances of 2.0 and 3.2 m^2 s^{-2} from paired buoys located about 40 and 110 km apart. Our values also compare well with equivalent values for ships of between 4.0 and 4.8 m^2 s^{-2} in the region of interest for U_{10N} (Kent and Berry, 2005).

4.4. Regression of ranked data

The regression of ranked data is equivalent to the 'method of cumulative frequency distributions', used by Lindau (1995a). In this procedure, both datasets are sorted separately in ascending order, then the ranked

Table I. Statistics of differences between paired ship and buoy wind speeds separately for measured and estimated ship winds and for east and west coasts. Statistics are the number of pairs, the ROEV for ship and buoy wind speeds, and the ratio of buoy/ship ROEV c

	No. of pairs	ROEV (m^2 s^{-2})		c
		ship	buoy	
East coast measured U_{10N}	2759	4.5	2.1	0.47
East coast U_E	2026	7.2	2.1	0.29
East coast U_{EL}	2026	5.4	2.1	0.39
West coast measured U_{10N}	7607	4.3	2.1	0.46
West coast U_E	3065	7.3	2.0	0.27
West coast U_{EL}	3065	5.6	2.0	0.35

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data are matched quantile by quantile. This can be visualized through plotting the regression line on a quantile–quantile (QQ) plot of the data. The slope of the OLS regression line of the ranked Y on ranked X data is given by

$$\text{OLS(Ranked } Y|\text{Ranked } X): \qquad \hat{\beta}_4 = \frac{s_{xy}}{s_{xx}} \tag{6}$$

where s_{xy} in this case is the covariance of the ranked matched pairs. If the relationship between the two variables is non-linear then a polynomial expression can be used to match the curvature. Alternatively, the method of Freilich and Challenor (1994) could be used to derive a fully empirical relation between the distributions.

Lindau (1995a) used a regression of ranked data to derive an improved Beaufort equivalent scale with a non-linear relationship between measured and estimated ship winds. We followed a similar approach and ranked individual ship U and buoy U separately, then matched the ranked values. The ranked distributions showed an approximately linear relationship. The error characteristics of the ranked data are not the same as for the unranked pairs, and it is now appropriate to perform an OLS($Y|X$) regression on the ranked data, which we call a QQ linear (QQL) regression.

5. RESULTS

5.1. *Effect of adjustments for known inhomogeneities*

The comparison and regression of ship and buoy data were performed for east and west coasts separately. However, we found that the differences in results for east and west coasts were slight, so some results are presented for buoys on both coasts grouped together. A comparison of buoy winds and measured ship wind speeds shows a difference of 25% (ship$U$ > buoy$U$) between the two distributions; the difference was very similar for estimated ship winds and buoy wind distributions. Frequency distributions in Figure 2 show original (a) and height-adjusted (b) ship and buoy wind speed distributions, for east coast measured pairs. The height adjustment, in particular, makes a significant change to the distributions, bringing them much

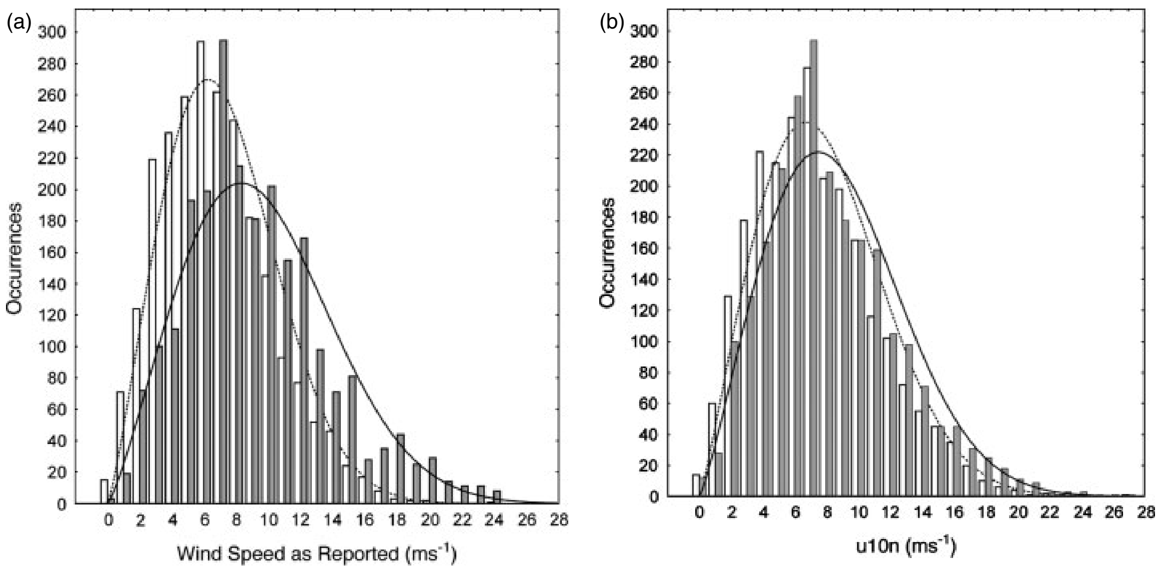

Figure 2. Histograms showing distribution of east coast collocated anemometer measured ship (grey bars) and buoy wind speeds (white bars). Also shown are Weibull distributions fitted to the distributions for ship wind speed (solid line) and buoy wind speed (dotted line). (a) Ship and buoy winds as reported; (b) ship and buoy U_{10N}

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Table II. Distribution statistics for quality-controlled west and east coast buoy and measured ship wind speeds, for wind speeds both as reported (U_z) and adjusted for height using Walmsley (1988) if ship temperatures available) or using log profile otherwise (U_{10N})

Coast	Wind speed	No. of pairs	Lower quartile (m s^{-1})	Median (m s^{-1})	Upper quartile (m s^{-1})	Maximum (m s^{-1})	Quartile range (m s^{-1})
Both	Buoy U_z	9618	5.2	7.3	9.6	24.3	4.4
	Ship U_z	9618	6.7	9.3	12.3	30.9	5.6
	Buoy U_{10N}	9618	5.7	8.1	10.6	27.2	4.9
	Ship U_{10N}	9618	5.9	8.2	11.2	27.2	5.3
West	Buoy U_z	7241	5.4	7.4	9.7	23.6	4.3
	Ship U_z	7241	6.7	9.3	12.9	30.9	6.2
	Buoy U_{10N}	7241	5.9	8.2	10.7	26.3	4.8
	Ship U_{10N}	7241	5.9	8.3	11.2	27.1	5.3
East	Buoy U_z	3523	4.6	6.8	9.3	24.3	4.7
	Ship U_z	3523	6.2	8.7	12.3	28.3	6.1
	Buoy U_{10N}	3523	5.0	7.5	10.3	27.2	5.3
	Ship U_{10N}	3523	5.8	8.0	11.2	27.2	5.4

closer together. Buoy winds are increased by about 8%, whereas the overall ship wind reduction was about 11%. Table II shows statistics for wind speed distributions for east and west coasts' paired observations for measured winds, both as reported and corrected for height and from vector to scalar. For each statistic, the agreement between ship and buoy winds is improved by the adjustment for height, confirming that this is an important step in the homogenization of ship and buoy wind speeds.

For ship winds, we used Walmsley (1988)-adjusted U_{10N} if ship temperatures were available, and used log-adjusted U_{10N} otherwise. For the subset of data pairs with ship air and sea temperatures, we compared U_{10N} adjusted by both methods. Use of different methods introduces a small inhomogeneity into the adjusted dataset. Overall, Walmsley (1988)-adjusted U_{10N} were about 3% higher than log-adjusted U_{10N}. Winds in cases of extremely stable or extremely unstable atmospheric stratification were excluded from the analysis completely (15% of east coast and 9% of west coast reports, of the ship data with temperatures).

5.2. Comparison of regression models

Figure 3 shows collocated ship and buoy U_{10N} from the east coast along with the regression lines from the models, OLS($Y|X$), OLS($X|Y$), EV and QQL (described in Section 4; regression parameters are given in Table III). As expected, the two OLS regressions give the upper and lower values for the regression, with the QQL and EV regression parameters falling between them. The QQL and EV regressions fall slightly below the 1 : 1 line, suggesting that the ships typically report slightly stronger wind speeds than the buoys after the known inhomogeneities and error structure have been accounted for. Figure 3 shows the importance of

Table III. Best fit regression coefficients from four regression methods (see Section 4), for east coast paired anemometer ship and buoy U_{10N}

Regression method	Intercept (m s^{-1})	Slope
OLS($Y|X$)	1.504	0.731
OLS($X|Y$)	−2.222	1.164
EV	−0.765	0.994
QQL	−0.152	0.924

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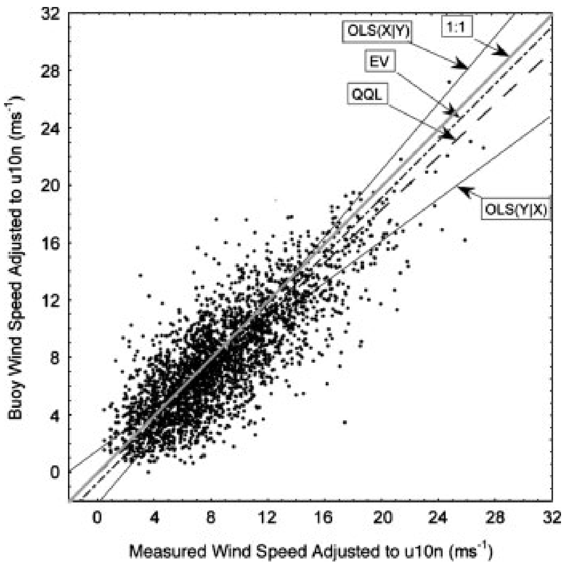

Figure 3. Scatter plot for Atlantic collocated ship and buoy U_{10N} showing OLS($Y|X$) and OLS($X|Y$) (solid), EV (dot dash) and QQL (dashed) regression lines (see Section 4, Table III) along with the 1 : 1 line of agreement (grey)

accounting for the error structure of the dataset, and that the use of the OLS regression will give strongly biased regression estimates.

Applying the EV regression results to the ship wind speed data decreased the individual values slightly, but otherwise did not change the shape of the distribution as the slope is almost one. This indicates that the U_{10N} values from the ships and buoys have a similar distribution except for their random error characteristics and a systematic bias. The bias of -0.8 m s^{-1} (Table III) is significant and perhaps suggests the relationship is slightly non-linear (Hinton and Wylie, 1985). The QQL regression equation was obtained by matching the quantiles of both ship and buoy winds, so it gives a ship wind speed distribution closest to the buoy wind speed distribution. The largest impact is on the higher and lower percentiles. The QQL regression also preserves seasonal climatological characteristics better (Thomas and Swail, 2002).

5.3. Regression results

5.3.1. Anemometer-measured ship wind speeds. Figure 4 is a QQ plot for buoy and ship measured U_{10N} for the west coast. Table IV gives the regression parameters for each coast. The intercepts are small, within 0.5 m s^{-1} of the origin. The slope is slightly steeper for the west coast (0.94 compared with 0.92), indicating that ship winds need to be reduced by about 6% on the west coast and by 8% on the east coast to homogenize them with buoy winds. Almost all west coast paired reports were from merchant (and unidentified type) vessels, whereas a high proportion on the east coast were from GVS. When the GV data were analysed separately from the rest, the slope of the QQL regression line for the non-GV was 0.94, similar to the west coast (Figure 5, Table IV). The GV reports contained a larger bias, with a QQL line slope of 0.89. This suggests that differences in results for each coast could be due to the types of ship reporting in each region, in addition to any environmental differences. Overall, however, we did not find statistically significant differences in the regression results for each coast, so we derived regression equations for both coasts combined. For measured ship winds, this yields a regression reduction of about 6% overall.

5.3.2. Regression results for visually estimated ship wind speeds. Figure 6 shows the QQ plot for visually estimated ships winds for both U_E and U_{EL} against buoy U_{10N}. The effect of the Lindau adjustment on U_E is to remove the curvature that is evident in the relationship between buoy U_{10N} and U_E, and also to reduce the winds, on average, bringing them into better agreement with the buoy winds. An approximately linear

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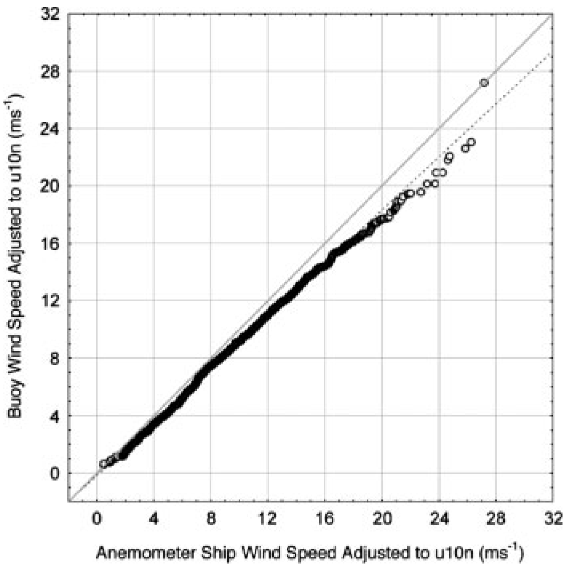

Figure 4. QQ plot comparing collocated east coast buoy U_{10N} and anemometer-measured ship U_{10N}. The dashed regression line shows the linear relationship for ranked data (Table IV); the solid line is 1 : 1 agreement

Table IV. QQL regression results for adjusted ship and buoy wind speed pairs (x represents buoy U_{10N} (m s^{-1}) and y represents adjusted ship wind (U_{10N} or U_{EL} (m s^{-1})). For measured ship winds, results are for winds adjusted using (a) Walmsley (1988) if possible, otherwise log profile, and for (b) log profile only; and grouped by all data, by coast, and by GV/non-GV type. U_{EL} wind speed results are for all data pairs, and grouped by night and by day

Ship winds	No. of data pairs	Walmsley (1988)/log profile adjusted y = ship U_{10N} (m s^{-1})	Log profile adjusted y = ship U_{10N} (m s^{-1})
Measured			
All data	9618	$y = 0.124 + 0.937x$	$y = 0.049 + 0.951x$
East coast only	2377	$y = -0.152 + 0.924x$	$y = -0.245 + 0.939x$
West coast only	7241	$y = 0.238 + 0.939x$	$y = -0.150 + 0.976x$
Non-GVs (both coasts)	8422	$y = 0.192 + 0.939x$	$y = 0.113 + 0.952x$
GVs (mainly east coast)	1196	$y = -0.064 + 0.891x$	$y = -0.117 + 0.903x$
Estimated		$y = U_{EL}$(m s^{-1})	
U_{EL}	4616	$y = -0.531 + 0.966x$	
U_{EL}, night only	2041	$y = -0.404 + 0.970x$	
U_{EL}, day only	2575	$y = -0.646 + 0.964x$	

difference in slope of about 3% remains between U_{EL} and buoy U_{10N} (Table IV). This is similar for each coast, so the data are again analysed for both coasts combined. Visual estimates of wind speed are harder to make at night (e.g. Kent *et al*., 1993) and we therefore also analysed night and daytime data separately (Table IV). The data showed a tendency for the daytime wind speed distribution to be slightly stronger than the night-time, although overall the differences are small.

5.4. Application to ICOADS

To test the wider applicability of the methodology derived in this paper, we apply the corrections and homogenization techniques to buoy and ship wind speeds from ICOADS for the period 1980 to 2002. Instead of generating a paired data set and applying rigorous quality control, we use all ship data passing ICOADS

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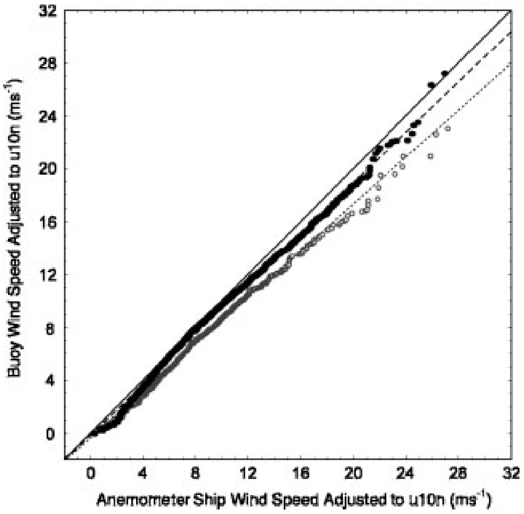

Figure 5. As Figure 4, but for data combined for east and west coasts but separately for GVs (open circles, dotted line) and non-GVs (closed circles, dashed line) and line of 1 : 1 agreement (solid line); see Table IV for linear regression coefficients

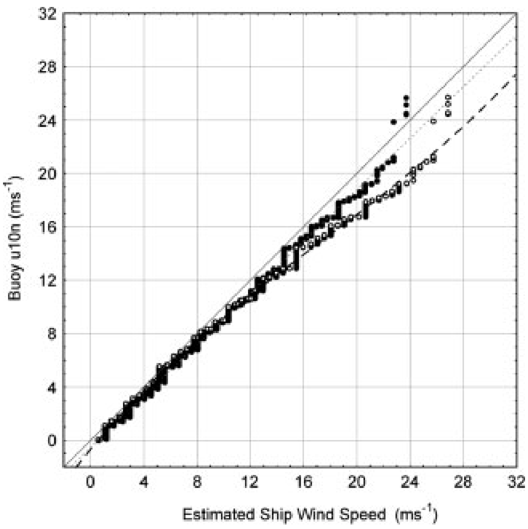

Figure 6. As Figure 4, but for buoy U_{10N} and ship U_E and U_{EL} for east and west coasts combined. Estimated wind speeds as reported (U_E, open circles, polynomial fit dashed line) and estimated wind speeds adjusted to Lindau scale (U_{EL}, closed circles, dotted line); linear regression, see Table IV

QA reported in a month in a $2^\circ \times 2^\circ$ area around the buoy site to construct distributions. We also note the problems with the quantization of the buoy FM-13 reports (Section 2.1). The ship data are extremely inhomogeneous; for example, at the buoy 46 184 location the ship data in the surrounding area in the early 1980s contain about 50% visual observations, and by 2000 about 25% are visual observations; on the east coast the mean anemometer height has nearly doubled from around 20 m to slightly under 40 m.

Figure 7 shows a section of data from the buoy 46 184 location for the period 1986 to 1996. Buoy data are only available from late 1988. The time series shows monthly values of the 90th percentile for uncorrected, corrected and homogenized ship wind speeds and the corrected buoy wind speed (where available). It is clear that the methodology applied has improved the agreement between ship and buoy winds for these relatively high exceedance values. An exception is the relatively low buoy wind speed in the winter of 1989–90;

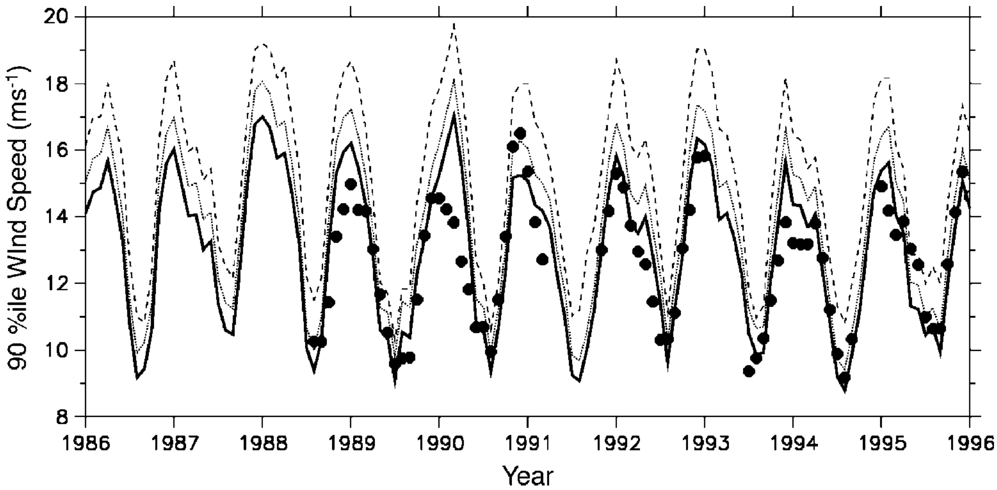

Figure 7. Time series of monthly values of 90th percentile wind speeds from buoy 46 184 on the west coast. Wind speeds are ship winds as reported (dashed line), height-corrected wind speeds (dotted line), homogenized ship wind speeds (solid line) and corrected buoy wind speeds (filled circles)

however, internal MEDS buoy status reports indicated that the buoy vector mean winds for this period are suspect because of compass errors.

The good agreement of the homogenized ship and buoy wind speeds is confirmed in Figure 8, which shows, for east and west coast data separately, the differences between ship and buoy estimates of selected distribution statistics. As expected, the uncorrected ship and buoy wind speed distributions differ throughout the range, with differences increasing with higher exceedances (east coast only shown) and the agreement for ship and buoy U_{10N} is much closer. For both east and west coast data the agreement is again improved by the homogenization procedure, especially for the statistics in the upper part of the distribution, with all statistics calculated above the median agreeing on average to better than 0.5 m s^{-1}. Comparison of the statistics for the individual buoys (not shown) reveals variability between the ship and buoy differences at each site.

6. DISCUSSION

6.1. Adjustment for measurement height

The most important source of inhomogeneity between buoy and anemometer-derived ship wind speeds results from their significantly different measurement heights, which in this study is 5 m for the NOMAD buoys and typically 30 to 40 m for the ship observations. Adjustment for measurement height improves the agreement between ship and buoy wind speeds substantially.

A larger homogeneity adjustment is required for U_{10N} calculated from Walmsley (1988) than for U_{10N} calculated from the log profile formula alone (Table IV compares the regressions for the Walmsley (1988) and log-adjusted ship winds combined, with those for all log-adjusted ship winds). Adjusting to the reference height while taking atmospheric stratification into account gives a larger residual difference between ship and buoy wind speeds, overall, than the log profile correction, for which neutral conditions are assumed. This is a systematic consequence of the stability-dependent height adjustment method reducing ship winds less (and increasing buoy winds less) than the log-profile height adjustment method *in unstable conditions*, as slightly unstable conditions were most frequently observed.

The stability-dependent correction for height requires knowledge of the air and sea surface temperatures. Any error in the temperature (Berry *et al.*, 2004; Kent and Kaplan, 2005) used to make the stability-dependent height correction could apparently act to worsen the collocated comparisons. However, the overall consistency of VOS winds is improved by the full stability-dependent height adjustment method (Kent and Berry,

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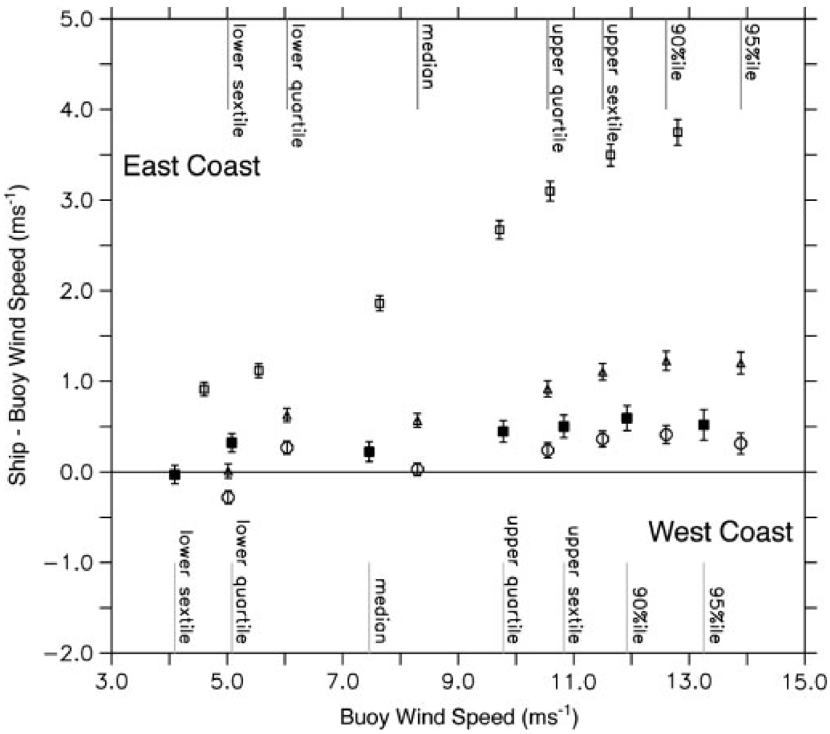

Figure 8. Average differences between ship and buoy estimates of selected wind speed distribution statistics for east and west coast buoys separately. Markings indicate distribution quantiles for corrected buoy wind speed for east coast (upper) and west coast (lower). Differences are plotted for the buoy wind speed distribution lower and upper sextiles, upper and lower quartiles, the median and the 90th and 95th percentiles. Uncorrected ship and buoy (open squares: east coast), corrected ship and buoy (open triangles: east coast) and homogenized ship and corrected buoy (open circles: east coast; filled squares: west coast). Error bars represent the standard error of the mean

2005), which is preferred to log profile adjustment. The use of log-profile-adjusted winds when temperature information is unavailable could introduce an inhomogeneity of a few percent and would be significant if, for example, air and sea temperatures were only available for certain periods. The decision on whether to include full stability effects for part of the record would have to be made depending on the application. When temperature information is unavailable, some wind speeds made in either extremely stable or unstable conditions will be inappropriately adjusted. It is desirable to have information on anemometer height for individual ships; however, if individual heights are unavailable then generic heights can be assumed, which could vary with time, region, ship type or recruiting country.

Reports from ships which make visual wind speed reports based on sea state are already equivalent to U_{10N}. Use of the Lindau scale, rather than the operational scale (WMO, 1970), is recommended to homogenize these visual reports with ship anemometer wind speeds. Conversion to the Lindau scale removes much of the non-linearity in the relationship between estimated ship and buoy wind speeds and reduces the variance of the differences by between 13 and 20%. However, some differences still remain, even at lower wind speeds. Some ships that report visual estimates do have anemometers onboard. If observers use this anemometer to aid in the visual estimate, then it is not known whether they correct for ship speed and direction or adjust for anemometer height.

6.2. *Adjustment for residual sources of inhomogeneity*

Once the corrections for known inhomogeneity have been applied we can analyse the residual differences between ship and buoy wind speeds. Analysis is complicated by the different ROEVs in the ship and buoy

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winds, with the variance in the ship winds two to three times larger than that in the buoy winds. The EV regression model accounts for these differences in variance and shows that agreement between the ship and buoy wind speeds is typically better than 10%. If the different ROEV is not accounted for, then differences could be erroneously estimated to be 30% or more.

For this application our goal is to find an equation to use to homogenize wind distributions that do include measurement error. The regression of ranked data produces a relationship that is the most effective at transforming the ship wind distribution to have the same statistical characteristics as that of the buoy. To homogenize measured ship and buoy U_{10N}, the ship U_{10N} needs to be reduced by about 6% (Table IV). Different regression equations may be developed for different surface layer stability categories or height-adjustment methods, if analysis shows that these give statistically significant results. Once most of the non-linear difference between buoy and ship visual winds has been removed using the Lindau scale, a linear ranked regression is then adequate to homogenize the data by decreasing the ship visual winds by 4% and subtracting 0.5 m s^{-1} (Table IV). The estimated ship wind to buoy wind relationship is slightly different for night-time compared with daytime observations, but these are not corrected separately, as factors such as the influence of any onboard anemometers should also be investigated.

6.3. Possible sources of residual inhomogeneity

6.3.1. Ship winds. Any errors in the height adjustment due to incorrect stability assumptions or theoretical limitations may contribute to the residual differences. Ship winds are affected by air flow distortion, which may be of comparable size to the residual differences (Moat *et al*., 2005), although more work is needed to quantify air flow distortion over VOS. We showed that U_{10N} distributions from government vessels, as a group, differ from the rest. We also expect differences between different types of merchant ship (Thomas and Swail, 2004; Moat *et al*., 2005). We did not account for a possible high bias in visual averages of an analogue anemometer dial. Errors in calculating true winds from platform relative winds could introduce consistent differences if shipping lanes are aligned with prevailing winds (Gulev, 1999). New logging systems mean that the occurrences of such errors should reduce over time. Ship heading with respect to the prevailing winds and waves may also affect the visual estimate of wind (Thomas and Swail, 2004). Such factors, and others, such as possible variations in the Beaufort scale with time and recruiting country (Lindau, 1995b) and the influence of anemometers on ships reporting U_E (Kent *et al*., 1993), also require further investigation.

6.3.2. Buoy winds. Although we have used buoy U_{10N} as truth in this study, some uncertainty in buoy wind characteristics remains. We noted earlier that buoy scalar winds, as used in this study, may be biased slightly high due to buoy motion (Taylor *et al*., 2002) but are perhaps preferred for their smaller random observational error. We have also noted problems with compasses and the anemometer dead band affecting wind direction and vector wind speeds. Careful QA is required in order that large amounts of erroneously low buoy winds do not enter the archive, as unattended operation means that problems may persist for many months (in particular when vector means only were reported). The source of the buoy data is also important: ICOADS-archived buoy winds have an additional source of error to those from the MEDS archive, due to the discretization of the archived speeds.

In rough seas the buoy wind speed may be measured at heights below the wave crests and buoy movement within waves can cause errors, although recent work suggests these errors may be small (Taylor *et al*., 2002). In the presence of surface waves, Large *et al*. (1995) suggested that the vertical gradient in wind speed is greater than predicted by similarity theory, but Hervey (2000) found that a wave-dependent correction based on Large *et al*. (1995) produced a positive bias in the adjusted buoy wind speeds. Hare *et al*. (1997) define the portion of the surface layer that is significantly affected by the presence of the underlying waves as the wave boundary layer. Further research in this area may yield methods that use wave measurements to adjust buoy winds to equivalent winds above the wave boundary layer. More study to understand and quantify the overall impact of waves on buoy winds is required.

6.4. *Application of homogenization methods to ship winds over time*

The regression relationships developed in this paper will apply to ship winds reported in the 1980s to 1990s. The practice of adjusting for measurement height will apply to ship winds observed outside of this time period as well, although the height adjustment methodology may need to vary depending on the additional information available (anemometer height, air and sea temperatures). However, as observing practices change over time, the net effect of the residual errors will also change. Thus, the statistical relationship between ship and buoy winds of the 1980s to 1990s will not apply to earlier or later decades. For later periods it would be possible to develop new relationships to be applied to specific time frames, or to different categories of ship observations, such as automated 10 min average winds and the human observer's average of winds displayed on an analogue dial.

For time periods before the existence of buoy wind observations, other approaches are needed. Progress has been made by Ward and Hoskins (1996) and Lindau (1995b) using the consistency of ship winds and pressures. Ward and Hoskins (1996) used relationships for gridded datasets of monthly mean pressure and vector mean wind speed. Lindau (1995b) used relationships for individual observations. In both methods, the relationship between pressure gradients and wind was assumed invariant over time and the pressure record homogeneous. Differences in the pressure–wind relationship were attributed to changes in the wind record, and adjustments made. It should be noted that in neither of these studies were changes in the wind measurement height accounted for.

7. CONCLUSIONS

Adjusting measured wind speeds to a standard reference height of 10 m significantly improves the agreement between ship and buoy wind speeds, which are typically measured at between 20 and 40 m and at around 5 m height respectively. Residual differences are about 6%.

Where temperature information is available, accounting for stability while adjusting to 10 m (e.g. Walmsley, 1988) should also improve agreement between measured ship and buoy wind speeds; but, for this adjustment to be effective, good quality coincident air and sea temperatures are required. Stability-dependent height-corrected ship wind speeds were on average about 3% greater than log-profile-adjusted ship winds. In this study we have used log-profile-adjusted winds where there was not enough information to account for stability, but this may not be appropriate if trends with time are being considered and temperature data availability varies with time.

Using the Beaufort equivalent scale of Lindau (1995a) for estimated winds removes much of the bias and non-linearity in the relationship between estimated ship wind speeds and buoy U_{10N}. As with the measured winds, there are significant residual differences.

The choice of regression method used to analyse residual differences between ship and buoy U_{10N} is important. The EV regression method gives the true functional relationship: ship and buoy U_{10N} agree to within 2% for measured wind speeds and to within 5% for estimated wind speeds. To homogenize statistical distributions of adjusted ship winds to agree with those of adjusted buoy winds, we use a regression of ranked data. Results of the ranked regression analysis were applied to monthly distributions of adjusted ICOADS wind speeds with good success.

Remaining potential sources of inhomogeneity between ship and buoy wind speeds include, for visual estimates: night and day, recruiting country, and sea state; for measured: atmospheric stability and wave height, averaging interval differences, and vessel type. More work is needed to understand these differences. If some of these residual sources of inhomogeneity could be accounted for directly, then the regression relationships should be recalculated using the adjusted data.

Climate researchers working with marine datasets with different characteristics than those described here may find it appropriate to develop individual regression relationships for their particular datasets. As observing methods change over time, e.g. with the increase in numbers of automated ship wind measurements, new statistical relationships between ship and buoy winds can be developed. However, prior to the advent of buoy

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wind observations, temporal changes in winds due to changes in observation method will have to be assessed using other methods.

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