P5.3 EVALUATION OF WIND ALGORITHMS FOR REPORTING WIND SPEED AND GUST 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, 2001). 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 winds over different time intervals to future winds 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. Wind direction is not considered in this paper. 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 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.

Twenty cases were considered with 12 hours of data per case. All cases occurred on days in May 2005, representing a wide range of wind speed averages and maxima as recorded by the prop and vane anemometer. Table 1 lists the average wind speed 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 were while 'PM' was from ~1200-2400 GMT); Column 3 is the 2-min average wind speed; and Column 4 is the maximum 1-s wind speed. Most of the cases had average wind speeds between 10-20 kts and maxima of 30-40 kts.

Table 1. Wind Data Characteristics.

Date	AM/ PM	Ave Wind Speed (kts)	Max Wind Speed (kts)
05/01/05	AM	12.37	40.39
05/02/05	PM	9.71	23.17
05/03/05	PM	9.73	23.55
05/07/05	AM	11.71	38.47
05/07/05	PM	22.60	51.65
05/08/05	AM	21.31	47.07
05/08/05	PM	19.39	39.10
05/09/05	AM	16.33	36.26
05/09/05	PM	12.39	31.10
05/12/05	PM	11.95	33.80
05/21/05	PM	12.09	30.63
05/22/05	AM	9.74	26.35
05/23/05	AM	3.51	11.16
05/23/05	PM	7.08	18.08
05/24/05	AM	3.94	14.49
05/24/05	PM	12.64	32.52
05/25/05	AM	16.72	38.31
05/25/05	PM	15.59	36.95
05/26/05	AM	12.39	38.13
05/26/05	PM	10.79	27.27

2. APPROACH

In order to perform the evaluation, a standard time frame had to be set for comparing past data to future data. As noted in the previous section, this time period was chosen to be 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

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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 speeds;
- Time series of the ratio of BW to FW averages;
- Time series of the differences in BW and FW maximum wind speeds;
- Time series of ratios of the BW to FW maximum wind speeds; and
- Experimental histograms and cumulative distribution (CDF) plots of these quantities.

In a related matter, scatter plots were used to explore relationships between maximum wind speed and the average and standard deviation of the wind speed. This included examining scatter plots of maximum wind speed 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 speed, along with the average wind speed, can be used to provide reasonably good estimates of maximum wind speeds.

Standard statistical testing was also performed. The Standard t-test was used to compare average wind speeds for various BW averaging times ranging from ½ min to 20 min relative to 2-min FW averaging values. Evaluation of the maximum values was performed with the Standard F-test, which compares standard deviations of the wind speed for various BW times ranging from ½ min to 20 min vs. 2-min FW time values of the parameter. Note that the applicability of this test is based on the one-to-one relationship between maximum wind speed and standard deviation inherent in the data.

The plots for the t-tests and F-tests give the percentage of samples that satisfy the hypothesis that the wind and maximum wind speed (gust) are the same for the BW time intervals as the 2-min FW time interval.

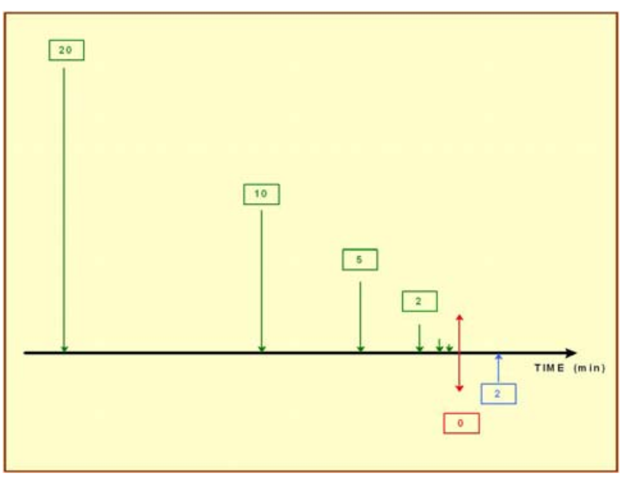

Fig. 1. Time intervals for wind analysis.

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.

4. WIND SPEEDS AND GUSTS

4.1 Time Series

Wind Speeds - Fig. 2 is a sample time series plot of the difference between the 5-min BW average wind speed and the corresponding FW 2-min wind speed; Fig. 3 is the ratio plot for the same time series. The plots are for the May 7 PM 12-h period that had an overall average wind speed of 22.6 kts and maximum wind speed of 51.65 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.

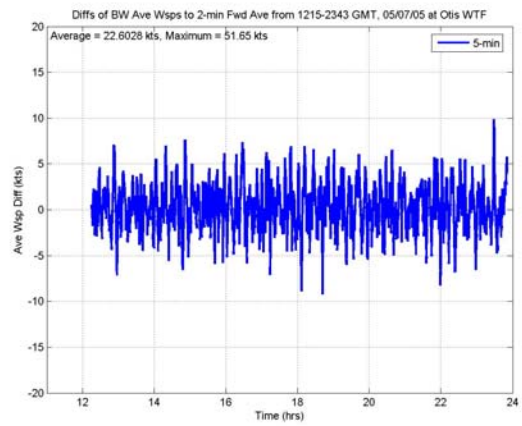

Fig. 2. Sample time series plot of the difference of 5-min BW average wind speed from 2-min FW average wind speed.

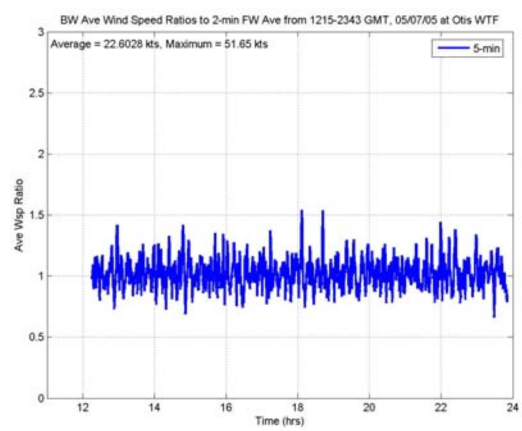

Fig. 3. Sample time series plot of the ratio of the 5-min BW average wind speed to the 2-min FW average wind speed.

The conclusion can be seen in Fig. 4, 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 ±5-kt error limits. In addition to providing straightforward insights into the choice of best BW averaging times to use for predicting FW 2-min average wind speeds, the time series results also provide insights into expected errors. As expected, a single 1-s observation will produce the greatest error in predicting the average FW 2-min wind speed; 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 (±5-kts; ±3.5-kts; ±3-kts; ±2.5-kts; ±2-kts; ±2^{+}-kts) for corresponding BW time sampling periods of (1-s; 30-s; 1-min; 2-min; 5-min; 10-min). The same results are evident in similar plots of the ratios of the average wind speeds.

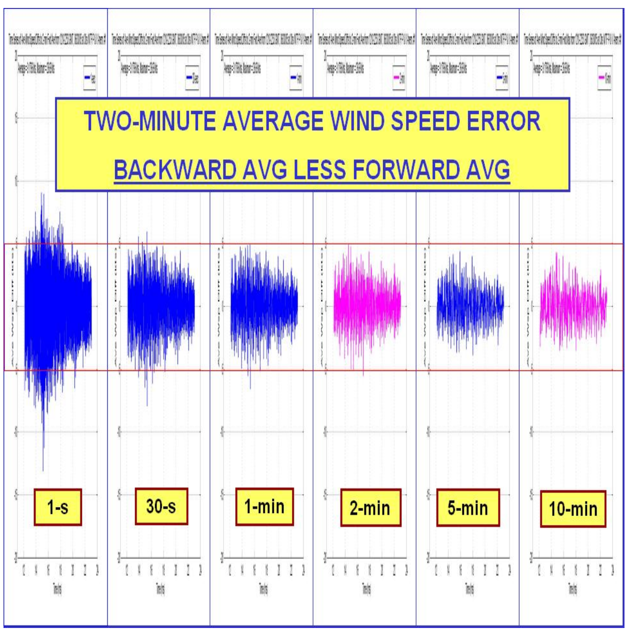

Fig. 4. Comparisons of time series showing the differences between backward averages of wind speed with varying averaging times to 2-min forward average wind speeds. The 12-h time period for this event occurred during the PM on May 22.

Very High Wind Gusts - Wind gusts are considered by evaluating plots of the difference of maximum wind speeds over BW time intervals and corresponding values occurring over 2-min FW time intervals (wsp_{BW} – wsp_{FW}); plots of the ratios of maximum wind speeds over the above BW time intervals to corresponding 2-min FW time intervals can provide similar insights, but care must be exercised in interpretation since the results are dependent on both wind speed and the difference in maxima. In addition to using difference plots for observing the sensitivity of the predictions of gusts to BW sampling time intervals, they can also be used for gauging the sensitivity of the predictions to both missed and excess gust reports, based on selected thresholds for the differences. For discussion here, error thresholds of ±5 kts for gust detection are applied to the difference plots. When the difference between the maxima are outside these limits, they can be categorized as either an excess report if the difference is greater than the upper threshold of 5 kts and missed reports if the difference is less than the lower threshold of –5 kts. 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. 5, 6 and 7 show time series plots of the differences between BW maxima and the 2-min FW maxima for BW time sampling periods of 2-min, 5-min and 10-min, respectively. The data are from a very high wind and gusty day on May 7, and, thus, are indicative of uncommon behavior. The plots also highlight the assumed ±5 kts limits for determining missed and excess gust 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. 6 and 7 produce biases that increase with sampling time. Thus, one can trade off occurrences of excess reports with occurrences of missed reports, depending on BW sampling time. The tradeoffs are readily seen be noting the amount of time the differences reside outside the ±5 kts limits in each of the figures. Alternatively, quantitative measures of these parameters can be obtained from the CDF and 1-CDF curves shown in Fig. 8. The results are typical of all the data sets and are summarized in Table 2 for both ±5 and ±3 kts limits. For reports to pilots, the consequence of the excess gust reports is considered much less important than that of not knowing of the possible existence of gusts. A sense of these tradeoffs can be gleaned from Fig. 8 and the results given in Table 2. It is also useful to examine the 10-min result in light of the fact that airport gust reports use BW 10-min maximum wind speeds to establish gust reports. Using the 5 kt criteria, the 10-min BW maximum wind speed during this very high wind gust event would have missed only 3% of those occasions when 2-min FW gusts exceeded the reported by more than 5 kts. On the other hand, the same procedure would have produced excess reports 44% of the time, that is, the difference between the BW 10-min predictions exceed their corresponding 2-min FW maxima by more than 5kts 44% of the time. Comparison of this result with the 2-min BW case, shows that, although this BW time period would reduce excess reports by around a factor of just over 2, this condition would be accompanied by a six-fold increase in missed reports.

Typical High Wind Gusts – It is of interest to contrast the very high wind gusts event with other events that are more typical of days with significant gusts. A sample

CDF set of plots for this type of event is given in Fig. 9. The plots show considerable improvements in the times when the differences reside outside the ±5 and ±3 kt thresholds. The quantitative estimates of the percentage of times the predicted values fall outside these thresholds are given in Table 3. The typical gust day produces missed gust predictions around 0.2% of the time compared to 3% for the very high wind case, and excess reports 19% of the time compared to 44%.

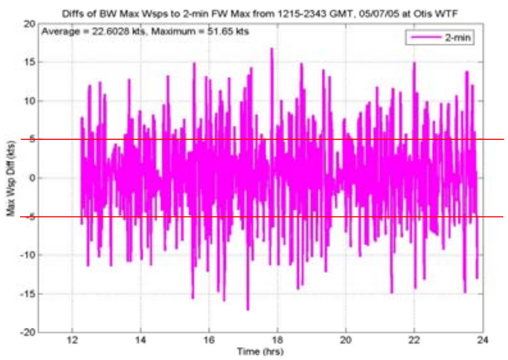

Fig. 5. Sample time series plot of the difference of the 2-min BW maximum wind speed and the corresponding 2-min FW maximum wind speed.

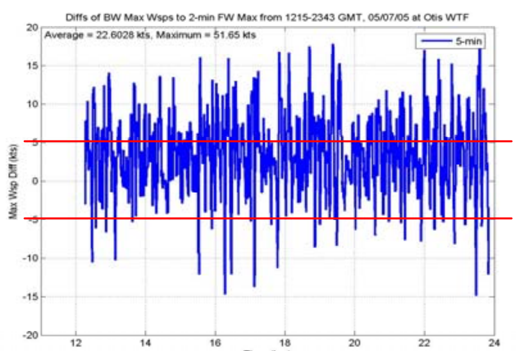

Fig. 6. Sample time series plot of the difference of the 5-min BW maximum wind speed and the corresponding 2-min FW maximum wind speed.

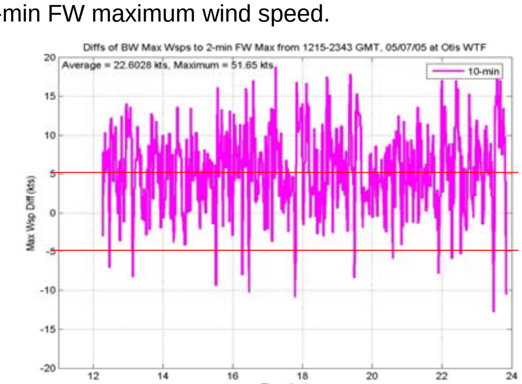

Fig. 7. Sample time series plot of the difference of the 10-min BW maximum wind speed and the corresponding 2-min FW maximum wind speed.

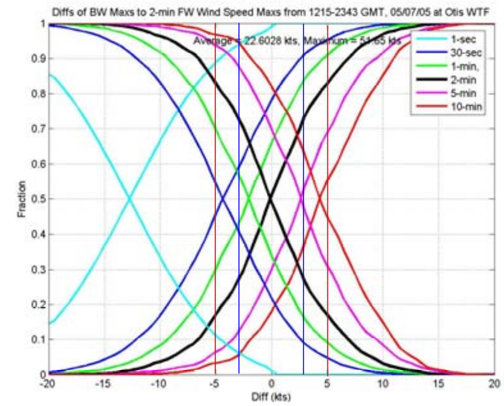

Fig. 8. Very high wind case: CDF (1-CDF) plots of the percentage of times that the differences between BW maxima and forward 2-min maxima exceed (are less than) maximum wind speed difference values. ±5 and ±3 kts criteria are highlighted by the vertical lines for easy reference.

Table 2. Sensitivity of Missed and Excess Reports of Wind Speed Maxima to BW Sampling Time (May 7).

Error Type	Threshold Difference in Wind Speeds (kts)					
	2-min		5-min		10-min	
	±5	±3	±5	±3	±5	±3
Missed	18%	28%	7%	12%	3%	5%
Excess	18%	28%	31%	48%	44%	64%

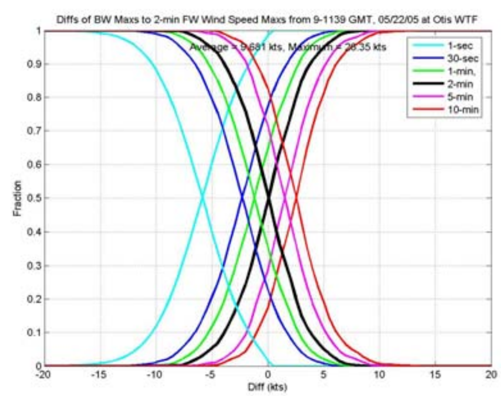

Fig. 9. Typical high wind case: CDF (1-CDF) plots of the percentage of times that the differences between BW maxima and forward 2-min maxima exceed (are less than) maximum wind speed difference values.

Table 3. Sensitivity of Missed and Excess Reports of Wind Speed Maxima to BW Sampling Time (May 22).

Error Type	Threshold Difference in Wind Speeds (kts)					
	2-min		5-min		10-min	
	±5	±3	±5	±3	±5	±3
Missed	5%	17%	1%	6%	~0.2%	3%
Excess	5%	17%	11%	32%	19%	46%

4.2 Hypothesis Testing: t-test

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, two standard statistical tests were performed on the data. The standard t-test is the parametric procedure for significance testing of sample means from two independent samples. The test applies to evaluating whether or not the average difference between BW average wind speeds for 30-s, 1-min, 2-min, 5-min, 10-min and 20-min time intervals and their corresponding 2-min FW averages is zero. The tests were done at 0.01, 0.05, 0.10 and 0.20 significance levels, implying confidence intervals of 99%, 95%, 90% and 80%, respectively. The 0.05 significance level is the level most often used in statistical analyses. t-tests, separately assuming equal and unequal variances, were performed on all the data identified in Table 1. The equal variance results for three different 12-h periods are shown Figs. 10, 11 and 12. The plots give the percentage of times when the hypothesis is accepted under different BW sampling periods and significance levels. Fig. 10 represents typical high gust conditions; Fig. 11 very high wind gust conditions; and Fig. 12 relatively calm gust conditions. By and large, all results suggest that performance does not depend much on BW sampling time periods for times greater than around 2-min. However, performance definitely degrades for BW sampling times less than 2-min. The next sequence of results are given in Figs. 13-15, assuming unknown and unequal variances between samples. The results are very similar to those generated assuming equal variances, most likely indicating that most samples satisfy or nearly satisfy the assumption of equal variances.

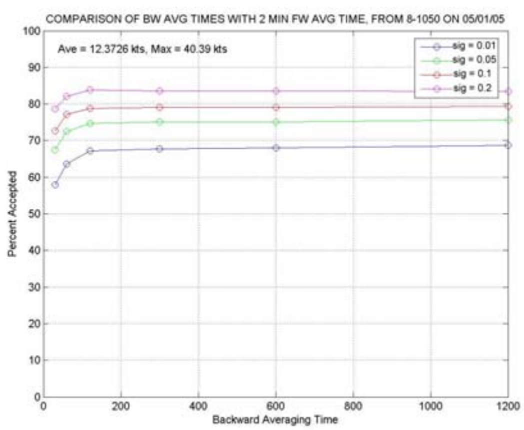

Fig. 10. Typical t-test results for high gust conditions, assuming equal variances.

Fig. 11. Typical t-test results for very high gust conditions, assuming equal variances.

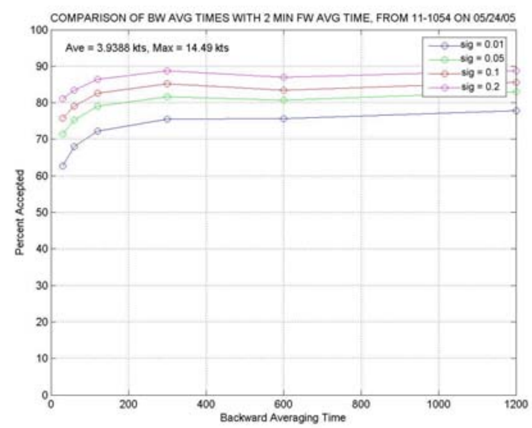

Fig. 12. Typical t-test results for relatively calm gust conditions, assuming equal variances.

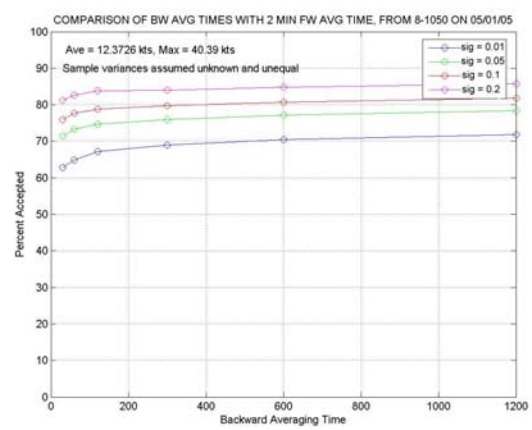

Fig. 13. Typical t-test results for high gust conditions, assuming unequal variances.

Fig. 14. Typical t-test results for very high gust conditions, assuming unequal variances.

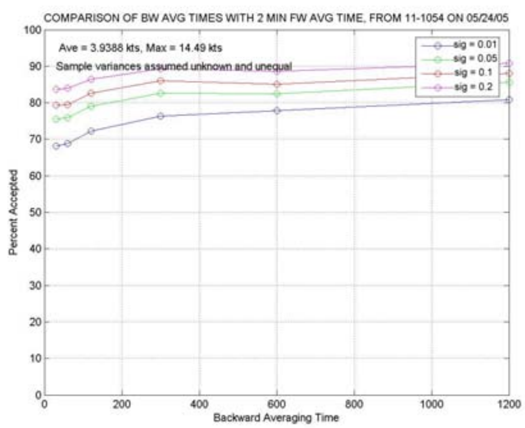

Fig. 15. Typical t-test results for relatively calm gust conditions, assuming unequal variances.

4.3 Hypothesis Testing: F-test

The standard F-test is used here to evaluate the hypothesis that both data sets (BW and FW) are sampled from distributions with the same variances. The tests strictly apply to the variances of the samples, but are related here in terms of the standard deviation from which it is possible to estimate maximum values as shown later in Sect. 5. The F-test thus relates to the standard deviations of sample wind speeds for 0.5-min, 1-min, 2-min, 5-min, 10-min and 20-min BW time intervals and the 2-min FW time interval at 0,01, 0.05, 0.10 and 0.20 significance levels, all relative to the sample standard deviation of corresponding 2-min FW values. The underlying premise is that reasonable estimates of maximum wind speed $S_{\max}$ during a given time interval is reasonably estimated by

$$S_{\max} = \hat{S} + k\sigma \qquad (1)$$

where $\hat{S}$ is average wind speed, k is a proportionality constant and σ is the standard deviation of the wind speed.

Sample plots of the F-test results are given in Figs. 16-18. As with the t-tests, they show the acceptance percentage that the hypothesis is accepted as a function of BW time intervals during varying12-h cases. Plots of the events considered show a slowly and monotonically increasing acceptance rate as the duration of BW times increases, ranging from 2-20 min. The plots show the higher the significance level of the test, the higher the acceptance rate. The acceptance rate at the 0.05 significance level ranged from 39-65% for 5-min BW time interval; 41-71% for 10-min BW time interval; and 44-77% for 20-min BW time interval.

Fig. 17 shows the results for a very high wind gust case. This was of one of the stronger wind events to have occurred during the selected events. Note that the acceptance percentages increase much less rapidly over 2-20 min BW time intervals at all significance levels. Fig. 18 shows results for a relatively calm gust case. The improvement with BW time intervals is more rapid than either of the other two cases, suggesting that the event was more dominated by longer period boundary layer turbulence.

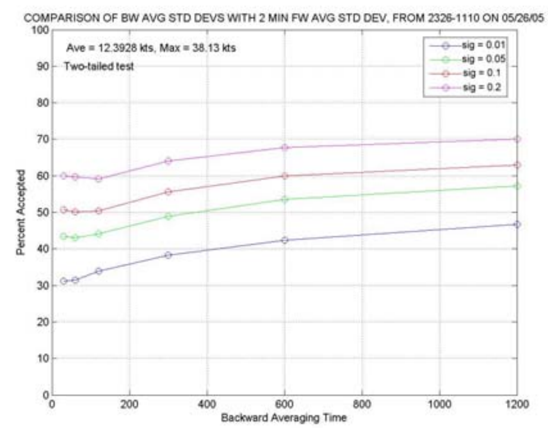

Fig. 16. Typical F-test results for high gust conditions.

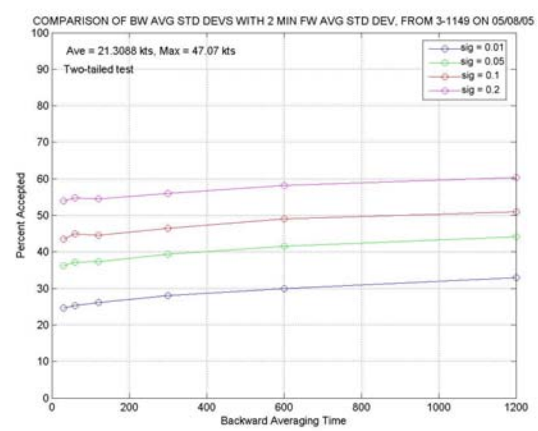

Fig. 17. Typical F-test results for very high gust conditions.

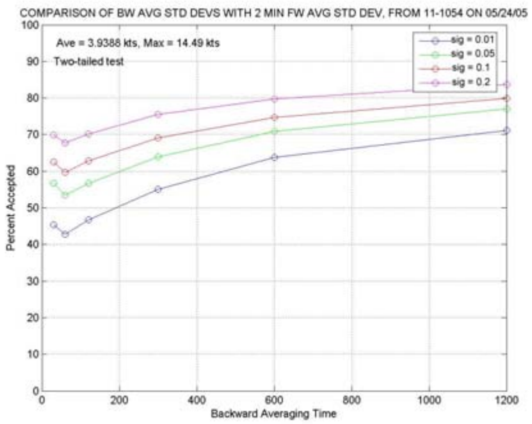

Fig. 18. Typical F-test results for relatively calm gust conditions.

5. WIND SPEED MAXIMA AND STANDARD DEVIATION

As noted in the last section, the statistical tests for comparing effects of different BW time sampling for estimating FW standard deviations were employed to evaluate and determine the best BW sampling times for predicting 2-min FW maximum wind speeds. This section demonstrates the efficacy of using standard deviations for estimating maximum values. The results support the possibility of using standard deviation of wind speed as an alternative means for establishing maximum wind speed or gust reports at airports. The concept is first explored via Monte Carlo simulation, sampling from a normal distribution. The results are illustrated in Fig. 19, which is a plot of the fraction of maxima in a statistical sample set that would exceed $k\sigma$ where k is the proportionality factor in Eq. 1 and σ is the standard deviation. The maximum wind speed in any statistical sample can be estimated by setting a number of samples out of the total sample that would be expected to exceed a given value of k. For example, a value of $k = 3$ means that ~6% of the data would exceed $k\sigma$; for a 2-min period with 1-s independent samples, this translates into ~7 samples exceeding this value of $k\sigma$. An expectation of 1 sample out of 120 implies a fraction of ~0.008; this suggests that a value of $k \simeq 3.7$ is needed to statistically stipulate the maximum value associated with a 2-min wind speed sample. The process is actually more complicated than this analysis, since the samples are not all independent. Autocorrelation computations on 1-s wind speed samples indicate that the correlation time can vary between around 3 to 20-s, depending on conditions. Using a decorrelation time of 5-s (consistent with ASOS sampling), leads to a maximum occurrence consistent with a probability of 1/24 = 0.042 or ~4%. The simulation in Fig. 19 indicates that the corresponding proportionality factor for translating standard deviation to a 5-s maximum gust should be ~3.1. This analysis demonstrates how the maximum deviation of wind speed from the mean wind speed can be estimated from the standard deviation of the wind speed.

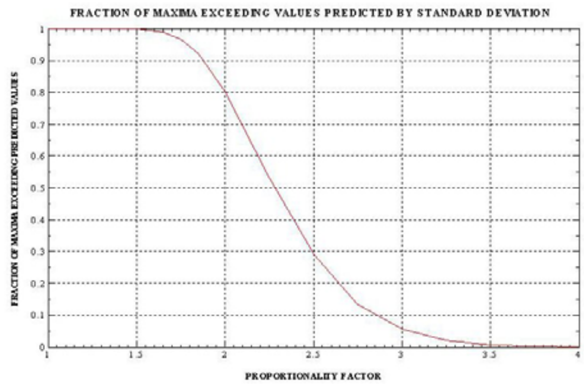

Fig. 19. Monte Carlo simulation results showing the fraction of maxima in a given sample that exceed values of the product of a proportionality factor k and the standard deviation.

Scatter plots were generated to test the standard deviation hypothesis. These consist of plots of peak deviation of the wind speed (defined as the maximum minus the sample average) versus the sample standard deviation of the wind speed. The sampling times were non-overlapping time intervals of 1-min, 2-min, 3-min, 4-min, 5-min, 6-min, 7-min, 8-min, 9-min, 10-min, 15-min and 20-min. These plots showed that the maximum deviation is about 3 times the sample standard deviation, consistent with expectations based on the previous simulation analyses. A sample plot for 5-min sampling times is shown in Fig. 20; the mean proportionality factor is readily seen to be ~3.

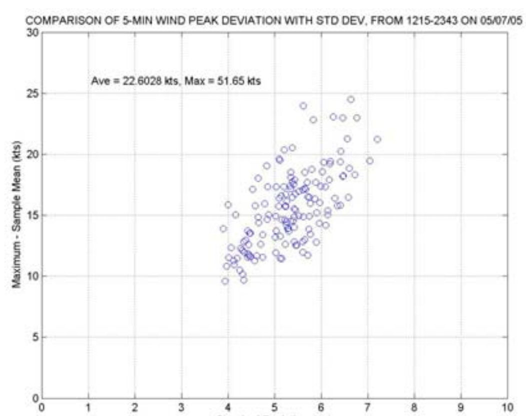

Fig. 20. Sample scatter plot of peak deviation vs. standard deviation for a 5-min wind speed sample data set.

In order to evaluate the hypothesis of using standard deviation to estimate maxima, comparisons of maxima derived from standard deviations and actual maxima were performed. A sample result is shown in Fig. 21 for 5-min samples and $k = 3$.

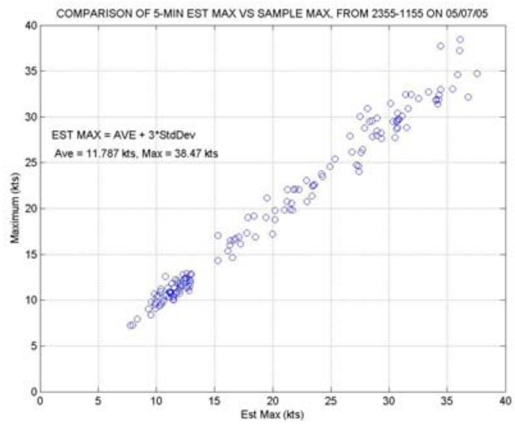

Fig. 21. Sample scatter plot of maximum wind speeds versus the estimated maximum wind speeds derived from the wind speed means and standard deviations.

It is of interest to examine the functionality of the standard deviation estimator for maximum wind speed, using the BW 10-min sampling period for the maximum and the 2-min BW for the maximum derived from the standard deviation. This is done through comparison of Figs. 22 and 23. Fig. 22 is a scatter plot that shows the dependence of the ratio of the predicted 2-min FW maximum wind speed based on the BW observed maximum value. The same ratio, using the standard deviation of the BW 2-min sampling period with $k = 3$ is given in Fig. 23. The results are strikingly similar to Fig. 22, implying that 2-min BW standard deviation can produce comparable estimates of FW 2-min maxima to those derived from 10-min BW maxima.

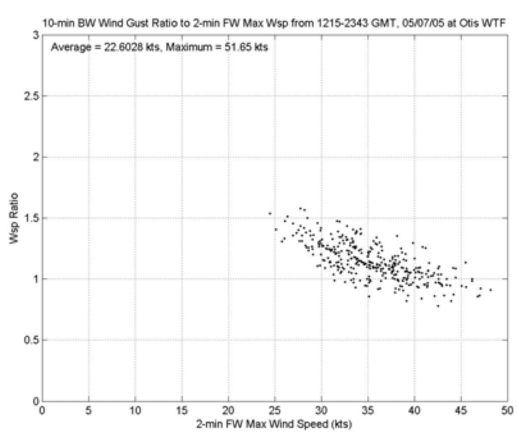

Fig. 22. Scatter plot of the ratio of the 10-min BW maxima to the actual 2-min FW maxima versus the 2-min FW wind speed maxima.

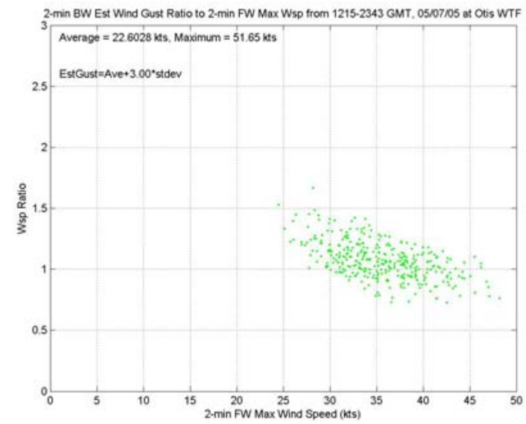

Fig. 23. Scatter plot of the ratio of the 2-min BW maxima estimated from the standard deviation to the actual 2-min FW maxima versus the 2-min FW wind speed maxima.

6. SUMMARY

This paper examined several simple methods of evaluating short-term wind speed/gust prediction, focusing on 2-min forward values estimated from backward wind data. The data analyzed in this paper suggest that 2-min BW averaging and 10-min look backs for gusts are reasonable standards, although the data provide evidence that 5-min BW averaging and look backs for both parameters should produce better results.

It appears that the use of standard deviation as a means for generating gust values has merit, and may possibly lead to effective means of improving gust reports, particularly during changing meteorological conditions. This hypothesis requires further in-depth study.

Finally, it is clear that a more sophisticated approach to reporting winds could improve predictions, reducing both missed reports and excess reports. Essentially, current methods used may be considered naïve compared to state-of-art time series analysis methods. The latter includes topics such 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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