Mesoscale Meteorological Structure of a High-Ozone Episode during the 1995 NARSTO-Northeast Study

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ABSTRACT
Observations and numerical model fields were analyzed to study the meteorological structures contributing to high concentrations of lower-tropospheric ozone over the northeastern United States on 14–15 July 1995. It was found that the episode is characteristic of high-ozone events associated with the Bermuda high, having light winds, high temperatures, few clouds, and sparse rain over the entire region. The specific distribution of ozone at the peak of the episode on 14 July is of particular interest, however, since only the area from the urban corridor to the Atlantic Coast experienced ozone exceedances of the National Ambient Air Quality Standard. The analyses showed that an Appalachian lee trough (APLT) played a vital role in this pattern. Mesoscale structures associated with the APLT that affected ozone formation and distribution included 1) south-southwesterly winds east of the trough, which favored accumulation of emissions in an airstream that passed directly along the urban corridor; 2) west to northwesterly winds behind the APLT, which led to lower accumulation of emissions in that sector; 3) mixing depth contrasts across the APLT, which favored less dilution of primary and secondary pollutants to the east of the trough; and 4) low-level convergence and upward vertical velocities at the APLT, which led to the development of an elevated mixed layer over the planetary boundary layer on the east side of the trough, where pollutants could be trapped and transported for long distances by a low-level jet.

1. Introduction
It is well known that meteorological conditions are a crucial factor contributing to poor air quality, in addition to the two other factors of emissions and atmospheric chemistry. Many studies have been conducted in North America, Europe, and Asia to define the meteorological conditions conducive to high tropospheric ozone concentrations [considered to be an exceedance of the National Ambient Air Quality Standard (NAAQS) of 120 ppb for 1-h ozone concentrations (National Research Council 1991) or the newer 8-h standard of 80 ppb]. Results indicate that very different local and regional meteorological influences can be dominant in various settings. For example, frequent subsidence inversions that occur below the elevation of surrounding mountain ranges tend to trap pollutants in the Valley of Mexico (Jauregui 1988; Fast 1998) and the Los Angeles Basin (Edinger 1959; Blumenthal et al. 1978; Shultz and Warner 1982). In these regions, high pollution concentrations are expected to be associated primarily with local emissions. In the midwestern United States, lake breezes and shallow boundary layers over Lake Michigan trap and recirculate pollutants into nearshore communities over the mesoscale region of the lake environment (Lyons et al. 1995). In the eastern United States and western Europe, dense regional populations lead to widespread anthropogenic emissions of ozone precursors, so that tropospheric ozone generally is considered to be a regional problem, not simply a local issue (e.g., Kumar and Russell 1996). In the northeastern United States (hereinafter referred to as the “Northeast”), for example, ozone concentrations are a product not only of urban-scale and mesoscale production of ozone, but also can be influenced strongly by transport of ozone from the midwestern and southeastern United States over distances that exceed 1000 km and on timescales of one or more days (Wolff et al. 1977). Therefore, before proposed ozone abatement strategies for meeting the NAAQS can be designed and evaluated effectively, it is vital to understand the meteorological conditions that lead to poor air quality for a given region.

An important recent development designed to accelerate the investigation and remediation of tropospheric ozone is embodied in the North American Research Strategy for Tropospheric Ozone (NARSTO). NARSTO was established by the U.S. Environmental Protection Agency (EPA) and many public, private, and academic organizations from the United States, Canada, and Mexico to develop the scientific basis for understanding the
meteorological and chemical processes by which ozone is formed and to provide the air quality policy and management community with credible assessment tools and guidance (U.S. EPA 1994). In the summer of 1995, this consortium conducted the NARSTO-Northeast field study to provide the observational database necessary to understand the regional ozone problem better. The NARSTO-Northeast study area extends from Virginia to Maine, and from the Appalachian Mountains eastward to the Atlantic coast. The objectives of the study reported here as part of the NARSTO-Northeast effort are 1) to identify the key meteorological structures over the Northeast that led to the high-ozone episode of 12–15 July 1995 and 2) to assess the ability of a mesoscale numerical model to simulate those structures.

The case of 12–15 July was chosen for this investigation because it was the most intense and extensive high-ozone episode in the Northeast during the summer of 1995. Concentrations of greater than 100 ppb were common over the entire coastal–urban region from Virginia to Maine on the afternoon of 14 July, with a peak value of 175 ppb observed at Madison, Connecticut (Fig. 1). Exceedances of the NAAQS were recorded at 37 monitoring sites on 14 July and at 36 sites on 15 July (Fig. 2). Ozone concentrations reached a maximum of 185 ppb on 15 July just before the episode ended. Lower-tropospheric ozone in the Northeast is of great importance because high population densities across the region mean that the potential aggregate impact on human health can be very large.

Because mesoscale features are expected to be important for describing the key meteorological structures in this case, a combination of manual analyses and numerical modeling techniques was used. Direct observations from the NARSTO observation network (described below) provide valuable and accurate information. Even in the case of a special field study, however, the data generally are too sparse to resolve many of the important three-dimensional mesoscale structures. Model simulations, on the other hand, have very good spatial and temporal resolution but may contain errors caused by initialization uncertainty, physical-parameterization inaccuracies, and limitations of the model numerics. Each approach has strengths and weaknesses, but a combination of the two can provide greater insights into the actual structure of a given case.

Section 2 of this paper will present an analysis of the meteorological observations that describes the principal synoptic and mesoscale features of the 12–15 July 1995 episode. A brief description of the Fifth-Generation Pennsylvania State University–National Center for Atmospheric Research (PSU–NCAR) Mesoscale Model (MMS) and the experiment design will be provided in section 3. The results of the numerical experiment will be presented in section 4. Section 5 will integrate and discuss the findings of the meteorological investigations from an air quality perspective.

2. Case description and data analysis

a. Synoptic environment

The episode of 12–15 July 1995 was analyzed using both standard and special observations from the NARSTO-Northeast data archives. In general the large-scale pattern during the period was characteristic of the common summertime condition in which the climatologically persistent Bermuda high strengthens and extends westward over the eastern United States. In this case the ridge was quite broad, with the ridge axis lying east–west through the Carolinas and Tennessee (Fig. 3). Thus, the Northeast was subject to a weak west-southwesterly synoptic-scale flow that persisted for almost the entire period. Corrie and Yarnal (1992) have identified this pattern as one of three types associated with nearly 90% of the high-ozone events in the Northeast. At the beginning of the period, early on 12 July, a weak cold front on the northern margin of the Bermuda high had just passed southward into northern Virginia, where it soon dissipated (not shown). The Canadian air behind the cold front was relatively clean and only seven sites across the Northeast reported exceedances of the NAAQS on 12 July (Fig. 2). However, conditions soon developed that would lead to widespread reports of high ozone concentrations by 14 July.

During 12–14 July, a low pressure system initially in southern Manitoba (51°N, 102°W at 0000 UTC 12 July, not shown) traveled northeastward across James Bay into Labrador at 54°N, 60°W, where it deepened to 991 hPa by 1200 UTC 14 July (Fig. 3). Behind this low, pressures gradually rose over the Northeast on 13 July, as the Bermuda high strengthened over the southeastern United States. A surface warm front associated with the passage of the Canadian low extended southeastward from Wisconsin to West Virginia at 1200 UTC 12 July and slowly moved eastward across western New York and Pennsylvania before dissipating around 1500 UTC 13 July (not shown). The warm front marked the leading edge, at the surface, of hot air (35°–37°C) arriving from the Midwest with the returning southwesterly winds to the north of the ridge axis of the Bermuda high. By 1200 UTC 14 July, the warm air mass had replaced the somewhat cooler air (32°–34°C) that was previously over the Northeast.

At 850 hPa, strong warm advection was occurring over the Midwest and Northeast by 1200 UTC 12 July, as a midlevel trough trailing the Canadian low began to lift out of the eastern Great Lakes and New England (Fig. 4). Warming continued at stations throughout the Northeast through 14 July (Fig. 5). In addition, a moderate subsidence inversion associated with the Bermuda high covered the entire region (not shown). The base of the inversion varied between about 1.5 and 2.5 km above ground level (AGL). Widespread haze developed beneath the inversion, but clouds and rain were suppressed by the stable layer for much of the episode. Thus, as the case developed from 12 to 14 July, synoptic
conditions generally were excellent for photochemical production of ozone (hot air and high solar energy), and the transport and mixing conditions (stable capping inversion and light winds) also favored high concentrations over the Northeast.

As shown in Fig. 5, 850-hPa temperatures began to fall over the region by 1200 UTC 15 July. The cooling occurred when a cold front, previously quasi-stationary across the western Great Lakes on 14 July (Fig. 3), advanced southward from Lake Ontario and the St. Lawrence Valley on 15 July. During the night (from 0000 to 0900 UTC 16 July), a large mesoscale convective system (MCS) developed over western Pennsylvania and expanded to cover Pennsylvania, Maryland, Delaware, northern Virginia and West Virginia, and eastern Ohio (not shown). Combined with the northwesterly winds behind the advancing cold front, the clouds and rain of the MCS effectively ended the high-ozone episode.

b. Mesoscale influences

Inspection of Fig. 1, however, shows that the entire Northeast did not experience high concentrations of ozone as the episode peaked on the afternoon of 14 July. The ozone exceedances clearly are clustered along the Atlantic coastal plain and urban corridor. Concentrations over inland areas of Pennsylvania, New York, and New England, on the other hand, were only 60–90 ppb, despite high solar energy. The visible-range satellite imagery reveals that the entire Northeast had only scattered shallow cumulus on that day, with the exception of the Adirondack Mountains in northern New York (not shown). Of course, strong emissions in the urban and industrial areas are likely to be responsible in part. However, there are important mesoscale influences superimposed on the synoptic conditions that also strongly affected the development of the observed ozone pattern and concentrations in this case. The nature and role of those mesoscale meteorological features are revealed through analysis of the special data and, later, by the numerical simulation.

First, an analysis of the standard and special surface data revealed the development of an Appalachian lee trough (APLT) on 13 July. This trough is a common feature accompanying summer cases in which anticyclonic flow brings westerly winds across the mountain chain (Weisman 1990). Especially when the dynamic forcing in such cases is weak, the deepest column of hot air forms in the air descending just to the east of the mountains. Surface pressures fall as a hydrostatic response to the heated column of air, and, aided by conservation of absolute vorticity, the winds turn cyclonically across the mesoscale low pressure trough east of the mountains (Carlson 1991). Pagnotti (1987) has found that the APLT is associated with about 70% of the high-ozone cases in the Mid-Atlantic region (New York, New Jersey, Connecticut). Once the APLT formed on 13 July, it persisted for the entire episode and reached maximum intensity at 1200 UTC 14 July (Fig. 6). Afterward, a weak upper-level short wave passing to the north dragged the APLT eastward, beginning about 0000
UTC 15 July, until it disappeared with the arrival of the cold front around 0000 UTC 16 July.

Figure 6 also shows that the APLT is split into two troughs over New Jersey, New York, Pennsylvania, and New England on the morning of 14 July. In New Jersey and southern New York, the eastern surface trough may be associated with the boundary between warm inland air and cooler marine air. Later in the day, this eastern trough may be reinforced by the arrival of a coastal sea breeze. The western surface trough lies just to the east of the highest terrain of the Appalachian Mountains and thus represents a typical lee trough. The 1010-hPa frontal wave in southern Canada is associated with the short wave that pushes the trough eastward later that evening on 15 July.

The enhanced upper-air observation network for NARSTO-NE consisted of special sodars, radar profilers, radio acoustic sounding systems (RASS), and a special radiosonde site in Maryland (Fig. 7). In addition, data were collected from the standard radiosonde reports and Next Generation Radar (NEXRAD) Weather Surveillance Radar-1988 Doppler (WSR-88D) radars operated by the National Weather Service (NWS). Integration of the NEXRAD radial wind measurements across all azimuths yields a sounding of the vector wind, called a velocity azimuth display (VAD) wind. The NWS provides VAD soundings for all NEXRAD sites, and they were incorporated hourly into the NARSTO-NE archives during the field study. The error characteristics of these winds have been evaluated by Michelson and Seaman (2000) and filtered to remove unreliable data. The quality-checked VAD winds provided a valuable source of information to fill gaps in the upper-air observing network.

Figure 8 shows an analysis of the standard and special...
Fig. 4. NCEP 850-hPa height (dam) and temperature (°C) analysis for 1200 UTC (0800 EDT) 12 Jul 1995.

Fig. 5. Evolution of 850-hPa temperatures (°C) at four northeastern sites from 10 to 16 Jul 1995 during the NARSTO-Northeast high-ozone episode. Sites are Albany (ALB), Brookhaven (OKX), Pittsburgh (PIT), and Dulles (IAD).

NARSTO-Northeast data at 925 hPa for 1200 UTC 14 July. Because of the sparsity of the upper-air data, only one trough is analyzed here, although it is quite possible that the dual-trough pattern shown in Fig. 6 does extend through this level. There is considerable streamline convergence along the APLT at this level, and winds to the east of the trough reach 30 kt (15 m s⁻¹) in a nocturnal low-level jet (LLJ) over Long Island. An analysis of these upper-air data by Ray et al. (1998) indicates that the LLJ is an important mechanism for transporting ozone and other constituents during this period from the Mid-Atlantic region to New England. Streamline convergence along the trough suggests that upward vertical velocities may be induced in this zone. This hypothesized upward motion would provide a mechanism by which ozone could be lifted above the mean height of the daytime mixed layer, where it could be transported by the higher-speed winds aloft. Although a kinematic analysis of the observations can imply this vertical transport, a more detailed examination of this mechanism is provided in section 5 using 3D numerical model products.
These analyses imply that the high concentrations of ozone observed on 14 July are affected strongly by the APLT. The 925-hPa streamlines show that winds just east of the trough have mostly south-southwesterly directions, so that mean boundary layer winds during the day are nearly parallel to the trough axis. Consequently, the flow just ahead of the trough is aligned approximately with the urban corridor, where emissions should be especially high. Thus, the pretrough airstream would accumulate emissions rapidly during its passage over the corridor. The west-northwesterly flow behind the trough, on the other hand, is consistent with the advection of cleaner air into New England and central New York, where ozone concentrations were only 55–80 ppb on that afternoon (Fig. 1). Consequently, this flow has not traversed the urban and industrial centers of the Midwest and the East Coast. The streamlines also reveal that air from the Ohio Valley, with its richer emissions, arrives in western Pennsylvania and West Virginia, where Fig. 1 shows that ozone concentrations behind that portion of the trough are somewhat higher (75–95 ppb, except greater in the urban area around Pittsburgh). A similar analysis of the winds at 850 hPa (not shown)
indicated a pattern that was comparable with that shown for the 925-hPa level. Thus, the main elements of the horizontal flow in the lowest 1.5 km are consistent with the pattern of observed ozone as the episode approached its peak intensity.

The horizontal flow revealed by the observed winds is not the only important meteorological factor that affects air quality. The depth of the afternoon mixed layer also has a potentially important influence on ozone concentrations. Although radiosondes and profilers provided some information about the mixing depths, the observations were too sparse to be conclusive in the vicinity of the trough. Therefore, a numerical simulation becomes a vital supplement to the data and enables a more complete 3D picture to emerge.

3. Model description and experiment design

The numerical model chosen for this study is the PSU–NCAR MM5 nonhydrostatic mesoscale model. MM5 is a nested-grid, primitive-equation model with a terrain-following sigma (nondimensionalized pressure) vertical coordinate (Dudhia 1993; Grell et al. 1994). In this study, four nested domains were used (Fig. 9). A 108-km grid covered most of North America and a 36-km mesoalpha-scale grid covered the United States east of the Rocky Mountains. Next, a 12-km domain covered the eastern United States from the Great Lakes and northern New England nearly to the Gulf of Mexico. Finally, a 4-km mesobeta-scale grid covered a region of 612 km × 444 km, centered on the Mid-Atlantic states (Fig. 10). All domains had 32 layers, with the lowest calculation level at 10 m. There were 14 layers below 1500 m AGL to provide high resolution within the mixed layer. The top of the model was at 100 hPa. All model layers are defined using a time-invariant “background” pressure field based on a standard atmospheric lapse rate. Forecast variables include the three wind components, temperature, water vapor, cloud water and ice, precipitation water and ice, and the perturbation pressure.

MM5 included surface fluxes of heat, moisture, and momentum, and a 1.5-order turbulent kinetic energy (TKE)-predictive planetary boundary layer (PBL) scheme to represent turbulent processes (Gayno et al. 1994). A column radiation parameterization was used to calculate temperature tendencies due to shortwave and longwave radiative flux divergences (Dudhia 1989).
Fig. 9. Location of the four nested domains for MM5.

Fig. 10. Terrain in the 4-km MM5 domain. Contour interval is 50 m. Lines AB and CD represent locations of vertical cross sections for diagnosis of simulated fields.
For subgrid-scale deep convection, the Kain–Fritsch scheme was used on the 36-km and 12-km domains (Kain and Fritsch 1990, 1993), and the Anthes–Kuo convection scheme was used on the 108-km grid (Anthes 1977). All four domains used explicit microphysics with a simple ice scheme (i.e., no mixed-phase processes) to represent resolved-scale saturated processes (Dudhia 1989). The 4-km domain did not use parameterized convection because it was assumed that deep convection can be resolved reasonably well by the explicit microphysics at this scale (Weisman et al. 1997). Although that assumption may not be true universally, it is acceptable in this case in which most of the convection is infrequent and is well organized into mesoscale systems. In any case, the treatment of subgrid-scale convection at mesh sizes below about 10 km is problematic because some key parameterization assumptions begin to break down. For example, it cannot be assumed that the convective updrafts represent a negligible fraction of the grid area in such small cells.

The MM5 experiment reported here covered 6.5 days from 1200 UTC 12 July to 0000 UTC 19 July 1995. Three-dimensional initial and lateral boundary conditions for wind, temperature, and mixing ratio were prepared at 12-h intervals on the 108-km domain from standard NWS data and 2.5° spectral analyses obtained from the National Centers for Environmental Prediction (NCEP). Similar two-dimensional surface fields were acquired for pressure and sea surface temperature. Terrain and land use were specified using archived datasets that reside at NCAR. Initial conditions for the three finer domains were obtained by interpolation from the 108-km grid. The 108-km and 36-km domains were two-way interactive. The 12-km and 4-km domains, however, received boundary conditions from the next coarser grid but did not feed information back to the larger domains (one-way interactive nest interfaces).

The experiment design for the MM5 also included the four-dimensional data assimilation (FDDA) system described by Stauffer and Seaman (1990, 1994). FDDA was applied specifically to reduce error growth at the larger scales while allowing the 4-km solutions, which are the object of the experiment, to develop solely from dynamical and physical forcing. FDDA was accomplished by relaxing the model solutions at every time step toward the synoptic-scale 3D analyses of wind, temperature, and mixing ratio that were described above. These fields were blended into MM5’s 108-km, 36-km, and 12-km solutions using a continuous-relaxation approach known as analysis nudging. On the outer two domains, the nudging coefficient \( G \) which determines the \( e \)-folding time (or rate) of the assimilation, was set to \( 2.5 \times 10^{-4} \) s\(^{-1}\) for wind and temperature and to \( 0.1 \times 10^{-4} \) s\(^{-1}\) for mixing ratio. The analysis nudging coefficient for wind and temperature was reduced substantially on the 12-km mesh to \( G \) equal to \( 1.0 \times 10^{-4} \) s\(^{-1}\) because the features resolved in the 108-km analyses cannot resolve the mesobeta-scale circulations expected to emerge in the model solutions at the finer scales.

No data assimilation was done on the 4-km domain in this experiment. Limiting FDDA to the outer three domains was designed to provide accurate lateral boundary conditions for the 4-km domain while allowing the model’s 4-km solutions to develop without artificial forcing. By reducing the phase and amplitude errors in the synoptic-scale solution, the mesobeta-scale structures on the innermost grid were found to have skill consistent with statistics reported for typical air quality episodes simulated using FDDA-assisted models (Michelson 1998; Seaman et al. 1995; Lyons et al. 1995). Furthermore, on the outer three domains, no FDDA was applied below 850 hPa. This data assimilation strategy ensured that important surface-forced features such as the APLT, LLJ, and sea breeze could develop in the fields used to supply boundary conditions to the 4-km domain (i.e., on the 12-km grid) without being damped by assimilation of the synoptic-scale analyses.

### Table 1. Summary of statistical skill for surface-layer winds averaged over the 4-km domain for 1200 UTC 12 Jul to 0000 UTC 19 Jul 1995.

<table>
<thead>
<tr>
<th>Date</th>
<th>Mean error wind speed (m s(^{-1}))</th>
<th>Mean error wind direction (°)</th>
<th>Rms error wind speed (m s(^{-1}))</th>
<th>Index of agreement</th>
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<tbody>
<tr>
<td>12</td>
<td>1.68</td>
<td>−1.20</td>
<td>1.99</td>
<td>0.33</td>
</tr>
<tr>
<td>13</td>
<td>0.81</td>
<td>−4.72</td>
<td>1.55</td>
<td>0.53</td>
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<td>14</td>
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<td>−4.99</td>
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<tr>
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<td>−1.61</td>
<td>1.81</td>
<td>0.58</td>
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</tbody>
</table>

4. Numerical results

In this section, model results are examined to extend the understanding of the mesoscale structure of the 12–15 July NARSTO-Northeast high-ozone episode beyond what can be seen in the more sparse observations. Before the specific structures of the numerical solutions are investigated, it is helpful to review briefly the results of a statistical evaluation for the full 6.5 days for which the experiment was run (see section 3). Table 1 presents the statistics for surface-layer winds, using several common measures of skill (Stauffer and Seaman 1990). The table shows small mean errors (biases) for speed and direction, modest root-mean-square errors (rms error), and a case-average index of agreement \( I \) of 0.58. This index of agreement, which is a measure of how well the solutions represent the spatial variability of the winds (Willmott et al. 1985), is typical of that for mesoscale models. However, if the 12-h model “spinup” period of 12 July is ignored, the case-averaged \( I \) rises to 0.63, which is very good. For the winds aloft, Table 2 shows that the skill of the simulation actually is some-
what better than at the surface. This improvement mostly is because the winds in the surface layer tend to be influenced by buildings, small-scale (unresolvable) terrain, and other obstacles or heterogeneity, so that local variability is greater than it is farther aloft. Next, the accuracy of the surface thermal simulations is summarized in Table 3. It shows very low bias in the surface temperatures, and the most typical errors (mean absolute errors) are only 1.7°C. Finally, a comparison between the model’s predicted morning and afternoon mixing depths and radiosonde observations revealed case-averaged mean errors of only 28 m, with mean absolute errors of 412 m. Since the skill is comparable to that reported in other recent modeling studies related to events with poor air quality (e.g., Seaman et al. 1995; Lyons et al. 1995), these results indicate that, in most respects, the model did well at predicting some of the key variables that are most important for air quality applications. A more extensive statistical evaluation for this case, including comparison with a variety of numerical experiments not discussed here, is given by Michelson (1998).

The investigation of model results begins with a set of backward trajectories calculated for a 12-h period ending at 0000 UTC 15 July (Fig. 11). The parcels were released at about 120 m AGL and do not experience dispersion effects from boundary layer turbulent mixing, even though the model’s wind field includes turbulent processes. That is, the trajectories are based solely on the three-dimensional advection by the model-resolved winds, using a two-step iterative procedure that ensures accuracy of the parcel motion (Haagenson et al. 1987).

Three flow regimes can be detected in the trajectories. Parcels arriving in Pennsylvania, New York, and western Maryland (parcels 2–5, 8–10, 12, 15–17, and 20) have experienced mostly westerly flow behind the APLT. There is considerable directional shear in this region, but most of these parcels are too close to the surface to encounter the full effect of the northwesterly winds observed behind the trough at 925 hPa (compare directions over Pennsylvania in Figs. 8 and 11). A number of the trajectories in this group (e.g., 3, 4, 15, 16, and 20), however, exhibit cyclonic histories over Pennsylvania associated with the western branch of the APLT that was evident at the surface during early morning of the same day (Fig. 6). In addition, these particular parcels originated at somewhat higher levels (about 900–950 hPa) and, during the first 6 h, experienced sinking in the northwesterly flow crossing the Appalachian Mountains behind the trough position. A second cluster of parcels (parcels 18, 21, and 22) shows that the low-level air close to the Atlantic coast exists within the general anticyclonic circulation of the Bermuda High (also see Fig. 3). This flow should be relatively clean because it traverses land only along the coastal plain in Virginia and the Delmarva Peninsula.

Last, a third group of parcels can be found just east of the APLT (parcels 1, 6, 7, 11, 13, 14, 19, 23, and 24). These low-level trajectories indicate that parcels arriving at urban areas east of the trough (Washington, District of Columbia; Baltimore; Philadelphia; central New Jersey; New York City; Long Island; and southern Connecticut) have experienced mostly straight southwesterly low-level flow and high ozone concentrations east of the APLT.

Next, Fig. 12 shows the potential temperature and mixing depth at 2000 UTC 14 July along a vertical cross section through Baltimore and across the Delmarva Peninsula (section AB shown in Fig. 10). This cross section lies approximately perpendicular to the APLT, which intersects the line AB just west of Baltimore (Fig. 10). The mixing depth reveals important details of the mesoscale structure and is important for understanding the pollutant concentrations in this case. The cross section reveals that shallow stable boundary layers exist over the Chesapeake Bay and Atlantic Ocean, and deeper mixed layers exist over land. Two distinct land regimes are clearly visible on either side of the APLT.
The isentropes indicate that the thermal contrast between the two air masses is concentrated at the trough. Also, notice that the air between 100 and 850 m AGL (approximately 1000–930 hPa) over the Chesapeake Bay remains fairly well mixed above the shallow stable surface layer. This result indicates that the TKE-predictive turbulence scheme is producing correctly a stable thermal internal boundary layer while maintaining gradually decaying turbulent energy in the deeper (outer) unstable layer as it is advected over the narrow water body.

As one moves northeastward along the trough, the contrast between the hot inland air mass and the modified marine air is expected to decrease as the latter continues to flow over land and the urban corridor. Figure 14 shows potential temperature and mixing depth at 2000 UTC 14 July, perpendicular to the APLT in
Pennsylvania and New Jersey along the vertical cross section CD (shown in Fig. 10). The eastern APLT at this time and location intersects the trough about 20 km west of the Delaware Valley. First, note that the mixed layer has its maximum depth (about 1700 m) immediately at the eastern APLT, as was found farther south along section AB. This maximum is caused by the low-level horizontal convergence in the unstable air along the trough. Upward vertical velocities are found in a 20-km band across the trough throughout the boundary layer (Fig. 15). Maximum upward motion in section CD is 0.38 m s\(^{-1}\) about 850 m AGL. A second zone of deeper mixed-layer depths lies about 100 km northwest of the main eastern trough (Fig. 14). This second mixed-depth maximum in section CD lies just east of the last
range of mountains in the Appalachian chain and is associated with the western branch of the split surface trough analyzed in Fig. 6. Two relative humidity maximums (75%–80%) are found at the top of the boundary layer at both trough locations (not shown). West of the primary (eastern) APLT, mixing depths average about 1250 m, and, to the east of the trough, the mean depth of the mixed layer is only about 650 m. Notice that the thermal contrast across the trough in section CD has decreased to 2–3°C. Nevertheless, despite the decreasing thermal contrast, the mixing-depth contrast between the two air masses remains quite strong.

The large difference in mixed-layer depths across the APLT in the two cross sections is an important factor contributing to the contrast in ozone concentrations on either side of the trough. Mixing depths east of the trough are lower because they occur in an air mass with only moderately modified marine characteristics. Thus, the lower mixing depths mean that pollutants are diluted less to the east of the trough than to the west. Furthermore, Figs. 14 and 15 indicate that, along the trough, ozone and other pollutants caught in the rising plume at the convergence line are lofted into a zone between 900 and 860 hPa, where an elevated mixed layer extends eastward above the capping inversion in New Jersey. This elevated mixed layer lies between the 308 and 307 K isentropes in Fig. 14 and from the trough position to the Atlantic coast, while a distinctly stable layer lies below it, capping the PBL. Pollutants injected into this elevated plume can remain aloft and be transported northeastward over long distances in the nocturnal LLJ (Ray et al. 1998). Ozone at this height is protected from destructive processes, primarily surface deposition and titration by nitrogen oxide emissions, associated with the earth’s surface. Thus, MM5 has developed a detailed and realistic thermal structure that is highly valuable in understanding the pattern and transport of high ozone concentrations as observed on 14–15 July 1995.

5. Summary

The NARSTO-Northeast observations were analyzed to study the meteorological structures that contributed to high concentrations of ozone on 14–15 July 1995. Additional information was supplied by running the PSU–NCAR MM5 during this episode. The numerical model proved to be a valuable tool, supplying important information about this case that was not revealed directly in the special data.

The midtropospheric synoptic-scale flow into the Northeast during the period of interest was mostly from the west because of the intensification and westward extension of the large subtropical Bermuda high, which had its east–west axis over North Carolina and Tennessee. Subsidence in the subtropical high inhibited the formation of widespread cloud and convection over the study region. The high also was responsible for strong warm advection from the Midwest at the beginning of the episode. The combination of analyses and model results shows that synoptic conditions were ideal for photochemical ozone production over the entire Northeast during the period. The high concentrations, however, were confined to the major urban corridor and coastal plain. Therefore, additional insights about the mesoscale structures were needed to understand the particular pattern of ozone measurements observed on 14 July.

Through combined evaluation of the data and numerical results, a three-dimensional conceptual model for the meteorological structure of the Northeast’s 12–15 July 1995 high-ozone episode has emerged. Figure 16 presents, in schematic form, the principal features of this conceptual model. (In the following discussion, italics will indicate specific features shown in the figure.) First, a synoptic-scale midtropospheric flow with a westerly component (broad arrow) crossed the Appalachian Mountains, where it was forced to sink and warm adiabatically. Because of this warming, pressures fell, creating the mesoscale Appalachian lee trough (heavy dashed line). The development of the APLT proved to be a crucial factor leading to the observed ozone pattern in this case. As a result of the trough formation and conservation of potential vorticity in the midtropospheric flow, winds ahead of the trough turned cyclonically to become south-southwesterly. This weak low-level flow caused boundary layer winds just ahead of
the trough to be parallel to the trough axis and therefore to be aligned directly along the urban corridor, where emissions are especially high. The generally westerly flow to the west of the APLT is consistent with advection of somewhat cleaner air behind the trough. This scenario favored higher concentrations ahead of the APLT position.

The south-southwesterly flow ahead of the APLT means that this air had a marine origin in the western part of the Bermuda high \((H)\) over the Atlantic Ocean and Chesapeake Bay and only lately had been modified by its passage over the coastal plain. As such, the anticyclonic synoptic-scale flow over the ocean (thin arrows) initially should have been relatively clean before encountering the high emissions of the eastern United States. Despite rapid warming due to the surface sensible and latent heat fluxes over land, this air remained a few degrees cooler than the hotter air to the west of the APLT. This temperature difference resulted in shallow PBL depths to the east of the APLT, compared to the deep boundary layer west of the trough. The shallower mixing depths to the east were capped by the advection of the hot Midwestern air mass at middle levels, since the winds near the APLT veered strongly with height (long medium-width arrows). Thus, the south-southwesterly low-level flow ahead of the trough resulted not only in longer exposure of this air to high emissions but also in lower mixing depths and less dilution of the primary and secondary pollutants.

In addition, there was low-level convergence along the APLT as the westerly flow behind the trough encountered the south-southwesterly flow ahead of it. This convergence forced rising motion along the trough, which helped to transport low-level ozone and other pollutants to the top of the locally deepened boundary layer (long medium-width arrows). Since the mixed-layer depth was deepest along the convergence zone, these pollutants could then be injected into an elevated mixed layer that formed above the shallower boundary layer to the east of the trough. Once injected into that level by the westerly middlelevel winds, the elevated ozone was protected from surface deposition and other destructive processes, and it could be transported over long distances in the nocturnal LLJ present ahead of the trough over Long Island. In portions of the Northeast, the sea breeze, valley breeze, deep convection, and shallow cloud processes probably caused modification to the regional circulation and affected low ozone concentrations, as well. This combination of mesoscale influences provides a coherent explanation for the very high concentrations of ozone found to the east of the APLT in this episode.

To summarize the principal characteristics of this episode and their importance for understanding air quality in the northeastern United States, the following points are notable.

1) Favorable synoptic-scale conditions for high ozone concentrations, associated with the Bermuda high, included light winds, high temperatures, few clouds, and sparse rainfall.
2) South-southwesterly winds east of an APLT favored accumulation of emissions in an airstream that passed directly over the urban corridor.
3) Westerly to northwesterly winds and sinking motion behind the APLT led to lower accumulation of emissions in that sector.
4) Mixing-depth contrasts across the APLT favored less dilution of primary and secondary pollutants to the east of the trough.
5) Low-level convergence and upward vertical velocities at the APLT led to the development of an elevated mixed layer over the planetary boundary layer on the east side of the trough. These structures can lead to injection of boundary layer pollutants into the elevated mixed layer.
6) Pollutants trapped in an elevated mixed layer are protected from surface deposition processes while the development of a nocturnal LLJ can lead to rapid, long-range transport.

Of course, the alignment and intensity of the mesoscale features associated with the APLT in this episode are not identical to all APLT cases. Nevertheless, the high correlation found by Pagnotti (1987) between APLTs and high ozone concentrations in the Northeast suggests that the structures found here are not unusual. More research is warranted to verify the connection between these specific trough features and high ozone concentration. These results, however, indicate that we can understand these connections and, with sufficiently detailed numerical models, we should be able to forecast such events. Thus, it may be possible to develop case-specific pollution control strategies that restrict the most severe emission-reduction measures only to those cases forecasted to have important air quality degradation conditions. The benefit of such case-specific strategies to the economy, while ensuring the health and quality of life for the region’s population, could be enormous.

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