11.2 MESOSCALE ANALYSIS AND WRF MODEL VERIFICATION OF A LOW-LEVEL JET, BAY BREEZE, AND UNDULAR BORE AT THE HOWARD UNIVERSITY BELSTVILLE RESEARCH CAMPUS

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1. MOTIVATION

A lidar network provides many advantages, such as for use in studies in pollution, mesoscale meteorology, and climate, as well as satellite and model validation. In the United States, the ceilometers that are a component of the Automated Surface Observing Systems (ASOS) and Automated Weather Observing Systems (AWOS) that are used by the National Weather Service (NWS) and the Federal Aviation Administration (FAA) comprise an operational lidar network. However, ceilometer data is used primarily for calculating the height of cloud base and cloud layers and the vertical profiles of aerosol backscatter used in the cloud base height calculations are not utilized nor saved (Demoz et al. 2009). Other lidar networks exist (i.e. the Atmospheric Radiation and Measurement (ARM) network and the Micro Pulse Lidar Network (MPLNET)), though their coverage is far more sparse and their data may be more useful for satellite validation in a variety of climate regimes.

Analysis using backscatter profiles from a Vaisala CT25K ceilometer at the Howard University Beltsville Research Campus (HUBRC) reveals the extent to which ceilometer data is useful for more than finding cloud base heights. It provides high temporal and vertical resolution of boundary layer aerosol information. We use three mesoscale boundary layer phenomenon, a low-level jet, a sea breeze convergence zone, and a bore / solitary wave, that were observed with a 915 MHz wind profiler, ceilometer, and instrumented tower at the HUBRC to show the utility of archived ceilometer data and comparisons of observed data to the Weather Research and Forecasting (WRF) model run for the low-level jet case.

2. SITE AND DATA DESCRIPTION

The HUBRC is located in Beltsville, MD, at 39.054°N latitude, -76.877°E longitude, or about 10 miles northeast of Washington D.C. and is GMT-4 hours during daylight saving time. The instruments 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 instrument with temperature, pressure, and relative humidity sensors, and a sonic anemometer. The temporal resolution of the tower data is one minute, as is the wind profiler data. The ceilometer records a profile approximately every 15 seconds. The Howard University Raman Lidar (HURL) is also located at this site. The ASOS and lidar stations used are located within 50 km of Beltsville and shown in Fig. 1.

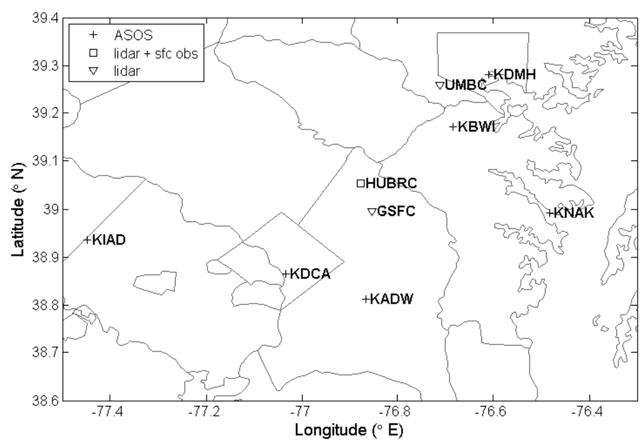

Figure 1. Locations of data collection in Maryland, Washington D.C., and northern Virginia. The station abbreviations are as follows: Baltimore Inner Harbor (KDMH), University of Maryland Baltimore County (UMBC), Baltimore Washington International Airport (KBWI) in Baltimore, U.S. Naval Academy (KNAK) in Annapolis, HUBRC in Beltsville, NASA-Goddard Space Flight Center (GSFC) in Greenbelt, Andrews Air Force Base (KNAK), 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.

Data from the ASOS stations include scheduled hourly and special METAR reports. From the METAR reports, the temperature, dew point, wind speed and direction, and sea level pressure are used in this

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analysis. Although ASOS data of higher temporal resolution is available by request from the National Climatic Data Center (NCDC), the hourly data is used because is it archived and obtained from the Meteorological Assimilation Data Ingest System (MADIS) database where it is publicly available.

3. LOW LEVEL JET

Low level jets (LLJ) are well-documented over the Great Plains (Bonner 1968; Whiteman et al. 1997) as they serve to advect moisture and temperature, which are important for pre-convective conditions and sustaining nocturnal convection (Johnson and Mapes 2001). LLJs are also a common occurrence over the mid-Atlantic area of the eastern United States and have important implications related to pollution transport and air quality. Zhang et al. (2006) found that 60% of LLJs occurring in the Mid-Atlantic region had wind directions that were southerly to westerly. Given this, Ryan (2004) noted that during southwesterly LLJs, ozone concentrations over the region are enhanced with 44% of the days exceeding the 8-hour Code Orange threshold (85 ppbv). Fig. 2 gives an example of an elevated ozone level episode associated with a LLJ.

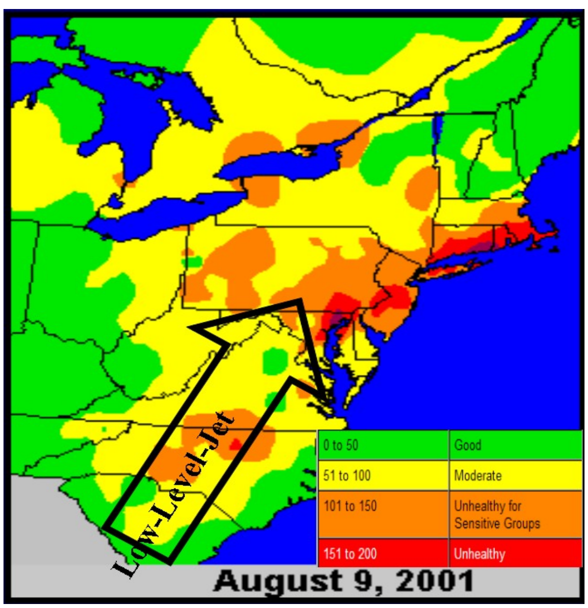

Figure 2: Air quality index during an ozone episode (Ryan and Piety 2001).

The LLJ event for this analysis occurred during the evening and into the early morning hours of 2-3 August 2007. The eastern United States was under the influence of high pressure and weak synoptic forcing with clear skies indicated by satellite imagery and ASOS observations. Data during this LLJ event at HUBRC is shown in Fig. 3. The speed maximum of the LLJ is clearly seen in the wind profiler speed and the wind direction during this time is southwesterly. Notice the clearing of the aerosols in the boundary layer at the height of the wind speed maximum in the ceilometer data while the LLJ was occurring. The LLJ's contribution to pollution episodes lies in its ability to vertically transport pollutants from the residual layer into the stable boundary layer below the nocturnal temperature inversion (Taubman et al. 2008). The bottom panel of Fig. 3 shows the normalized relative backscatter of the Micro Pulse Lidar (MPL) at the NASA Goddard Space Flight Center (NASA/GSFC). While the MPL is useful for obtaining aerosol profiles and other optical properties through the troposphere and lower stratosphere (Spinhirne 1993), an issue arises for vertical ranges closest to the telescope due to the diverging beam not overlapping with the field of view until higher altitudes (Campbell et al. 2002). MPL normalized relative backscatter (NRB) from University of Maryland Baltimore County (UMBC) during the LLJ is shown in Fig. 4 where the aerosol layer above the wind speed maximum can be seen.

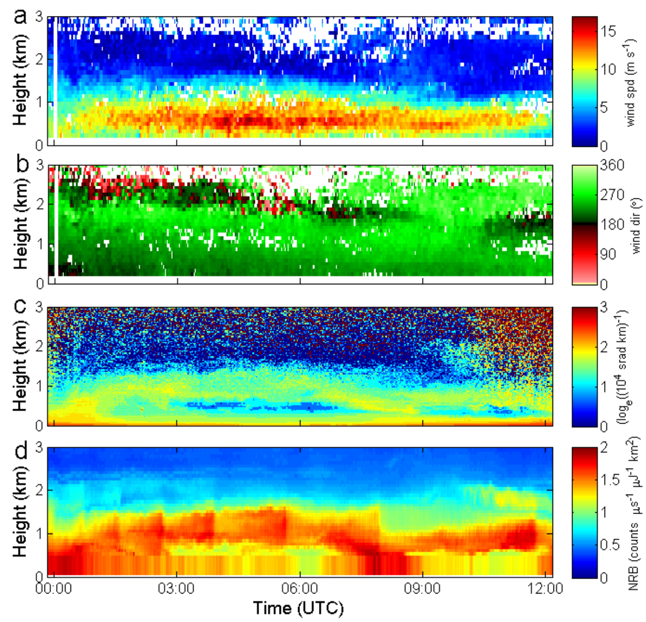

Figure 3: Data from LLJ event at HUBRC. a) wind profiler speed, b) wind profiles direction, c) Vaisala CT25K ceilometer backscatter, and d) Micro Pulse Lidar normalized relative backscatter at NASA Goddard Space Flight Center.

4. BREEZE FRONT / CONVERGENCE ZONE

The afternoon of the following day, 4 August 2007, had conditions that were similar to the previous day. The cold front that was over the Great Lakes region had moved across Ohio and was now near the Pennsylvania-Maryland border as shown in Fig. 5. The front was not well-defined in terms of its temperature gradient, being only about 3°C, though the dew point gradient was stronger, being about 5° to 9°C. That afternoon, a convergence zone developed near coast of the Chesapeake Bay and slowly moved westward and inland through central Maryland throughout the afternoon and early evening hours and

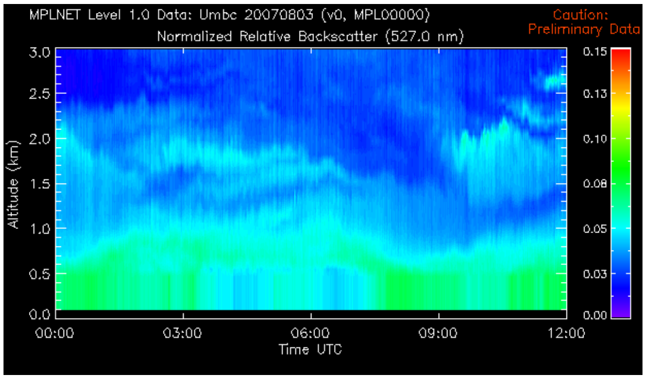

Figure 4: Normalized relative backscatter from the Micro Pulse Lidar at UMBC during the LLJ on 3 August 2007.

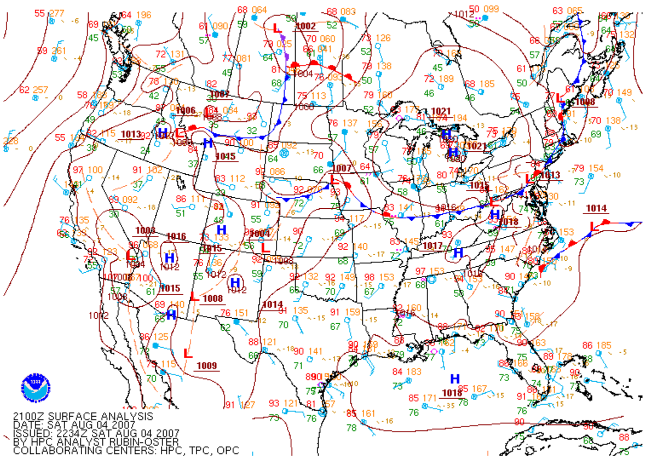

Figure 5: Surface analysis at 2100 UTC on 4 August 2007.

is seen as a fine line of reflectivity on the LWX Weather Surveillance Radar – 1988 Doppler (WSR-88D) in Fig. 6. From the position of this line through time, the breeze front was found to have a speed of only 1.9 m s^{-1} with a direction almost due west of 89.7°. Fig. 7 shows the position of the breeze front as it passes near the station location identified in Fig. 1.

As the breeze front reached HUBRC, it is seen in the change in wind speed and direction of the profiler as well as the uplift of aerosols in the ceilometer data in Fig. 8. The uplifted aerosols mark the altitude of the boundary between the previous afternoon's air mass and the marine layer at the surface. The wind speed near the surface increases after the passage of the front while the wind direction changes from northwesterly to easterly. In the red-green color scale for the wind direction, red (green) represents an easterly (westerly) component and lighter (darker) shades indicate northerly (southerly) wind direction components. The westerly-moving marine layer is seen in the profiler wind speed as having an easterly wind from the surface to 1 km and northerly wind above 1 km.

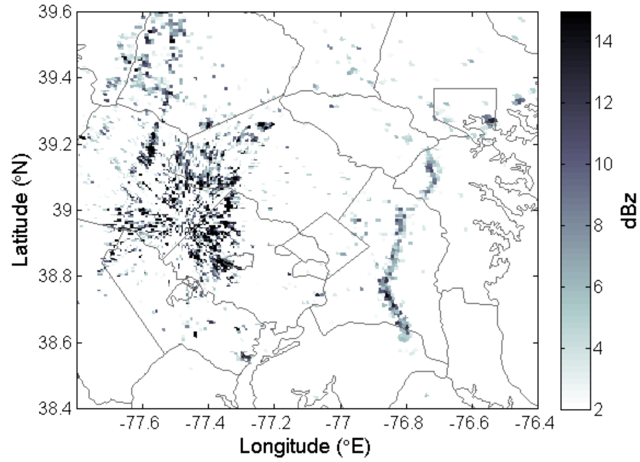

Figure 6: LWX WSR-88D 0.5° reflectivity at 2204 UTC on 4 August 2007. The breeze front is the darker line near the -76.8°E longitude meridian.

Evidence of the breeze frontal passage is found in the ASOS and HUBRC tower data as well, shown in Fig. 9. From examination of the surface data, the breeze is believed to have developed and moved ashore from the Chesapeake Bay shortly after 1700 UTC as indicated by the temperature decrease and wind shift from westerly to easterly at KNAK. As it reached other stations, the wind direction can be seen to shift from northerly to easterly. Note that sunset is shortly after 0000 UTC and that sky cloud coverage during the afternoon was reported as no more than scattered.

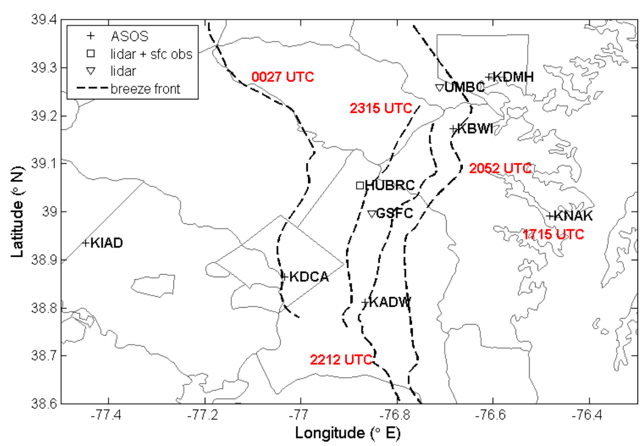

Figure 7: Breeze front locations on 4-5 August 2007.

5. BORE / SOLITARY WAVE

During the early-morning hours of 5 August, the cold front in Fig. 5 continued to move south toward central Maryland. In examining radar reflectivity data from 0700 to 0900 UTC (0300 to 0500 EDT), a fast-moving fine line of higher reflectivity was seen to move from the Baltimore area southwestward toward Washington D.C. Fig. 10 is a still image at 0739 UTC

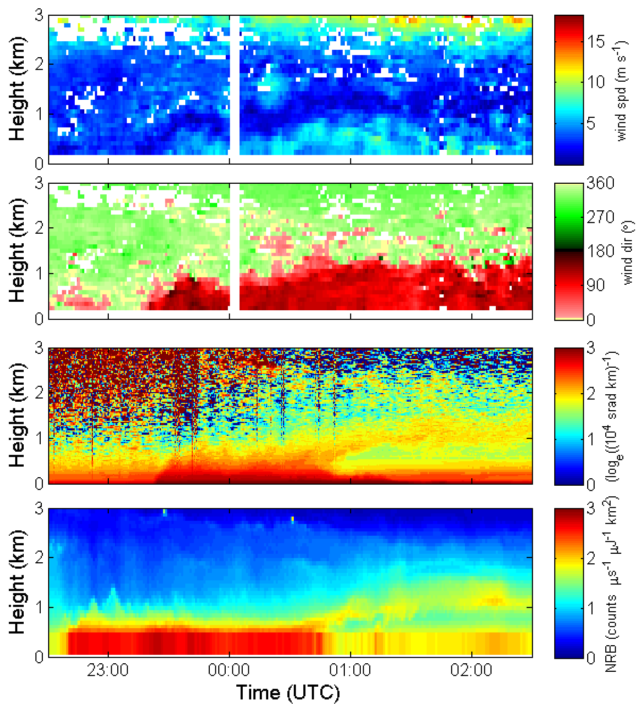

Figure 8: As in Figure 3, but for 4-5 August 2007.

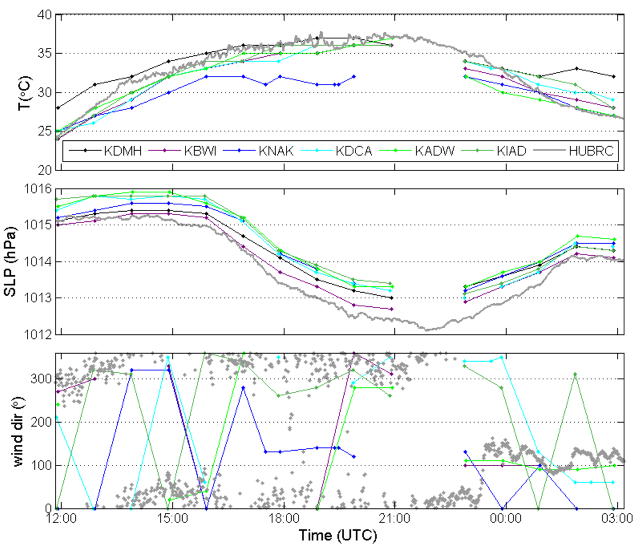

Figure 9: ASOS and HUBRC tower surface temperature, sea level pressure (SLP), and wind direction on 4-5 August 2007. The HUBRC tower temperature is 3 meters above ground level.

when the fine line was most-visible amidst the anomalous propagation returns due to the nighttime inversion (or “ground clutter”). The position of the fine reflectivity line was marked in Fig. 11 at times when it was distinguishable from the ground clutter and the wave was calculated to have a speed of almost 8 m s^{-1} from a direction of 39°.

The wind profiler and ceilometer exhibit notable features during the passage of this wave. Referring to Fig. 12, at approximately 0800 UTC, the wind speed below 0.5 km increases to about 15 m s^{-1} and the

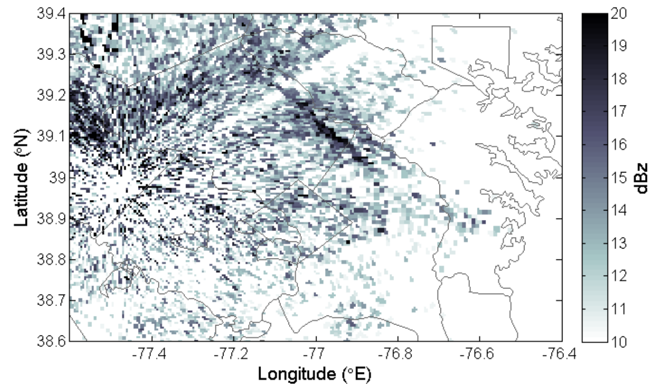

Figure 10: As in Fig. 6, but for 0739 UTC 5 August 2007. The bore/solitary wave is the dark line above the center of the figure.

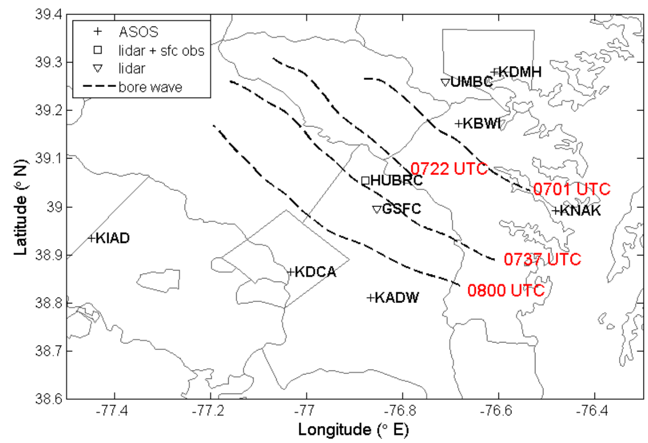

Figure 11: Bore wave locations on 5 August 2007.

wind direction shifts from southeasterly to northeasterly and the ceilometer indicates an oscillation in a layer up to 1 km (shown up-close in Fig. 13). It is a rather interesting setup that has evolved in the boundary layer during the period of this analysis. Fig. 12 shows the boundary, just above 2 km between the marine layer and the air that was previously in the boundary layer prior to the passage of the breeze convergence zone. Another boundary becomes visible as the bore / solitary wave propagates into the marine layer. Cold front passages are traditionally indicated by changes in wind speed, wind direction, temperature, and dew point. Fig. 14 reveals that at several of the ASOS stations , there was an increase in wind speed at least 1-2 hours before there was an appreciable decrease in the dew point. At HUBRC, at the time the ceilometer indicates the wave passage, there is a 3°C temperature increase in the 3 m AGL temperature and the wind speed of the anemometer and lowest level of the wind profiler experienced both an increase in the wind speed and variability of the wind speed. The associated pressure jump with the bore / solitary wave is less than 0.5 hPa. The main part of the front passed HUBRC after 0900 UTC when there was a substantial clearing of aerosols by the associated winds.

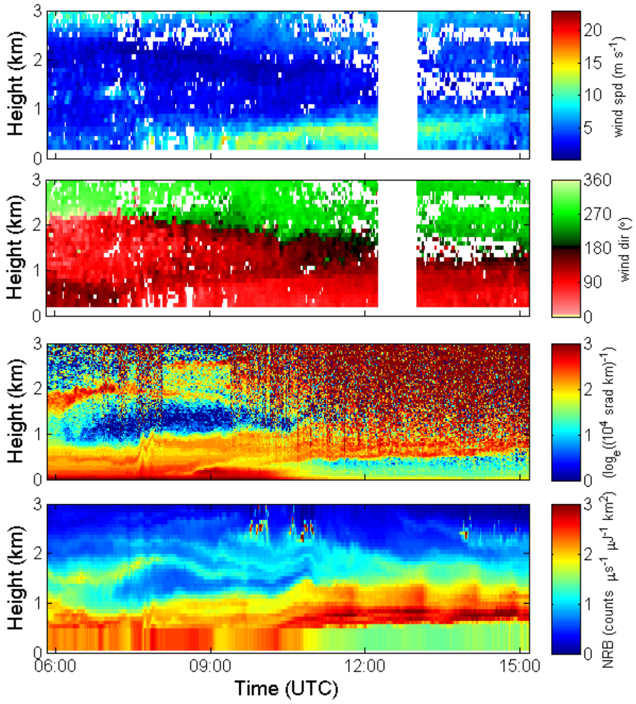

Figure 12: As in Fig. 8, but for 5 August 2007.

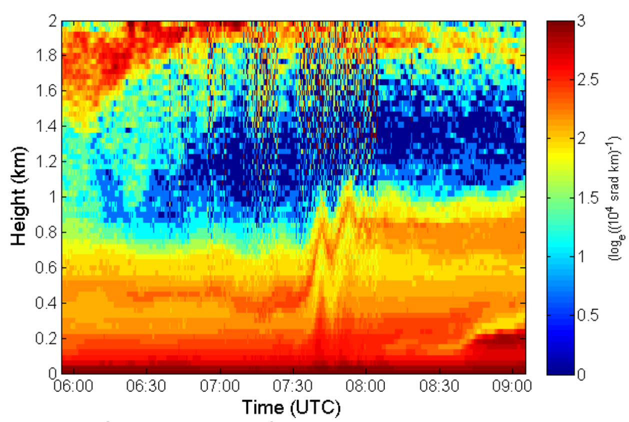

Figure 13: Close-up image of the ceilometer backscatter data near the time of the bore / solitary wave passage.

6. MODEL COMPARISON WITH OBSERVATION

The WRF model was run for the LLJ occurrence on 3 August 2007. A sensitivity study was conducted using three planetary boundary layer (PBL) schemes (MRF, YSU, and MYJ). Overall, the WRF model captured the LLJ well with underestimating the height of the LLJ by about 0.1 km and the speed by 1.5 $m\ s^{-1}$. The MYJ scheme was found to perform the best. A comparison of wind speed profiles for the different PBL schemes with rawinsonde and wind profiler is shown in Fig. 15. Profiles of observed and modeled water vapor mixing ratio (WVMR) are also compared to rawinsonde and shown for each scheme in Fig. 16. Time-height series of WVMR are compared to lidar ratio (Fig. 17) and found to be in good qualitative agreement. The underestimation of the LLJ height can also be seen.

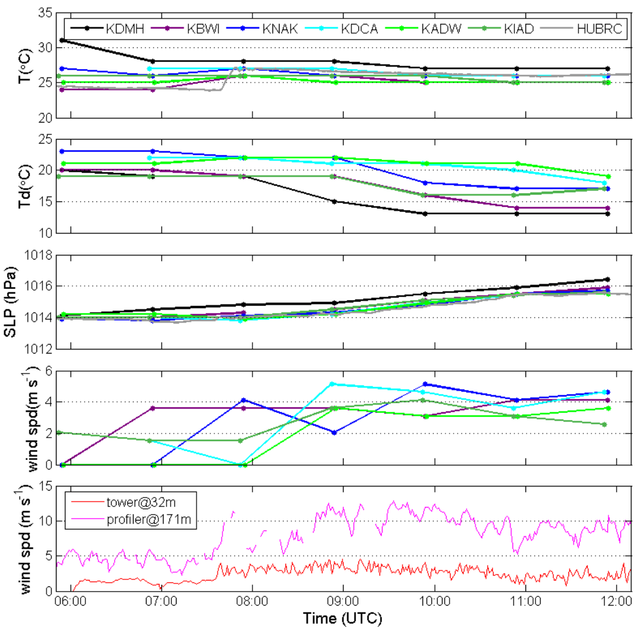

Figure 14: ASOS and HUBRC tower data for 5 August 2007. Panels from top to bottom are temperature, dew point, sea level pressure, wind speed at ASOS stations, and tower wind speed with lowest level of wind profiler wind speed.

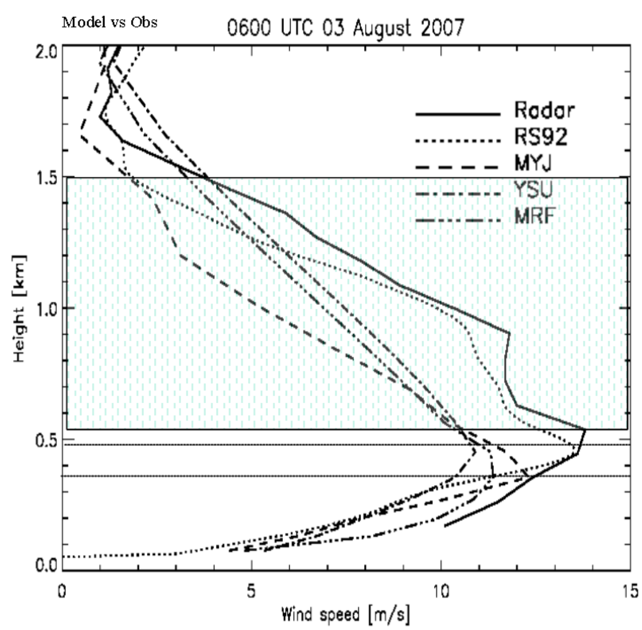

Figure 15: Observed wind profiles of wind profiler and RS92 rawinsonde with WRF PBL schemes.

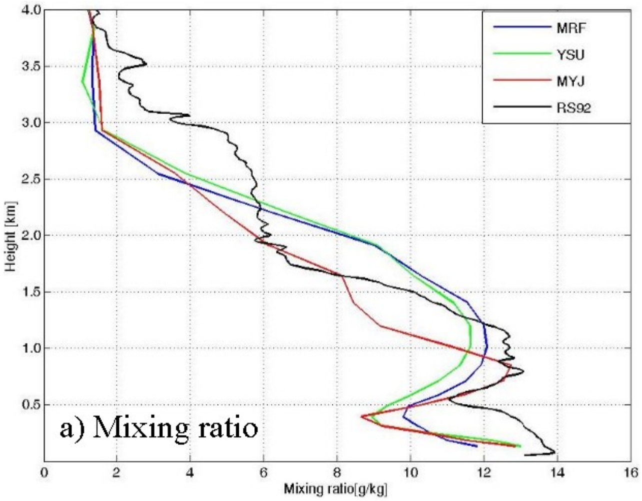

Figure 16: Water vapor mixing profile observed by RS92 rawinsonde compared to mixing ratio profiles of the WRF PBL schemes.

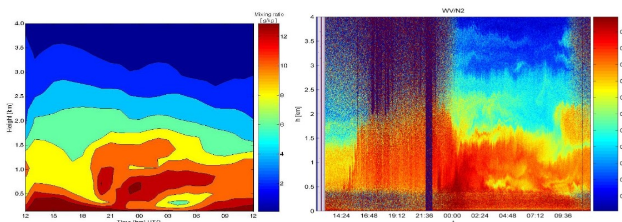

Figure 17: WRF WVMR (left) and Raman lidar ratio (right) during the LLJ.

7. SUMMARY AND FUTURE WORK

From the occurrence of a LLJ, bay breeze, and bore wave within several days' time at the HUBRC, one can see the detail of data that is captured by the ceilometer. Having this data at more locations could prove to be a valuable asset for mesoscale model verification in terms of the timing of mesoscale events as well detailed profiles of their boundary layer properties. We recognize that archiving this data would be a great undertaking, but only the ceilometer backscatter profiles in the lowest 2-3 km may be of the greatest importance since solar radiation during the day can obscure information above the boundary layer. In terms of estimating potential storage amounts, at the HUBRC, if the ceilometer data is saved in a compressed format, it generally can take less than 2 Mb per day with the full profiles being saved.

Future work would include use of ASOS data that is of higher temporal resolution (i.e. the 1-minute data archived by NCDC). The WRF model would also be run for the breeze convergence zone and bore / solitary wave cases to see the extent that it captures these features.

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