10.3 COMPARISON OF RAPID UPDATE CYCLE (RUC) MODEL CROSSWINDS WITH LIDAR CROSSWIND MEASUREMENTS AT ST. LOUIS LAMBERT INTERNATIONAL AIRPORT†

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1. INTRODUCTION

Turbulence associated with wake vortices generated by arriving and departing aircraft pose a potential safety risk to other nearby aircraft, and as such this potential risk may apply to aircraft operating on Closely Spaced Parallel Runways (CSPRs). To take wake vortex behavior into account, current aircraft departing/landing standards require a safe distance behind the wake generating aircraft at which operations can be conducted. The Federal Aviation Administration (FAA) and National Aeronautics and Space Administration (NASA) have initiated an improved wake avoidance solution, referred to as Wake Turbulence Mitigation for Departures (WTMD). The process is designed to safely increase runway capacity via actively monitoring wind conditions that impact wake behavior (Hallock, et al., 1998; Lang et al., 2005).

An important component of WTMD is a Wind Forecast Algorithm (WFA) being developed by MIT Lincoln Laboratory (Cole & Winkler, 2004). The WFA predicts runway crosswinds from the surface up to a height of approximately ~300 m (1000 ft) once per minute and thus forecasts when winds favorable for WTMD will persist long enough for safe procedures for a particular runway (Lang et al., 2007). The algorithm uses 1–4 hr wind forecasts from the Rapid Update Cycle (RUC) model operated by the National Oceanic and Atmospheric Administration/ National Centers for Environmental Prediction (NOAA/NCEP) for upper atmospheric wind profiles.

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Detailed description of the RUC model can be found elsewhere (Benjamin et al., 1994; 2004a; 2004b). Briefly, the RUC model inputs are assimilations of high frequency observations from a suite of meteorological sensors, including Automated Surface Observing System (ASOS), rawinsonde profiles, satellite, airborne sensors from commercial aircraft, etc. The vertical layers of the atmosphere are resolved approximately isentropically. The model is run hourly, producing hourly forecasts out to 24 hours. The coverage of the RUC grid includes the continental United States, southern Canada, northern Mexico, and adjacent coastal waters.

Here we evaluate the performance of RUC in predicting crosswinds with reliability sufficient to support WTMD. For RUC validation, *in situ* wind profile data were obtained from a Light Imaging Detection and Ranging (LIDAR) deployed at St. Louis Lambert International Airport (STL).

The focus of this study is to provide a general quantitative characterization of the difference between RUC predictions and LIDAR measurements of the runway crosswinds. Particular attention was given to cases with inaccurate RUC crosswind forecasts, and cases when significant horizontal and vertical shears occur during situations of convective weather or proximity to large scale weather features, e.g., air mass fronts. (In practice, WTMD procedures and existing weather sources in the Control Tower will manage, to an acceptable level of risk, the hazard exposure associated with the extreme wind shift examples presented here.) Also included was examination of performance degradation with longer RUC forecast horizons and coarser horizontal resolutions, which may be relevant with regard to actual operational forecast data availability, or future applications of the operational concept to include arrival operations. A detailed report for this study is also available (Huang et al., 2007).

2. DATA DESCRIPTION

Two sets of data for STL Runways 12R/30L and 12L/30R are available for this study: LIDAR measurement data with 1-min time interval and RUC profile (hourly) initialization data from Feb.–Dec.

2004, and LIDAR data and RUC real-time (1-min) forecast data from Oct. 2006 to Jan. 2007. The 1-min LIDAR values were obtained after the original 5-sec data were passed through a 2-min median filter, and the 1-min RUC forecast data came from linear interpolation of hourly values (Macky et al., 2007; Huang et al., 2007; Robasky and Clark, 2007). Analysis for Runway 12R/30L is presented here.

2.1. 2004 Datasets

In 2004, a broad-angle scan scheme was applied to operate the LIDAR system. Thus, LIDAR coverage for the desired runways (12R/30L and 12L/30R) was limited to continuous scans of roughly 15 minute duration per each 75 minute interval. The available heights for LIDAR were 15–290 m.

The available data for RUC in 2004 were the model initialization data at each hour, i.e., the observational meteorological data reanalyzed for input of the RUC model. The RUC profiles from the surrounding 20-km RUC grid points have been interpolated to the location of the airport (Figure 1).

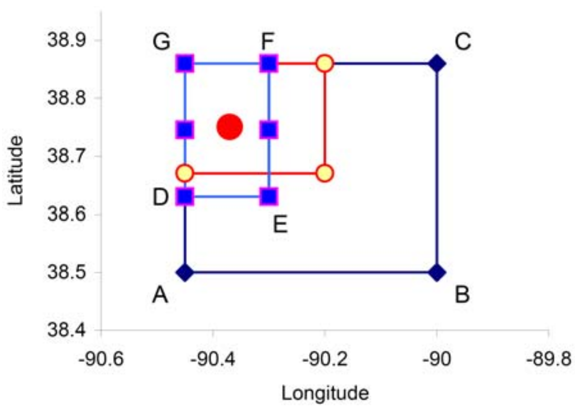


Figure 1. RUC grid positions surrounding STL. The diamond is the 40-km resolution grid (Oct. 2006, ended on Oct. 25, 2006). The yellow-filled circle is the 20-km resolution grid used in 2004. The blue-filled square is the 13-km resolution grid. The airport is marked with a red dot.

2.2. 2006–2007 Datasets

In Oct. 2006 – Jan. 2007, the LIDAR system was adjusted to scan the desired runways continuously, and it reached a larger vertical range (5–360 m). The RUC data came from archives of the WFA real-time forecast output stream. Thus, the RUC data were such that the 1–4-hr forecast crosswind values had already been converted to 1-min values. In addition, the RUC real-time forecast data at four nearby RUC grid points (40- or 13-km resolution) were recorded separately. The 40-km RUC grid was used prior to Oct. 25, 2006, and the 13-km grid was used thereafter. The RUC forecast horizon ranged from one to four hours. While RUC data of all grid points were analyzed, only those of Grid Point G are illustrated to cover periods of both 40- and 13-km resolutions.

3. METHOD

3.1. Data preparation

The crosswinds were computed from the horizontal wind components (u, v). LIDAR winds were processed via linear interpolation so that their height increment was five meters. The RUC crosswind at a particular height was aligned to the LIDAR crosswinds at the nearest 5-m level. Data for four height levels were compared: 25 m, 65–75 m, 120–140 m, and 200–235 m.

For 2006–2007 RUC data, the height-matching and grouping were performed similar to that for the 2004 data, except that 2006–2007 LIDAR data have six height levels available for comparison: surface RUC vs. 5-m LIDAR, 20 m, 60–65 m, 120–135 m, 195–220 m, and 315–360 m.

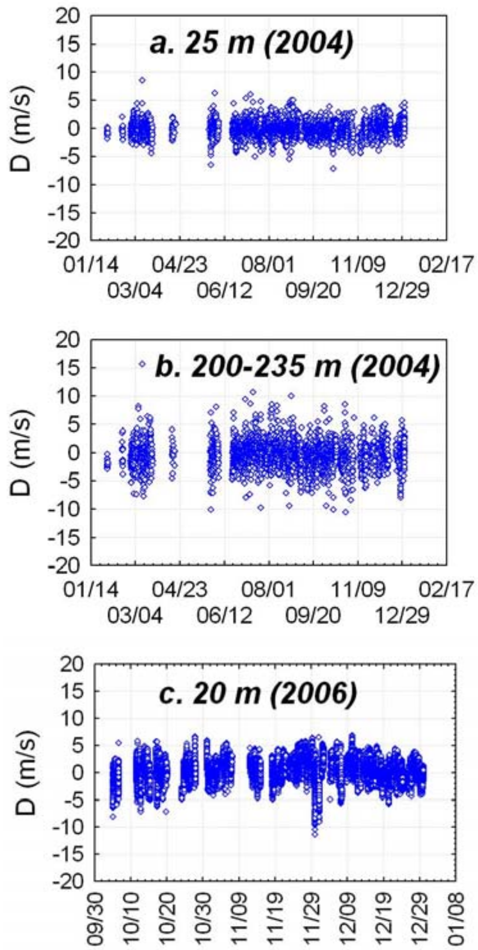
3.2. Data analysis

Data for Runway 12R/30L were analyzed for both datasets. At each height group, LIDAR and RUC data were first plotted for visual inspection of their temporal variations, correlations, and outliers. For pairwise comparison, the difference (D) between the RUC and LIDAR crosswinds was calculated. Histograms were constructed to study the frequency distribution of the LIDAR and RUC crosswinds as well as D. One-sample t-tests were used to evaluate the statistical significance of the RUC-LIDAR crosswind differences. Cases with large RUC-LIDAR crosswind differences were examined for their association with false WFA forecasts. Because the WFA is most susceptible to rapid wind shifts, special attention was paid to the cases with strong vertical windshear and frequent wind direction change. Crosswind differences for different RUC forecast horizon times were compared to determine whether RUC forecast performance degraded with increasing forecast horizons. Finally, differences from the RUC 40-km resolution were compared with those from the 13-km resolution.

4. RESULTS AND DISCUSSION

4.1. Similarity of temporal variations of RUC and LIDAR crosswinds

The temporal variations of LIDAR and RUC crosswinds are examined. Plots of RUC-LIDAR crosswind differences (D) at 20 m and 200 m levels are shown in Figure 2. The majority of the RUC forecast crosswinds show overall good accuracy and consistent variation over time. No severe degradation can be seen when comparing the RUC forecast crosswind with the RUC initialization crosswind. On the other hand, the RUC-LIDAR crosswind difference (D) has more extreme values for 2006–2007 (forecast data) than 2004 (initialization data), presumably owing to the additional variation associated with RUC forecast uncertainty. Furthermore, variation of the RUC-LIDAR difference increases slightly with height.



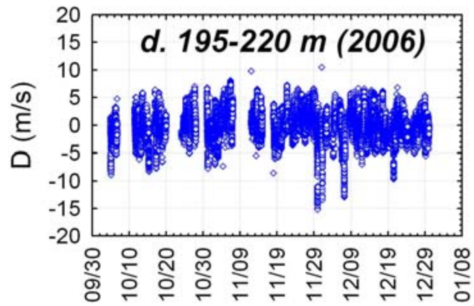
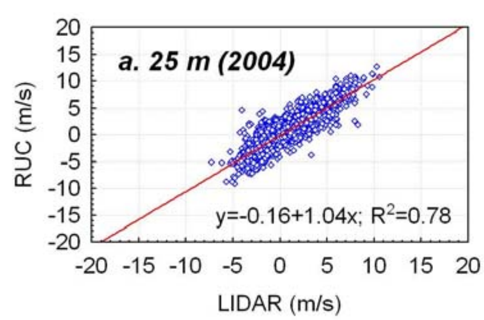


Figure 2. Temporal variation of the RUC-LIDAR crosswind difference (D, m/s) at different heights. a, b. 2004 RUC hourly initialization data. c, d. 2006–2007 RUC forecast data.

4.2. Correlations of RUC and LIDAR Crosswinds

The couplings of RUC and LIDAR crosswinds at different heights and at different magnitudes are examined by plotting the RUC crosswinds against the LIDAR crosswinds and performing linear regression analysis (Figure 3). A linear correlation between RUC and LIDAR crosswinds is clearly seen throughout the whole crosswind range. Moreover, the slopes of the regression lines are close to 1. (The median slope is 0.89 and the range of slope was 0.87–1.04 for 2004 data; it is 1.09 and 0.91–1.15 for 2006–2007 data.) The intercepts of the regression lines are close to 0. (The median intercept for the RUC hourly initialization data was -0.13 m/s with a range of -0.17 to -0.06 m/s, while the median intercept for the RUC forecast data was 0.03 m/s with a range -0.54 to 0.34 m/s). The bias direction and magnitude of the intercepts for the 2004 and 2006–2007 datasets are consistent and comparable. This further confirms the good agreement of the RUC (initialization and forecast) crosswind and LIDAR crosswind over a wide range of crosswind values. Also seen is that the 2004 dataset has far fewer outliers than the 2006–2007 dataset especially at high elevations.



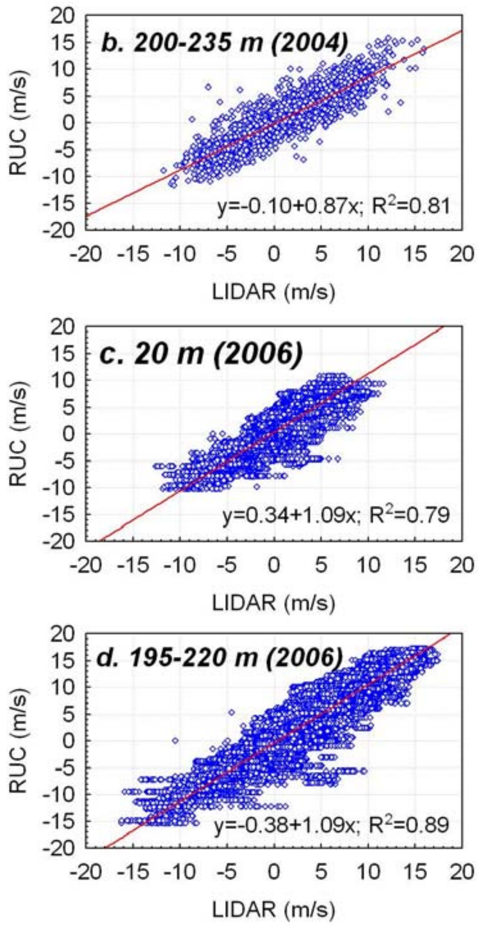


Figure 3. Correlation and linear regression of RUC and LIDAR crosswinds at different heights. a, b. 2004 RUC initialization data. c, d. 2006-2007 RUC forecast data.

4.3. Accuracy of Mean RUC Crosswinds

We use simple statistics, the mean and standard deviation of the LIDAR-RUC crosswind difference (D), to measure the deviation of RUC crosswinds. This choice is justified by the normal distribution of the values of D. For both RUC initialization data and RUC forecast data D is all centered near 0, suggesting little or no bias.

The summary statistics of the LIDAR, RUC, and their difference data, specifically arithmetic mean, standard deviation, standard error, median, minimum, and maximum, are listed in Table 1. For the RUC initialization crosswinds, the difference ranges from -0.40 to -0.13 m/s across all heights. For the RUC forecast crosswinds, the differences are -0.40 to 0.42 m/s. This deviation is well within the estimated wind speed measurement uncertainty of 1.8 m/s for the 10-km lower troposphere at a spatial resolution of ≤10 km and a temporal resolution of ≤10 min, and it is comparable to the reported accuracy of wind measurement using SODAR/RASS (Benjamin et al., 1999; Frech & Jolzapfel, 2006). In short, the forecast uncertainty of RUC crosswinds appears comparable to those associated with some other direct wind measurement systems.

The height-dependency of the RUC wind accuracy is visible in Figure 4, where the arithmetic mean crosswinds and crosswind difference are plotted. As the height increases, the RUC crosswind departs from the LIDAR crosswind more noticeably, and the variation of crosswind differences is larger. The sample standard deviation of D increases by 0.2–0.3 m/s from any individual height level to one level up for both RUC initialization data and RUC forecast data.

The variation of the RUC-LIDAR crosswind difference (1.3–2.5 m/s, standard deviations in Table 1) is comparable to previous studies using the 20-km resolution version of RUC. In one study, RUC showed a ~3.8 m/s of root-mean-square (RSM) wind vector difference (which is equivalent to the sample standard deviation of D in this study) from rawinsonde observations at the 850 mb level (Benjamin et al., 2002). In another study, a month of 3-hr surface forecast data from the RUC 20-km resolution model at 27 major U.S. airport hubs collected in Jan. 2002 showed a RSM wind speed bias of -4.2 to 3.3 m/s (it is -1 to 0.4 m/s with median of -0.05 m/s for STL) (Schwartz & Benjamin, 2002). Smirnova et al. (2004) compared surface forecast wind from the RUC 20-km resolution version with surface measurements made in New Hampshire for the period of Jul.17 – Aug.3, 2004. The wind speed bias is 0.14 m/s. Further, Benjamin et al. (2004c) compared RUC 10-m forecast wind speed against METAR observations over the full RUC domain during Apr.–Sep. and Oct.–Dec. 2002, and the RSM difference was 1.65–1.95 m/s for 1–6-hr forecast.

Table 1. Descriptive statistics for LIDAR and RUC crosswind data and their differences (D). The units are m/s.

1a. 2004 RUC initialization data

Height	25 m	65–75 m	120–140 m	200–235 m
LIDAR				
mean (s.d., stderr)	0.62 (2.33, 0.01)	0.86 (3.33, 0.01)	1.26 (4.37, 0.01)	1.77 (5.52, 0.01)
Median (min, max)	0.43 (-11.33, 17.17)	1.04 (-13.00, 21.40)	1.54 (-14.11, 21.51)	1.86 (-16.83, 21.63)
RUC				
mean (s.d., stderr)	0.58 (2.80, 0.04)	0.76 (3.48, 0.05)	1.06 (4.29, 0.07)	1.44 (5.28, 0.09)
Median (min, max)	0.71 (-9.13, 12.65)	1.00 (-10.59, 13.29)	1.38 (-11.62, 15.83)	1.68 (-17.27, 20.96)
D				
mean (s.d., stderr)	-0.13 (1.31, 0.02)	-0.15 (1.61, 0.02)	-0.27 (1.98, 0.03)	-0.40 (2.23, 0.04)
Median (min, max)	-0.12 (-7.10, 8.56)	-0.22 (-8.56, 11.41)	-0.29 (-10.08, 13.69)	-0.37 (-10.58, 15.63)

1b. 2006–2007 RUC forecast data, grid point G

Height	5 m	20 m	60–65 m	120–135 m	195–220 m	315–360 m
LIDAR						
mean (s.d., stderr)	0.72 (2.72, 0.01)	0.94 (3.01, 0.01)	1.36 (3.50, 0.01)	2.18 (4.54, 0.02)	3.09 (5.87, 0.02)	4.10 (7.37, 0.03)
Median (min, max)	1.03 (-11.01, 10.35)	1.39 (-12.58, 11.60)	1.87 (-14.09, 12.96)	2.82 (-15.24, 14.30)	3.41 (-16.22, 17.37)	4.20 (-19.12, 21.61)
RUC						
mean (s.d., stderr)	0.96 (2.81, 0.01)	1.36 (3.69, 0.01)	1.75 (4.46, 0.02)	2.34 (5.52, 0.02)	2.98 (6.78, 0.02)	3.70 (8.04, 0.03)
Median (min, max)	1.28 (-9.91, 8.55)	1.92 (-10.23, 10.76)	2.54 (-11.95, 12.47)	3.32 (-13.60, 14.12)	3.78 (-15.45, 17.30)	4.32 (-18.38, 20.38)
D						
mean (s.d., stderr)	0.23 (1.34, 0.005)	0.42 (1.71, 0.006)	0.39 (1.97, 0.007)	0.16 (2.14, 0.02)	-0.11 (2.30, 0.008)	-0.40 (2.50, 0.01)
Median (min, max)	0.26 (-9.08, 6.02)	0.48 (-11.38, 6.81)	0.50 (-11.64, 7.54)	0.30 (-13.71, 9.25)	-0.07 (-15.23, 10.50)	-0.32 (-17.06, 13.92)

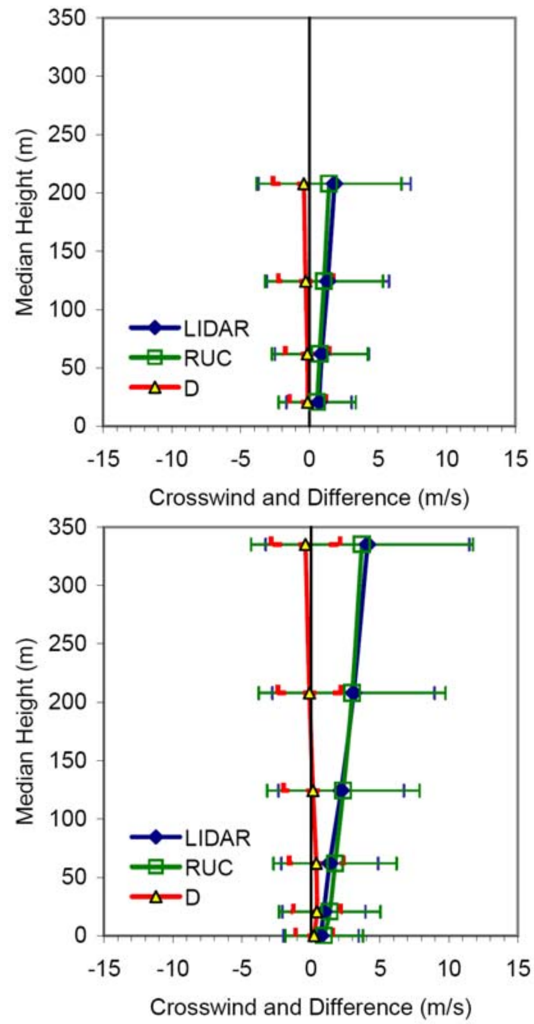


Figure 4. Mean LIDAR and RUC crosswinds and their differences at different heights. The error bars are one sample standard deviation (1 s.d.). Top. 2004 RUC initialization data. Bottom. 2006–2007 RUC forecast data.

The RUC model wind uncertainty is of the same magnitude as the inter-annual variation of winds. The sample standard deviation (*s.d.*) of the LIDAR crosswinds was higher by a range of 0.7 m/s (at 20–25 m height level) to <0.4 m/s (at higher elevations) from 2004 to 2006–2007. For RUC, the standard deviation increased by 0.9–1.5 m/s.

The ranges of crosswind values from RUC (initialization and forecast data) are either comparable or slightly smaller than those from LIDAR. Two possible explanations can account for this slightly reduced variability of RUC crosswinds. One, RUC 1-min data come from interpolation of the hourly forecast data, so they are likely to be smoother than the instantaneous (2-min) LIDAR measurement. Two, RUC data are representative of a large region while LIDAR is sensitive to localized events, thus the latter is likely to be more variable than the former.

For RUC initialization data, the difference between RUC and LIDAR winds can be attributed to measurement uncertainties, spatial and temporal variation of winds, and the methodology applied in the RUC initialization scheme. For RUC forecast data, additional variation in D can be attributed to RUC forecast skill uncertainty. Although based on different data sets, a comparison of the crosswind differences between the RUC initialization data and forecast data can be made to provide a rough estimate of the RUC mean model uncertainty in forecasting vector winds out to a few hours, which is 0.3–0.5 m/s for each similar height.

4.4. Case Studies

4.4.1. Episodes of large RUC-LIDAR crosswind difference

Periods of major differences are inspected individually and Figure 5 gives one example. Studies of weather conditions during these episodes indicate that large D times are mostly associated with rain storms, snow storms, and thunderstorms. (In practice, WTMD operations would not be allowed when these weather conditions are observed in the general vicinity of the airport.) Consistent with Figure 4, the RUC crosswind deviates from the LIDAR crosswind more severely at higher heights than at the lower levels when these events occurred. For the cases examined, only 3 out of 19 episodes were under clear weather conditions (~15%) and the corresponding RUC-LIDAR crosswind differences are relatively small compared to those during the weather events. Study shows that when these situations are encountered, RUC either improperly times the wind shift, or completely misses the shorter duration changes of local wind (Huang et al., 2007).

Examination of RUC errors in relation to WFA errors shows that the conservative nature of WFA prevents a majority of large crosswind errors (e.g., > 3 *s.d.*) from causing false predictions of crosswind favorable to avoid a wake vortex encounter. Study shows that during the analysis period, only four false green WFA error instances (0.036% of time) were detected.

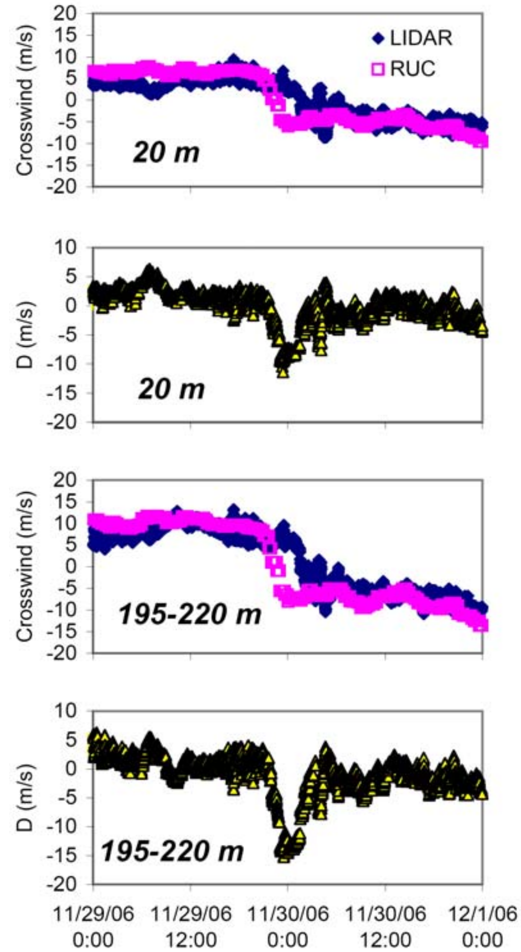


Figure 5. Crosswinds and RUC-LIDAR differences during a large D period (11/29/06-12/1/06).

Two of them are indeed related to the unfavorable wind above the surface, i.e., RUC errors, which occurred in association with the passage of synoptic-scale frontal systems. However, RUC errors associated with transient inclement weather would be less likely to affect safe WTMD procedures in practice, as the visible evidence of the approaching weather would allow opportunity for manual override (i.e., shut down) of WTMD operations.

4.4.2. Cases with strong vertical crosswind shear

The relationship of RUC crosswind accuracy and vertical windshear, an indicator of frontal events and/or thunderstorms, is studied. Individual vertical crosswind profiles of the cases with largest shear in 2004 (0.9 m/s/10m) and 2006 (1.5 m/s/10m) are also shown in Figure 6.

No strong general correlation between crosswind difference and vertical shear is observed (not shown). The RUC-LIDAR crosswind difference is again height-dependent, but the overall accuracy of the strong vertical shear cases is within the average range of all cases. Further, the bias due to windshear for the RUC initialization data and the forecast data seems to be in the same range.

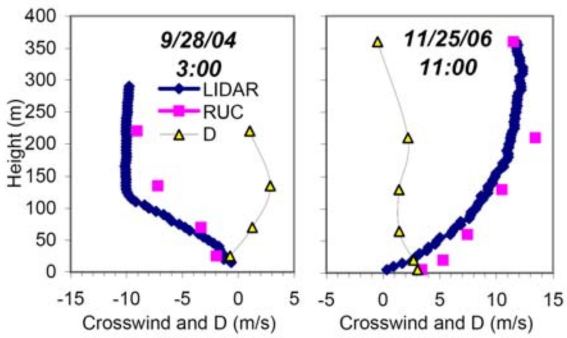


Figure 6. Vertical profiles of LIDAR (blue diamond), RUC (red square) crosswinds and their differences (yellow triangle) in units of m/s for cases when strong crosswind shear is encountered.

Again, this finding is consistent with previous studies about the RUC winds during storm environments. For example, one study showed the 0–6 km wind vector difference resulted in a mean error of -0.6 m/s and mean absolute error of 3.1 m/s (Thompson et al., 2000). Another study showed that for the RUC initialization winds, the RUC u-wind component was within 0.5 m/s of the observed values, and the v-wind was within 1 m/s difference range (Thompson et al., 2002).

4.5. Other comparisons

Other studies include the effect of the RUC forecast horizon (1–4 hr) and the effect of RUC horizontal resolutions (13 vs. 40-km). Different forecast horizons seem to result in similar mean RUC-LIDAR difference, although the 1-hr forecast seems slightly better than the rest at the height of 315–360 m, and the variation for the 4-hr forecast time also seems to be larger than those for shorter forecast time. Moreover, change in RUC horizontal resolution from 40 km to 13 km does not seem to affect the RUC crosswind accuracy greatly in our datasets.

5. CONCLUSIONS AND FUTURE WORK

This paper presents a general quantitative comparison of RUC forecast-derived crosswinds with high resolution LIDAR wind measurements at STL, at heights from near-ground to ~300m. The comparison suggests that the RUC crosswinds show reasonably good overall accuracy, and the RUC crosswind forecast can be a reliable source for obtaining crosswinds for the WFA.

Investigation of RUC performance in support of WTMD will continue for the demonstration system that is currently deployed at Houston International Airport (IAH). Additionally, it is recognized that the performance of RUC in estimating winds below 300 m (~1000 ft) may not be as reliable for airports whose local winds are affected by regional- or local-scale effects, such as thermally induced circulations (e.g. land-sea breezes) or topographical wind channeling. One candidate WTMD airport of note is San Francisco International Airport (SFO) which is subject to both phenomena, and will be the subject of further investigation. Additionally efforts will be needed to investigate the suitability of RUC wind forecasts to support Wake Turbulence Mitigation for Arrivals (WTMA), which would require a considerably longer wind forecast lead time.

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