A METHODOLOGY FOR HOMOGENIZING WIND SPEEDS FROM SHIPS AND BUOYS

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INTRODUCTION

Homogeneous surface marine wind observations are important for analysis of long-term climate trend and variability and for air-sea flux calculations used to drive atmosphere-ocean circulation models. Surface marine wind observations are used for input into numerical weather prediction and ocean wave models, for wind diagnosis in forecasting, and for validation of other sources of climatological marine winds such as NWP reanalysis data and satellite wind estimates. However, the wind fields are inhomogeneous due to different measuring or observing methods used by ships and moored weather buoys.

The first marine wind observations were visual estimates based on the effect of the wind on the sea state or on the ship itself. There have been increasing numbers of wind speeds measured by anemometers on ships in recent decades. Meteorological buoys have added increasing numbers of observations in the last 2 decades. Remotely sensed marine winds from satellite are a more recent source of data. Each source of wind speed data will introduce inhomogeneities in a wind speed database that does not account for differences in the measurement or observation method. This was illustrated by Cardone *et al.* (1990) who showed that an apparent climate trend toward increasing wind speeds over several decades was due to a change toward more observations from ships with anemometers, mounted at increasingly larger heights as larger ships have been built. Moored buoy anemometer heights, however, are typically only between 5 and 10 m. Also, flow distortion over the large ships can cause the wind to speed up or slow down over the anemometer (Dobson, 1981). Visually estimated ship winds have other sources of error, as discussed by Kent and Taylor (1996). They show the impact of the choice of Beaufort equivalent scale on the difference between estimated and measured winds.

The averaging method used to determine the 10 minute mean wind speed can also cause differences in the wind speeds. Up until 1997, the Canadian buoys reported a vector mean wind, which gives speeds 3 to 7% lower than a scalar mean wind (Axys, 1996b, Gilhousen, 1987). The observer on a ship estimates the average from watching an analog dial, probably over a much shorter interval of time than 10 minutes.

Moored buoys are more subject to wave motion and wave sheltering in high seas than ships. There has been considerable discussion on how the measurements of mean wind speed reported by moored weather buoys may be lower than the true wind speed during high wave conditions, and that the peak wind reported by the buoy may be more representative of the prevailing wind (Cardone *et al.*, 1996). Significant variability in wind speed and direction between the crest and trough of individual waves, proportional to wave height, has been observed at an experimental buoy (Axys, 1996b). A subsequent study, SWS-2, involved a buoy making detailed high wind and wave observations while located near the Hibernia and Shoemaker rigs on the Grand Banks of Newfoundland, with simultaneous detailed observations taken from a nearby research vessel over the winter of 1997/1998 (Skey *et al.*, 1999; this volume).

The purpose of this study is to examine the relationship between collocated moored buoy and ship wind speeds, making corrections for different estimation methods where possible. The ship reports were extracted from the Comprehensive Ocean Atmosphere Data Set (COADS) Release 1a, (Slutz *et al.*, 1985, Woodruff *et al.*, 1987), for the period from 1980 to 1995. In an earlier similar study (Thomas,1998), buoy data from Canada's east and west coasts were also extracted from the COADS dataset. However there were problems with not all reports being archived, and some artificial binning of the wind speeds. Also, since the source for those reports were the ship code format messages, only one mean wind speed was available. To obtain a more complete dataset, including the peak or gust wind reported by the buoy, the moored buoy data are extracted from the Environment Canada Operational Data Acquisition System (ODAS) as archived by the Canadian Marine Environmental Data Service (MEDS). This data included mean and peak (or gust winds) from both anemometers. The meteorological and oceanographic measurements reported by the buoy were not quality controlled, so this was a necessary first step to this study.

DATA SOURCES

The COADS archive in LMRF format was searched for any ship reports within 2° x 2° boxes centered on each buoy location. Reports with either measured or estimated ship wind speeds were collected. For the measured wind reports, air and sea temperature were needed as well, in order to adjust measured wind speeds to a standard reference level, taking atmospheric stability into account. The height of the thermometer and anemometer were needed to do this height adjustment. This information was obtained from the electronic form of WMO Publication 47 (WMO, 1980; Kent and Oakley, 1995), produced annually. It was also supplemented by information from the Canadian Ship Information Database. The ship reports were matched up by callsign to information from WMO Publication 47. There was a change of format in the Pub. 47 files in 1995, so the older files were converted to the new format. With this change, the barometer height was reported instead of the platform height of the ship. Thermometer height is assumed to be one metre above the platform height, and at the same height as the barometer. Thermometer and anemometer heights are needed to adjust the wind speeds to a standard reference level, described below. If a match in call sign was not found in the same year as the observation, the WMO Pub 47 files were searched forward and back 2 years. Most matches were in the same year as the observation.

The MEDS archive of AES ODAS buoys is normally available in Format B files. MEDS made the fields from the Format B files available in comma-delimited flat files. The oceanographic fields included the significant wave height and peak period recalculated from the wave spectral data, the reported significant wave height and peak period, as well as the maximum wave height (actually twice the maximum positive displacement until about 1998). The meteorological fields included both mean and peak (gust) wind speeds from both anemometers, atmospheric pressure from 2 sensors, air and sea temperature. A report by Axys (1996a), describes the sensors, data reduction, and buoy locations. The mean wind speed was a vector mean for the first several years; then the scalar mean was also added as an additional field and archived by MEDS, and finally more recently the scalar mean became the only mean wind speed reported by the buoys. Prior to January 1989 the MEDS archive did not include many of these fields. Only one mean wind was archived, and no air temperature. For that reason the period of study was restricted to 1989 and onward. Data from the 3 NOMAD buoys on

Canada's west coast (46004, 46036, and 46184), and the 6 NOMAD buoys on Canada's east coast (numbered 44137-44142) were analyzed.

Pairs of ship and buoy observations, taken within the same hour and within 100 km, were created. The pairs were separated into those with measured ship wind speeds and those with estimated speeds, using the wind speed indicator field in the COADS archive. These sets are referred to as "East coast 1989-1995", and "West coast 1989-1995". There are also results from a separate analysis, consisting of all the reports from the Canadian NOMADS on both coasts, that reported both a vector and scalar wind speed between 1994- Nov. 1998. This set is referred to as "1994-1998".

QUALITY CONTROL

COADS LMRF reports include a quality control flag for some of the reported fields. The COADS group uses a trimming flag of more than 5, corresponding to a value more than 4.5 standard deviations from the monthly climate mean for the area, to "trim" data for calculation of the COADS enhanced statistics. These flags, for the u and v components of the wind, were used to eliminate the strongest, and with rare exceptions, erroneous, wind speeds from the paired dataset. The trimming flags were also used to eliminate reports with erroneous air and sea temperatures, in the case of measured wind speed reports.

If ship wind speed was high and the corresponding wave height measurement from the neighboring buoy was lower than a given limit (see Table 1), the ship wind speed was not used. The ship wind speed adjusted to 10 m effective neutral was used in this test. These values come from examining a scatter plot of quality controlled buoy ship wind speeds, adjusted to 10 m effective neutral, plotted versus the significant wave height, and approximating the limits.

Most ships reporting a measured wind speed showed a wind indicator (WI) of 4, meaning originally measured in knots. The archive of wind speeds is in m/s. Some of the same ships that reported with WI = 4 very occasionally reported with WI = 1 (wind speed measured in m/s). If this was in error, the wind speed would be erroneously high. Except for Russian ships, which tended to report WI =1, ships were not used if they reported WI = 1.

Table 1. Quality control limits for ship wind speeds.

Ship Wind Speed, U10N (m/s)	*Buoy Significant Wave Height (m)*
> 20	< 2
> 25	< 2.5
> 30	< 6

For estimated ship winds speeds, similar restrictions were used. The wind speed/wave height limits in Table 1 were used. If the WI =3 (originally estimated in knots) the report was used, but if WI = 0 (originally estimated in m/s) it was not used unless the ship's country was Russia. For measured ship winds, the requirement to know thermometer and anemometer height meant the ship must be identified in the WMO Pub. 47 to be used. For estimated ship wind speeds, this was not necessary. A COADS platform type, PT, of 5 is meant to indicate ships; however, there were periods when Canadian buoy reports were coded with PT=5, and some drilling rig reports were also coded with PT=5. Some of the callsigns in the paired ship-buoy sets suggested the "ship" was really a drifting buoy. For that reason, if the ship was not identified in the WMO Pub. 47, the report was not used.

NOMAD buoys use 2 anemometers, at heights of 5.25 and 4.45 m. The slightly higher anemometer tends to measure slightly higher wind speeds, as would be expected. Typically when a buoy anemometer fails it starts to report wind speeds of 0 or near 0. It may also fail gradually, reporting winds lighter than the other anemometer or lighter than the peak wind would indicate. The MEDS archive included all the wind fields but there was no indication as to which one was considered the primary (active) anemometer. A computer program compared the winds from the 2 anemometers, flagged erroneous or suspect values, and determined the best speed to use. The scalar 10 minute mean was used in preference to the vector 10 minute mean, when it was available. The stronger of the means from each anemometer was used, unless the gust factor (the ratio of 8-second gust speed to 10-minute mean speed) was outside a normal range, in which case the other mean wind speed was used. The allowed gust factor range was increased for light winds and very light winds. See Table 2 for the limits. The median gust factor was about 1.24.

Table 2. Limits for gust factors, by wind speed category.

Wind Speed Category (m/s)	*Low Limit for Gust Factor*	*High Limit for Gust Factor*
> 6	1.04	2.0
2 – 6	1.02	3.0
< 2	1.00	6.0

Using the stronger wind resulted in choosing the better wind most times, since in the majority of anemometer failures, the wind speed was too low. It was much rarer to get an erroneously high report. These would generally be obvious from a gust factor outside the normal range.

All of the fields were checked for being outside specified ranges, using the same limits as the operational decode of the Canadian buoys. The fields were checked for time continuity, following the method of Gilhousen (1998). This check involves setting a maximum allowable change in a given time period (not more than 3 hours) then flagging a new value if the change from the last report exceeds the maximum allowable. There are some exceptions to the time continuity check, for situations where greater changes in observations could be expected, such as near deep low pressure systems or with frontal passages, as indicated by low pressure, wind direction changes, etc. There was also a check for values that were not changing, or changing only a little. The reports were stored in a buffer and if the mean value of one field over the several hours in the buffer was less than a small amount, the values were all flagged. This was useful for catching wind speeds from a broken anemometer that sent speeds generally, but not always, just under 1 m/s. If both anemometers were broken and doing this, not every low speed would be flagged. For long periods when the data from 2 broken anemometers were archived, override dates were hard coded into the program, to flag all of the winds until the buoy was serviced.

WIND SPEED CORRECTIONS

Two different methods were used to correct the buoy wind speeds, prior to adjusting them from measurement height to a standard reference level. Wind speeds obtained from each method were compared separately to the paired ship winds. The first method was a simple correction applied to the vector mean wind speed only. The wind speed reported by the buoys was a 10 minute vector mean up to about 1994/1995 when a scalar mean was measured as well. For the vector mean, individual samples of the u and v components are calculated every second during the averaging period. The vector mean wind speed and direction come from the averaged u and v components. A study of a 3 m Discus buoy found that this vector averaging resulted in speeds 7% lower than the scalar mean (Gilhousen, 1987). A NOMAD buoy which collected data during several storms over one winter on the west coast showed that vector averaged speeds were 3% lower than the scalar means (Axys, 1996b). The percent difference between vector (u_v) and scalar (u_s) wind speeds is calculated as:

$$PDVS = 100(u_s - u_v)/u_v$$

Examination of the vector and scalar means from the MEDS archived buoy data also showed that the average difference between the vector and scalar mean was 3%. This value was used to correct the vector mean winds. The scalar means, when available, were used in this set as well, without correction. (This is generally the last 6 months of observations in 1995.) This set of winds used in the ship-buoy comparison is referred to as vector corrected/scalar. Subsequent analysis of the 1994-1998 buoy data set showed that an improved method to correct the vector speeds would make use of the wave height. Figure 1 shows a plot of the percentage difference between vector and scalar mean wind speed from hourly observations taken over 5 years, from 6 east and 3 west coast NOMAD buoys. This figure shows the percentage difference increasing with wave height. A correction of 3% corresponds to wave heights of 6 – 8 m, but for 12 – 13 m heights, the difference is about 6 %. For waves below about 4 m, increasing vector winds by 3% would actually be too much.

The second method attempts to deal with the problem of the 10 minute mean wind speed being reduced in high waves. During the 10 minute averaging period, the buoy would be riding up and down in the waves, and the anemometer would be sheltered at times in high seas. Also, if the waves were breaking over the buoy, the anemometers would at times be immersed in water, reducing the mean speed. There is an indication that something like this is happening from a plot of the gust factor versus the wave height (Figure 2a). The gust factor (f) is the ratio of the gust speed (g), divided by the mean speed (u).

Gust factors from scalar mean wind speeds from mid-1994 to November 1998 were used in this figure. Wind speeds of more than 6 m/s were used, since light winds tend to produce large gust factors. The figure shows the gust factor increasing with wave height. A similar plot of gust factor against wave steepness (not shown), defined to be $\textit{wave height} / (1.56?\textit{wave period}^2)$, does not show any increase. Assuming that the gust speed itself should not depend on sea state, the increase in the buoy gust factor with increasing wave height seems to confirm that the mean speed is being reduced in the higher seas. Gust factors from vector mean wind speeds showed a similar but greater increase with increasing wave height (Figure 2b). Cardone *et al.* (1996), for waves over 3m during the Halloween Storm of 1991, also found a dependence of vector gust factor on sea state, but did not see much of a change with the scalar gust factor. A greater effect would be expected for the vector mean winds, since the wind direction would vary around the individual wave crests, thereby reducing the vector averaged speed.

The gust factors are plotted as a function of the air-sea temperature difference in Figure 3. For this plot the winds were restricted to those greater than 6 m/s and wave heights to less than 5 m (to reduce contamination from gust factors in high seas when the mean wind might be too low, and the corresponding gust factor too large). This shows a clear linear relationship with increasing gust factor for increasing instability in the atmosphere (as indicated by increasingly negative air-sea temperature differences). This seems to be a reasonable result. A box plot, and regression line fitted to the medians, are used since the gust factor tends to have many outliers or extreme values, and the median is more robust in such cases. The regression equation is:

$$f_{\mathrm{stab}} = 1.193 - 0.009?(t_{\mathrm{air}} - sst)$$

This relationship is used to calculate a stability derived gust factor (f_{stab}), that can be used as a base gust factor expected for a particular atmospheric stability regime, if high waves were not reducing the measurement of 10 minute average wind. If we assume that the gust speed (the highest running 8 second average speed) is not much affected by the waves, then this gives us a mean wind speed, called a gust derived mean wind speed (u_{gd}), which is equivalent to a 10 minute scalar mean wind speed:

$$u_{\mathrm{gd}} = g/\mathrm{f}_{\mathrm{stab}}$$

If the stability derived gust factor were the same as the gust factor from measured gust and mean, then the gust derived wind speed would be the same as the reported scalar mean wind speed. If the stability derived gust factor were smaller, then the gust derived mean wind speed would be larger than the reported mean. The gust derived mean wind speed can be used as equivalent to a "corrected" scalar wind at 5 m, even for measured vector means. It is independent of the vector or scalar mean, since it is derived only from the reported gust speed and the air-sea temperature difference. A plot of the gust derived mean wind speed versus the scalar mean wind speed (not shown) indicates a nearly 1:1 relationship, but the gust derived wind speed tends to be higher than the reported speed, above about 18 m/s. Figure 4a shows this more clearly. The difference between the gust derived and scalar mean speed is plotted versus the gust derived mean speed. The difference becomes increasingly positive for higher wind speeds. A plot of $(u_{gd} - u_s)$ against the wave height (Figure 4b) shows the difference increases nonlinearly with wave height. This gust derived wind speed is calculated for every buoy report, adjusted to 10 m effective neutral, and compared to the ship wind speeds.

ADJUSTMENT OF BUOY AND MEASURED SHIP WIND SPEED FOR HEIGHT

Measured ship and buoy wind speeds were adjusted using Walmsley's (1988) method, to a reference height of 10 m. Walmsley's program was modified slightly to produce an effective neutral 10 m wind. This is the wind that would produce the same effect on the sea surface in neutral atmospheric conditions as the actual wind in a given atmospheric stability condition. This is done since estimated ship winds correspond to effective neutral wind speeds at 10 m. The effective neutral adjustment makes a difference to the 10 m wind mainly for lower wind speeds, with little effect on higher speeds. The height adjustment is necessary since winds increase with height in the atmosphere and there is quite a difference between the height at which buoys measure the winds, compared to that of the ships. Most Canadian buoys measure winds at about 5 m. Anemometers of ships passing by the 3 west coast buoys, and the furthest offshore east coast buoys, 44137 and 44141, are typically between 30 and 45 m. Anemometer heights of ships reporting near the other east coast buoys tended to be lower, between 15 and 30 m.

The adjustment method can have a large impact on the resulting wind speed, especially in stable conditions where the change in wind speed with height is the greatest, or when adjusting from high anemometer heights. Walmsley's method is quite similar to that of Smith (1981). It uses Monin-Obukhov similarity theory. Under assumptions of neutral atmospheric stability, this approach reduces to a logarithmic profile of wind speed in the vertical. Atmospheric stability is accounted for through use of the air- sea temperature difference. The surface roughness, which depends on the sea state, is approximated by a function of the wind speed. The calculation of a ratio of observed wind at some level to another wind at a reference level (the adjustment coefficient) is an iterative process, which does not converge for cases of high atmospheric stability and lower wind speeds. The area of non-convergence increases for adjustments from higher anemometer heights. Walmsley's method is an improvement on Smith's in that the algorithm is more stable and is able to calculate more adjustment coefficients closer to this theoretical high stability limit. The theory on which the adjustment method is based is valid for a range of z/L between –2.5 and 1.5. z/L is the measurement height divided by the Monin-Obukov length, which is a function of the measured wind speed. z/L is a dimensionless stability parameter that is negative for unstable conditions and positive for stable conditions. The height adjusted wind speeds were not used if z/L was outside the valid range. This tended to eliminate some of the lighter winds, since z/L is close to zero for stronger wind speeds whatever the air sea temperature difference.

The frequency of various atmospheric stability regimes varies considerably among the different buoy locations on Canada's east coast. The ones moored over the continental shelf, with colder water from the Labrador current, reported stable conditions more than half of the time, when warmer air from the southwest moves over the colder water. At these sites, assuming neutral stability when adjusting the wind speeds from ships would result in overestimates of the 10 m wind speed. The 2 buoys moored just off the edge of the continental shelf, near the warm waters of the Gulf Stream, report unstable conditions much more often. The most unstable atmospheric conditions occur in cold outbreaks when cold Arctic air from the mainland moves out over relatively warmer waters. Unfortunately, the MEDS archive did not include negative temperatures, through a coding error, so some of the colder events are missing from the study. The 3 NOMAD buoys on the west coast showed less variation, with neutral conditions being more common and smaller excursions from neutral.

There was not always enough information to adjust the ship wind speeds. If there was no match with a call sign in WMO Pub. 47, there was no information about sensor heights. Even if there was a match, the platform or barometer height was not always listed, and sometimes the anemometer height was missing. The ship also had to report air and sea temperature, in order to take stability into account. Typically, there are more ship reports with air temperature alone, than with both air and sea temperature. In this study, if any of this information was missing, if the adjustment method did not converge to a solution, or if *z/L* was outside the valid range, then the report was not used.

MEASURED SHIP-BUOY COMPARISONS

Results are presented for the measured ship/buoy pairs, for the east coast stations. There were 1305 valid points. Figure 5 shows the measured ship winds plotted versus the buoy vector mean winds. There is considerable scatter and the ship observations are biased high compared to the buoy values. Figure 7 shows the same observations adjusted to a standard reference level of 10 m, effective neutral, using the vector corrected/scalar mean wind speeds. The bias is much reduced. The box plot of Figure 7(b) shows a strong linear relationship between the height adjusted measured ship wind speeds and the buoy adjusted wind speeds. Figure 8 shows the same ship/buoy pairs, using the gust derived mean buoy wind speed and measured ship winds, both adjusted to 10 m effective neutral. Results are similar to the vector corrected/scalar mean wind speed comparisons.

Table 3 shows some statistics for each set of wind speeds. The second and third rows are for the buoy winds corrected by the 2 different methods. The fourth and fifth rows are for the buoy corrected wind speeds adjusted to 10 m effective neutral. The height adjustment of the buoy speeds has more effect on the average speeds than the correction methods. The corrected and height adjusted averaged wind speeds are still lower than the height adjusted ship winds, but the median difference has been reduced from about 2 m/s to 1 m/s. The maximum gust derived wind speed, height adjusted, is actually greater than the corresponding ship speed. The standard deviations of the gust derived speeds, both adjusted and not adjusted for height, are similar those of the vector corrected/scalar winds.

Table 3. Measured Ship and Buoy Mean Wind Speed Statistics (East Coast 1989-1995)

Wind Speed	*Mean (m/s)*	*Median (m/s)*	*Maximum (m/s)*	*Standard Deviation (m/s)*
buoy vector/scalar mean (B_U)	7.15	6.9	24.3	3.21
buoy vector corrected/scalar mean (B_U_VCS)	7.39	7.1	25.1	3.31
buoy gust derived mean (B_U_GD)	7.33	6.9	25.4	3.28
buoy vector corrected/scalar, ht. adj. (B_U10N)	7.85	7.5	27.2	3.63
buoy gust derived mean, ht. adj. (B_U10NGD)	7.78	7.4	27.6	3.62
ship measured (S_U)	9.87	9.3	28.3	4.22

ship measured, ht. adj. (S_U10N)	8.79	8.1	27.2	3.96

Table 4. Comparison of Measured Ship and Buoy Mean Wind Speed Statistics (East Coast 1989-1995)

Difference in Paired Ship –Buoy Wind Speeds	*Mean Difference (Bias) (m/s)*	*Median Difference (m/s)*	*Standard Deviation (m/s)*	*Correlation Coefficient Of Regression*	*Intercept Parameter (m/s) of Linear Fit Regression*	*Slope Parameter of Linear Fit Regression*
S_U – B_U	2.68	2.5	2.93	.719	3.09	.943
S_U - B_U_VCS	2.48	2.3	2.93	.722	3.07	.920
S_U - B_U_GD	2.55	2.4	2.90	.727	3.03	.934
S_U10N–B_U10N	.937	.99	2.89	.713	2.68	.778
S_U10N–B_U10NGD	1.01	.99	2.86	.718	2.66	.787

Table 4 shows some statistics for the differences between the various ship-buoy wind speed comparisons. The biggest change in the bias of ship compared to buoy speeds comes from the height adjustment. The vector corrected/scalar buoy winds have a slightly lower average bias, compared to the ship winds, than do the gust derived buoy speeds. However the standard deviations are slightly lower and the correlation coefficients are slightly higher for the gust derived speeds.

The ship wind speed was not corrected for effects of flow distortion over the ship. The ship anemometer measures an apparent wind, since the ship is moving. It is standard procedure for the observer on board the ship to determine the real wind by correcting for the ship's speed and direction, but it is not known if this was done, or done correctly for any particular report.

ESTIMATED SHIP-BUOY COMPARISONS

Estimated ship wind speeds are derived from visual observations of the sea state or effects on the ship itself via the operational Beaufort scale (WMO, 1970). They are equivalent to a 10 m effective neutral wind speed. While various improved scales have been proposed, the estimated ship winds here were not adjusted using any of them, in order to determine a relationship with the buoy winds from data based on the operational Beaufort scale.

The results for the east coast estimated ship/buoy reports are presented here. There were 2569 valid pairs. The plots of the ship estimated versus the buoy uncorrected mean wind speeds in Figure 6 show considerable scatter and the estimated ship wind speeds are biased high compared to the buoy winds. The effect of correcting the vector mean to a scalar mean and adjusting for height to 10 m, is to reduce the bias somewhat (see Figure 9). Figure 10 shows the estimated ship winds versus the gust derived mean buoy wind speeds adjusted to 10 m. There are several high ship wind speed outliers. The quantile-quantile plot (Fig 10c) shows that most data fit the same distribution, with the exception of a some high outliers – perhaps these would have been removed with a more thorough quality control of the ship data. The line in the box plot of Figure 10(b) is fitted to the median data points; however it seems to be affected by the variability due to small sample size at buoy wind speeds > 20 m/s. It does not fit the median points well for points < 20 m/s. A better regression would result from weighting the median by the number of points in each wind speed category.

Table 5 shows some basic statistics for each wind speed set. The second and third rows show the effect of the 2 correction methods, while the fourth and fifth show the effect of adjusting those corrected speeds to 10 m effective neutral. As with the measured ship-buoy comparison, the height adjustment has more impact on the average wind speeds than the correction method. The gust derived correction method seems to have most impact on the maximum speeds. The standard deviation for the gust derived speeds is slightly smaller than for the vector corrected/scalar speeds, both adjusted and not adjusted for height.

Table 6 gives statistics for the difference between ship and buoy wind speeds of each set. The wind speeds in the first column are described more fully in the previous table. The height adjustment of buoy speeds has more impact than the correction method on reducing the bias. The overall bias (difference between ship and buoy) is a little less for the vector corrected/scalar wind sets, than for the gust derived. However the correlation coefficient is slightly better for the gust derived speeds (both unadjusted and adjusted for height) than for the vector corrected/scalar speeds.

Table 5. Estimated Ship and Buoy Mean Wind Speed Statistics (East Coast 1989-1995)

Wind	*Mean (m/s)*	*Median (m/s)*	*Maximum (m/s)*	*Standard Deviation (m/s)*
buoy vector/scalar mean (B_U)	7.35	7.0	22.6	3.48
buoy vector corrected/scalar mean (B_U_VCS)	7.56	7.2	23.3	3.58
buoy gust derived mean (B_U_GD)	7.55	7.1	25.8	3.54
buoy vector corrected/scalar, ht. adj. (B_U10N)	8.09	7.6	25.7	3.93
buoy gust derived mean, ht. adj. (B_U10NGD)	8.08	7.6	28.5	3.90
ship estimated (S_U)	8.82	8.2	30.9	4.92

Table 6. Comparison Of Estimated Ship And Buoy Mean Wind Speed Statistics (East Coast 1989-1995)

Difference in Paired Ship – Buoy Wind Speeds	*Mean Difference (Bias) (m/s)*	*Median (m/s)*	*Standard Deviation (m/s)*	*Correlation Coefficient Of Regression*	*Intercept Parameter (m/s) of Linear Fit Regression*	*Slope Parameter of Linear Fit Regression*
S_U – B_U	1.47	1.2	3.37	.729	1.25	1.30
S_U - B_U_VCS	1.26	1.0	3.37	.729	1.25	1.00
S_U - B_U_GD	1.27	1.1	3.31	.740	1.07	1.03
S_U – B_U10N	.724	.52	3.39	.728	1.45	.911
S_U – B_U10NGD	.741	.55	3.34	.737	1.32	.928

DISCUSSION AND CONCLUSIONS

The vector to scalar averaging method correction, and the adjustment for height, substantially reduce the difference between collocated measured ship and buoy wind speeds, although a slight positive bias (ship stronger than buoy) remains. The height adjustment makes more of an impact than either of the 2 correction methods. The gust derived mean wind speed reduces the average bias by a slightly smaller amount than the vector corrected/scalar speeds, however the standard deviation and correlation coefficient are slightly better. The estimated ship/buoy comparison also shows a bias, which is reduced by correcting and adjusting the buoy speed. The bias is lower for the estimated ship-buoy unadjusted pairs, than for the measured ship-buoy unadjusted pairs. This may in part be because the estimated ship wind is already at 10 m, whereas the anemometer winds are generally measured at significantly higher heights. Results from the analysis of vector and scalar buoy winds suggest that it is possible to improve the vector correction method using a relationship with wave height. Results from the SWS-2 study will be helpful with this. The gust factor analysis for both vector and scalar based gust factors indicates that the scalar mean wind speed is also degraded in high seas. The scalar mean wind speed could be corrected with a factor that is a function of wave height, as was done in Cardone *et al*. (1996), but perhaps using parameters based on this larger dataset. This would be useful for archived buoy data that did not include a gust speed. It would be interesting to compare the results of correcting mean speeds in this way, with the gust derived mean wind speed.

Flow distortion (speed up or slow down) over the ship is another factor that has not yet been accounted for, that may be significant. This study is being continued to look at the ship/buoy pairs separated into ship type, starting initially with container ships and tanker ships. These may exhibit different flow distortion effects that would give different results when compared with nearby buoys.

There is considerable scatter in the data, even when ship-buoy pairs were within 100 km. A more thorough quality control of the ship data will help, but it is difficult to remove all sources of error in the ship data. Also, the magnitude of the adjustments for height, for stable atmospheric situations, or for high anemometer heights shows that the adjusted wind speeds are sensitive to the temperatures and the method used to adjust for height.

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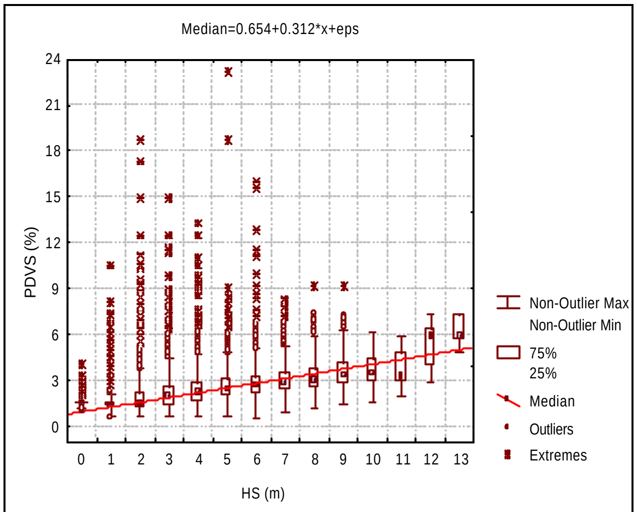

Fig. 1 Box plot of percentage difference between vector and scalar mean wind speed (1994-1998) vs. sig. wave height . Mean wind speeds > 6 m/s.

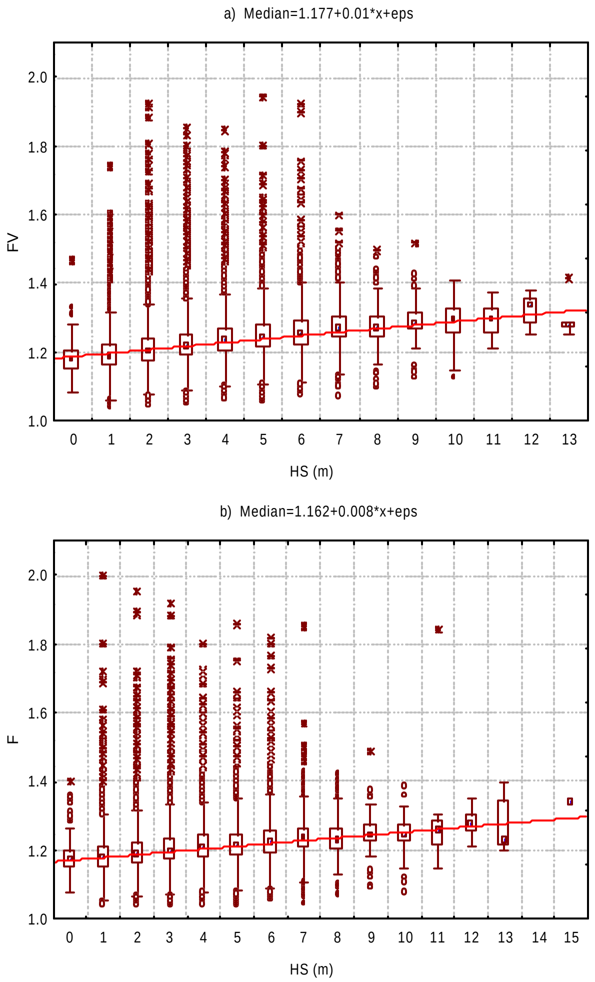

Fig. 2 Box plot of a) vector, FV, and b) scalar gust factor, F, vs. sig. wave height, HS (1994-1998). (Mean speed > 6m/s.)

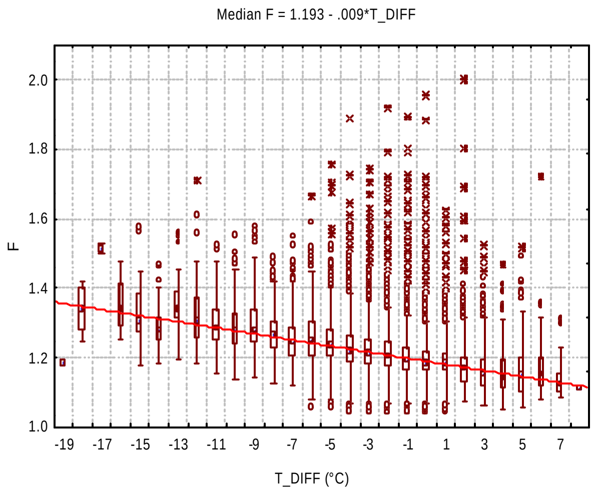

Fig. 3 Box plot of scalar gust factor vs. air-sea temperature difference (1994-1998). Scalar>6m/s & Hs<5m.

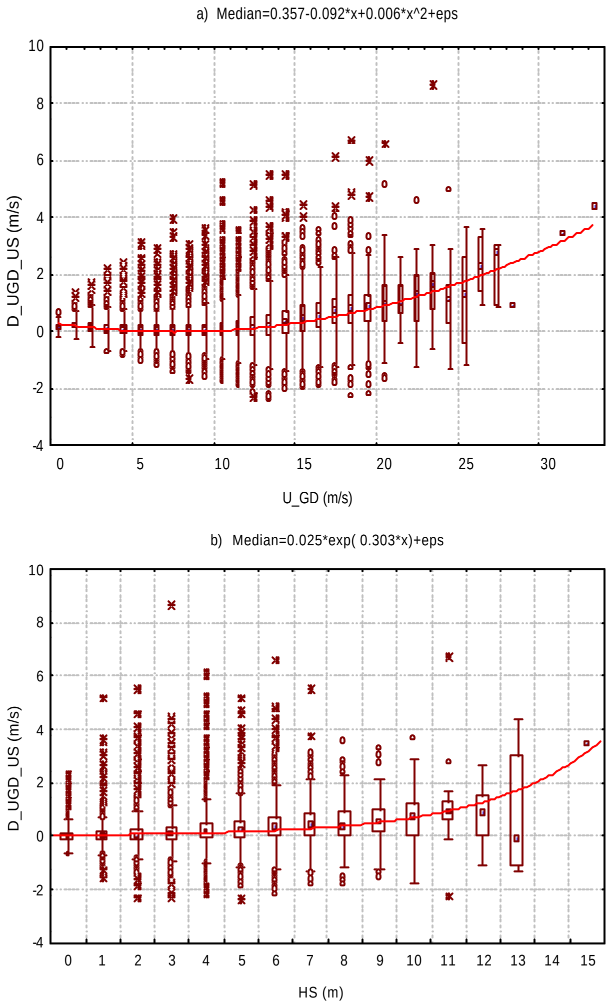

Fig. 4 Box plot of difference between gust derived & scalar mean speed, vs. a) gust derived speed & b) sig. wave height (1994-1998)

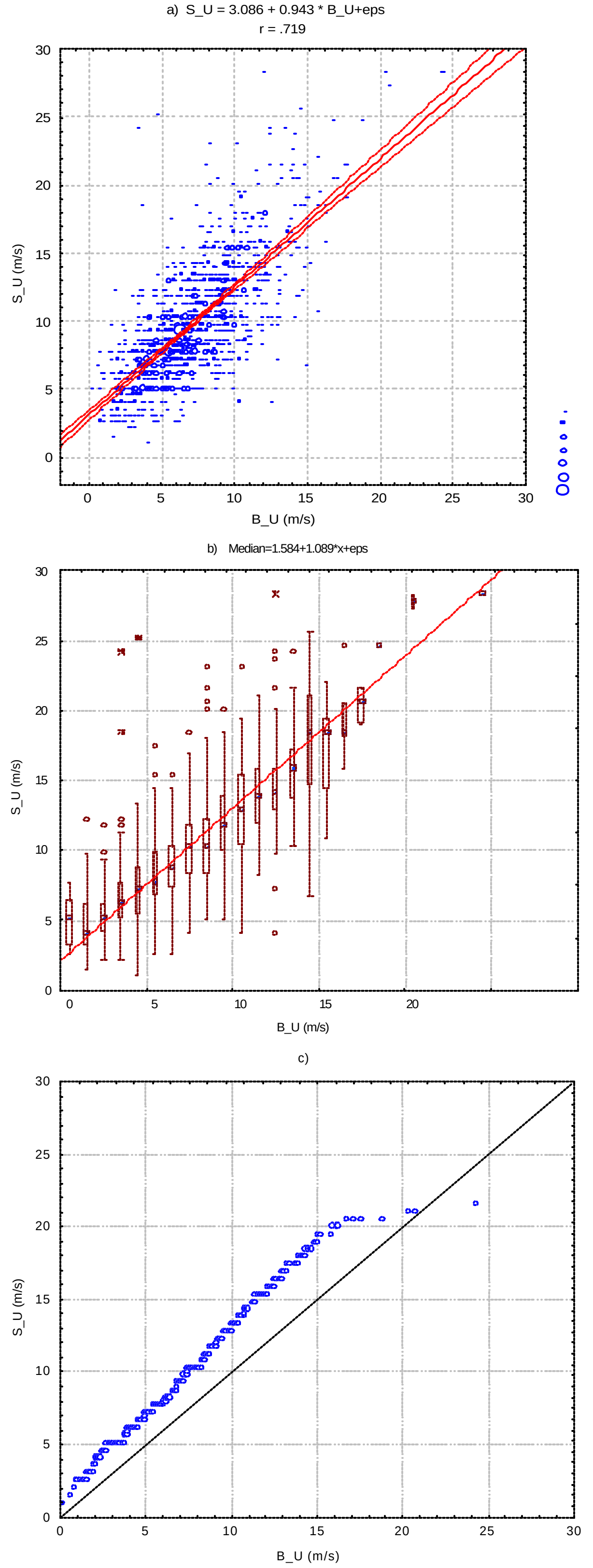

Figure 5 Measured ship vs. buoy mean wind speeds, unadjusted (east coast 1989-1995). a) Frequency scatterplot, b) box plot, & c) quantile-quantile scatterplot.

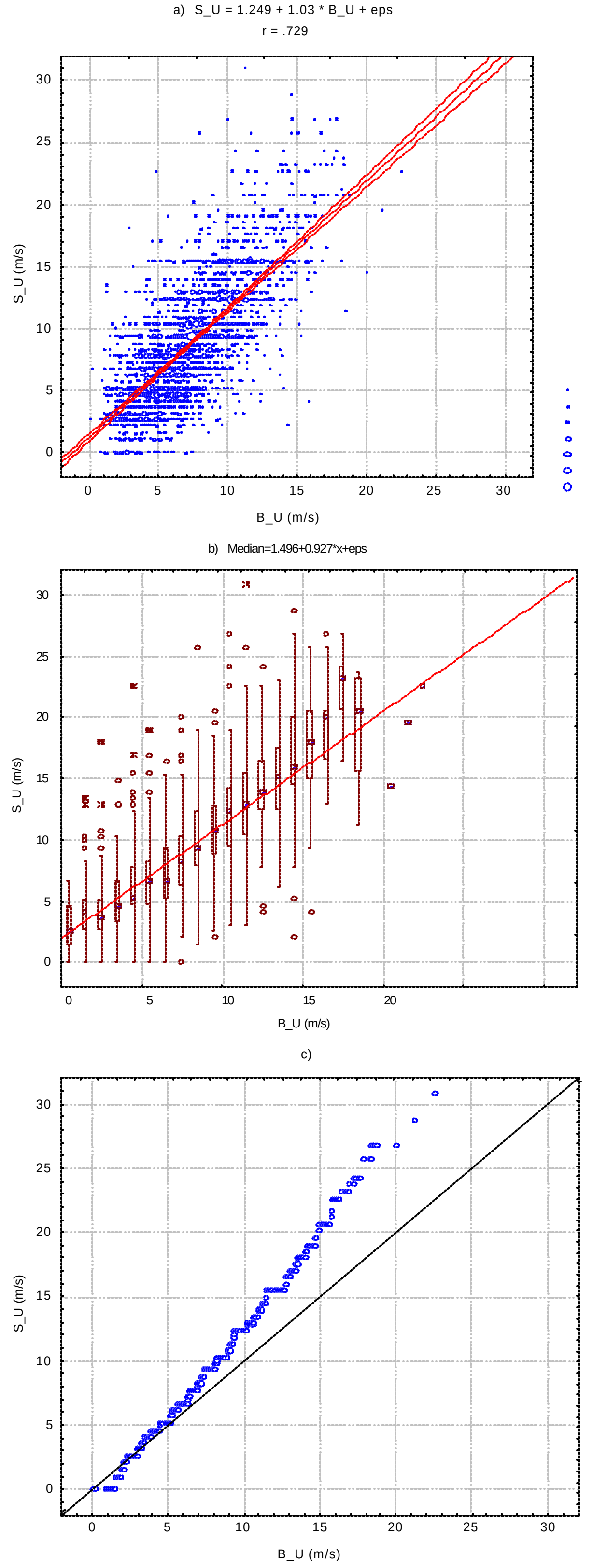

Figure 6 Estimated ship vs. buoy mean wind speeds, unadjusted (east coast 1989-1995). a) Frequency scatterplot, b) box plot, & c) quantile-quantile scatterplot.

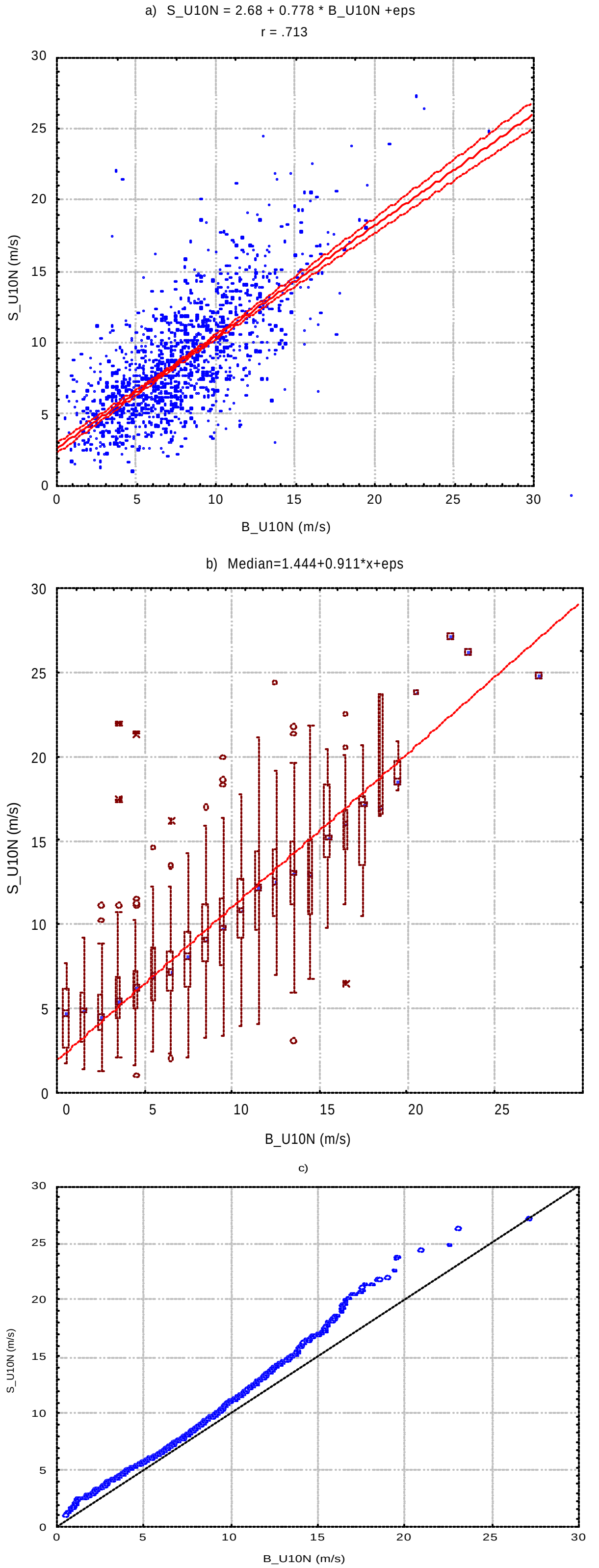

Fig. 7 Measured ship vs. vector corrected/scalar buoy mean speeds, 10 m effective neutral (east coast, 1989-1995). a) Frequency scatterplot, b) box plot, & c) quantile-quantile scatterplot.

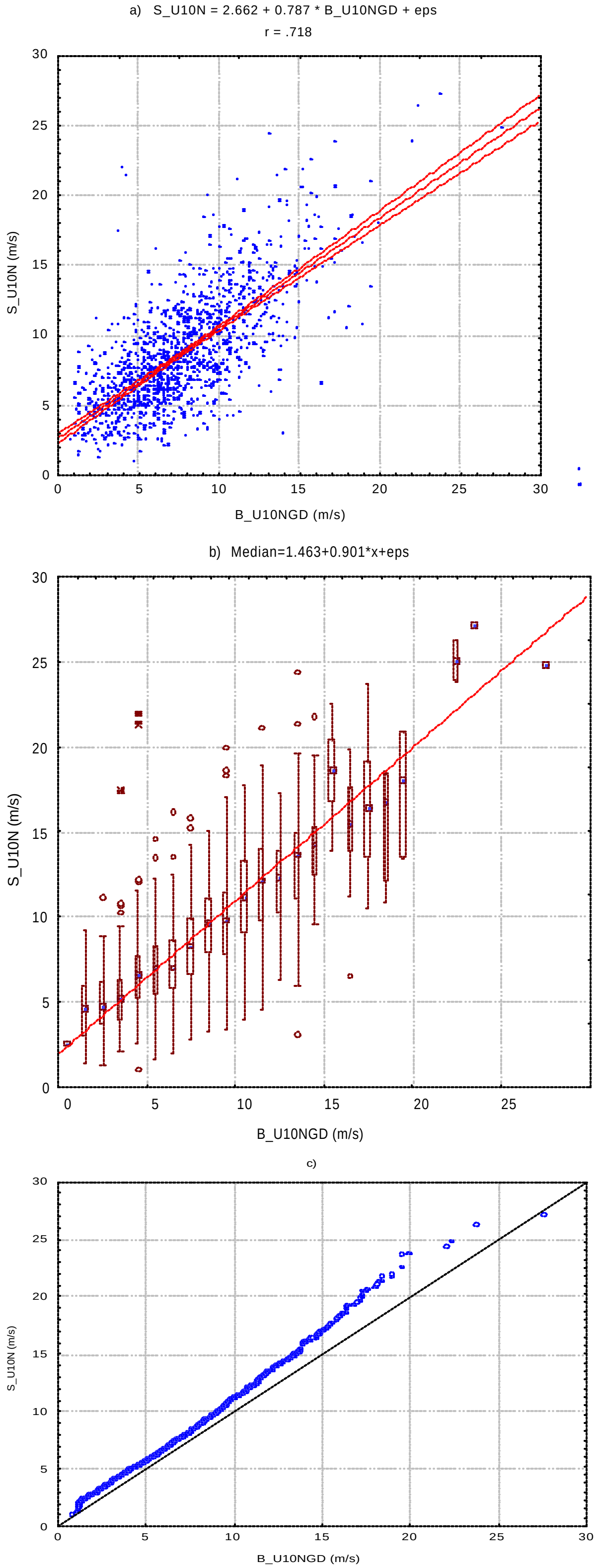

Fig. 8 Measured ship vs. gust derived mean buoy winds, 10 m effective neutral (east coast 1989-1995). a) Frequency scatterplot, b) box plot, & c) q-q plot.

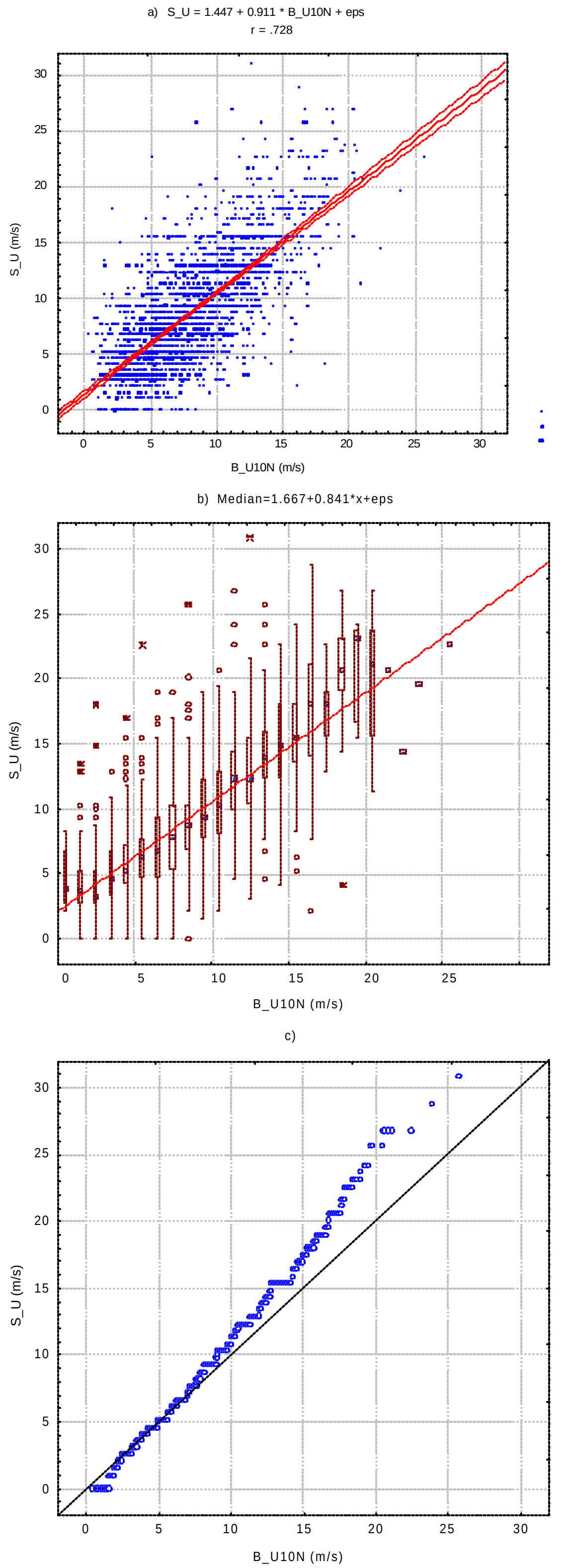

Fig. 9 Estimated ship vs. vector corrected/scalar buoy 10 m effective neutral winds (east coast 1989-1995) a) frequency scatterplot, b) box plot, & c) q-q plot.

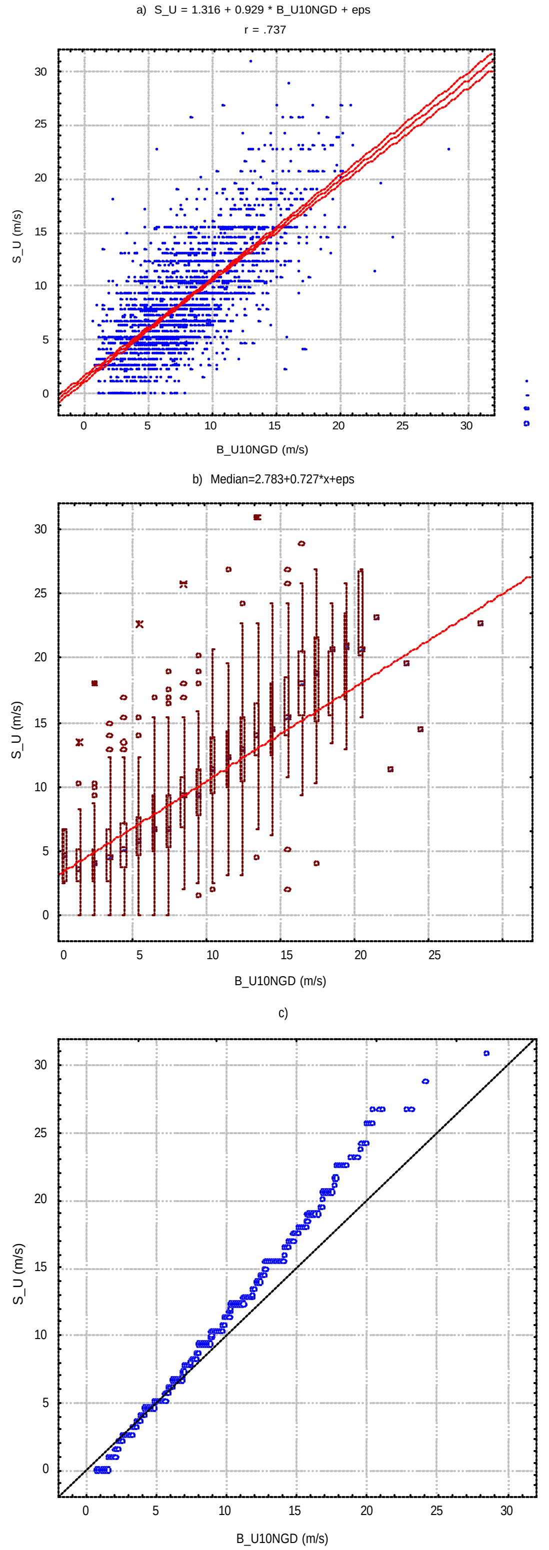

Fig 10 a) Estimated ship vs. gust derived mean buoy winds, 10 m effective neutral (east coast 1989-1995) a) frequency scatterplot, b) box plot, & c) q-q plot.