

METHODS TO HOMOGENIZE WIND SPEEDS FROM SHIPS AND BUOYS

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Introduction

Long term homogenous datasets of marine surface winds are required for climate analysis. However significant temporal changes, in the size and type of observing platform and in the method, have introduced inhomogeneities to databases of archived marine winds. An apparent increasing trend in marine wind speeds last century was related to the transition to more anemometer measurements, and a trend toward increasing anemometer heights as ship sizes increased [1]. We apply and assess methods to homogenize these data sets. This study uses wind reports from buoys moored in Canadian waters and reports of visually estimated and measured wind speeds from nearby ships, from 1980 to 1995. Buoy winds have less random observational error (ROE) than ship winds, and are the standard for validation of numerical model and remotely sensed data, but they do not extend very far back, in terms of the marine climate data record. Buoy winds regressed on ship winds give a relationship which we use to convert ship winds to have the same statistical characteristics as buoy winds.

Buoy and Ship Data Sources and Quality

The Canadian Marine Environmental Data Service (MEDS) provided moored data from 3 offshore NOMAD buoys on the west and 6 on the east coast of Canada, 1980-95. Ship reports came from the COADS (Comprehensive Ocean Atmosphere Data Set) Release 1a: 1980-95 [16]. Anemometer and thermometer heights came primarily from yearly electronic files of WMO Pub. 47 [15], matched by call sign to the ship report. We created a dataset of pairs of ship and buoy reports close in time and space (within 1 hr and 120 km). We applied a QC process to both 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 (determined by interquartile range of the differences), and individual ships with few reports in the database. We performed additional quality control on the buoy data, beyond that reported in [9,10], to flag and exclude cases with wind direction errors, which could reduce the quality of the vector mean wind speed.

Height Adjustment for Measured Winds

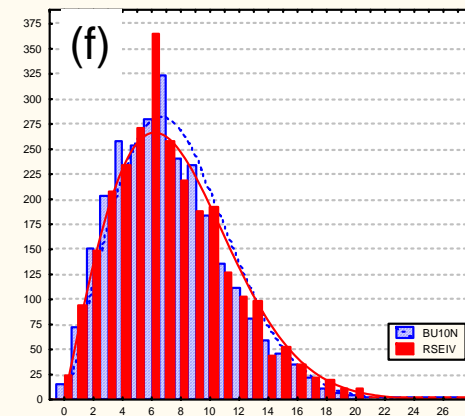
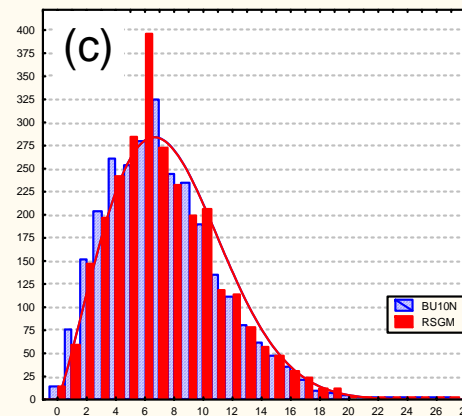
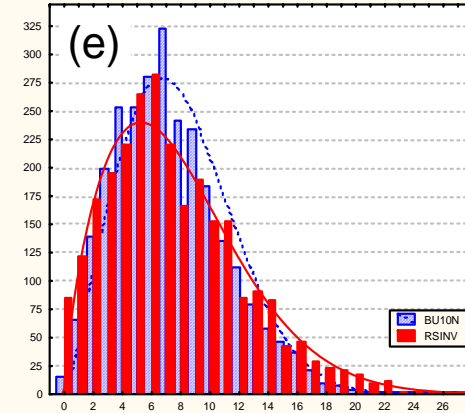
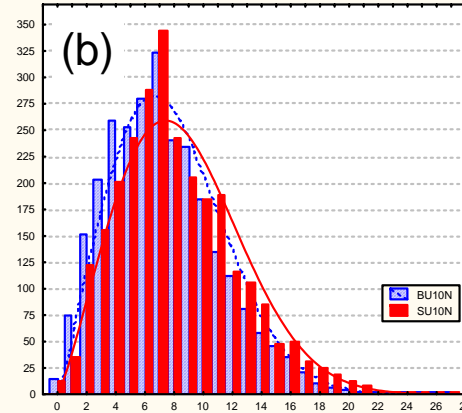
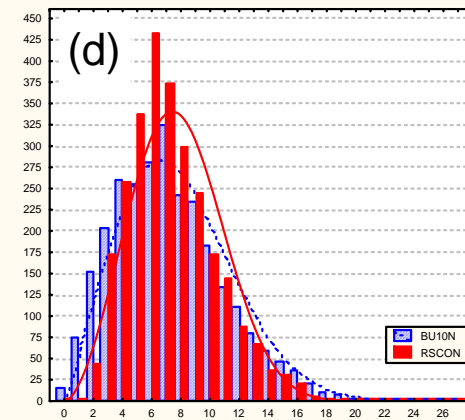
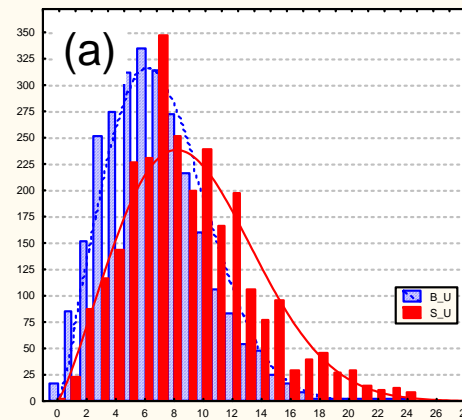
Typical ship anemometer heights range from 15 to 40 m, while buoy anemometers are at 5 m. We adjusted wind speeds to 10 m, effective neutral using Walmsley's method [13], which is based on Monin-Obukov similarity theory and accounts for atmospheric stability using air and sea temperatures. When temperatures were not available, we used the log profile formula, which assumes neutral stability. Comparison of ship winds adjusted both ways showed that using two different methods introduces a small inhomogeneity into the adjusted dataset. Log-profile-adjusted ship WS were a few percent lower than Walmsley-adjusted WS, overall. Particularly since air and sea temperature information for each wind report is less likely to be available with earlier reports, climatologists may prefer to adjust all winds in a marine data base using the log-profile method.

Averaging Interval Adjustment

The buoys report a 10 minute mean wind speed. The averaging method changed from vector to scalar near the end of the period. The buoys reported both averages for some months. The scalar mean wind speeds were 3% higher than the vector mean, on average [9]. We used that value to correct vector mean speeds. WMO guidelines for ship wind speed measurements specify a 10 minute average, but in practice it is likely a shorter interval. This would add variability to the observation, but not necessarily a bias, unless the observer tended to report the gusts. We did not apply a correction for averaging method to the ship measured wind speeds.

The frequency distributions show original (a) and height-adjusted (b) ship and buoy wind speed (WS) distributions, for west coast measured pairs.

The height (and averaging method) adjustments make a significant change to the distributions, bringing them much closer together. We will use regression methods to adjust ship winds, to remove remaining inhomogeneities.



Frequency distributions of east coast measured paired ship and buoy wind speeds, fitted to Weibull distribution

a) original buoy and ship
b) BU10N and SU10N, c)-f) BU10N and regressed SU10N winds, converted using: c) geometric-mean, d) conventional, e) inverse, and f) EIV regression equations.

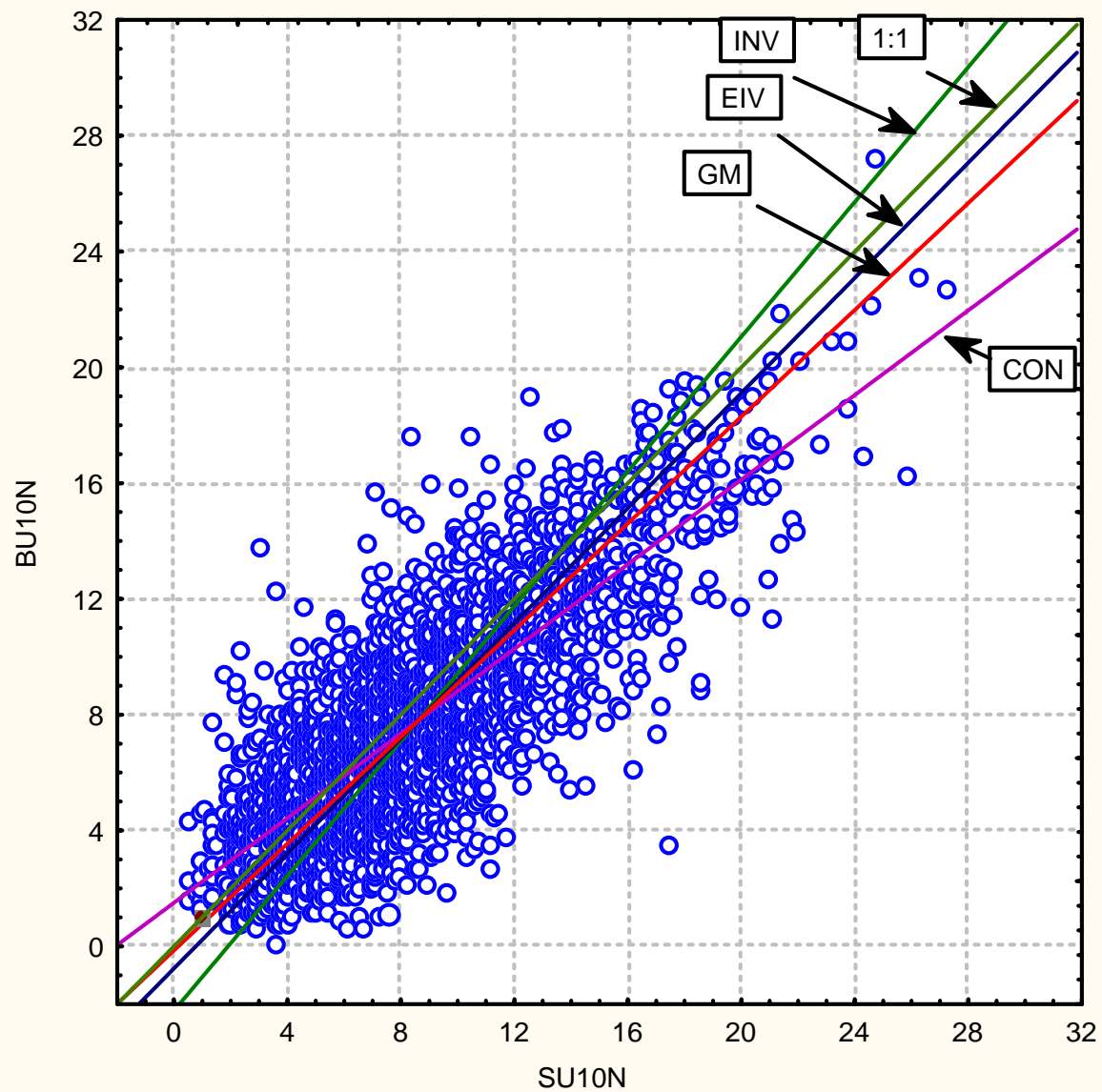
Regression of Buoy on Ship Winds

We assessed 4 linear regression methods: conventional (ordinary least squares (OLS($Y|X$))); its inverse (OLS($X|Y$)); error-in-variables (EIV); and geometric-mean (GM) regression. [5] describes use of the EIV method to compare ship and scatterometer winds. This method gives a true functional relationship between buoy and ship winds by using the ratio of the random observational error variance (ROEV) of each source to correct for the error. Following the methods in [3,2], we determined the ROEV for ship and buoy winds to be approximately 4.5 and 2.1, for ht.-adjusted measured speeds. Using the ratio of ROEV in the EIV regression equation, we obtained a slope of nearly 1. This indicates that once we have adjusted for height and corrected the regression for the ROE, the winds observed by the buoys and ships are close to the same thing. Some of the apparent bias was due to the large random observational error. However, our ultimate goal is not to find the functional relationship, but to find an equation to use to homogenize datasets that do include measurement error. For this reason the OLS regression is not useful either [12], since it is applicable when all of the random observational error is in the dependent variable, which is not the case.

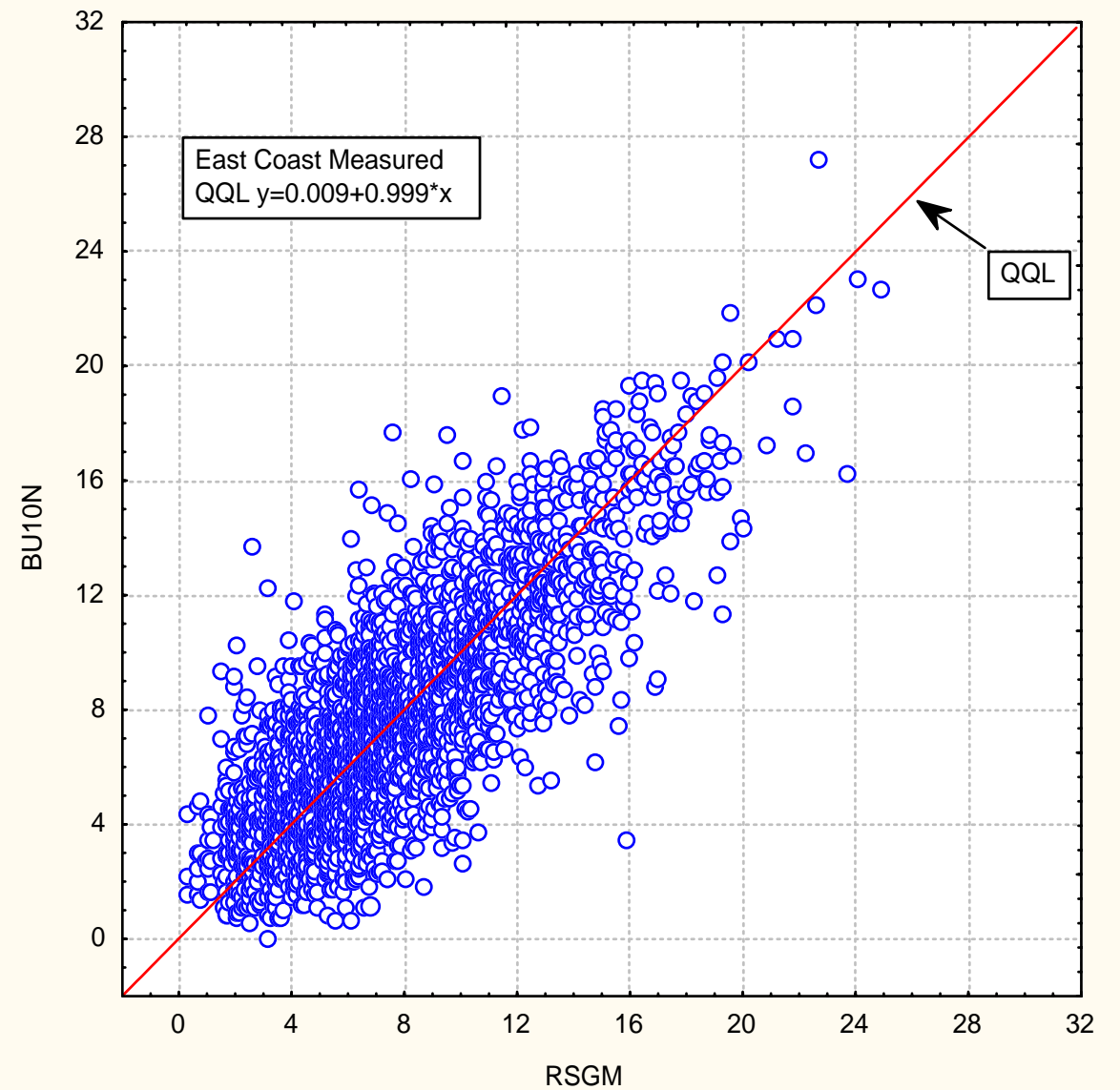
The geometric mean (GM) regression best fit line has a slope equal to the ratio of buoy/ship standard deviations, so applying this to ship winds scales them by this ratio. It is the same line obtained from doing an ordinary regression of ranked data (quantile-quantile plots of ranked ship and buoy wind speeds). This is similar to the method of cumulative frequency distributions used by Lindau [7].

Application of the Regression Adjustment

We adjusted the ship WS, using the linear equations obtained from regressing buoy on ship WS with each regression method (see lines in figure below, left). The previous figure shows the effect of each regression adjustment ((c) GM; (d) OLS; (e) its inverse; and (f) EIV) on the ship WS distribution, compared to that of the buoy. The GM regression equation was obtained by matching the quantiles of both ship and buoy winds, so it gives the closest result. The plot of GM-regressed ship and buoy winds (below, right) shows 1:1 agreement of the WS. In [10] we showed that the regression-adjustment changed the WS less in the centre of the distribution, and had most impact on higher and lower percentiles. We also showed it was better at preserving seasonal climatological characteristics.



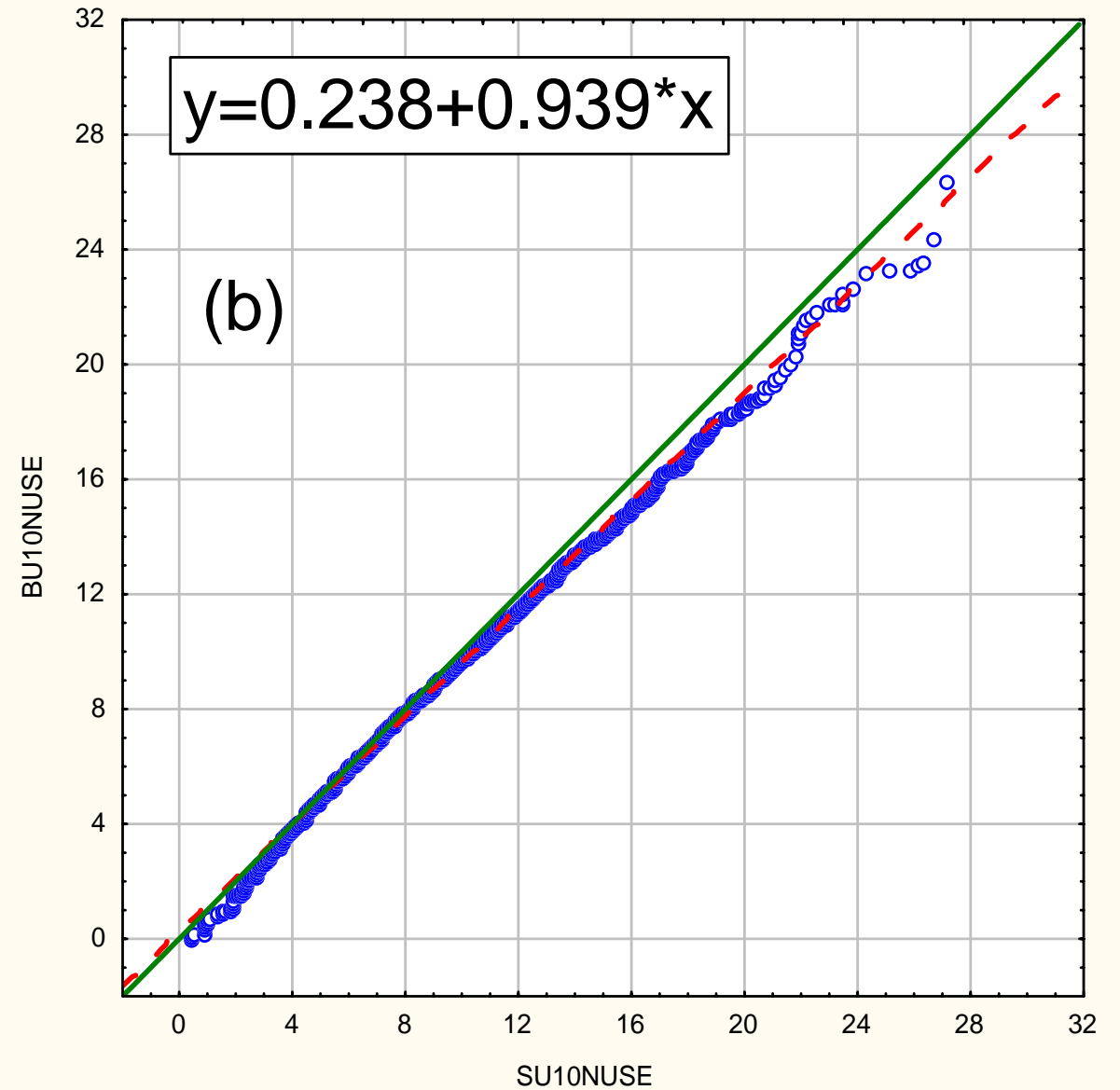
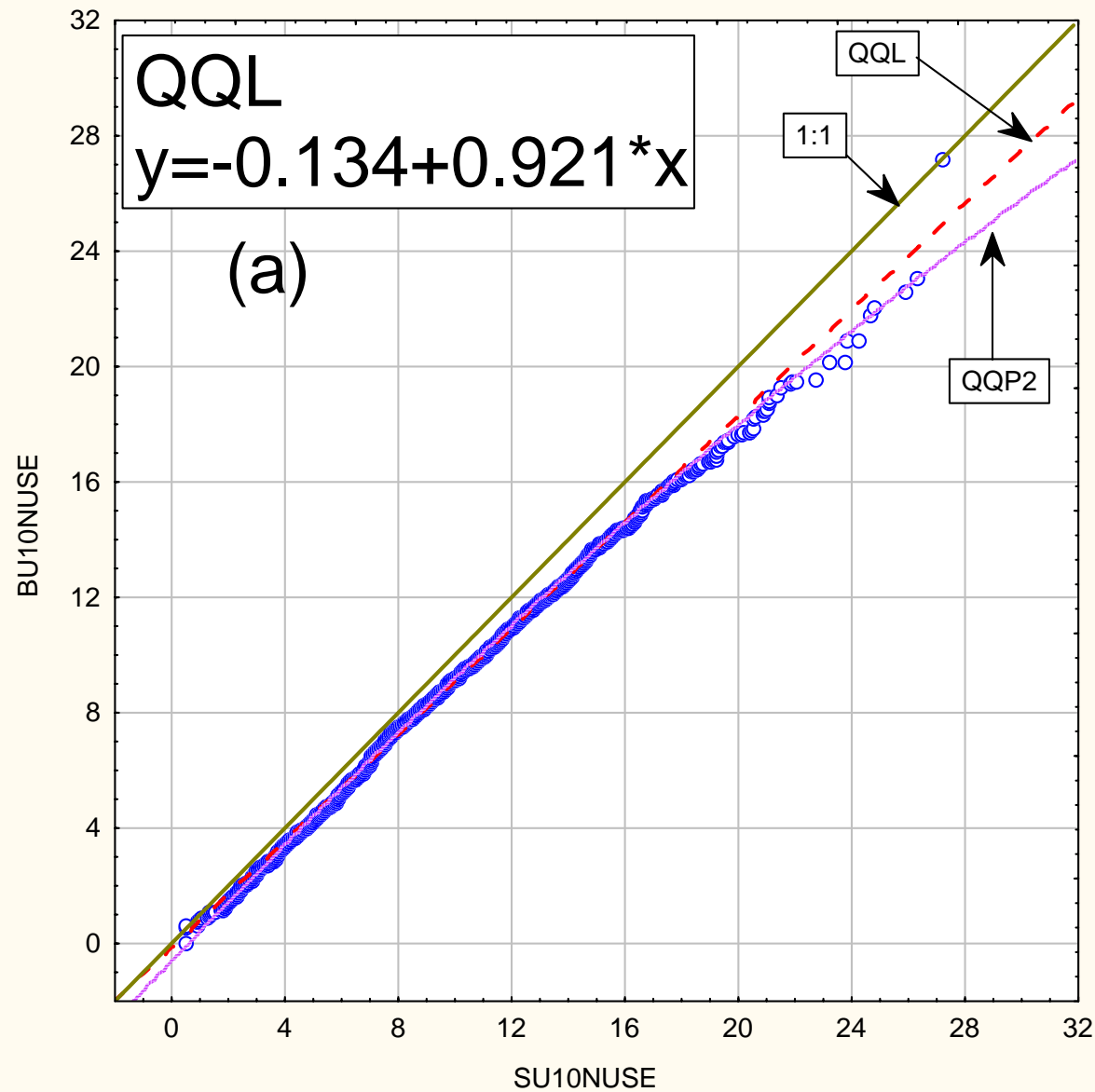
Scatter plot for east coast BU10N on, with 1:1 line (dashed) and best fit regression lines (solid), in order of steepness: INV inverse, OLS(X|Y), EIV, GM, and CON (conventional, OLS(Y|X)).



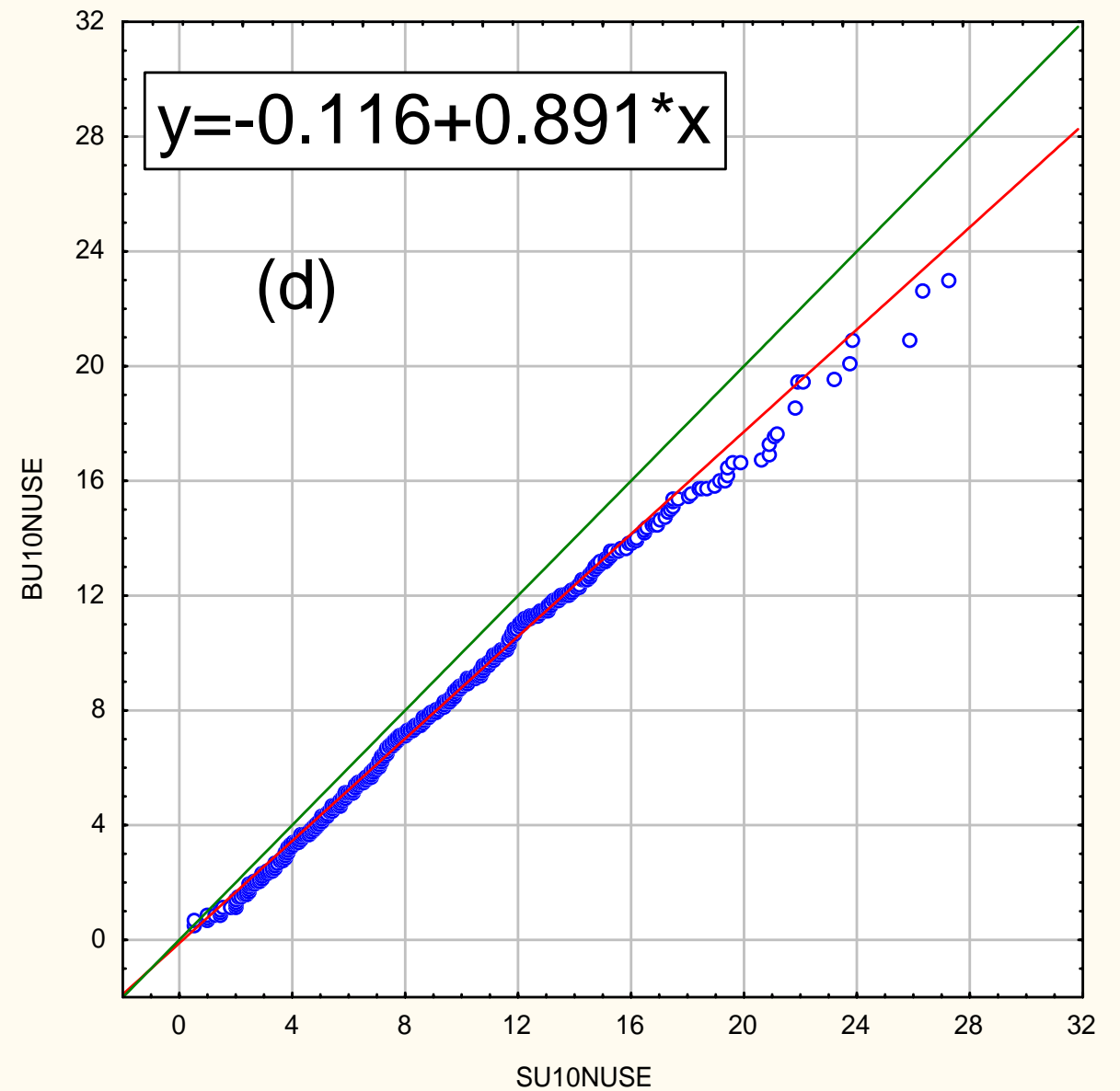
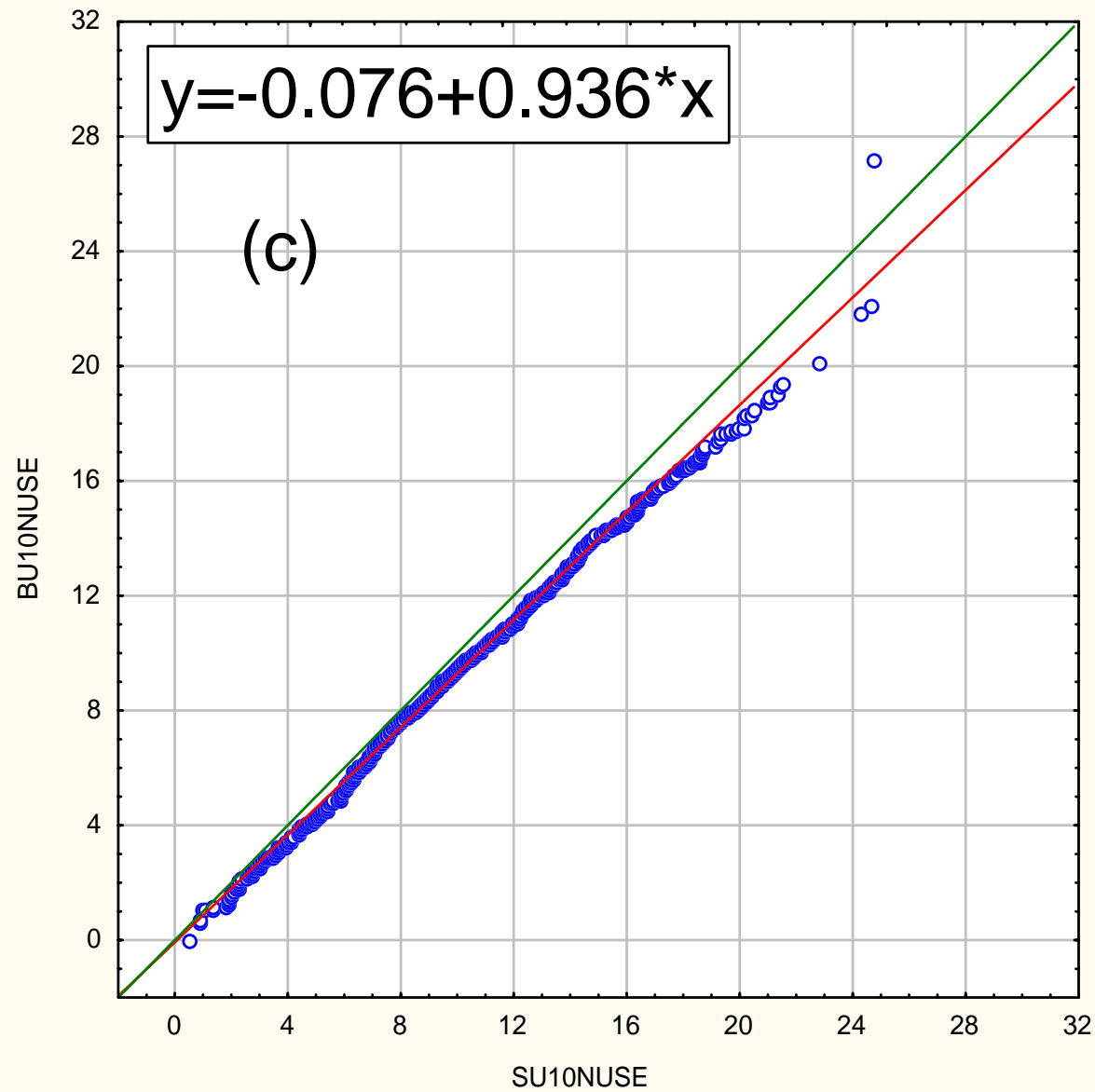
Scatter plot for east coast measured, of buoy adjusted wind speeds on GM regression-adjusted ship wind speeds, with GM regression best fit line, slope 1.0

Regional Differences

The figures below for east (a) and west (b) coasts are q-q plots for buoy and ship measured, height-adjusted WS. The linear regression line to the ranked matched data (QQL) is the same as the GM regression line of the data (shown for the east coast in previous figure, left). The intercepts of the straight lines for each coast are small, within .3 m/s of the origin. The slope is slightly steeper for the west coast. It is .94, indicating ship winds need to be reduced by about 6%, to homogenize them with buoy winds. Almost all west coast paired reports were from merchant vessels, while a high proportion on the east coast were from government vessels. When the non-government vessels (GV) were analyzed separately from the merchant vessels (figures c and d), the slope of the GM regression line for non-GV was .94, the same as the west coast. The GM line slope for government vessels was .89, corresponding to a higher bias in these ship WS. The higher WS values are still not fitting the straight line as well as on the west coast, indicating some other factors are affecting the data. We describe other factors significant to the ship-buoy relationships in [11].



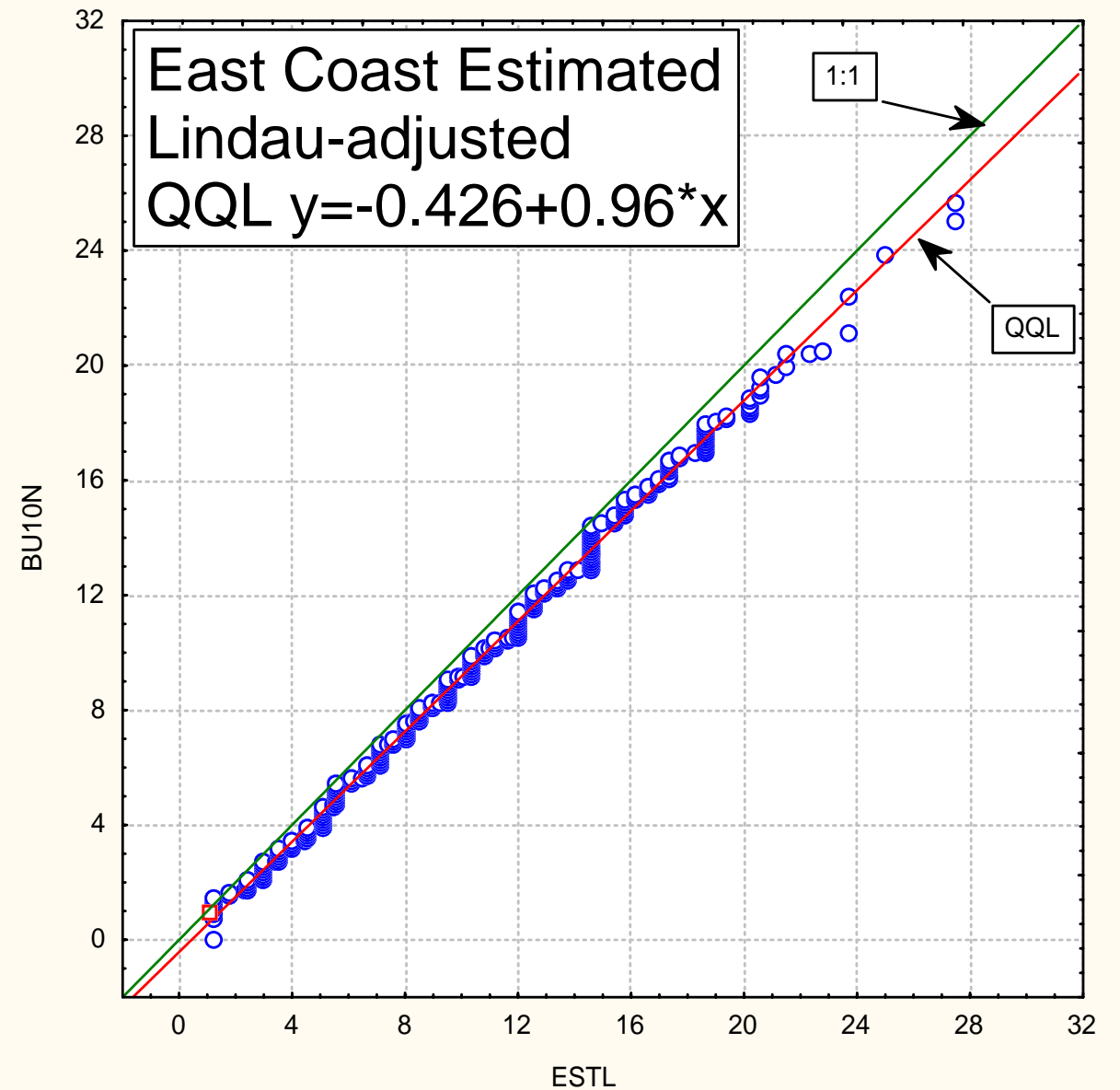
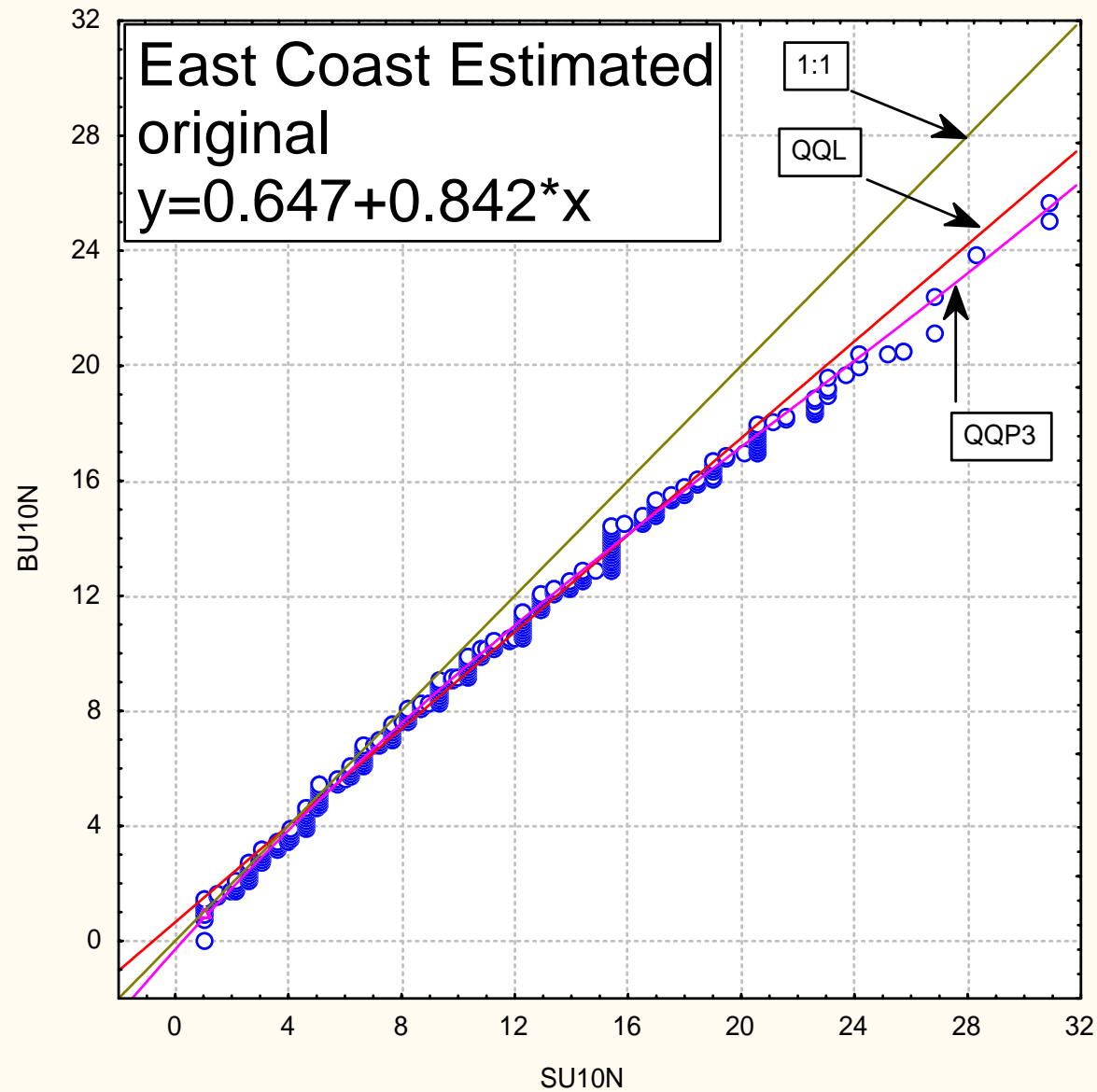
Quantile-quantile scatterplot for measured ship and buoy winds, BU10N on SU10N measured, with 1:1 line, and linear regression line, for east coast (left) (also showing 2nd order polynomial regression line) and west coast (right).



Q-Q scatter plots for east coast ht.-adjusted buoy and ship WS, for (c) non-government ships and (d) government ships (research and CoastGuard vessels).

Estimated Ship Wind Adjustment

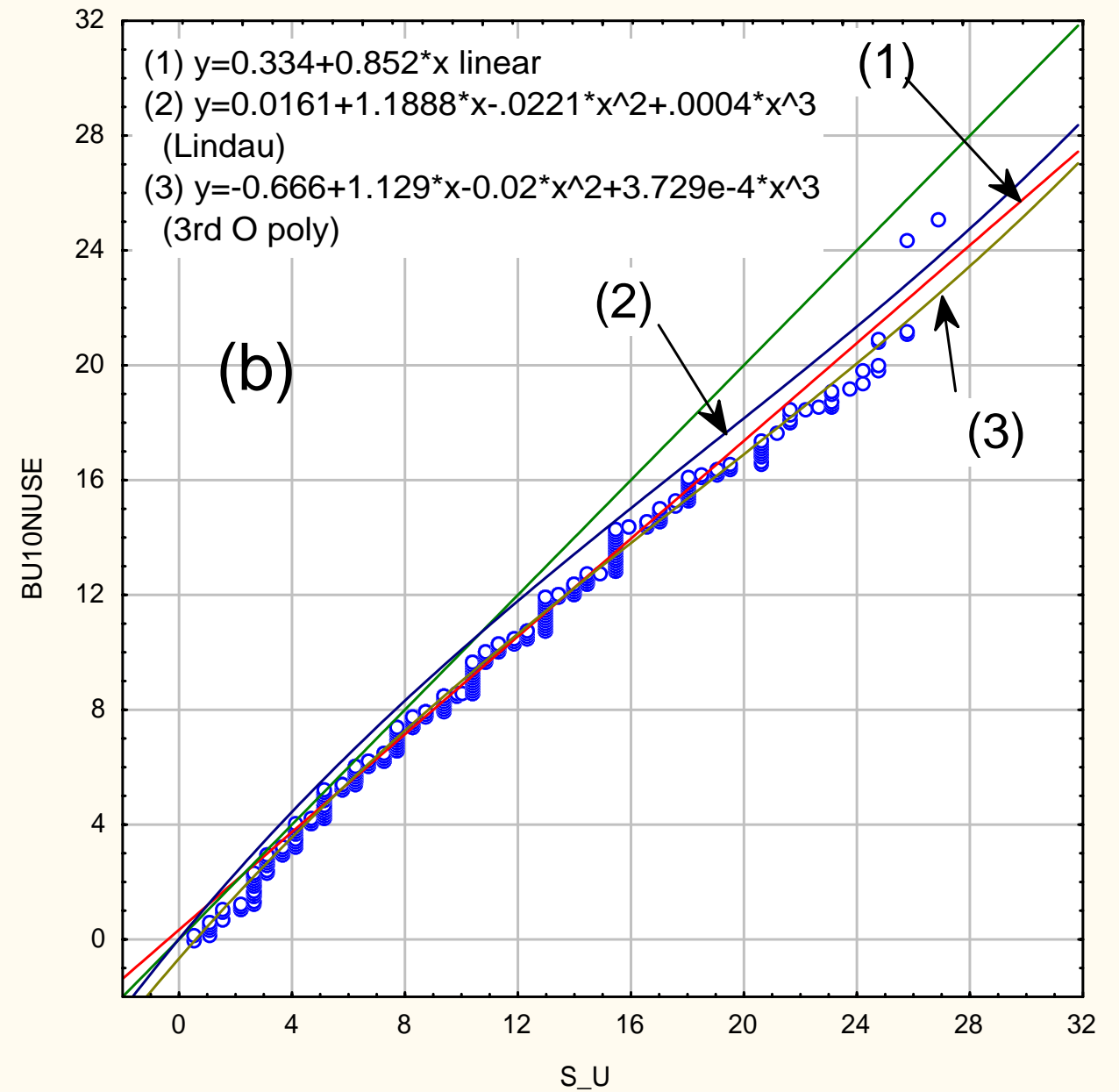
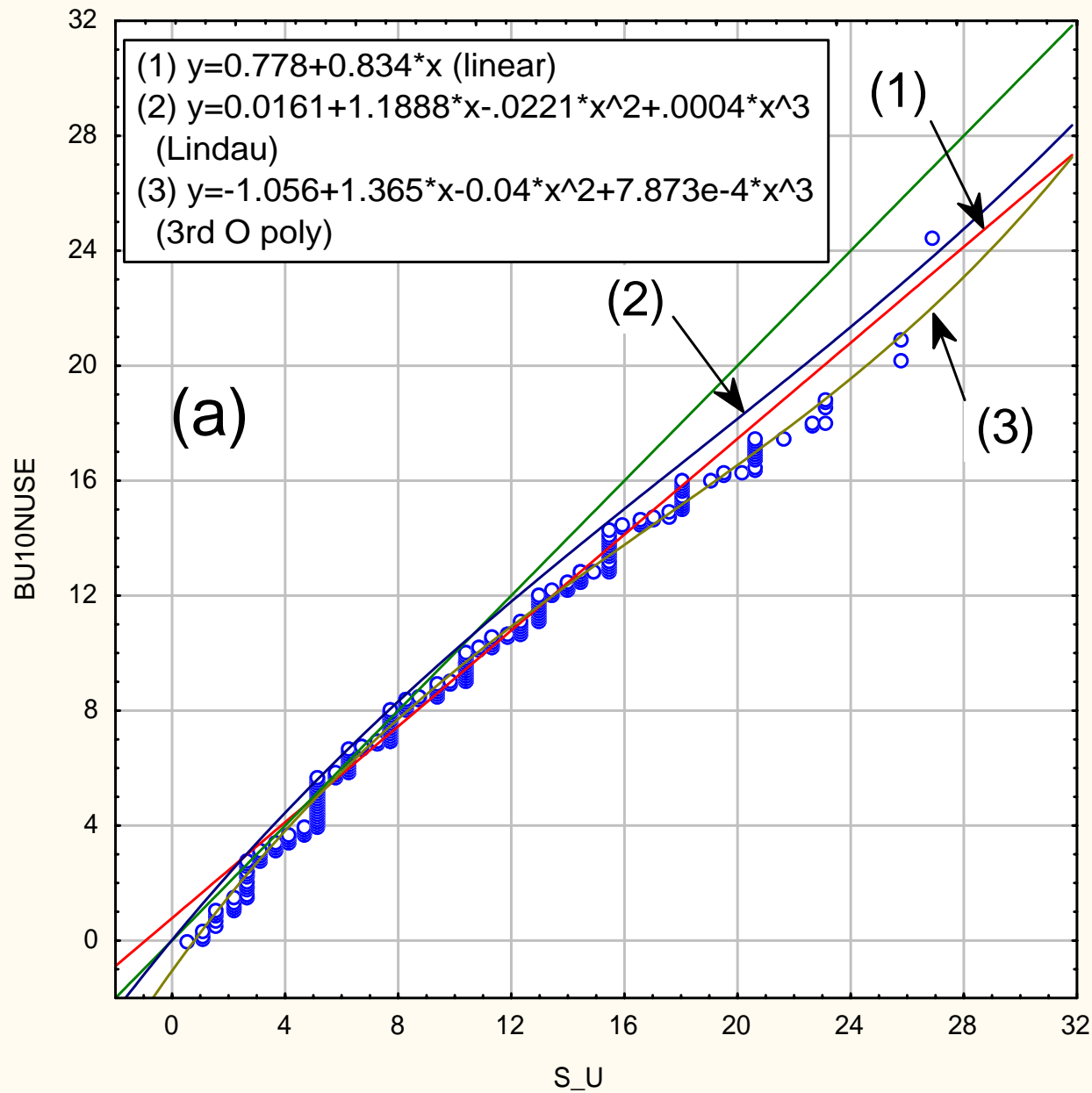
The operational Beaufort equivalent wind scale relates the ship observer's estimate of wave height and condition of the sea, to wind speed. It gives a wind speed equivalent to a 10 m effective neutral wind [14] so we did not adjust estimated winds for height. We adjusted estimated ship wind speeds using Lindau's improved Beaufort equivalent scale [7,4] which was derived using open ocean data and the method of cumulative frequency distributions, and gives estimated wind speeds more equivalent to measured ship winds. In order to apply Lindau's scale, we fit the values in the scale to a 3rd order polynomial, which fit the points quite closely, and used the resulting equation to adjust the estimated ship winds. We examined both the original estimated ship winds and the Lindau-adjusted estimated ship winds. Lindau's scale is non-linear, and is effective at remove the non-linearity present in the original data (see below). A difference remains, of about 4%, between adjusted ship WS and buoy WS.



(Left) Q-Q scatter plot of BU10N on SU10N (original estimated), with 1:1 line, and linear and 3rd order polynomial regression lines, and (right) q-q scatterplot of BU10N on estimated-Lindau-adjusted ship winds (ESTL), with 1:1 and linear regression line.

Night/Day Effects on Estimated Winds

Visual estimates of wave height are more difficult for observers at night and in reduced visibility. A study on the accuracy of ship's observations [6] found that for winds above 8 m/s, visual wind observations were underestimated at night (compared to daytime) unless the ship also carried a fixed anemometer. Our data confirmed that the day time WS distribution was generally stronger than the night time, for estimated wind speeds. It is not clear whether the difference is due to a low ship bias at night, or a high bias in the day time, or some combination. We explored this further in [11]. We can see the change in the points on the Q-Q scatter plots below, for west coast original estimated winds by night (left) and by day (right). At night the estimated winds in the lower part of the distribution fit much better with the buoy winds (closer to 1:1 line), while still curving away for higher values. By day, the estimated ship winds are clearly stronger than the buoy winds for most of the distribution. The plot for the east coast was fairly similar.



Q-Q scatter plot of west coast buoy on original estimated ship winds, by night (a) and by day (b), showing the 1:1 line, and (1) best fit (GM) line, (2) line for Lindau's adjustment, and (3) 3rd order polynomial best fit line to data.

Discussion on Improved Beaufort Scale and Application to Other Time Periods

The plot above shows the 3rd order polynomial line for the equation used to produce Lindau's scale adjustment. It is fairly close to the 1:1 line for the centre of the wind speed distribution, indicating it would change the original estimated wind speeds very little in that region. However, this data shows that by day especially, the original ship winds are relatively high compared to the buoy winds, so the Lindau-adjusted winds would still not agree well with buoy winds. The GM linear regression line fits the data points well in the middle but not the high end of the distribution. The 3rd order polynomial fits the curvature of the data points better. If it were used to adjust original estimated ship winds, it would give much better agreement to the buoy WS distribution.

Lindau found that there were temporal changes in the Beaufort equivalent scale. The published standard Lindau scale [7] is based on data from 1960-1971, whereas most of the data from this study is from between 1988-1995 (with some 1980-1988 west coast data). In [8] he showed that the relationship between pressure and wind for the year 1985 did not fit the relationship for when the standard Lindau scale was derived. He suggested using time dependent coefficients in the Lindau scale to account for decade to decade differences. It may be that a Lindau scale calibrated for the period of this study would fit the data better. It might be possible to extend a regression equation of buoy on estimated ship winds, to other time periods (to give buoy-equivalent winds). We could relate a regression line of buoy on estimated ship winds to the Lindau scale for the equivalent time period, then adjust that relationship through use of time dependent coefficients for the Lindau scales for other time periods. This might allow us to derive buoy-equivalent winds for earlier time periods.

Summary

We show that adjusting measured wind speeds to a standard reference height, and using Lindau's improved Beaufort equivalent scale for estimated winds, significantly improves the agreement between ship and buoy. We test several regression methods to remove the remaining difference. A geometric mean regression method produces a relationship that is most effective for converting the data set of ship winds to have the same statistical characteristics as the buoy winds. We show that the estimated ship wind to buoy relationship is different for night time compared to day time observations. Ship winds are affected by other factors, also, such as vessel type. Different ship-to-buoy relationships may be required to adjust ship winds affected by these factors.

References

- [1] Cardone, V. J., J. G. Greenwood, and M.A. Cane, 1990: On trends in historical marine data. *J. Climate*, **3**, 113-127.
- [2] Gilhousen, D.B., 1987: A field evaluation of NDBC moored buoy winds. *J. Atmos. Oceanic Technol*, **4**, 94-104.
- [3] Kent, E.C., P.G. Challenor, and P.K. Taylor, 1999: A statistical determination of the random observational error present in Voluntary Observing Ships meteorological reports. *J. Atmos. Oceanic Technol.*, **16**, 905-914.
- [4] Kent, E.C. and P. K. Taylor, 1997: Choice of a Beaufort Equivalent Scale. *J. Atmos. Oceanic Technol.* **14**, 228-242.
- [5] Kent, E.C., P.K. Taylor, and P.G. Challenor, 1998: A comparison of ship and scatterometer-derived wind speed data in open ocean and coastal areas. *Int. J. Remote Sensing*, **19**, 3361-3381.
- [6] Kent, E.C., B.S. Truscott, J.S. Hopkins and P.K. Taylor, 1991: The accuracy of ship's meteorological observation – results of the VSOP-NA. Marine Meteorology and Related Oceanographic Activities 26, World Meteorological Organization, Geneva, 86 pp.
- [7] Lindau, R., 1995a: A new Beaufort equivalent scale. Proc. Of Int'l COADS Winds Workshop, 1 May - 2 June 1994, Kiel, Germany, (Kiel: Institut fur Meereskunde/Christian-Albrechts-Universitat), 232-252.
- [8] Lindau, R., 1995b: Time dependent calibration of marine Beaufort estimates using individual pressure differences. Ibid.
- [9] Thomas, B.R. and V.R Swail, 1999: A methodology for homogenizing wind speeds from ships and buoys. *Preprints, WMO Workshop on Advances in Marine Climatology*. 8-15 Sept. Vancouver, B.C.
- [10] Thomas, B.R. and V.R. Swail, 2002: Methods to Reduce Biases in Wind Speeds from Ships and Buoys. *7th Int'l W'shop on Wave Hindcasting and Forecasting*, Oct. 21-25, 2002, Banff, AB, Canada, 523-534.
- [11] Thomas, B.R. and V.R. Swail, 2003: Effect of Vessel Type and Platform Relative Wind Direction on Comparison of Buoy and Ship Winds. *JCOMM Workshop on Advances in Marine Climatology (CLIMAR-II)*, 17-22 Nov., Brussels, Belgium.
- [12] Tolman, H.L., 1998: Effects of observation errors in linear regression and bin-average analyses. *Q. J. R. Meteorol. Soc.*, Vol. 124, 897-917.
- [13] Walmsley, J.L., 1988: On theoretical wind speed and temperature profiles over the sea with applications to data from Sable Island, N.S. *Atmosphere-Ocean* **26**(2), 202-233.
- [14] WMO, 1970: The Beaufort scale of wind force. Reports on marine science affairs, Rep. 3, World Meteorological Organization, Geneva, Switzerland, 22 pp.
- [15] WMO, 1980: International List of Selected, Supplementary and Auxiliary Ships, World Meteorological Organization No. 47, Geneva, Switzerland.
- [16] 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**, No. 1, 1-8.