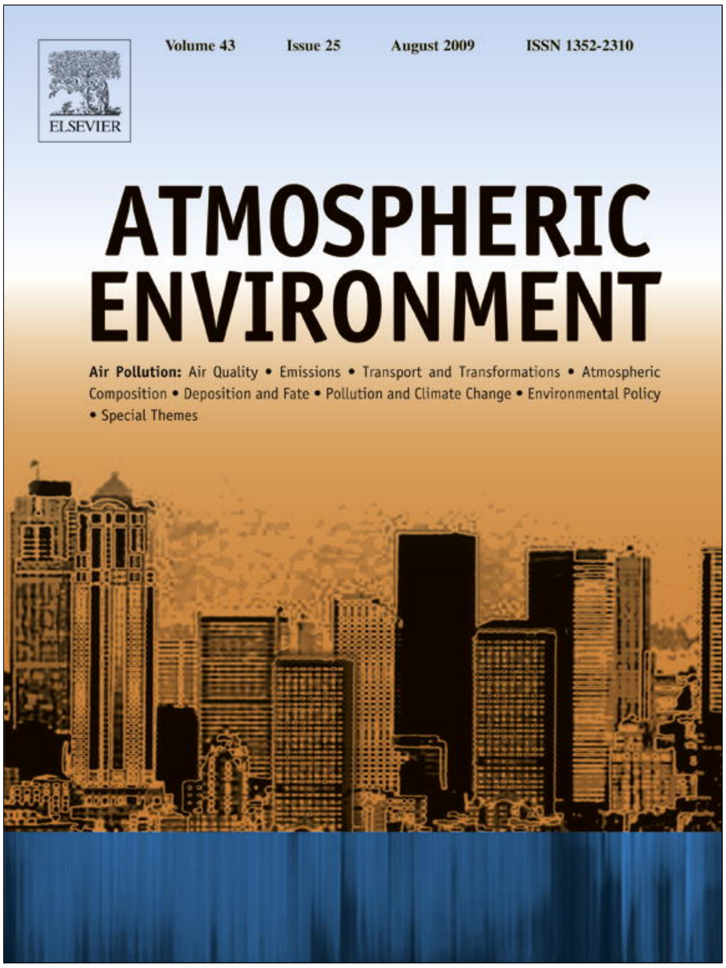
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Atmospheric characteristics conducive to high-ozone days in the Atlanta metropolitan area

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ABSTRACT

The purpose of this paper is to identify the atmospheric conditions associated with elevated ground-level ozone concentrations during June–August of 2000–2007 at 11 ozone-monitoring stations in the Atlanta, GA, USA metropolitan statistical area (MSA). Analyses were confined to high-ozone days (HODs), which had a daily maximum 8-h average ozone concentration in the 95th percentile of all June–August values. Therefore, each station had 36 HODs. The southeastern and far northern portions of the MSA had HODs with the highest and lowest ozone concentrations, respectively. HODs at nearly all Atlanta MSA ozone-monitoring stations were enabled by migratory anticyclones. HODs for most stations were hot, dry, and calm with low morning mixing heights and high afternoon mixing heights. All sets of HODs had daily mean relative humidities and afternoon mixing heights that, respectively, were significantly less than and significantly greater than mean values for the remaining days. Urbanized Atlanta typically was upwind of an ozone-monitoring station on its HODs; therefore, wind direction on HODs varied considerably among the stations. HODs may have been caused partially by NO_x emissions from electric-utility power plants: HODs in the southern portion of the MSA were linked to air-parcel trajectories intersecting a power plant slightly northwest of Atlanta and plants in the Ohio River Valley, while HODs in the northern portion of the MSA were linked to air-parcel trajectories intersecting two large power plants slightly southeast of the Atlanta MSA. Results from this study suggest that future research in the Atlanta MSA should focus on power-plant contributions to ground-level ozone concentrations as well as the identification of non-monitored locations with potentially high ozone concentrations.

1. Introduction

Ozone pollution is a major environmental concern in the southeastern United States due to the climate of the region as well as chemical emissions within and proximate to the region. The Southeast has a humid subtropical climate (Trewartha and Horn, 1980), and the summers often are hot with wet and dry periods controlled by the strength and location of the Bermuda High, the subtropical high-pressure cell in the North Atlantic Ocean (Diem, 2006). Ground-level ozone is formed by photochemical reactions involving volatile organic compounds (VOCs) and nitrogen oxides (NO_x) (Haagen-Smit, 1952; Crutzen, 1979). Ozone production in the Southeast during the summer is typically NO_x-sensitive resulting from high emission rates of biogenic volatile organic compounds (BVOCs), especially isoprene (Chameides et al., 1992; Guenther et al., 2000; Ryerson et al., 2000). In addition to having several metropolitan areas that serve as substantial area sources of NO_x, the Southeast also has large NO_x-emitting electric-utility power plants in the region, especially near Atlanta, and along the northern periphery of the region in the Ohio River Valley, northwestern Tennessee, and southwestern Kentucky (Fig. 1). Counties in the Southeast that currently have non-attainment status for the 8-h ozone National Ambient Air Quality Standard (NAAQS) exist within the following metropolitan statistical areas (MSAs): Atlanta, Georgia; Charlotte, North Carolina; and Knoxville, Tennessee (US Environmental Protection Agency, 2008).

The Atlanta MSA continues to be an excellent geographical domain for ozone research; substantial research on ground-level ozone in the MSA has occurred over the past several decades. The Atlanta MSA, with a population exceeding four million persons, is the largest ozone non-attainment area in the Southeast (US Census Bureau, 2001). Due to its large size, the Atlanta MSA had 11 ozone-monitoring stations in operation in 2008. Unlike the large metropolitan areas in the northeastern United States that form one contiguous non-attainment domain, the Atlanta MSA is geographically isolated from the two other non-attainment areas in the Southeast (Fig. 1). NO_x emissions from nearby and distant power plants may contribute significantly to either precursor concentrations or ozone concentrations or both in the Atlanta MSA:

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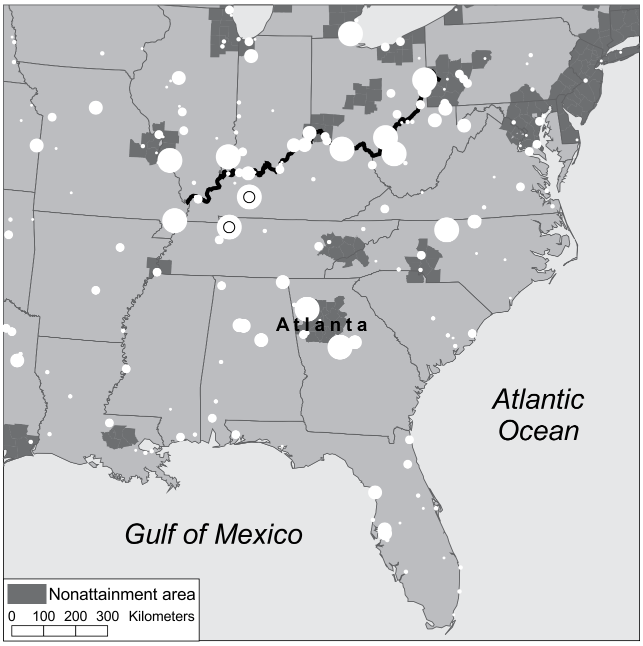

Fig. 1. Locations of the Atlanta non-attainment area and other non-attainment areas within a square domain centered on Atlanta. The thick black line is the Ohio River. The white circles are locations of electricity-generating power plants; only plants having at least 5000 short tons (i.e. 4.54 Gg) of annual NO_x emissions are shown. The largest circles have at least 40,000 short tons (i.e. 36.29 Gg), and the two power plants with at least 80,000 short tons (i.e. 72.57 Gg) are denoted by black circles. Non-attainment and NO_x-emissions data from 1999 were obtained from the US Environmental Protection Agency.

(1) there are several large power plants proximate to the MSA; and (2) the Ohio River Valley is ~700 km upwind of Atlanta on days with "northerly" flow in the lower troposphere. The present state of information regarding atmospheric conditions during ozone episodes in the MSA is as follows: (1) a high-pressure system over either the south-central United States (Imhoff et al., 1995) or over the Southeast (St. John and Chameides, 1997; Napelenok et al., 2007); (2) high temperatures (Cardelino and Chameides, 1995; Chang et al., 1996; St. John and Chameides, 2000; Cardelino et al., 2001; Cohan et al., 2005; Napelenok et al., 2007; Saylor et al., 1999); (3) low dew-point temperatures (Cardelino et al., 2001); (4) low amounts of cloud coverage (Cardelino et al., 2001); (5) light winds (Imhoff et al., 1995; Chang et al., 1996; St. John and Chameides, 1997; Saylor et al., 1999; Cardelino et al., 2001; Schictel and Husar, 2001; Cohan et al., 2005; Napelenok et al., 2007); (6) variable wind directions (Saylor et al., 1999; St. John and Chameides, 1997), westerly/northwesterly winds (Lindsay and Chameides, 1988; Cardelino and Chameides, 1995; Chang et al., 1996; St. John and Chameides, 1997), northwesterly winds (Chameides et al., 1988; St. John and Chameides, 2000), northerly winds (St. John and Chameides, 2000; Schictel and Husar, 2001; Cohan et al., 2005), easterly winds (Lindsay and Chameides, 1988), or southwesterly winds (Cardelino and Chameides, 1995); and (7) air entering the Atlanta MSA may have traveled over 600 km from the Midwest and the Ohio River Valley (Lindsay and Chameides, 1988). While there is a general consensus that ozone episodes coincide with high-pressure systems, hot conditions, and light winds, much uncertainty remains regarding the prevailing wind direction during ozone episodes.

The purpose of this project was to identify the atmospheric conditions, especially the prevailing wind direction, associated with elevated ground-level ozone concentrations at multiple locations throughout the Atlanta MSA. Existing Atlanta-ozone research in peer-reviewed journals has involved approximately a dozen ozone episodes, with as few as four episodes containing days with 8-h average exceedences, over an 18-year measurement period (i.e. 1983–2000), and reported atmospheric conditions for those days have been insufficient. Furthermore, there have been no published examinations of ozone concentrations at stations in the southern portion of the MSA that were established in 1999 and 2000. Finally, few attempts have been made to assess the potential influence of large point-source NO_x emissions within and near the Atlanta MSA, especially power plants southeast of the MSA, and in the Ohio River Valley on high ozone concentrations in the Atlanta MSA. Therefore, the specific objectives of this paper are to determine the following: (1) the ozone-exceedence season and associated high-ozone days (HODs) for the Atlanta MSA; (2) synoptic-scale circulation patterns of the HODs; (3) near-surface and lower-troposphere atmospheric conditions of the HODs; and (4) air-parcel back trajectories for the HODs.

2. Methodology

2.1. Preparation of ozone data

Daily maximum 8-h average ozone concentrations were computed using serially complete ozone records. Hourly ozone concentrations from March to October of 2000–2007 were obtained from the US Environmental Protection Agency for 11 ozone-monitoring stations within the Atlanta MSA (Fig. 2 and Table 1). The starting year of 2000 was chosen, because from 1999 to 2000 the number of stations with complete-season (i.e. March through October) data increased from nine to 11. The two

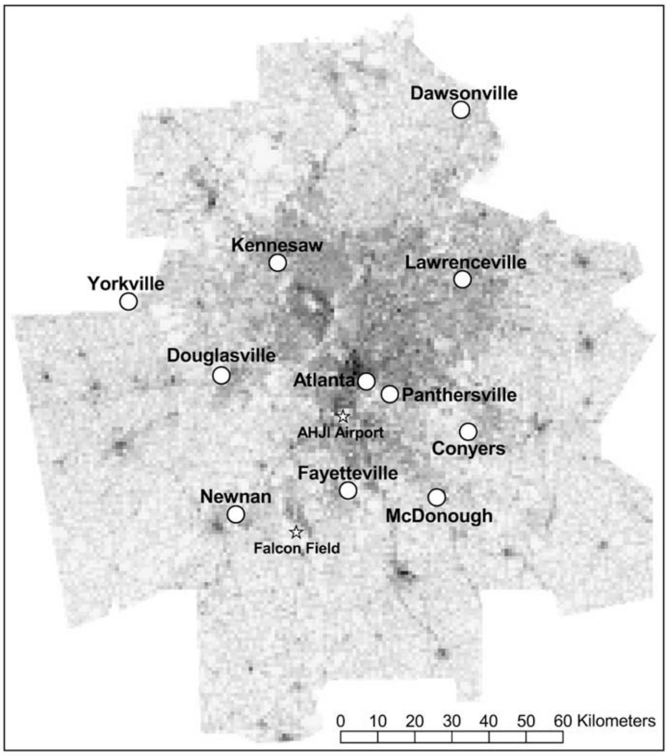

Fig. 2. Locations of the 11 stations within the Atlanta MSA that measured ozone concentrations during the entire 2000–2007 period. Also shown are the weather stations at Atlanta Hartsfield Jackson International (AHJI) Airport and Falcon Field. Street-length density, which is a proxy for urbanization, is shown as greyscale shading; light grey is low density and black is high density.

Table 1
The 11 ozone-monitoring stations in the Atlanta metropolitan statistical area that operated from 2000 to 2007. "EPA ID" is the identification number used by the US Environmental Protection Agency (EPA) and "% Missing" is the percentage of hours that did not have valid ozone measurements. Location type was designated by the EPA.

Station	EPA ID	Location type	% Missing
Atlanta	13-121-0055-44201-1	Suburban	1.8
Conyers	13-247-0001-44201-1	Rural	2.2
Dawsonville	13-085-0001-44201-2	Rural	3.6
Douglasville	13-097-0004-44201-1	Suburban	1.6
Fayetteville	13-113-0001-44201-1	Suburban	1.3
Kennesaw	13-067-0003-44201-1	Suburban	1.0
Lawrenceville	13-135-0002-44201-1	Suburban	5.8
McDonough	13-151-0002-44201-1	Suburban	1.6
Newnan	13-077-0002-44201-1	Suburban	4.8
Panthersville	13-089-0002-44201-1	Suburban	4.1
Yorkville	13-223-0003-44201-1	Rural	2.4

additional stations were McDonough and Newnan, which are located to the southwest and southeast of Atlanta, respectively. The original ozone dataset had 2.7% of the hours with missing ozone concentrations. If both the hour immediately before a missing value and the hour immediately after had valid values, then the missing value was replaced with the mean of those two concentrations. Linear regression models having data at station x as the predictor and data at station y as the predictand were used to produce replacement values for the remaining missing values. At least one model was developed for each station: the station with the highest correlation was used to develop the first model, the station with the second-highest correlation was used to develop the second model if necessary, the station with the third-highest correlation was used to develop the third model if necessary, and so on until all missing values were replaced. Moving 8-h means were computed from the hourly ozone concentrations, and the results were stored in the start hour of the 8-h period (US Environmental Protection Agency, 1998). The daily maximum 8-h average ozone concentration was then calculated for the 1960 days at the 11 stations.

2.2. Determination of exceedence season

The exceedence season was determined through the examination of monthly frequencies of exceedence days at the ozone-monitoring stations. Exceedence days in this study were days with daily maximum 8-h average ozone concentrations $\geq$85 ppb (i.e. the 8-h ozone NAAQS). With the concentrations in ppm, the third decimal digit was rounded, thereby resulting in a maximum non-exceedence concentration of 0.084 ppm (US Environmental Protection Agency, 1998). The exceedence season was comprised of consecutive months containing a large proportion of the exceedence days. Using all months, rather than a smaller set of months (i.e. exceedence season), would have weakened the atmospheric analyses, because there are considerable atmospheric differences among the 8 months (i.e. March–October) constituting the measurement season.

2.3. Determination of HODs

Environment-to-circulation analyses (e.g. Yarnal, 1993) were conducted only for HODs within the exceedence season. A HOD was a day in the exceedence season with a daily maximum 8-h average ozone concentration in the 95th percentile of all exceedence-season values; therefore, each station had 36 HODs. Using HODs, rather than exceedence days, guaranteed that each station would have the same number of cases thereby facilitating orderly comparisons among the stations. The number of shared HODs among pairs of stations was calculated to determine over-all similarities and differences among the stations prior to the atmospheric analyses.

2.4. Atmospheric analyses

Upper-air data extracted from the NCEP/NCAR Reanalysis dataset (Kalnay et al., 1996) of the Earth System Research Laboratory (ESRL) of the National Oceanic and Atmospheric Administration (NOAA) were used to create mean 850-hPa circulation patterns and calculate mean 925-hPa wind directions over the Atlanta MSA for each set of HODs. The gridded dataset had a spatial resolution of 2.5. Mean meteorological wind directions and wind speeds over each station location were estimated from interpolated isolines of zonal wind speeds and meridional wind speeds.

One-tailed ($\alpha = 0.01$) Student's t tests were used to test for significant differences between HODs and non-HODs for the following 14 atmospheric variables: daily maximum near-surface temperature; daily mean 925-hPa temperature; daily mean 850-hPa temperature; daily mean near-surface relative humidity; daily mean 925-hPa relative humidity; daily mean 850-hPa relative humidity; daily mean near-surface wind speed; daily mean 925-hPa wind speed; daily mean 850-hPa wind speed; daily mean sea-level pressure; daily mean 925-hPa geopotential height; daily mean 850-hPa geopotential height; morning mixing height; and afternoon mixing height. Temperature and dew-point temperature were used to calculate relative humidity for the near surface, at 925 hPa, and at 850 hPa. The near-surface data were collected at Atlanta Hartsfield-Jackson International Airport; the data were extracted from the Global Summary of the Day dataset of NOAA. Radiosonde data (i.e. data at 925 and 850 hPa) for 0 UTC and 1200 UTC were measured at Falcon Field and were obtained from NOAA's ESRL. Daily values of morning and afternoon mixing heights were provided by NOAA, which used the Holzworth (1972) method to estimate mixing heights. The near-surface dataset was serially complete. The percentage of valid values for 925-hPa temperature, 850-hPa temperature, 925-hPa relative humidity, 850-hPa wind speed, 925-hPa wind speed, 850-hPa geopotential height, 925-hPa geopotential height, morning mixing height, and afternoon mixing height were 92, 94, 92, 94, 64, 89, 94, 94, 97 and 97%, respectively.

Three-day back trajectories were modeled for each HOD. The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Draxler and Rolph, 2003) was run with the Eta Data Assimilation System (EDAS) data. The Air Resources Laboratory of NOAA provided the model and requisite data. Vertical motion was described by modeled vertical velocity. The starting heights, times, latitude, and longitude of the trajectories were 500 m a.g.l., 1500 UTC, 33.756°N, and −84.418°W, respectively. The starting location was the geographic center of the 11 ozone-monitoring stations, while the starting time was the typical first hour of the period comprising the daily maximum 8-h ozone concentration.

In order to assess whether power-plant emissions in the Ohio River Valley or the Atlanta region or both should be considered potential contributors to HODs, frequencies of trajectories intersecting the Ohio River Valley and individual power plants were calculated. Two-sample chi-square tests ($\alpha = 0.01$) were conducted for each set of HOD trajectories. Contingency tables for the tests specific to the Ohio River Valley contained the following frequencies: (1) HOD trajectories that intersected the Ohio River Valley; (2) HOD trajectories that did not intersect the Ohio River Valley; (3) non-HOD trajectories that intersected the Ohio River Valley; and (4) non-HOD trajectories that did not intersect the Ohio River Valley. The Ohio River Valley was delineated as a zone within 50 km of the Ohio River. Contingency tables for the tests specific to each Atlanta-region power plant outside the urban zone contained the following frequencies: (1) HOD trajectories that intersected the power plant; (2) HOD trajectories that did not intersect the power plant; (3) non-HOD trajectories that intersected the power plant; and (4) non-HOD trajectories that did not intersect the power plant. Since the finest spatial resolution of the trajectories was 40 km, each power-plant had a circular "footprint" with a 40-km radius.

3. Results

3.1. Exceedence season and HODs

Nearly 90% of exceedence days at all stations from March through October in the Atlanta MSA occurred during June, July, and August; therefore, those 3 months constituted the exceedence season (Fig. 3). There was little variation in frequencies of exceedence days among the three months: June, July, and August contained 28, 26, and 32%, respectively, of the exceedence days. The percentages of March–October exceedence days that occurred from June–August ranged from 69% at Dawsonville to 97% at McDonough (Table 2). Among the 11 stations, Atlanta had the most exceedence days during June–August. The second highest total occurred at McDonough, which is approximately 37 km southeast of the Atlanta station. Dawsonville had by far the lowest number of exceedence days. The mean 95th percentile ozone concentration among the 11 stations for June–August was 96 ppb. Atlanta had the highest minimum and mean 95th percentile ozone concentrations. The absolute highest daily maximum 8-h average ozone concentration (139 ppb) occurred at McDonough. Dawsonville had the lowest minimum, mean, and maximum 95th percentile ozone concentrations.

The HODs were distributed approximately evenly among the summer months, and most HODs were exceedence days. There was a total of 147 HODs within the exceedence season, with 46 days in June, 49 days in July, and 52 days in August. Finally, all HODs for all stations except Dawsonville, Newnan, and Yorkville also were exceedence days: 25, 86, and 61% of the HODs at the three respective stations were exceedence days.

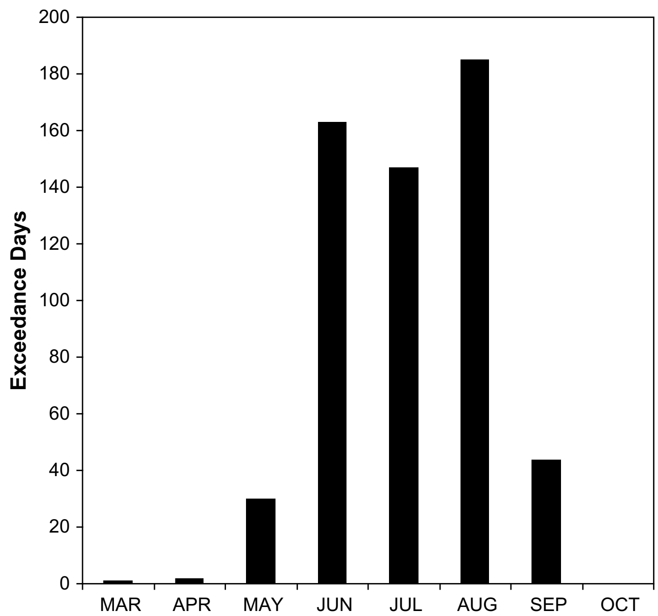

Fig. 3. Number of exceedence days per month in the Atlanta MSA from March to October of 2000–2007. Exceedence days are cumulative totals from the 11 ozone-monitoring stations in the MSA.

Table 2
Total number of ozone exceedences from March through October (M–O) and during June, July, and August (JJA) of 2000–2007. Also included are the minimum, mean, and maximum values of the 95th percentile (P95) of daily maximum 8-h average ozone concentrations (in ppb) for the JJA period.

Station	M–O	JJA	$P95_{min}$	$P95_{mean}$	$P95_{max}$
Atlanta	81	71	93	104	132
Conyers	59	54	90	100	119
Dawsonville	13	9	74	81	93
Douglasville	67	54	87	95	110
Fayetteville	41	38	86	96	127
Kennesaw	56	47	89	98	113
Lawrenceville	51	45	87	98	123
McDonough	68	66	92	103	139
Newnan	38	31	84	92	114
Panthersville	67	58	91	101	135
Yorkville	31	22	83	88	108

There were considerable differences in the number of shared HODs among the pairs of stations (Fig. 4). None of the stations shared all 36 HODs; the largest number was 28 for Atlanta and Panthersville, which were the two closest stations (i.e. separated by only 7 km). The eastern and western stations did not share many HODs: the lowest number of shared HODs was four for Conyers and Yorkville, which are separated by 98 km, while Panthersville and Douglasville, which are separated by 46 km, only shared six HODs. The southeastern stations (i.e. Atlanta, Conyers, Fayetteville, McDonough, and Panthersville) shared a large number of HODs, with the minimum number of shared HODs among pairs of stations being 20.

3.2. Atmospheric characteristics of HODs

Anticyclonic circulation over the Southeast was associated with all sets of HODs; however, there were noticeable circulation differences between southern-station sets of HODs and the rest of the sets of HODs (Fig. 5). HODs for the southern stations (i.e. Atlanta, Conyers, Fayetteville, McDonough, Newnan, and Panthersville) had the following circulation characteristics at 850 hPa: a closed anticyclone over the Southeast with typical seasonal geopotential heights over the Atlanta MSA; weak ridging over the Southeast and Midwest; and strong troughing over the far western

	ATL	CON	DAW	DOU	FAY	KEN	LAW	MCD	NEW	PAN	YOR
ATL	---	17	11	12	21	13	19	17	17	28	9
CON	17	---	6	6	19	9	14	24	12	20	4
DAW	11	6	---	10	5	17	16	6	5	9	6
DOU	12	6	10	---	8	14	9	8	14	7	19
FAY	21	19	5	8	---	9	14	25	18	22	7
KEN	13	9	17	14	9	---	12	9	6	11	13
LAW	19	14	16	9	14	12	---	12	11	17	5
MCD	17	24	6	8	25	9	12	---	16	21	5
NEW	17	12	5	14	18	6	11	16	---	15	8
PAN	28	20	9	7	22	11	17	21	15	---	7
YOR	9	4	6	19	7	13	5	5	8	7	---

Fig. 4. Number of high-ozone days shared between pairs of ozone-monitoring stations. The maximum possible value is 36. Stations are listed by the first three letters of their names.

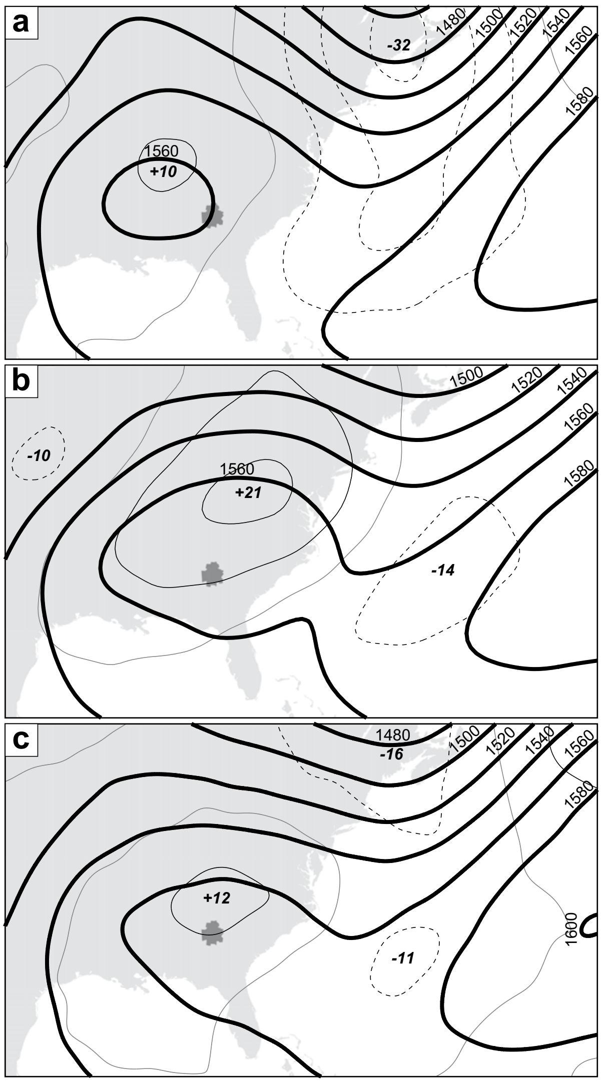

Fig. 5. Mean 850-hPa circulation patterns for high-ozone days during June–August of 2000–2007 at (a) Atlanta, Conyers, Fayetteville, McDonough, Newnan, and Panthersville, (b) Dawsonville, Douglasville, Kennesaw, and Yorkville, and (c) Lawrenceville. Dark solid lines, which have a 20-m contour interval, are the actual geopotential heights. Thinner lines (solid and dashed), which have a 10-m contour interval, are anomalies. The signed numbers indicate the strength of the anomaly centers. Units are meters. The Atlanta MSA is shown in darker shading.

Atlantic Ocean. HODs for the northwestern stations (i.e. Douglasville, Kennesaw, and Yorkville) and Dawsonville had the following circulation characteristics at 850 hPa: strong ridging over the eastern USA with significantly high geopotential heights over the Atlanta MSA; and weak troughing over the far western Atlantic Ocean. HODs for Lawrenceville had 850-hPa circulation characteristics that were similar to the typical seasonal circulation with the exception of weak ridging over the Southeast, weak troughing over the far western Atlantic Ocean, and significantly high geopotential heights over the Atlanta MSA.

HODs for most stations were hot, dry, and calm with low morning mixing heights and high afternoon mixing heights (Table 3). HODs had the following mean atmospheric conditions: a daily maximum near-surface temperature approaching 34 °C; a daily mean near-surface relative humidity of 55%; a daily mean near-surface wind speed of 2.5 m s^{-1}; a morning mixing height of 339 m a.g.l.; and an afternoon mixing height of 1957 m a.g.l. All sets of HODs had daily mean relative humidities (i.e. either at the near surface, 925-hPa, or 850-hPa) and afternoon mixing heights that, respectively, were significantly less than and significantly greater than mean values for the remaining days. Most sets of HODs had significantly high lower-troposphere temperatures, significantly low morning mixing heights, and significantly low wind speeds. Only HODs for Dawsonville, Douglasville, Kennesaw, and Yorkville had significantly high sea-level pressure and geopotential heights.

The Atlanta urban area typically was upwind of each station during HODs; therefore, the mean wind directions for HODs varied considerably across the Atlanta MSA (Fig. 6). Pairs of stations with approximately 180° differences in mean wind directions were as follows: Newnan (northerly) and Dawsonville (southerly); McDonough (northwesterly) and Kennesaw (southeasterly); and Conyers (westerly/northwesterly) and Yorkville (easterly/southeasterly). Douglasville and Lawrenceville were the only stations with HODs having easterly and southwesterly flow, respectively. Atlanta was the only station located firmly within the urban area; thus, its HODs had variable wind directions as indicated by the short length of the resultant wind vector.

Three-day back trajectories for HODs extended mostly to the "north" of the Atlanta MSA (Fig. 7). Trajectories extending to the north, northeast, and northwest entered the Atlanta region from the northeast/east, east/southeast, and northwest/north, respectively. Southerly back-trajectories were much more common on non-HODs (Fig. 6l). HODs for the southern stations had most trajectories extending into the Midwest, few trajectories extending

Table 3
Atmospheric characteristics of high-ozone days at the ozone-monitoring stations in addition to mean atmospheric conditions for all days within the study period (i.e. June–August from 2000 to 2007). Values for each station are deviations from the mean seasonal value; bold values represent significant ($\alpha = 0.01$) deviations. The variables are temperature (T) in °C, relative humidity (R) in %, wind speed (W) in m s^{-1}, sea-level pressure (SLP) in hPa, geopotential height in m a.s.l., morning mixing (MH_M) and afternoon mixing height (MH_A) in m a.g.l.; values are reported for the surface (S), 925 hPa (925), and 850 hPa (850). "T_S" is the daily maximum temperature, while other variables except for MH_M and MH_A are daily mean values.

Station	T_S	T_{925}	T_{850}	R_S	R_{925}	R_{850}	W_S	W_{925}	W_{850}	SLP	H_{925}	H_{850}	MH_M	MH_A
Atlanta	**+2.3**	**+1.8**	+0.9	**−15**	**−16**	**−12**	**−0.8**	**−2.2**	**−2.2**	+0.1	+3.2	+5.9	**−150**	**+509**
Conyers	**+3.0**	**+2.6**	**+1.9**	**−14**	**−16**	**−11**	**−0.4**	**−1.5**	**−1.4**	−0.7	−2.5	+2.6	**−189**	**+491**
Dawsonville	+0.7	+0.4	−0.4	**−15**	**−16**	**−11**	**−0.9**	**−1.0**	**−1.3**	**+2.3**	**+14.0**	**+13.1**	**−130**	**+485**
Douglasville	**+1.8**	**+1.5**	+0.6	**−12**	**−8**	**−8**	−0.3	**−1.1**	**−1.2**	**+1.0**	**+10.1**	**+12.2**	−97	**+337**
Fayetteville	**+2.8**	**+2.1**	**+1.4**	**−16**	**−16**	**−13**	**−0.4**	**−1.6**	**−1.9**	−0.7	−1.5	+2.2	**−171**	**+560**
Kennesaw	**+1.5**	+0.9	−0.1	**−16**	**−17**	**−12**	**−0.9**	**−1.7**	**−2.2**	**+1.6**	**+12.3**	**+12.4**	−114	**+525**
Lawrenceville	**+1.9**	**+1.9**	**+1.1**	**−13**	**−15**	**−10**	**−0.8**	**−1.5**	**−1.9**	+0.5	+6.4	**+9.5**	**−210**	**+446**
McDonough	**+3.1**	**+2.4**	**+1.7**	**−15**	**−16**	**−12**	−0.3	**−1.9**	**−1.9**	−0.9	−2.4	+2.2	**−166**	**+465**
Newnan	**+2.6**	**+2.2**	+1.1	**−15**	**−20**	**−14**	−0.2	−0.9	−1.1	−0.7	−3.3	−0.1	**−237**	**+519**
Panthersville	**+3.0**	**+2.6**	**+1.8**	**−15**	**−17**	**−13**	**−0.6**	**−2.1**	**−2.2**	−0.7	−2.0	+2.8	**−176**	**+507**
Yorkville	**+1.2**	+0.6	−0.1	**−9**	**−5**	−6	−0.1	−0.5	−0.9	**+1.3**	**+12.3**	**+10.4**	−85	**+260**
Seasonal mean	31.4	22.6	17.4	69	69	73	3.0	5.4	5.5	1016.5	822.6	1553.4	496	1493

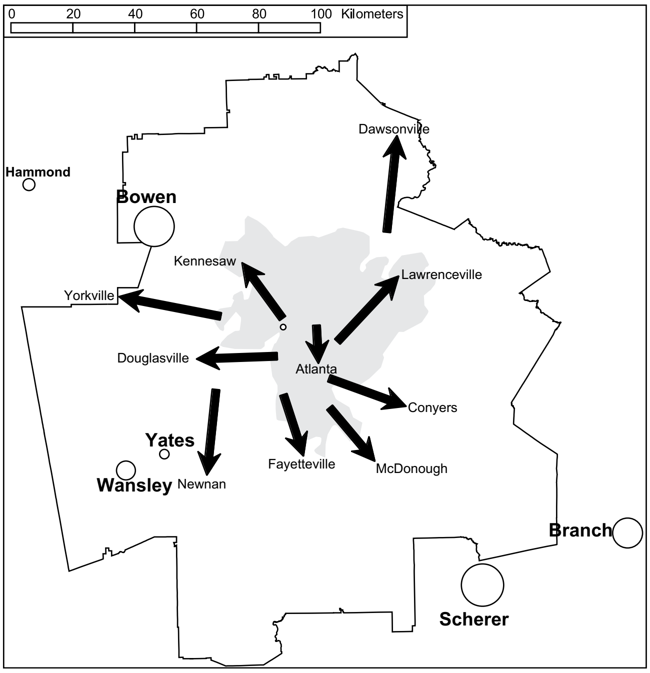

Fig. 6. Mean 925-hPa wind-direction arrows for high-ozone days from June to August of 2000–2007 at 10 ozone-monitoring stations in the Atlanta MSA. The length of an arrow is proportional to the vector wind speed. The arrow for Panthersville is not shown because it interferes with the Atlanta arrow; the mean wind direction for Panthersville was 310°. The grey polygon is the core urban zone based on street-length density as shown in Fig. 2. The open circles are locations of electricity-generating power plants; circle sizes are proportional to NO_x emissions. Estimates of annual NO_x emissions from 1999 for Scherer, Bowen, Branch, Wansley, Hammond, Yates, and McDonough are 39.6, 37.8, 28.4, 17.9, 11.4, 9.0, and 5.1 Gg, respectively. Plant McDonough is the power plant in the urban zone.

eastward to the Atlantic Ocean, and no trajectories reaching the Gulf of Mexico. HODs for the northwestern stations and Dawsonville had most trajectories extending northeastward/eastward. HODs for Lawrenceville had similar trajectories to HODs for the rest of the northern stations, with the major difference being that trajectories for Lawrenceville HODs had fewer trajectories reaching the Atlantic Ocean and extending into the Northeast. The percentage of HOD trajectories reaching the Ohio River Valley ranged from 19% for Dawsonville to 56% for Newnan. About half the HODs for the southernmost stations (i.e. Fayetteville, McDonough, and Newnan) had trajectories intersecting the Ohio River Valley; those three stations were the only stations with a significantly large number of trajectories that reached the Ohio River Valley.

Atlanta-region power plants located outside the urban zone often were upwind of the ozone-monitoring stations on HODs (Table 4). The following applied to approximately half the HODs at the listed stations: Plant Bowen was upwind of Conyers and McDonough; Plant Scherer was upwind of Kennesaw and Dawsonville; Plant Branch was upwind of Yorkville and Kennesaw; and Plants Wansley and Yates were upwind of Lawrenceville and Dawsonville. Compared to trajectories on non-HODs, the only plants that involved disproportionately large frequencies of trajectories were Plants Scherer and Branch: HODs at Dawsonville and Kennesaw were associated with air flow from Plant Scherer, and HODs at Yorkville were associated with air flow from Plant Branch.

4. Discussion

This study has found the ozone-exceedence season to be longer than expected and maximum ozone concentrations along with large numbers of exceedences to occur in the southeastern portion of the MSA. Previous Atlanta-ozone research suggests that ozone exceedences occur only in July, August, and, to a lesser degree, September; however, this research finds that the exceedence season is comprised of June in addition to July and August. June actually has more exceedences than does July. During the exceedence season, the maximum ozone concentrations occur southeast of downtown Atlanta. This is the first study to not only perform a robust analysis of ozone concentrations measured south/southeast of Atlanta but also to show that the maximum ozone concentration in the MSA can occur at the McDonough station. There were elevated ozone concentrations ~130 km southeast of Atlanta at Macon, Georgia on 17 August 2000, which was the date when McDonough had the maximum ozone concentration; therefore, it is possible that extremely high ozone concentrations occur south/southeast of McDonough in the Atlanta MSA.

Migratory anticyclones, most of which moved from west to east, provided the atmospheric conditions conducive to HODs at nearly all Atlanta MSA ozone-monitoring stations. The anticyclones during HODs at all stations except Lawrenceville, which was the only station located northeast/east of Atlanta, were either strong or substantially disconnected from the Bermuda High, thereby contradicting the Vukovich (1995) statement that high-pressure systems associated with high ozone concentrations in the southern United States are usually weak and not well organized. When migratory anticyclones do occur in the southeastern United States, temperatures increase, relative humidity decreases, insolation increases, winds weaken, the morning mixing height decreases, and the afternoon mixing height increases. Increased solar radiation increases the production of ozone (e.g. Sillman, 1999), while both high temperatures and increased insolation increase BVOC emissions (e.g. Guenther et al., 1993). Low wind speeds reduce pollutant dilution (e.g. Rao et al., 2003). Low morning and high afternoon mixing heights facilitate high ground-level ozone concentrations during the afternoon: ozone trapped above the nocturnal mixed layer is essentially protected from titration by nitric oxide (e.g. Aneja et al., 1997), and a deep daytime mixed layer enables the entrainment to the surface of ozone that was previously above the nocturnal mixed layer (e.g. Kim et al., 2007).

On HODs for all ozone-monitoring stations, the Atlanta urban area is the most logical primary source of ozone, ozone-precursor chemicals, or both. While most previous studies have been too general regarding wind direction, Lindsay and Chameides (1988) do note that easterly winds are present during ozone episodes northwest of Atlanta and westerly/northwesterly winds are present during ozone episodes southeast of Atlanta. The mean 925-hPa wind direction on HODs is tied directly to the location of the center of the 850-hPa anticyclone with respect to Atlanta (Figs. 5 and 6). Southern locales receive Atlanta pollution when the center of the anticyclone is west/northwest of Atlanta. Northern locales receive Atlanta pollution when the center of the anticyclone is east of Atlanta. Western locales receive Atlanta pollution when the center of the anticyclone is northeast of Atlanta. Northeastern locales receive Atlanta pollution when the seasonal mean circulation is present.

NO_x emissions from electric-utility power plants also may be responsible for HODs in the Atlanta MSA. Power-plant plumes can be brought to the surface through fumigation during the afternoon hours (Duncan et al., 1995), and the deep afternoon mixed layer on HODs should promote enhanced fumigation. One of the highest ozone concentrations ever recorded in the Atlanta MSA may have been caused by ozone production within a power-plant plume and subsequent entrainment of the plume to the surface (St. John and Chameides, 2000). Within the Atlanta modeling domain, which covers an area of 25,600 km^2 centered on downtown Atlanta, ~90%

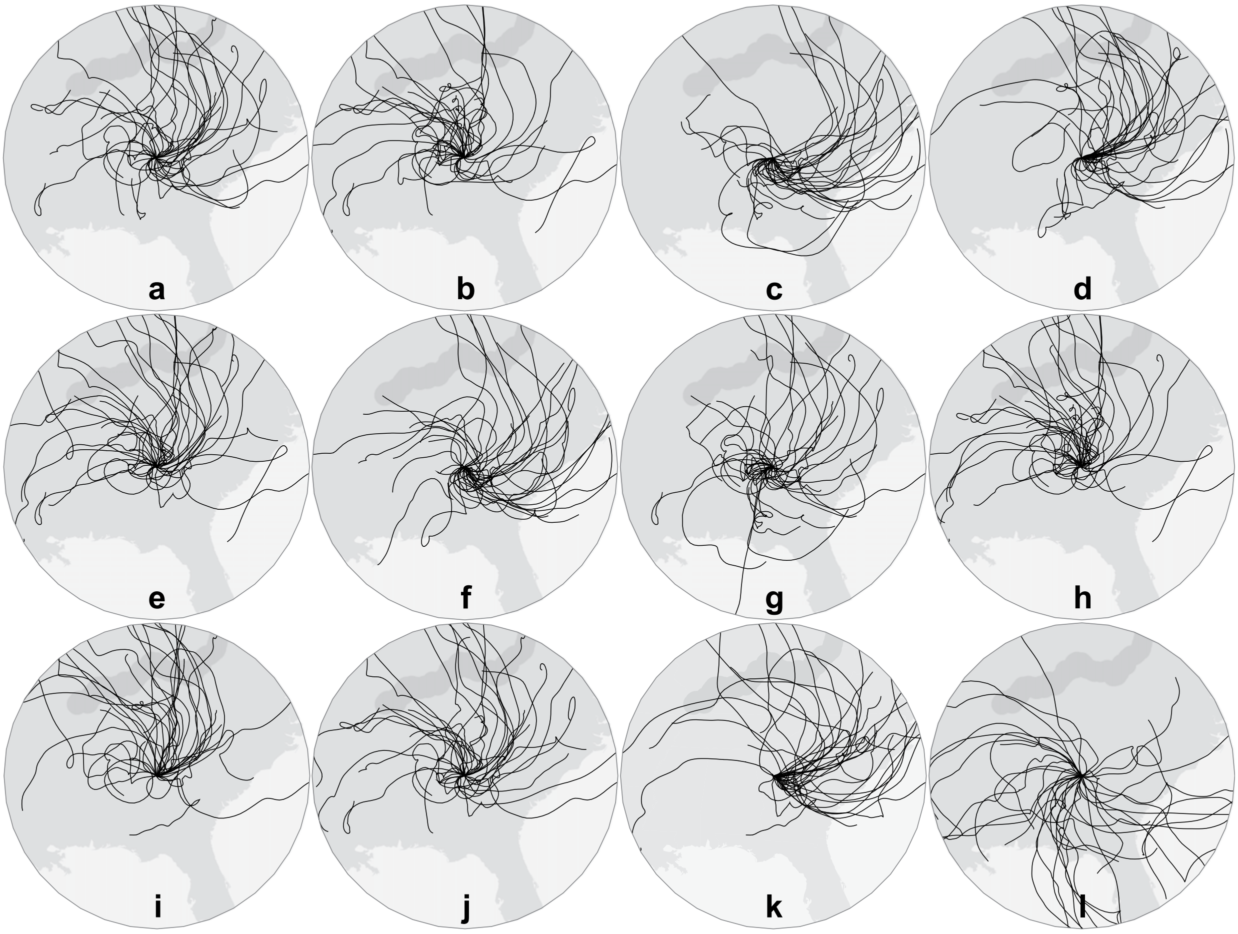

Fig. 7. Backward trajectories for high-ozone days during June–August of 2000–2007 at (a) Atlanta, (b) Conyers, (c) Dawsonville, (d) Douglasville, (e) Fayetteville, (f) Kennesaw, (g) Lawrenceville, (h) McDonough, (i) Newnan, (j) Panthersville, and (k) Yorkville. Also included is (l) a random sample of 36 days that were not high-ozone days. Some of the trajectories extended beyond the circle (800-km radius) centered on Atlanta.

of anthropogenic NO_x emissions come from Plants Bowen, McDonough, Wansley, and Yates (Chang et al., 1996). Two of three ozone episodes in August 1992 had significant point-source contributions from one or more of the above power plants (Duncan et al., 1995). NO_x emissions from Plants Branch and Scherer, which are located southeast of the Atlanta MSA and probably have collective NO_x emissions nearly equivalent to that of Plants Bowen, McDonough, Wansley, and Yates combined, may also contribute to high ozone concentrations in the Atlanta MSA, with the target area being the northwestern/northern portion of the MSA. In addition, emissions from Plant Bowen may contribute to HODs in the southeastern portion of the MSA, while emissions from Plants Wansley and Yates may contribute to HODs in the northeastern portion of the MSA. Pollutant transport from the Ohio River Valley is most likely to contribute to HODs at locales in the far southern portion of the Atlanta MSA. These results are similar to the findings of Lindsay and Chameides (1988), where ∼25% of trajectories for days with high ozone concentrations in the MSA can be traced back to the Midwest and Ohio River Valley; however, the percentage of trajectories extending back to those regions was substantially higher for this study. Over-all, HODs in the southern portion of the MSA may be caused partially by NO_x emissions from Plant Bowen and power plants in the Ohio River Valley, while HODs in the northern portion of the MSA may be caused partially by NO_x emissions from Plants Scherer and Branch. In both instances, the power-plant plumes probably mix with the urban plume, because the power-plant plumes have to pass over urbanized Atlanta before reaching the ozone-monitoring station that eventually will measure relatively high ozone concentrations for that station.

Table 4
Percentage of high-ozone days for each ozone-monitoring station that had back trajectories intersecting six Atlanta-region power plants and the Ohio River Valley (ORV).

Station	Bowen	Branch	Hammond	Scherer	Wansley	Yates	ORV
Atlanta	22	19	14	28	22	28	39
Conyers	50	11	22	14	22	22	28
Dawsonville	11	33	8	44	44	47	19
Douglasville	6	25	3	22	14	17	39
Fayetteville	36	14	22	17	19	22	47
Kennesaw	11	39	6	53	25	31	22
Lawrenceville	28	19	25	31	50	56	28
McDonough	44	11	22	14	22	22	42
Newnan	19	11	14	6	8	8	56
Panthersville	33	19	14	22	25	28	39
Yorkville	6	44	6	31	3	6	31

5. Conclusions

This paper presents an assessment of atmospheric conditions conducive to elevated ground-level ozone concentrations from 2000 to 2007 at 11 ozone-monitoring stations in the Atlanta MSA. Analyses were confined to high-ozone days (HODs) within the exceedence season, which was comprised of June, July, and August; those 3 months contained 90% of all days that exceeded the 8-h ozone NAAQS over the March–October period. An HOD was a day in the exceedence season with a daily maximum 8-h average ozone concentration in the 95th percentile of all exceedence-season values; therefore, each station had 36 HODs. There were a total of 147 HODs within the exceedence season; nearly all stations had either all or a majority of the HODs also being exceedence days. The southeastern and far northern portions of the MSA had HODs with the highest and lowest ozone concentrations, respectively. HODs at nearly all Atlanta MSA ozone-monitoring stations were enabled by migratory anticyclones. HODs for most stations were hot, dry, and calm with low morning mixing heights and high afternoon mixing heights. All sets of HODs had daily mean relative humidities and afternoon mixing heights that, respectively, were significantly less than and significantly greater than mean values for the remaining days. Urbanized Atlanta typically was upwind of an ozone-monitoring station on its HODs. Therefore, wind direction on HODs varied considerably among the stations, which were dispersed throughout the MSA. Finally, HODs may have been caused partially by NO_x emissions from electric-utility power plants. HODs in the southern portion of the MSA were linked to air-parcel trajectories intersecting a power plant slightly northwest of Atlanta and plants in the Ohio River Valley, while HODs in the northern portion of the MSA were linked to air-parcel trajectories intersecting two large power plants slightly southeast of the Atlanta MSA.

This paper has elucidated the strong influence of atmospheric conditions on high ground-level ozone concentrations within the Atlanta MSA, and the methods are transferable to other MSAs, especially those MSAs with abundant ozone and meteorological data. This research has also revealed the following research questions:

- What is the contribution of plumes from Plants Scherer and Branch as well as from electric-utility power plants in the Ohio River Valley on ground-level ozone concentrations, especially concentrations exceeding the federal standard, in the Atlanta MSA?
- How high are the ozone concentrations in the non-monitored portions of the MSA, especially between 50 and 100 km southeast of downtown Atlanta?

The highest 8-h average ozone concentration was measured ~40 km southeast of Atlanta; thus, it is possible that even higher concentrations existed even farther to the southeast. The trajectory analyses indicated that NO_x emissions from power plants may be responsible for high-ozone days in some portions of the Atlanta MSA. Therefore, modeling work in the Atlanta MSA that focuses on power-plant contributions to ground-level ozone concentrations as well as the identification of ozone "hot spots" is needed.

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