JP2.9 EVALUATION OF WIND ALGORITHMS FOR REPORTING WIND DIRECTION FOR USE IN AIR TRAFFIC CONTROL TOWERS

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1. INTRODUCTION

The recommended methods of deriving wind speed, wind direction and wind gust values for use by controllers in air traffic control towers have been established by the International Civil Aviation Organization (ICAO). Standard practice is to use the most recent 2-minute averages for wind speed and wind direction reports, and the most recent 10-minute maximum wind speed to determine the wind gust report. This paper compares the properties of past wind directions over different time intervals to future wind directions over a 2-min time interval. The latter interval is considered to be most applicable to aircraft on final approach and is representative of the time it takes for a modern aircraft to reach the touchdown point on the runway from the outer marker, which ranges from around 4-7-nm from the runway threshold. The results demonstrate that established algorithms recommended by ICAO and used generally throughout the U.S. are reasonable for the application. Also, no attempt is made to evaluate other possibly better ways of predicting near-term wind parameters based on more sophisticated time-series methods of parameter estimation, even though methods such as Kalman filtering are expected to produce superior results to the current, simple, methods employed in aviation meteorology.

All wind data considered here were obtained from the Propeller (Prop) and Vane Anemometer mounted on the C-tower at Otis Weather Test Facility (WTF) located at the Otis Air National Guard Base (ANGB) on Cape Cod, Massachusetts. Anemometer data are archived in hourly ASCII text files in 1-s samples. 12-h files were constructed during days with wind gusts reported from official hourly surface weather observation or METAR reports from the automated weather station at Falmouth, MA (FMH), located about a mile from the Otis WTF.

Several cases were considered with 12 hours of data per case. All cases occurred on selected days in May 2005, which were also considered by Seliga et al. (2006) in analyzing wind speeds and gusts. All but one of the cases had wind directions ranging from N to SE. Most of the cases had average wind speeds between 15-20 kts with maxima of 35-42 kts.

Table 1 lists the characteristic wind directions (excluding any outliers), average wind speeds and maximum 1-s wind speeds over the 12 h periods for these cases. Column 1 is the date; Column 2 indicates which part of the day the data was recorded ('AM' corresponds to data from ~0000-1200 GMT while 'PM' was from ~1200-2400 GMT); Column 3 is the wind direction range; Column 4 is the event average wind speed; and Column 5 is the maximum 1-s wind speed for the event.

Table 1. Wind Data Characteristics.

Date	AM/ PM	Wind Direction Range (deg)	Ave Wind Speed (kts)	Max Wind Speed (kts)
05/01/05	AM	171-313	13.74	37.84
05/07/05	AM	9-135	14.58	40.37
05/24/05	PM	12-117	15.43	34.08
05/25/05	AM	10-134	20.13	40.57
05/25/05	PM	8-95	18.97	35.77
05/26/05	AM	1-115	15.31	41.90

2. APPROACH

In order to perform the evaluation, a standard time frame was established for comparing past data to future data. As noted in the previous section, this time period was chosen as 2-min, consistent with the approximate time required for a modern aircraft to reach the touchdown point on the runway from the outer marker. Thus, all metrics are relative to parameters measured forward (FW) and backward (BW) from any instant of time. Fig. 1 illustrates graphically how the comparisons are made for time sampling intervals ranging stepwise from 1-s backwards in time to as long as 20-min. Time intervals of interest are: BW: instantaneous (1-sec), 30-sec, 1-min, 2-min, 5-min, 10-min, 20-min; and 2-min FW. The green lines and numbers illustrate the BW times; the red line and number the current sample and the blue line and number the 2-min FW time.

The analyses are based on the following plots:

- Time series of the differences of BW to FW averages of wind directions;
- Time series of the differences in BW and FW wind direction ranges;

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- Experimental histograms and cumulative distribution (CDF) plots of these quantities.

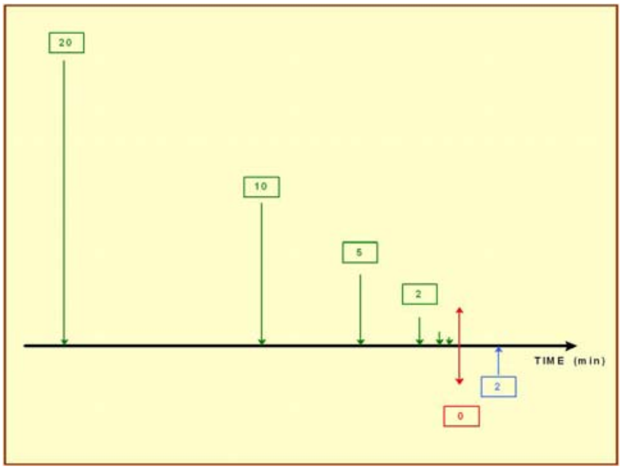

Fig. 1. Illustration of time intervals for wind analyses based on relating a forward 2-min prediction of wind parameters to the same parameters derived from various backward time intervals.

In a related matter, scatter plots were used to explore relationships between wind direction range and the average and standard deviation of the wind direction. This included examining scatter plots of wind direction ranges vs. standard deviations for BW time intervals ranging from 1-min to 20 min vs. 2-min FW time. The scatter plots provided empirical evidence that the standard deviation of the wind direction, along with the average wind direction, can be used to provide reasonably good estimates of wind direction ranges.

To account for the north wind anomaly, algorithms by Fisher (1987, 1993) were used. Fisher's algorithms provided results that are close to results of the ICAO algorithm (ICAO, 2001), but are much simpler for computing variance and standard deviation. Fisher's algorithms are as follows:

Mean Wind Direction

For *n* wind samples having directions θ_i, the mean wind direction $\bar{\theta}$ is found via the following computations, where the ambiguity in direction angle is solved through consideration of the quadrant of $\bar{\theta}$ based on the signs of C and S.

$$C = \sum_{i=1}^{n} \cos(\theta_i) \tag{1.1}$$

$$S = \sum_{i=1}^{n} \sin(\theta_i) \tag{1.2}$$

$$\bar{\theta} = \tan^{-1}\left(\frac{S}{C}\right) \tag{1.3}$$

Standard Deviation of Wind Direction

This computation requires the amplitude component of the first trigonometric moment that is given by

$$\bar{R} = \left[\left(\frac{C}{n}\right)^2 + \left(\frac{S}{n}\right)^2\right]^{\frac{1}{2}} \tag{1.4}$$

$$\bar{R} \le 1 \tag{1.5}$$

The corresponding sample circular variance V in radians squared and circular standard deviation v in degrees are

$$V = 1 - \bar{R} \tag{1.6}$$

and

$$v = \left[-2\ln(1-V)\right]^{\frac{1}{2}} = \left[-2\ln(\bar{R})\right]^{\frac{1}{2}} \tag{1.7}$$

3. DEFINITIONS

Wind Gust is defined here as the maximum of the wind speed during the time interval of interest.

Average Wind Speed is the statistical mean of the wind during the time interval of interest.

North Wind Anomaly is the step change in wind directions when these directions change across the circular transition value, say, e.g., from just less than 360^o to 0^o and higher (0^o ≤ θ < 360^o) or from just less than 180^o to –180^o or less (-180^o ≤ θ < 180^o).

Wind Direction Range is the difference between the minimum and maximum wind directions within a given time interval; all wind directions during the interval must reside within the sector bounds of the minimum and maximum wind directions.

4. WIND DIRECTIONS DURING GUST EVENTS

4.1 Time Series

Wind Speeds and Directions - Fig. 2 is a sample time series plot of the difference between the FW 2-min wind speed and corresponding 5-min BW average wind speed. The plots are for the May 7 AM 12-h period that had an overall average wind speed of 14.58 kts and maximum wind speed of 40.37 kts. Comparisons of similar plots with different BW averaging times show that the best averaging times for predicting forward 2-min wind average speeds is ~5-min.

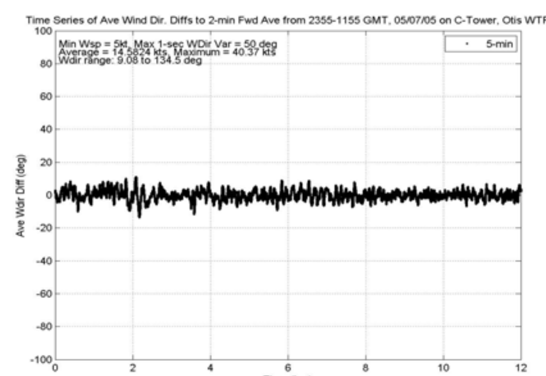

Fig. 2. Sample time series plot of the difference of 5-min BW average wind direction from 2-min FW average wind speed.

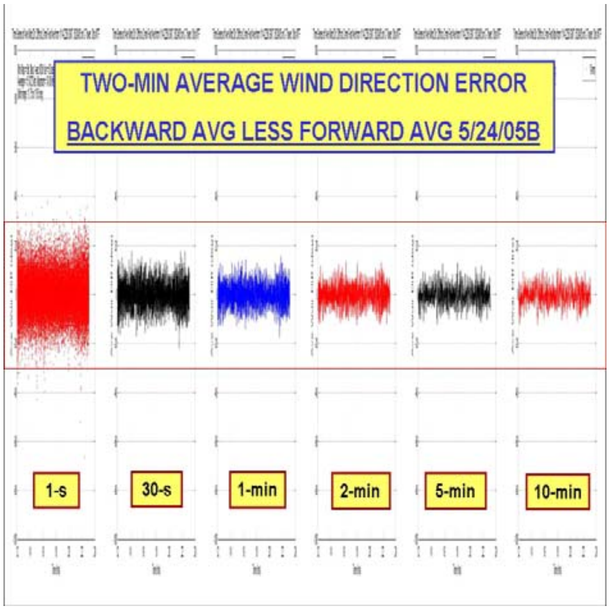

Fig. 3. Comparisons of time series showing the differences between backward averages of wind direction with varying averaging times to 2-min forward average directions. The 12-h time period for this event occurred during the PM on May 24.

This conclusion can be seen in Fig. 3, which gives a series of highly compressed time series of this difference for varying BW time averages. The errors are indicated by the time series' excursions from zero. The least errors are seen to occur with ~ 5-min BW averaging, although there is little difference between this result and the 10-min averaging result. Also, the 2-min BW averaging results indicate errors greater than the 5-min values; these errors are not significantly different in magnitude. For reference, the red lines in Fig. 4 indicate $\pm 30^o$ error limits, which is half of the definition width of a variable wind direction METAR report. In addition to providing straightforward insights into the choice of best BW averaging times to use for predicting FW 2-min average wind directions, the time series results also provide insights into expected errors. As anticipated from sampling theory, a single 1-s observation will produce the greatest error in predicting the average FW 2-min wind direction; this error can be greater than the BW 5-min result by more than a factor of 2 for much of the time. Visual interpretation of the results is readily apparent as well. That is, the respective expected errors for the various BW sampling times are approximately $(\pm 20^o; \pm 15^o; \pm 12^o; \pm 10^o; \pm 8^o; \pm 8^o)$ for corresponding BW time sampling periods of (1-s; 30-s; 1-min; 2-min; 5-min; 10-min).

Wind Shifts - Wind direction shifts are considered by evaluating plots of the difference of wind direction ranges over BW time intervals and corresponding values occurring over 2-min FW time intervals. In addition to using difference plots for observing the sensitivity of the predictions of shifts to BW sampling time intervals, they can also be used for gauging the sensitivity of the predictions to both missed and false shift reports, based on selected thresholds for the differences. For discussion here, error thresholds of $\pm 30^o$ for shift detection are applied to the difference plots. When the difference between the maxima are outside these limits, they can be categorized as either a false report if the difference is greater than the upper threshold of 30^o and missed reports if the difference is less than the lower threshold of -30^o. Note that the thresholds may differ, depending on the criteria of different users. Also, histograms of the data and their corresponding cumulative distribution functions can be used to quantify the statistics of these determinations.

Figs. 4, 5 and 6 show time series plots of the differences between the 2-min FW ranges and BW ranges for BW time sampling periods of 2-min, 5-min and 10-min, respectively. The data are from the same typical gusty day of May 7. The plots also highlight the assumed $\pm 30^o$ limits for determining missed and false shift reports. The BW 2-min plot is centered about zero, since the sampling periods are equal in duration. The longer 5-min and 10-min BW difference plots in Figs. 5 and 6 produce biases that increase with sampling time. Thus, one can trade off occurrences of false reports with occurrences of missed reports, depending on BW sampling time. The tradeoffs can be quantified by noting the amount of time the differences reside outside the $\pm 30^o$ limits in each of the figures (note that different limits can be selected). Another way of quantifying these tradeoffs is to employ sample cumulative distribution functions, CDF and 1-CDF curves, as shown in Fig. 7. The results are typical of all the data sets and are summarized in Table 2 for both $\pm 30^o$ and $\pm 20^o$ limits.

A sense of these tradeoffs can be gleaned from Fig. 7 and the corresponding results given in Table 2. It is of interest to examine the 10-min result, since airport wind shift reports use BW 10-min wind direction ranges to establish shift reports. Using the 30^o criteria, the 10-min BW wind direction range during this event would have missed only 9% of those occasions when 2-min FW wind direction shifts exceeded the reported values by more than 30^o. On the other hand, the same procedure would have produced false reports <1% of the time, that is, the difference between the BW 10-min predictions exceed their corresponding 2-min FW ranges by more than 30^o <1% of the time. Comparison of this result with the 2-min BW case, shows that, although this BW time period would somewhat reduce false reports, this condition would be accompanied by a ~ten-fold increase in missed reports.

4.2 Box Plots and Figure of Merit

In order to gain insight into the statistical significance of the results that were derived from examining the properties of the time series of the differences, box plots of the differences between the BW averages and the 2-min FW averages and of the differences between the BW ranges and 2-min FW ranges were generated. Figure of merit plots corresponding to the box plots were also generated.

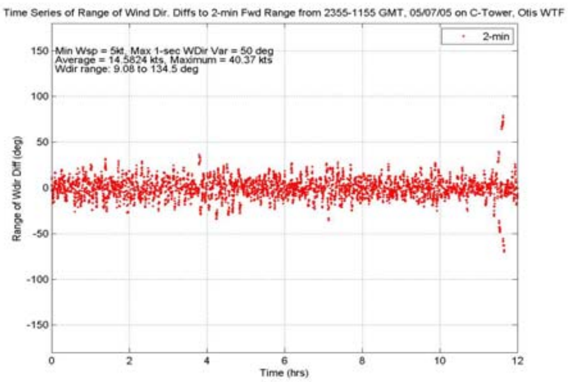

Fig. 4. Sample time series plot of the difference of the 2-min BW wind direction range and the corresponding 2-min FW range.

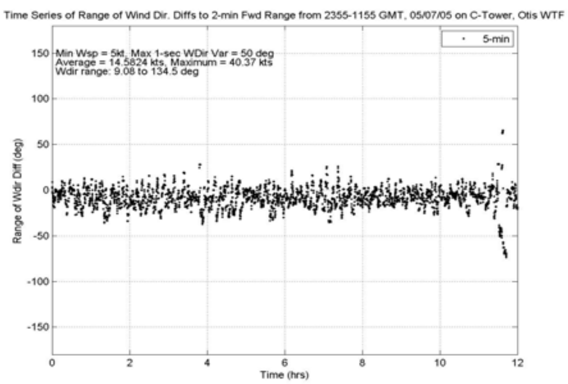

Fig. 5. Sample time series plot of the difference of the 5-min BW wind direction range and the corresponding 2-min FW range.

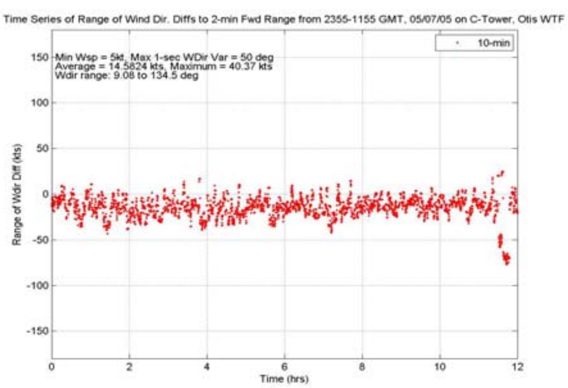

Fig. 6. Sample time series plot of the difference of the 10-min BW wind direction range and the corresponding 2-min FW range.

Box plots – Fig. 8 shows a box plot of the differences between the BW averages and the 2-min FW averages of a typical wind event. Fig. 9 shows a box plot of the differences between the BW ranges and the 2-min FW ranges of the same wind event. For each BW time interval plotted: (1-s, 30-s, 1-min, 2-min, 5-min, 10-min, 15-min, 20-min) in Fig. 8 and (30-s, 1-min, 2-min, 5-min, 10-min, 15-min, 20-min) in Fig. 9, the leftmost end of the plot segments represent the following ordered percentiles of the differences (2.5, 5, 10, 25, 50, 75, 90, 95, 97.5). The '◊' inside the tallest rectangle represents the 50th percentile or median of the sample distribution.

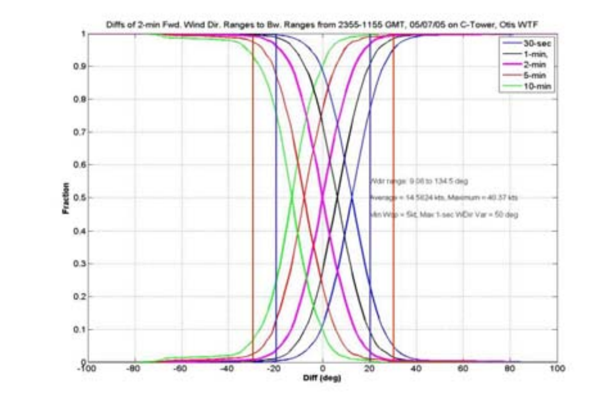

Fig. 7. Sample CDF (1-CDF) plots of the percentage of times that the differences between forward 2-min and BW ranges exceed (are less than) maximum wind direction range values; ±30° and ±20° criteria are highlighted by the vertical lines for reference.

Table 2. Sensitivity of Missed and False Reports of Wind Direction Shifts to BW Sampling Time (May 7).

Error Type	Threshold Wind Direction Difference (degs)					
	2-min		5-min		10-min	
	±30°	±20°	±30°	±20°	±30°	±20°
Missed	~1%	3%	2%	12%	8%	25%
False	<1%	2.5%	<1%	1%	0%	<1%

The previously observed comparison of the 5-min BW and 10-min BW time intervals vs the 2-min FW time interval is also evident in Fig. 8. The tradeoff between missed and false wind shift predictions for the 2-min FW time interval is also evident in Fig. 9 and is consistent with the CDF plots.

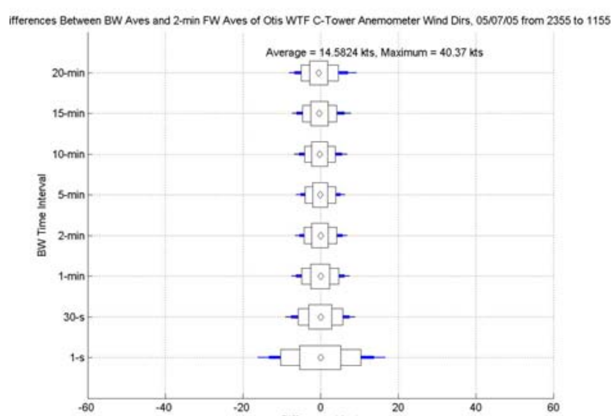

Fig. 8. Typical box plot of the differences between the 2-min FW averages and BW averages of wind direction.

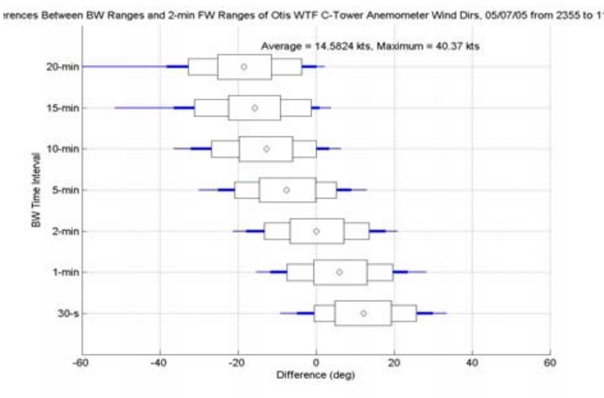

Fig. 9. Typical box plot of the differences between the 2-min FW and BW ranges of wind direction.

The previously observed comparison of the 5-min BW and 10-min BW time intervals vs the 2-min FW time interval is evident in Fig. 8. The tradeoff between missed and false wind shift predictions for the 2-min FW time interval can be seen and supports the CDF plot analysis in Fig. 9.

Figure of Merit – Fig. 10 shows a figure of merit plot that indicates the ratio of 2-min FW averages to corresponding spreads of the BW wind direction averages (defined by the differences of 97.5th and 2.5th percentiles). The figure confirms the result that the best estimator of the forward spread derives from a 5-min BW time interval sample of spread.

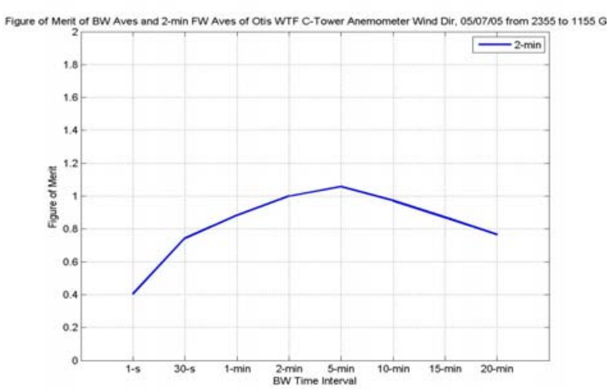

Fig. 10. Typical figure of merit index based on the ratio of the 2-min FW average wind directions to the spread of the BW average values.

5. WIND DIRECTION RANGES AND STANDARD DEVIATION

Figs. 11, 12 and 13 show typical plots of wind direction range vs standard deviations, corresponding to 2-min, 5-min and 10-min BW time intervals, respectively. This event produced similar standard deviations for all time periods, ranging from around 5 to 12^{o}. There appears to be a good correlation with considerable spread the wind range varying between about 4 to 6 times the standard deviation for the 2-min BW value at deviations less than around 10^{o}. For a given time interval, wind direction standard deviation is therefore a general predictor of wind direction range.

This relationship changes, depending on the BW time interval as seen from comparisons of Figs. 11 through 13. Note also that the deviations of wind direction range vary with standard deviation; i.e., the size of the wind direction range increases with BW time interval, while the spread of wind direction decreases with BW time interval. The significance of this behavior has not been established.

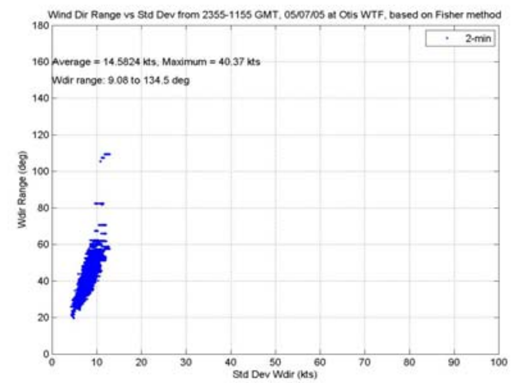

Fig. 11. Scatter plot of wind direction range vs wind direction standard deviation for 2-min time interval.

Plots of standard deviations of wind direction versus averages of wind speeds and standard deviations of wind speeds were also examined as shown in Figs. 14 and 15 for 5-min samples. The results indicate no apparent correlation of standard deviation of wind direction with wind speed or standard deviation of wind speed.

6. SUMMARY

This paper examined several simple methods of evaluating short-term wind direction shift prediction, focusing on 2-min forward values derived from backward wind direction data. The results suggest that 2-min BW averaging for average wind direction and 10-min BW look-backs for wind range are reasonable standards for aviation reporting. The data provide evidence that 5-min BW averaging and look backs for both parameters may be optimum.

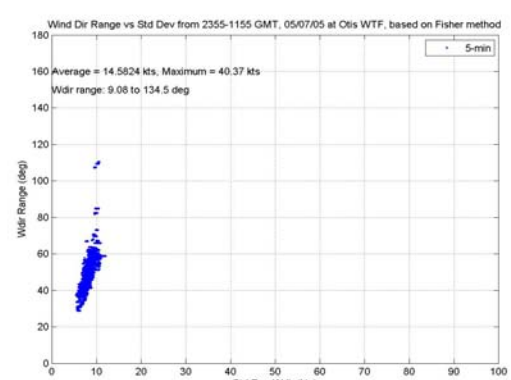

Fig. 12. Scatter plot of wind direction range vs wind direction standard deviation for 5-min time interval.

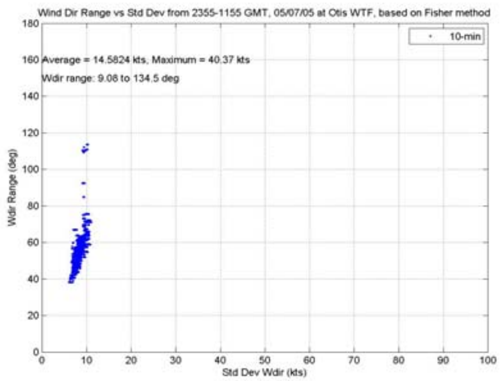

Fig. 13. Scatter plot of wind direction range vs wind direction standard deviation for 10-min time interval.

The wind direction range was found to correlate with wind direction standard deviation, similar to results of Markee (1963) who analyzed wind data over 15-min, 30-min and 60-min time intervals. The findings here also agreed with his results that showed that the wind direction range is not correlated with wind speed standard deviation (not a good predictor).

These limited results show that, irrespective of the many studies of winds that have been performed previously, much remains to be learned. In particular, more sophisticated approaches to analyzing winds should improve predictions, reducing both missed reports and false reports. Essentially, current methods may be considered naive compared to state-of-art time series and statistical analysis methods, including such topics as: time series filtering; neural networks; and fuzzy logic modeling (e.g., see Anderson, 1976; Box and Jenkins, 1970; Kendall, 1984; Montgomery et al., 1990).

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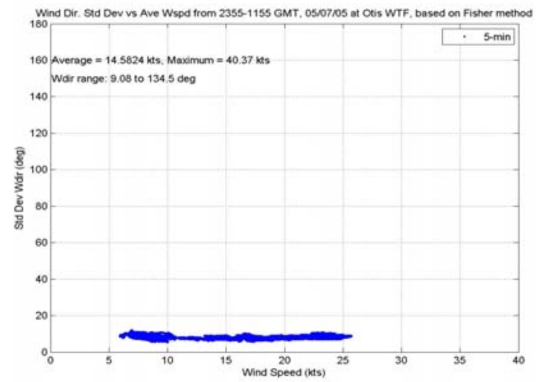

Fig. 14. Scatter plot of wind direction standard deviation versus average wind speed.

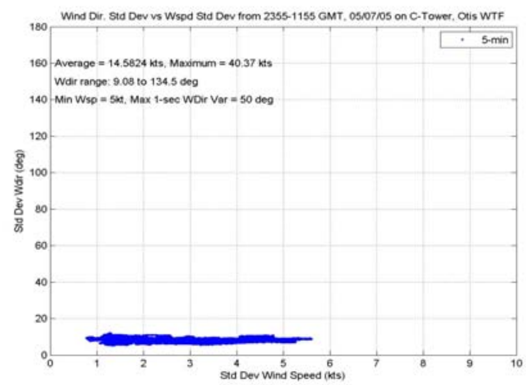

Fig. 15. Scatter plot of wind direction standard deviation versus wind speed standard deviation.