A Field Evaluation of NDBC Moored Buoy Winds

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ABSTRACT

Several field intercomparisons of buoy winds were conducted to investigate the quality of the observations. Differences between dual anemometers on the same buoy were calculated during tropical cyclones. The speed and direction differences did not grow appreciably with increasing wind speed, and at no time was the speed difference greater than 1 m s^{-1}. Differences between winds measured at colocated buoys and a buoy moored near a platform were investigated. Standard deviations of speed differences were less than 1 m s^{-1} and direction differences were less than 11°. The differences were slightly larger in certain sea states in the interbuoy comparison. No similar evidence was found when buoy winds were compared to platform winds.

Several comparisons were conducted to help quantify errors that arise when buoy winds are used as comparison data for satellite-based scatterometer and altimeter winds. First, 8.5 min average winds were compared to hourly average winds to investigate effects introduced by the buoy's short averaging period. Second, speed and direction differences between pairs of buoys located 39 and 109 km apart were calculated to determine differences due to spatial variation in the wind field. Differences due to spatial variations were larger than differences introduced by the short averaging period. Therefore, researchers are urged to compare remotely sensed winds with buoy winds only when the distance between the center of the footprint and the buoy is considerably less than 100 km.

1. Introduction

The National Data Buoy Center (NDBC) operates a variety of buoys that measure winds, sea level pressure, air temperature, sea surface temperature and wave spectra. In addition to being used for real-time forecasts, buoy winds serve as comparison data for remotely sensed winds obtained from scatterometers and altimeters. Because of this usage, researchers have a need to know the accuracy of buoy winds. Chelton and McCabe (1985) have speculated that much of the difference between buoy and scatterometer winds is due to difficulties in measuring the wind from a buoy. Indeed, the poor quality of buoy winds obtained during the Joint Air–Sea Interaction (JASIN) experiment substantiates their point (Weller et al., 1983).

An extensive set of field comparisons were performed during 1984 and 1985 to investigate the accuracy of buoy wind measurements. Differences between dual anemometers on the same buoy were calculated for significant storm episodes. Differences between winds measured at colocated buoys and platforms were investigated. These differences were examined to see if the comparisons deteriorated under high wind or wave conditions. Significant deteriorations could indicate that buoy motion was adversely affecting the measurements.

There are other fundamental reasons for error when scatterometer winds are compared to buoy winds. The scatterometer provides an instantaneous measurement over a finite footprint, while buoys provide temporally averaged measurements at a point. Chelton and McCabe (1985), Brown (1983) and Pierson (1983) describe this problem in some detail. Two comparisons are presented that may help to quantify this problem. First, the 8.5-min average winds are compared to hourly average winds from the same buoy to investigate the differences introduced by a short averaging period. Second, in order to provide some assessment of horizontal variability, winds are compared for two pairs of buoys located 39 and 109 km apart.

2. Anemometer and payload characteristics

Different types of anemometers have been favored at different times during NDBC's history. Cup and vane anemometers were never considered for use on an operational buoy after the early 1970s for the same reasons as listed by Weller (1983). These reasons include overspeeding in gusty winds and errors introduced by vertical components of the wind resulting from buoy motion. Vortex-shedding anemometers were used extensively in the late 1970s. However, these anemometers suffered from sporadic failures during precipitation and were phased out during the 1981–84 period. Bendix Aerovane propeller anemometers were introduced in the early 1970s and became NDBC's most common anemometer by 1981. At present, it is the only type in operational use, though R. M. Young propeller anemometers are undergoing field testing. All data presented in this paper were collected by the Bendix anemometer.

More specifically, the model used is the commercially available Bendix Model No. 120 with ruggedized propellers. Distant constants, threshold speeds, and other specifications are listed in Mazzarella (1972). The Belfort Type L anemometer is used interchangeably with the Bendix model since Belfort acquired Bendix, and the characteristics are similar.

Two different on-board processors, called payloads, are currently being used by NDBC. One payload, called the General Service Buoy Payload (GSBP), was introduced in 1978 and produces vector averages of wind speed. Individual samples of the u and v components are obtained every second for 8.5 min. Average speed and direction are then produced from the averaged components.

The other payload, called the Data Acquisition, Control and Telemetry (DACT) payload, was introduced in 1983 and produces scalar wind averages (i.e., separate and independent averages of speed and direction). The payload is used for all stations in the Coastal Marine Automated Network (C-MAN). The C-MAN stations are located at lighthouses, piers and beachfront or offshore towers. The DACT payload is also used for several coastal and Great Lakes buoys. Direction and speed are sampled every second, but the averaging period depends on the installation. For buoys, the averaging period is 8 minutes; elsewhere, the period is 2 minutes. One requirement for DACT payloads is that users be able to access the data in synoptic code via a phone line. As a necessary consequence, wind speeds are reported to the nearest knot (0.5 m s^{-1}) and directions to the nearest 10°. A field comparison of vector and scalar averaged winds is presented in section 6.

NDBC calibrates each sensor before each use in the field. The frequency in Hertz (Hz) of the output signal from each anemometer is obtained at 15 wind speeds ranging from 2 to 60 m s^{-1}. Because the relationship is linear, a single calibration coefficient for the slope, b, is determined,

$$b = [\sum_{i=1}^{n} (y_i/x_i)^2/n]^{1/2} \quad (1)$$

where y_i is the sensor output in Hz and x_i is the actual speed in the wind tunnel for n different calibration speeds. The computed speeds, s_i, are then calculated from this slope, $s_i = y_i/b$. If more than one measured speed, x_i, differs from its computed speed, s_i, by more than 5% or 0.5 m s^{-1}, whichever is greater, then the anemometer is rejected from operational use. The calculated slopes for each individual sensor are used to calculate the speed in real-time for the GSBP payload. A standard slope is used for all similar sensors for DACT payloads.

In order to document typical calibration errors, the mean (XBAR) and standard deviations (SD) of $s_i - x_i$ are shown in Table 1 for five anemometers. These statistics were calculated before and after deployment in the field using the slopes determined before deployment. These anemometers were chosen because they did not experience any failures during field use. Failures are detected by duplicate anemometers on the same platform or buoy. The length of use in the field ranged from 3 months to over 1 year.

TABLE 1. Wind speed errors for 5 anemometers as determined by calibration before and after deployment. The mean errors, XBAR, and the standard deviation, SD, are in m s^{-1}.

Anemometer serial no.	Before deployment		After deployment	
	XBAR	SD	XBAR	SD
054	0.38	0.11	0.14	0.20
035	−0.02	0.24	−0.08	0.13
016	0.04	0.25	0.35	0.52
082	0.05	0.20	−0.03	0.27
069	−0.22	0.36	0.08	0.21
Overall	0.05	0.23	0.09	0.27

In general, the data show that the calibration method performs well and that the calibration is stable over the life of field deployments. The NDBC-stated system accuracy for wind speed calls for $(XBAR^2 \pm SD^2)^{1/2}$ to be within ±1.0 m s^{-1} or +10%, whichever is greater. Therefore, calibration errors account for about one-fourth of the NDBC error budget, or about 0.25 m s^{-1}.

In order to measure wind direction from buoys, compasses are used to determine the sensor's orientation with respect to magnetic north. Fluxgate compasses are used with GSBP payloads, and digital compasses are used with DACT payloads. Several adjustments are performed prior to installation. The compasses are placed on a shoreside compass range where direction errors are determined every 15°. The mean direction errors are then subtracted from each reading and the magnetic variation is then added via software. The deviation of these errors about the mean is then one source of wind direction error. The standard deviation of these errors for four, randomly chosen compasses was 2.3°. The largest single error was 4.9°.

The magnetic field of the buoy also influences the compass readings. This effect is limited to large discus buoys which are constructed of steel. Therefore, instead of indicating a true magnetic direction, the compass reading is deflected by the magnetic field of the buoy. These readings are corrected by placing tiny iron bars in specific positions adjacent to the compass. These bars compensate for the field's effects. This adjustment requires spinning the buoy several times before deployment and is a difficult procedure. It eliminates the large 20 to 40° errors, but some residual error remains. When these errors were combined with the compass range errors for the same four anemometers, the standard deviation grew to 2.8°. The largest single error was 6.5°.

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3. Hull characteristics and buoy motion

Three types of buoy hulls are used by NDBC: large discus buoys, NOMAD buoys and 3-m discus buoys, formerly called E-Buoys. Large discus buoys owned by NDBC are 10 and 12 m in diameter, with an anemometer height of 10 m. Large Navigational Buoys (LNBs) are 12-m discus buoys operated by the Coast Guard primarily for coastal navigation purposes. NDBC operates and maintains the payload and sensors on LNBs. The anemometer height on LNBs is 13.8 m. NOMAD buoys are 6-m, boat-shaped hulls whose anemometer heights are 4.9 and 4.1 m. Both the large discus buoys and the NOMADs have long been in operational use and their photographs appear in Hamilton (1980).

The newest hull type, the 3-m discus buoy, is shown in Figure 1. This buoy was developed by the Woods Hole Oceanographic Institution and is considerably less expensive than the other two hull types. The NDBC conducted extensive field evaluations of data collected from this buoy during 1983 and 1984 before it was certified for operational use. Some of the field evaluations are presented in sections 5 and 6. The anemometer heights are 4.9 and 3.7 m.

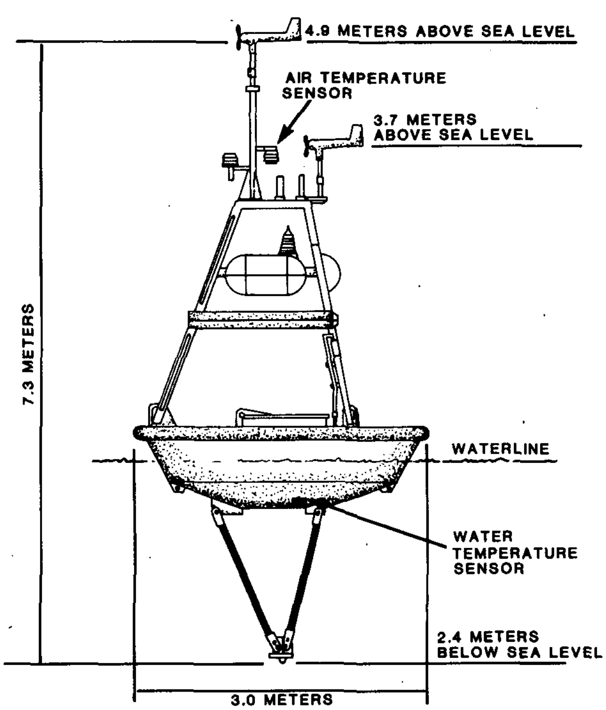

FIG. 1. The 3-m discus buoy with positions of the sensors.

The average pitch response of each buoy has been calculated in order to estimate effects of buoy motion. A hull/mooring dynamics model developed by Oceanics, Inc. provided data on buoy motion for various wave frequencies. The model provided pitch response amplitude operators (RAOs), expressed in terms of degrees of pitch per meter of wave height, as a function of wave frequency. The Pierson-Moskowitz sea spectrum,

$$S(w) = 8.1(10^{-3}g^2w^{-5})\exp[-0.74(g/Uw)^4] \quad (2)$$

where g is the gravitational acceleration constant, U the wind speed, and w the wave frequency, was then used with the RAOs to determine pitch response spectra, $S_{\text{response}}(W)$, for each frequency:

$$S_{\text{response}}(W) = S(w)\text{RAO}(w)^2. \quad (3)$$

Subsequently, the average pitch, P, was calculated by

$$p = 1.25(M_0)^{1/2} \quad (4)$$

where M_0 is the area under the pitch response spectral curve. Equations (2) through (4) were solved for wind speeds ranging from 5 to 30 m s^{-1} for all three hull types. Figure 2 shows the results of these calculations expressed in terms of average pitch versus significant wave height. All three hull types have similar pitch responses. The average pitch angles do not increase much for significant wave heights between 3 and 13 meters. The angles remain below 10 degrees for significant wave heights under 11 meters for all three buoys. Significant wave heights greater than 11 meters comprise less than 0.001% of NDBCs archival data. Pond (1968) related average pitch to errors in measuring wind speed gradient and Reynolds stress, assuming sinusoidal buoy motion. His conclusion was that pitches on the order of 10 degrees produce a negligible effect on these measurements. An NDBC analysis of the effects of buoy pitch on horizontal wind speed measurements yielded conclusions similar to Pond's in both form and end results. Therefore, it appears that buoy motion has an insignificant effect on wind speed measurement based on theoretical considerations.

4. Duplicate sensor comparisons on the same platform

All NDBC buoys and C-MAN stations have duplicate anemometers. Monitoring data from both sensors is helpful in diagnosing failures in near real time (Gilhousen, 1985). At any given time, 60 to 75% of buoys have both anemometers functioning. Of the buoys that have an anemometer fail, the failure is often not so fatal as to preclude using the data for monitoring the performance of the working anemometer. For example, worn bearings or a cracked propeller may suddenly decrease wind speeds 15–30%. Thereafter, the difference between the two speeds is roughly constant.

During 1985, tropical cyclones passed within 110 km of six NDBC buoy and four C-MAN stations. Eight of these stations had both anemometers in working

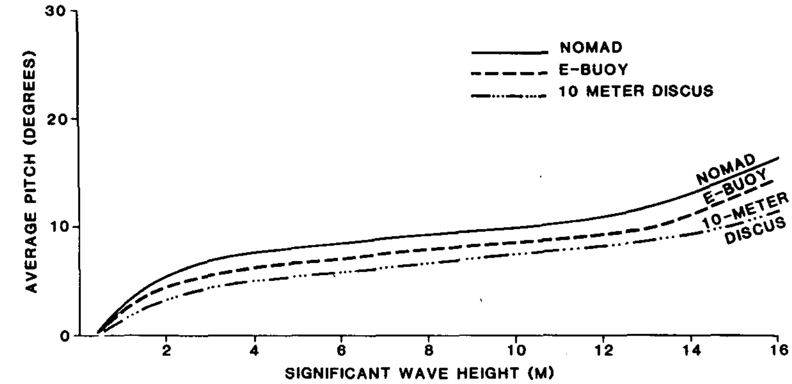

FIG. 2. Average pitch angle for NDBC hull types as a function of the significant wave height. The 3-m discus buoy is labeled as the E-Buoy.

order throughout the passage of the storms. These stations are listed in Table 2. In order to assess how data compared from these duplicate anemometers, several weeks of data centered around the passage of these storms were examined. The mean difference, called the bias (B), and the standard deviation of the differences (SD) between duplicate speeds and directions, were computed. All buoy stations and all C-MAN stations were grouped separately for these calculations. These statistics were also calculated for various ranges of wind speed to see how well the sensors tracked together with increasing wind speed.

The results for wind speed are shown in Figure 3. Overall, the biases and standard deviations are about the same for buoys as they are for C-MAN stations on fixed platforms. The SDs are well within 1 m s^{-1}. In fact, the greatest single difference between any two anemometers was 1 m s^{-1}. This is an excellent result considering that the anemometers are mounted on opposite sides of the centerline and are therefore subject to different instantaneous accelerations. The highest sustained wind speed measured by a buoy was 33.0 m s^{-1}, and the highest significant wave height was 14.2 m.

TABLE 2. NDBC buoy and C-MAN stations which experienced at least gale force winds from 1985 tropical cyclones and which had dual anemometers functioning. Location is given in degrees of N. latitude and W. longitude.

Station	Location (°N,	°W)	Storm name	Hull type	Payload type
41002	32.3	75.3	Gloria	Nomad	GSBP
42001	25.9	89.7	Danny	Large discus	GSBP
42007	30.1	88.9	Elena	Large discus	DACT
44009	38.5	74.6	Gloria	Large discus	DACT
44012	38.8	74.6	Gloria	Large discus	DACT
ALSN6	40.5	73.8	Gloria	Platform	DACT
CHLV2	36.9	75.9	Gloria	Platform	DACT
SVLS1	31.9	80.6	Bob	Platform	DACT

The SDs do show a gradual rise with increasing wind speed, but the SDs increase more rapidly for the platforms than for buoys. This is a surprising result if buoy motion is suspected to be a significant source of error in wind measurement. For, if that were the case, differences between duplicate sensors located on buoys would be larger than differences between duplicate sensors located on platforms in storm episodes. Perhaps turbulence generated by the structure and navigation gear on these platforms is the cause for the greater differences. A more probable explanation is that the shorter, 2-min scalar averages performed by the C-MAN stations caused larger SDs.

The calculations for wind directions are shown in Figure 4. The Bs and SDs are consistently larger for measurements taken on a buoy. This is probably the result of compass errors due to buoy motion. Wind directions measured at C-MAN stations do not use compasses because the sensors are aligned with true north upon installation. The SDs for both buoys and C-MAN stations are generally within the 10°, stated system accuracy. The deviations do not increase with higher speed categories at C-MAN stations. The SDs increase for buoys until the 15 to 20 m s^{-1} range, and then decrease thereafter.

5. Buoy intercomparisons

In order to qualify the 3-m discus buoy for operational use, this buoy collected data at three locations where other NDBC data were available. One of these locations was in eastern Lake Superior, where a 3-m discus buoy was moored 3.3 km WNW of a NOMAD moored at station 45004 (47.2°N, 86.5°W). Both buoys had the GSBP payload and were equipped with dual Bendix anemometers. Statistics summarizing the differences between all four speeds and directions were computed. These statistics include the correlation coefficient (r), the bias (B), the standard deviation (SD) and the functional precision (FP) where FP = (B^2

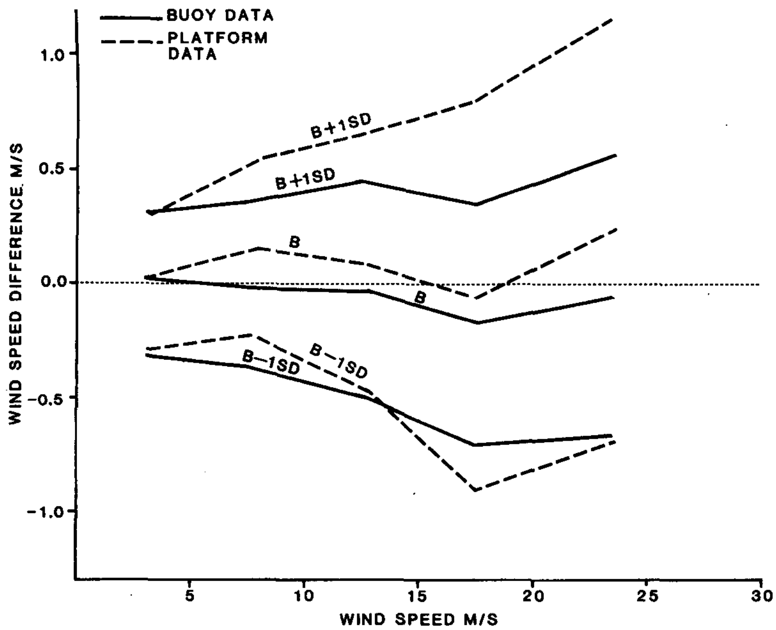

FIG. 3. Statistics summarizing the difference in wind speeds between duplicate anemometers. The bias (B) plus and minus one standard deviation (SD) are plotted as a function of wind speed.

+ SD^2)$^{1/2}$ (Hoehne, 1977). October 1984 was chosen because several storm episodes occurred during the month. Wind speeds reached 14.7 m s^{-1} and significant wave heights reached 5.0 m.

Table 3 presents the summary statistics for both wind speed and direction comparisons. The FP for both speed and direction are somewhat greater for the interbuoy differences than the intrabuoy differences. However, the interbuoy FP are still within 1.0 m s^{-1} and 10°. The interbuoy differences are slightly greater for higher wind speeds. The SD of these differences for wind speeds greater than 7.5 m s^{-1} is 0.88 m s^{-1}, while for speeds less than 4.0 m s^{-1}, the SD is 0.64 m s^{-1}.

Scatterplots were produced in Fig. 5 to see if the

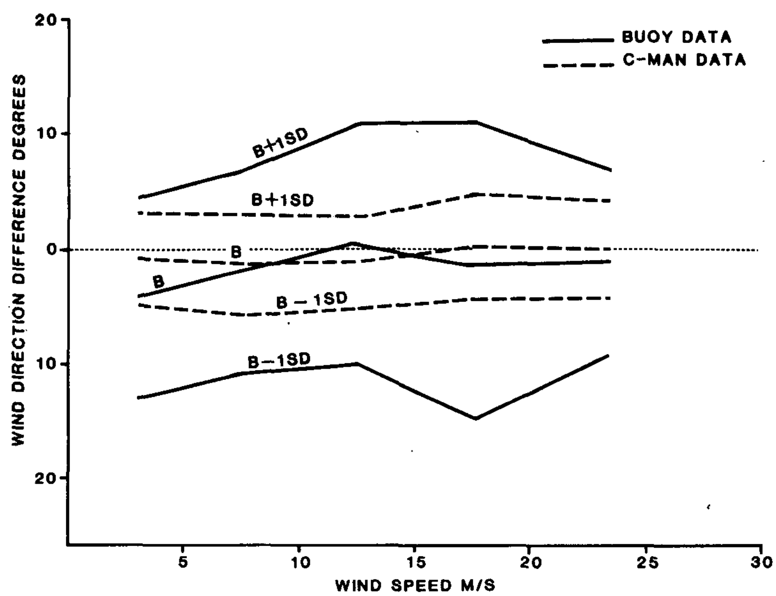

FIG. 4. As in Fig. 3 except for wind direction.

TABLE 3. Summary statistics for wind speed and direction differences between the 3-m discus buoy and the NOMAD buoy. The sample size is 717 cases. The notation used under the "Comparison" heading refers first to the buoy type, 3M for 3-m discus buoy and N for NOMAD, then to the anemometer number, 1 or 2. Speed differences are in meters per second and direction differences are in degrees.

	Speed				Direction			
Comparison	r	B	SD	FP	r	B	SD	FP
3M1–3M2	0.991	0.476	0.385	0.612	0.982	−4.12	5.57	6.93
N1–N2	0.993	0.272	0.401	0.485	0.903	−5.54	5.03	7.48
3M1–N1	0.955	−0.162	0.784	0.796	0.929	1.41	9.16	9.27

interbuoy differences are related to wind speed, wave height or abrupt changes in the wind field. Figure 5a presents the NOMAD speeds vs 3-m discus buoy wind speeds stratified by wave conditions. Wave heights above 2.5 m appear as asterisks, while wave heights above 0.8 m with dominant wave periods below 4.5 sec appear as diamonds. NDBC was particularly interested in how the data compared in this last category, which signifies "choppy" wave conditions. The 3-m discus buoy was observed to have greater buoy motion than the NOMAD in these conditions.

The high and "choppy" wave cases show slightly higher wind speed for the NOMAD than the 3-m discus buoy. For the high wave cases, B is 0.78 m s^{-1}; while for the "choppy" cases, B is 0.61 m s^{-1}. However, several prominent outliers exist which are not part of either category. Figure 5b shows the same scatterplot stratified according to wind speed and direction tendencies. If the wind speed changed by more than 2.5 m s^{-1} or the direction shifted more than 30° in the past hour at either of the two buoys, the case was plotted as a diamond. Some of the larger speed differences appear as diamonds in Fig. 5b. This means that a legitimate discontinuity in the wind field passed the buoys and perhaps affected the comparison. This notion is further strengthened by examining Fig. 5c, which compares the wind direction using the same stratification and symbols. Virtually all of the large direction differences are associated with abrupt changes in speed or direction. To summarize, the few large direction and speed differences between the two buoys do not appear to be related to buoy motion, rather they appear to be caused by legitimate discontinuities in the wind.

6. Buoy versus platform winds

During the fall of 1984, a 3-m discus buoy was moored 1.3 km NNE of a C-MAN station located on an offshore tower at Chesapeake Light Station, Virginia (36.9°N, 75.7°W). Winds measured on the platform were compared to winds measured by the buoy. The results from Thornthwaite et al. (1965) were used to site the anemometers where airflow disturbances due to the platform would be minimized. The anemometer height on the platform was 33.3 m and on the buoy was 3.6 m. The platform's anemometers were located 5.8 m above the control tower and 11.0 m above the main flight deck. Two anemometers were located on the platform, and only one on the buoy. The buoy had a GSBP payload while the platform had a DACT payload. The method outlined in Eqs. 2–4 of Liu et al. (1979), which assumes a constant flux layer, was used to correct the speeds from both the platform and the buoy to 10 m before any comparisons were made. October 1984 was chosen for the comparisons because of the passage of Hurricane Josephine. Wind speeds reached 19.5 m s^{-1} on the platform and the significant wave heights reached 3.6 m.

A scatterplot shown in Fig. 6 compares the speeds measured on the buoy with the speeds measured by one of the platform's anemometers. Some summary statistics are presented in Table 4. Overall, the functional precision, or comparability, between the buoy and platform is 1.0 m s^{-1}. The SD of the difference between the buoy and platform's speeds is about the same as the SD of the difference between the platform's two anemometers. This SD does not increase with higher wind speeds. For wind speeds greater than 8.0 m s^{-1}, the SD is 0.70 m s^{-1}, while for speeds less than 4.0 m s^{-1}, the SD is 0.69 m s^{-1}. Figure 7 shows that the differences between the buoy and platform's speeds are approximately normally distributed. Figure 8 shows a time-series plot with platform speeds labeled as station CHLV2 and the buoy's speeds labeled as station 44010. Both speeds track together reasonably well. Mesoscale peaks and valleys in the wind are measured well by the buoy, despite significant wave heights of up to 3.6 m.

The only disturbing point is that buoy speeds are lower than the platform speeds for high wind speed events. This is most likely the result of the difference in averaging methods. The buoy's speeds were vector averaged, while the platform's were scalar averaged. Field comparison of both averaging methods were performed for the same anemometer at buoy station 41001 in March 1984. This comparison is shown in Figure 9. The two averaging methods yield equal speeds for speeds less than 8 m s^{-1}. For speeds greater than 8 m s^{-1}, the vector averaged speeds are about 7% lower than the scalar averaged speeds. A similar relationship between scalar and vector averaging methods has been observed at a number of stations, in a variety of atmospheric conditions. This result helps to explain most of the bias between the buoy and platform speeds.

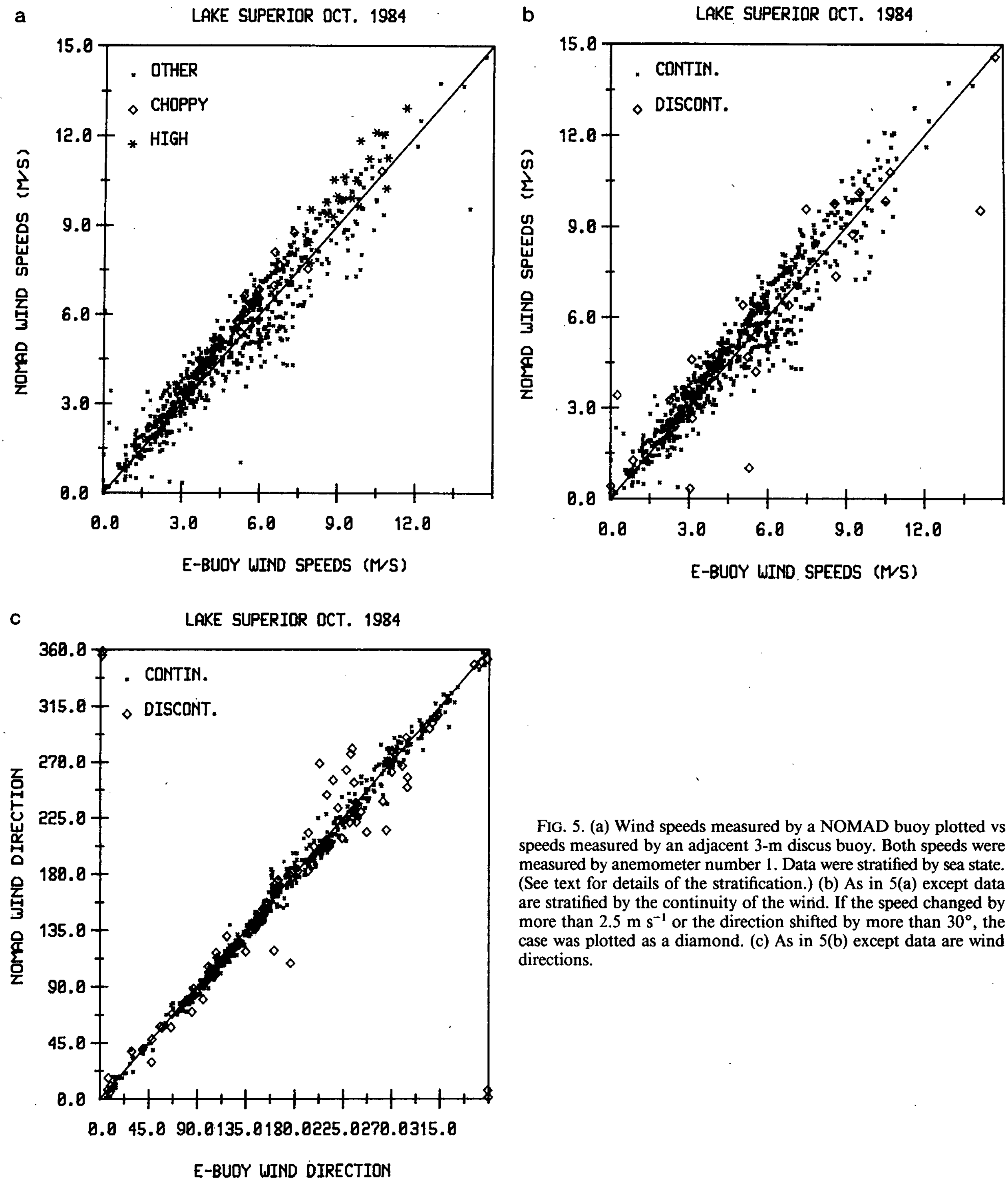

FIG. 5. (a) Wind speeds measured by a NOMAD buoy plotted vs speeds measured by an adjacent 3-m discus buoy. Both speeds were measured by anemometer number 1. Data were stratified by sea state. (See text for details of the stratification.) (b) As in 5(a) except data are stratified by the continuity of the wind. If the speed changed by more than 2.5 m s^{-1} or the direction shifted by more than 30°, the case was plotted as a diamond. (c) As in 5(b) except data are wind directions.

Wind directions from the buoy and the platform were also compared, though this comparison was hampered by an installation problem at CHLV2. The sensor was not aligned properly with north, and though the error was corrected after the 3-m discus buoy was recovered, the amount of error was never recorded. Therefore, a bias calculation would be meaningless, but the SD of the differences is still meaningful. The SD of the differences between the buoy and the platform is 10.42 degrees. This is roughly twice the SD of

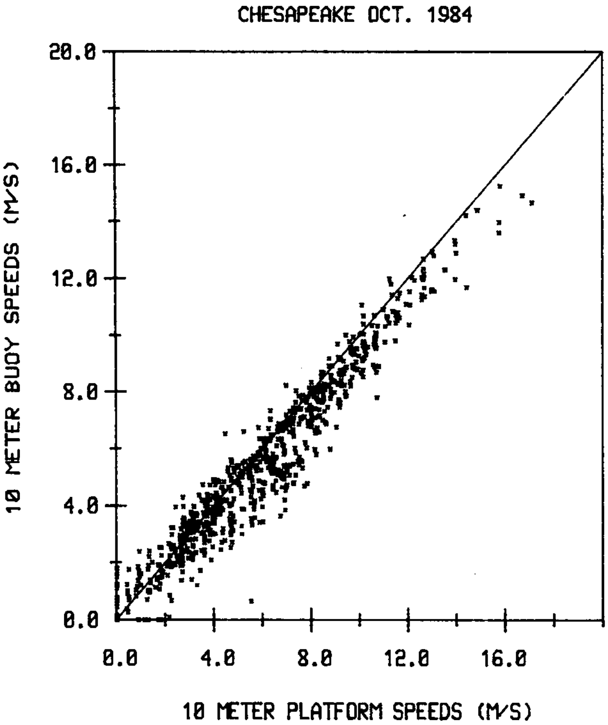

FIG. 6. Wind speeds from a 3-m discus buoy are compared to speeds measured by anemometer number 1 on an adjacent platform. Both speeds were adjusted to a 10 m height before plotting.

the difference between the two sensors located on the platform, which is 4.94°. Figure 10 shows that the differences between the buoy and the platform are greater in light wind speeds. This result does not support the notion that buoy motion is impacting the measurement of wind. Figure 10 simply confirms that directions are more variable in light wind speeds.

TABLE 4. Summary statistics for wind speed differences in meters per second between a colocated 3-m discus buoy and a platform. Sample size is 712 cases. Platform 1 refers to the first anemometer on the platform; platform 2 refers to the second.

Comparison	r	B	SD	FP
Platform 2–platform 1	0.992	−0.112	0.500	0.512
Buoy–platform 1	0.971	−0.592	0.814	1.001

7. Averaging times and spatial variation

Several sources of error exist in comparing the accuracy of remotely sensed winds from a satellite with buoy observations. First, buoys average the wind for only 8.5 min. This is a relatively short period of time compared to the time it takes for an air parcel to travel the length of a satellite footprint. For example, a parcel moving at 8 m s^{-1} would take about 100 minutes to travel 50 km. Second, legitimate spatial differences in the wind exist between the buoy location and other locations within the satellite footprint.

Additional data comparisons were conducted in order to help quantify these errors. On several West Coast buoys, hourly average winds were calculated in addition to the standard 8.5-min averages. (In reality, these winds are averaged for 58 min to allow 2 min for data transmission.) These measurements were obtained on buoys funded by the Minerals Management Service for environmental assessment purposes. This required the payload to be powered continuously. Hourly average winds are not routinely available on other buoys.

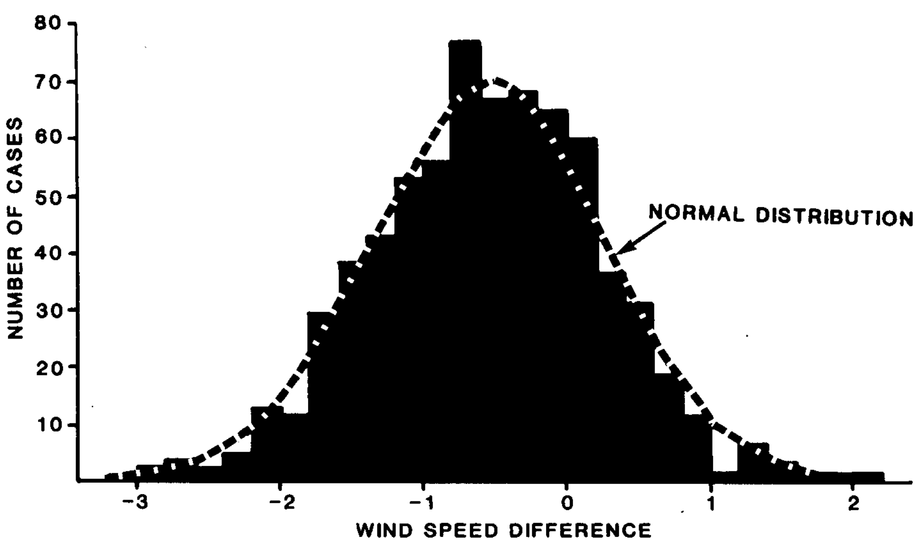

FIG. 7. The frequency distribution of wind speed differences between the 3-m discus buoy and the platform.

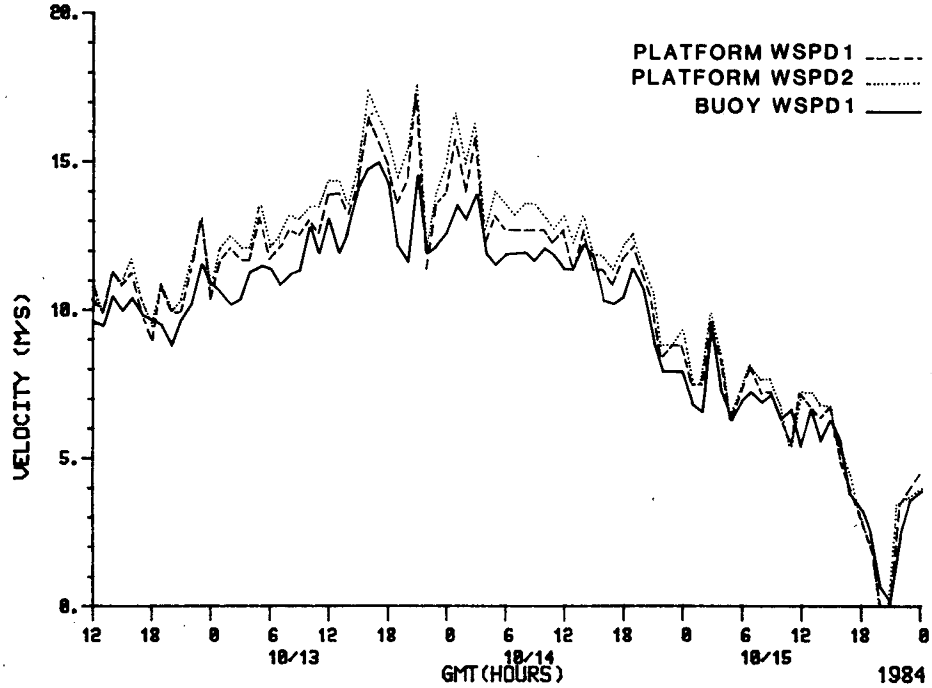

FIG. 8. Time series of platform and 3-m discus buoy wind speeds during the passage of Hurricane Josephine. Both speeds were adjusted to a 10 m height.

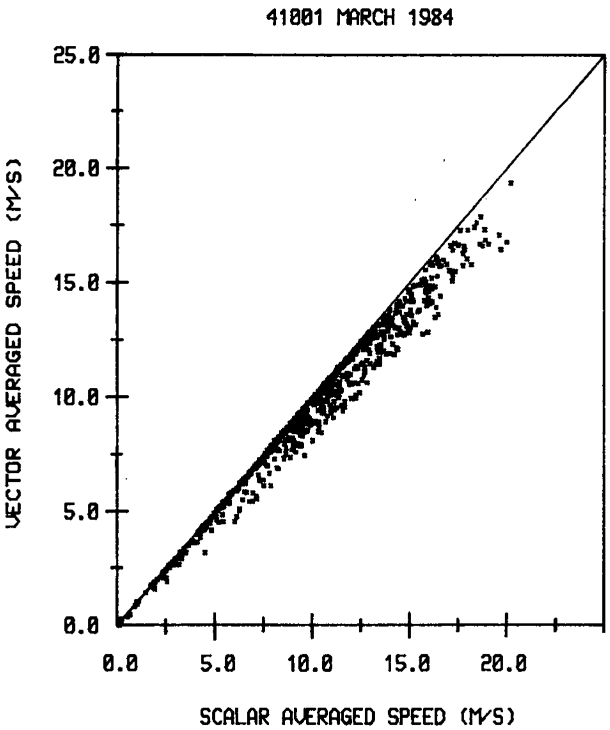

FIG. 9. A comparison of scalar and vector averaging techniques for wind speed.

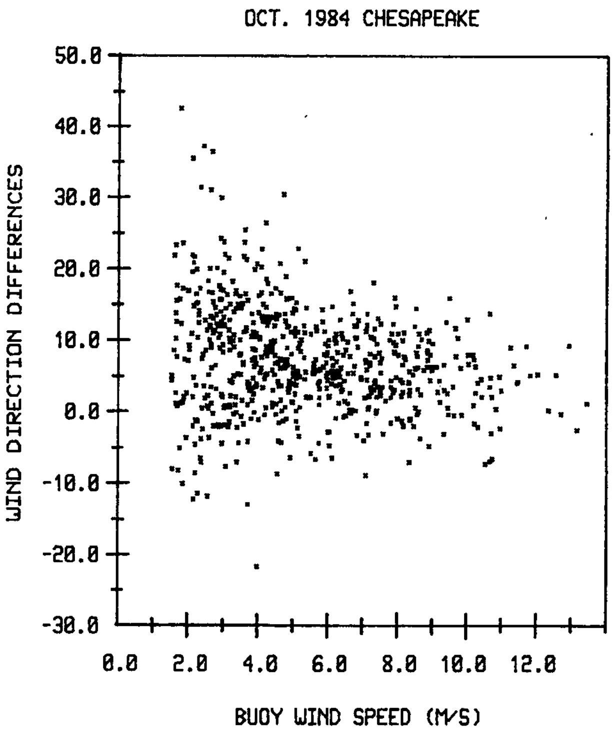

FIG. 10. Wind direction differences between a 3-m discus buoy and an adjacent platform plotted as a function of buoy wind speed.

A statistical comparison between the two averaging times was conducted and should help document the error attributed to using a short averaging period. Also, winds from several buoys positioned 40 to 110 km apart were compared to investigate spatial differences.

November 1983 data for buoy station 46022 (40.8°N, 124.5°W) were chosen to investigate the errors attributed to the short averaging period. The monthly average wind speed was 8.7 m s^{-1} and the maximum 8.5-min average speed was 23.8 m s^{-1}. The data were culled to eliminate discontinuities in wind speed and direction. If the speed changed by more than 2.5 m s^{-1} or the direction shifted by more than 30° in the last hour, both the current and the previous hour's observation were discarded. The bias and the SD of the difference between the hourly and 8.5-min averages were calculated for the resulting sample of 627 cases.

The speed bias was 0.06 m s^{-1}, and the SD was 0.60 m s^{-1}. The maximum speed difference was 3.62 m s^{-1}. The direction bias was 1.1° and the SD was 5.3°. The maximum direction difference was 32.3°. These differences are not much greater than differences obtained between duplicate anemometers on the same platform. Differences of this magnitude would not seem to impact initial analyses for numerical weather predictions or scatterometer and altimeter verifications.

Pierson (1983) predicted that the SD of the difference between the hourly and 8.5-min average speeds would be somewhat higher. More specifically, he hypothesized that for neutral and unstable atmospheric conditions, a sample of cases whose mean speeds were near 15 m s^{-1} and whose minimum speed was 10 m s^{-1} would have a SD in the 0.7 to 1.4 m s^{-1} range. When the sample was restricted to include only cases above 10 m s^{-1}, the mean speed was 13.9 m s^{-1}, the bias was 0.12 m s^{-1}, and the SD was only 0.58 m s^{-1}. The vast majority of the cases had neutral or unstable conditions.

In order to investigate spatial displacement errors, winds measured by two pairs of buoys were compared. One pair consisted of September 1985 data from buoy stations 44009 and 44012. These stations are positioned 39.5 km apart east of the entrance to Delaware Bay. The other pair consisted of March 1984 data from stations 44003 and 44008. These stations were located 109 km apart on the Georges Bank, south of Cape Cod. Though a number of West Coast buoys are spaced 50 to 120 km apart, these data were not compared because wind at many of the buoys is influenced by coastal topography.

Table 5 gives the summary statistics for these comparisons. The SDs are roughly twice the SDs for differences between 8.5-min and hourly average winds. It would appear that errors due to the spatial variability would be larger than the errors introduced by the short averaging period.

Also, the SD increases with greater separation of the buoys. The SD of the differences between 44003 and 44008, located 109 km apart, are roughly 3.5 times the SD between dual sensors located on the same buoy.

TABLE 5. Summary statistics comparing speed and direction differences between buoy pairs. Also summarized are differences between duplicate sensors on each buoy, referred to as "duplicate".

	Speed			Direction		
Comparison	*r*	B	SD	*r*	B	SD
44003–44008	0.804	0.25	1.79	0.648	2.31	23.19
44009–44012	0.902	0.09	1.41	0.685	1.02	20.66
44003 duplicate	0.990	0.23	0.42	0.913	2.43	5.75
44008 duplicate	0.981	−0.11	0.55	0.887	3.40	7.88
44009 duplicate	0.990	−0.15	0.44	0.829	7.30	9.65
44012 duplicate	0.991	0.14	0.45	0.677	1.26	10.00

The same comparison for winds at 44009 and 44012, located only 39.5 km apart, shows differences two to three times the SD between dual sensors. Undoubtedly, the errors due to spatial differences in the wind field vary according to season and location. However, this type of error would be reduced if researchers could limit the maximum distance at which a comparison would be conducted to say, 30 or 40 km. This distance limitation should not restrict the sample size because of the following reasons. First, the number of buoys have increased from 19 in 1978 (during Seasat operations) to 47 at the end of 1985. The geographical coverage of the buoys is considerably greater with stations extending from the equatorial Pacific to Hawaii, the Bering Sea and the Gulf of Maine. Second, all stations now routinely report hourly observations. This was not the case in 1978. Third, about 12 lighthouses or platforms having C-MAN stations are located greater than 20 km offshore. These also should be considered as a source for comparison data since they have excellent exposure to the wind.

8. Quality of other meteorological measurements

Buoy air temperatures, sea surface temperatures and sea level pressures are needed in order to calculate parameters like the Monin-Obukhov stability length and the friction velocity. Therefore, some brief documentation of the quality of these measurements is presented in Table 6. Biases and SDs were calculated for differences in the same measurement at colocated stations. These were interbuoy or buoy-versus-platform comparisons where the distance between the stations is less than 5 km. Biases and SDs were also computed for differences between duplicate sensors on the same buoy. The error budget for $(B^2 \pm SD^2)^{1/2}$ for air and sea surface temperature is ±1°C. The budget for sea level pressure is ±1 hPa (mb). All measurements appear well within their error budget. Note that buoys do not routinely contain duplicate sea surface temperature sensors.

Air temperatures are measured by a Yellow Springs thermistor. The sensor height is 10 m for large discus buoys, 5 m for NOMAD buoys, and 3 m for 3-m discus

TABLE 6. Summary statistics of differences between other meteorological measurements. Temperatures are in degrees C and pressure in hPa.

	Colocated stations				Same station			
Measurement	Total number of months	Number of locations	B	SD	Total number of stations	Number of locations	B	SD
Air temperature	3	1	−0.08	0.28	4	2	−0.03	0.08
Sea surface temperature	3	3	0.13	0.22		No dual sensors		
Sea level pressure	3	2	−0.35	0.18	4	2	−0.04	0.05

buoys. The sea surface temperature is measured by a similar thermistor sealed in epoxy in a copper slug, clamped to the inside of the hull. The unit is then covered by insulating plastic. Measuring the water temperatures through the hull does not introduce appreciable error, except for isolated cases when the water is highly stratified in the Great Lakes. The sensor depth is 1 m for both large discus buoys and NOMAD buoys. The sensor depth for 3-m discus buoys is 0.5 m. Both the air and water temperature sensors are sampled only once per hour. The time variability of these measurements is considerably less than sea level pressure, and the sensors have a 90-sec time constant. Sea level pressures are measured by Rosemount transducers inside the hull at the waterline. This sensor is sampled every second for 8.5 minutes and then averaged.

9. Conclusion

Field evaluation of buoy winds document the excellent quality of wind speed and direction measurements. Standard deviations of speed differences between two stations separated by less than 5 km are about 0.6 to 0.8 m s^{-1}. Standard deviation of direction differences are about 9 to 11°. Scatterplots show linear relationships, centered around the diagonal, with no obvious biases between the sensors at any range of wind speed. In this regard, field comparisons of winds are better than those obtained during JASIN (Weller, 1983). The wind speed comparisons do show slightly larger differences in high or "choppy" sea states in Lake Superior. No such differences were found in the Chesapeake Light comparison.

Correlations of wind speeds obtained from colocated buoys and platforms are above 0.92. These correlations are comparable to correlations between Seasat scatterometer wind speeds that were separated by less than 100 km (Wylie et al., 1985). These correlations are much better than those obtained by ship observations. The standard deviation of wind direction differences between colocated buoys are also comparable to similar Seasat calculations. Therefore, NDBC wind observations appear to be the highly correlated, calibrated reference needed to obtain good comparison data for altimeter and scatterometer winds.

Differences between 8.5-min and hourly average winds were somewhat less than what was expected. The differences were not much greater than differences obtained between duplicate anemometers on the same platform. On the other hand, spatial variations in the wind field can introduce a large amount of error over a small distance. Differences between pairs of buoys located 39 to 109 km apart are more than twice the differences between colocated buoys. Researchers should therefore limit the comparison distance to considerably under the 100 km used during Seasat. Perhaps an array of several buoys covering the size of a footprint could be established in order to obtain spatially averaged winds.

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