4.4 COMPARISON OF WIND MEASUREMENTS AT THE HOWARD UNIVERSITY BELTSVILLE RESEARCH CAMPUS

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1. INTRODUCTION

The measurement of tropospheric wind is of great importance to numeric weather prediction, air transportation, and wind-generated electricity. Wind lidar technology allows higher temporal measurement of wind profiles with greater spatial localization than the radiosonde. These technologies are compared during a wind measurement campaign in February and March of 2009 at the Howard University Beltsville Research Campus (HUBRC) in Beltsville, MD. The instrumentation used in this campaign includes the Goddard Lidar Observatory for Winds (GLOW), VALIDAR, a LEOSPHERE WINDCUBE70, a wind profiler, radiosondes launched on site and at the National Weather Service (NWS) forecast office in Sterling, VA, and commercial aircraft wind observations. The second section gives the site and instrumentation descriptions. The third section makes comparisons between GLOW, VALIDAR and radiosondes during a clear sky case in February 2009, as well as qualitative comparisons between lidar, aircraft and radiosone. The fourth section gives comparisons between GLOW, VALIDAR, a LEOSPHERE WINDCUBE70, and radiosondes during a cold front passage in March 2009, as well as qualitative comparisons between lidar, sonde, and aircraft. The fifth section provides a summary.

2. SITE AND DATA DESCRIPTION

The HUBRC is located in Beltsville, MD, at 39.054°N latitude, -76.877°E longitude, or about 16 km northeast of Washington D.C. and is GMT-4 hours during daylight saving time. The instruments permanently located on site used in this analysis include a 915 MHz wind profiler (operated by the Maryland Department of the Environment), a Vaisala CT25K ceilometer, and a 30-meter tower instrumented with temperature, pressure, and relative humidity sensors, and a sonic anemometer. Unless otherwise noted, all ceilometer backscatter data has been averaged using a moving average of 10 minutes in time and 120 meters in the vertical.

Wind lidars located on-site for the measurement campaign include GLOW, VALIDAR, and a LEOSPHERE WINDCUBE70, all of which are ground-based and mobile. GLOW is a direct detection Doppler wind lidar using a double-edge molecular technique (Korb et al. 1998). During normal usage, it can profile into the lower stratosphere (up to 35 km) (Gentry et al. 2001), however, due to an etalon modulation problem discovered after the campaign (Chen 2011), GLOW was not able to produce usable data near clouds and in areas of heavy aerosol loading and there was a reduction in its vertical range. VALIDAR is a coherent Doppler wind lidar that uses a 2-μm wavelength laser to calculate the Doppler shift, providing wind speed and direction from the backscatter of atmospheric aerosols (Koch et al. 2007; 2010). The vertical range is dependent on sufficient aerosol concentrations and it is capable of profiling cirrus clouds. The WINDCUBE70 is a commercially-made wind lidar by LEOSPHERE. Like VALIDAR, it uses the Doppler shift from aerosol backscatter to calculate wind speed and direction and under cloudy or hazy conditions, has a maximum vertical range of 1.5 km. It is portable and can be carried by two people. During the campaign, the WINDCUBE70 had an incorrect optical prism installed that limited its vertical range to below what it would typically be.

Besides the wind lidars and permanent instrumentation at HUBRC, Vaisala RS92-SGP radiosondes launched on site and Sippican Mark IIA radiosondes launched twice-daily at the NWS office in Sterling, VA, (located near KIAD in Fig. 1) also provided wind profiles. Both types of radiosondes use Global Position System (GPS) to calculate wind data. The Vaisala sondes have a 2-second time resolution and the NWS sondes have a 1-second time resolution (which were obtained from the National Climatic Data Center's Radiosonde Replacement System – 1 Second BUFR data set). Wind observations from commercial aircraft using the Aircraft Communications Addressing and Reporting System (ACARS), were also used, but thus far in a qualitative sense for visual profile comparison. The data were obtained from the

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Meteorological Assimilation Data Ingest System (MADIS) database. ACARS data from aircraft taking-off and landing at the three surrounding major airports in Fig. 1 (BWI, DCA, and IAD) were used in addition to aircraft passing over the area. ACARS data were limited to within a 50 km radius of HUBRC. Unfortunately, the wind profiler was experiencing technical difficulties and was not reliably producing data until about the final week of the measurement campaign.

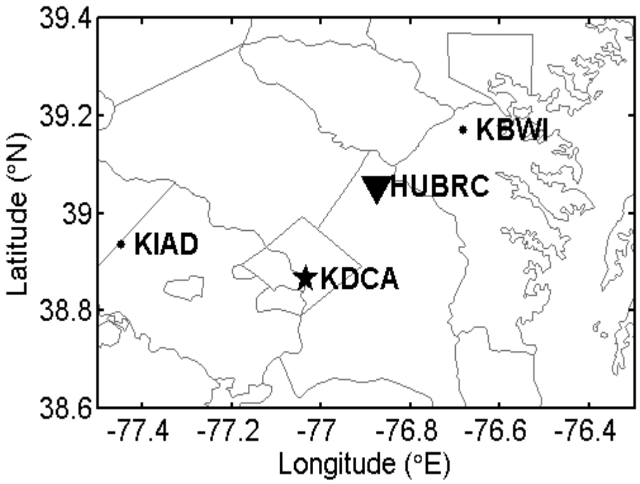

Figure 1. Locations of data collection in Maryland, Washington D.C., and northern Virginia. The station abbreviations are as follows: Baltimore Washington International Airport (KBWI) in Baltimore, HUBRC in Beltsville, MD, Regan National Airport (KDCA) in Washington D.C., and Dulles International Airport (KIAD) in Chantilly, VA. The Chesapeake Bay is located on the right side of the figure. It is approximately 50 km from HUBRC to KIAD.

3. CLEAR SKY COMPARISONS

The first time period selected for comparison is during clear conditions between 2300 UTC on 24 Feb and 0400 UTC on 25 Feb 2009. During this time, there were 2 RS92 radiosondes, launched at 0059 and 0329 UTC, a NWS radiosonde launched at 2312 UTC, and both GLOW and VALIDAR were in operation. The WINDCUBE70 had not yet arrived on-site. As seen in Fig. 2, the 30-meter tower temperature shows a nocturnal inversion present with the levels at the bottom of the tower being 3-4°C cooler than the top of the tower. The anemometer shows light northerly winds less than 2 m s^{-1} and the ceilometer backscatter does not indicate clouds at least up to 5 km.

Since radiosondes are the standard and most commonly used technology for measuring entire atmospheric profiles with high vertical resolution, the radiosondes launched during this time period are compared to the lidars. Fig. 3 shows the difference between the lidar and radiosonde wind speed profiles. For each sonde, sections of GLOW and

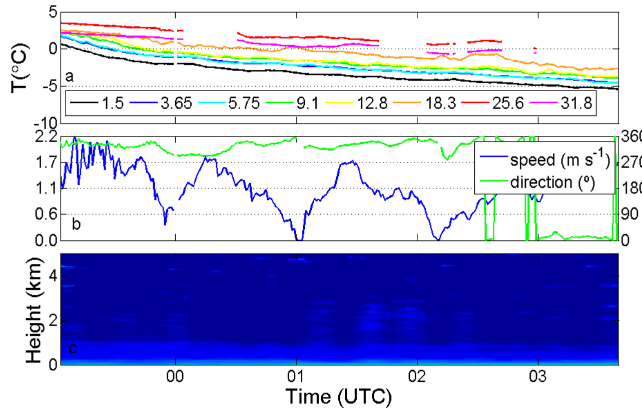

Figure 2. Ambient conditions from 2300 UTC 24 Feb – 0400 UTC 25 Feb 2009. (a) 30-meter tower temperature (heights indicated as meters above ground level (AGL) in the legend), (b) tower wind at 30 m AGL, and (c) ceilometer backscatter.

VALIDAR profiles that matched in time and height were located within the data and the corresponding section of the sonde profile was interpolated to the heights of the matching section of the lidar profiles. The GLOW profiles do not start until about the 2 km level due to sensor saturation near the telescope. The difference of the lidar minus the sonde speed is plotted and the root mean squared (rms) of the differences of all levels are calculated. The GLOW profiles are 33-minute laser shot moving averages every 3 minutes and the VALIDAR profiles are approximately every 3 minutes. The rms difference of the sonde with GLOW is generally less than 1.5 m s^{-1} and the rms difference with VALIDAR is generally less then 1 m s^{-1}. In the comparison with the NWS sonde, it should be noted how closely the differences of GLOW and VALIDAR mirror each other between 3 and 6 km. As a reminder, although the profiles are matched in time and height, they are not matched in location since the sonde drifts during flight.

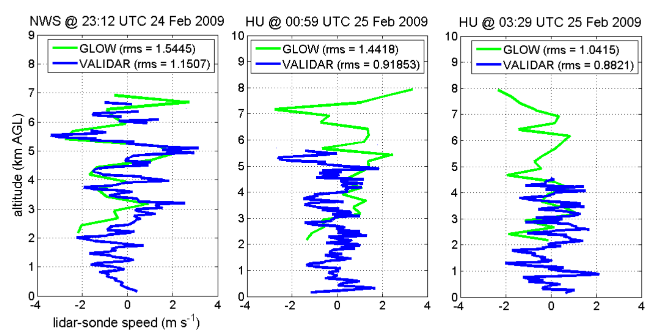

Figure 3. Difference of lidar minus radiosonde speed from profiles that are matched in time and height and interpolated to the lidar levels.

Examining the data in a more qualitative sense, Figs. 4 and 5 provide a visual comparison of wind speed and direction for data available during the sonde flight times. In both figures, the GLOW profile is a 33-minute shot averaged profile such that the averaging time of the profile begins near the sonde launch time and the GLOW error bars are the random uncertainty at each height level. The VALIDAR profiles are approximately a 15-minute (5-profile) average beginning at the sonde launch time. Its error bars are the standard deviation of the averaged data at each level. ACARS data are collected from the sonde launch time to 1 hour afterward within a 50 km radius of HUBRC.

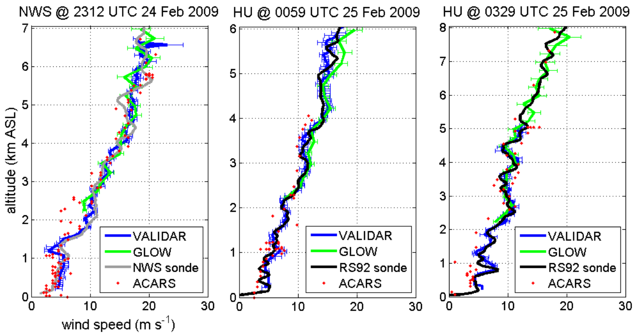

Figure 4. Wind speed of radiosonde, GLOW, VALIDAR, and ACARS during the sonde flights in the clear sky case analysis time period.

To compare the performance of the wind lidars relative to each other, we start by inspecting time-height data, shown in Fig. 6, to determine the usable vertical range and it appears that 5 km is a suitable maximum height. The intent of showing the ceilometer backscatter data is to identify areas of the data that may be unsuitable for GLOW to use. Heavy aerosol loading and areas of precipitation or virga affect the quality of GLOW due to the etalon modulation issue and the ceilometer can identify areas that should not be used. The areas of suspected precipitation or heavy aerosol loading appear as positive outliers in the distribution of the ceilometer backscatter data. The outliers are identified using a fourth-spread method detailed in section 2C of Hoaglin et al. (1983). Because the sky is clear for this analysis period, the lidar data will not be disregarded based on ceilometer backscatter.

Next, the data needs to be interpolated to the same points in time and height. So as to not generate data by interpolation, the lidar data are interpolated to the lowest time-height resolution of the data being used. Since both the GLOW and VALIDAR time resolution is approximately 3 minutes, the resolution of the GLOW data is used since its vertical levels are 250 m apart, whereas the VALIDAR levels are about 54 m apart. Both the ceilometer and VALIDAR are interpolated in time and height to the GLOW time-height resolution. Due to the sampling rate at which the backscatter is digitized and how many samples are used to form a range bin, VALIDAR has a velocity resolution of about 1 m s^{-1} and the data are given at discrete values. This can be seen in Fig. 7. Although the GLOW data are interpolated to the height level plotted in Fig. 7, its data are not produced at discrete values because it is a direct detection lidar. Since the GLOW profile used in the analysis is a 33-minute shot average, the VALIDAR data are calculated with an 11-profile moving average to approximately match the time resolution of the GLOW profiles and to account for the velocity resolution. After averaging the VALIDAR data, the result of interpolating it to the GLOW time-height resolution is shown in Fig 8.

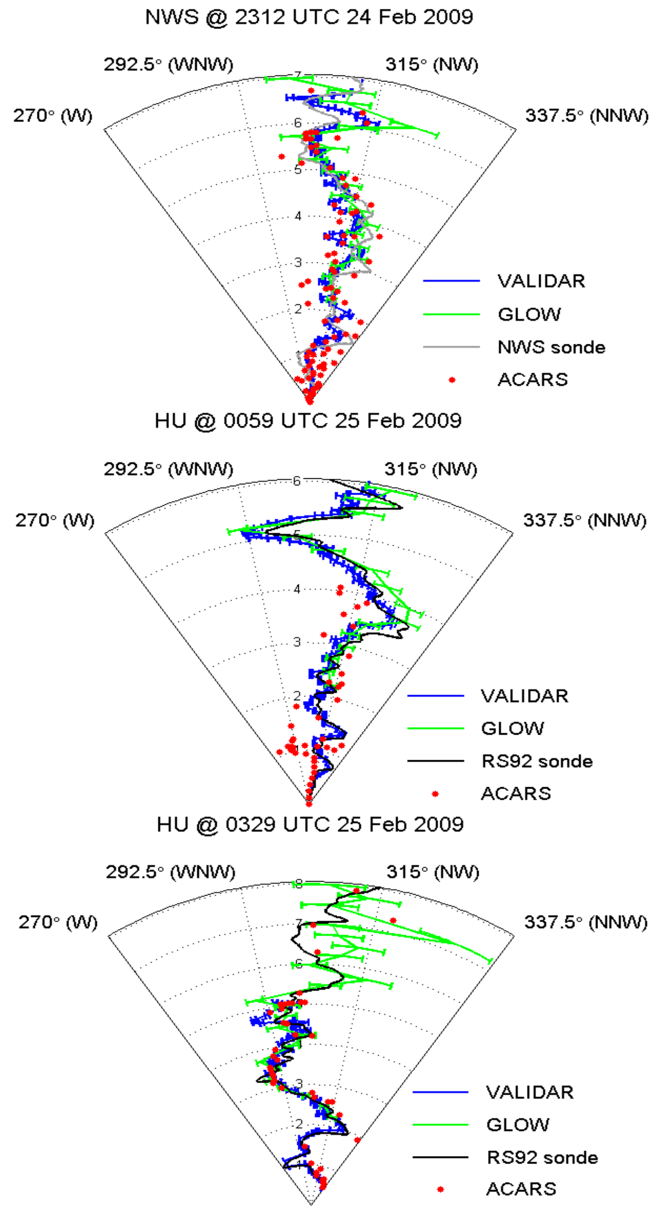

Figure 5. Wind direction of radiosonde, GLOW, VALIDAR, and ACARS during the sonde flights in the clear sky case analysis time period. Range rings are height (in km above sea level) and radials are wind direction (in degrees from true north).

With the data interpolated to the same time-height grid, each GLOW-VALIDAR wind speed pair was compared. A histogram of GLOW minus VALIDAR differences are shown in Fig. 9 and a linear regression of the data pairs is shown in Fig. 10. From the histogram and the regression equation, there is generally a ±1 m s^{-1} speed difference, with GLOW being slightly faster on average as indicated by the median of the distribution and the positive y-axis intercept of the regression equation. The correlation of the data pairs was found to be good, with a r^2 coefficient value of 0.88.

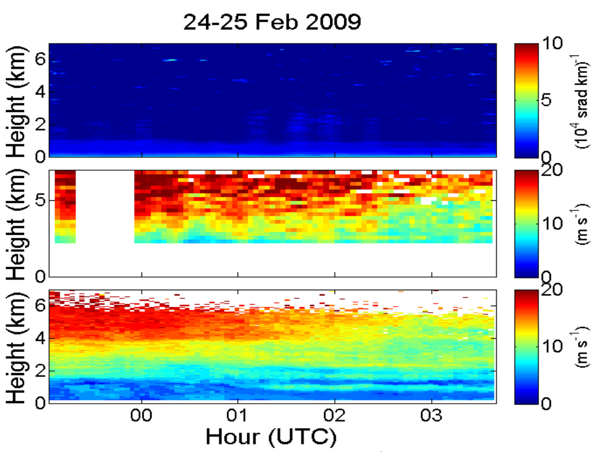

Figure 6. Wind lidar and ceilometer data for clear sky case. (top) ceilometer backscatter, (middle) GLOW 9-minute shot averaged wind speed profiles, and (bottom) VALIDAR wind speed.

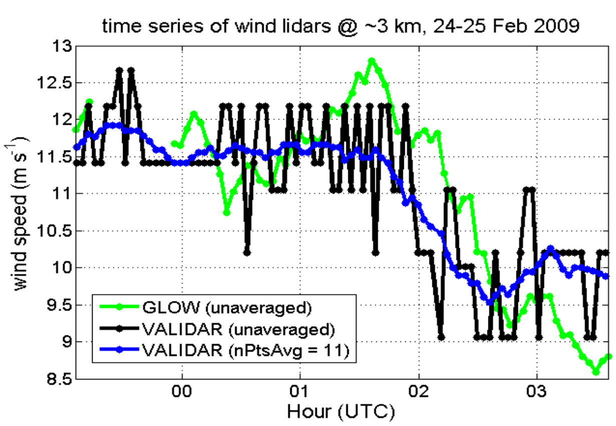

Figure 7. Time series of GLOW (33-minute shot average) and VALIDAR data at the VALIDAR height level nearest to 3 km. The GLOW data are interpolated to this height. The blue line is an 11-point moving average of the VALIDAR data.

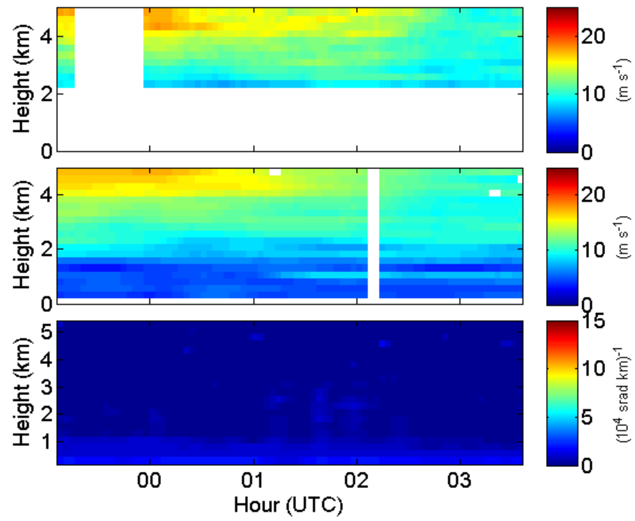

Figure 8. Time-height interpolated data for 24-25 Feb 2009. (top) GLOW (33-minute shot average) wind speed, (middle) VALIDAR wind speed with 11-point horizontal smoothing interpolated to GLOW resolution, and (bottom) ceilometer backscatter interpolated to GLOW resolution.

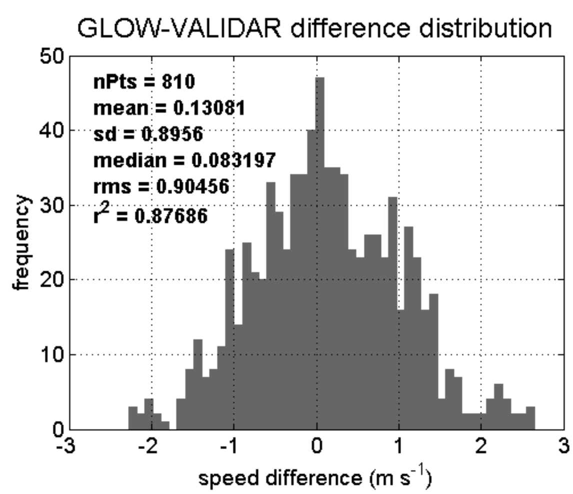

Figure 9. Clear sky case GLOW-VALIDAR wind speed difference distribution.

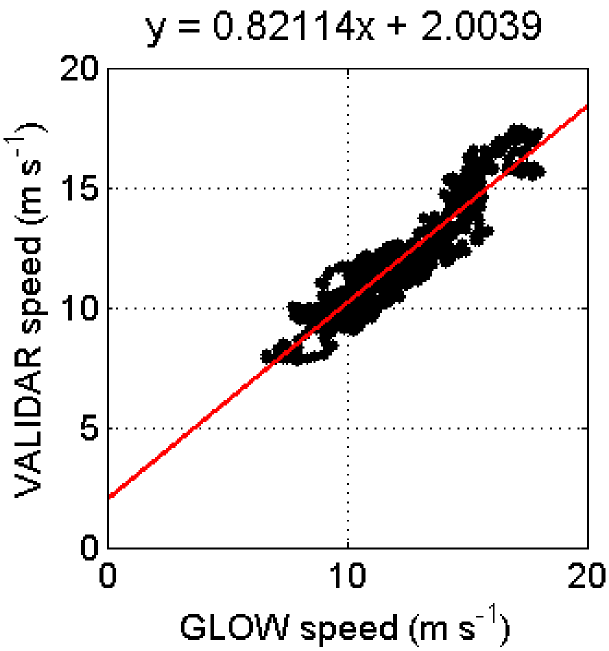

Figure 10. Linear regression of GLOW-VALIDAR clear sky points.

4. COLD FRONT COMPARISONS

The next time period selected for analysis is between 1815 UTC 11 March and 0215 UTC 12 March 2009 during the passage of a cold front. During this time, there was a RS92 radiosonde launched at 2223 UTC and a NWS radiosonde launched at 2306 UTC. In addition, GLOW, VALIDAR, and the LEOSPHERE WINDCUBE70 were in operation. During this time, to better compare with VALIDAR, GLOW was using only 5% of the power it normally uses, which allowed its usable range to begin below 1 km. Because of the presence of clouds, precipitation, and wind profiles that are more dynamic than in calm conditions, this analysis time serves to identify characteristics of operation in adverse weather conditions. The ambient conditions at HUBRC for this time period are shown in Fig. 11. The column of higher reflectivity before 1900 UTC in the ceilometer is precipitation. The cold front passed at approximately 2100 UTC, as indicated by the decrease in temperature, the increase in speed and variability of the wind, and the clearing of aerosols in the boundary layer. Sunset occurred shortly after 2300 UTC, confirming that the temperature decrease in not associated with the diurnal cycle.

Before looking at the sonde comparisons, the effect of the cloud cover on the vertical range of the lidars must be known. The ceilometer is indicating a well-defined cloud deck between 3 and 4 km between 1800 and 2330 UTC (Fig. 12). Because of the issue with GLOW, it can only profile reliably up to just below the cloud base. This is seen throughout the analysis time period as the usable range follows the cloud base and the apparent higher wind speeds at cloud level (Fig. 12) are an artifact of the etalon modulation issue. The vertical range of VALIDAR is also determined by cloud height. The VALIDAR usable data closely follows the cloud top height, above which aerosol concentrations are too low in the free troposphere to continue profiling. The altitudes used for this analysis time were from 1 – 2.5 km. Unlike the clear sky case, the ceilometer backscatter was used to identify areas of high aerosol concentration and precipitation. The areas that were removed for analysis were the rain shaft before 1900 UTC, the boundary-layer aerosols before 2100 UTC and the low clouds between 2200 and 2300 UTC between 1 and 3 km in the ceilometer backscatter (top panel in Fig. 12). As with the clear sky case, the GLOW data used are profiles produced every 3 minutes where each profile is a 33-minute moving shot average with a 250 meter vertical resolution. VALIDAR profiles are calculated using an 11-profile moving average of 3-minute profiles to approximately match the GLOW time resolution and these averaged profiles are interpolated to the GLOW time-height resolution. The results of the interpolation are shown in Fig. 13. The time-height ratio of GLOW to VALIDAR wind speed pairs in shown in Fig. 14. Notice that the shape of the areas whited-out correspond to the shapes of the higher-aerosol backscatter features in Fig. 12. The results of the analysis are given in Figs. 15 and 16. The rms difference of all the levels is about 1.86 m s^{-1} and the correlation coefficient is about 0.84, with GLOW tending to show slower speeds than VALIDAR. This also evident visually in the color plots in Fig. 13.

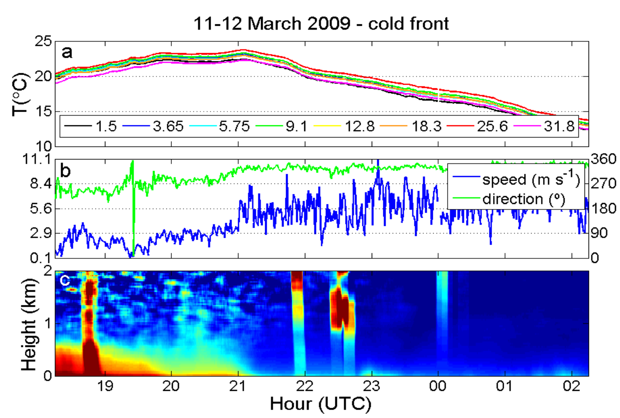

Figure 11. Ambient conditions from 1815 UTC 11 March – 0215 UTC 12 March 2009. (a) 30-meter tower temperature (heights indicated as meters above ground level (AGL) in the legend), (b) tower wind at 30 m AGL, and (c) ceilometer backscatter.

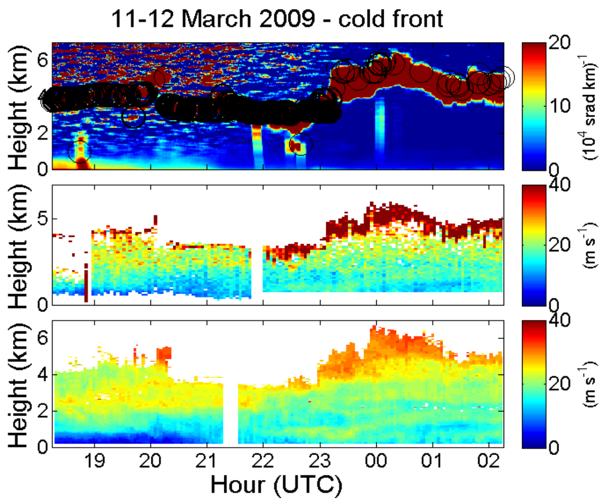

Figure 12. Wind lidar and ceilometer data for the cold front case. (top) ceilometer backscatter with ceilometer-indicated cloud base (O), (middle) GLOW 3-minute shot averaged wind speed profiles at 100 m vertical resolution, and (bottom) VALIDAR wind speed.

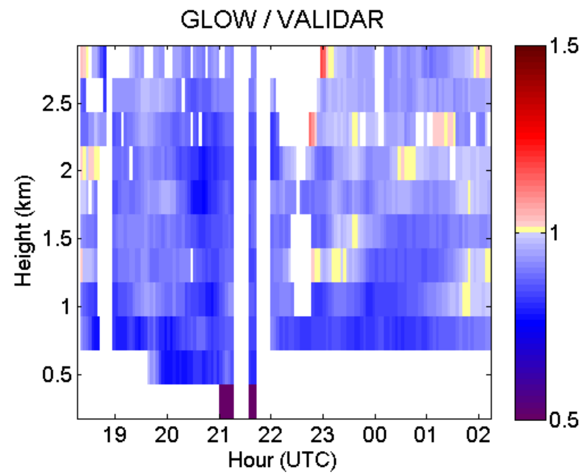

Figure 14. Ratio of GLOW to VALIDAR wind speed for the cold front case.

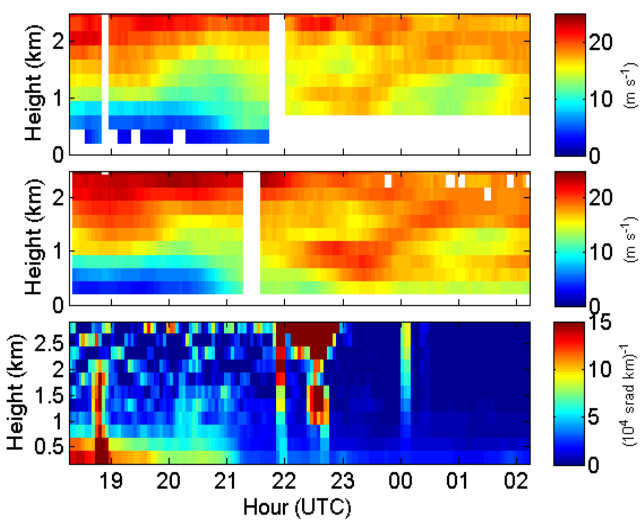

Figure 13. Time-height interpolated data for 11-12 March 2009. (top) GLOW (33-minute shot average) wind speed, (middle) VALIDAR wind speed with 11-point horizontal moving average interpolated to GLOW resolution, and (bottom) ceilometer backscatter interpolated to GLOW resolution.

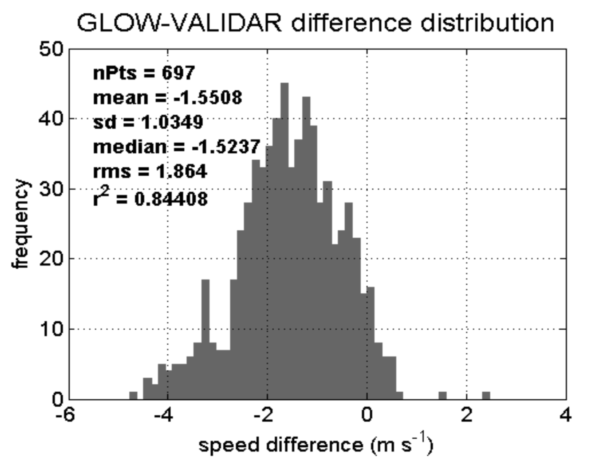

Figure 15. Cold front case GLOW-VALIDAR wind speed difference distribution.

After seeing how the lidar vertical ranges are affected by clouds, we can compare the lidar to the sondes. Fig. 17 shows the difference of the wind speed profiles of the sondes and lidars (sonde subtracted from lidar) matched in time and height. The rms difference for the cold front case is larger than for the clear sky case, possibly because there is more variability in the ambient wind profile in presence of stronger synoptic forcing and the vertical range of the lidar are reduced, allowing fewer points to be used for the analysis. Figs. 18 and 19 show wind speed and direction profiles for the cold front analysis time. The error bars and averaging times are those used in Figs. 4 and 5. During the NWS sonde, the excursion in GLOW wind speed and direction between 3 and 3.5 km is suspected to be a result of its laser issue. Again, as with the clear sky case, the profiles visually compare well.

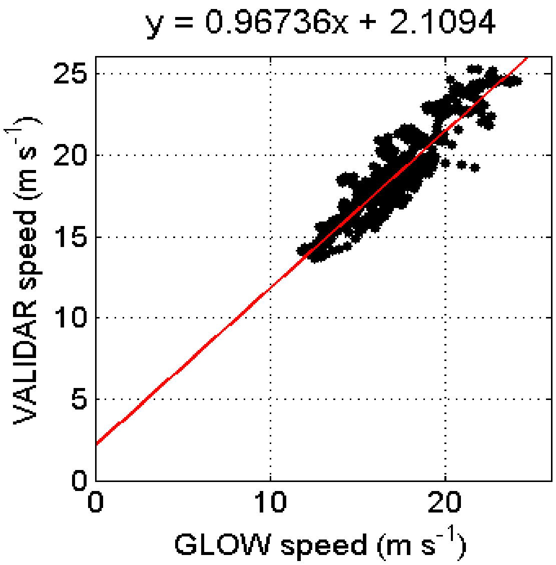

Figure 16. Linear regression of cold front GLOW-VALIDAR points.

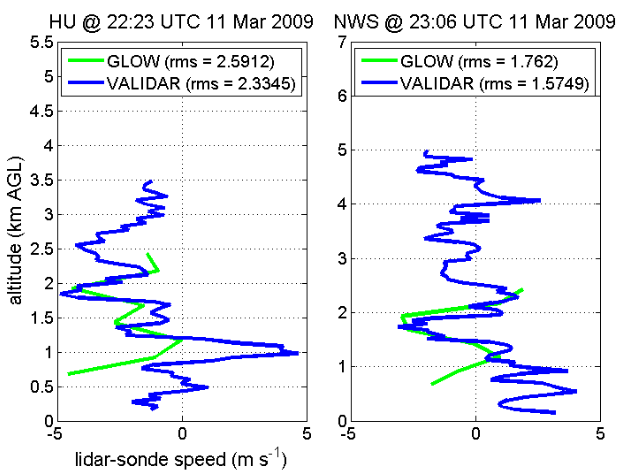

Figure 17. Difference of lidar minus radiosonde speed from profiles that are matched in time and height and interpolated to the lidar levels.

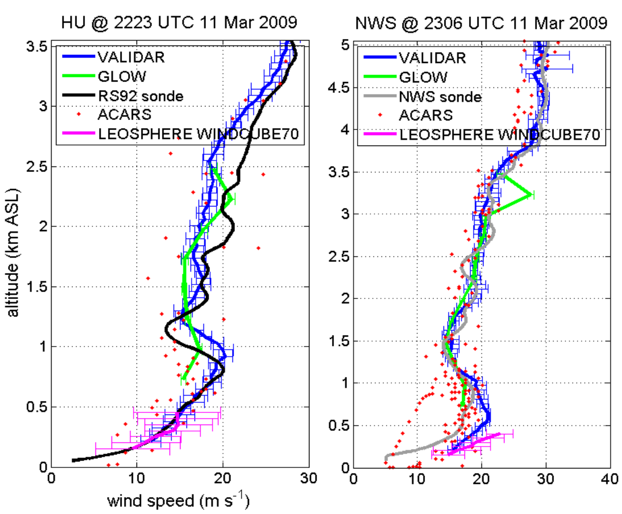

Figure 18. Wind speed of radiosonde, GLOW, VALIDAR, and ACARS during the sonde flights in the cold front case analysis time period.

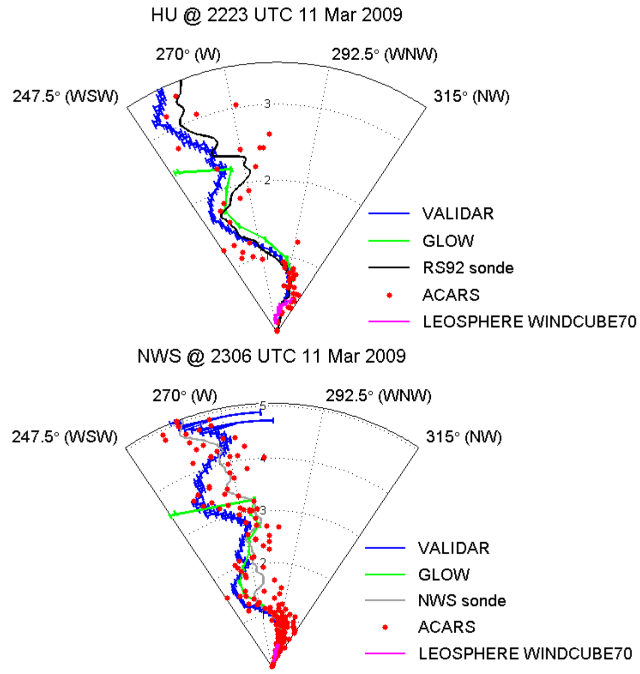

Figure 19. Wind direction of radiosonde, GLOW, VALIDAR, and ACARS during the sonde flights in the cold front case analysis time period. Range rings are height in km ASL and radials are wind directions.

The final portion of the cold front case examines wind speed comparisons between VALIDAR and the LEOSPHERE WINDCUBE70. The same analysis time is used as the GLOW-VALIDAR comparison (1815 – 0215 UTC), but the height is limited to 1 km. The data used during this time is shown in Fig. 20. Notice that the when the cold front passes, the vertical range of the WINDCUBE70 is reduced due to the lower concentration of boundary-layer aerosols. For the analysis, the data are interpolated to the VALIDAR time-height resolution (shown in Fig. 21) as the height resolution of VALIDAR is slightly lower than the WINDCUBE70 and the WINDCUBE70 produces a profile every minute. Before interpolating, the WINDCUBE70 data is averaged using a 9-profile moving average and the VALIDAR data is averaged using a 3-profile moving average to make the time resolution of the profiles similar and to allow VALIDAR to be averaged (as opposed to using a 3-profile WINDCUBE70 average and not averaging VALIDAR). The results of this comparison are shown in Figs. 23 and 22 with there being approximately a 1.4 m s^{-1} rms difference between the WINDCUBE70 and VALIDAR and a correlation of the interpolated wind speed pairs of almost 0.97. The quality of the comparison is also confirmed in Figs. 18 and 19 where the WINDCUBE70 compares well with the sondes and ACARS. For the speed profiles plotted in Fig. 18, the 2223 UTC sonde wind speed below 1 km seems to match VALIDAR and the WINDCUBE70 better than the 2306 UTC sonde, but it is noted that the 2306

UTC sonde is launched from 50 km away and this figure shows a reasonable amount of difference.

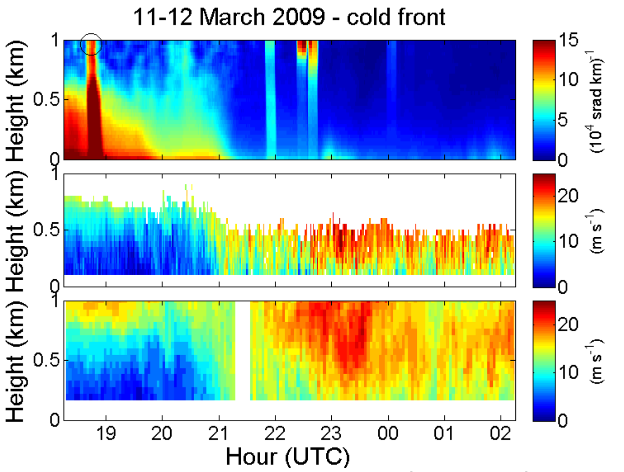

Figure 20. Wind lidar and ceilometer data for the cold front case. (top) ceilometer backscatter with ceilometer-indicated cloud base (O), (middle) LEOSPHERE WINDCUBE70 wind speed, and (bottom) VALIDAR wind speed.

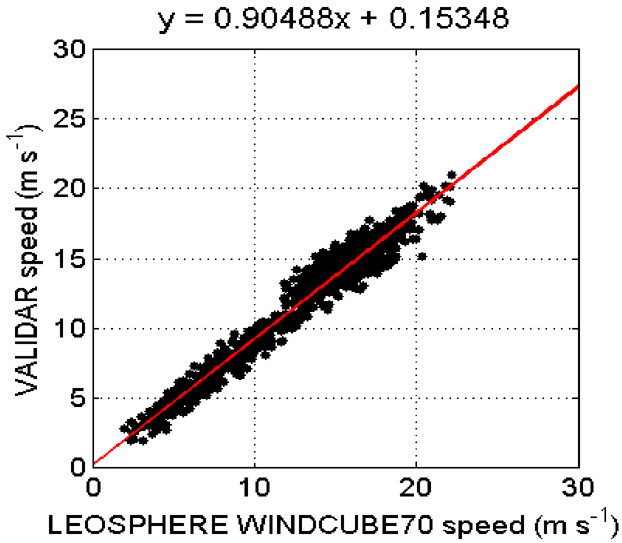

Figure 22. Linear regression of cold front WINDCUBE70-VALIDAR points.

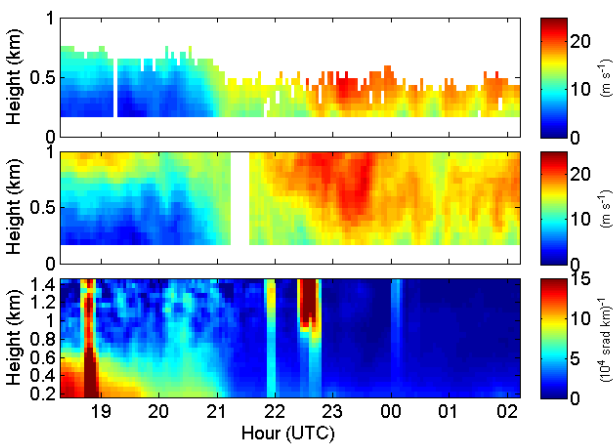

Figure 21. (top) LEOSPHERE WINDCUBE70 wind speed with 9-point horizontal moving average interpolated to VALIDAR resolution, (middle) VALIDAR wind speed with 3-point horizontal moving average and (bottom) ceilometer backscatter interpolate to VALIDAR resolution.

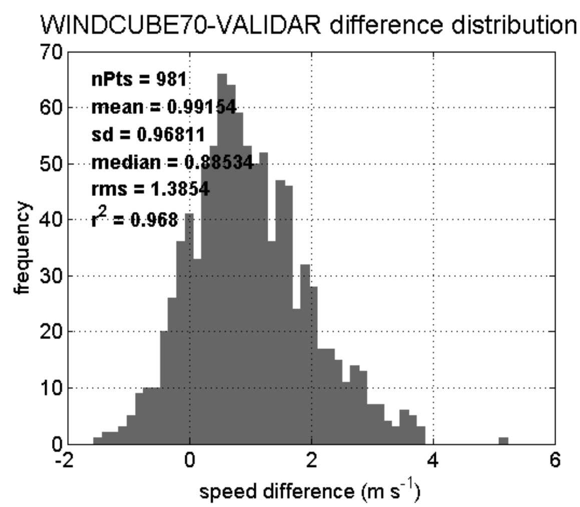

Figure 23. Cold front case WINDCUBE70-VALIDAR wind speed difference distribution.

5. SUMMARY

During the wind measurement campaign at the HUBRC in February and March of 2009, three different wind lidars were operated side-by side and compared with radiosondes launched on-site and from the NWS office at Sterling, VA, and with ACARS aircraft data. Table 1 summarizes the parameters and results of the wind speed comparisons. In the comparisons with radiosondes, GLOW generally has a rms difference of less than 1.5 m s^{-1} and VALIDAR has a rms difference about 1 m s^{-1}. The agreement between the WINDCUBE70 and VALIDAR is encouraging since both instruments use the same measurement principles. Although directional information was not included in the numeric analysis, Figs. 5 and 19 show, at least in a qualitative sense, that the wind directions also compare favorably.

The reader is reminded that GLOW and the LEOSPHERE WINDCUBE70 were not operating in optimal conditions. GLOW had an etalon modulation issue that was not discovered until after the campaign and is being investigated now for correction. In addition, it was operated at 5% of normal laser power for a portion of the cold front case analysis time period. This limits the altitude range that data will be recorded, but makes it possible to compare with the other wind lidars. The WINDCUBE70 came installed with an incorrect optical prism that was limiting its vertical range. Note also that the averaging time used for the GLOW-VALIDAR comparisons was about 33 minutes (each GLOW profile was made from a 33-minute moving average of the laser shot counts and the VALIDAR data were an 11-profile moving average of 3-minute profiles) and was 9 minutes for the WINDCUBE70-VALIDAR comparisons. The rationale for using the longer averaging times in the comparisons is that the 3-minute (not averaged) profiles of GLOW and the 1-minute profiles of the WINDCUBE70 are able to capture smaller-scale variability, but the ~1 m s^{-1} resolution imposed in the data analysis of VALIDAR wind speeds sets an artificial boundary for the data that can mask the amplitudes of the smaller-scale features and processes. It is possible that the VALIDAR data could be processed at a finer resolution, but option to do this was not available at the time of the measurement campaign. Having a smaller VALIDAR wind speed resolution may permit comparisons with shorter averaging times and capture smaller-scale variability features. Despite this limitation for temporal comparisons, both GLOW and VALIDAR compared well when matched with radiosonde profiles.

	GLOW-VALIDAR	WINDCUBE70-VALIDAR
Height range (km AGL)	1 – 5 (clear) 1 – 2.5 (cold front)	0 – 1
Averaging time (minutes)	33	9
Vertical resolution (m)	250	54
r^2 correlation coefficient	0.88 (clear) 0.84 (cold front)	0.97
regression	y = 0.82x + 2.0 (clear) y = 0.97x + 2.1 (cold front)	y = 0.90x + 0.15
rms difference (m s^{-1})	0.90 (clear) 1.86 (cold front)	1.39

Table 1. Numeric results of GLOW, VALIDAR, and WINDCUBE70 comparisons.

6. ACKNOWLEDGMENTS

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7. REFERENCES

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8. CITATION

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