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A DETAILED CHARACTERIZATION OF THE WINTERTIME BOUNDARY LAYER USING TETHERED BALLOONS

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1. INTRODUCTION

A detailed examination of the structure and evolution of the wintertime boundary layer was conducted from 3 January – 14 February 2004 near Lancaster, PA in support of the research objectives of the Mid-Atlantic/Northeast – Visibility Union. Two tethered balloons were used to deploy meteorological sensors, condensation particle counters, laser-diode scatterometers, and filter samplers to altitudes of 700 m AGL, while a suite of ground-based instruments measured trace gas and particle concentrations and meteorological parameters. January 2004 was characterized by a very active synoptic pattern that frequently brought Arctic air into the mid-Atlantic region and resulted in this being the 10th coldest January on record. Tethered balloon measurements were primarily limited to times when progressive anticyclones moved over the site, bringing clear skies, strong nocturnal radiational cooling, and generally light wind speeds. Daytime conditions were marked by the rapid development of the nearly adiabatic mixed layer of uniform winds extending to a depth of 500 – 700 m AGL and capped by a subsidence inversion. The nighttime periods were considerably more interesting with complex stratification embedded in and above the inversion, with significant variability in wind speed and direction, water vapor mixing ratio, particle concentration, and scattering coefficient observed across layers that were often only tens of meters thick. Depending on the atmospheric condition around sunset and the rate of development of the nocturnal inversion, high concentrations of particles were found trapped near the surface and/or in shallow stable layers within the inversion. The tethered balloons were deployed to capture this detail by first performing a vertical profile using the 12 m^3 blimp to examine the boundary layer structure. Once potential layers of interest were identified in the profile, a second balloon was parked at that altitude to conduct long-duration (10-12 hour) time series of meteorological variables and particle concentrations. The measurements obtained using the single-site tethered balloons are being integrated into a regional context by incorporating surface and aloft observations from the NWS network, as well as regional profiler data and WRF and Eta model output. Preliminary results suggest that high concentrations of particles (12,000 – 50,000 cm^{-3}) are trapped in wintertime stable layers, and are subsequently mixed to the surface the following day. Moreover, black carbon appears to contribute a significant fraction to the total particle count in winter. Finally, tethered balloons provide detailed profiles of meteorological variables (T, p, z, q, and vector wind) with vertical resolution of 0.3 m that show considerable structure and variability in the wintertime boundary layer. These data can be used to validate boundary layer parameterization schemes used in numerical models.

2. DATA COLLECTION

The aloft data shown in this paper were collected using two Millersville University tethered balloons. Instruments were deployed on a 12 m^3 blimp, which was used to obtain vertical profiles of T, p, RH, wind speed and direction, optical scattering coefficient (as a proxy of PM2.5 concentration), and total particle count to a maximum altitude of 700 m with a vertical resolution of 0.3 m. Each profile took approximately 45-60 minutes to complete. From 3 Jan – 14 Feb 2004, a total of 102 vertical profiles were completed. The temporal distribution of these profiles is shown in Fig. 1 (top). When a particulate matter event was anticipated, the first vertical profile was used to locate layers of particular interest such as those with significant variability or exceptionally high particle counts or optical scattering coefficient. Once a layer was identified, the second balloon, a 12 m^3 oblate

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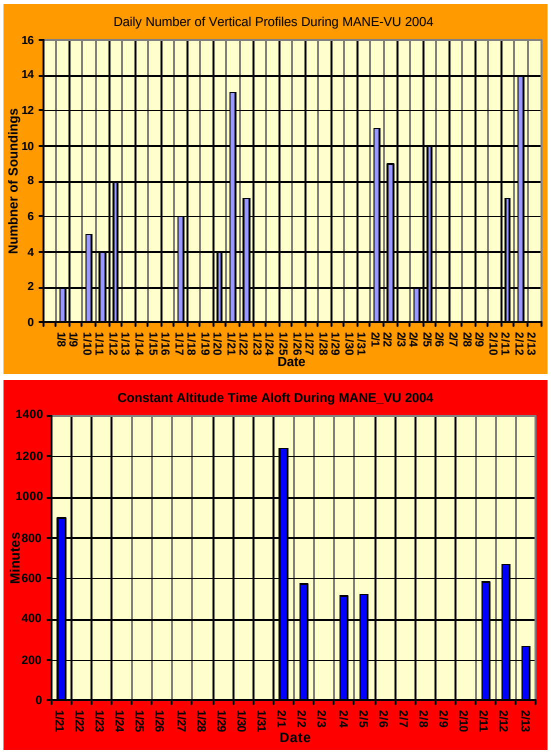

Fig. 1. The daily number of vertical profiles (top) and the daily number of total minutes (bottom) that the two Millersville tethered balloons were deployed.

spheroid with a free lift capacity of 7.5 kg (calm winds), was deployed to that altitude and “parked” there for durations as long as 10 hours. The daily number of total minutes the constant altitude (CA) balloon was aloft is shown in Fig. 1 (bottom). In all, the CA balloon logged a total of 87 hours aloft. The constant altitude balloon carried the same instruments as the vertical profiler, plus an impaction sampler for integrated PM2.5 mass.

A particular challenge for this project was the winterizing of instruments to insure they remain within the manufacturer’s specifications, while outside ambient surface and aloft temperatures were frequently below 0 F and -15 C, respectively. Creating insulated instrument pockets and packing the pockets with chemical hand warmers accomplished the winter “hardening”.

In addition to the aloft instruments, a suite of surface-based instruments were employed to document the surface condition as well as to provide a mean of comparison with aloft instruments. The surface instruments consisted of trace gas analyzers for CO, $NO/NO_2/NO_X$, and SO_2, an Aethalometer for black carbon concentration, TSI Condensation Particle Counter (Model 3007) for total particle count, MetOne particle sizer for particle count in six size bins ranging from 0.3 to > 0.8 microns, surface meteorological tower, laser-diode scatterometer as a proxy indicator of PM2.5 mass, and a TSI three-wavelength nephelometer for total and back scattering coefficients.

In order to place the balloon-borne and surface measurements into a regional context, upper air and surface observations from the NWS network, satellite and radar imagery, WRF and Eta model initialization fields, and HYSPLIT back trajectories were archived for analysis and interpretation.

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3. OVERVIEW OF WINTER 2004

January 2004 was the 10th coldest on record in the mid-Atlantic region with a -6 F departure from normal (see Fig. 2). The month was also drier than normal with only 30% of normal precipitation (Fig. 2). In February 2004, both temperature and precipitation returned to near normal values, however, during the field study in the first half of February the temperature was -2 F below normal and the precipitation was twice that of normal.

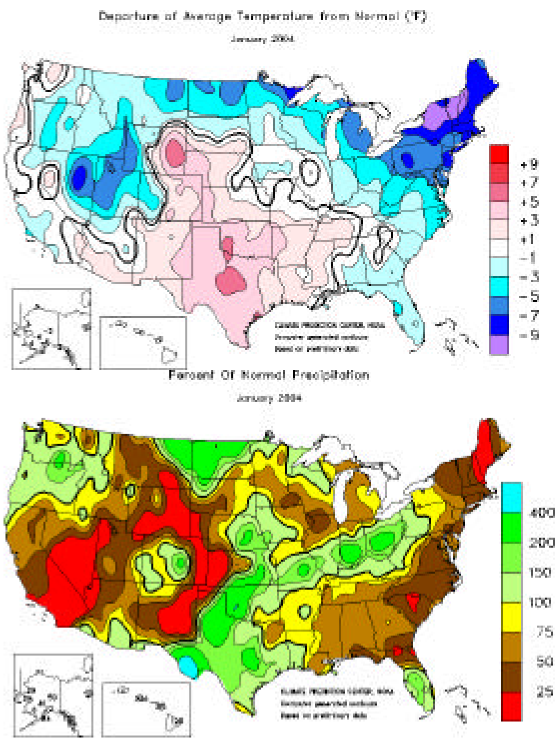

Fig. 2. Departures of temperature (top) from normal and percent of normal precipitation (bottom) for January 2004.

The synoptic setting for winter 2004 was dominated by an active pattern of cyclones and anticyclones propagating over the mid-Atlantic region. Continental polar and arctic air masses controlled the atmospheric condition, although their influence was more related to their frequency of occurrence than that of a few quasi-stationary anticyclones dominating for long durations, as is more typical of summer. The propagation of atmospheric short waves caused the strength and orientation of synoptic gradients to change rapidly over a period of hours, which induced significant interactions/coupling between the upper troposphere and the surface in the vicinity of the frontal boundaries. Unlike the summer atmosphere, which is often barotropic aloft, the winter condition is mostly baroclinic at the upper levels, so that there is much less likelihood of stagnation in winter since air masses are more progressive in a baroclinic field.

Six episodes were documented during this six-week field project. The daily number of vertical profiles as shown in Fig. 1 can identify these episodes. Each episode had a duration that lasted between one and four days, which was generally determined by the length of time that an anticyclone would establish an influence over the site location.

These synoptic-scale wintertime patterns have an effect on the characteristics and evolution of the boundary layer through deep coupling of the upper troposphere in the vicinity of fronts, and significant de-coupling in the boundary layer under clear and cold nocturnal conditions. As a result, the wintertime daytime boundary layer (WBL) is very different from that of its summertime counterpart. Because of the stronger aloft gradients and attendant wind in winter, the daytime WBL more closely approximates a mechanically driven Ekman layer with a height that is largely determined by the altitude where winds reach geostrophy, rather than the summertime case where buoyancy dominates and the BL height coincides with the mean tops of thermals. On the other hand, cold air advection aloft in the post-frontal winter environment can lead to significant boundary layer mixing and alter the radiative properties through the formation of stratocumulus clouds. At night under clear sky conditions, the cold WBL is replete with detail in the vertical structure within the nocturnal inversion. The inversion is often confined to 100 meters above the surface and exhibits shallow, stably-stratified layers with pockets of high aerosol count (~10^4 cm^{-3}) and scattering coefficient. Moreover, local and regional intrusions of pollutants, wind, temperature, and moisture anomalies were advected over the site and captured by the balloon measurements without the slightest trace of their existence at the surface.

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4. THE WINTERTIME BOUNDARY LAYER AT A MID-ATLANTIC SITE

The Millersville University MANE-VU site was located at a semi-rural, agricultural setting typical of the region at latitude 39° 59.43’ N, longitude 076° 23.16’ W, and an elevation of 100 m MSL. The site was chosen because of it is representative of the mid-Atlantic piedmont area about halfway distant between the Atlantic coastal plain and the Appalachian Mountains. It has the potential to be affected by four major urban areas: Pittsburgh 300 km to the west, New York City 150 km to the northeast, and Baltimore and Philadelphia with a 100 km radius to the south and east respectively. Lancaster, PA (pop. 50,000) lay 9 km east of the site. The tethered balloons were authorized to an altitude of 700 m AGL. The surface was snow covered for the middle third of the 6-week project. The objective of the project was to document the meteorological conditions and particulate concentrations in a wintertime boundary layer and relate these findings to the surface measurements and the regional context.

There is a paucity of information in the literature on the structure and evolution of mid-latitude wintertime boundary layers. Most cold-climate studies are those that have been conducted in the polar regions far removed from the influences of local and regional pollution sources that affect the boundary layer. This study is particularly interesting because of its location. The mid-Atlantic region in winter is subject to frequent short waves (“Alberta clippers”) and less frequent but significant and pervasive replacements of air masses due to changes in the Rossby wave pattern. Unlike the summer when the upper level jet stream is well to the north and the upper troposphere is largely barotropic (Ryan et al, 1999), the wintertime condition is greatly affected by large-scale excursions of the polar and subtropical jet streams. Synoptic gradients are principal drivers that easily overwhelm the boundary layer forcing. In the vicinity of frontal boundaries, the upper and lower troposphere can be coupled and momentum and scalars (e.g., heat, pollutants etc.) can be transported to the near-surface layers. At night under clear sky conditions and intense radiational cooling, significant boundary layer structure develops and appears to be closely connected to the local features of ground cover and proximity to human activity (e.g., vehicle traffic, residential burning, industrial emissions, etc.). The nocturnal inversion is often confined to only 100 m with marked stratification over the entire depth of the WBL. Momentum, heat, trace gases and particulates can be transported aloft without any evidence of their presence at the surface. In the absence of overwhelming synoptic gradients the strength of the static stability is enough to prevent downward mixing at night.

Another feature that was virtually absent during this study was the nocturnal boundary layer jet. The boundary-layer-driven LLJ is a recurrent feature over the mid-Atlantic piedmont region in summer (Philbrick et al. 2000). It is not surprising that the LLJ was absent since most of the WBL forcing is induced from aloft. Surface temperature discontinuities between the mountains and the coastal plain are diminished in winter and replaced by synoptic gradients. While wind speed was observed to increase as expected at the top of the nocturnal inversion, the primary driver for these winds was aloft gradients, and not boundary-layer-induced baroclinicity. In summary, the principal difference between summer and winter boundary layer forcing is that in summer the dynamics are generated at the surface and transported upward primarily by buoyancy, whereas the WBL forcing is driven by aloft mechanisms associated with the propagation of waves and their attendant gradients.

4a. Case Study: 2 February 2004

Six case studies were documented between 3 January and 14 February 2004. A feature common to all episodes was the passage of a progressive high pressure system over the study area, and with it the predictable rotation of the wind from a northerly direction to a southerly direction over time. Because of the rapid propagation speed of these anticyclones, the winds were often observed to rotate as much as 270° in a matter of hours.

The 2 February 2004 case study is included as an example of the detailed structure observed during MANE-VU 2004. Fig. 3 shows air temperature measured by the vertical profiling balloon at two different times. The first profile of temperature (Fig 3 top) was obtained between 0911-0943 EST when the near-surface layers were experiencing a weak drainage flow over a snow-covered surface (the site was at the bottom of a small hill rising to the southwest). The drainage resulted in mixing of a layer 50 m deep, weakening the inversion, and increasing the average deviation of all meteorological variables. This mixing marked the beginning of an increase in NO_X, total scattering coefficient, and black carbon concentration that persisted throughout the daytime period (Fig 4).

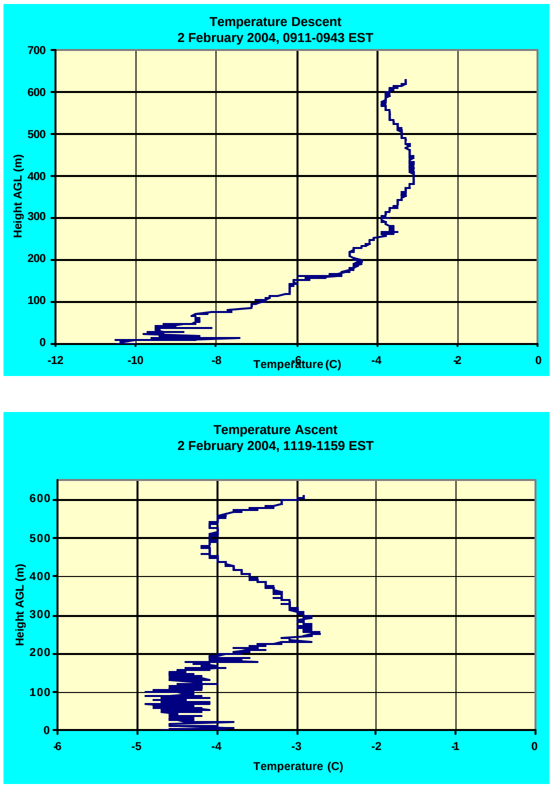

Fig. 3. Temperature profile on 2 Feb 2004 at 0911-0943 EST (top); and 1119-1159 EST (bottom). Note the change in the depth of the isothermal layer and the increased variability.

By 1119-1159 EST (Fig 3–bottom), the synoptic influence had overwhelmed the boundary layer drainage above 50 m AGL and brought air into the region from the southeast in association with a continental polar air mass centered north of the Great Lakes region. The depth of the isothermal layer had increased to about 150 m, while the remnant inversion persisted to 250 m AGL.

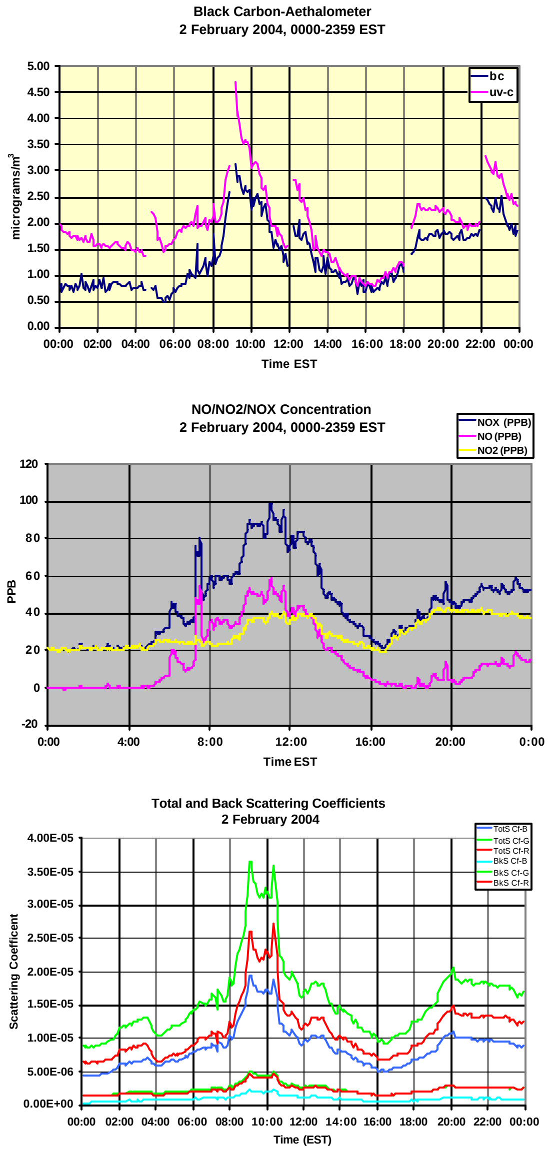

Fig. 4. Time traces of Black carbon, NO/NO$_2$/NO$_X$, and total and back scattering coefficient for 2 Feb 2004.

Considerable stratification was observed in the vertical profiles of total particle count at 0911-0943 and 1119-1159 EST (Fig. 5). The highest concentrations (16,000 cm^{-3}) were observed in the 50 m layer near the surface, and were likely due to local residential burning (i.e., coal furnaces, wood stoves) and drainage in to the study area. Above the surface layer, particle counts diminish by a factor of eight in the remnant inversion before increasing again to a local maximum of 7000 cm^{-3} at 270 m AGL. This secondary peak appears to be associated with particles trapped in an aloft inversion.

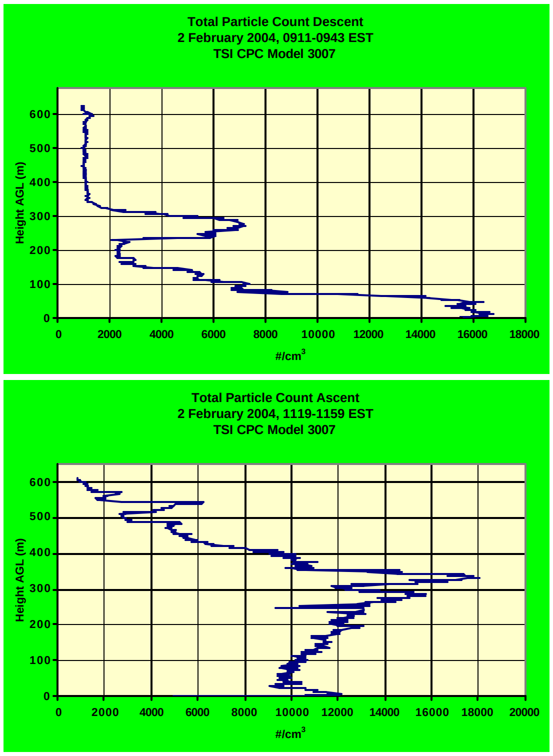

Fig. 5. Vertical profiles of total particle count obtained using a TSI Model 3007 CPC at 0911-0943 and 1119-1159 EST.

By 1119-1159 EST, the particle count at the surface had decreased from 16,000 to 11,000 cm^{-3}, but a notable layer of high particle count was observed residing at the top of the inversion. This feature is embedded in southeasterly flow (3 ms^{-1} @ 150°) and is probably a combination of both local and regional influences, which also contributed to the elevated amounts of trace gases, scattering coefficient, and black carbon at the surface.

5. DISCUSSION AND SUMMARY

The single case study presented here is by no means intended to be an exhaustive account of the complex structure and evolution of the WBL. Instead, it is intended as an example to illustrate many of the problems associated with the interpretation of WBL structure and evolution, and is admittedly preliminary in this regard. However, several noteworthy features are present in this example that can be applied to all the cases documented as part of this study. Strong wintertime synoptic-scale gradients can easily overwhelm boundary layer forcing mechanisms. This has advantages and disadvantages. The greatest advantage is that numerical models typically do better at simulating progressive wintertime systems than they do with quasi-stationary summertime events that have only weak upper level support and embedded mesoscale circulations. Thus, models should be capable of reasonably predicting the effects of significant intrusions of momentum, heat, and scalars associated with synoptic-scale waves.

The disadvantages are associated with the complex stratification that develops during those periods when an area is under the influence of high pressure. With low sun angles and strong nocturnal radiational cooling, deep stratification ensues that can trap pollutants and particles in shallow layers often only 50-100 m thick. Snow cover slows the development of the daytime mixed layer and reduces discontinuities that would otherwise enhance differential heating/cooling. Moreover, it is common to observe deep capping inversions at 300-500 m AGL persisting well in to the daylight hours, and sometimes through the entire diurnal period. During these periods when the WBL exhibits complex structure, it is difficult to ascertain whether a particular feature is locally or regionally generated. Buoyancy is not an important forcing mechanism in winter, except when cold air advection intrudes into an area in the post-frontal environment. Therefore, mechanical processes largely determine the height of the WBL. On several days this height is the altitude at which winds reach geostrophic balance, with shear-driven mechanical production being the principal component of the friction term. Unlike summer where a nearly adiabatic residual layer is a common boundary layer occurrence, the WBLs observed in this study were noted for their strong capping inversions separating the near-surface layers from the free atmosphere. Diurnal variability was largely confined to the layer between the surface and the top of the inversion. The colder surface, especially snow covered, inhibited the development of the daytime mixed layer by delaying the erosion of the inversion, and promoted the occurrence of drainage flows at night and into the early morning hours.

The results presented herein should be considered preliminary. Considerably more work is needed and planned using the data collected during this 6-week period.

6. ACKNOWLEDGEMENTS

The authors extend their appreciation to the team of 18 dedicated undergraduate students who endured the intense cold, exposure to the elements, poor air quality, and long hours (often 18-20 hours/day during an episode) to collect and analyze the measurements obtained during this marathon 6-week study that took place while classes were in session. A special thanks to John Yorks for his data processing effort. The authors also wish to thank the Northeast States Coordinated Air Use Management, George Allen, and the Mid-Atlantic Northeast Visibility Union for funding this study.

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