Upper-Level Atmospheric Circulation Patterns and Ground-Level Ozone in the Atlanta Metropolitan Area

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ABSTRACT

The purpose of this paper is to identify middle-troposphere circulation patterns associated with high ozone concentrations during June–August of 2000–07 in the Atlanta, Georgia, metropolitan statistical area (MSA), which is located in the southeastern United States. The methods involved classifying daily 500-hPa geopotential height fields into synoptic types, determining the mean atmospheric conditions (i.e., daytime temperature, daytime relative humidity, daytime cloud cover, morning mixing height, and afternoon mixing height) for the types, determining the mean daily maximum 8-h average ozone concentrations for the types, and performing back-trajectory analyses for high-ozone types. There were a total of 12 synoptic types, and significantly high ozone concentrations across the MSA coincided with the three following types: Atlanta under a continental anticyclone, Atlanta to the east of a continental anticyclone and west of a trough, and Atlanta under the western side of a trough. The continental-anticyclone type was much more prevalent than the other two types. When the MSA was under or just to the east of a continental anticyclone, atmospheric conditions were conducive to increased in situ ozone production and pollutant carryover from the previous day. Between 45% and 60% of the days with those circulation patterns had ozone concentrations exceeding the federal standard. When the Atlanta MSA was under the western side of a trough, not only did the potential for in situ ozone production and pollutant carryover contribute to high ozone concentrations, but there also was a high potential for pollutant transport from the Ohio River valley into the Atlanta MSA.

1. Introduction

Ground-level ozone often is present in unhealthy concentrations throughout much of the eastern United States, especially in the Atlanta, Georgia, metropolitan statistical area (MSA). The Atlanta MSA is an ozone nonattainment area (i.e., an area that has violated the federal ozone standard) as are many other metropolitan areas in the eastern United States (Fig. 1). The Atlanta MSA is unique in comparison with other large nonattainment areas in the eastern United States because of its relative isolation from other nonattainment areas. Moreover, the Atlanta MSA has a humid subtropical climate type as opposed to a combination of humid subtropical and humid continental climates, which is common for most other MSAs in the eastern United States (Trewartha

and Horn 1980). Among all MSAs in the eastern United States, the Atlanta MSA had the most days from May to September of 2000–09 classified as having ozone concentrations that were unhealthy for sensitive groups; it had at least 20% more unhealthy days than did the Philadelphia MSA, which had the second-largest number of days (EPA 2009b). In the Atlanta MSA, elevated ozone levels have been linked to increased rates of pediatric asthma events (Mulholland et al. 1998; Tolbert et al. 2000; Friedman et al. 2001), and ozone concentration appears to be a viable predictor of respiratory-related visits to emergency rooms (Tolbert et al. 2007).

The Atlanta MSA, which has a population exceeding five million persons (U.S. Census Bureau 2009), is located in the interior portion of the southeastern United States, and emissions conditions in this region are conducive to high ozone concentrations (Fig. 1). Ground-level ozone is formed by photochemical reactions involving volatile organic compounds (VOCs) and nitrogen oxides (NO_x) (Haagen-Smit 1952; Crutzen 1979). The Atlanta MSA has substantial emissions of VOCs from both anthropogenic

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FIG. 1. Locations of the Atlanta nonattainment area and other nonattainment areas within a square domain centered on Atlanta. 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. Nonattainment and NO_x-emissions data from 1999 were obtained from the EPA. [The figure is adapted from Fig. 1 in Diem (2009).]

and biogenic sources and NO_x from anthropogenic sources during the summer: daily emissions of biogenic VOCs (BVOCs), anthropogenic VOCs, and anthropogenic NO_x are approximately 900, 600, and 700 t (EPA 2009a,c). The high emission rates of BVOCs in the region make ozone production in Atlanta predominantly sensitive to atmospheric concentrations of NO_x (Chameides et al. 1992; Guenther et al. 2000; Ryerson et al. 2000). Also, several large NO_x-emitting electric-utility power plants are located proximate to the MSA, whereas many large NO_x-emitting power plants are located hundreds of kilometers north of Atlanta in and just south of the Ohio River valley (Fig. 1).

Previous Atlanta ozone research has provided information on near-surface atmospheric conditions on days with elevated ozone concentrations (Cardelino and Chameides 1995; Imhoff et al. 1995; Chang et al. 1996; St. John and Chameides 1997, 2000; Saylor et al. 1999; Cardelino et al. 2001; Schictel and Husar 2001; Cohan et al. 2005; Napelenok et al. 2007; Diem 2009). In comparison with the rest of the days during the summer (i.e., June–August), high-ozone days (i.e., days with daily maximum 8-h average ozone concentrations in the

95th percentile of all summer values) have significantly high temperatures and afternoon mixing heights and significantly low relative humidities and mean daily wind speeds (Diem 2009). High temperatures (Cardelino and Chameides 1995; Chang et al. 1996; Saylor et al. 1999; St. John and Chameides 2000; Cardelino et al. 2001; Cohan et al. 2005; Napelenok et al. 2007), low relative humidity (Cardelino et al. 2001), and 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) also have been found for days during ozone episodes. Diem (2009) also shows that high-ozone days have significantly high afternoon mixing heights and significantly low morning mixing heights in comparison with the rest of the summer days.

Information about specific synoptic-scale circulation patterns for days with elevated ozone concentrations in the Atlanta MSA is lacking. The mean 850-hPa circulation pattern for high-ozone days entails an anticyclone over and to the north of the Atlanta MSA and troughing off the eastern coast of the United States (Diem 2009). However, because the above circulation patterns are composites of dozens of days, it is possible that no days have ever had a pattern resembling the mean pattern. The ozone-episode studies provide even less information: St. John and Chameides (1997) and Napelenok et al. (2007) report a high pressure system during ozone episodes, and Imhoff et al. (1995) report an upper-level anticyclone over Texas during an episode.

For the eastern and southern United States, high ozone concentrations are linked to the location of an eastward-moving high pressure system. In the northeastern United States, high ozone concentrations are expected on the western side of a surface anticyclone, where high temperatures prevail (Vukovich 1995). Synoptic typing (i.e., placing daily synoptic-scale circulation patterns into categories) performed in Comrie and Yarnal (1992) and Comrie (1994) shows that high ozone concentrations in Pittsburgh, Pennsylvania, and rural central Pennsylvania both tend to occur when the locations are under the western side of an anticyclone, which also enables southwesterly transport of pollutants from the Ohio River valley. Along the same lines, high ozone concentrations in the midwestern United States are associated with an anticyclone over the northeastern United States (Hogrefe et al. 2004). Also using a synoptic-typing method, Rohli et al. (2004) found a connection between high ozone concentrations across Louisiana and a surface anticyclone over the southeastern United States, and associated with the surface anticyclone was an upper-level anticyclone west of Louisiana and the western side of a trough to the east of the state.

Despite the existence of dozens of studies of Atlanta ozone in peer-reviewed journals, no Atlanta-based study has examined specific summer season circulation patterns with respect to ground-level ozone in the Atlanta MSA. Moreover, there does not appear to be any information on the relationships between middle-troposphere circulation and ground-level ozone in the eastern United States. Therefore, the overall aim of this paper is to use a synoptic-climatological approach to identify middle-troposphere circulation patterns associated with high ozone concentrations in the Atlanta MSA. Because nearly 90% of ozone exceedance days in the Atlanta MSA occur during June–August (Diem 2009), this study examines only summer season (i.e., June–August) days from 2000 to 2007. The objectives are to determine the following: 1) typical circulation patterns during the summer season, 2) typical atmospheric conditions for each pattern, 3) typical ozone characteristics for each pattern, and 4) the potential roles of in situ ozone production, pollutant carryover from the previous day, and regional pollutant transport in causing variations in ozone concentrations among high-ozone synoptic types (i.e., types with significantly high ozone concentrations or significantly large numbers of exceedance days or both).

2. Method

a. Synoptic typing

A manual classification of 500-hPa circulation patterns was used to determine the synoptic types over the Atlanta MSA during the summer season (i.e., June–August). The classification of the atmospheric circulation is the first stage of synoptic-climatological research that relates circulation to another variable (Barry and Perry 1973). A manual, rather than automated, classification was performed because it facilitates greater insight into climatic subtleties that might otherwise be missed using an automated procedure (Yarnal et al. 2001). The 500-hPa level was chosen over surface patterns for two reasons: 1) the 500-hPa patterns are smoother and thus much easier to place confidently into the appropriate categories using a manual approach and 2) 500-hPa patterns are linked to patterns in the lower troposphere and at the surface. Gridded 500-hPa geopotential height data were extracted from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis dataset (Kalnay et al. 1996) of the National Oceanic and Atmospheric Administration Earth System Research Laboratory (NOAA/ESRL). The globally gridded data had a spatial resolution of 2.5° and a temporal resolution

of 1 day. The geographic scale for the typing, which initially was based on a cylindrical equidistant projection, ranged from 22.3° to 45.0°N latitude and from 70.8° to 98.1°W longitude. The geographic scale of Fig. 1 is equivalent to the scale used for the typing. The 500-hPa geopotential heights over the domain noted above were contoured at 20-m intervals to produce daily circulation maps. A random sample of 147 days (i.e., 20% of the population) from 2000 to 2007 was first examined to identify the synoptic types. Each year had either 18 or 19 random days. The classification was then applied to all days for 1978–2007, which included the 736 days in the 2000–07 period. The 2000–07 frequencies were compared with the 1978–2007 period to verify that the former sample period represented sufficiently the relevant climatic period (i.e., 1978–2007).

Transitions in synoptic types were analyzed to determine the temporal sequencing of circulation patterns. The probability of synoptic-type occurrence on the day following a given synoptic type was calculated for every combination of synoptic types. Because a day could be followed by a day with the same synoptic type, this procedure yielded within-type transition probabilities, which are useful for assessing the persistence of synoptic types.

b. Determination of atmospheric conditions of synoptic types

Mean daytime temperature, mean daytime relative humidity, mean daytime cloud cover, mean morning mixing height, and mean afternoon mixing height were calculated for each synoptic type. Hourly temperature, relative humidity, and cloud cover data were collected at Atlanta Hartsfield-Jackson International Airport and were extracted from the NOAA Integrated Surface Hourly Database. Daily values of morning and afternoon mixing heights were provided by NOAA, which used radiosonde data collected at Falcon Field, in Peachtree City, Georgia, and the Holzworth (1972) method to estimate mixing heights. The datasets were nearly serially complete: only 2% of the hours were missing values for temperature, relative humidity, or cloud cover, and only 3% of the days were missing mixing-height values. Either one-tailed Student's t tests or one-tailed Mann–Whitney U tests were used to test for significant differences between days within a synoptic type and the rest of the days. Therefore, both a parametric test (i.e., Student's t test) and a nonparametric test (i.e., Mann–Whitney U test) were employed. If the number of days was greater than or equal to 30, then the parametric test was used; otherwise, the nonparametric test was used.
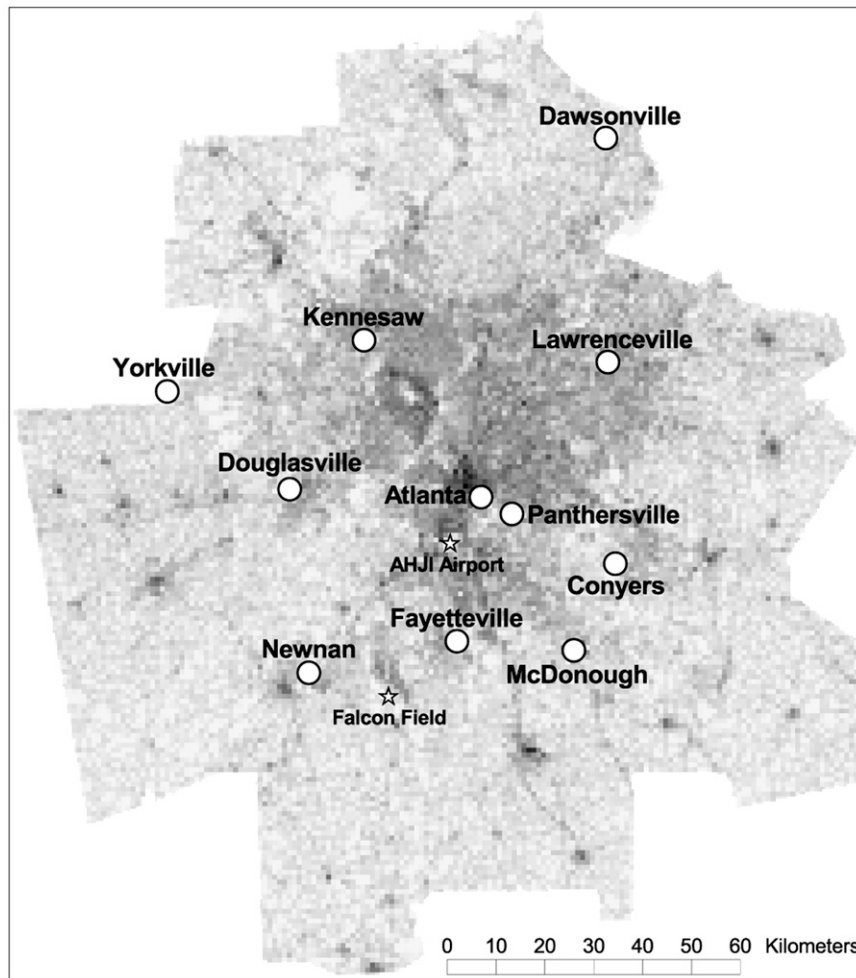
FIG. 2. Locations of the 11 stations within the Atlanta MSA that measured ozone concentrations during the entire 2000–07 period. Also shown are the weather stations at Atlanta Hartsfield-Jackson International Airport (AHJI) and Falcon Field. Street-length density, which is a proxy for urbanization, is shown as grayscale shading; light gray is low density and black is high density. [The figure is adapted from Fig. 2 in Diem (2009).]

c. Determination of ozone characteristics of synoptic types

Daily maximum 8-h average ozone concentrations were computed at all ozone-monitoring stations within the Atlanta MSA. Hourly ozone concentrations from June to August of 2000–07 were obtained from the U.S. Environmental Protection Agency (EPA) for 11 ozone-monitoring stations (Fig. 2; Table 1). The original ozone dataset had just 2% of the hours with missing ozone concentrations. Except for the exclusion of data in March, April, May, September, and October, the dataset was identical to that described in Diem (2009); therefore, refer to that paper for detailed information on how each record was made serially complete prior to the calculation of daily maximum 8-h average ozone

concentrations. In addition to assessing the within-type variability of MSA-wide ozone concentrations, the same procedure described in section 2b involving the Student's t and Mann–Whitney U tests was used to determine the significance of ozone concentrations for the synoptic types and the preceding days.

Exceedance days in this study were days with daily maximum 8-h average ozone concentrations greater than or equal to 85 parts per billion (ppb), which is the air-quality standard for ozone. With the concentrations in parts per million (ppm), the third decimal digit was rounded, thereby resulting in a maximum nonexceedance concentration of 0.084 ppm (EPA 1998). The percent contribution of each synoptic type to the total number of exceedance days was calculated. To determine if the Atlanta MSA had a disproportionately large number of

Station	EPA ID	% missing
Atlanta	13-121-0055-44201-1	1.9
Conyers	13-247-0001-44201-1	1.3
Dawsonville	13-085-0001-44201-2	2.0
Douglasville	13-097-0004-44201-1	0.6
Fayetteville	13-113-0001-44201-1	0.8
Kennesaw	13-067-0003-44201-1	0.3
Lawrenceville	13-135-0002-44201-1	5.4
McDonough	13-151-0002-44201-1	1.5
Newnan	13-077-0002-44201-1	3.5
Panthersville	13-089-0002-44201-1	2.9
Yorkville	13-223-0003-44201-1	1.8

exceedance days under a synoptic type, two-sample chi-square tests were conducted for each station–type combination. Contingency tables contained the following frequencies: 1) exceedance days that occurred under a particular synoptic type, 2) exceedance days that occurred under the rest of the synoptic types, 3) nonexceedance days that occurred under a particular synoptic type, and

4) nonexceedance days that occurred under the rest of the synoptic types.

d. Assessment of regional pollutant transport and surface circulation for selected synoptic types

Two-day back trajectories were modeled for days in high-ozone synoptic types. In addition, 30 trajectories were produced for days not in the above synoptic types. The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Draxler and Rolph 2009) was run with data from the Eta Data Assimilation System. The Air Resources Laboratory of NOAA provided the model and requisite data. Vertical motion was described by modeled vertical velocity. The starting heights, times, latitudes, and longitudes of the trajectories were 500 m AGL, 1500 UTC, 33.756°N, and 84.418°W, respectively. The starting location was the geographic center of the 11 ozone-monitoring stations, and the starting time was the typical first hour of the period experiencing the daily maximum 8-h ozone concentration.

The back trajectories were produced to assess the potential for transport of pollutants originating from power plants within 800 km of Atlanta into the MSA. Emissions from power plants inside and within 50 km
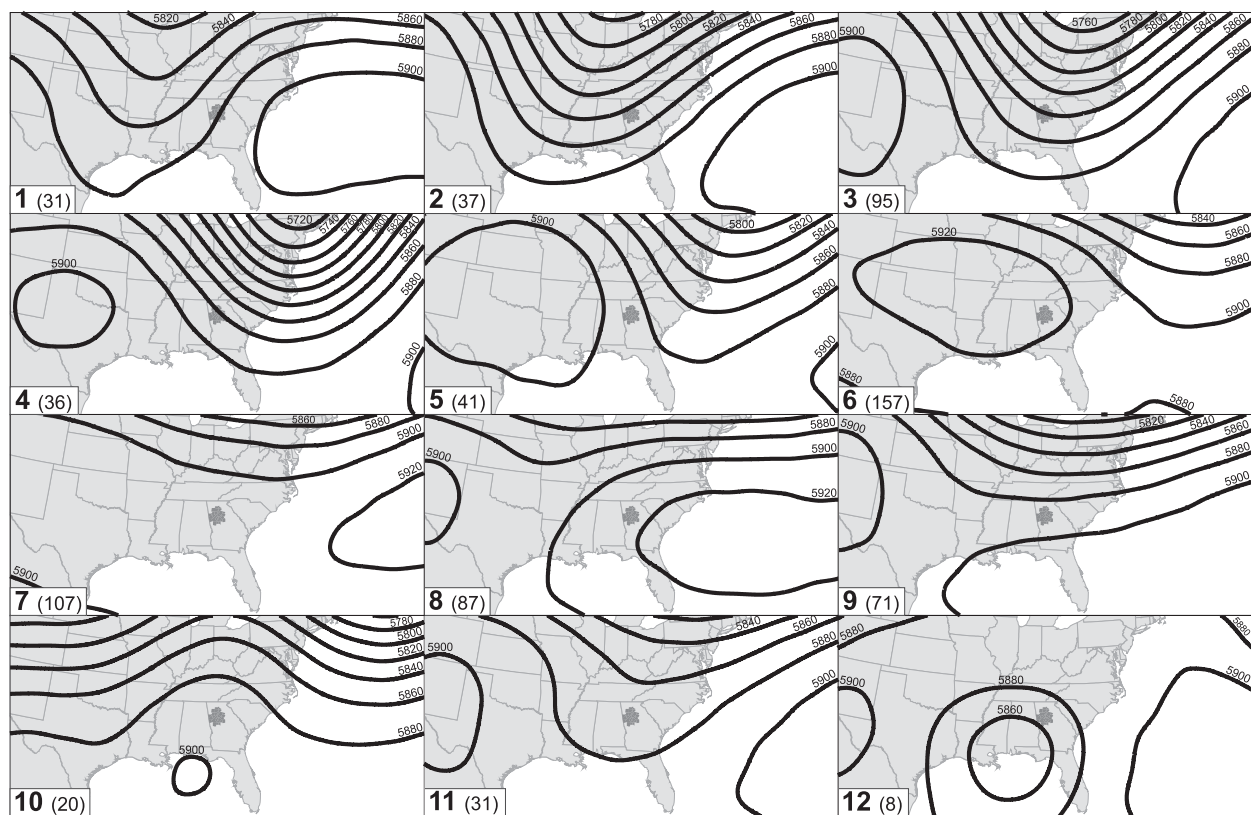

FIG. 3. Mean 500-hPa geopotential heights during June–August of 2000–07 for the 12 synoptic types. The frequency of each type is shown in parentheses. The contour interval is 20 hPa. The dark region within North America is the Atlanta MSA.

of the MSA were excluded from the analysis. Annual emissions of NO_x from electric-service point sources (i.e., power plants) were obtained from EPA. The NO_x emissions were gridded at 80-km resolution because the trajectories were produced from data having spatial resolutions as coarse as 80 km. The trajectories were intersected with the gridded NO_x data within a geographic information system, thereby calculating the total amount of power-plant emissions associated with each trajectory. As described in section 2b, either one-tailed Student's *t* tests or one-tailed Mann–Whitney *U* tests were used to test for significant differences in NO_x emissions between days within a synoptic type and the rest of the days. In addition, frequencies of trajectories intersecting the Ohio River valley were calculated. As noted earlier, the Ohio River valley contains many large NO_x-emitting power plants, and for this study it was delineated as a zone within 50 km of the Ohio River. Two-sample chi-square tests were conducted for each set of trajectories. Contingency tables for the tests specific to the Ohio River valley contained the following frequencies: 1) trajectories for a particular type that intersected the Ohio River valley, 2) trajectories for a particular type that did not intersect the Ohio River valley, 3) trajectories for nontype days that intersected the Ohio River valley, and 4) trajectories for nontype days that did not intersect the Ohio River valley.

Surface circulation maps were created for the high-ozone types. Sea level pressure data were extracted from the NCEP–NCAR reanalysis dataset (Kalnay et al. 1996) of NOAA/ESRL. The gridded dataset had a spatial resolution of 2.5° and a temporal resolution of 1 day. Isobars were drawn at 1-hPa intervals.

3. Results and discussion

The classification of 500-hPa circulation patterns produced 12 synoptic types, with substantial differences in frequencies among the types (Fig. 3). All types were named based on the location of the Atlanta MSA with respect to circulation features. If the 500-hPa geopotential heights over the Atlanta MSA were equal to or greater than 5900 m, then that day was classified as an anticyclone day. The criteria for the anticyclone days were that type-6 (i.e., under continental anticyclone) days had higher heights over the continent than over the ocean, type-7 (i.e., under continental/maritime anticyclone) days had 5900-m heights extending longitudinally across the domain, and type-8 (i.e., under maritime anticyclone) days had higher heights over the ocean than over the continent. Type 6 was the most frequent circulation pattern; this pattern was present on ~20% of the days. The Atlanta MSA was under a portion of an

TABLE 2. Summary information for the 12 synoptic types. Description refers to the location of the Atlanta MSA with respect to features in the middle troposphere. Values shown are percentages of days during June–August of 2000–07 and 1978–2007 that were a specific type.

Type	Description	2000–07	1978–2007
1	East of trough and west of anticyclone	4	5
2	Under eastern side of trough	5	7
3	Under trough axis	13	13
4	Under western side of trough	5	6
5	East of anticyclone and west of trough	6	6
6	Under continental anticyclone	21	21
7	Under continental/maritime anticyclone	15	12
8	Under maritime anticyclone	12	8
9	North of anticyclone and south of trough	10	9
10	Under ridge	3	2
11	Under weak trough	4	6
12	North of cyclone	1	1

anticyclone or ridge on ~50% of the days, and the types involved were 6, 7, 8, and 10 (i.e., under ridge). The Atlanta MSA was under either a portion of a trough or an upper-level cyclone on ~30% of the days, and the types involved were 2 (i.e., under eastern side of trough), 3 (i.e., under trough axis), 4 (i.e., under western side of trough), 11 (i.e., under weak trough), and 12 (i.e., north of cyclone). Approximately 20% of the days were transitional between anticyclones/ridging and cyclones/troughing; the types involved were 1 (i.e., east of trough and west of anticyclone), 5 (i.e., east of anticyclone and west of trough), and 9 (i.e., north of anticyclone and south of trough). Only 2% of the days remained unclassified. There were only subtle differences in the percent occurrences of the synoptic types between 2000–07 and 1978–2007 (Table 2).

Persistence prevailed for most of the synoptic types; the most likely synoptic type for a day was the type on the previous day (Fig. 4). The four most persistent types—in descending order based on transition probabilities—were types 6, 3, 7, and 8. These types also were the four most frequently occurring types and thus can be considered the core synoptic types. Type 12 also has a high within-type transition probability; however, the small number of days with this type prohibits a sound analysis. Type 6 was an extremely persistent type: nearly 70% of the days following a type-6 day also were type-6 days and only 5% of the type-6 occurrences did not persist for more than 1 day.

Several typical between-type transitions existed (Fig. 4). The most likely types for the last days of type-2, -3, -4, -5,

To Type

	1	2	3	4	5	6	7	8	9	10	11	12
1	**0.42**	0.16	0.03	0.00	0.00	0.00	0.06	0.19	0.13	0.00	0.00	0.00
2	0.08	**0.38**	0.27	0.00	0.00	0.00	0.00	0.08	0.14	0.00	0.05	0.00
3	0.01	0.04	**0.60**	0.15	0.06	0.00	0.03	0.00	0.03	0.01	0.06	0.00
4	0.00	0.03	0.09	**0.31**	0.20	0.06	0.06	0.06	0.09	0.09	0.03	0.00
5	0.00	0.00	0.07	0.10	**0.32**	0.24	0.07	0.00	0.02	0.05	0.07	0.05
6	0.01	0.00	0.02	0.01	0.06	**0.69**	0.10	0.03	0.04	0.01	0.01	0.01
7	0.01	0.00	0.05	0.00	0.01	0.24	**0.52**	0.06	0.08	0.01	0.04	0.00
8	0.08	0.00	0.01	0.00	0.00	0.06	0.14	**0.59**	0.10	0.02	0.00	0.00
9	0.01	0.06	0.09	0.06	0.01	0.03	0.13	0.15	**0.35**	0.01	0.07	0.01
10	0.05	0.00	0.00	0.00	0.00	0.16	0.11	0.16	0.16	**0.37**	0.00	0.00
11	0.07	0.07	0.13	0.00	0.10	0.03	0.13	0.10	0.17	0.00	**0.20**	0.00
12	0.25	0.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.63**

(From Type — row labels at left)

FIG. 4. Probabilities of synoptic-type transitions during June–August of 2000–07. A boldface number is the largest probability for a type.

-6, -7, -8, and -9 episodes to make a transition to were types 3, 4, 5, 6, 7, 6, and 7, respectively. Two common sequences of synoptic types, accounting for consecutive days with the same type, were 1) 2, 3, 4, 5, and 6 and 2) 8, 7, and 6. Therefore, sequences of types tended to converge on type 6.

Atmospheric conditions at Atlanta differed substantially among the synoptic types (Table 3). Under types 1, 2, and 12, Atlanta had lower daytime temperatures, higher daytime relative humidities, and more daytime cloud cover than normal, along with relatively high morning mixing heights and relatively low afternoon mixing heights. Under type 3, Atlanta had lower daytime temperatures than normal. Under type 4, Atlanta had lower daytime relative humidities and less daytime cloud cover than normal along with relatively low morning mixing heights. Under type 5, Atlanta had higher daytime temperatures, lower daytime relatively humidities, and less daytime cloud cover than normal. Under type 6, Atlanta had higher daytime temperatures, lower daytime relative humidities, and less daytime cloud cover than normal along with relatively low morning mixing heights and

TABLE 3. Atmospheric characteristics at Atlanta for the synoptic types 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. The variables are daytime temperature T (°C), daytime relative humidity RH (%), mean daytime cloud coverage C (%), morning mixing height MH_M (m AGL), and afternoon mixing height MH_A (m AGL).

Type	T	RH	C	MH_M	MH_A
1	−1.4*	+10.1*	+18*	+146*	−266*
2	−3.1*	+12.0*	+15*	+88**	−472*
3	−1.7*	−1.1	−2	−10	−46
4	−0.5	−11.5*	−17*	−70**	+133
5	+0.7**	−6.2*	−13*	−19	+102
6	+2.1*	−5.2*	−7*	−79*	+197*
7	+0.5*	+1.6	+4*	+32	−5
8	+0.6*	+2.1**	+1	+33**	+56
9	−0.8*	+4.8*	+8*	+16	−130**
10	0.0	−5.5	−10**	−29	+172
11	−0.6**	+3.4**	+7	+82**	−72
12	−2.3*	+12.2**	+25**	+175**	−508*
Season	27.2	63.7	67	496	1493

* Significant at the 0.01 level.
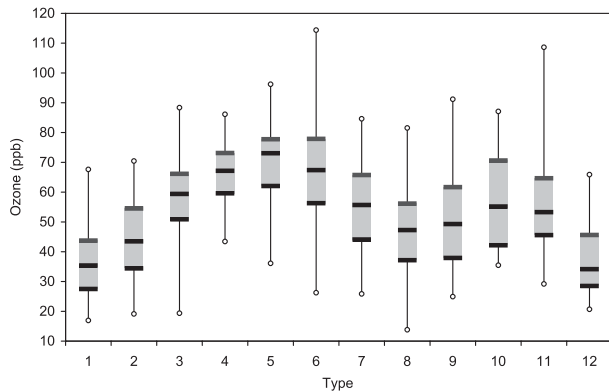** Significant at the 0.05 level.

FIG. 5. Box-and-whisker plot showing the variability of mean domainwide daily maximum 8-h-average ozone concentrations during June–August of 2000–07 for each synoptic type. Shown are the minimum values, first-quartile values, median values, third-quartile values, and maximum values.

heights. Under type 9, Atlanta had lower daytime temperatures, higher daytime relative humidities, and more daytime cloud cover than normal along with lower afternoon mixing heights. Under type 10, Atlanta had less daytime cloud cover than normal. Under type 11, Atlanta had lower daytime temperatures and higher daytime relative humidities than normal along with relatively high morning mixing heights.

Types 4–6 had the highest MSA-wide ozone concentrations (Fig. 5). Those three synoptic types had the three largest third-quartile, median, and first-quartile values among the types, with type 5 consistently having the largest values. Among the three types, type 6 had the most variability in ozone concentrations.

Significantly high ozone concentrations were associated only with types 4–6 (Figs. 6 and 7). All 11 ozone-monitoring stations had significantly high concentrations under those three types. The other nine types did not have significantly high ozone concentrations at any of the stations. Significantly high ozone concentrations also occurred on the days preceding each of those three types; as noted earlier, many of the preceding days had the same synoptic type as the following day. Type 4 was unique among the three high-ozone types: significantly high

relatively high afternoon mixing heights. Under type 7, Atlanta had higher daytime temperatures and more daytime cloud cover than normal. Under type 8, Atlanta had higher daytime temperatures and relative humidities than normal along with relatively high morning mixing
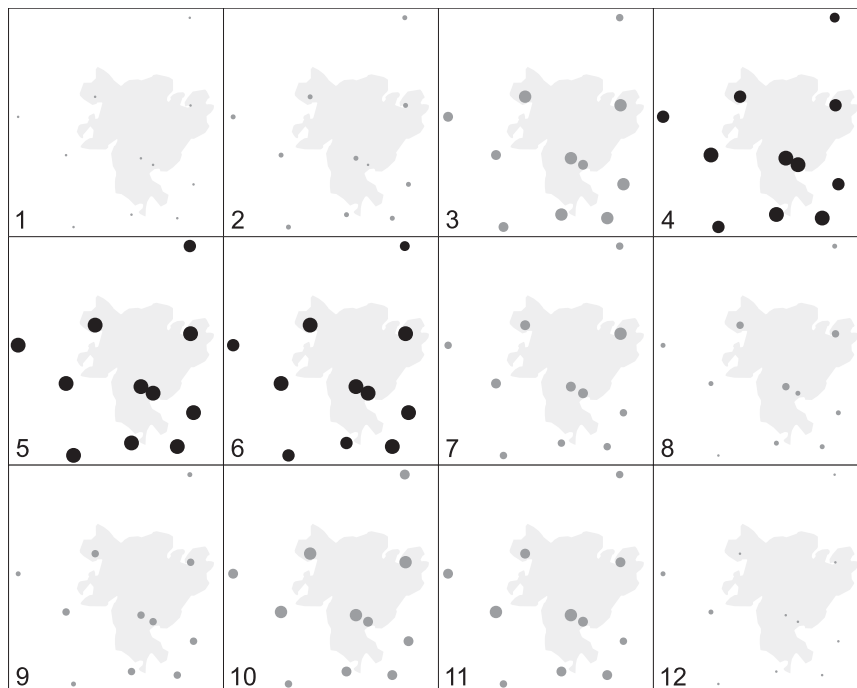

FIG. 6. Mean ozone concentrations for the 12 synoptic types at the 11 ozone-monitoring stations. The ranges of concentrations (ppb) for the proportional symbols are as follow: 30.8–42.2, 42.3–48.7, 48.8–54.0, 54.1–58.2, 58.3–67.0, and 67.1–76.5. Stations represented by black circles had significantly ($\alpha = 0.01$) higher ozone concentrations for that particular synoptic type in comparison with the rest of the days. The gray polygon is the core urban zone based on street-length density as shown in Fig. 2.
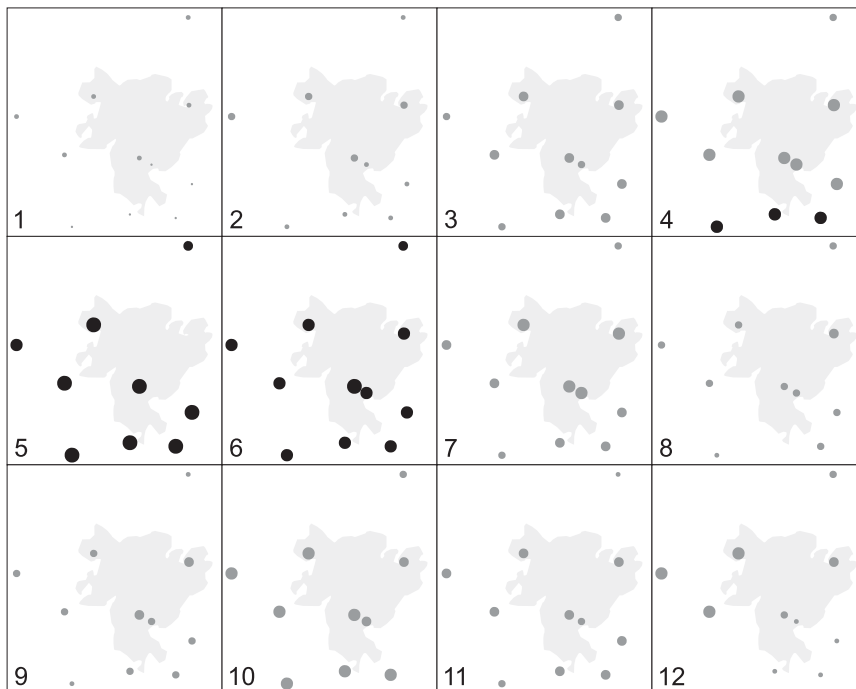
FIG. 7. As in Fig. 6, but on the day preceding the occurrence of a synoptic type. Stations represented by black circles had significantly ($\alpha = 0.01$) higher ozone concentrations for that particular day in comparison with the rest of the days.

ozone concentrations on the preceding day occurred only at the southernmost stations.

Only types 5 and 6 had disproportionately large numbers of ozone-exceedance days in the Atlanta MSA (Fig. 8). Over 40% of the exceedance days were type-6 days, and nearly 50% of type-6 days were exceedance days. Only 14% of exceedance days occurred under type 5, and nearly 60% of type-5 days were exceedance days.

Back trajectories and the associated pollutant-transport potential varied considerably among the high-ozone types (i.e., types 4–6) (Fig. 9; Table 4). When progressing from the western side of a trough (i.e., type 4) to a continental anticyclone (i.e., type 6), there was a consistent decrease in the percentage of back trajectories extending northward from the Atlanta MSA. The NO$_x$ emissions from electric services transported into the Atlanta MSA may have been over 50% larger for type 4 when compared with the seasonal mean. The NO$_x$ emissions for type 4 were significantly higher than the NO$_x$ emissions for the rest of the days. Type 5 had slightly above average transport values, and type 6 had slightly below average values. Type 4 had a significantly large number (i.e., 60%) of back trajectories intersecting the Ohio River valley. Only 28% and 12% of the back trajectories for types 5 and 6, respectively, intersected the Ohio River valley.

The relative roles of in situ ozone production, pollutant carryover, and regional pollutant transport in causing type 4 to be a high-ozone synoptic type are difficult to determine. Although type-4 days did not have relatively high temperatures, the days were less humid, had less cloud cover (i.e., more sunlight), and had lower morning heights and higher afternoon mixing
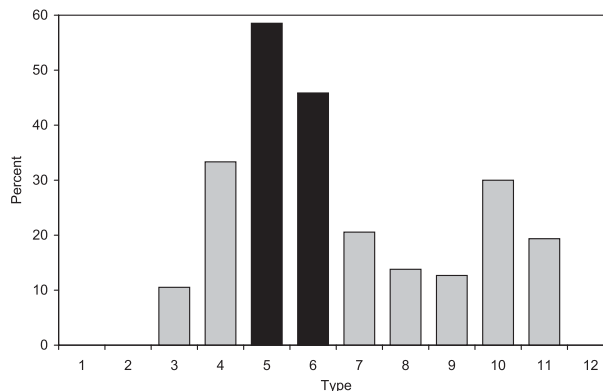

FIG. 8. Percentage of days from June to August of 2000–07 within a synoptic type that were exceedance days. An exceedance day was a day with a daily maximum 8-h-average ozone concentration of greater than or equal to 85 ppb at any of the 11 ozone-monitoring stations. Significantly high frequencies at the 0.01 level are represented by black bars.
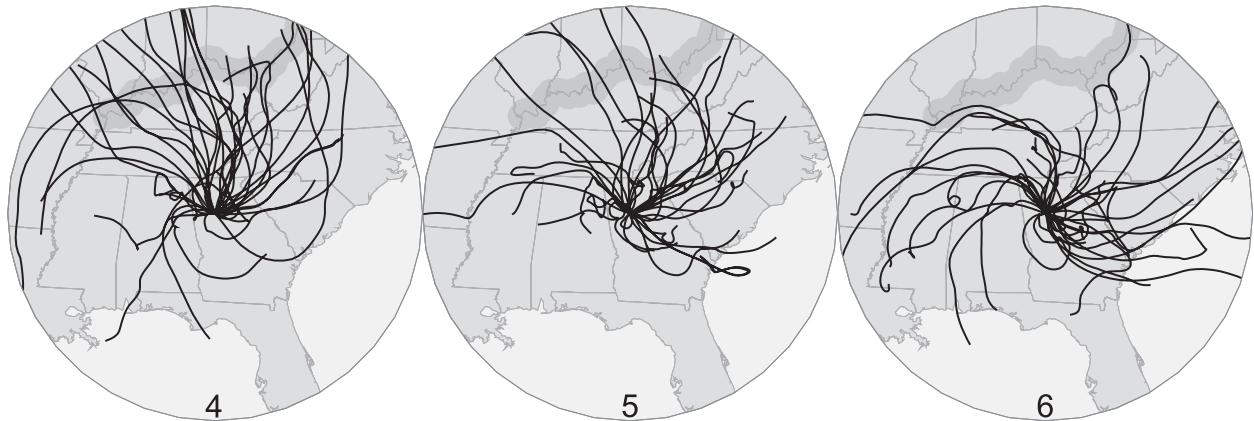
FIG. 9. Back trajectories during June–August of 2000–07 for types 4–6. Only 36 trajectories could be created for type 4; therefore, 36 randomly selected trajectories are shown for the other types. Some of the trajectories extended beyond the circle (800-km radius) centered on Atlanta. The shaded region in the eastern/midwestern United States is the Ohio River valley.

heights than did a typical summer day. High temperatures and increased sunlight favor ozone production (e.g., Sillman 1999); thus, the relative lack of cloud cover for type-4 days probably led to increased in situ ozone production. Low morning mixing heights and high afternoon mixing heights indicate a relatively high potential for afternoon entrainment of ozone. 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 enhanced entrainment of ozone to the surface (e.g., Kim et al. 2007). Nevertheless, days preceding type-4 days, which typically were either type-4 or -3 days, did not have significantly high ozone concentrations throughout the MSA; thus, ozone concentrations carried over from the previous day probably were not exceptionally high. Type 4 did, however, have the highest potential for regional pollutant transport among the three high-ozone types: type-4 back trajectories tended to intersect large power plants on the way to and within the Ohio River valley.

In situ ozone production, pollutant carryover, and, to a lesser degree, regional pollutant transport likely contributed to type 5 having high ozone concentrations. Of all the synoptic types, type 5 had the highest ozone concentrations and the largest percentage of days that were exceedance days. Type-5 days were hotter, were less humid, had less cloud cover, and had lower morning heights and higher afternoon mixing heights than did a typical summer day. These conditions were conducive to ozone production and ozone carryover from the previous day, which was typically either another type-5 day or a type-4 day. While the potential for regional pollutant transport was not significantly high for type 5, it was larger than what would be expected for a typical

summer day; thus, the regional transport of pollutants into the MSA cannot be eliminated as a partial cause of the high ozone.

Type 6 had high ozone concentrations, presumably due almost entirely to in situ production and pollutant carryover. Type 6 was an extremely prevalent and persistent synoptic type, and type-6 days had atmospheric conditions that were similar to those of type-5 days. Therefore, in situ ozone production and ozone carryover should have been enhanced under this synoptic type. The back trajectories revealed that the type did not have consistent airflow; thus, it is not surprising that approximately half the exceedance days in Atlanta with plume recirculation (i.e., the recirculation of a pollution plume on consecutive days) identified in St. John and Chameides (1997) occurred under type 6. There was no evidence of regional pollutant transport contributing to the high ozone concentrations.

The progression from types 4 to 5 to 6 indicates that high ozone concentrations were associated with the eastward movement of a surface anticyclone (Fig. 10). The surface anticyclone was located between 1000 and 2000 km east of the upper-level anticyclone, and it was

TABLE 4. Characteristics of 2-day back trajectories for days within types 4–6. Here, NO_x is the percent difference from the seasonal mean value for NO_x emissions from power plants and ORV is the percent of trajectories that intersected the Ohio River valley.

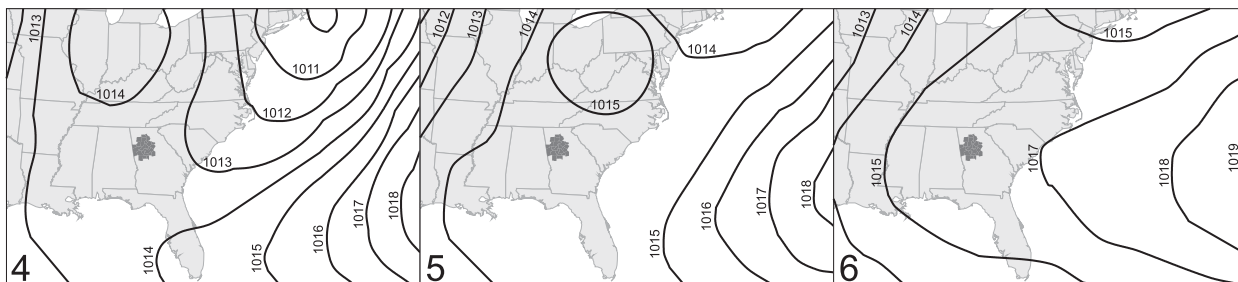| Type	NO_x	ORV
4	+51*	61*
5	+13	28
6	−3	12

* Significant at the 0.01 level.

FIG. 10. Mean sea level pressure (hPa) during June–August 2000–07 for types 4–6. The contour interval is 20 hPa. The shaded region in the eastern United States is the Atlanta MSA.

typically located north of the Atlanta MSA. These results are congruent with those from Rohli et al. (2004), in which high-ozone days in Louisiana were associated with a surface anticyclone centered over the southeastern United States and an upper-level anticyclone southwest of Louisiana. With respect to the regional transport of pollutants, the results from this study differ from the results from synoptic-typing studies in the northeastern United States: the transport of pollutants into the Atlanta MSA from the Ohio River valley is most likely when the MSA is on the eastern side or southern side rather than on the western side (e.g., Comrie and Yarnal 1992; Comrie 1994) of a surface anticyclone, which is the case for the northeastern United States. For example, the combination of a surface anticyclone over the midwestern United States and a surface trough over the northeastern United States, which is the situation for type 4, has been linked by Hogrefe et al. (2004) to higher ozone concentrations in the southeastern United States relative to the northeastern United States.

4. Conclusions

This research revealed that 3 out of 12 middle-troposphere circulation patterns were associated with high ozone in the Atlanta MSA: Atlanta under the western side of a trough, Atlanta east of an anticyclone and west of a trough, and Atlanta under a continental anticyclone. The continental anticyclone pattern was the most common pattern among all 12 patterns; it occurred on 20% of the days. Nearly 50% of the days on which Atlanta was under a continental anticyclone had ozone concentrations exceeding the federal ozone standard. The percentage approached 60% when Atlanta was east of an anticyclone and west of a trough. The surface circulation for the middle-troposphere circulations associated with high ozone involved an eastward-moving high pressure system. In comparison with the rest of the days during the summer season, temperatures and afternoon mixing heights were high, and relative humidity,

cloud cover, and morning mixing heights were low when Atlanta was under or just to the east of a middle-troposphere continental anticyclone. Regional transport of pollutants into the Atlanta MSA was likely when the region was under the western side of a trough. As a consequence, all three circulation patterns had either potentially increased in situ ozone production or potentially increased pollutant carryover or both, and the troughing pattern probably increased pollutant transport from power plants in and near the Ohio River valley into the Atlanta MSA.

More synoptic-climatological research of ground-level ozone in the southeastern United States is needed. Suitable study areas include not only the Atlanta MSA but also the Birmingham, Alabama, and Charlotte, North Carolina, MSAs, both of which are within 400 km of Atlanta. It is recommended that an automated synoptic typing of sea level circulation patterns be conducted for each of those MSAs in order for circulation–ozone relationships in southeastern urban areas to be compared directly with previously published results for the northeastern United States.

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