AN ACCURACY STATEMENT FOR METEOROLOGICAL MEASUREMENTS OBTAINED FROM NDBC MOORED BUOYS

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ABSTRACT

Researchers using National Data Buoy Center (NDBC) moored buoy data as "sea truth" to validate winds remotely sensed from spacecraft are particularly interested in the quality of buoy data. Since most buoys have dual meteorological sensors, differences between dual anemometers, barometers, and air temperature sensors are summarized as a means of documenting this quality. Also, field experiments were conducted where small, 3-meter discus buoys were moored adjacent to larger buoys and an offshore platform. Differences between sensors located on the different buoys/platforms are summarized to see if buoy motion adversely affects measurement accuracy. Results indicate that the data quality meets published accuracy statements and that data quality is acceptable from all NDBC buoys.

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 "sea truth" for remotely sensed winds obtained from scatterometers and altimeters. Because of this usage, researchers have a great need to know the accuracy of buoy winds. Chelton and McCabe [1] 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 was substantiated by Weller et al. [2].

An extensive amount of field comparisons was performed during 1984 and 1985 to investigate the accuracy of buoy wind measurements. Differences between winds measured at colocated buoys and platforms were summarized. 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 [1], Brown [3], and Pierson [4] describe this problem in detail. Two comparisons are presented that may help to quantify this problem. First, the 8.5-minute average winds are compared to hourly average winds from the same buoy to investigate the errors 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 kilometers 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 1970's for the same reasons listed by Weller et al. [2]. Vortex-shedding anemometers were used extensively in the late 1970's. However, these anemometers suffered from sporadic failures during precipitation and were phased out during the 1981-1984 period. Bendix Aerovane propeller anemometers were introduced in the early 1970's 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. Distance constants, threshold speeds, and other specifications are listed by Mazzarella [5]. 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 minutes. 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). C-MAN stations are located at lighthouses, piers, and beachfront or offshore towers. The DACT payload is also used for some 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 meter/second) and directions to the nearest 10 degrees. A field comparison of vector and scalar averaged winds is presented in Section 5.

NDBC's policy is to calibrate each sensor before each use in the field. The output of each anemometer in hertz (for GSBP payloads) or volts (for DACT payloads) is obtained at 15 wind speeds ranging from 2 to 60 meters/second. Because the relationship is linear, a single calibration coefficient for the slope, b, is determined.

$$b = \left(\sum_{i=1}^{n} (y_i/x_i)^2/n \right)^{1/2} \qquad (1)$$

where y_i is the sensor output in hertz or volts 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 percent or 0.5 meter/second, 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

Table 1. **Wind Speed Errors for Five Anemometers as Determined by Calibration Before and After Deployment.***

ANEMOMETER SERIAL NO.	BEFORE DEPLOYMENT XBAR	BEFORE DEPLOYMENT SD	AFTER DEPLOYMENT XBAR	AFTER DEPLOYMENT 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

*The mean errors, XBAR, and the standard deviations, SD, are given in meters/second.

deployment in the field using the slopes determined before deployment. These anemometers were chosen because they did not experience any failures during field use. The length of use in the field ranged from 3 months to over a year.

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 ± SD to be within ± 1.0 meter/second. Therefore, calibration errors account for about one fourth of the NDBC error budget.

In order to measure wind direction from buoys, compasses are needed 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. First, the compasses are placed on a shoreside compass range where direction errors are determined every 15 degrees. 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 degrees. The largest single error was 4.9 degrees.

Second, the magnetic field of the buoy also influences the compass readings. This effect is limited to large discus buoys that 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 the difficult procedure of spinning the buoy several times before deployment. It eliminates the large 20- to 40-degree 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 degrees. The largest single error was 6.5 degrees.

The NDBC-stated system accuracy for wind direction calls for XBAR ± SD to be within ± 10 degrees. Again, calibration errors account for about one fourth of the error budget for wind direction.

3. HULL CHARACTERISTICS AND BUOY MOTION

Three types of buoy hulls are used by NDBC: discus buoys, Naval Oceanographic and Meteorological Automatic Device (NOMAD) buoys, and E-Buoys. Large discus buoys owned by NDBC are 10 and 12 meters in diameter with anemometer heights of 10 meters. Large Navigational Buoys (LNBs) are 12-meter discus buoys operated by the Coast Guard primarily for coastal navigation purposes. NDBC operates and maintains the payload and sensors on LNBs. The anemometer heights on LNBs are 13.8 meters. NOMAD buoys are 6-meter, boat-shaped hulls whose anemometer heights are 4.9 and 4.1 meters. Both the large discus buoys and the NOMADs have long been in operational use, and their photographs appear in reference 6.

The newest hull type, the E-Buoy, is shown in Figure 1. This 3-meter discus buoy was developed by Woods Hole Oceanographic Institution and is considerably less expensive than the other two hull types. 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 4 and 5. The anemometer heights are 4.9 and 3.7 meters.

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,

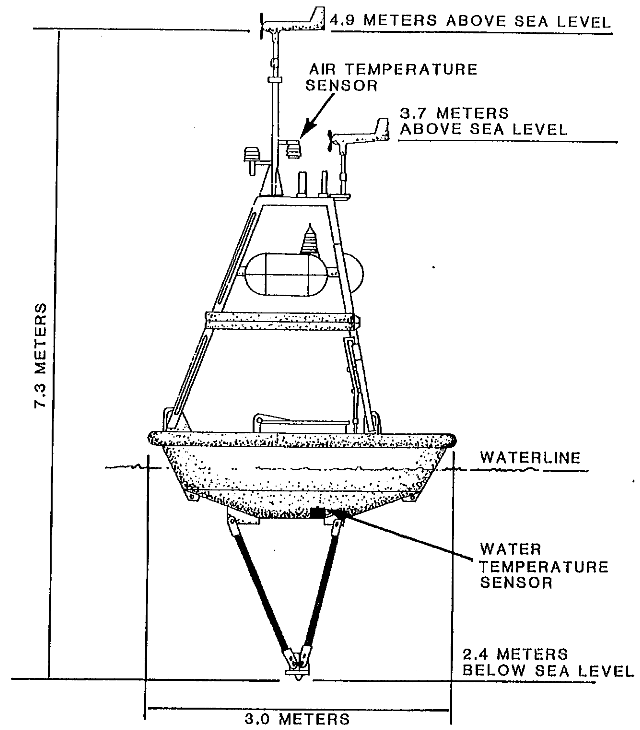

Figure 1. The E-Buoy With Positions of Sensors.

$$S(w) = 8.1 \times 10^{-3} g^2 w^{-5} \exp(-0.74(g/uw)^4) \qquad (2)$$

where g is the gravitational acceleration constant, U is the wind speed, and w is the wave frequency, was then used with the RAOs to determine pitch response spectra, S(r), for each frequency:

$$S(r) = S(w)[RAO(w)]^2 \quad . \qquad (3)$$

Subsequently, the average pitch, P, was calculated by

$$P = 1.25(M_0)^{1/2} \qquad (4)$$

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 meters/second 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 percent of NDBC's archived data. Pond [7] related average pitch to errors in measuring wind speed assuming sinusoidal buoy motion. His conclusion was that pitches on the order of 10 degrees produce a negligible effect on the measurement of wind. Therefore, it appears that buoy motion has a negligible effect on wind speed measurement based on theoretical considerations.

4. BUOY INTERCOMPARISONS

In order to qualify the E-Buoy for operational use, this buoy collected data at three locations where other NDBC data were available.

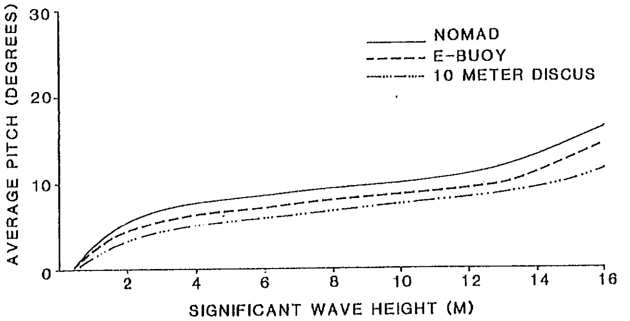

Figure 2. Average Pitch Angle for NDBC Hull Types as a Function of the Significant Wave Height.

One of these locations was in eastern Lake Superior, where an E-Buoy was moored 3.3 kilometers 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), and the standard deviation (SD). October 1984 was chosen because several storm episodes occurred during the month. Wind speeds reached 14.7 meters/second and significant wave heights reached 5.0 meters.

Table 2 presents the summary statistics for both wind speed and direction comparisons. Data from all four anemometers were in excellent agreement. The SDs for both speed and direction are somewhat greater for the interbuoy differences than the intrabuoy differences. However, the interbuoy SDs are still within the stated accuracy standards.

Scatterplots were produced in Figures 3(a) through 3(c) to see if the interbuoy differences are related to wind speed, wave height, or abrupt changes in the wind field. Figure 3(a) shows the E-Buoy wind speeds versus the NOMAD speeds, stratified by wave conditions. Wave heights above 2.5 meters appear as asterisks, while wave heights above 0.8 meter with dominant wave periods below 4.5 seconds appear as diamonds. NDBC was particularly interested in how the data compared in this last category, which signifies "choppy" wave conditions. The E-Buoy was observed to have greater buoy motion than the NOMAD in these conditions.

Neither the "choppy" nor the high wave cases appear to be related to the speed differences between the two buoys. Figure 3(b) shows the same scatterplot stratified according to wind speed and direction tendencies. If the wind speed changed by more than 2.5 meters/second or the direction shifted more than 30 degrees 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 Figure 3(b). 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 Figure 3(c), 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.

Table 2. Summary Statistics for Wind Speed and Direction Differences Between the E-Buoy and the NOMAD Buoy.*

COMPARISON	SPEED			DIRECTION		
	r	B	SD	r	B	SD
E1—E2	0.991	0.476	0.385	0.982	−4.12	5.57
N1—N2	0.993	0.272	0.401	0.903	−5.54	5.03
E1—N1	0.955	−0.162	0.784	0.929	1.41	9.16

*The sample size is 717 cases. The notation used under the "Comparison" heading refers first to the buoy type, E for E-Buoy and N for NOMAD, then to the anemometer number, 1 or 2. Speed differences are in meters/second and direction differences are in degrees.

5. BUOY VERSUS PLATFORM WINDS

During the fall of 1984, an E-Buoy was moored 1.3 kilometers 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 anemometer height on the platform is 33.3 meters and on the buoy was 3.6 meters. The buoy had a GSBP payload while the platform had a DACT payload. The method outlined in Equations (2) through (4) of Liu et al. [8] was used to correct the speeds from both the platform and the buoy to 10 meters before any comparisons were made. October 1984 was chosen for comparison because of the passage of Hurricane Josephine. Wind speeds reached 19.5 meters/second on the platform and the significant wave heights reached 3.6 meters. Two anemometers were located on the platform, and only one on the buoy.

A scatterplot shown in Figure 4 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 3. Overall, the buoy speeds and platform speeds are in good agreement. 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. Figure 5 shows that the difference between the buoy and platform's speeds are approximately normally distributed. Figure 6 shows a time-series plot with platform speeds labeled as station CHLV2 and buoy speeds labeled as station 44010. Both speeds track together remarkably well. Mesoscale peaks and valleys in the wind were measured well by the buoy, despite significant wave heights up to 3.6 meters.

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 speeds were scalar averaged. A field comparison of both averaging methods was performed for the same anemometer at buoy station 41001 in March 1984. This comparison is shown in Figure 7. The two averaging methods yielded equal speeds for speeds less than 8 meters/second. For speeds greater than 8 meters/second, the vector-averaged speeds were about 7 percent lower than the scalar-averaged speeds. This result helps to explain most of the bias between the buoy and platform speeds.

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 E-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 the difference between the two sensors located on the platform, which is 4.94 degrees. Figure 8 shows that the differences between the buoy and the platform are greater in light wind speeds. Again, this result does not support the notion that buoy motion is impacting the measurement of wind. Figure 8 simply confirms that directions are more variable in light wind speeds.

6. 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 minutes. 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 meters/second would take about 100 minutes to travel 50 kilometers. Second, legitimate spatial differences in the wind could exist between the buoy and the satellite footprint, the center of which could be up to 100 kilometers.

Several 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-minute averages. (In reality, these winds are averaged for 58 minutes to allow 2 minutes 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, and therefore the hourly average winds are not routinely available. A statistical comparison between the two averaging times

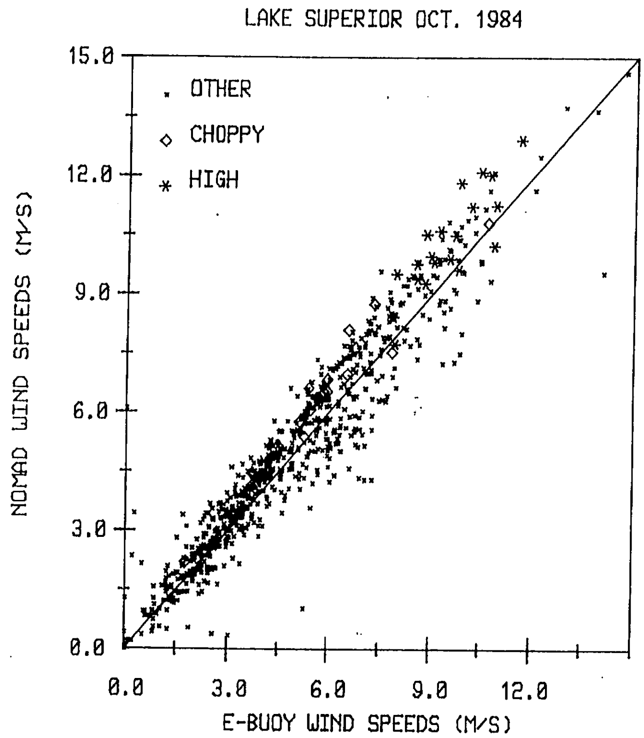

Figure 3(a). Wind Speeds Measured by a NOMAD Buoy Versus Speeds Measured by an Adjacent E-Buoy. Data Are Stratified by Sea State—See the Text for Details.

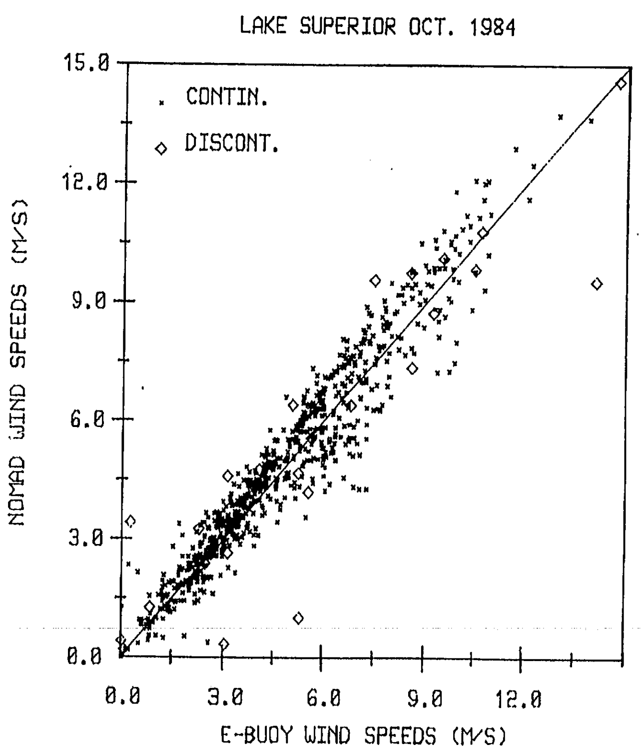

Figure 3(b). Wind Speeds Measured by a NOMAD Buoy Versus Speeds Measured by an Adjacent E-Buoy. Data Are Stratified by Time Continuity of the Wind Field—See Text for Details.

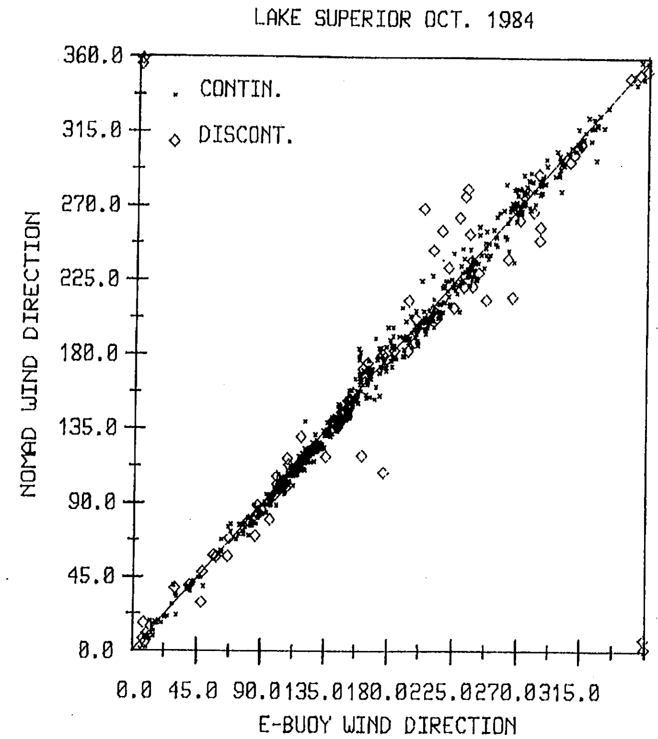

Figure 3(c). Wind Directions Measured by a NOMAD Buoy Versus Directions Measured by an Adjacent E-Buoy.

was conducted and should help document the error attributed to using a short averaging period. Also, winds from several buoys positioned 40 to 110 kilometers 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 meters/second and the maximum 8.5-minute average speed was 23.8 meters/second. The data were culled to eliminate discontinuities in wind speed and direction. If the speed changed by more than 2.5 meters/second or the direction shifted by more than 30 degrees 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-minute averages was calculated for the sample of 627 cases.

The speed bias was 0.06 meter/second, and the SD was 0.60 meter/second. The maximum speed difference was 3.62 meters/second. The direction bias was 1.1 degrees and the SD was 5.3 degrees. The maximum direction difference was 32.3 degrees. 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 [4] predicted that the SD of the difference between the hourly and 8.5-minute 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 meters/second and whose minimum speed was 10 meters/second would have an SD in the 0.7 to 1.4 range. When the sample was restricted to include only cases above 10 meters/second, the mean speed was 13.9 meters/second, the bias was 0.12 meter/second, and the SD was only 0.58 meter/second. 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 kilometers apart east of the entrance to Delaware Bay. The other pair consisted of March 1984 data from stations 44003 and 44012. These stations were located 109 kilometers apart on the Georges Bank south of Cape Cod. Though a number of

Table 3. **Summary Statistics for Wind Speed Differences in Meters/Second Between a Colocated E-Buoy and a Platform.***

COMPARISON	r	B	SD
Platform 2—Platform 1	0.992	−0.112	0.500
E-Buoy—Platform 1	0.971	−0.592	0.814

*Sample size is 712 cases. Platform 1 refers to the first anemometer on the platform; Platform 2 refers to the second.

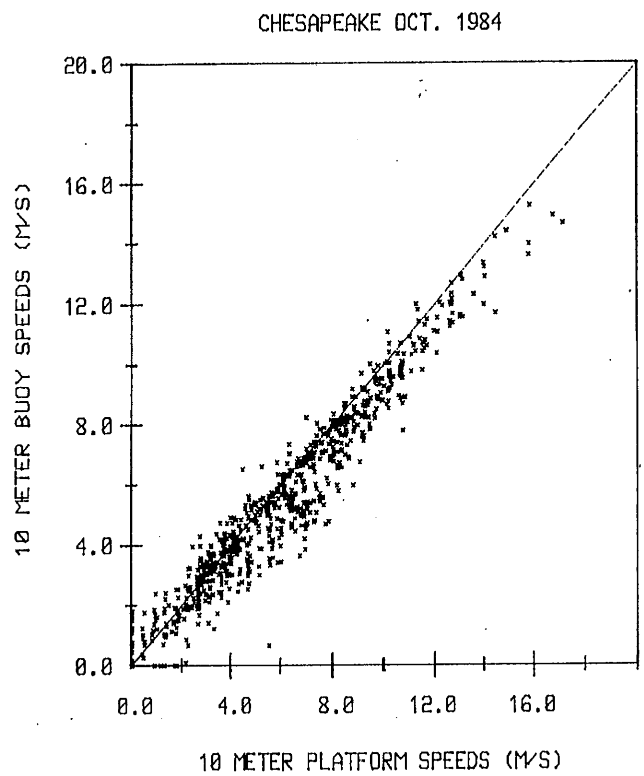

Figure 4. Wind Speeds From an E-Buoy Are Compared to Wind Speeds From an Adjacent Platform. Both Speeds Were Adjusted to a 10-Meter Height Before Plotting.

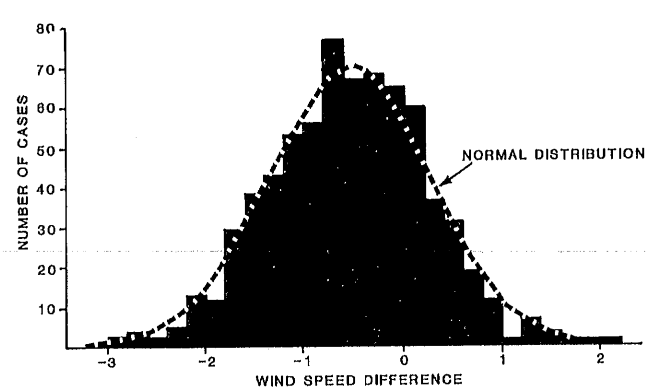

Figure 5. Frequency Distribution of Wind Speed Differences Between the E-Buoy and the Platform.

West Coast buoys are spaced 50 to 120 kilometers apart, these data were not compared because wind at many of the buoys is influenced by coastal topography.

Table 4 gives the summary statistics for these comparisons. The SDs are roughly twice the SDs for differences between 8.5-minute and hourly average winds. It would appear that errors due to the spatial displacement of the satellite footprint and the buoy are 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 kilometers, are roughly 3.5 times the SD between dual sensors located on the same buoy. The same comparison for winds at 44009 and 44012, located only 39.5 kilometers apart, shows differences 2 to 3 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 kilometers. 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 kilometers offshore. These also should be considered as a source for "sea truth" data since they have excellent exposure to the wind.

7. 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 5. Biases and SDs were calculated for differences in the same measurement at colocated stations. These were inter-buoy or buoy-versus-platform comparisons where the distance between the stations is less than 5 kilometers. Biases and SDs were also computed for differences between duplicate sensors on the same buoy. The error budget for B ± SD for air and sea surface temperature is ± 1 degree Celsius. The budget for sea level pressure is ± 1 hPa (millibars). 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 Thermistors. The sensor height is 10 meters for large discus buoys, 5 meters for NOMAD buoys, and 3 meters for E-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 temperature 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 meter for both large discus buoys and NOMAD buoys. The sensor depth for E-Buoys is 0.5 meter. Both the air and water temperature sensors are sampled only once per hour because

Table 4. **Summary Statistics Comparing Speed and Direction Differences Between Buoy Pairs.***

COMPARISON	SPEED			DIRECTION		
	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

*Also summarized are differences between duplicate sensors on each buoy, referred to as "Duplicate."

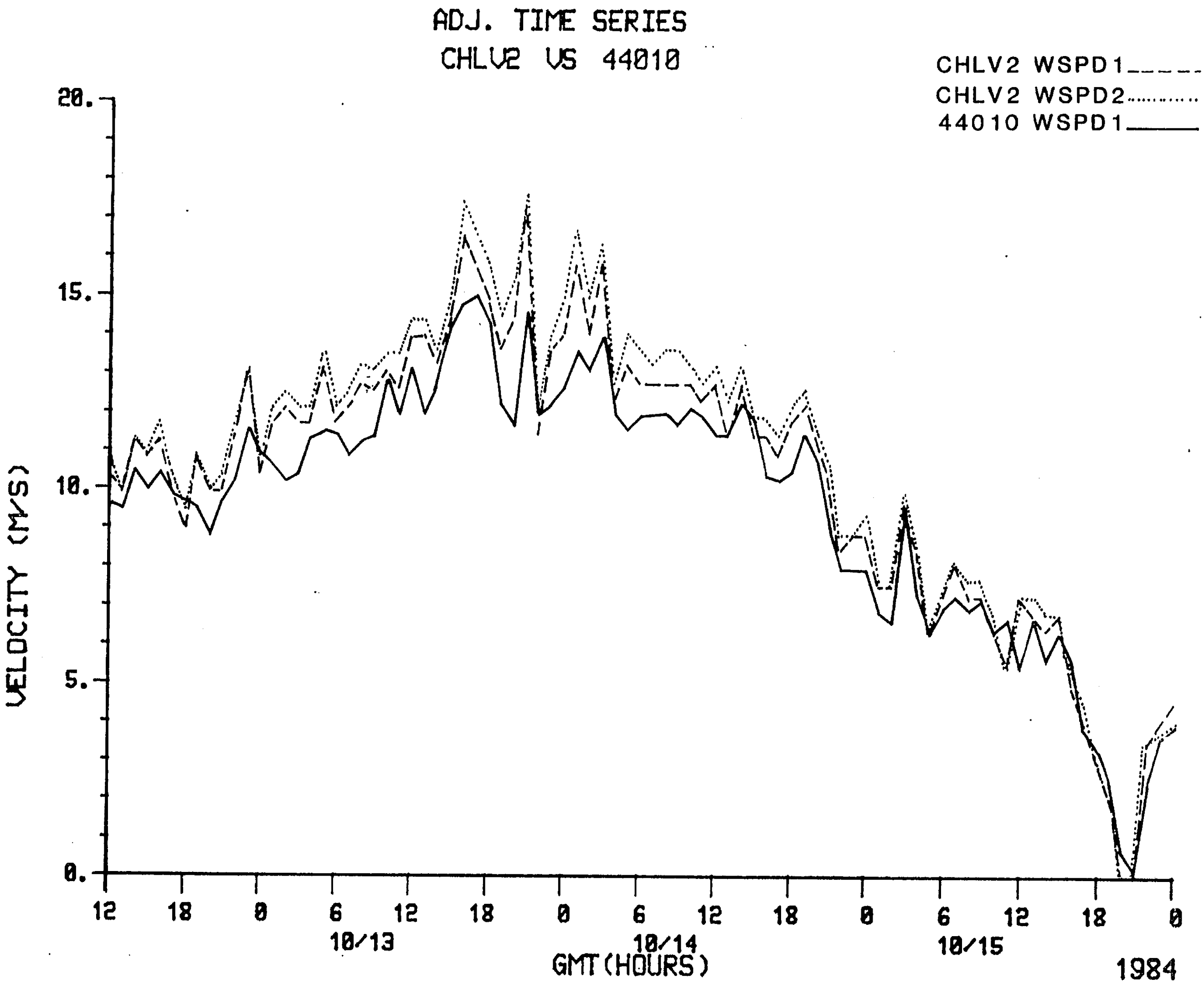

Figure 6. Time Series of Platform (CHLV2) and E-Buoy (44010) Wind Speeds During the Passage of Hurricane Josephine. Both Speeds Were Adjusted to a 10-Meter Height.

of the sensor's long, 90-second, 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.

8. CONCLUSIONS

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 kilometers are about 0.6 to 0.8 meter/second. The standard deviations of direction differences are about 9 to 11 degrees. No obvious biases exist between the sensors at any range of wind speed. The measurements are seemingly unaffected by sea state, and therefore do not appear to be hampered by buoy motion. The quality of these measurements are much better than the winds measured by buoys during JASIN [2].

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 kilometers [9]. These correlations are much better than those obtained by ship observations. The standard deviations 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 "sea truth" for altimeter and scatterometer winds.

Differences between 8.5-minute and hourly average winds were less than what was expected. Hourly average winds probably will not appreciably improve the correlations between remotely sensed winds and buoy winds. 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 kilometers apart are more than twice the differences between colocated buoys. Researchers should therefore limit the comparison distance to considerably under the 100 kilometers used during SEASAT.

ACKNOWLEDGMENTS

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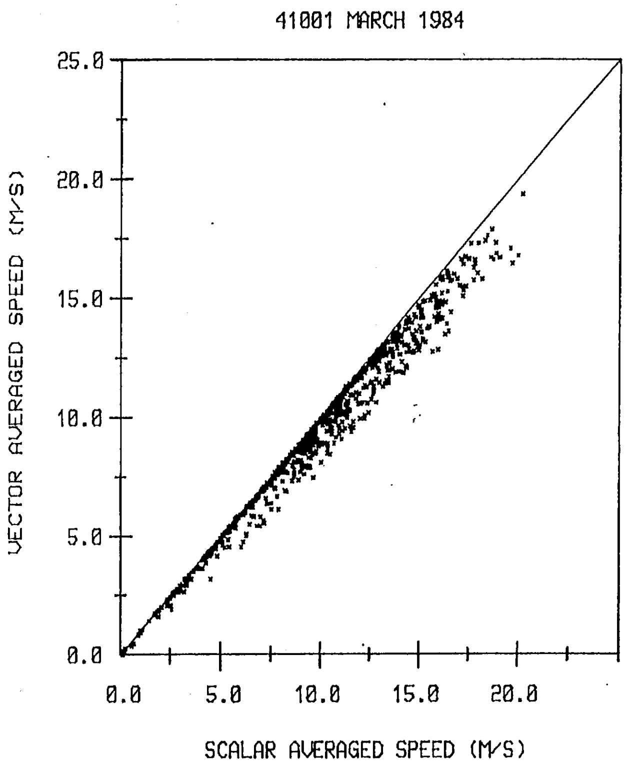

Figure 7. A Comparison of Scalar and Vector Averaging Techniques.

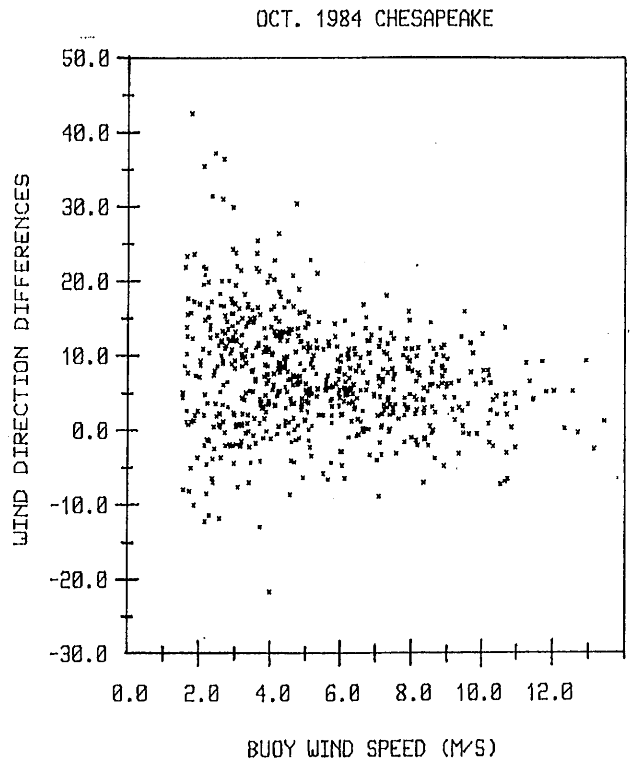

Figure 8. Wind Direction Differences Between an E-Buoy and an Adjacent Platform Plotted as a Function of Buoy Wind Speed.

Table 5. Summary Statistics of Differences Between Other Meteorological Measurements. Temperatures are in Degrees Celsius and Pressures are in hPa.

MEASUREMENT	COLOCATED STATIONS				SAME STATION			
	TOTAL NO. OF MONTHS	NO. OF LOCATIONS	B	SD	TOTAL NO. OF MONTHS	NO. 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

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