



Shipboard multisensor merged wind profiles from the New England Air Quality Study 2004

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[1] The New England Air Quality Study (NEAQS) was a regional portion of the International Consortium for Atmospheric Research on Transport and Transformation (ICARTT) planned by groups in North America and Europe to develop a better understanding of the factors that shape air quality in their respective regions and the remote North Atlantic. The NOAA research vessel *Ronald H. Brown* was only one of a number of platforms given the task of monitoring the emissions of aerosol and ozone precursors and the atmosphere in which they reside. Two remote and one in situ sensor were used to measure wind profiles. A radar wind profiler (RWP) permanently deployed on the ship and corrected in real time for ship motion provided continuous hourly profiles at 60- and 100-m vertical resolutions. A high-resolution Doppler lidar (HRDL) was also operated during the experiment and provided continuous low-level wind profiles. Rawinsondes were launched 4–6 times daily and provided a detailed profile of winds. Initial results show that the RWP, HRDL, and rawinsonde data compare very well. The ability of HRDL to monitor low-level winds below the minimum range gate of the RWP, while the RWP wind data extend to a much greater height than can be reached by HRDL, make the two systems complementary. Single merged profiles were generated using the RWP and HRDL data, which in turn were used to calculate trajectories to help better understand the transport of pollutants within the Gulf of Maine.

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1. Introduction

[2] During summer 2004 a unique set of instruments was deployed on board the NOAA research vessel *Ronald H. Brown* (*RHB*) as part of the New England Air Quality Study (NEAQS). NEAQS is a regional portion of the International Consortium for Atmospheric Research on Transport and Transformation (ICARTT) planned by groups in North America and Europe to develop a better understanding of the factors that shape air quality in their respective regions and the remote North Atlantic. The *Ronald H. Brown* was only one of a number of platforms, including land sites and aircraft, given the task of monitoring the emissions of aerosol and ozone precursors and the atmosphere in which they reside.

[3] This paper will discuss three primary sensors, two remote and one in situ, used to measure wind profiles. Rawinsondes using Global Positioning System (GPS) wind tracking were launched 4–6 times daily, providing a detailed profile of winds. A radar wind profiler (RWP)

permanently deployed on the ship and corrected in real time for ship motion, provided continuous hourly profiles at 60- and 100-m vertical resolutions. A high-resolution Doppler lidar (HRDL) with 30-m along-beam resolution was operated during the experiment by NOAA's Earth Systems Research Laboratory (ESRL; formerly the Environmental Technology Laboratory; ETL). Each instrument has its own strengths and limitations. This paper will compare data from the three instruments and discuss the unique opportunity of combining RWP and HRDL data into a single profile that is a much more useful representation of the winds.

[4] Initial results show that rawinsonde (balloon), RWP, and HRDL data compare very well. Limitations with the minimum range of the RWP and possible sea-clutter contamination in the lower 0.5 km can be overcome by using HRDL to fill in to lowest levels. In a similar fashion height coverage of HRDL can be augmented by the RWP. The radar and lidar systems operated unattended providing continuous profiles, while the balloon provided a full atmospheric profile, but only episodically when launched by the crew.

2. System Descriptions

[5] Figure 1 shows the RWP antenna, with the turtle-shell-like protective cover, mounted aft starboard side. The *RHB* system [Law *et al.*, 2002] is a low-power 915-MHz

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Figure 1. Electronically stabilized phased array 915-MHz antenna (arrow): NOAA research vessel *Ronald H. Brown* looking aft.

RWP designed to gather atmospheric data to altitudes of 3–5 km AGL nominally. If precipitating clouds are present, scattering from the water droplets makes it possible to obtain data at higher altitudes. This system is composed of three major components: the 90-element phased array antenna, the motion control and monitoring system (MCM), and the signal processing system (SPS). The electronically stabilized antenna has the capability of compensating for ship motion (roll, pitch, yaw) at 10 Hz through monitoring the ship's motion and computerized control of each element in the phased array antenna. Real time displays of motion-corrected winds are available to the scientists on board through a separate user computer. For NEAQS, standard output was 60-min averaged winds for the RWP and 7 min averaged winds measured every 15 min for HRDL. Both RWP and HRDL are capable of producing winds with higher temporal resolution.

[6] The RWP system on board the ship employs ESRL's advanced multiplex-picking signal processing system that provides meteorological products from averaged Doppler spectra [Wolfe *et al.*, 2001; Weber and Wuertz, 1991]. It differs from the traditional "consensus" signal processing in recognizing that averaged Doppler spectra may contain multiple spectral peaks, where the atmospheric signal may not be the strongest. Also incorporated into the signal processing is real time motion compensation.

[7] The high-resolution Doppler lidar [Grund, 1995; Grund *et al.*, 2001] developed at ESRL, obtained unique high temporal and spatial resolution wind measurements aboard *RHB* during the NEAQS 2004 field campaign. This Doppler lidar (Figure 2), an active remote sensing system with a motion compensated hemispheric scanning capability, is similar in many respects to the more familiar Doppler weather radar, except it uses a solid state laser to transmit eyesafe near infrared ($2.02 \mu\text{m}$) radiation instead of radio-frequency waves. During this project, the lidar transmitted an 8 cm diameter, diffraction limited beam (0.3 mrad divergence). Having no sidelobes, the lidar can scan to within a few meters of the surface of the ocean (limited by the stability of the motion compensation system). Although the along-beam range resolution of the lidar pulse is 30 m, low angle scanning allows for much finer vertical resolution in the calculated wind profiles.

[8] The principal scattering targets at this wavelength are atmospheric dust and/or aerosol particles. They are ubiquitous in the lower troposphere and allow the lidar to obtain

signal in clear air. The lidar operates with a pulse repetition frequency of 200 Hz and provides range resolved estimates of aerosol backscatter, which is related to aerosol concentration and line-of-sight (LOS) wind speed at a rate of 2 Hz. Depending on the availability of scattering targets, the lidar can typically measure wind speed radially out to 3–5 km with a precision of 0.1 m/s in the high signal strength region. Such a region is usually defined by the aerosol boundary layer, typically from the surface to 2 km altitude, although the presence of thin cirrus or additional aerosol loading can often extend this region to higher altitudes. In this project, the height of the measurement was limited by either optically attenuating clouds at the top of the marine boundary layer or the lack of scattering targets above.

[9] Using a differential GPS orientation sensor, the real time motion compensation system corrects for changes in ship orientation by adjusting the pointing of the hemispheric scanner. This allows for scans at a constant low elevation angle independent of changing platform orientation. The system also provides correction to the LOS velocities due to platform motion.

[10] During NEAQS, HRDL operated continuously from 9 July through 12 August 2004 with only occasional interruptions occurring during heavy rain, dense fog, and system maintenance. The scanning strategy used during NEAQS included sweeps along both constant azimuth and elevation angles to provide high vertical resolution information on wind speed, turbulence, and the distribution of aerosols in the boundary layer. A series of full azimuth scans at increasing elevation angles (typically 2, 7, 12, and 30°) were used to provide both high vertical resolution near the surface and adequate vertical coverage through the top of the marine boundary layer. This scan sequence took approximately 7 min and was repeated every 15 min. Because the sequence combines LOS wind speed data from several elevation angles (and hence several inherent vertical resolutions), the data are sorted by height into a grid with exponentially decreasing resolution (from 5 m at the surface to 55 m at a height of 2.0 km). The data at each height bin were processed to produce vertical profiles of the horizontal



Figure 2. High Resolution Doppler Solid State Lidar (HRDL) system on board the NOAA research vessel *Ronald H. Brown* looking aft.

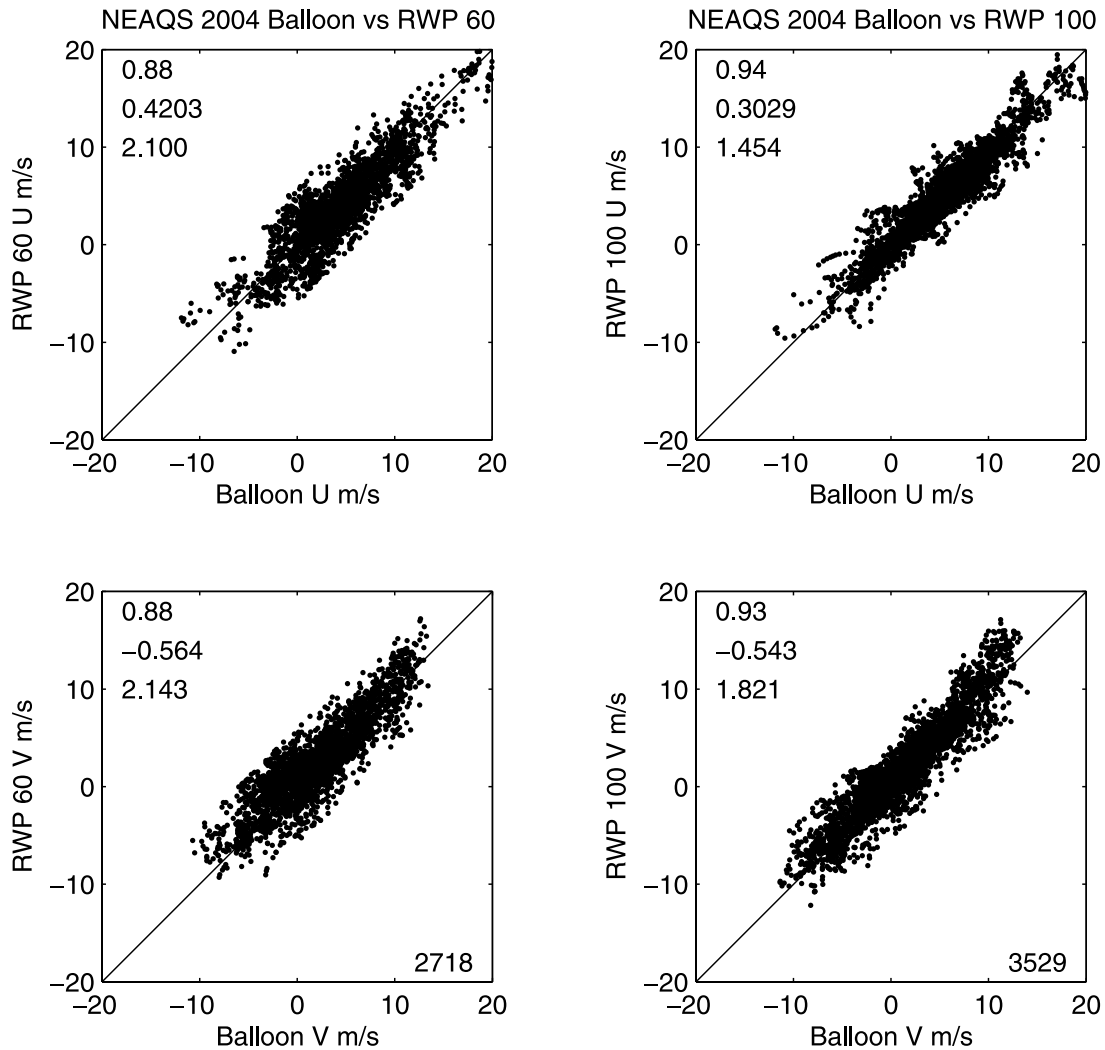


Figure 3. U/V horizontal wind component scatterplots from NEAQS 2004. RWP versus balloon: 60- and 100-m modes for all heights. Values in the upper left corner are correlation coefficient, mean difference, and standard deviation of differences. The number in the lower right corner is the number of points in this comparison.

wind using the velocity-azimuth display (VAD) technique [Browning and Wexler, 1968].

[11] The balloon sounding system used GPS wind finding digital rawinsondes. A total of one hundred and twenty-three balloons were launched at 4–6 hour intervals and for special events such as an aircraft flyover. Standard 5 m s^{-1} average ascent rates produced 10-m vertical resolution temperature, relative humidity (RH), and wind profiles. The new digital sonde made it possible to obtain accurate wind profiles immediately above the release point. Of course, unlike the RWP and HRDL, the balloon drifts downwind, hence its wind profiles are not vertically aligned above the ship. This difference introduces uncertainty and accounts for some of the discrepancy when comparing the balloon-borne rawinsonde profiles with those from the remote sensors.

3. RWP, HRDL, and Rawinsonde Comparisons

[12] The NEAQS cruise took place in July and August 2004 and monitored the boundary layer within the Gulf of

Maine in support of ICARTT and regional air pollution interests. Balloon soundings were compared to both RWP and HRDL hourly average winds. For this comparison, HRDL data from all azimuthal scan sequences over an hour were combined to form hourly averaged wind profiles. Balloon launch times were matched to the nearest 60-min averaged RWP and HRDL data. Data not within a ± 15 min window of launch times and cases where there were problems with one of the measurement systems were removed from this comparison. Balloon, RWP, and HRDL wind speed and direction data were converted to U and V components. Balloon data were then linearly interpolated to the same wind levels measured by the RWP and HRDL, respectively, to provide both temporal and spatial consistency among all three measurement systems.

[13] Scatterplots for the balloon and RWP horizontal U and V wind components appear in Figure 3 for the 60- and 100-m vertical resolution modes. Mean differences between RWP and balloon winds were small and consistent with previous comparisons [Weber and Wuertz, 1990; Martner et al., 1993] for land-based RWPs. Results from the 60 m

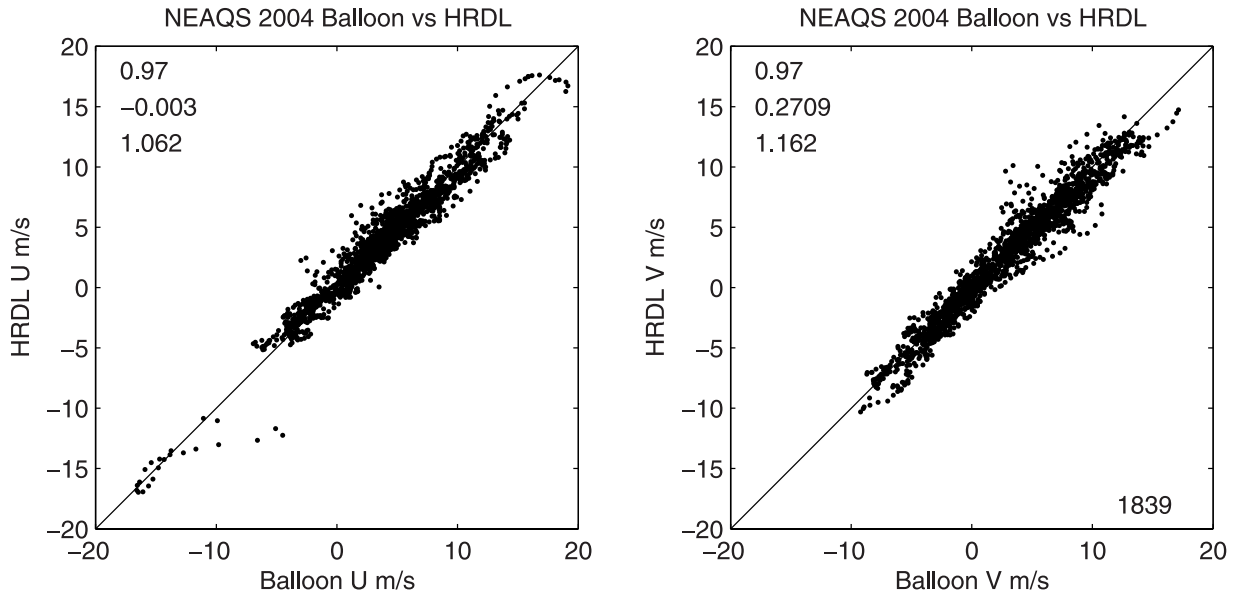


Figure 4. U/V horizontal wind component scatterplots from NEAQS 2004. HRDL versus balloon for all heights. Values in the upper left corner are correlation coefficient, mean difference, and standard deviation of differences. The number in the lower right corner is the number of points in this comparison.

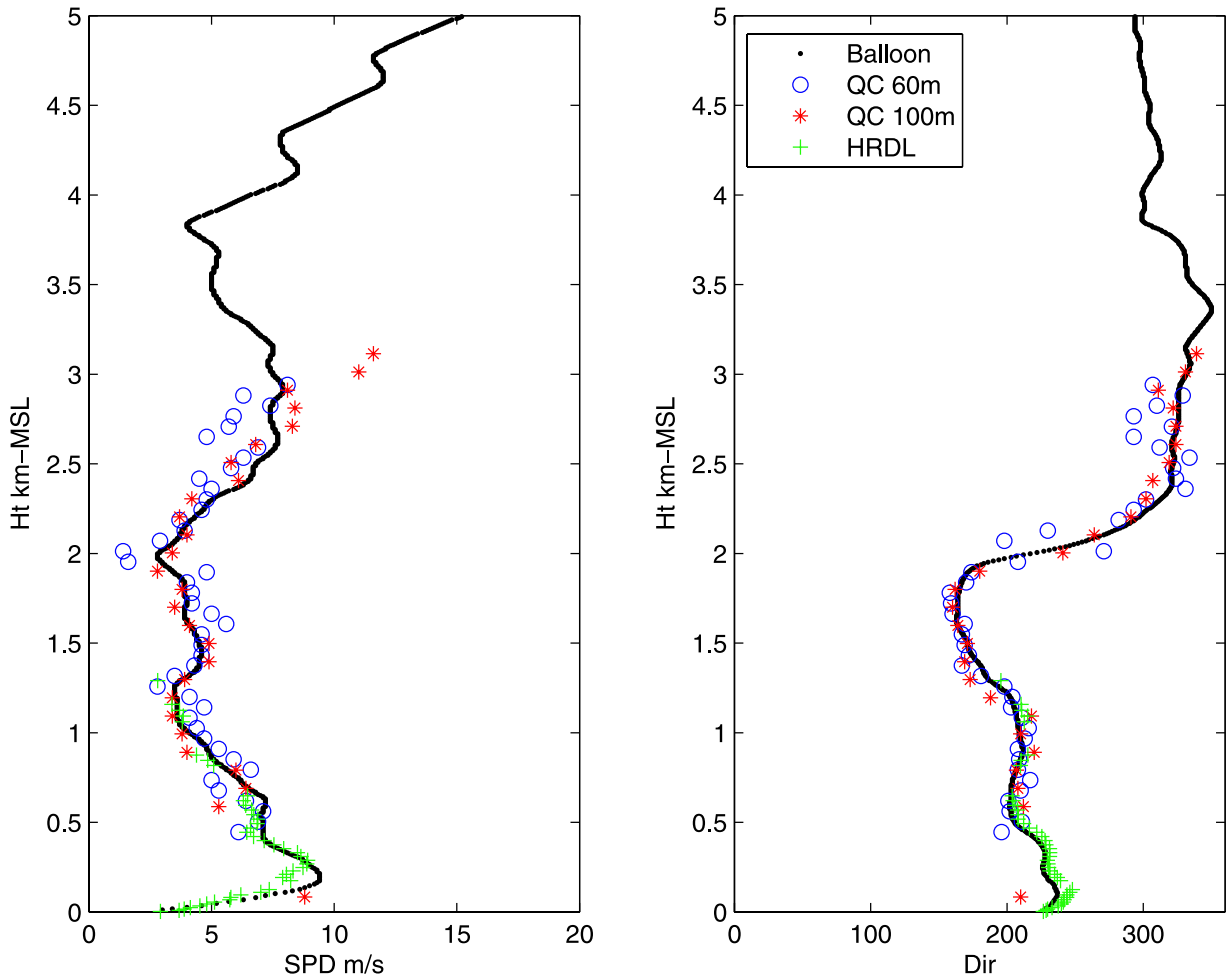


Figure 5. Wind profiles on 12 July 2004 at 1100 UTC. Balloon, radar wind profiler (60-m and 100-m), and high-resolution Doppler lidar.

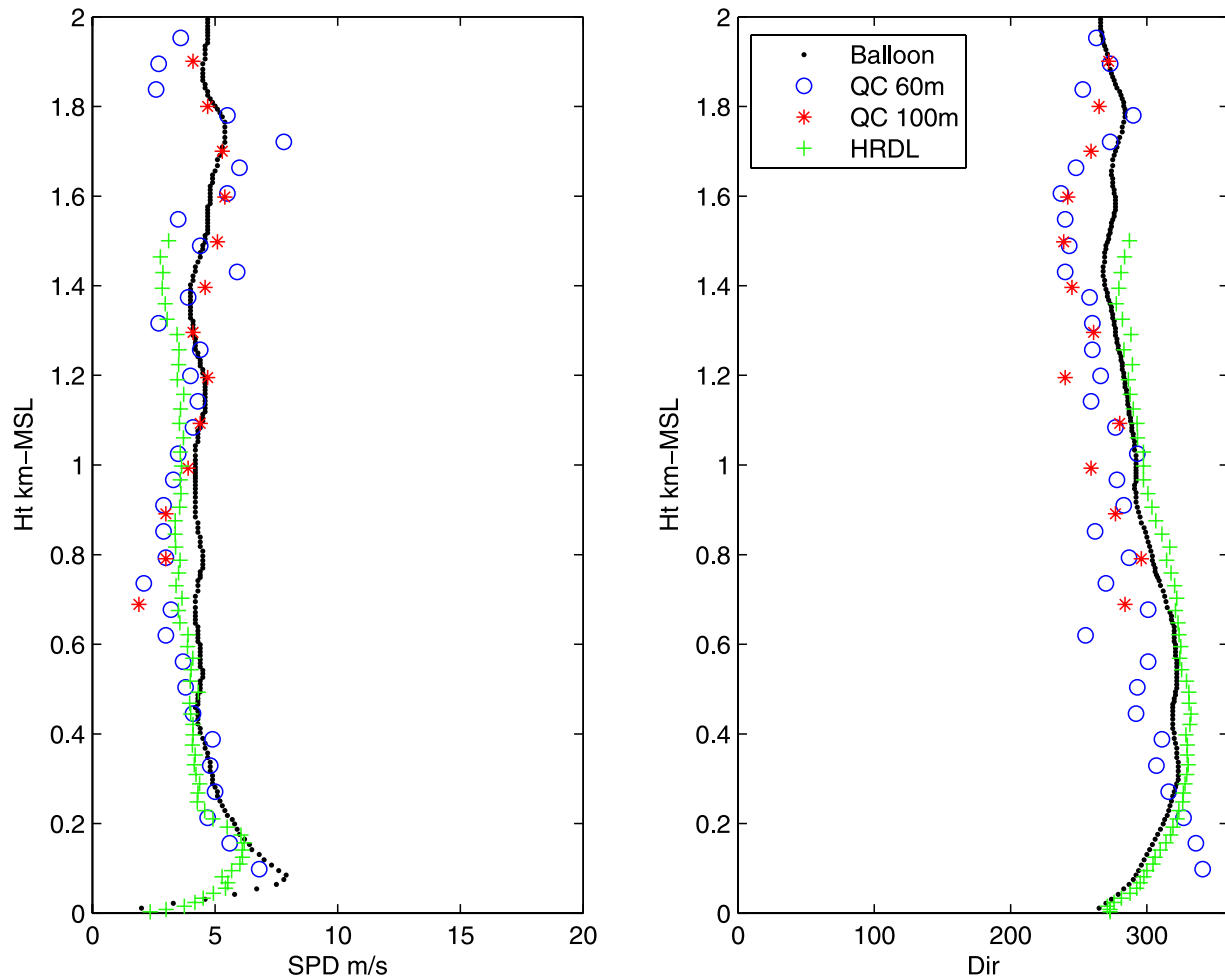


Figure 6. Wind profiles on 21 July 2004 at 0459 UTC. Balloon, radar wind profiler (60-m and 100-m), and high-resolution Doppler lidar.

mode show slightly more scatter and reduced height coverage as might be expected because of lower transmitted power and therefore lower return signal in this mode. The RWP data were quality controlled using both an automated method described by *Weber and Wuertz* [1991] and by manually reviewing the signal-to-noise ratio plots. The manual method was used as an attempt to eliminate any outliers in the lowest range gates where sea clutter occurs and in the higher gates where signal strength is near its detection threshold. More analysis is needed using ship motion and sea state information to help sort out possible interference periods that may still slip through the quality control process.

[14] Scatterplots for the balloon and HRDL horizontal U and V hourly wind components appear in Figure 4. Strong correlation and minimal scatter are consistent with a reported LOS velocity accuracy of 0.1 m s^{-1} for HRDL and also seen when comparing wind profiles. Even though time series of HRDL wind-barb profiles show a fair amount of temporal and spatial variability, both the balloon and HRDL consistently capture nearly identical wind profiles. Normal operation height range of HRDL was up to 1.0 km, reaching a maximum height of 2.0 km. The amount of scatter in Figures 3 and 4 attributed to natural variability would depend on the atmospheric conditions. For light winds there would be less variability expected as compared

to strong winds or in the presence of either temporal or spatial wind shear. There are no known measurements of the natural variability of the wind over the Gulf of Maine.

[15] Figures 5 and 6 show comparison profiles of all three measurement techniques. Note that time is the end time of the hourly averaging period. Figure 5 is an example of an elevated direction shear depicted by both the balloon and RWP data. HRDL data again very nicely capture the lowest 1.0 km wind structure. Figure 6 is an example where all three measurements depict a speed shear in the lowest 0.2 km. During this period HRDL is able to reach a maximum altitude of 1.4 km. Figure 7 shows a period where HRDL only reaches 0.4 km, at which point the RWP data start and continue to follow the balloon. Reviewing HRDL backscatter scans, balloon temperature/RH profilers, and cloud height information from a ceilometer, operated during the same period, helps to explain the differences in maximum height coverage for these three cases. For 12 and 21 July, weak backscatter signal in the HRDL profiles matches cloud heights from the ceilometer. Balloon temperature and RH profiles show similar structure with a 3–4°C surface inversion and near 100% RH at cloud height. This shallow layer is capped by a drier mixed layer extending up to 2.0 km. HRDL backscatter profiles and ceilometer cloud height data on 29 July both show a cloud layer varying in

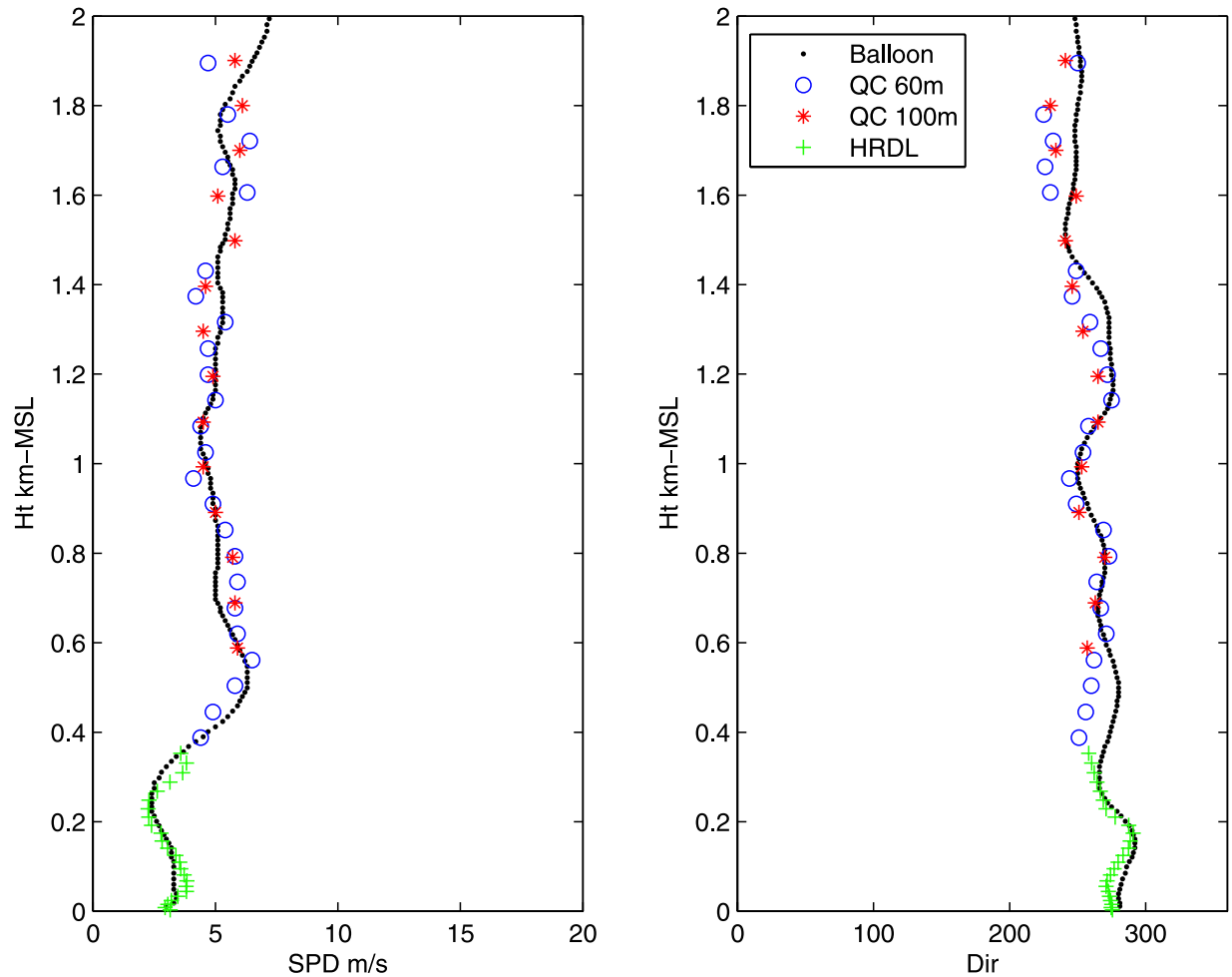


Figure 7. Wind profiles on 29 July 2004 at 1106 UTC. Balloon, radar wind profiler (60-m and 100-m), and high-resolution Doppler lidar.

height from 0.4–0.7 km. The balloon RH profile at this time confirms a cloud layer (0.4–1.0 km). Hence the HRDL signal on 29 July was unable to penetrate much beyond the cloud base.

[16] Because of the overlap in the RWP and HRDL wind profiles, it is possible to make a direct comparison of measurements taken at the same time and in nearly the same space. Figures 8 and 9 compare the data from the RWP 100-m mode with HRDL. Profiles of hourly averaged U and V components from HRDL and RWP were interpolated to a common height grid and stratified into four separate height ranges (0–0.5, 0.5–1.0, 1.0–1.5, 1.5–2.0 km). As expected, there are fewer points within 0–0.5 km range because of the removal of RWP data affected by clutter. Lower correlation, higher mean differences and higher standard deviation of differences for this same height range compared to the three upper ranges possibly indicate there were still some clutter-contaminated data in the comparison. Fewer comparison points within the 1.5–2.0 km range are a manifestation of the variability in the maximum height coverage of HRDL.

4. RWP and HRDL Merged Profiles

[17] As discussed earlier, a unique opportunity provided by these data is the ability to create a single or merged wind

profile using both the RWP and HRDL data. Techniques for creating merged profiles from different profiling instruments are discussed by *Wolfe et al.* [1995] and *Cogan et al.* [1997]. The main factors controlling how data can be merged are their spatial and temporal differences and their accuracies. *Cogan et al.* [1997] uses an equation incorporating temporal and spatial weighting factors times the accuracy ratio for the two instruments. This equation is best used for data that are nonoverlapping in height and have different temporal resolution. However, the RWP and HRDL operated during NEAQS have similar temporal resolution and overlap in their spatial coverage, so for this reason we chose a simple merging technique to create a single wind profile containing both RWP and HRDL hourly averaged data. The HRDL data are used to their maximum height and then the remaining profile is filled with RWP data. The reasons for this simple method of merging were to take advantage of the higher vertical resolution of HRDL and the fact that results show lower variability and slightly better agreement for HRDL when compared to the balloon data (Figure 4).

[18] Figure 10 shows the height coverage statistics for both instruments as a percentage of the total possible points. It shows, for example, that HRDL data (green line) yield useful wind measurements 50% of the time at a height of

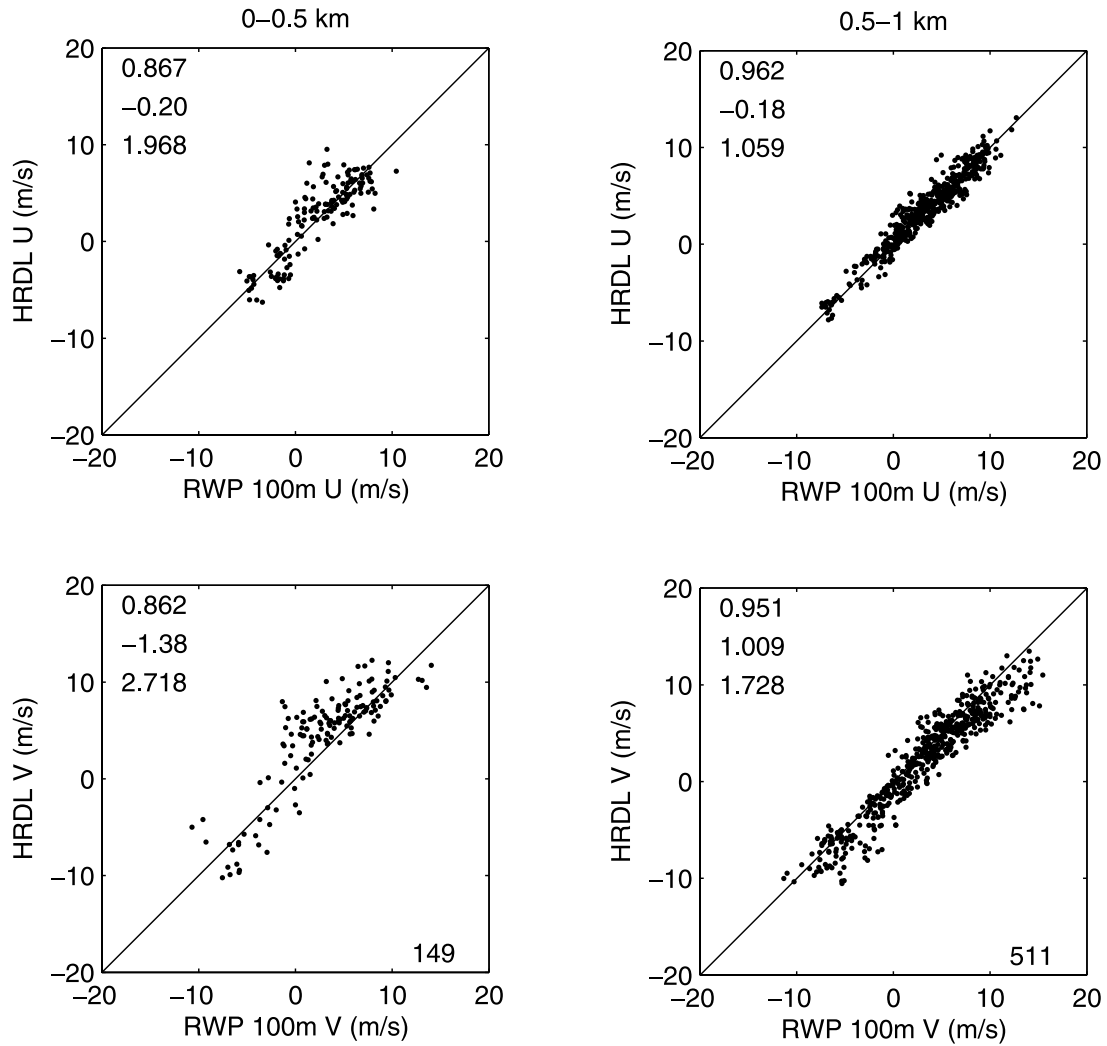


Figure 8. U/V horizontal wind component scatterplots from NEAQS 2004. RWP versus HRDL: stratified into heights for 0–0.5 km and 0.5–1.0 km. Values in the upper left corner are correlation coefficient, mean difference, and standard deviation of differences. The number in the lower right corner is the number of points in this comparison.

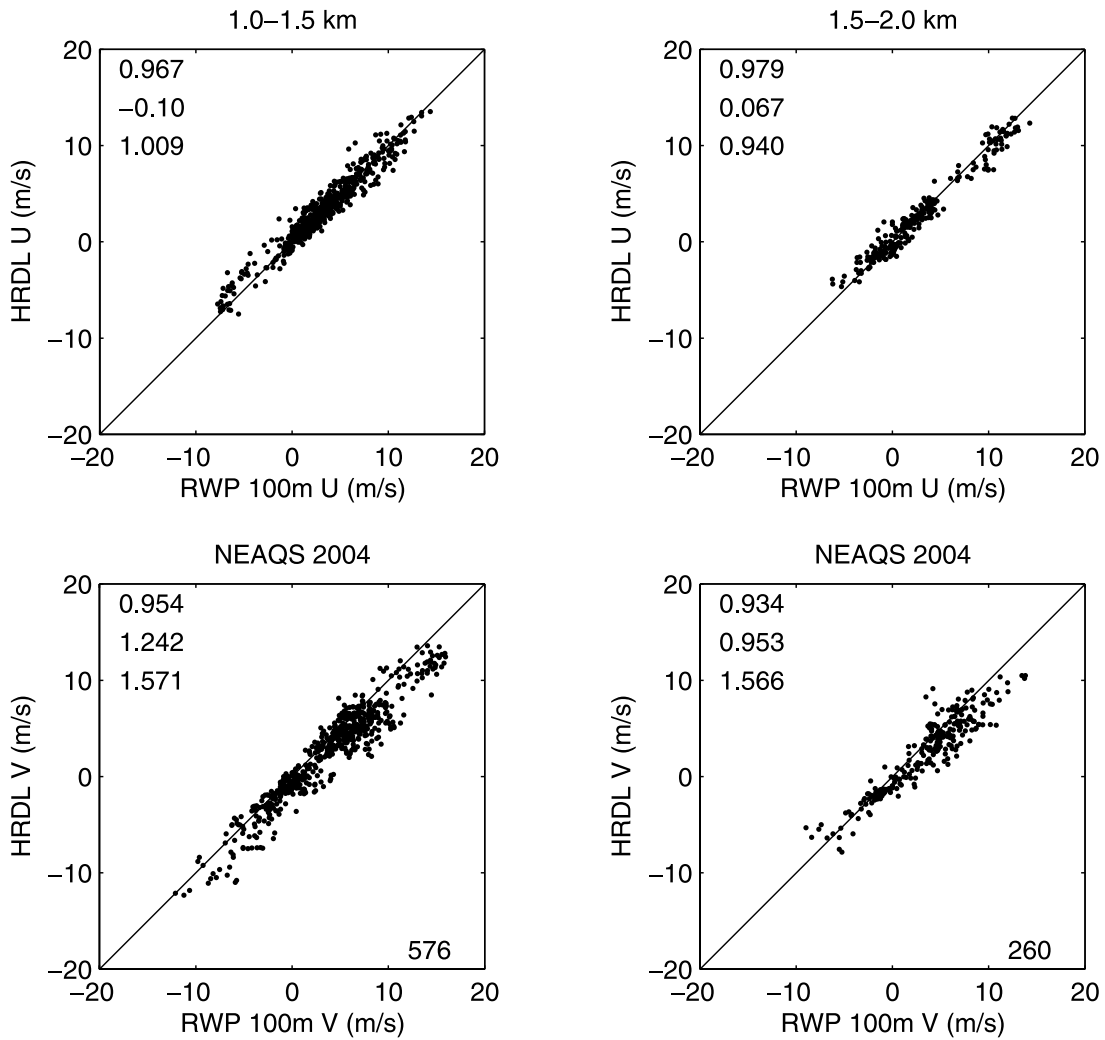


Figure 9. U/V horizontal wind component scatterplots from NEAQS 2004. RWP versus HRDL: stratified into heights for 1.0–1.5 km and 1.5–2.0 km. Values in the upper left corner are correlation coefficient, mean difference, and standard deviation of differences. The number in the lower right corner is the number of points in this comparison.

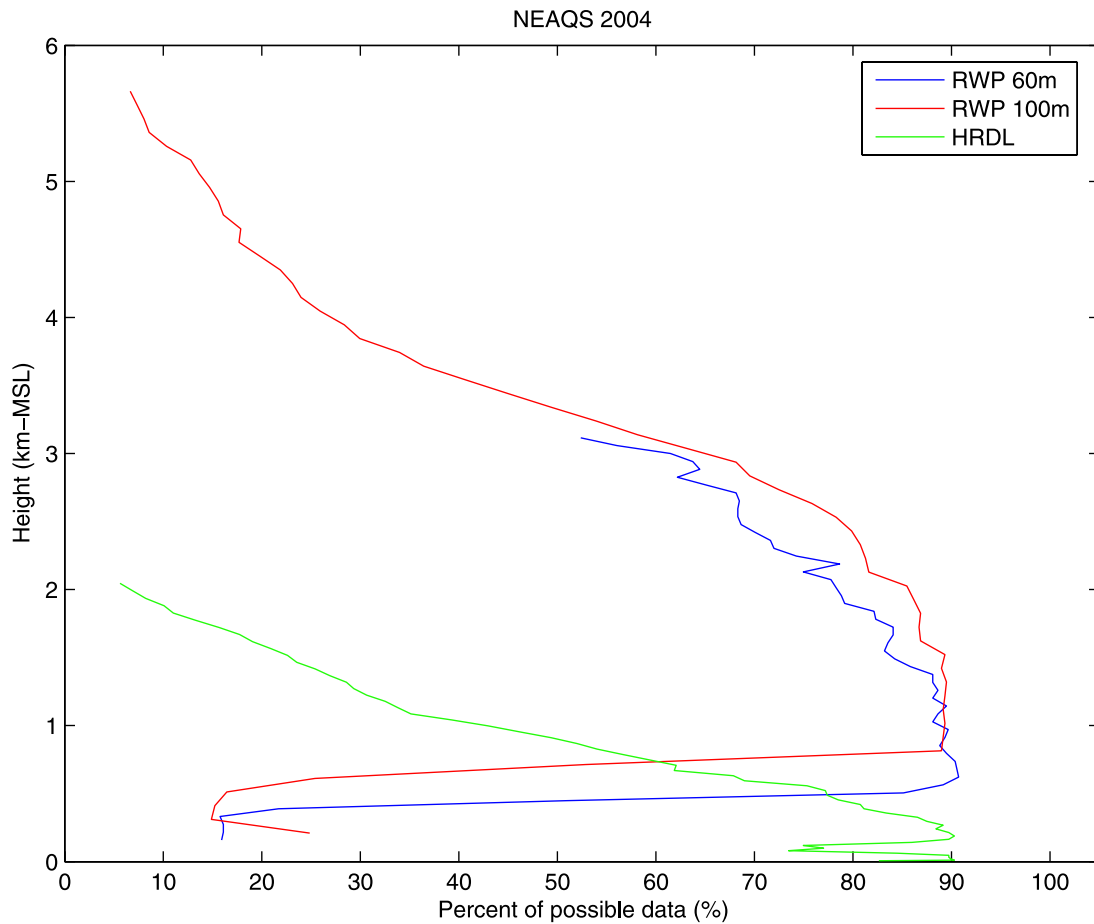


Figure 10. Height coverage statistics for RWP and HRDL data.

0.9 km, whereas the 100-m RWP data (red line) yield wind measurements 50% of the time at 3.4 km. The graph shows that HRDL produces good wind measurements far more often than the RWP for heights below about 0.5 km. The opposite is true for heights above about 1.0 km. Thus the two systems complement each other in terms of height coverage. The variation in the maximum range of both instruments is controlled principally by atmospheric conditions. HRDL is dependent on atmospheric aerosols for scattering, while the RWP is dependent on gradients of refractive index, which are generally dominated by RH gradients. From Figure 10 the make-up of the merged profiles can also be determined. The merged profiles were classified into 2 data sets: RWP 60 m and HRDL and RWP 100 m and HRDL data. For the former mode 80% of the merged profiles will contain HRDL data up to a height of 0.5 km, while for the latter mode 60% of the merged profiles will contain HRDL data up to 0.8 km.

[19] Both these instruments were significantly affected by the highly stable marine layer over the Gulf of Maine [Angevine et al., 2006]. The temperature inversion found at the top of the marine layer acts as a boundary to both aerosols (HRDL) and humidity (RWP). As described by Angevine et al. [2004] and Angevine et al. [2006], there are other factors often creating multiple stable layers including offshore flow that is modified as it passes over the water. Figure 11 is the range-corrected signal-to-noise ratio (SNR)

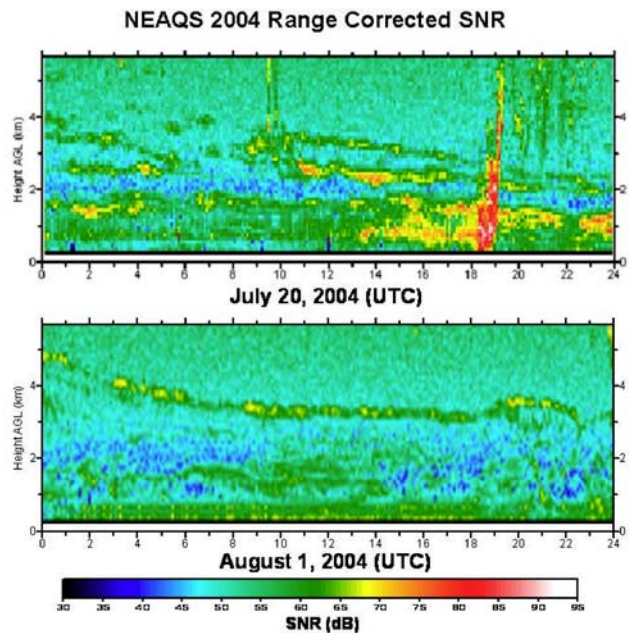


Figure 11. Examples of range-corrected SNR for the vertical pointing beam on 2 days during NEAQs 2004: 20 July 2004 and 1 August 2004.

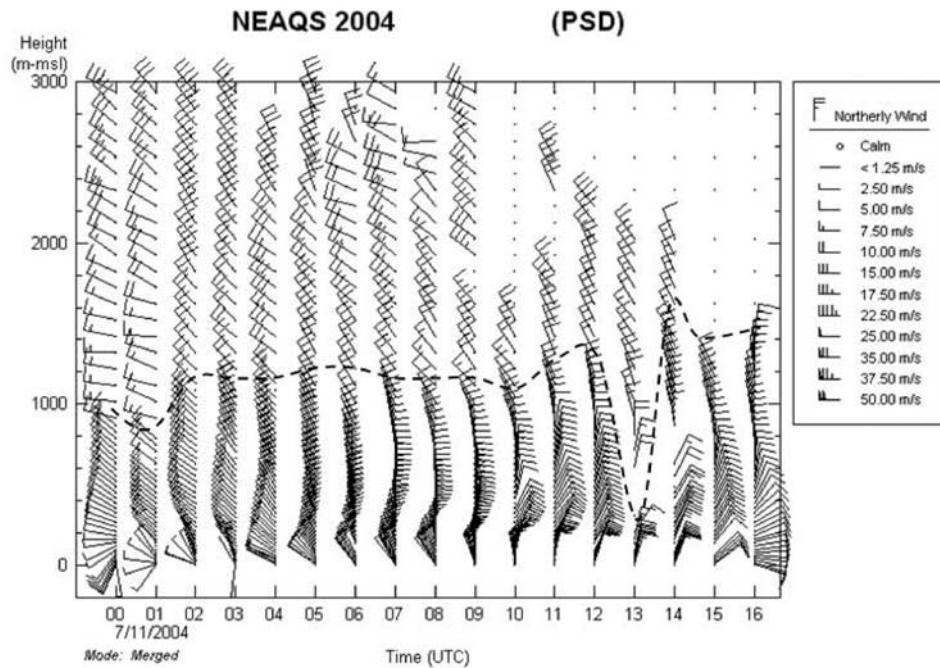


Figure 12. Merged time height profiles of RWP 100 m and HRDL winds: 11 July 2004, 0000–1200 UTC. Dashed line represents the top of the HRDL wind profile.

or backscatter power for the RWP 100-m mode showing examples of the layering and complexity found in the atmosphere during NEAQS 2004. The top image showing 24 hours during 20 July depicts multiple layers with a period of rain showers indicated by the higher SNR (red) values around 1800 UTC. The lower image for 1 August has a continuous layer throughout the day at around 3–4 km.

Also visible on 1 August 2004, is a region of clutter characterized by the dark green band in the lowest 0.5 km.

[20] Merged profiles are shown in Figures 12 and 13 for 11 July 2004: 0000–1600 UTC and 11 July 2004, 2000 UTC to 12 July 2004, 1000 UTC, respectively. The height at which the HRDL profile stops and the 100 m RWP profile begins is indicated by the dashed line. Note that HRDL has

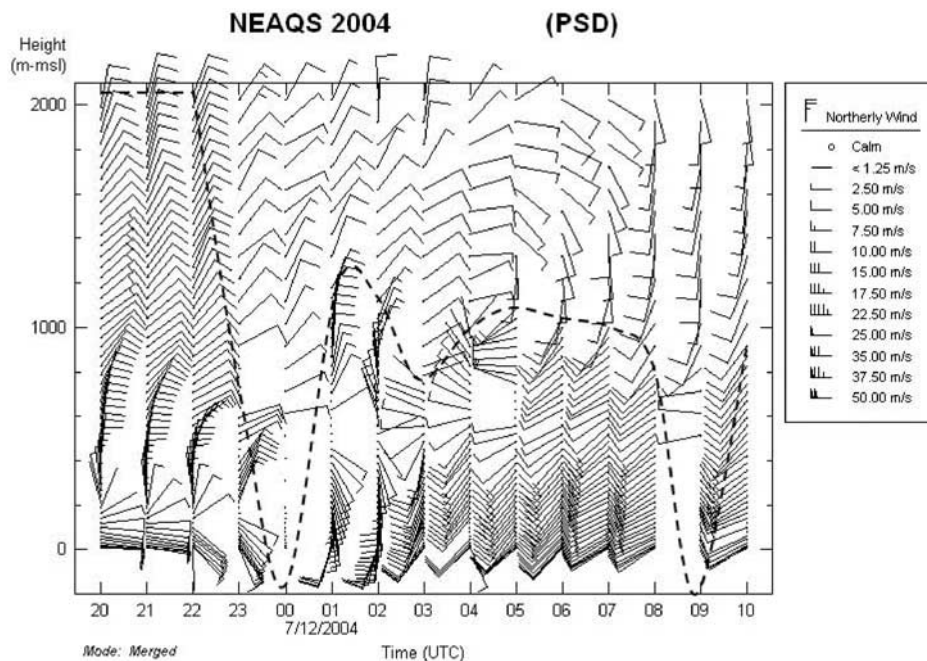


Figure 13. Merged time height profiles of RWP 100 m and HRDL winds: 11 July 2004, 2000 UTC to 12 July 2004, 1000 UTC. Dashed line represents the top of the HRDL wind profile.

exponentially decreasing vertical resolution from 5 m at the surface to 55 m at a height of 2.0 km. Detailed vertical structure and temporal changes are captured by HRDL in the lowest 1.0 km in Figure 12. Figure 13 shows even more complex structure and how the merged profiles are able to retain the vertical and temporal continuity. Both HRDL and RWP are capable of producing wind profiles with higher temporal resolution, even though the data depicted in Figures 12 and 13 are hourly averages. Again, the maximum height of the HRDL data is related to the top of the aerosol backscatter layer.

[21] Trajectories (backward and forward) were calculated using these data as part of a larger profiler network during NEAQS 2004 [White *et al.*, 2006]. Cox *et al.* [2000] discuss the value to trajectory calculations using continuous wind profiles as does White *et al.* [2006] especially during active weather patterns. These merged wind profiles provided an important component in calculating the lower and upper level transport of pollutants, as these measurements were the only wind profiles available over the Gulf of Maine. The episodic and manpower-intensive balloon soundings from the ship, although extremely valuable for providing wind, temperature and relative humidity profiles, could not match the continuous nature of these remote sensor wind profiles.

5. Conclusions

[22] Several earlier studies have confirmed the ability of Doppler radars and lidars to provide accurate wind profiles from ground-based locations. The task is much more challenging, however, from ship-based systems. This analysis has provided insight into the performance and operational characteristics of the *RHB* radar wind profiler and a high-resolution Doppler lidar deployed during NEAQS 2004. These results confirm that the electronically stabilized RWP, even in a high-clutter environment, and the motion-compensated HRDL can continuously measure and produce accurate real time winds. Also shown is the ability of HRDL to monitor low-level winds below the minimum range gate of the RWP, while the RWP wind data extend to much greater heights than can be reached by HRDL. Hence the two systems complement each other nicely in terms of height coverage.

[23] Comparisons of RWP and HRDL allowed us to merge these data with confidence. Merged profiles will provide an important component in understanding the transport of pollutants during NEAQS 2004, especially within the Gulf of Maine. Winds from HRDL are important to air quality work and understanding low-level and local transport of pollutants. Winds from RWP are equally important for understanding long-range transport. Through the merged profiles, the strengths of each instrument are

being utilized to more accurately measure the atmospheric winds.

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