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COMPARISON OF BOUNDARY LAYER WINDS FROM NWS LFM OUTPUT AND INSTRUMENTED BUOYS

Robert W. Reeves and Peter J. Pytlowany

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COMPARISON OF BOUNDARY LAYER WINDS FROM NWS LFM OUTPUT AND INSTRUMENTED BUOYS

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ABSTRACT. Measurements of the surface wind by 15 instrumented buoys are compared with boundary layer winds predicted by the National Weather Service's (NWS) Limited-area Fine-mesh Model (LFM). The buoy observations at 0600 GMT and 1800 GMT are selected and compared directly to the 6-hour LFM predictions for the nearest grid point; the predictions are made twice-daily and are valid for those times. Comparisons are presented for two cases: 1) single, 12-hourly wind prediction-observation pairs, and 2) weekly average prediction-observation pairs. Typical vector magnitude LFM-buoy differences are between 3 ms^{-1} (m/sec) and 5 ms^{-1} for individual pairs, and between 1 ms^{-1} and 1.5 ms^{-1} for weekly averages. The mean LFM speeds are greater than the mean buoy speeds, and mean direction differences are less than 15 percent. The root-mean-square direction differences for single comparisons are between 30° and 50°, or roughly an octant of direction. Frequency distributions for speed and direction are shown seasonally for the single observations and predictions. The LFM 12-hourly distributions are skewed toward higher speeds relative to the observations, but the direction distributions show very good agreement, suggesting the usefulness of the LFM data base to construct climatologies.

I. INTRODUCTION

Estimates of the surface wind over the ocean are required for a variety of marine applications where wind-driven currents are important. Some applications are related to water quality involving surface-borne material, e.g. estimating transport and dispersion of oil resulting from tanker mishaps or pollutants from industrial discharges. Other applications are studies of the upwelling of nutrients in coastal areas with persistent along-shore surface winds, the transport of fish larvae in the surface layer, and the decrease in the supply of dissolved oxygen in shallow coastal water resulting from the combined effects of very light wind and water density stratification.

The problem is that measurements of the wind over the ocean are sparse, with routine observations limited to the few permanent weather ships and instrumented buoys and supplemented by occasional observations by vessels of the merchant fleet. Along the ecologically important coastal shelf regions the most reliable wind observations are obtained by buoys deployed by the National Oceanic and Atmospheric Administration's NOAA Data Buoy Center (NDBC). While these provide adequate information for a number of locations, the coverage is limited and leaves vast areas devoid of data.

Because of the sparseness of continuous and reliable observations, the user is forced to resort to alternative methods for estimating the wind over the open ocean. In this report we examine the possibility of using boundary layer wind predictions generated by a numerical model as estimates of the surface winds. Another possibility is to use the continuous record at a land-based coastal meteorological station to extrapolate conditions to the offshore location. However, local circulation patterns related to the topography and land-sea breezes often render the coastal report unrepresentative of the offshore points (Overland and Gemmill, 1977). The output from an atmospheric prediction model has the desirable feature of having estimates which are uniformly gridded over a wide region and continual in time. The model we used is the Limited-area Fine-mesh Model (LFM) of the National Weather Service (NWS) of NOAA (Gerrity, 1977).

The principal objective of this study is to evaluate the LFM boundary layer winds as estimators of the winds at the sea surface. Sea surface buoy observations are average winds measured by anemometers at nominal heights of 5 m or 10 m, and LFM boundary layer predictions represent mean winds over the 50-mb layer of the atmosphere adjacent to the sea surface. If the midpoint of this layer is considered to be roughly at 25 mb below the surface pressure value the LFM predictions are approximately representative of winds at heights of 200 to 250 m above the sea surface.

The LFM output will be used as it was generated with no attempt made to adjust or correct the winds in order to account for this difference in height. The evaluation will be made from a comparison of the LFM output with wind data from 15 instrumented buoys, the designation of which will serve to identify the intercomparison set discussed (Table 1). The data will be stratified into broad categories in order to examine the differences related to wind speed and direction, season, and geographical region. Results are presented for an individual (12-hourly) comparison, for applications where a single estimate of the wind is a requirement or estimates of the LFM biases are sought. Further comparisons are performed on weekly averages, for applications where a climatological estimate is sufficient or where a weekly estimate is required for a problem (estimating oil or larvae transport over an extended period).

II. BEHAVIOR OF THE WIND IN THE BOUNDARY LAYER

A number of factors can contribute to the differences between predictions of mean wind values for the boundary layer and actual measurements of the wind near the sea surface. First, one can expect to find differences simply because the wind speed and direction are not constant with height in the boundary layer. Thus, a "perfect" prediction of the mean wind at approximately 200 m will differ from the surface wind by an amount that can vary with atmospheric stability and horizontal thermal advection. Second, horizontal gradients of the wind can introduce spatial differences since the buoys and LFM grid points are not collocated.

Third, the natural variability of the wind brings into question how representative a single buoy reading is of the mean flow. Intercomparisons of data from collocated wind sensors can give a reliable expectation of minimum speed and direction differences. Extensive intercomparisons between shipboard wind measurements and those from an instrumented buoy were conducted during the GARP* Atlantic Tropical Experiment (GATE). Godshall, Seguin, and Sabol (1976) reported a standard deviation (σ) of wind speed differences to vary between approximately 0.5 ms^{-1} (m/sec) and 1.0 ms^{-1} for 3-min averages. A number of GATE studies for the same experiment reported wind speed difference values as high as 1.2 ms^{-1} with wind direction difference values from 10° to 30°.

Additional factors contributing to the differences are errors in either the LFM prediction or the buoy measurement or both. For purposes of this study, the buoy data will normally be considered "ground truth", even though real errors may exist in the buoy data and contribute significantly to the difference.

III. DESCRIPTION OF DATA SOURCES AND PROCESSING

The set of LFM forecast values is derived on a uniform grid over a polar stereographic projection with a grid interval of 190.5 km true at 60°N latitude. The fine mesh grid is limited to North America and the coastal waters of the Atlantic and Pacific Oceans and the Gulf of Mexico. Since 1977, the Techniques Development Laboratory (TDL) of NWS has routinely archived a set of LFM variables for a portion of the grid. The LFM boundary layer winds used in this study were 6-hour predictions valid for 0600 GMT and 1800 GMT for the period September 1977 to December 1981. A set of 15 instrumented buoys, each with a long time series of wind data, was selected for comparison with the LFM boundary layer estimates (Table 1).

Table 2 lists the buoy numbers and locations, and the corresponding LFM grid point coordinates; the Row (R) and Column (C) values denote cells within the LFM-I grid used by NWS for the final analyses and display products, an array comprised of 45 rows and 53 columns with (R1, C1) at the lower left corner. The buoys, maintained and deployed by NDBC, are depicted on a map of North America in figure 1. The data, which are automatically recorded at hourly intervals (3-hourly for 1975-1979), are periodically placed in the archives at the National Climatic Data Center (NCDC). The wind sensors are anemometers mounted at heights of either 5 m or 10 m above the sea surface and each is either a propeller or vortex shedding type. Data are usually sensed at 1-sec intervals, although some of the instruments have the capability for sensing at one-eighth of a second intervals. In this study, a single wind observation represents an average for an 8.5-min period beginning 20 minutes before the hour. The 8.5-min average for an individual buoy is compared directly with the LFM boundary layer prediction for the same hour and for the grid point nearest the buoy. Weekly averages are formed from 14 twice-daily values. If fewer than ten comparisons are available, the weekly value is considered missing.

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* Global Atmospheric Research Program.

IV. METHOD OF ANALYSIS

The analysis consists of direct comparisons of the individual and weekly average winds for the buoys and the nearest LFM grid points. For the analysis of the weekly average data, the zonal (u) and meridional (v) components are computed from direction and speed, and computations are performed on the scalar differences. The following quantities were computed for the comparison of individual data points:

i) mean difference of LFM-buoy wind direction
ii) root-mean-square wind direction difference
iii) mean difference of LFM-buoy wind speed
iv) root-mean-square wind speed difference
v) magnitude of mean vector difference
vi) root-mean-square vector difference

The following quantities were computed for the weekly data:

i) mean magnitude and standard deviation of the weekly vector wind
ii) mean difference and standard deviation of the magnitudes of weekly mean vectors (LFM minus buoy)
iii) average magnitude and standard deviation of the weekly wind vector difference of LFM and buoy
iv) ratio of magnitude of mean vector difference to the magnitude of the mean vector
v) mean weekly LFM wind speed

Frequency distributions of wind speed and direction were computed from the sets of individual observations or predictions. The LFM distribution used data only if there was a corresponding buoy observation for that time, and vice-versa. Eight class intervals were selected for the direction (θ), corresponding to the octants centered at N, NE, E, SE, S, SW, W, NW with the right (clockwise) limit included within each class, e.g. $337.5° < \theta \leq 22.5°$ (Octant 1). The following eight class intervals were selected for speed (S) (ms^{-1}): 0-1 (calm), 1-4, 4-7, 7-10, 10-13, 13-16, 16-19, and ≥ 19, e.g. 4-7 is equivalent to $4 \leq S < 7$. The results for summer (June through August) and winter (December through February) are also discussed. Since the wind speeds at 10 m are almost always greater than the speeds at 5 m, the data sets for those heights were analyzed separately. The buoys which recorded data at both the 5 m and 10 m levels (not concurrently) were G10, G11, and W14.

V. DISCUSSION OF RESULTS

A. Comparison of Weekly Average Data

Averages over periods longer than a few hours or days are desirable for a number of applications. One of the objectives of this study was to determine the suitability of the LFM data set as a source of climatological information. Averages over one week, corresponding roughly to a synoptic period, were computed as potential "building blocks" for construction of a climatological data set. A summary of the LFM-buoy weekly average comparisons is presented in table 3, and the results are grouped according to geographical location. Because of inaccuracies in wind-driven currents derived from LFM weekly averages, modeling surface advection of fish larvae or pollutants, for example, can incur positional errors. In estimating these errors, the important quantities to consider are the mean absolute vector differences (Table 3, Col. e), which vary between 0.9 ms^{-1} and 1.6 ms^{-1} and are roughly 20-to-40-percent of the mean weekly magnitude of the wind vector (Table 3, Col. a).

The magnitudes of the weekly mean vector averages of the LFM data are generally between 3 ms^{-1} and 5 ms^{-1} for buoys off the Atlantic and Gulf of Mexico coasts and around 6 ms^{-1} for the Pacific Coast buoys. By comparison, the mean LFM wind speeds, over all available times from the individual (12-hourly) data range from 6.1 ms^{-1} for buoy G11 comparisons to as high as 9.5 ms^{-1} for buoy E04 comparisons.

The mean average weekly speed differences are given in table 3, col. c. For Atlantic Coast comparisons involving buoys E04, E05, E06, E01, E03, and E08, the mean differences are a few tenths of a meter per second and not significantly different from 0 ms^{-1}. For all other comparisons, the mean differences are positive (LFM speed greater than buoy) and significantly different from 0 ms^{-1} at the 95 percent confidence level based on Student's t-test. For the Atlantic Coast comparisons, buoys E02 and E07 apparently record significantly lower speeds. For most of the Gulf of Mexico and Pacific Coast comparisons, the LFM weekly mean wind speeds are nearly 1 ms^{-1} higher than the buoy wind speeds. The single exception here is the G09 comparison, where the speed difference is only 0.3 ms^{-1}.

The distribution of the weekly vector differences for summer and winter are shown for a selection of comparisons involving buoys representative of four geographical regions. The summer and winter distributions for buoy comparisons E05 (Atlantic Northeast), E03 (Atlantic Southeast), G10 (Gulf of Mexico) and W13 (Pacific Northwest) are shown in figures 2 through 9.

The LFM-buoy differences were examined next for possible wind direction dependence by grouping based on LFM direction according to the four quadrants-northwest, northeast, southeast, and southwest. The data were analyzed two ways: first from computations of mean direction and speed differences and then from mean zonal (u) and meridional (v) component differences. Figure 10 shows the mean vector differences for buoys E02, E04, and E05. The average vector difference of all 122 weekly values for buoy E02 is 1.6 ms^{-1}, but the vector differences for all the quadrants are oriented roughly in the direction of the mean wind and have relatively high magnitudes, an obvious direction dependence. That this is an indication of a speed bias can be seen in figure 11 which shows a speed bias of 2 ms^{-1} to 3 ms^{-1}. There appears to be an excessive southerly component for the southerly winds.

The direction and speed biases for buoys E02, E04, and E05 are shown in figure 11; they are perhaps a little more revealing than the mean vector depiction for this set of buoys and show a definite positive direction difference (LFM directions are rotated clockwise from the buoy directions) for buoys E02 and E04, and for all quadrants except southeast for buoy E05. All three comparisons show a positive relative bias for southeast winds. This may be an indication of the greater veering of the wind with height which could be expected during warm advection with southeast winds. All comparisons also show a relative speed bias with southeasterly flow. Buoy E02 displays a conspicuous speed bias, the average over all weekly observations being 2.6 ms^{-1}.

Atlantic Coast comparisons for buoys E06 and E07, located off the mid-Atlantic coast, are summarized in figures 12 and 13. The comparisons for both buoys reveal an obvious speed bias with a maximum also for southeast winds, 2.2 ms^{-1} for E07 and 1.3 ms^{-1} for E06. The wind sensors were mounted at 5 m for E06 and E07. The results of the comparisons for the Atlantic Southeast shown in figures 14 and 15 present a very different picture. The speed biases for buoys E01, E03, and E08 are negligible in the mean with no obvious direction dependence. The directional biases appear to be negative for winds with an easterly component; i.e., there appears to be a tendency for a slight northerly bias of the LFM winds when they are from the east. This can be seen rather conclusively in the plots of the mean wind vector differences, especially for the E01 and E03 comparisons.

The Gulf Coast comparisons are plotted in figures 16 and 17. For the weekly data, there are too few averages to make a meaningful comparison for the northwest or southwest winds. There appears to be a slight negative directional bias for G09 and G10, with no bias for G11. All Gulf Coast comparisons show a slight (<1 ms^{-1}) speed bias (LFM > buoy).

For the Pacific Northwest comparisons (Figures 18 and 19) there is a negative directional bias for all quadrants and all buoy comparisons, with the exception of W14, from the southeast. The speed biases are close to zero except for southeast and southwest winds when they vary from 0 ms^{-1} for W15 for southwest winds to as great as 2.5 ms^{-1} for W13 for southeast winds. This effect is also shown very dramatically in the mean wind vector difference plots.

B. Frequency Distributions of the Individual (12-hourly) Data

In order to determine the suitability of the LFM data as a substitute for observed data for climatological purposes, a set of frequency distributions of speed and direction was constructed using the individual observations. Eight class intervals were selected for the direction, corresponding to the octants, and eight class intervals were selected for speed (Section IV). The data were also categorized by season; the months of March through May for spring, June through August for summer, September through November for autumn, and December through February for winter.

The speed and direction distributions for the 15 buoys and their corresponding LFM grid points for summer and winter appear in tables 4 through 7.

The LFM speed distributions are skewed toward higher values, particularly in the winter. This result is not surprising since the mean speed differences (LFM minus buoy) varied from 0.0 ms^{-1} to 2.7 ms^{-1}. This difference is especially noticeable for buoys E07, E08, and G12; these are the buoys nearest the coastline. Wind speed histograms and wind roses for summer and winter for a representative sampling of the buoy-LFM pairs are shown in figures 20 through 29.

Atlantic Northeast

The buoy and LFM data are in basic agreement, both showing maximum winter frequencies from the west and northwest and maximum summer frequencies from the south to west, as shown in the wind roses of figures 20 and 21 for winter and summer, respectively, for the LFM-buoy E05 comparison.

The only exception to this basic agreement of LFM and buoy data is in winter for buoy E07, where the maximum frequency is from the northwest at about 40 percent for the buoy, while the LFM is roughly 25 percent (Table 7).

Buoy E02 is a special case worth a little more attention. The mean speed difference (LFM-buoy) of 2.7 ms^{-1} is much larger than for any of the other comparisons. By comparing the speed distributions of E02 with the two nearby buoys, E04 and E05, we can conclude that the buoy E02 anemometer must be measuring speeds low (Tables 4 and 5).

Atlantic Southeast

The winds off the southeast coast exhibit a seasonal behavior similar to the winds off the northeast coast, with a maximum winter frequency from the northwest and maximum summer frequency from the south to southwest. The distributions for comparisons involving buoy E08 for winter and summer are shown in figures 22 and 23. The LFM tends to overestimate the frequency of easterlies and underestimate the frequency of westerlies in the winter. The frequency distribution for summer for buoy E08, which is roughly 40 miles off the South Carolina coast, displays a complicated behavior, with a double mode at southwest and northeast to east (Table 6). The LFM data, however, reveal a similar behavior.

Gulf of Mexico

The surface flow over the Gulf of Mexico is predominantly from the east. During winter there is a broad maximum in the frequency distribution for winds with an easterly component which can be seen in figure 24 for the buoy G10 comparison. The buoy and LFM data show similar behavior. In the summer comparison, there is a sharp mode from the east to southeast, as shown in figure 25.

Buoy G12 displays somewhat different characteristics from the other Gulf buoys. The winter distribution of winds for buoys and LFM are similar, with predominant flow from the north to east, as depicted in figure 26. However, the summer distribution is very different, with the buoy reporting a high frequency of winds from the south to west, the total for the three octants exceeding 50 percent, with the LFM predicting approximately half that. The summer distribution for the comparison involving buoy G12 is shown in figure 27. Buoy G12 is located within 25 miles of the Gulf coast, and the statistics may reflect coastal influences in the summer.

Pacific Northwest

Off the northwest Pacific coast the wintertime weather patterns produce southerly to westerly flow much of the time. This is reflected in the frequency distribution for both buoys and the LFM, with the mode at south and the minimum between northeast and east. This is shown for the W13 comparison in figure 28.

During the summer, with the eastern Pacific anticyclone firmly established off the U.S. coast, the flow is predominantly from the north at W13, which we note on figure 29, and from the west to northwest at W15, which is located further north off the Canadian coast. There is a distinct minimum in frequency from the southeast to northeast.

C. Comparison of Individual (12-hourly) Data

In this section, we compare single buoy measurements and LFM forecasts in order to evaluate the mean quality of the basic individual forecast of each set without data stratification. The sample sizes for this study were considerably greater than for Cardone's (1978) comparison (<500) with the number of LFM-buoy paired differences exceeding 2000 for five of the buoys. A summary of the entire intercomparison data set for each buoy, giving the mean and root-mean-square (rms) speed and direction differences appears in table 8. The mean directional biases in LFM forecasts (Table 8, Col. b) ranged from -8° for Gulf Coast buoy G10 (5 m data) to 14° for buoy G12 (10 m data), also in the Gulf of Mexico. The rms direction differences give a clue to the typical error in individual measurements, and those values are mostly between 40° and 50°. The mean speed biases in LFM forecasts (Table 8, Col. d) ranged from 0.0 ms^{-1} at Atlantic Coast buoys E01, E03, and E08, to 2.7 ms^{-1} at Atlantic Coast buoy E02. The LFM average speeds were equal to or greater than the buoy speeds for each comparison. The three buoy comparisons with the largest mean directional biases also possessed large speed biases: E02 with 2.7 ms^{-1}, G02 with 1.5 ms^{-1}, and G12 with 1.1 ms^{-1}. LFM forecasts at buoy E07 had a 1.5 ms^{-1} speed bias.

The mean vector difference (absolute) between the LFM and buoy data varied between 3.0 ms^{-1} to 4.9 ms^{-1}, with the Atlantic and Pacific Coast buoys recording slightly larger values than the Gulf Coast buoys. Mean vector errors of this magnitude may be intolerably large for many applications where only a single prediction is available. For example, consider the case where a single surface wind estimate is used to compute the trajectory of a particle on the surface of the ocean. Taking the wind to be in error by 5 ms^{-1} (comparable to the mean vector error at Pacific Coast buoy W15), and assuming the surface current to be 3 percent of the surface wind, we would be in error by 65 km in the computation of the particle's position after 5 days.

VI. SUMMARY

Measurements of the surface wind recorded by instrumented buoys were compared with LFM predictions of the boundary layer wind. The purpose of the comparison was to determine the suitability of using the LFM estimates as surrogates for surface measurements. Data from 15 buoys for the period September 1977 to December 1981 were included in the study. Comparisons were made for single prediction-observation pairs and for weekly averages. One set of comparisons was made using the entire available data without stratification. The LFM average speeds were equal to or greater than the buoy speeds for each comparison, with biases ranging up to 2.7 ms^{-1}. The root-mean-square differences in speeds were generally between 2 ms^{-1} and 3 ms^{-1}. The mean vector (magnitude) differences varied between 3 ms^{-1} and 5 ms^{-1} with root-mean-square vector differences between 2 ms^{-1} and 3 ms^{-1} for most of the buoy comparisons. The mean directional biases were less than 10° except for the comparisons involving buoys E02 (10.0°) and G12 (14.0°). The root-mean-square direction differences ranged between 38° and 52°, roughly one octant of direction.

Frequency distributions of speed and direction for the buoy and LFM were constructed for winter and summer. The LFM and buoy data were in basic agreement with both depicting the seasonal differences very well. The LFM speed distributions were skewed toward higher values than the buoy. The distribution of directions for the buoys in coastal areas (G12, E06, E07, and E08) did not agree as well with the LFM distributions as did the distributions for comparisons involving the buoys located offshore.

The weekly averages for the buoys and the LFM showed much better agreement than the individual comparisons, with the mean vector magnitude differences varying between 0.9 ms^{-1} and 1.6 ms^{-1} and standard deviations between 0.6 ms^{-1} and 1.4 ms^{-1}. The ratios of mean vector difference to mean vector wind ranged between 0.20 and 0.37.

VII. CONCLUSIONS

Comparison of individual forecast-observation pairs yielded typical vector differences of 3 ms^{-1} to 5 ms^{-1} and direction differences of 30° to 50° (roughly an octant of wind direction). For example, the use of a single observation to compute a 5-day ocean surface trajectory could result in an error in the final position of the advected substance or pollutant of 40 km to 65 km.

The weekly average LFM-buoy vector differences were 0.9 ms^{-1} to 1.6 ms^{-1}, only slightly larger than typical wind instrumental biases. Corrections for known speed biases between LFM and buoy could reduce the differences by an additional amount. Thus for many applications which require weekly averages, the LFM boundary layer values may provide adequate estimates where buoy winds are not available. An example where the LFM averages could be used successfully would be in ocean surface transport for periods of 1 week or more.

One of the buoys, E02, had an obvious and significant bias in wind speed. The conclusion that the buoy speeds were too low was based on an examination of the wind statistics for other Northeast coast buoys and LFM grid points.

The frequency distributions for buoys and LFM points well offshore were sufficiently similar so that one can conclude that the LFM data can be used to construct climatologies of the wind over the ocean. The lack of agreement between LFM and buoy data for near-coastal comparisons render the applications questionable.

Since the LFM-buoy comparisons within a geographical area exhibit similar behavior, correction schemes might be devised to bring the LFM data more in agreement with the buoy observations. Development and testing of a correction scheme is the objective of further study.

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Table 1.--Periods of LFM-buoy intercomparison data availability for each paired set.

Buoy	NOAA Number	Periods of Intercomparison Data Availability
E 01	B41001	9/01/1977 - 9/21/1977 4/15/1978 - 1/23/1979 9/27/1979 - 10/03/1979 10/15/1979 - 10/25/1979 11/24/1979 - 5/29/1981 11/27/1981 - 12/31/1981
E 02	B44003	9/01/1977 - 11/10/1977 1/25/1978 - 2/23/1978 4/08/1978 - 12/13/1978 3/22/1979 - 7/05/1979 9/06/1979 - 6/22/1980 7/17/1980 - 12/31/1981
E 03	B41002	9/01/1977 - 7/15/1978 1/20/1979 - 1/14/1980 4/22/1980 - 11/11/1981
E 04	B44004	9/22/1977 - 6/19/1979 8/09/1979 - 10/16/1979 11/28/1979 - 6/21/1980 10/03/1980 - 5/16/1981
E 05	B44005	12/16/1978 - 5/28/1980 12/02/1980 - 1/30/1981 3/19/1981 - 12/31/1981
E 06	B44002	9/01/1977 - 9/16/1977 10/20/1977 - 9/09/1978 11/15/1978 - 12/24/1978 2/07/1979 - 9/30/1980
E 07	B44001	9/01/1977 - 12/19/1977 7/13/1978 - 7/15/1978 7/28/1978 - 2/12/1979 3/28/1979 - 10/26/1979
E 08	B41004	6/27/1978 - 9/23/1978 10/05/1978 - 1/31/1980 5/14/1980 - 2/02/1981 6/25/1981 - 7/04/1981 9/07/1981 - 12/31/1981
G 09	B42002	9/01/1977 - 12/31/1981
G 10 (5 m)	B42001	9/01/1977 - 12/29/1977 4/02/1978 - 9/25/1979
G 10 (10 m)	B42001	12/05/1979 - 2/12/1980 4/04/1980 - 12/31/1981
G 11 (5 m)	B42003	9/01/1977 - 10/30/1979 1/13/1980 - 7/04/1980
G 11 (10 m)	B42003	9/12/1980 - 12/31/1981
G 12	B42005	12/13/1978 - 5/13/1980
W 13	B46002	9/01/1977 - 12/31/1981 (5/1981 Missing)
W 14 (10 m)	B46005	10/11/1977 - 5/31/1980
W 14 (5 m)	B46005	6/01/1980 - 4/30/1981 (5/1981 Missing) 6/01/1981 - 12/31/1981
W 15	B46004	9/01/1977 - 10/24/1977 9/18/1978 - 4/30/1981 (5/1981 Missing) 6/01/1981 - 12/31/1981

Table 2.--Coordinates of paired sets of buoy and LFM grid point locations.

		Buoy				LFM			
Set No.	Coastal Location	Number	NOAA Number	Latitude (°N)	Longitude (°W)	Row	Column	Latitude (°N)	Longitude (°W)
1.	Atlantic	E01	B41001	35.0	72.0	22	45	35.1	71.3
2.	Atlantic	E02	B44003	40.8	68.5	26	44	40.8	68.5
3.	Atlantic	E03	B41002	32.3	75.3	19	44	32.2	75.5
4.	Atlantic	E04	B44004	39.0	70.0	25	44	39.5	69.7
5.	Atlantic	E05	B44005	42.7	68.3	27	43	42.9	69.0
6.	Atlantic	E06	B44002	40.1	73.0	24	42	39.9	74.0
7.	Atlantic	E07	B44001	38.7	73.6	23	43	37.9	73.4
8.	Atlantic	E08	B41004	32.6	78.7	18	42	32.2	79.2
9.	Gulf	G09	B42002	26.0	93.5	11	35	26.2	93.1
10.	Gulf	G10	B42001	26.0	90.0	11	37	25.6	90.3
11.	Gulf	G11	B42003	26.0	86.0	12	40	25.7	85.6
12.	Gulf	G12	B42005	30.0	85.9	15	39	30.0	85.6
13.	Pacific	W13	B46002	42.5	130.0	24	15	42.1	130.6
14.	Pacific	W14	B46005	46.0	131.0	26	16	45.6	130.6
15.	Pacific	W15	B46004	51.0	136.0	30	16	51.2	135.1

Table 3.--Comparison of LFM-buoy weekly average winds. Buoys are grouped by geographical area.

The quantities tabulated are: (a) mean magnitude of the weekly wind vector, (b) standard deviation of (a), (c) mean difference of the magnitudes of the weekly mean vector (LFM minus buoy), (d) standard deviation of (c), (e) average magnitude of weekly wind vector difference of LFM and buoy; (f) standard deviation of (e), (g) ratio of (e) to (a); (h) mean LFM wind speed, (i) total number of weekly comparisons. All units for (a) through (h) are given in m/sec (ms^{-1}).

	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)
Buoy	$\overline{\lvert \vec{V}_L \rvert}$	σ	$\overline{\lvert \vec{V}_L \rvert - \lvert \vec{V}_B \rvert}$	σ	$\overline{\lvert \Delta \vec{V} \rvert}$	σ	$\dfrac{\overline{\lvert \Delta \vec{V} \rvert}}{\overline{\lvert \vec{V}_L \rvert}}$	$\overline{s}$	**No.**
Atlantic Northeast									
E 02	4.3	2.1	1.4	1.3	1.6	1.0	.37	8.5	122
04	5.0	2.6	.1	1.4	1.1	.8	.22	9.5	136
05	4.4	2.4	-.0	1.1	.9	.6	.20	8.3	102
06	3.4	2.0	.2	1.2	1.0	.8	.29	6.9	112
07	3.8	2.3	.7	1.2	1.1	.9	.29	7.4	59
Atlantic Southeast									
E 01	4.1	2.4	-.1	1.3	1.0	.8	.24	8.2	95
03	3.8	1.9	-.1	1.3	1.0	.9	.26	7.3	158
08	3.3	1.6	.2	1.2	.9	.7	.27	6.6	103
Gulf of Mexico									
G 09	4.1	1.7	.3	1.1	.9	.7	.22	6.4	194
10	4.6	1.8	1.1	1.2	1.3	1.0	.28	6.4	162
11	4.1	1.7	.7	1.1	1.1	.7	.27	6.1	183
12	3.6	1.9	.9	1.4	1.3	1.0	.36	7.1	66
Pacific Northwest									
W 13	6.0	2.8	1.0	1.5	1.4	1.2	.23	8.4	198
14	5.8	3.2	.9	1.9	1.6	1.4	.28	8.5	184
15	6.4	3.4	.7	1.9	1.6	1.3	.25	9.3	158

Table 4.--Frequency distribution of wind speed in percent for summer for paired buoys and LFM grid points. Each class interval is left inclusive. Percentages denoted by "*" are values >0 and <0.5.

Pair	No. of Obs.	Wind Speed (ms^{-1}) 0-1	1-4	4-7	7-10	10-13	13-16	16-19	≥ 19
E01	328	3	16	41	28	12	1	0	0
LFM	328	1	24	35	28	10	1	*	0
E02	379	8	46	37	7	1	*	0	0
LFM	379	1	25	30	28	14	3	*	0
E03	607	3	18	44	27	8	*	0	0
LFM	607	2	18	42	30	7	1	0	0
E04	265	2	17	43	28	9	2	*	*
LFM	265	1	24	38	24	11	1	0	0
E05	269	1	23	45	26	4	*	0	0
LFM	269	1	29	33	26	10	1	0	0
E06	480	3	38	42	13	4	*	0	0
LFM	480	2	34	41	20	3	0	0	0
E07	255	9	35	41	13	2	*	0	0
LFM	255	3	31	38	24	5	0	0	0
E08	381	3	26	33	32	5	1	0	0
LFM	381	1	31	42	21	4	1	0	0
G09	615	2	34	43	17	3	1	0	0
LFM	615	2	41	40	13	2	1	0	*
G10	655	4	42	37	13	3	1	0	*
LFM	655	2	33	43	18	3	1	*	*
G11	591	4	42	43	10	1	*	0	0
LFM	591	3	33	47	16	2	0	0	0
G12	180	6	40	35	17	3	0	0	0
LFM	180	2	39	39	12	6	2	0	0
W13	701	1	13	36	40	9	*	0	0
LFM	701	1	15	35	31	16	3	*	0
W14	694	2	16	38	34	9	*	*	0
LFM	694	2	19	35	30	12	1	*	0
W15	518	1	12	40	34	12	1	*	0
LFM	518	1	20	38	29	9	2	*	0

Table 5.--Frequency distribution of wind speed in percent for winter for paired buoys and LFM grid points. Each class interval is left inclusive. Percentages denoted by "*" are values >0 and <0.5.

		Wind Speed (ms^{-1})							
Pair	No. of Obs.	0-1	1-4	4-7	7-10	10-13	13-16	16-19	≥ 19
E01	422	*	8	20	21	26	17	6	2
LFM	422	0	9	20	24	22	13	8	4
E02	301	1	15	28	28	21	6	2	0
LFM	301	1	9	18	26	21	12	7	7
E03	516	1	8	23	26	26	14	2	2
LFM	516	1	9	26	28	22	10	3	1
E04	702	1	6	17	24	24	20	6	3
LFM	702	*	7	17	23	19	18	9	7
E05	465	1	8	16	27	23	15	8	3
LFM	465	*	10	22	20	22	13	8	5
E06	384	0	9	26	33	24	7	2	0
LFM	384	1	10	25	27	24	8	5	1
E07	149	1	15	23	32	23	5	0	0
LFM	149	1	7	18	21	25	14	12	3
E08	410	2	16	29	28	21	5	*	0
LFM	410	1	13	25	31	23	7	1	*
G09	676	1	19	38	29	11	3	*	0
LFM	676	1	16	37	30	12	3	1	*
G10	563	2	19	39	28	10	2	0	0
LFM	563	1	13	36	35	13	3	1	*
G11	676	1	16	40	32	10	1	*	0
LFM	676	1	14	37	34	12	2	*	0
G12	326	1	25	32	29	10	2	0	0
LFM	326	*	8	27	35	19	10	1	1
W13	761	1	13	23	34	18	8	2	1
LFM	761	*	11	20	24	21	13	6	5
W14	659	1	7	19	28	27	14	3	1
LFM	659	*	7	19	25	20	13	9	5
W15	588	1	7	12	23	25	21	6	4
LFM	588	*	8	14	20	20	17	11	9

Table 6.--Frequency distribution of wind direction in percent for summer for paired buoys and LFM grid points. Each class interval is an octant centered on the designated direction and right (clockwise) inclusive.

Pair	No. of Obs.	Wind Direction							
		N	NE	E	SE	S	SW	W	NW
E01	328	10	9	9	6	25	31	6	5
LFM	328	9	11	7	7	11	37	13	5
E02	379	13	7	10	6	19	19	18	8
LFM	379	10	10	6	8	12	21	9	15
E03	607	4	10	12	11	19	30	10	4
LFM	607	3	9	12	10	18	32	13	3
E04	265	9	6	7	6	25	22	14	11
LFM	265	12	7	6	6	15	26	14	14
E05	269	9	6	5	6	25	23	15	12
LFM	269	12	7	5	7	23	18	19	9
E06	480	9	5	8	7	18	22	23	8
LFM	480	14	12	6	7	13	23	13	13
E07	255	15	7	8	5	21	21	16	7
LFM	255	9	10	11	10	15	20	16	9
E08	381	5	13	16	7	13	30	14	2
LFM	381	4	14	9	10	13	23	19	7
G09	615	4	7	26	43	14	3	2	1
LFM	615	6	10	26	32	16	6	3	2
G10	655	6	10	31	29	16	3	2	2
LFM	655	6	13	34	32	9	3	2	1
G11	591	7	12	44	15	12	3	4	3
LFM	591	4	13	36	26	11	4	3	2
G12	180	7	11	15	13	17	15	21	2
LFM	180	11	14	21	21	7	3	13	9
W13	701	47	3	1	1	4	8	15	21
LFM	701	38	3	1	2	4	9	16	27
W14	694	29	3	2	3	9	10	17	28
LFM	694	23	3	2	3	9	15	19	28
W15	518	14	4	3	6	14	14	24	22
LFM	518	6	3	3	9	15	17	21	24

Table 7.--Frequency distribution of wind direction in percent for winter for paired buoys and LFM grid points. Each class interval is an octant centered on the designated direction and right (clockwise) inclusive.

Pair	No. of Obs.	Wind Direction N	NE	E	SE	S	SW	W	NW
E01	422	18	7	5	4	11	12	15	27
LFM	422	17	11	7	6	11	17	12	20
E02	301	13	9	6	6	9	9	22	26
LFM	301	16	9	7	7	10	12	18	22
E03	516	15	8	8	7	13	10	20	21
LFM	516	16	13	11	9	10	11	16	16
E04	702	13	5	7	4	8	9	23	30
LFM	702	14	8	6	5	9	12	18	28
E05	465	17	5	5	6	6	9	25	28
LFM	465	12	6	8	6	8	9	24	28
E06	384	14	10	9	2	7	10	25	23
LFM	384	15	6	7	4	8	15	21	25
E07	149	13	4	5	2	13	7	14	41
LFM	149	13	4	7	8	11	9	24	24
E08	410	21	17	5	5	10	8	22	13
LFM	410	16	15	9	9	9	11	13	17
G09	676	18	15	18	22	17	2	2	6
LFM	676	16	19	20	24	9	4	3	5
G10	563	18	20	21	15	13	3	2	9
LFM	563	16	24	21	20	6	2	3	8
G11	676	22	15	21	13	11	3	4	10
LFM	676	17	24	21	14	9	4	3	9
G12	326	23	15	20	11	8	4	7	12
LFM	326	19	23	17	11	8	8	5	9
W13	761	12	6	6	12	24	14	15	10
LFM	761	7	8	5	11	22	22	13	11
W14	659	11	7	8	14	20	13	14	13
LFM	659	9	7	6	14	23	18	12	11
W15	588	12	5	9	13	19	12	18	13
LFM	588	8	7	8	16	19	17	14	11

Table 8.--Mean LFM-buoy differences for each buoy data set. Column (a) is the number of observations, (b) the mean direction difference, (c) the rms direction difference, (d) the mean speed difference, (e) the rms speed difference, (f) the mean vector (magnitude) difference, and (g) the rms vector (magnitude) difference. Z_{anem} is the anemometer height (m) of the buoy wind measurements.

		(a)	(b)	(c)	(d)	(e)	(f)	(g)
BUOY	Z_{anem}	No.	$\overline{(\Delta\theta)}$	rms $\Delta\theta$	$\overline{(\Delta S)}$	rms ΔS	$\overline{\lvert\Delta\vec{V}\rvert}$	rms $\lvert\Delta\vec{V}\rvert$
E 01	10	1381	-2.1	46.5	-0.0	2.8	4.5	3.0
02	5	1746	+10.0	42.4	+2.7	3.0	4.8	2.5
03	10	2302	-1.3	42.1	-0.0	2.7	4.0	2.4
04	10	2001	+4.5	37.7	+0.5	3.0	4.5	2.7
05	10	1516	-2.6	41.9	+0.2	2.6	4.1	2.4
06	5	1644	+0.4	50.9	+0.7	2.6	4.1	2.3
07	5	878	-4.1	48.7	+1.5	2.9	4.5	2.8
08	5	1530	-0.1	45.4	+0.0	2.7	3.9	2.3
G 09	10	2816	-6.5	39.7	+0.4	2.5	3.4	2.1
10	5	1108	-8.0	45.0	+1.5	2.6	4.0	2.2
10	10	1235	-5.1	41.9	+0.3	2.4	3.5	2.1
11	5	1755	-2.7	41.6	+0.6	2.4	3.4	2.1
11	10	894	+3.3	41.0	+0.4	2.2	3.0	1.7
12	10	967	+14.0	52.4	+1.1	3.0	4.5	2.4
W 13	10	2883	-4.4	38.3	+0.9	3.0	4.1	2.6
14	5	762	-2.8	40.0	+0.9	3.0	4.1	2.8
14	10	1920	-5.2	41.4	+0.4	3.3	4.7	3.1
15	10	2322	-6.9	40.8	+0.2	3.5	4.9	3.3

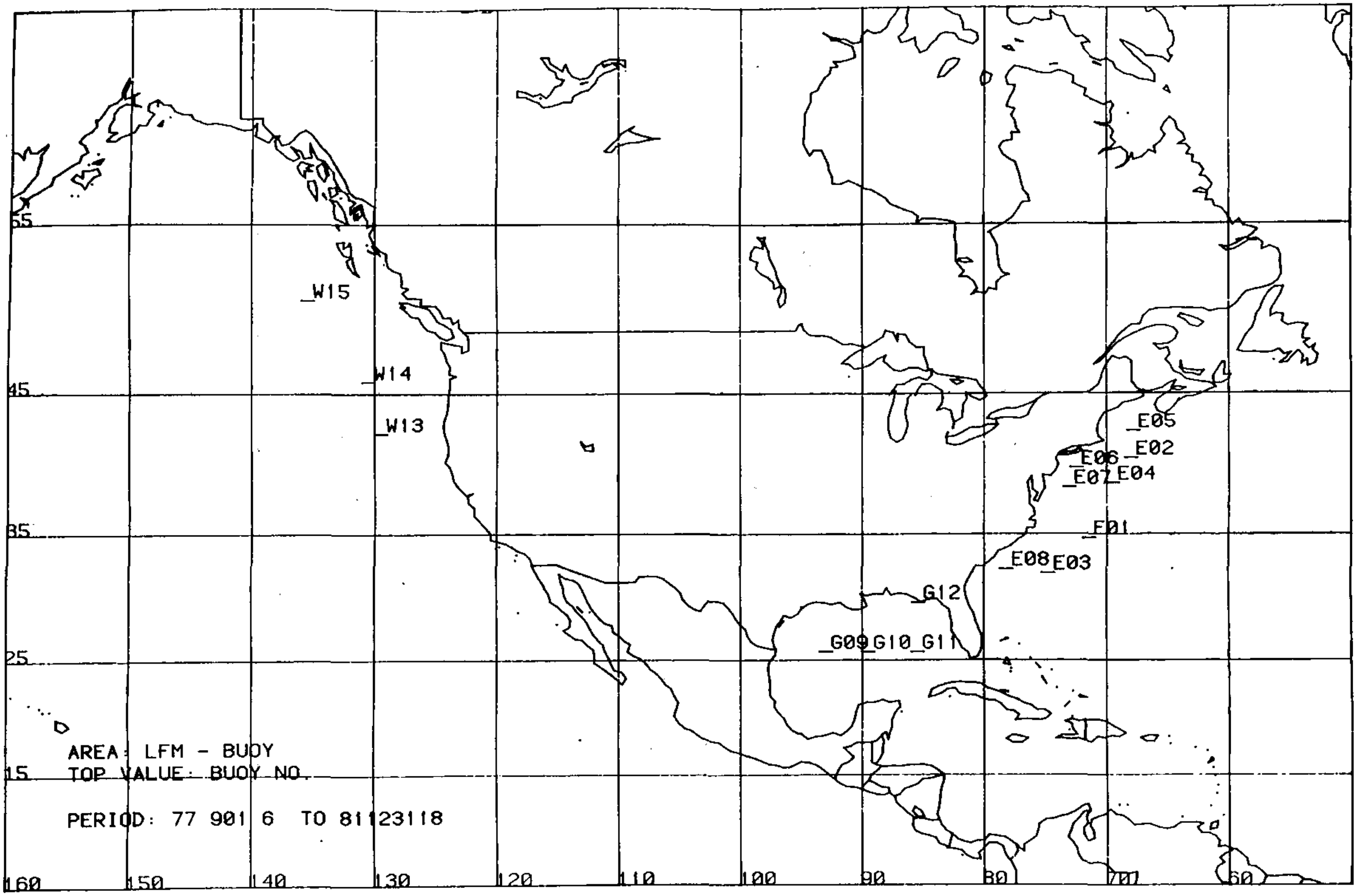


Figure 1.--Locations of NDBC buoys selected for this study.

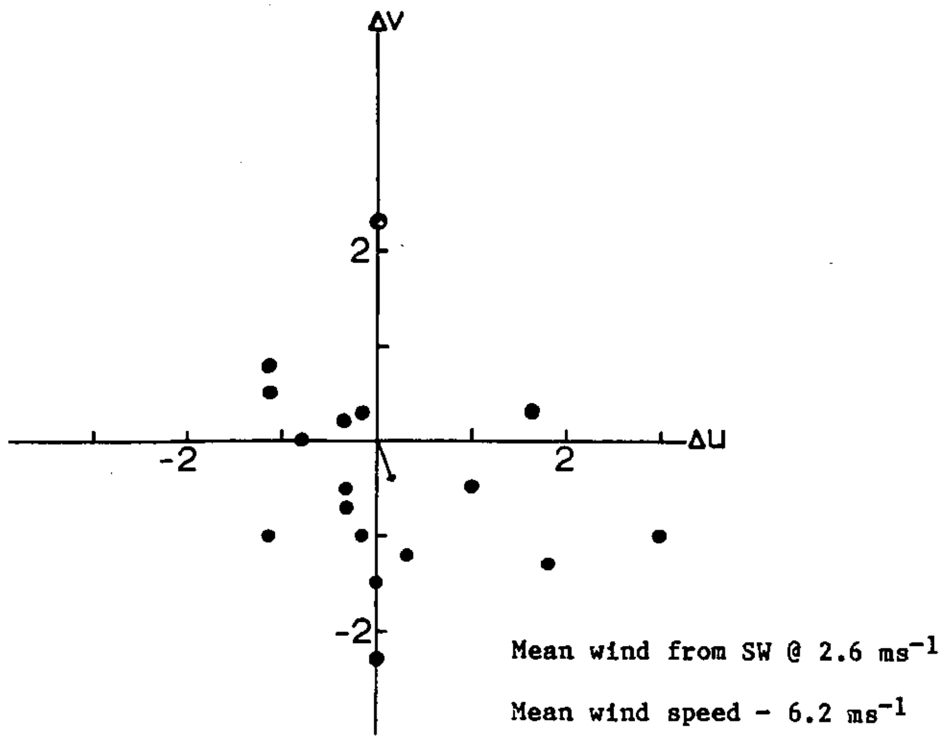


Figure 2.--Distribution of weekly wind vector differences (LFM minus buoy) for buoy E05 for summer. The mean weekly difference vector is indicated by the arrow.

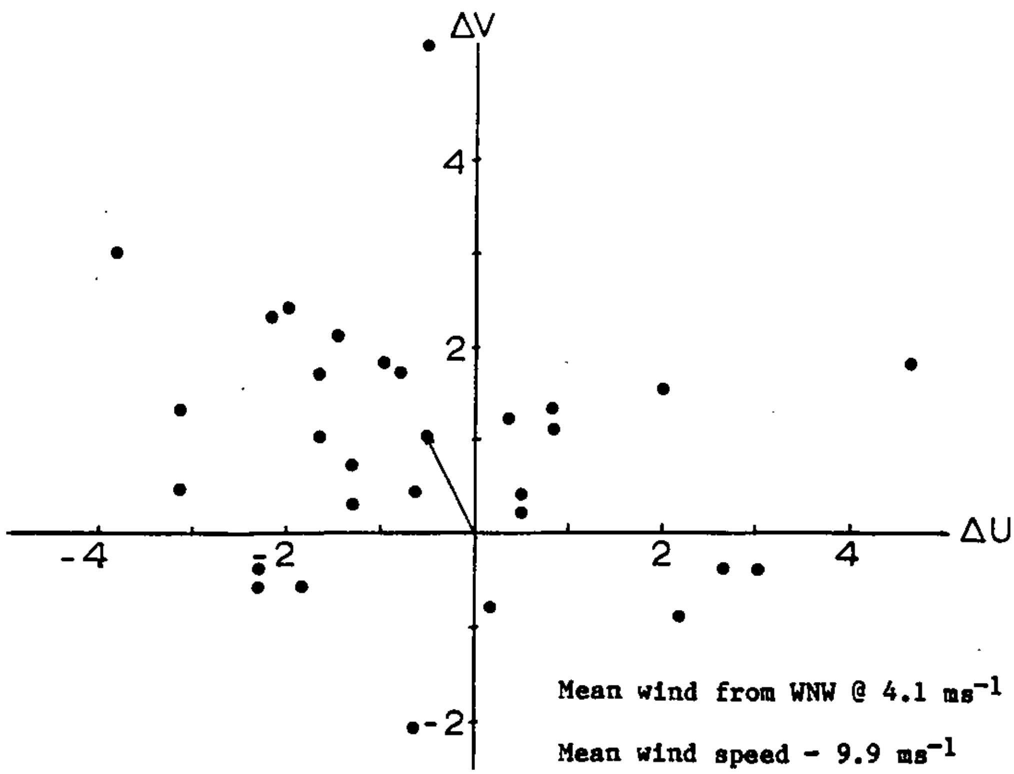


Figure 3.--Distribution of weekly wind vector differences (LFM minus buoy) for buoy E05 for winter. The mean weekly difference vector is indicated by the arrow.

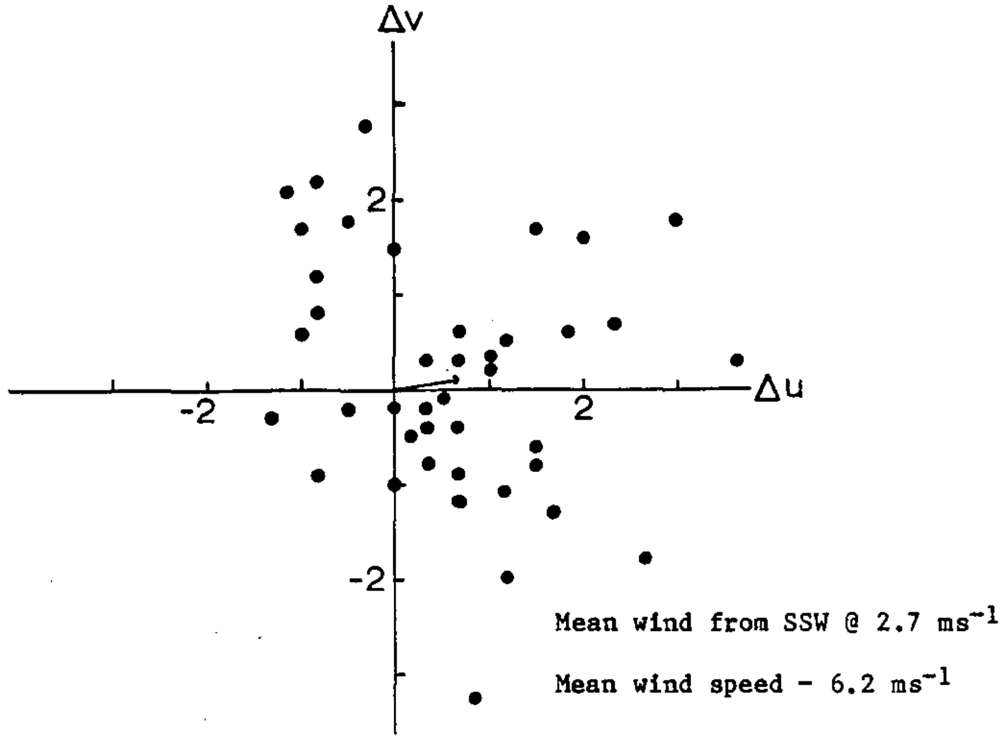


Figure 4.--Distribution of weekly wind vector differences (LFM minus buoy) for buoy E03 for summer. The mean weekly difference vector is indicated by the arrow.

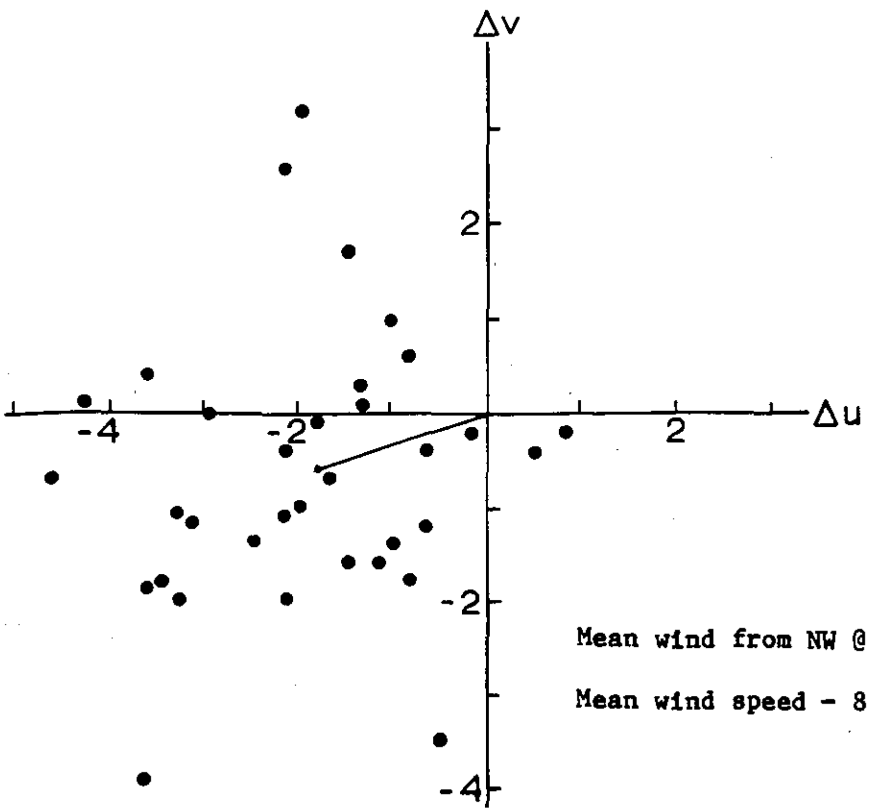


Figure 5.--Distribution of weekly wind vector differences (LFM minus buoy) for buoy E03 for winter. The mean weekly difference vector is indicated by the arrow.

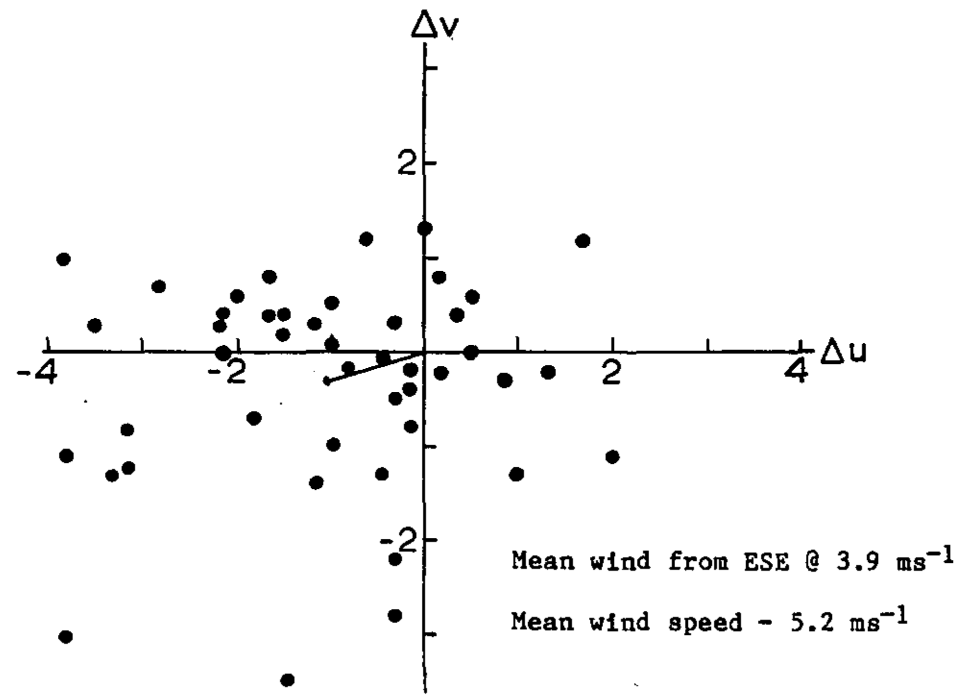


Figure 6.--Distribution of weekly wind vector differences (LFM minus buoy) for buoy G10 for summer. The mean weekly difference vector is indicated by the arrow.

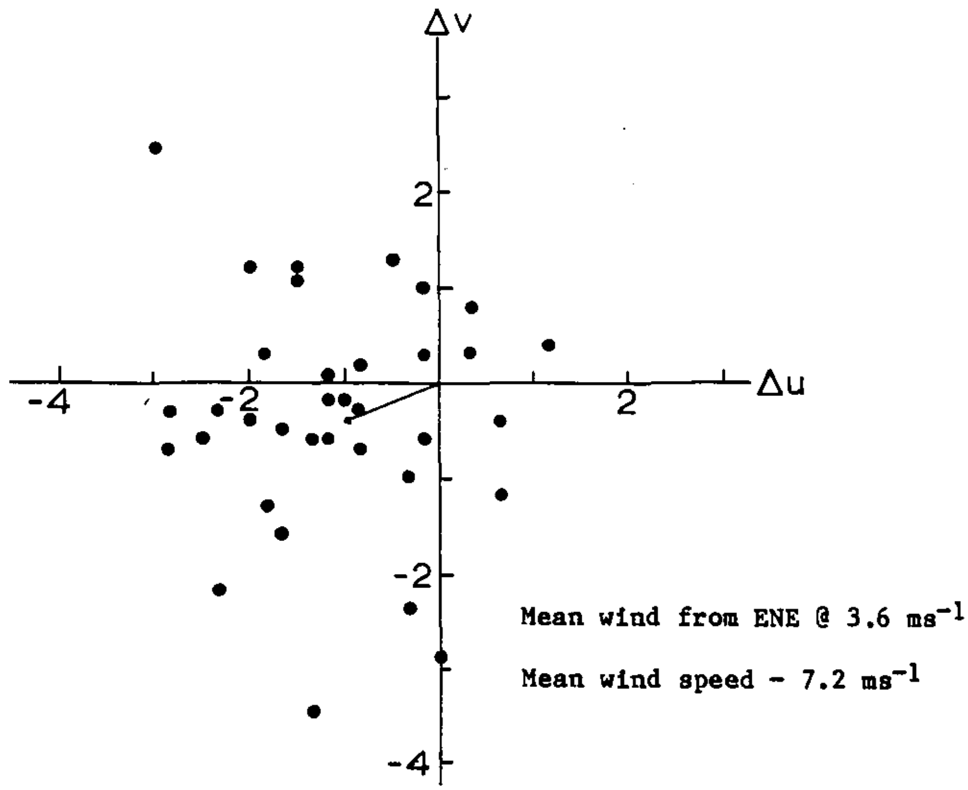


Figure 7.--Distribution of weekly wind vector differences (LFM minus buoy) for buoy G10 for winter. The mean weekly difference vector is indicated by the arrow.

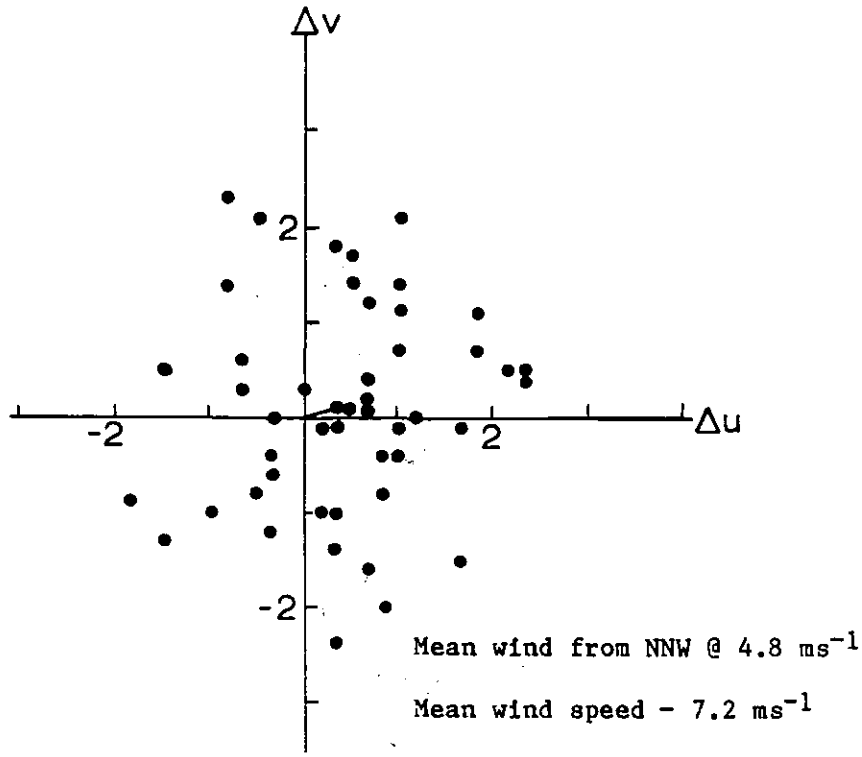


Figure 8.--Distribution of weekly wind vector differences (LFM minus buoy) for buoy W13 for summer. The mean weekly difference vector is indicated by the arrow.

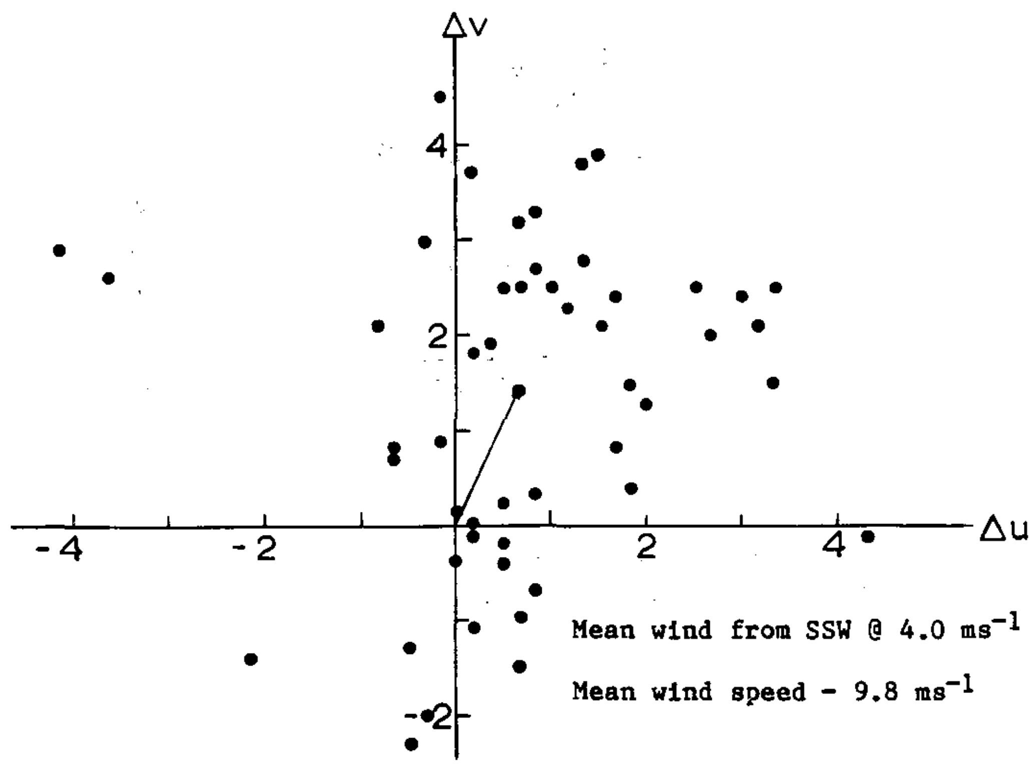


Figure 9.--Distribution of weekly wind vector differences (LFM minus buoy) for buoy W13 for winter. The mean weekly difference vector is indicated by the arrow.

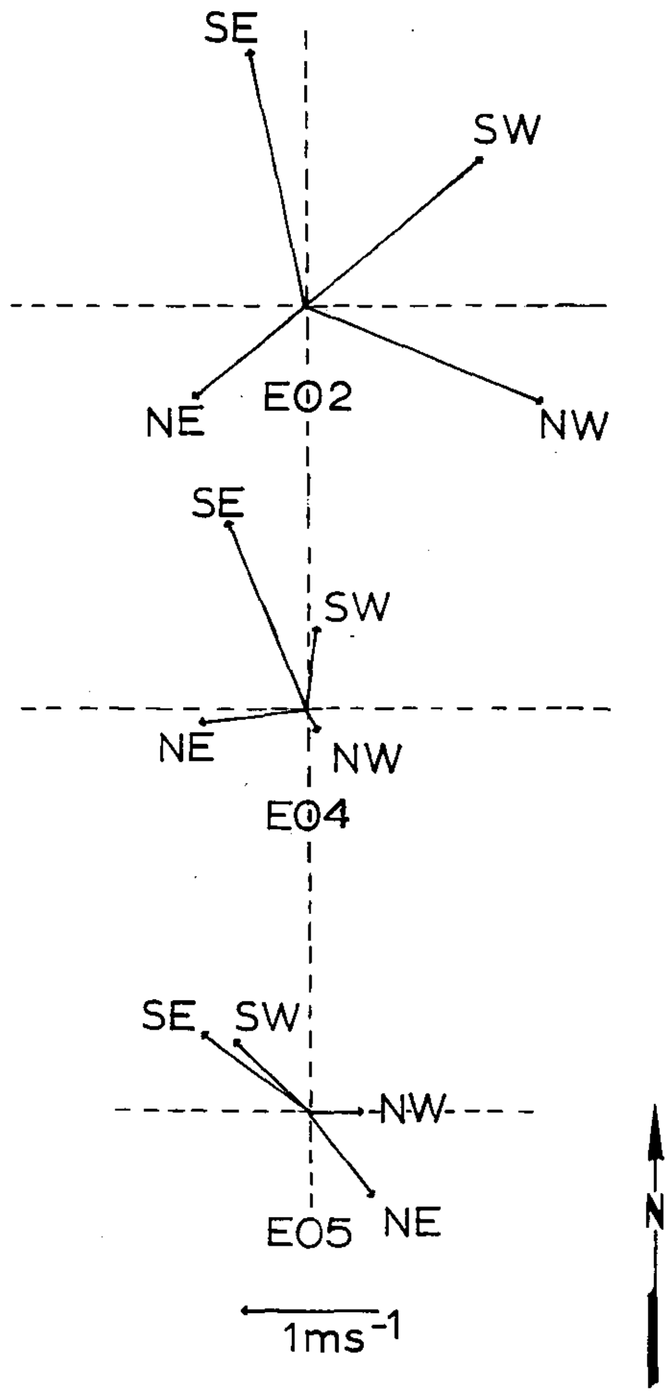


Figure 10.--Mean weekly vector differences (LFM minus buoy) as a function of LFM wind quadrant for buoys E02, E04, and E05.

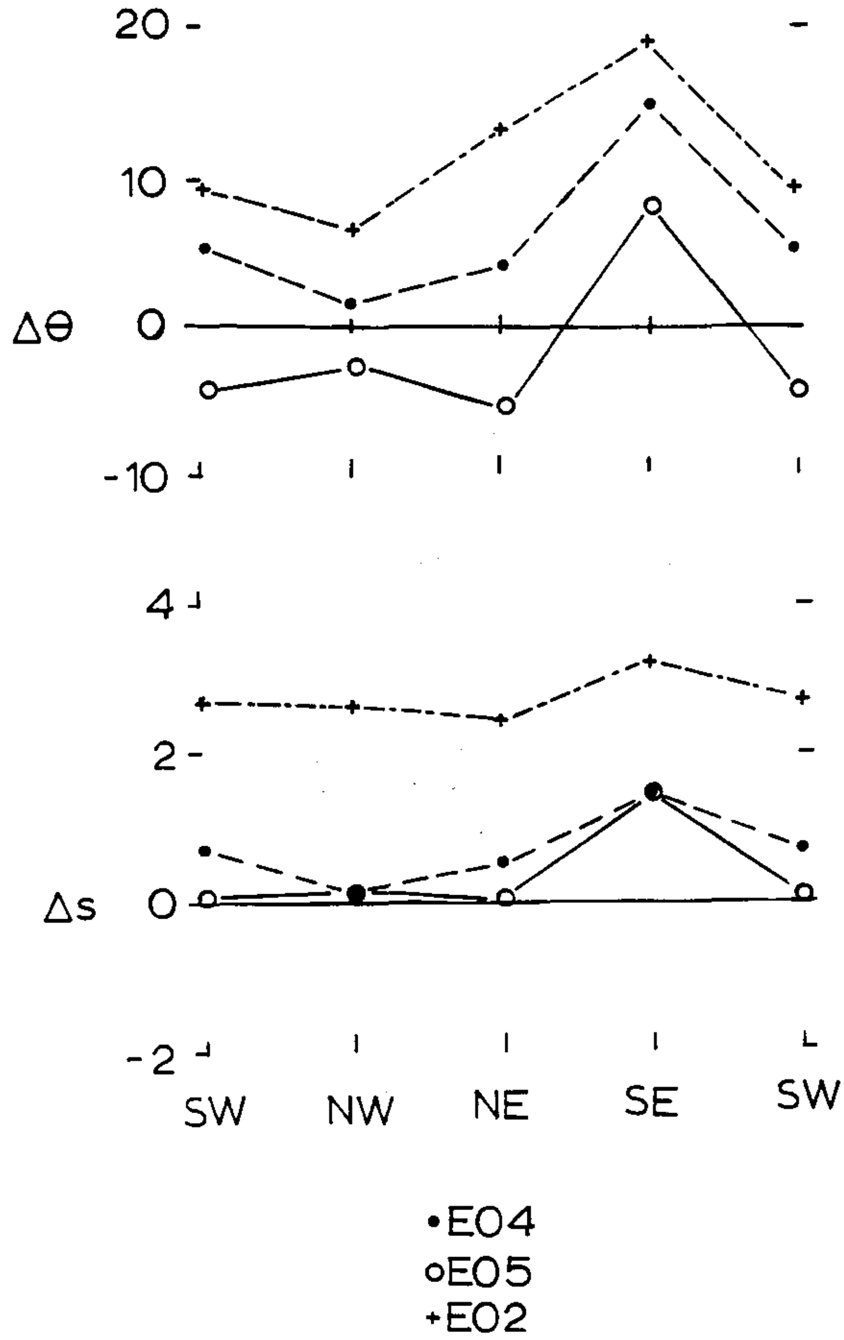


Figure 11.--Mean weekly LFM minus buoy direction differences (top in °) and speed differences (bottom in ms^{-1}) versus LFM wind direction quadrant for buoys E04, E05, and E02.

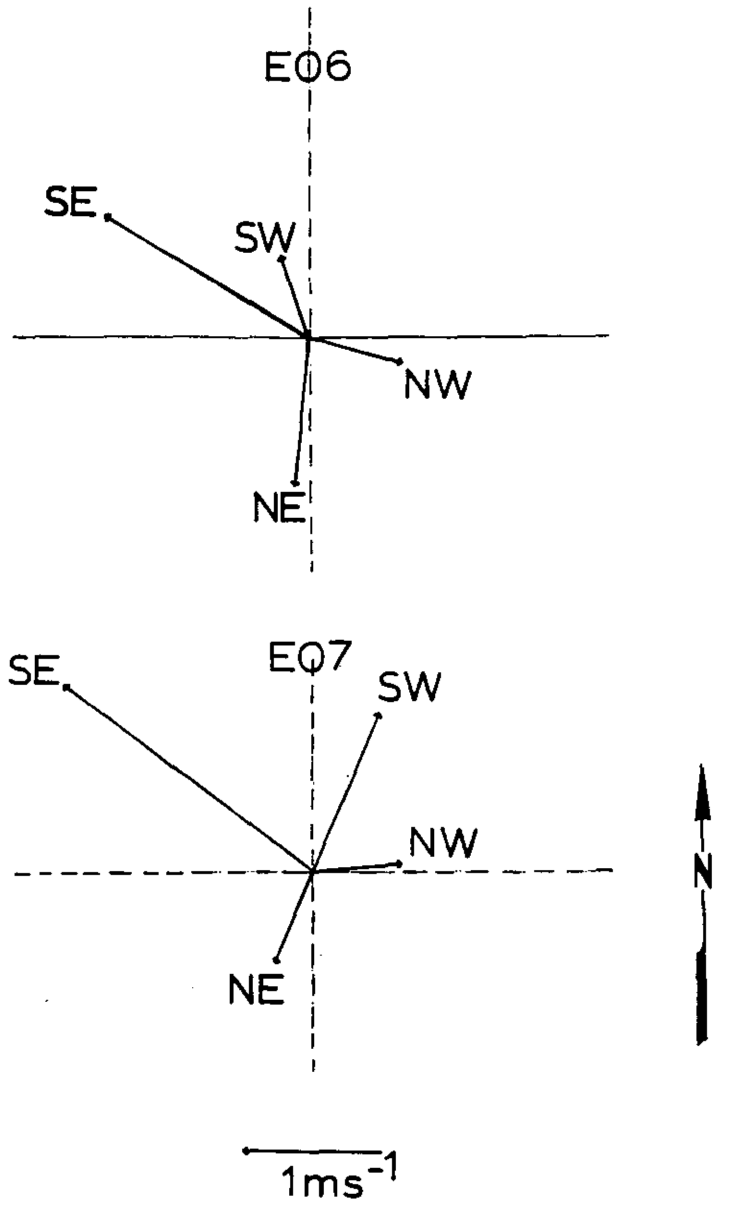


Figure 12.--Mean weekly vector differences (LFM minus buoy) as a function of LFM wind quadrant for buoys E06 and E07.

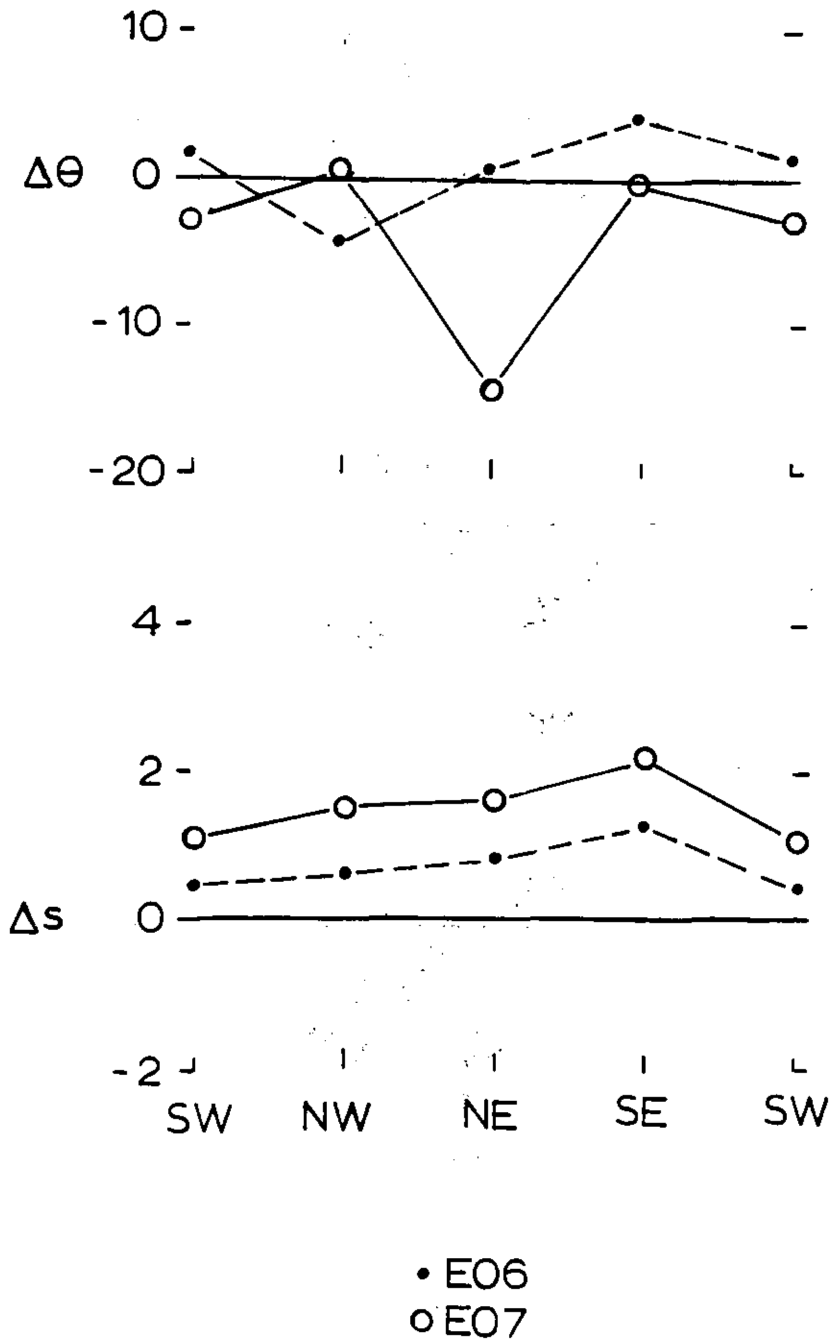


Figure 13.--Mean weekly LFM minus buoy direction differences (top in °) and speed differences (bottom in ms^{-1}) versus LFM wind direction quadrant for buoys E06 and E07.

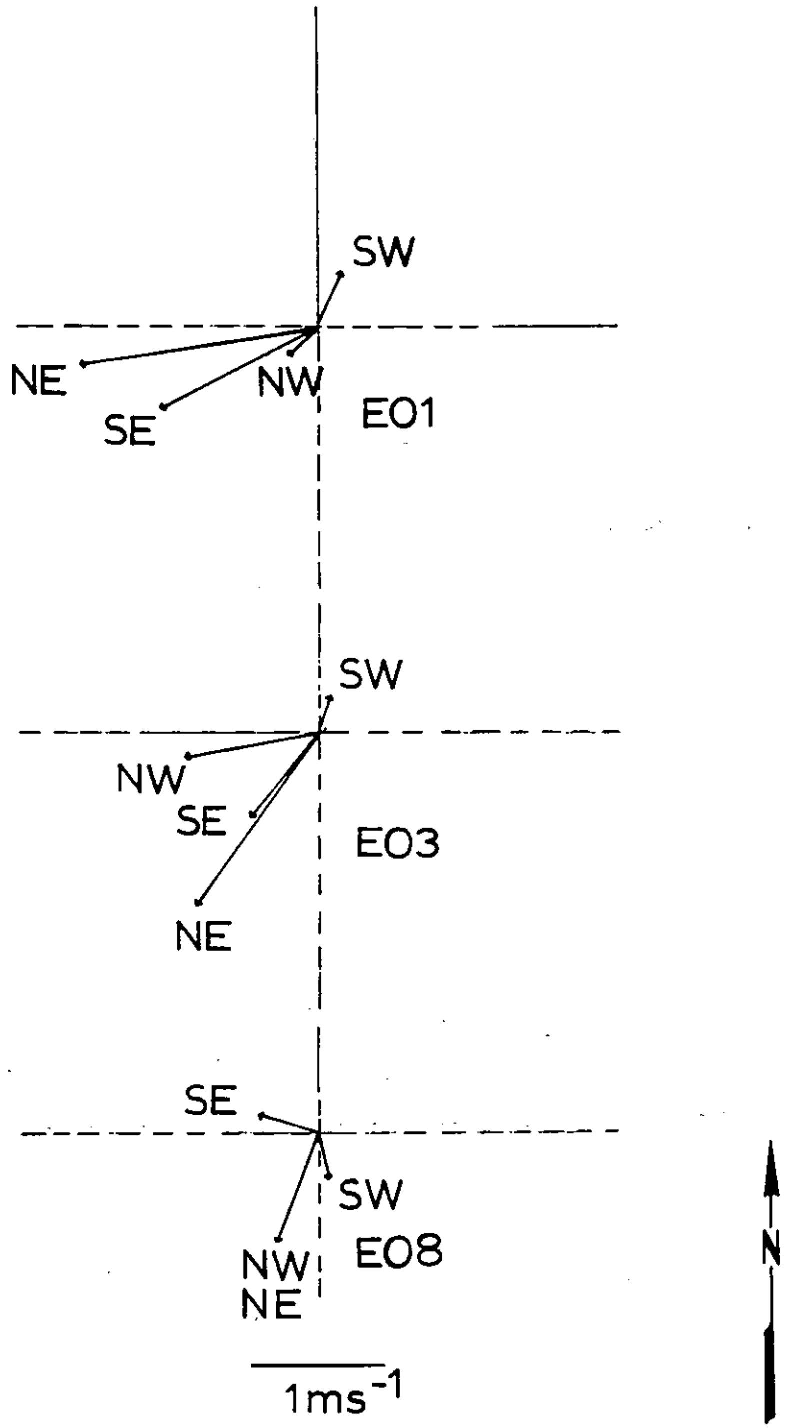


Figure 14.--Mean weekly vector differences (LFM minus buoy) as a function of LFM wind quadrant for buoys E01, E03, and E08.

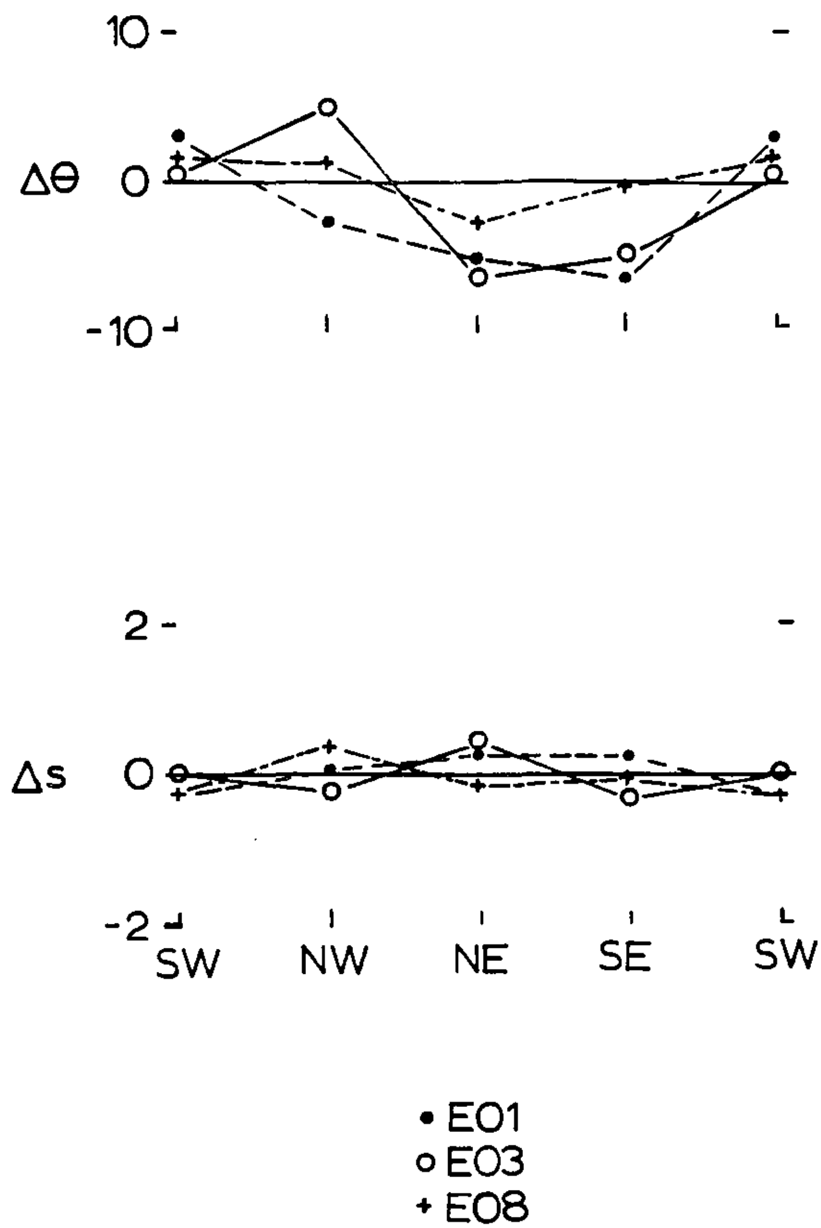


Figure 15.--Mean weekly LFM minus buoy direction differences (top in °) and speed differences (bottom in ms^{-1}) versus LFM wind direction quadrant for buoys E01, E03, and E08.

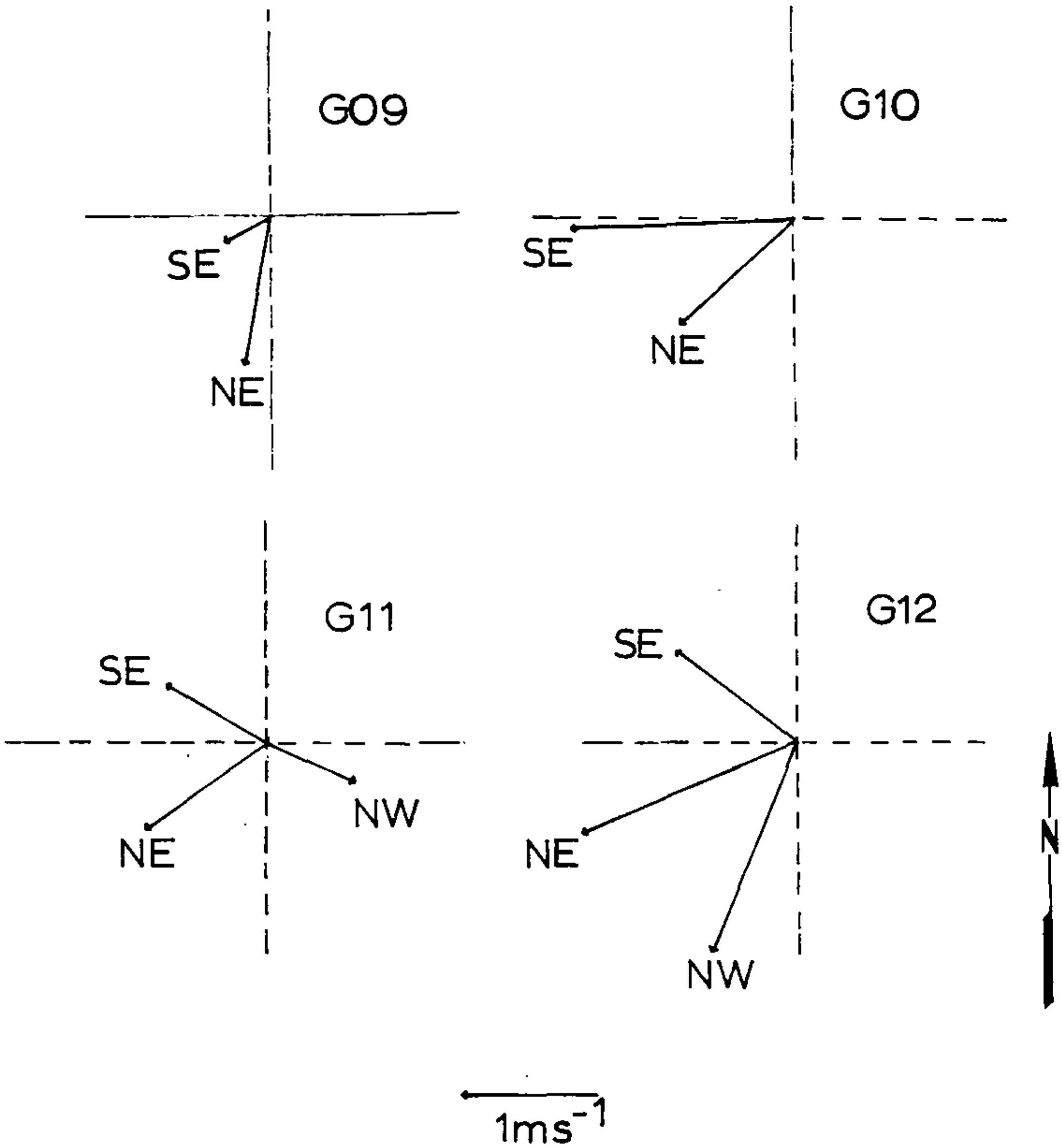


Figure 16.--Mean weekly vector differences (LFM minus buoy) as a function of LFM wind quadrant for buoys G09, G10, G11, and G12.

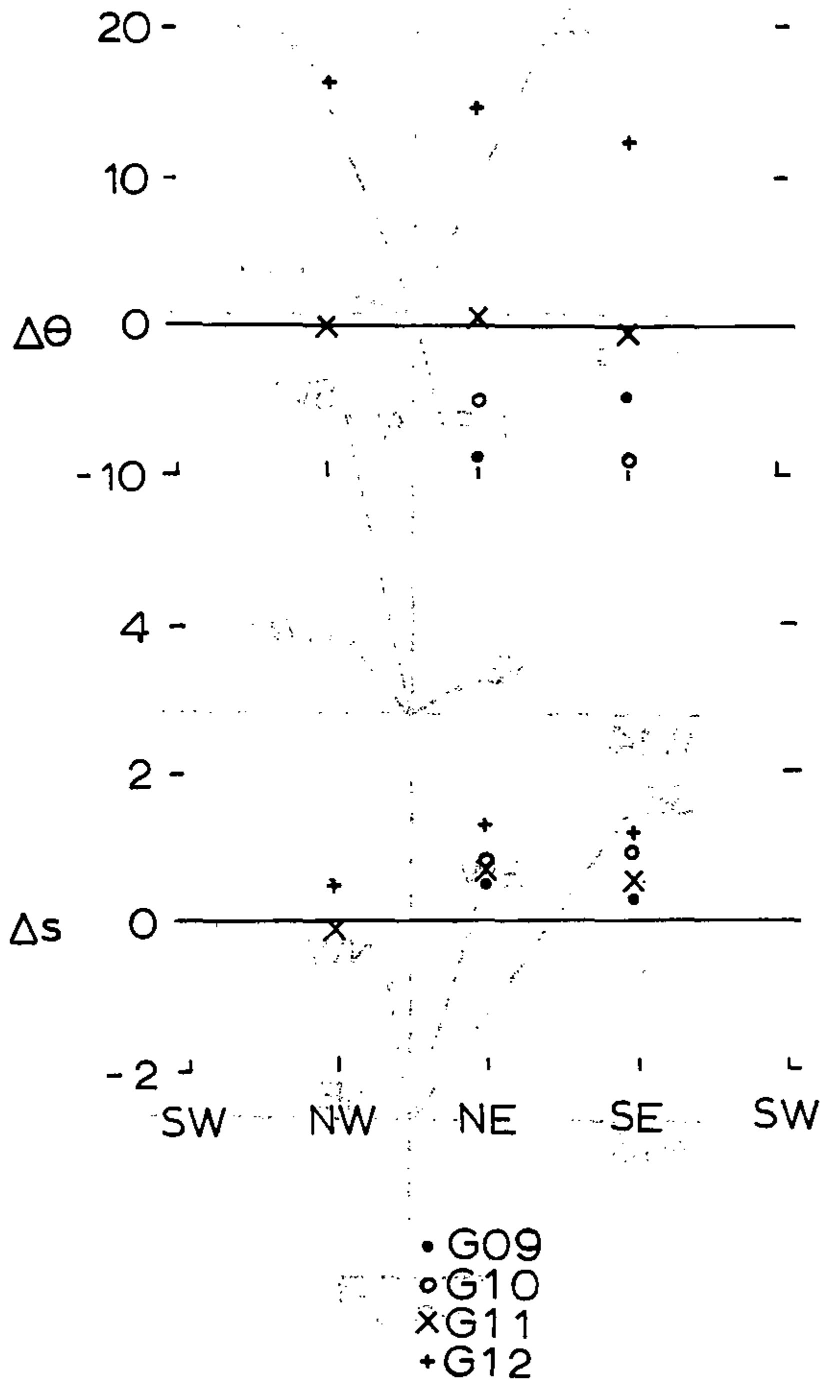


Figure 17.--Mean weekly LFM minus buoy direction differences (top in °) and speed differences (bottom in ms^{-1}) versus LFM wind direction quadrant for buoys G09, G10, G11, and G12.

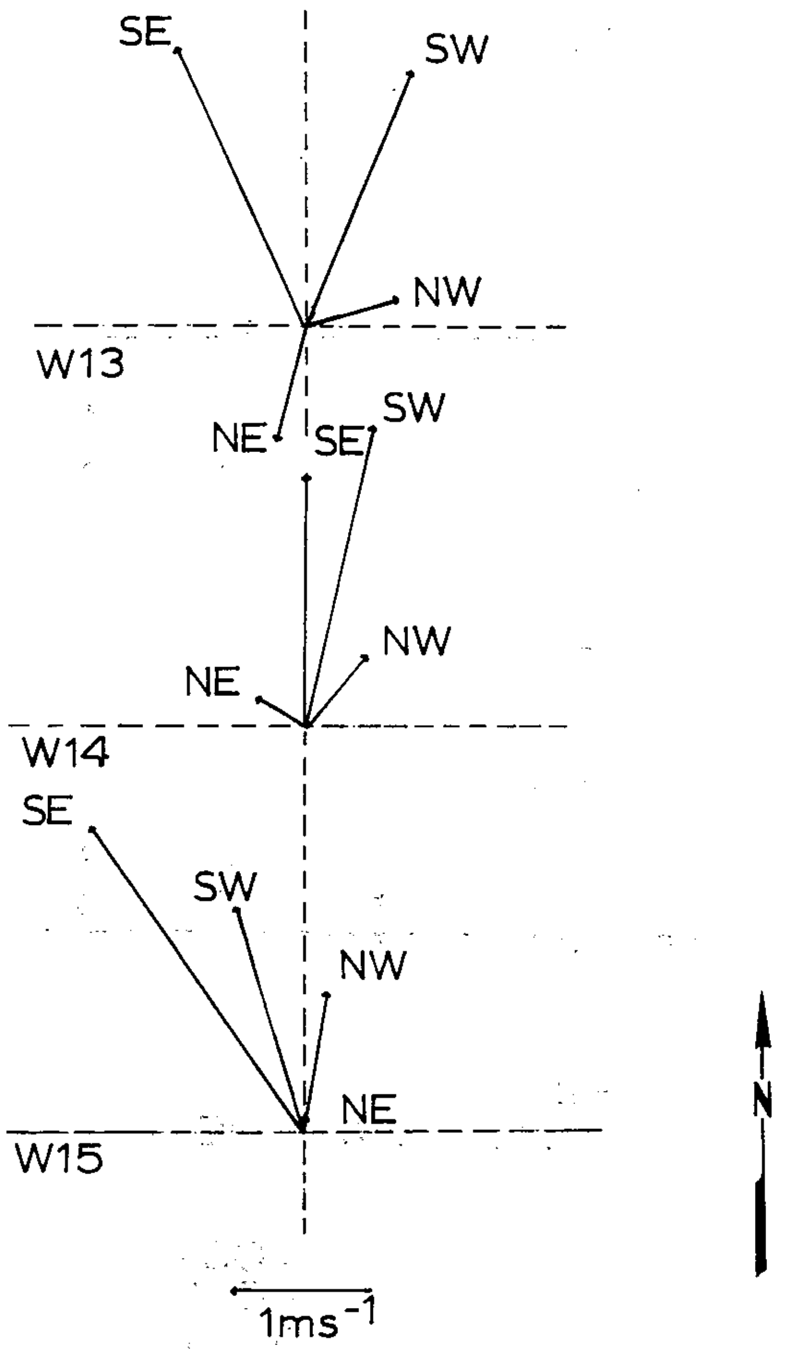


Figure 18.--Mean weekly vector differences (LFM minus buoy) as a function of LFM wind quadrant for buoys W13, W14, and W15.

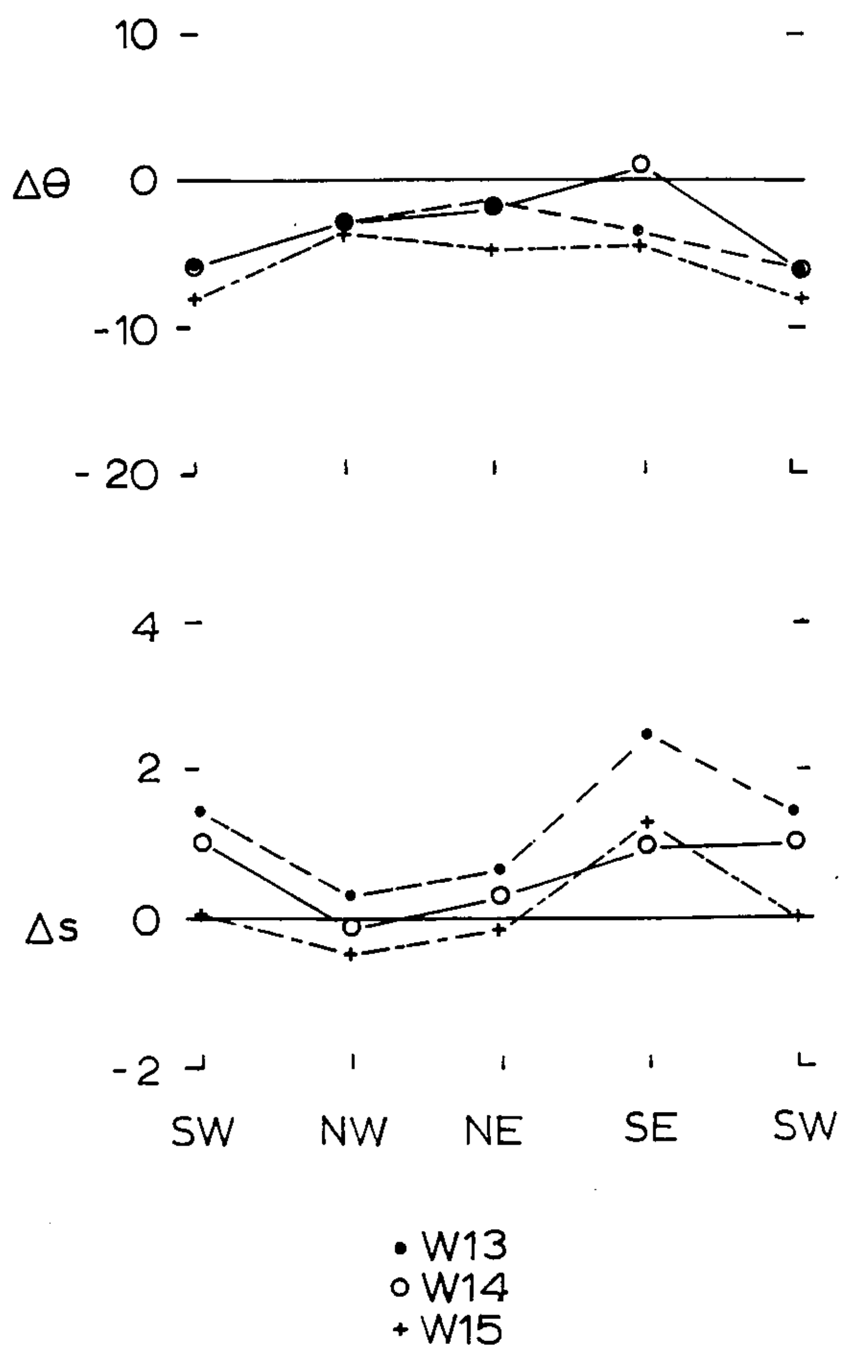


Figure 19.--Mean weekly LFM minus buoy direction differences (top in °) and speed differences (bottom in ms^{-1}) versus LFM wind direction quadrant for buoys W13, W14, and W15.

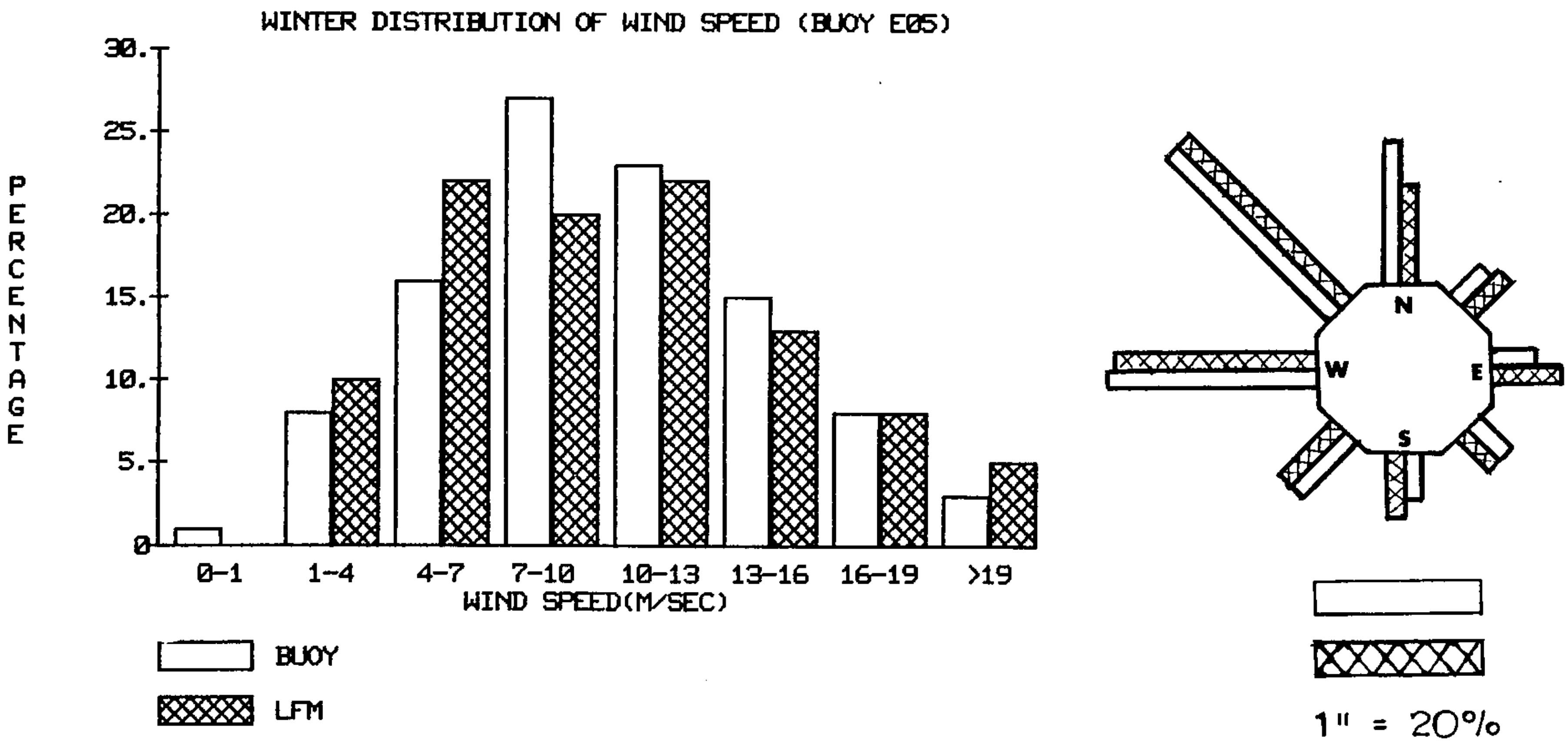


Figure 20.--Frequency distribution in percent of wind speed (left) and wind direction (right) for LFM and buoy E05 for winter.

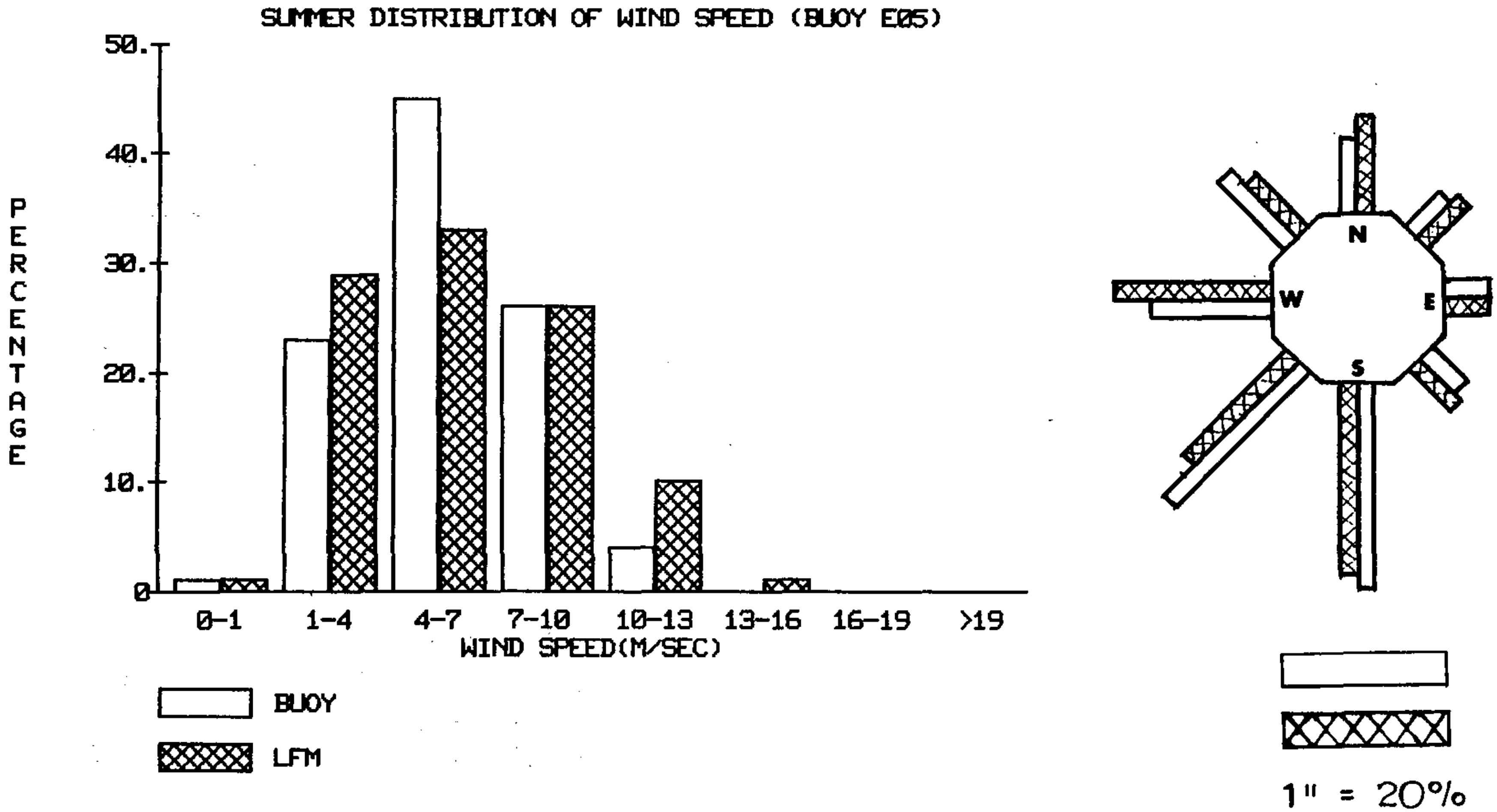


Figure 21.--Frequency distribution in percent of wind speed (left) and wind direction (right) for LFM and buoy E05 for summer.

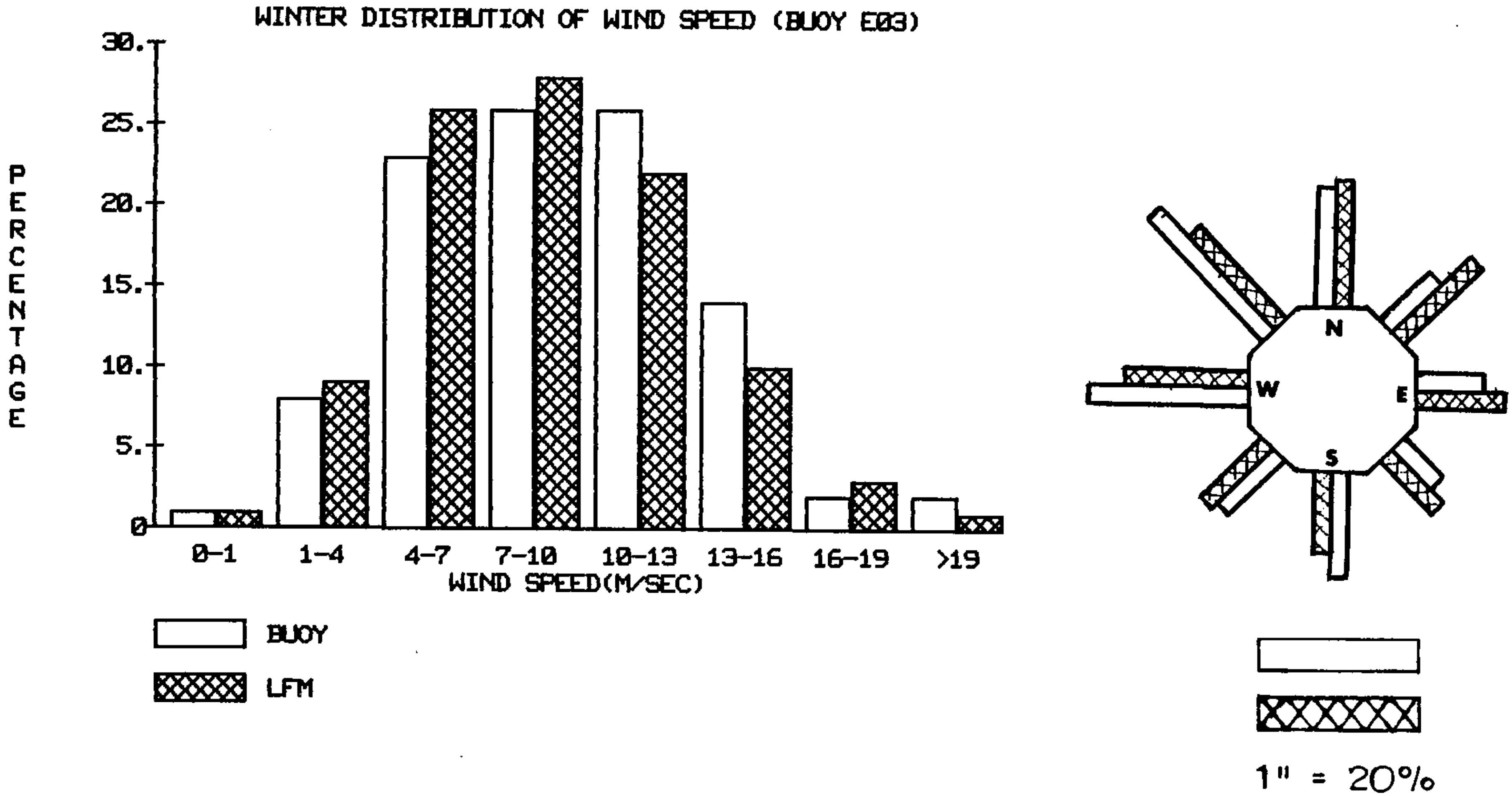


Figure 22.--Frequency distribution in percent of wind speed (left) and wind direction (right) for LFM and buoy E03 for winter.

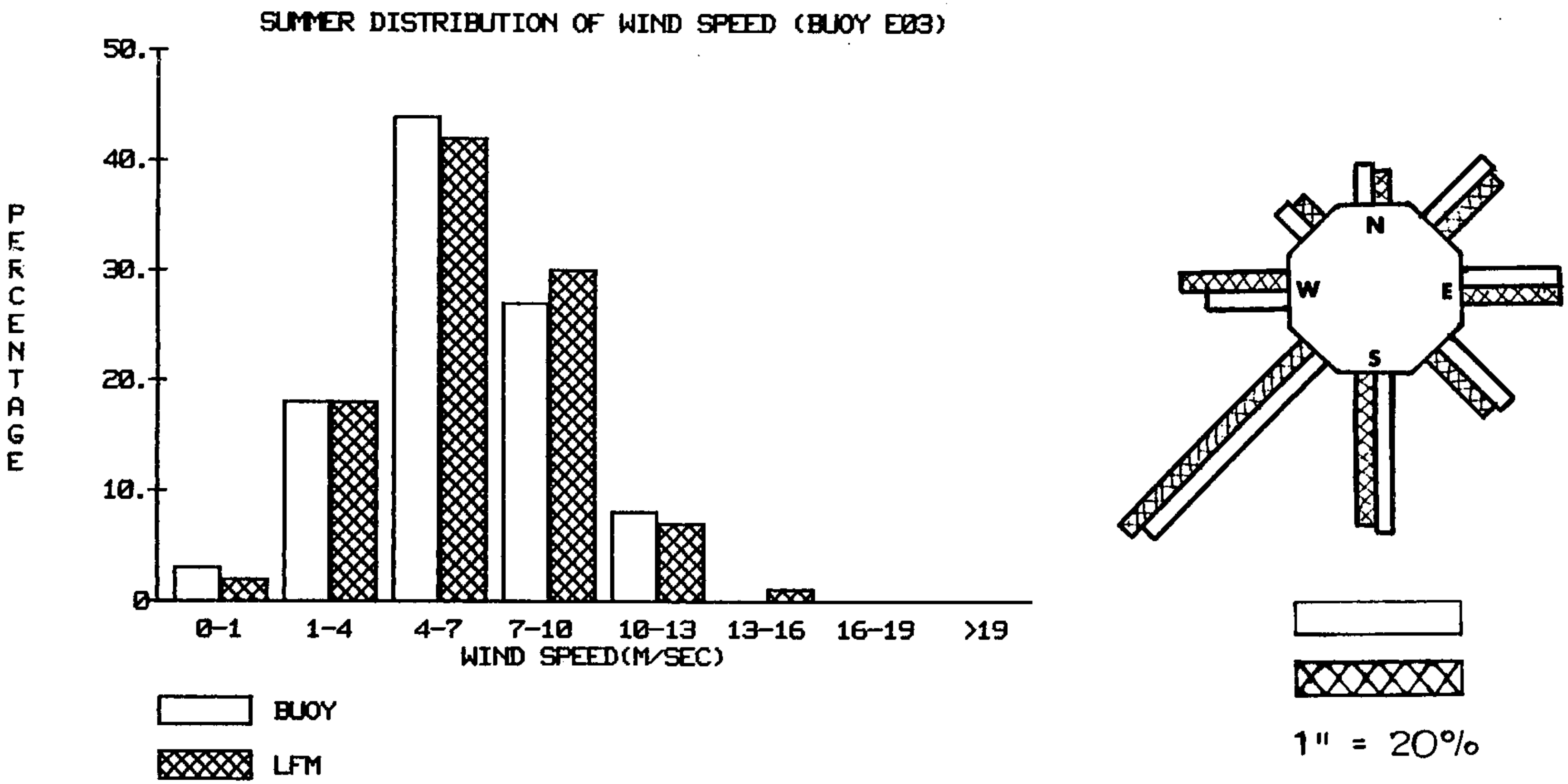
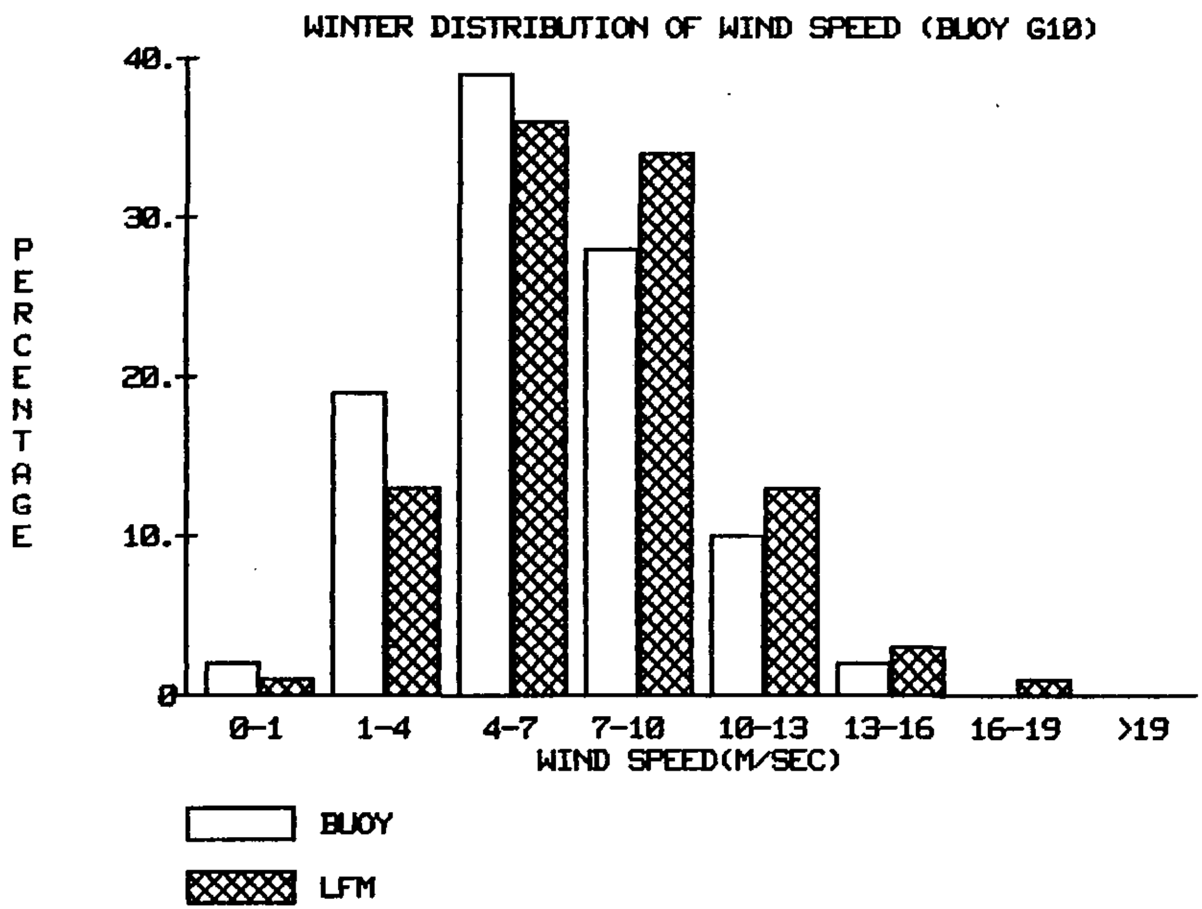


Figure 23.--Frequency distribution in percent of wind speed (left) and wind direction (right) for LFM and buoy E03 for summer.



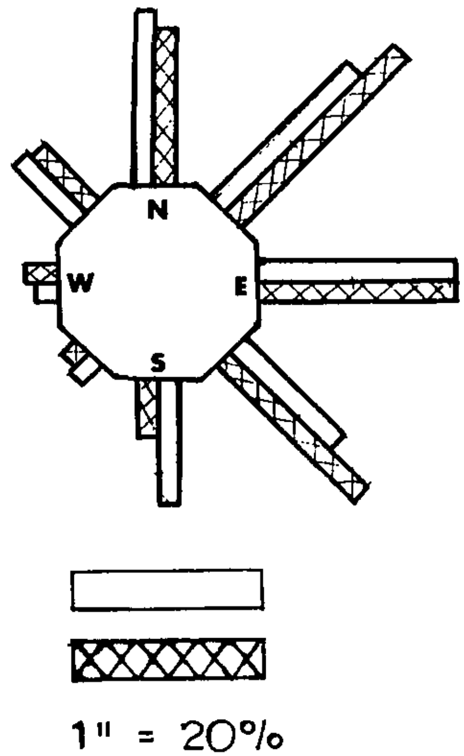
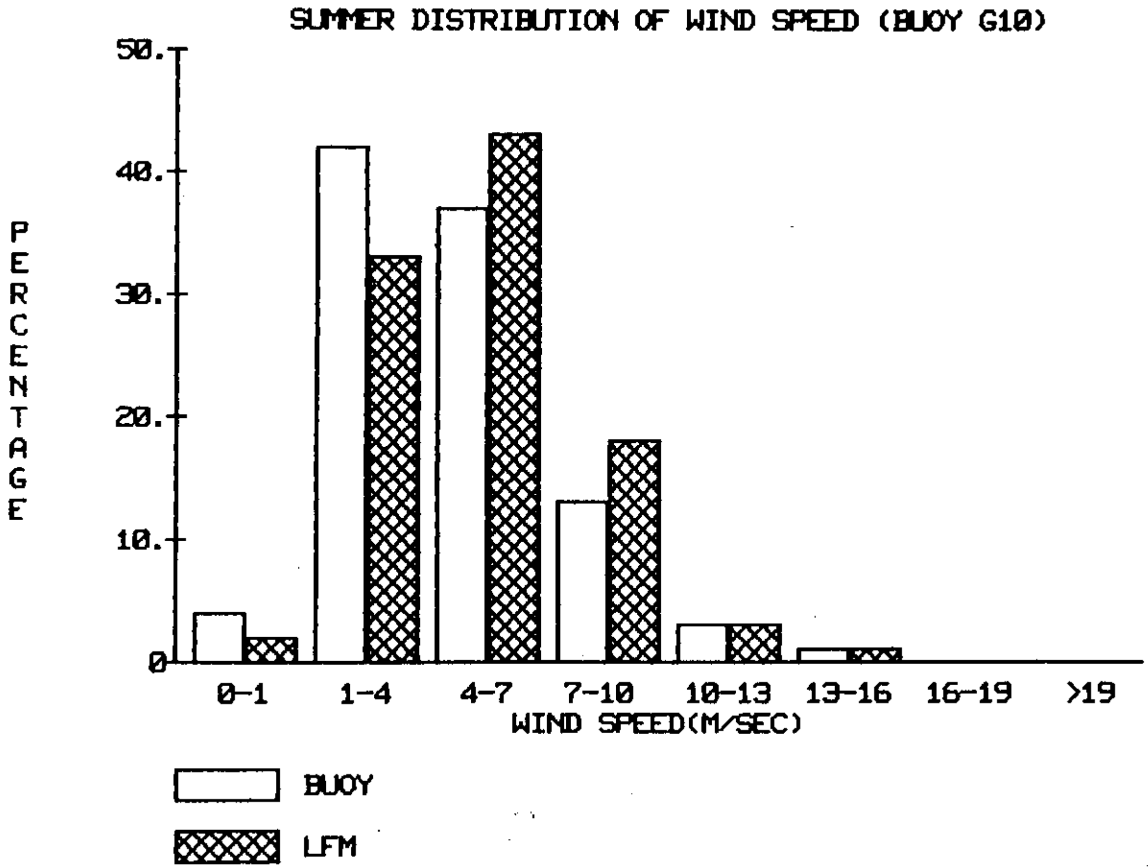


Figure 24.--Frequency distribution in percent of wind speed (left) and wind direction (right) for LFM and buoy G10 for winter.



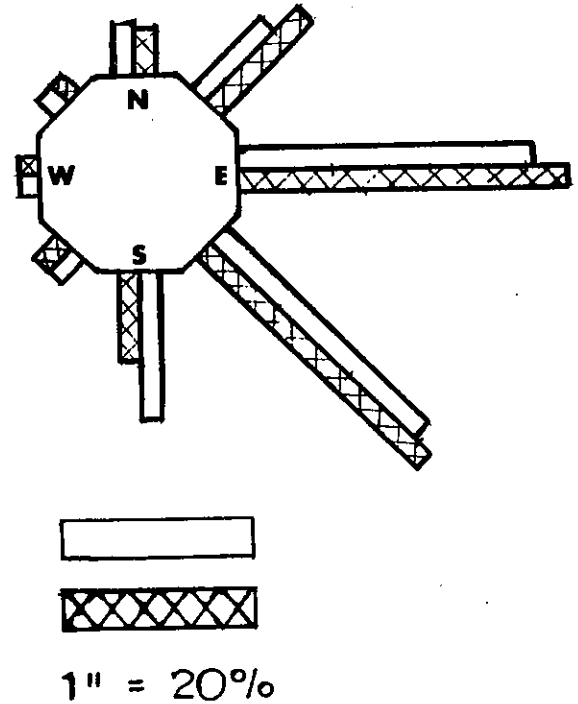


Figure 25.--Frequency distribution in percent of wind speed (left) and wind direction (right) for LFM and buoy G10 for summer.

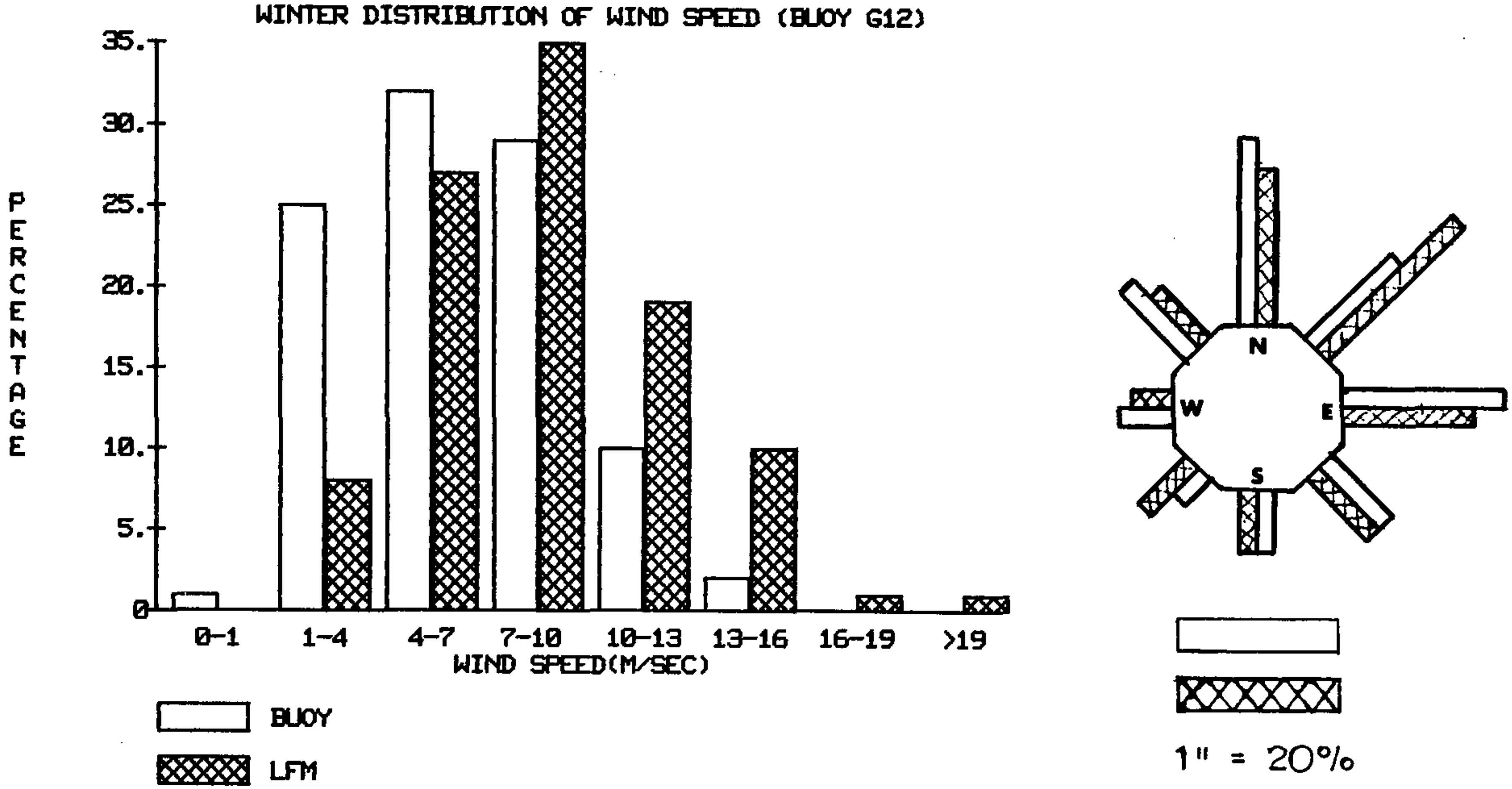


Figure 26.--Frequency distribution in percent of wind speed (left) and wind direction (right) for LFM and buoy G12 for winter.

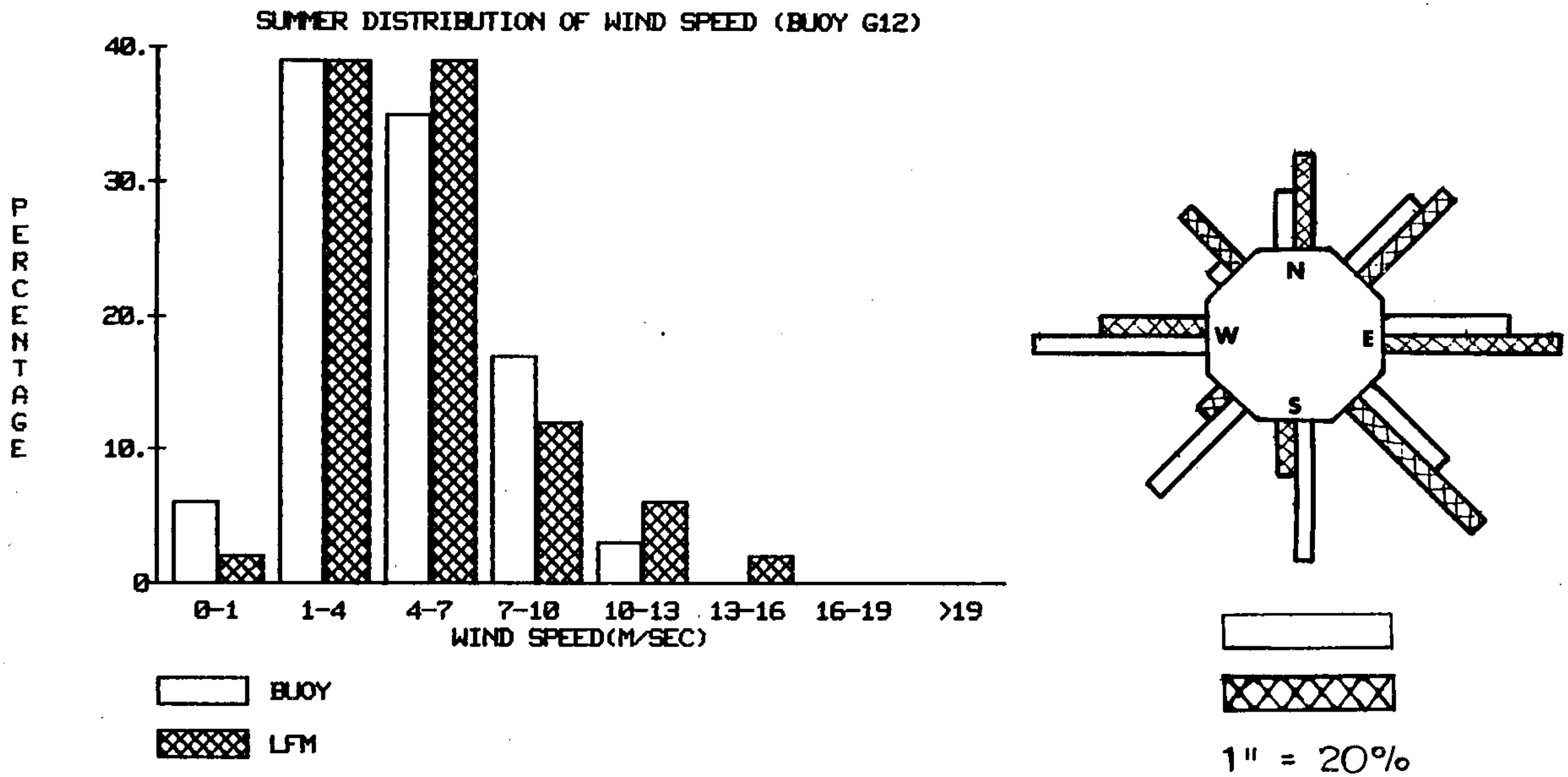


Figure 27.--Frequency distribution in percent of wind speed (left) and wind direction (right) for LFM and buoy G12 for summer.

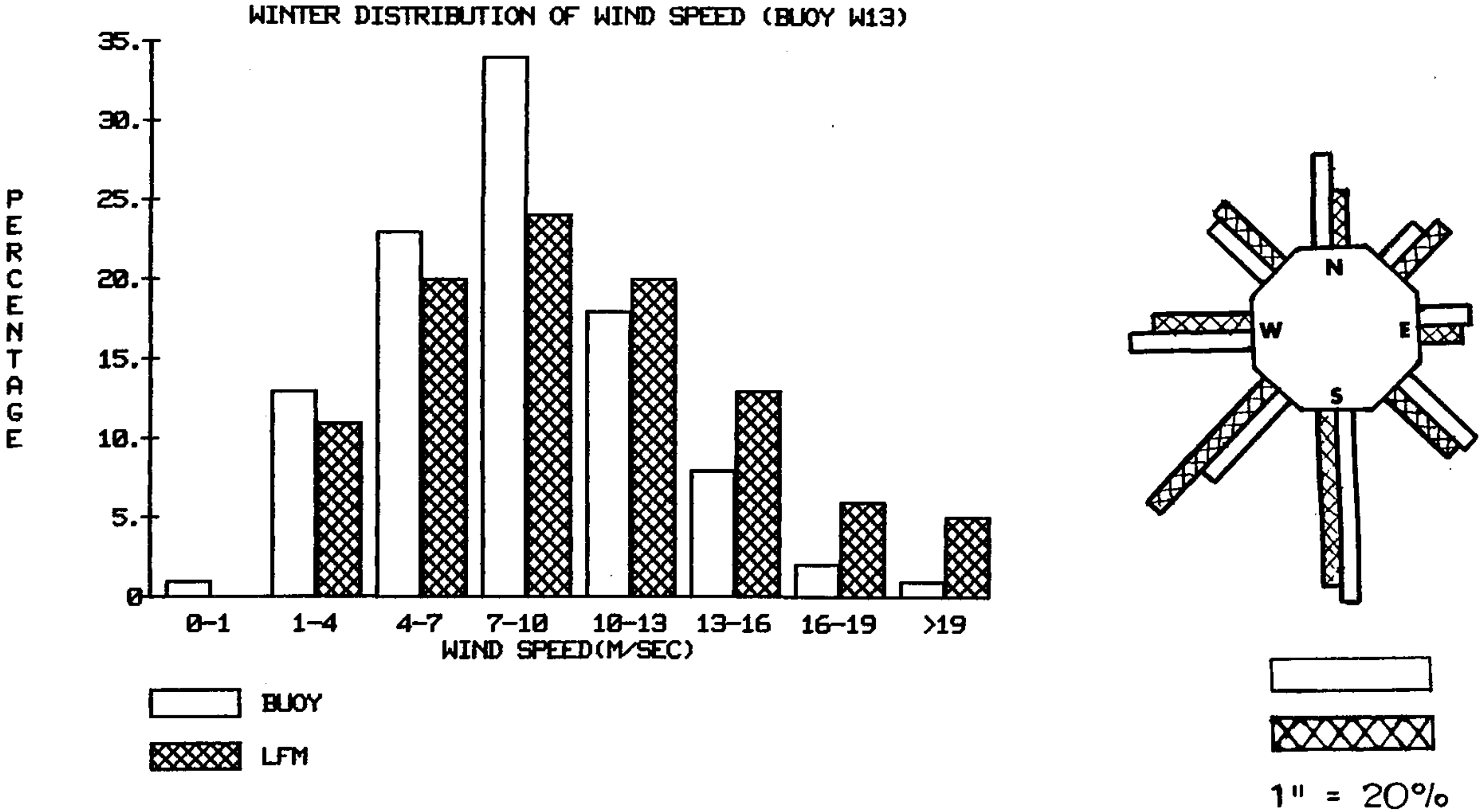


Figure 28.--Frequency distribution in percent of wind speed (left) and wind direction (right) for LFM and buoy W13 for winter.

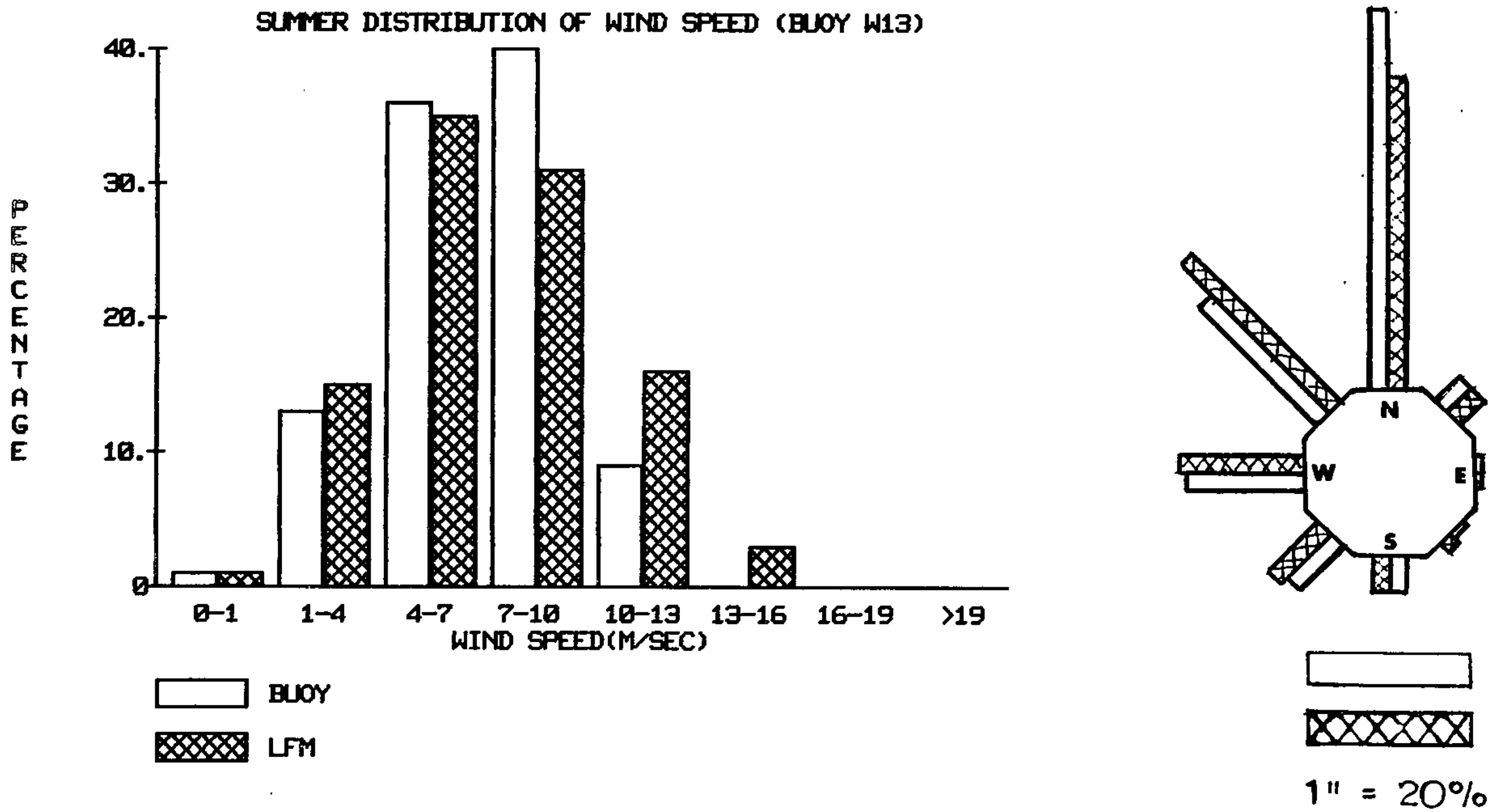


Figure 29.--Frequency distribution in percent of wind speed (left) and wind direction (right) for LFM and buoy W13 for summer.