Tropospheric Ozone in Louisiana and Synoptic Circulation

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(Manuscript received 11 September 2003, in final form 20 April 2004)

ABSTRACT

Tropospheric ozone (O_3) is a pollutant of increasing concern in many urban areas in the United States. There is an increasing need to understand the geographical and meteorological properties associated with O_3, particularly because of the changing criteria that are being implemented by the U.S. Environmental Protection Agency to monitor O_3. This research examines the relationship between O_3 mixing ratios in Louisiana and surface and low-tropospheric synoptic circulation patterns. Results suggest that local conditions and synoptic influences are both important in determining the behavior of observed O_3 in Louisiana during this period in which ''exceedance'' frequencies decreased until 2000–01, at which time they increased again. Furthermore, the expected pattern of surface anticyclonic activity, low-tropospheric ridging, weak pressure gradients, and subsidence from the lower troposphere is found to be associated with anomalously high O_3, both at most local sites in the state and on days with anomalously high O_3 statewide. More surprising, however, is the tendency for high O_3 to be associated with low surface pressure in the Great Plains, perhaps in advance of a midlatitude wave cyclone to the north. This and other surface patterns may be linked to advection from the southeastern Texas urban–industrial corridor. A temporally increasing tendency for surface and lower-tropospheric ridging over the 1994–2001 study period provides at least a partial explanation for the absence of a frequency decline in statewide anomalously high ozone days during a time of increasing public awareness and concern for meeting the O_3 standard.

1. Introduction

Tropospheric ozone (O_3) is becoming a pollutant of increasing concern in many urban areas in the United States. Approximately 50 metropolitan areas in the United States exceed the U.S. Environmental Protection Agency's (EPA) primary standard of 125 parts per billion (ppb) averaged over a 1-h period more than three times in any 3-yr period. Moreover, the number of metropolitan areas in nonattainment is increasing because as a metropolitan area is deemed to meet the standard, it becomes subjected to the new, generally more stringent standard of 85 ppb averaged over an 8-h period (Hsu et al. 2000). Because of the economic implications associated with repeated noncompliance with these standards, including reduced federal highway funding, requirements for the use of cleaner-burning fuels, and caps on industrial growth, local environmental and economic planners have become increasingly interested in understanding the factors that contribute to O_3 ''exceedances'' so that these federal clean-air standards can be met.

Baton Rouge, Louisiana, is one metropolitan area that fails to meet the existing standard, despite exceedance frequencies that generally decreased until 2000, at which time they increased again. In February of 2003, it was reclassified from the ''serious'' category into the more ominous ''severe'' category. Quantitative models have already been investigated for predicting O_3 mixing ratios in Baton Rouge (Rohli et al. 2003).

One phenomenon related to Louisiana O_3 that has not yet been investigated completely, however, is the role of advection. In specific terms, Louisiana officials claim that advection may transport O_3 from distant sources such as the southeast Texas urban–industrial corridor toward sites in Louisiana. Such a phenomenon may suggest that O_3 problems in Louisiana may not be solely the result of local emission of the nitrogen oxides (NO_x) that serve as precursor pollutants to O_3, and such a phenomenon could have some impact on policy and

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alerting the public about imminent poor air quality. Modeling studies have recently been undertaken to assess the role of O_3 transport (e.g., Barna and Lamb 2000; Jiang et al. 2003), but no formal synoptic approach has investigated this phenomenon in Louisiana.

2. Purpose

The purpose of this research is to identify the relationship between tropospheric O_3 concentrations and surface and low-tropospheric synoptic weather patterns in Louisiana. Additional analyses are undertaken to eliminate spurious nonmeteorological effects produced by local emissions, by considering separately the days with high mixing ratios statewide. Moreover, we are interested in the effect of synoptic circulation throughout the year, even outside of the traditionally defined ''O_3 season'' of 1 May through 31 October. To be specific, do unseasonably high tropospheric O_3 mixing ratios recur under the same synoptic pattern(s)? Does this (these) pattern(s) advect O_3 from other areas, particularly the urban–industrial corridor of southeastern Texas?

3. Literature

a. Ozone

Ozone is a photochemical oxidant formed from reactions between NO_x and hydrocarbons (HC) in the presence of sunlight. Both of these precursor compounds result from automobile and industrial emissions, and HC also result from biogenic emissions. The complex interactions among NO_x, HC, and a combination of meteorological variables such as temperature, atmospheric stability, incoming shortwave radiation, inversion height, and long-range transport determine the location, severity, and duration of a tropospheric O_3 pollution event (Chock et al. 1982; Altshuller 1986; Seinfeld 1989; Comrie 1990). Because synoptic-scale circulation affects all of the above meteorological features, this research seeks to identify the synoptic-scale circulation patterns that influence O_3 concentrations in Louisiana.

b. Ozone and synoptic-scale circulation

Synoptic climatology seeks to relate the atmospheric circulation to an environmental variable using empirical and statistical techniques (Yarnal 1993). Many studies have examined the relationship between pollution, such as O_3, and synoptic-scale circulation in various regions (e.g., Chock et al. 1982; Altshuller 1986; Heidorn and Yap 1986; Comrie 1990, 1992; Comrie and Yarnal 1992; McKendry 1994; McGregor and Bamzelis 1995; O'Hare and Wilby 1995; Leighton and Spark 1997; Shahgedanova et al. 1998; Greene et al. 1999; Lennartson and Schwartz 1999; Cheng and Lam 2000). Other studies include other variables, such as temperature, wind, and radiation, in the forecasting, analysis, and classification of high tropospheric O_3 events (Ryan et al. 1992; Moody et al. 1995; Ellis et al. 2000). Little research has been conducted on synoptic circulation associated with O_3 on the central Gulf Coast—a region that is affected frequently by ''back of the high'' extratropical anticyclonic activity (Rohli and Henderson 1997) and Gulf of Mexico anticyclonic weather events (Muller 1977) and thus possibly O_3 advection. The most closely associated comprehensive synoptic climatological study conducted was for Birmingham, Alabama (Greene et al. 1999).

c. Principal Components Analysis

One method of extracting the major modes of variability in a dataset is through principal components analysis (PCA). In PCA, each of the original variables is replaced by a combination of principal components that are linearly independent of each other and are ordered in the amount of variance they explain. The matrix of loadings is used to quantify the correlations between the original data and each component and is calculated as

$$\mathbf{L} = \mathbf{E}\mathbf{\Lambda}^{0.5}, \tag{1}$$

where $\mathbf{E}$ is the matrix of eigenvectors and $\mathbf{\Lambda}$ represents the eigenvalue matrix.

In analyses that include spatial and temporal observations of the same variable, the spatial pattern of loadings for each component identifies the geographical regions that are affected most directly by variability explained by that component. Likewise, principal component scores are calculated to identify temporal relationships between the original variables and the principal components. Thus, PCA can allow for the simultaneous characterization of variability in a variable across space and time.

Rotation of the principal components is necessary to minimize problems related to domain-shape dependence (Buell 1975, 1979; Legates 1991), subdomain instability, sampling, and inaccurate portrayal of the physical relationships in the input (Richman 1986) when PCA is used to identify the spatial mode of variability over a mapped surface (White et al. 1991; Yarnal 1993). Orthogonal rotation procedures maintain the ''purity'' of each component identified by ensuring that the components remain uncorrelated with each other while still optimizing the explained variance among the set of retained components. Because of this preservation of orthogonality among components, ''varimax'' is generally considered to be an effective rotation scheme in map-pattern classification (Yarnal 1993) such as this analysis. Oblique rotation schemes are preferred for regionalizations, for which shared variance among components is not as problematic (e.g., Fovell 1997; Comrie and Glenn 1998).

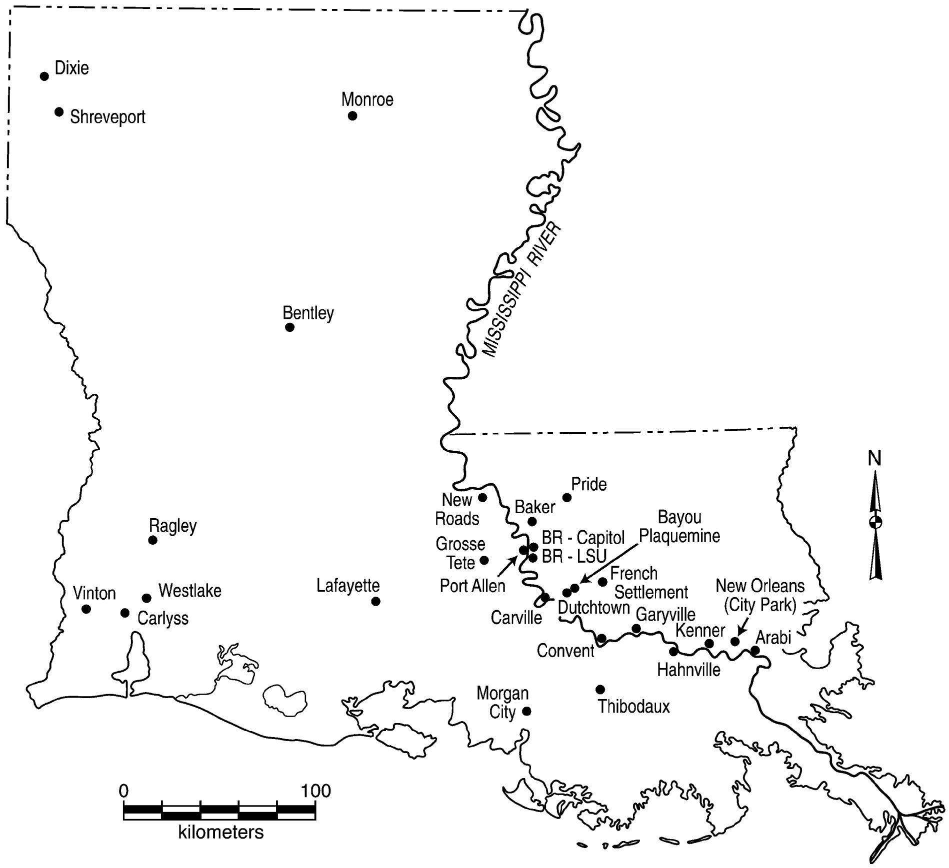

FIG. 1. Ozone-monitoring sites in Louisiana.

4. Data and method

a. Tropospheric ozone

Hourly average O_3 mixing ratio data were collected by the Louisiana Department of Environmental Quality (LDEQ; M. Vanichchagorn 2001, personal communication). These data consist of the set of 29 stations in Louisiana for which hourly tropospheric O_3 mixing ratios are monitored for the 1995–2000 period (Fig. 1). Because of poor data coverage, LeBleau was eliminated from consideration.

The procedures used to handle missing observations from the LDEQ data are identical to those implemented by EPA for assessing compliance according to the most updated standard (U.S. Code of Federal Regulations Title 40, Part 50, Appendix I, Section 2.1: Data Reporting and Handling Conventions; available online at http://ecfr.gpoaccess.gov). To be specific, running 8-h averages are computed from the hourly O_3 mixing ratio data for each hour of the year, with the resulting data stored in the first hour of the 8-h period. An 8-h mean is computed if at least six of the hourly averages of the 8-h period are available. For cases in which only six (or seven) hourly averages are reported, the 8-h mean is computed on the basis of the hours available, using six (or seven) as the divisor. A daily maximum 8-h mean mixing ratio is computed based on the 24 8-h mixing ratios and is considered to be valid if at least 18 of the 24 8-h averages can be computed or if the daily maximum 8-h average mixing ratio for that day is at least 85 ppb (regardless of how many missing observations are present). In accordance with EPA's guidelines, any day in which the above criterion is not met is still considered to be valid if the maximum daily 8-h average mixing ratio exceeds the standard. Data completeness at the 28 sites ranges from 90.3% (Grosse Tete) to 96.5% (Garyville) and averages 94.0%.

To eliminate short-term and seasonal variation in absolute O_3 mixing ratios (Rao et al. 1997) to facilitate comparison of O_3 levels across the year, the daily peak O_3 data are statistically standardized by month at each site. The result is a time series of daily *z* scores over the 6-yr period for each site, calculated by subtracting the mean daily peak O_3 for that month from the daily observation and then dividing by the standard deviation. Thus, the mean *z* score for the set of approximately 180 days in each of the 12 months is 0.0 and the standard deviation is 1.0. Because this study also addresses unseasonably high O_3 days on the statewide scale (i.e., regardless of whether a single local emission may have produced a local exceedance), it is important to identify a method for defining a ‘‘statewide anomalously high

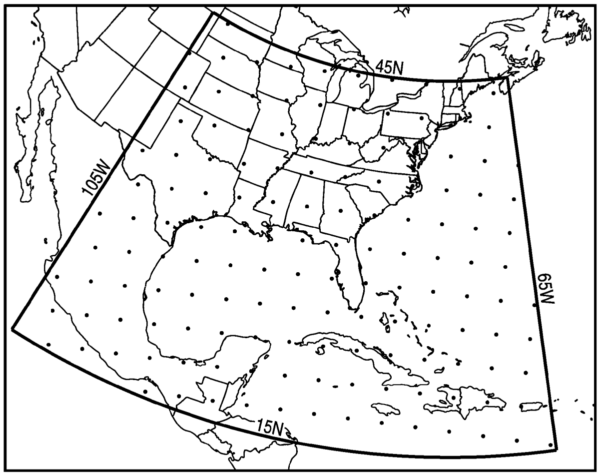

FIG. 2. Data points used in SLP, 850-hPa, and 700-hPa flow pattern analysis.

O_3 day'' (SAOD). Any day for which at least one-third of the available sites (28 possible) had a *z* score over 2.0 (i.e., the upper 2.2% of the distribution) was considered to be a SAOD.

b. Sea level pressure/Geopotential height data

Daily 1200 UTC sea level pressure (SLP) and 850- and 700-hPa geopotential height data were obtained from the National Centers for Environmental Prediction's 1977-point octagonal grid (University Corporation for Atmospheric Research 2002). The purpose is to link synoptic-scale flow patterns with O_3 mixing ratios in Louisiana. Even though the O_3 data were only available for the 1995–2000 period, SLP–geopotential height data for 1994–2001 were included for this part of the analysis. The expanded dataset was used to provide a sufficient number of observations by month to provide a representative climatological description of SLP and upper-level heights, which represents flow patterns from the surface to approximately 3 km. A total of 49 days were missing from the dataset, yielding an analysis of 2873 daily maps at each of the three levels, while peak O_3 mixing ratio data were available for a maximum of 2192 days [365 days $\times$ 6 years (1995–2000) plus two leap-year days].

The spatial domain is bounded by 15°–45°N and 105°–65°W, resulting in an extraction of 141 data points from the 1977-point grid for each of the three levels (Fig. 2). The domain was selected so that the pressure field is centered on Louisiana and is sufficiently large to detect synoptic-scale variability associated with the Bermuda high on the east while still avoiding the high elevations (and, therefore, ''upper level'' data that actually represent the near-surface atmosphere) of the mountain cordillera of western North America. The northern and southern boundaries of the study region were selected to facilitate the depiction of pressure variability associated with both midlatitude wave cyclones (in the north) and tropical disturbances (in the south).

The SLP–geopotential height data were statistically standardized by month to eliminate their natural variability through the course of the year and to facilitate their comparison across space and time with the standardized O_3 data. PCA was run on this standardized dataset for SLP (and in separate analyses, also for 850- and 700-hPa geopotential heights) to identify the modes of variability across the study region. In all three datasets, varimax rotation of principal components was performed to eliminate spurious spatial patterns of SLP/geopotential height across the study area. The spatial pattern and sign of loadings were used as an indicator of the pressure fields that explain the most daily SLP–geopotential height variability in the study region.

For each daily dataset, temporal trends in SLP–geopotential height values (represented by the scores matrix) were identified, because temporal changes in pressure and height values may represent long-term changes in flow patterns (which in turn may affect O_3 concentrations). For this analysis, simple linear tests for trend in observations [numbered sequentially from 1 (1 January 1994) through 2922 (31 December 2001) vs rotated PCA score by component] were conducted for each dataset. The standardized daily 8-h peak O_3 mixing ratio was then correlated with the daily varimax-rotated PCA score for the components retained after rotation.

For all SAODs identified, a composite map of the pressure–geopotential height field was produced for each of the three synoptic levels. This analysis provides a snapshot of the synoptic circulation exclusively during anomalously high O_3 days rather than during all days, as was provided by the spatial pattern of loadings. Furthermore, mean PCA-generated scores on the SAODs were calculated at each level. The spatial pattern of loadings for those components whose scores show the highest departures from zero are those associated most directly with a SAOD.

5. Results and discussion

a. Characteristics of daily peak 8-h O_3 mixing ratios

Each of the 28 stations has daily peak 8-h O_3 mixing ratios that correlate significantly with those at every other station. A total of 48 days from the 1995–2000 period were found to have O_3 mixing ratios exceeding 2.0 std dev above the mean for that month at one-third of the available sites in the state. Each month of the year is represented in this SAOD dataset.

b. Sea level pressure patterns

1) ALL DAYS

Examination of a scree plot (Cattell 1966) of the eigenvalues in the initial PCA procedure and a priori knowledge of the number of major modes of variability in surface atmospheric circulation suggest that six components, collectively explaining 85.9% of the dataset variance, should be retained for rotation. As expected in an orthogonal rotation procedure such as varimax, components are uncorrelated with one another. The spatial pattern of loadings for each of the six retained components is shown in Figs. 3a–f. Component 1 shows maximum explained variance in the southwestern part of the study area, over the Bay of Campeche. This result is somewhat surprising, but perhaps only because few studies have concentrated on variability in a similar study domain as that employed here. Component 2 identifies maximum loadings in the Caribbean, perhaps associated with the Bermuda high. This pattern has been identified previously for a similar study area (Vega 1994). The third component shows a pattern of highest loadings in the western Atlantic Ocean with a secondary area of opposite sign concentrated over the upper midwestern United States. The fourth component suggests variability over the Great Plains, and the fifth and sixth components also identify specific regions of high variability over the eastern Great Lakes and Florida, respectively.

Scores for rotated component 1 are significantly (defined as probability $\alpha \leq 0.05$) positively correlated to standardized O_3 mixing ratio at 25 of the 28 sites, with no relationship at the remaining 3 sites (Table 1). Thus, on days when an intense surface ridge exists over the Bay of Campeche (Fig. 3a), O_3 levels are high in Louisiana. Because this pattern explains the most variability in the dataset, it appears likely that many days may have synoptic situations that could support high O_3 in Louisiana. This pattern also appears reminiscent of the ''Gulf high'' weather type (Muller 1977) and suggests that subsidence may trap locally generated O_3, in particular over southern Louisiana where most of the monitoring stations are located. Nevertheless, the spatial pattern also suggests circumstantially that synoptic-scale advection from the urban–industrial corridor of southeastern Texas may also be a contributor to O_3 problems in Louisiana.

In addition, because scores for rotated component 1 became more positive over time ($\alpha = 0.0001$), it is important to attempt to understand the physical mechanisms behind this trend so that an assessment can be made of whether this pattern might be expected to persist into the future. If so, the frequency of future exceedances might be expected to increase in Louisiana. However, such an investigation is beyond the scope of this research. Nevertheless, note that with a standardization approach such as that adopted here, even if the absolute and mean concentrations decrease, the same number of days will have *z* scores above 2.0.

In contrast to the results from analysis of component 1, O_3 levels associated with component 2 appear to be driven by local rather than synoptic advection. The pressure gradients depicted by the isolines of loadings are extremely weak across most of North America (Fig. 3b). Moreover, significant relationships to O_3 are found at all 28 sites, with 11 positive and 17 negative correlations. In general, positive relationships are found immediately north of urban and industrial areas, in particular in the New Orleans–Baton Rouge and Lake Charles petrochemical corridors, and negative relationships are found on the southern and western sides of urban and industrial areas. The results imply that slight breezes from the Gulf of Mexico may cause local drift but are not sufficiently strong to provide much synoptic-scale advection. Furthermore, component 2 is the only pattern other than component 1 to show a temporal trend in scores, with a significant increase over time ($\alpha = 0.0001$). If such a trend were to persist into the future, it might change the distribution of stations that experience exceedance days; stations south of urban and industrial areas may experience fewer future exceedance days in Louisiana.

Component 3 shows scores that are significantly negatively correlated with standardized O_3 concentration at all 28 sites (Table 1). Thus, on days when SLP is anomalously high over the western Atlantic (Fig. 3c), O_3 is anomalously low over Louisiana. This pattern would place Louisiana in a back-of-the-high synoptic situation, advecting O_3 and its precursors from the urban and industrial corridor of southeastern Louisiana northward (away from most of the monitoring sites) while the monitoring stations receive advection of relatively clean air from the Gulf of Mexico. Although component 2 also suggests return flow from the gulf, SLP gradients were very slight in that pattern; thus, dilution of pollutants was not as likely in the case of component 2 as it is for component 3.

Scores for rotated component 4 (Fig. 3d) are significantly negatively correlated with standardized O_3 mixing ratio at 25 sites (Table 1). This relationship is easily explained at the synoptic scale, because the positive mode of variability depicted by the loadings pattern in Fig. 3d would advect air from relatively sparsely populated and lesser-industrialized locations in Mississippi into Louisiana. This pattern is associated with below-normal O_3 levels throughout Louisiana. Few monitoring stations are located immediately southwest of major emission areas, but even those that are, such as Carville, Convent, Port Allen, and Bayou Plaquemine, tend to have significantly negative relationships between component-4 scores and O_3 levels. The inverse flow pattern suggested by rotated component 4 would produce surface southwesterly winds in a relatively steep SLP gradient (and above-normal O_3 mixing ratios) perhaps in advance of an approaching midlatitude wave cyclone, reminiscent of the ''frontal gulf return'' weather type (Muller 1977). This pattern of meteorological conditions is not normally associated with high O_3 but it appears to be important in Louisiana, possibly because of some O_3 advection from the west. In general, it appears that synoptic influences on O_3 may outweigh local factors in this pattern.

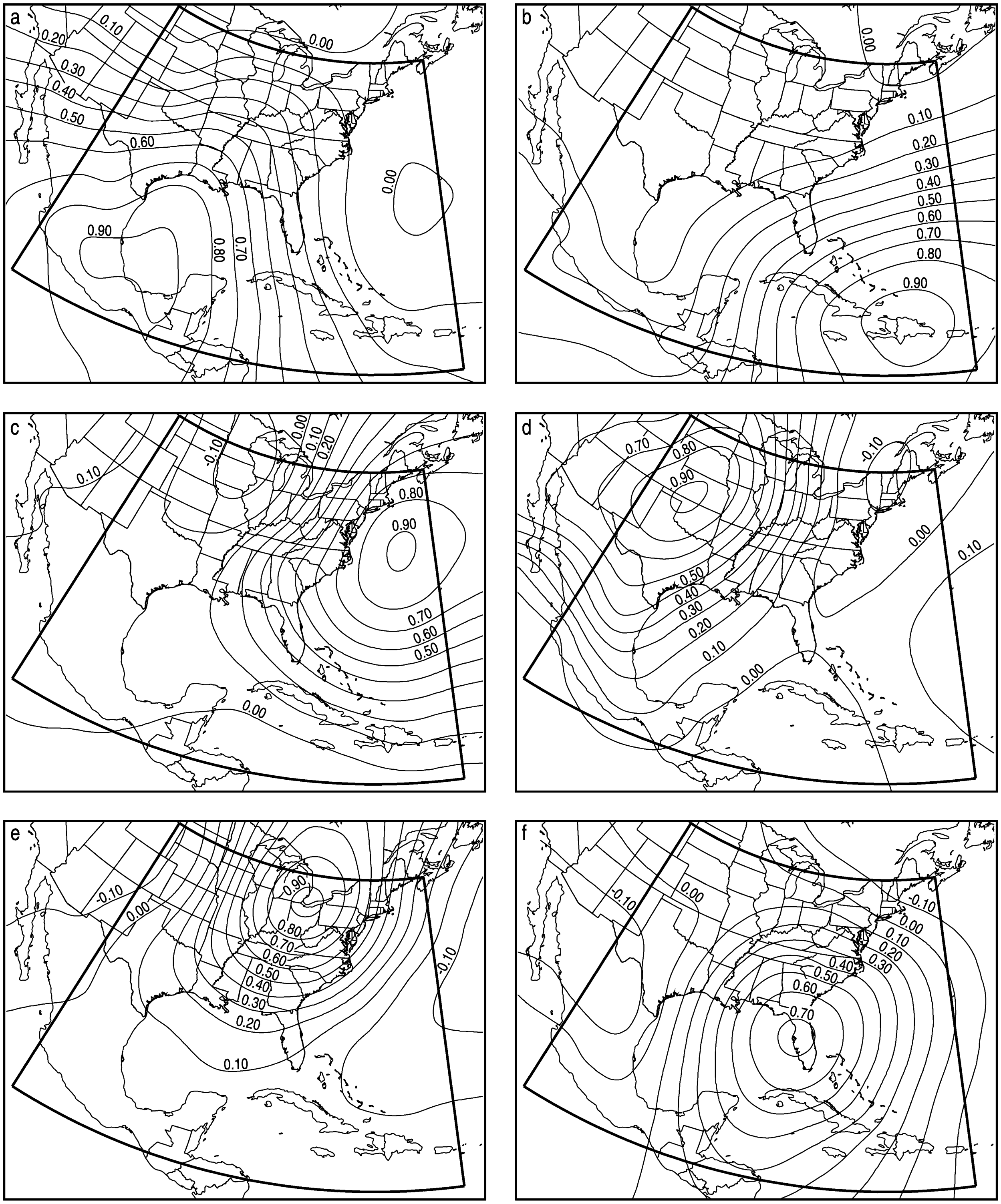

FIG. 3. Spatial pattern of loadings in rotated PCA based on monthly standardized daily SLPs: (a) component 1, (b) component 2, (c) component 3, (d) component 4, (e) component 5, and (f) component 6.

TABLE 1. Sites with significant correlations ($\alpha < 0.05$) between standardized ozone mixing ratios and PCA-generated scores, 1995–2000.

	SLP						850-hPa			700-hPa height		
	1	2	3	4	5	6	1	2	3	1	2	3
Arabi	+	−	−		+	−	+	−	−	+	−	−
Baker	+	−	−	−	+		+	−		+	−	−
Baton Rouge Capitol	+	−	−		+	−	+	−	−	+	−	−
Baton Rouge Louisiana State University	+	−	−	−	+	−	+	−	−	+	−	−
Bayou Plaquemine	+	−	−	−	+	−	+	−	−	+	−	−
Bentley	+	−	−	−		−	+	−	−	+	−	−
Carlyss	+	−	−	−		−	+	−	−	+	−	−
Carville	+	−	−	−		−	+	−	−	+	−	−
Convent	+	−	−	−	+	−	+	−	−	+	−	−
Dixie	+	−	−	−	−	−	+	−	−	+	−	−
Dutchtown	+	−	−	−		−	+	−	−	+	−	−
French Settlement	+	−	−	−			+	−	−	+	−	−
Garyville	+	−	−	−		−	+	−	−	+	−	−
Grosse Tete	+	−	−	−		−	+	−	−	+	−	−
Hahnville	+	−	−	−		−	+	−	−	+	−	−
Kenner	+	−	−			−	+	−	−	+	−	−
Lafayette	+	−	−	−	+	−	+	−	−	+	−	−
Monroe		+	−	−			+	−	−	+	−	−
Morgan City	+	+	−	−		+	+	−	−	+	−	−
New Orleans	+	+	−	−	−	+	+	−	−	+	−	−
New Roads		+	−	−	−		+	−	−	+	−	−
Port Allen	+	+	−	−	−	+	+	−		+	−	−
Pride	+	+	−	−	−		+	−	−	+	−	−
Ragley	+	+	−	−			+	−	−	+	−	−
Shreveport	+	+	−	−		−	+	−	−	+	−	−
Thibodaux		+	−	−		+	+	−	−	+	−	−
Vinton	+	+	−	−	−		+	−	−	+	−	−
Westlake	+	+	−	−	+		+	−	−	+	−	−

Scores for rotated component 5 are significantly positively correlated to standardized O_3 mixing ratio at eight sites and are significantly negatively correlated with standardized O_3 mixing ratio at six sites (Table 1). This pattern is suggesting that a surface anticyclone centered over the eastern Great Lakes would cause O_3 to drift from the New Orleans–Baton Rouge petrochemical corridor upriver toward Baton Rouge (Fig. 3e), where many of the sites with a positive correlation are located (Table 1). Arabi and Westlake are not located along that axis but rather appear to have O_3 levels that are positively associated with such circulation because of local plant emissions upwind. This synoptic-scale pattern would be associated with below-normal O_3 in northwestern Louisiana and New Orleans because a drift of O_3 from the southeastern center of industrial activity would disperse before reaching the Shreveport and Dixie sites and would advect relatively clean air into New Orleans. Nevertheless, the intricate pattern of associations appears to emphasize local advection in association with this component.

Scores for rotated component 6 are significantly negatively correlated with standardized O_3 mixing ratio at 16 sites and are positively correlated at 4 (Table 1). Thus, an anticyclone over peninsular Florida (Fig. 3f) is linked to below-normal O_3 in most of Louisiana because return flow from the Gulf of Mexico would be likely to displace O_3 northward from the petrochemical corridor and Baton Rouge (where no monitoring sites are located) in a fashion similar to the pattern produced by rotated component 3. In fact, several of the sites that do not display significant negative correlations are located north of centers of urban and industrial activity (e.g., Monroe, Pride, Baker).

2) SAODs

On the 47 SAODs with available data, the composite SLP field shows an anticyclone over the southeastern United States (Fig. 4). This flow puts Louisiana either under the surface anticyclone or in a back-of-the-high synoptic situation, which would cause the O_3 to drift northwestward from industrial southeastern Louisiana toward many of the monitoring sites. This back-of-the-high situation contrasts with that observed in Fig. 3c (which was inversely correlated with O_3) in that Fig. 3c suggests northerly advection from southeastern Louisiana toward Mississippi.

The fact that surface temperature departures for the 17 sites in Louisiana's Central Climate Division averaged 3.7°C above the 30-yr mean for each SAOD (with a standard deviation of 2.3°C) suggests that subsidence and sunshine are major factors in SAOD occurrence. Return flow from the south would be unlikely to produce such high departures because of the maritime influence and associated cloudiness. However, the weak SLP gra-

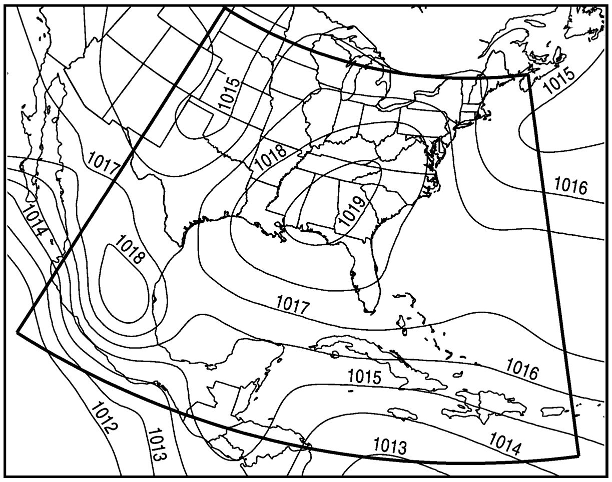

FIG. 4. Composite SLP pattern on days with anomalously high tropospheric ozone mixing ratios across Louisiana.

dients across most of the study area on those days suggest that O_3 drift from the southeast is occurring, but not to the extent that it would produce a significant ''cleansing'' effect from the Gulf of Mexico. Thus, it appears that both local and synoptic factors may contribute to O_3 loadings on SAODs.

Because of the standardization process, the mean score for all days in the time series on any component is zero. However, the set of rotated PCA scores on the SAODs shows large departures from zero on components 1, 2, and 4 ($\alpha = 0.05$; Table 2), and 3 ($\alpha = 0.10$; Table 2). For all six components, the sign of departures suggests that the same pattern of height anomalies that is associated with high ozone at most sites for the ''all days'' dataset is also linked to the SAODs. The strongest positive association on SAODs is for component 1, suggesting that the presence of a surface anticyclone over the western Gulf of Mexico and coincident ridge over the Mississippi valley is linked most closely to anomalously high O_3 mixing ratios statewide. This pattern shows that surface advection from the west may potentially be supporting such events. Nevertheless, the high variability within these O_3 days and the relatively small sample of days included invite caution in the interpretation of results.

Likewise, synoptic situations dominated by low SLP over the Caribbean (component 2), the Great Plains (component 4), or possibly the mid-Atlantic region (component 3) are associated with SAODs. The result for component 4 is particularly interesting because minimum mean scores on SAODs exist for component 4 (Table 2) and because this is the pattern that is not usually considered to be important in contributing to excessive O_3 events. Thus, it seems possible that a mechanism other than subsidence and clear skies associated with extreme atmospheric stability may be responsible for at least some of these SAODs. Such a pattern supports the notion that advection of surface air from the southeastern Texas industrial corridor relates to high O_3 in much of Louisiana.

TABLE 2. Mean rotated PCA-derived scores and T values on statewide anomalously high ozone days in Louisiana, by component and level.

	N	Mean	Std dev	T value (one-sided test)
SLP component 1	47	0.476	0.948	3.443**
SLP component 2	47	−0.279	1.046	−1.829**
SLP component 3	47	−0.216	0.899	−1.647*
SLP component 4	47	−0.303	0.881	−2.358**
SLP component 5	47	0.057	0.865	0.452
SLP component 6	47	−0.36	1.023	−0.241
850-hPa component 1	47	0.416	0.843	3.383**
850-hPa component 2	47	−0.297	0.932	−2.185**
850-hPa component 3	47	−0.024	0.963	−0.171
700-hPa component 1	47	0.613	0.932	4.509**
700-hPa component 2	47	−0.384	0.954	−2.670**
700-hPa component 3	47	−0.038	0.909	−0.287

* Significantly different from the set of scores for all days in time series (mean $\mu = 0$, std dev $\sigma = 1.0$) at $\alpha = 0.10$.

** Significantly different from the set of scores for all days in time series ($\mu = 0$, $\sigma = 1.0$) at $\alpha = 0.05$.

When the SAODs are segregated by season (Figs. 5a–d), similar composite SLP patterns emerge as for the composite map of SLP shown in Fig. 4. Louisiana is in a gentle pressure gradient in a back-of-the-high synoptic situation that would produce drifting from the south or southeast; this situation would be associated with high O_3 levels statewide. The winter and autumn synoptic patterns (Figs. 5a and 5d, respectively) appear to be nearly identical to that shown in Fig. 4. Spring is also similar (Fig. 5b), except that the high is larger and occupies much of the eastern United States. Summer (Fig. 5c) shows a weaker pressure gradient than the other seasons. Of course, caution should be exercised in the interpretation of these results, because of the low number of SAODs used in the seasonal compositing procedure (10 in winter, 11 in spring, and 13 each in summer and autumn).

c. 850-hPa analysis

Three components that collectively explain 72.3% of the dataset variance were retained for varimax rotation. The first rotated component (Fig. 6a) identifies an intense ridge over the southern Great Plains, with pronounced upstream and downstream troughs over the Atlantic and Pacific coasts of the United States. The second rotated component (Fig. 6b) shows a ridge over the Caribbean basin, with weak gradients over the north and western parts of the study area. Rotated component 3 (Fig. 6c) depicts an intense ridge over the mid-Atlantic

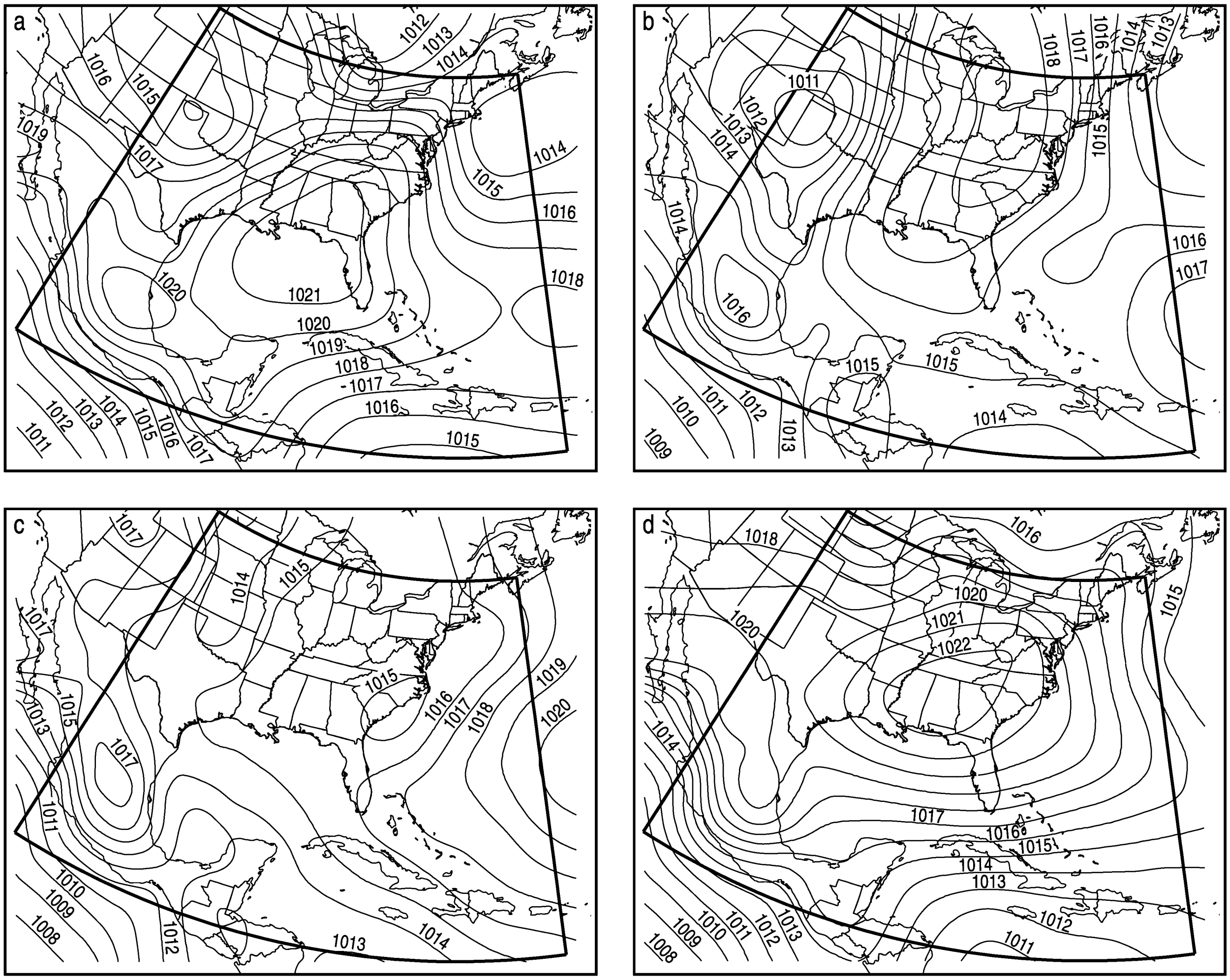

FIG. 5. As in Fig. 4, but by season: (a) winter (Dec–Feb; DJF), (b) spring (Mar–May; MAM), (c) summer (Jun–Aug; JJA), and (d) autumn (Sep–Nov; SON).

seaboard of the United States. The first and second components both show significantly increasing trends in scores over the 8-yr period. In addition, a near-significant ($\alpha = 0.057$) positive trend in scores occurs for component 3.

Standardized O_3 levels are correlated significantly with rotated PCA-generated scores at all 28 O_3-monitoring sites for the first two components (positively for the first component and negatively for the second, at all sites, Table 1). Thus, 850-hPa ridges immediately west of Louisiana and over the Caribbean basin are linked to above- and below-normal O_3 levels, respectively. The significant positive trends in these scores suggest that midcontinental ridging became a bigger contributor to the O_3 problem over time, because the increasing tendency for Caribbean ridging over time is linked to below-normal O_3 across Louisiana. The nearly significant temporal increase in scores for rotated component 3 (which is associated with below-normal O_3; Table 1) is also notable. The midcontinental ridge seems to have compensated for the other two circulation patterns that would have been operating to decrease the O_3 mixing ratios. Indeed, this midcontinental ridge has been linked to historical drought events (Walsh et al. 1982; Keables 1988; Groisman and Easterling 1994; Lettenmaier et al. 1994; Chang and Smith 2001).

The composite 850-hPa geopotential height field during SAODs (Fig. 7) shows very weak height gradients over the southern half of the study region, with a steeper gradient in the northern half. The ridge axis is situated almost directly over Louisiana, with the surface anticyclone appearing directly beneath the ridge-to-trough side of the 850-hPa wave (Fig. 4). Thus, while the presence of the 850-hPa ridge might suggest that subsidence is important, the strong vertical synoptic correlation might also suggest the importance of advection from the west.

Not surprising is that the significantly high positive scores for component 1 on SAODs (Table 2) confirm that an intense midcontinental 850-hPa ridge is associated with anomalously high O_3 mixing ratios across

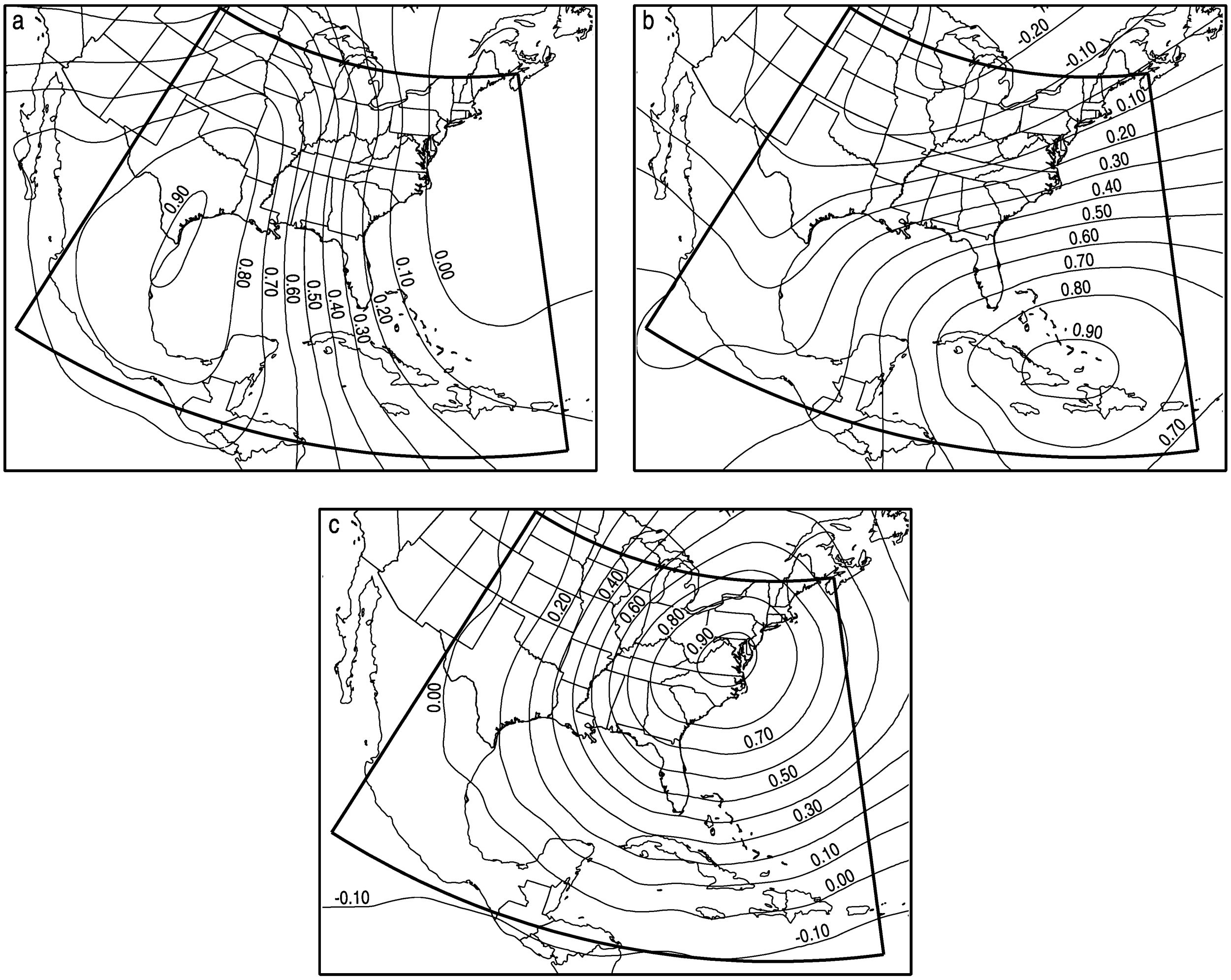

FIG. 6. Spatial pattern of rotated PCA loadings based on monthly standardized daily 850-hPa geopotential heights: (a) component 1, (b) component 2, and (c) component 3.

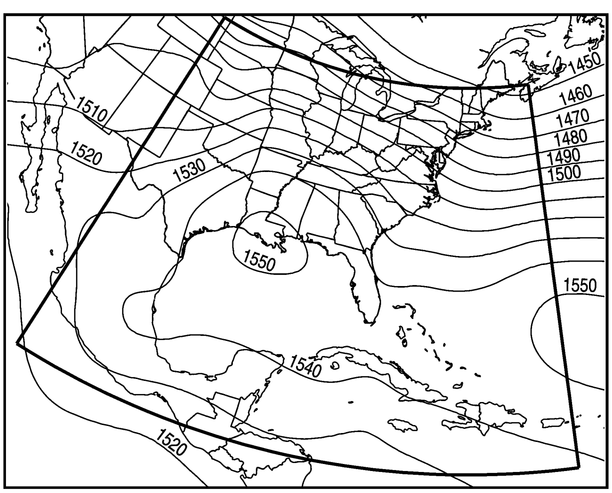

FIG. 7. Composite 850-hPa pattern on the days with anomalously high tropospheric ozone mixing ratios across Louisiana.

Louisiana. The second component shows significantly negative scores for SAODs (Table 2), suggesting that excessive O_3 days tend to be associated with below-normal height in the Caribbean (and associated ridging over the midcontinent). Thus, the synoptic pattern contributing to SAODs is similar to that associated with O_3 variability in general.

When the composites are examined by season (Figs. 8a–d), Louisiana again appears under the ridge axis that appears in the ''all SAOD'' composite (Fig. 7). In particular, a closed isohypse exists near Louisiana in winter and over Louisiana in autumn (Figs. 8a and 8d, respectively), and spring shows a well-developed ridge axis over the state (Fig. 8b). Figure 8c suggests that an extension from the Atlantic subtropical anticyclone across Louisiana is important on summer SAODs.

d. 700-hPa analysis

Three components were also retained for rotation at this level, explaining 71.5% of the dataset variance. The

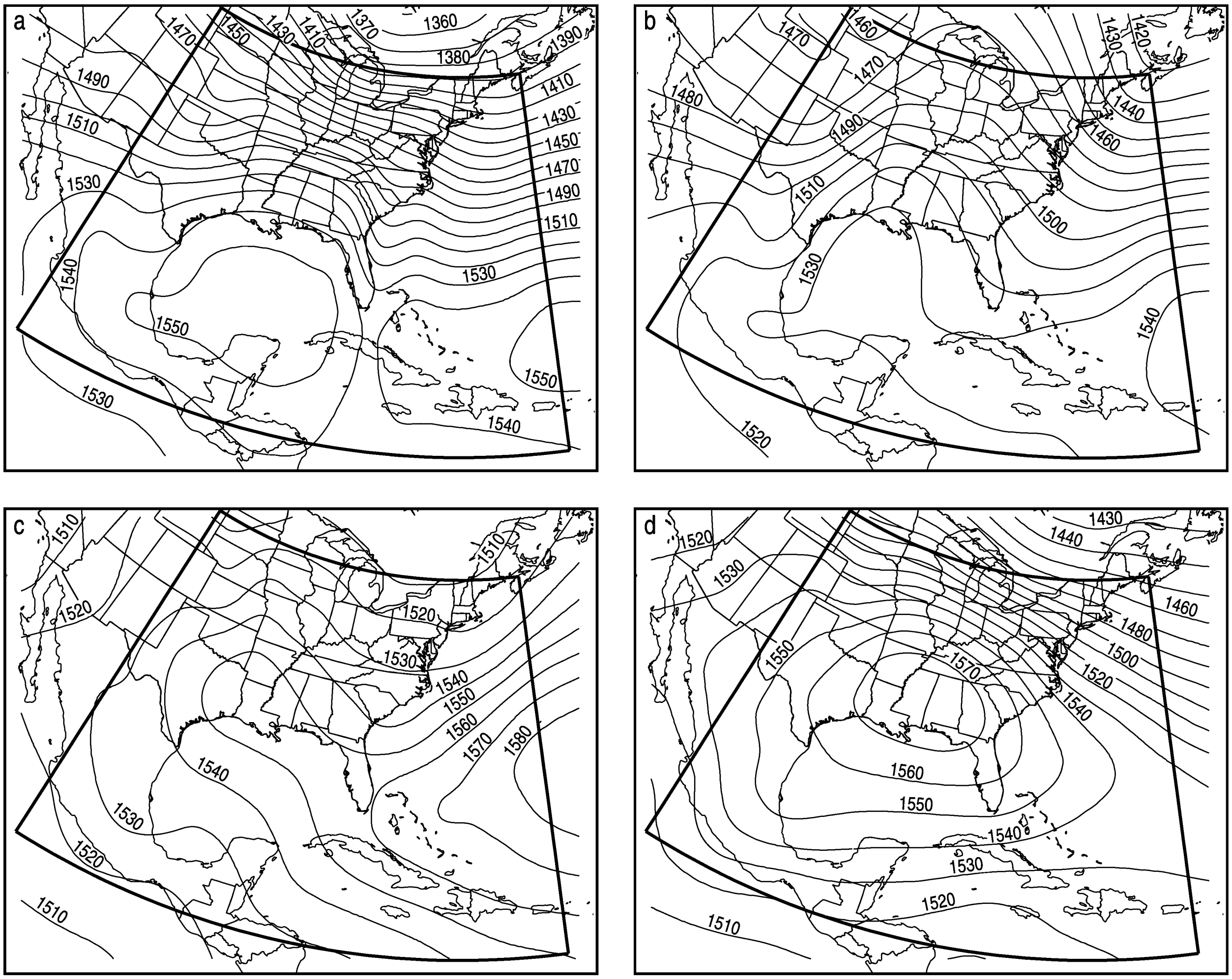

FIG. 8. As in Fig. 7, but by season: (a) winter (DJF), (b) spring (MAM), (c) summer (JJA), and (d) autumn (SON).

spatial patterns of the loadings after varimax rotation are depicted in Figs. 9a–c. The patterns are nearly identical to those at the 850-hPa level. The first component again shows a very prominent ridge over the southern Great Plains with troughs over western North American and the western Atlantic basin. Component 2 is associated with anomalously high heights over the Caribbean and low heights over the northern part of the study domain, suggesting zonal flow across the study area. The third component reveals an intense ridge over the eastern United States. The first and third components display significantly increasing scores over the study period.

Standardized O_3 mixing ratios show significant correlations to rotated PCA-generated scores for all three of the above patterns at all 28 sites in Louisiana (Table 1). Because O_3 is correlated positively with the first pattern and negatively with the third, it seems that the increasing prominence of these two patterns (revealed by their significantly increasing scores over time) resulted in the observed number of high-O_3 days throughout the study period. In specific terms, the increasing prominence of the pattern displayed in Fig. 9a created favorable conditions for high O_3. However, that tendency may have been somewhat offset by the increasing prominence of the pattern displayed in Fig. 9c, which advected flow from the Gulf of Mexico and had a cleansing effect on the atmosphere. From these patterns, it appears that 700-hPa flow from Texas directly contributes little O_3 advection toward Louisiana. However, the subsidence suggested by Louisiana's position on the ridge-to-trough side of the 700-hPa wave in Fig. 9a, combined with the near-surface advection from southeastern Texas suggested by the vertical synoptic correlation at the three levels, may explain the O_3 anomalies.

On SAODs, a very similar composite flow pattern to that observed at 850-hPa occurs (Fig. 10). A prominent ridge axis exists slightly west of the Mississippi River, with very weak height gradients south of Arkansas and much stronger gradients north of Arkansas. The first component again shows significantly positive mean scores on SAODs, and the second again shows significantly negative scores (Table 2). Therefore, the 700-

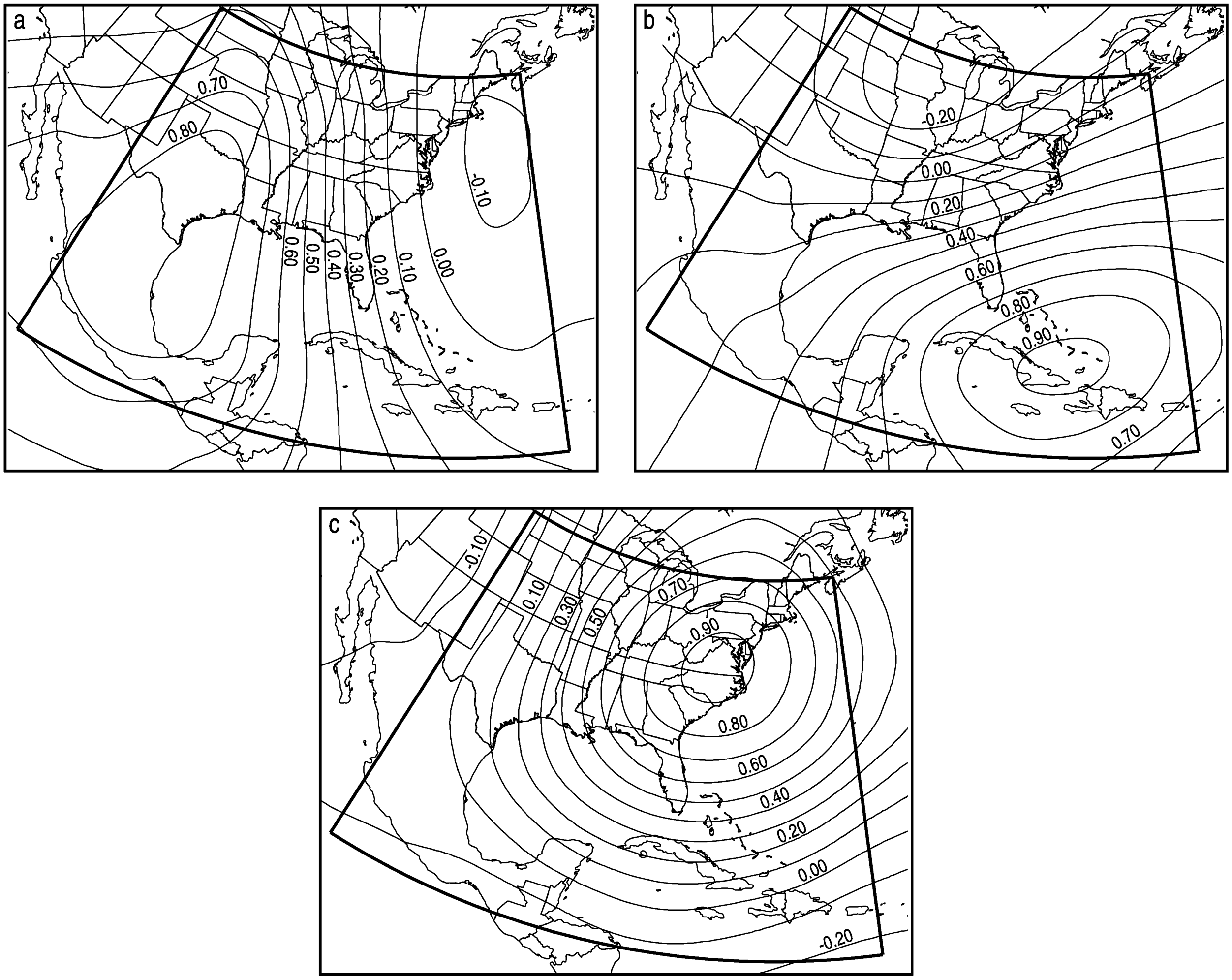

FIG. 9. Spatial pattern of rotated PCA loadings based on monthly standardized daily 700-hPa geopotential heights: (a) component 1, (b) component 2, and (c) component 3.

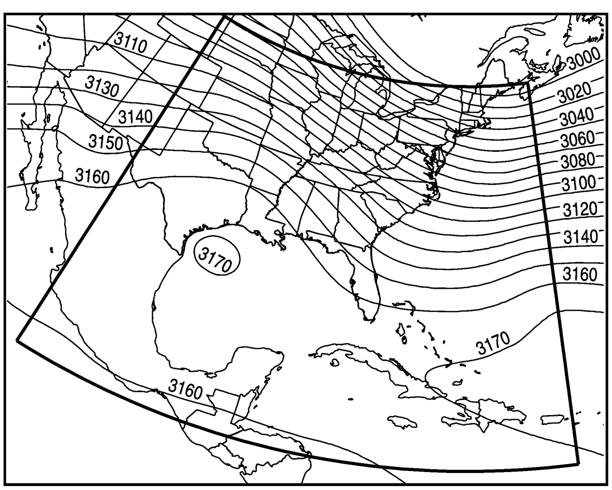

FIG. 10. Composite 700-hPa pattern on the days with anomalously high tropospheric ozone mixing ratios across Louisiana.

hPa analysis corroborates the results identified at the 850-hPa level. Together, the surface, 850- and 700-hPa patterns suggest that both lower-tropospheric subsidence and near–surface level advection from the west tend to be present in SAODs.

As was the case for the 850-hPa level and the surface, the seasonal composites on SAODs (Figs. 11a–d) identify synoptic features similar to that for the overall composite map (Fig. 10). As expected, a decrease in the isohypse gradient is apparent from the cold season to the warm season. Thus, similar synoptic patterns on SAODs exist throughout the year, but the increased isohypse gradient in the cold season may contribute to a greater amount of advection from the west than during the high-sun season.

6. Summary and future work

This research investigated the role of synoptic and local circulations in contributing to tropospheric O_3

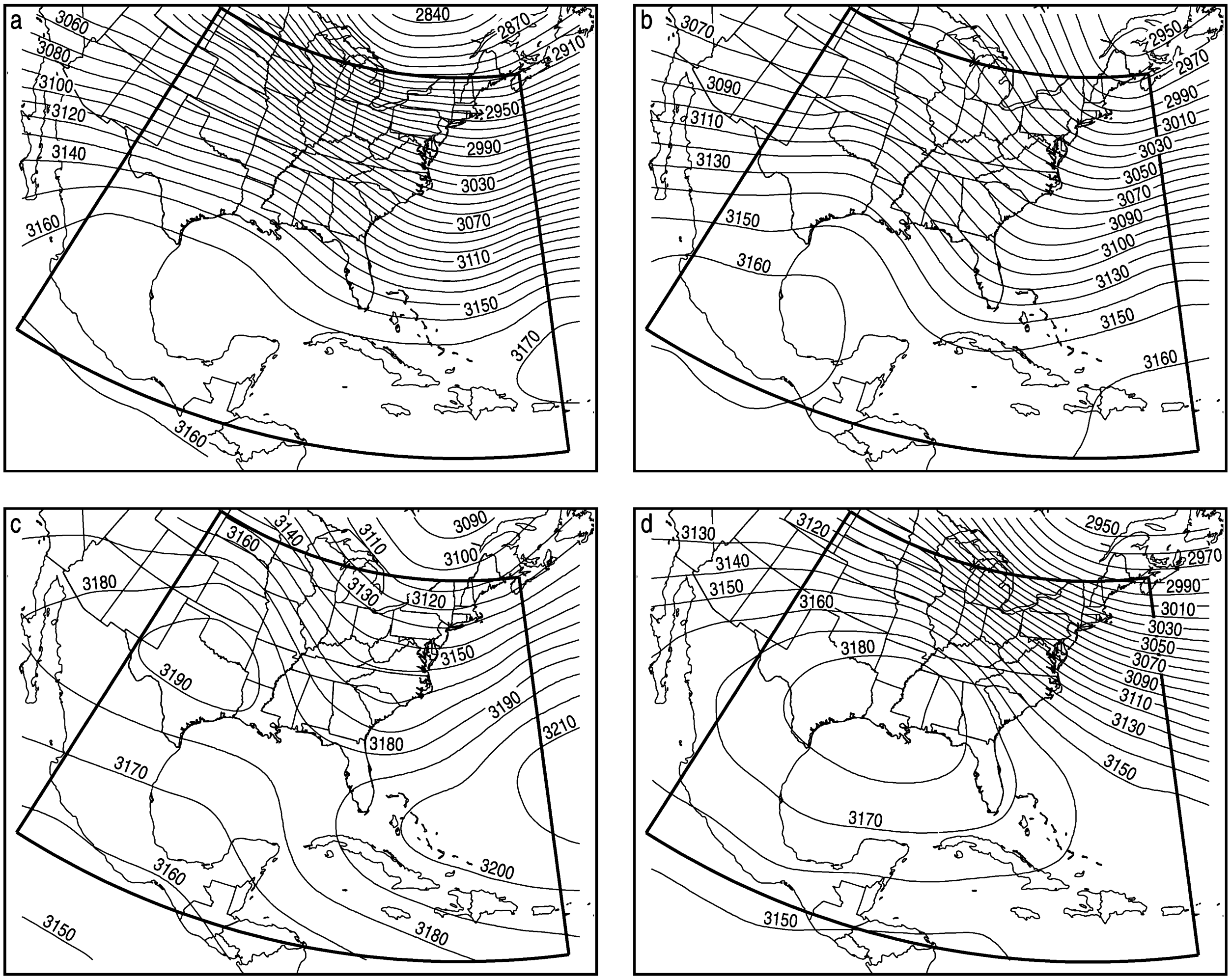

FIG. 11. As in Fig. 10, but by season: (a) winter (DJF), (b) spring (MAM), (c) summer (JJA), and (d) autumn (SON).

mixing ratios in Louisiana. Results suggest that capping inversions/subsidence and, in some cases, surface synoptic-scale advection from the west are important contributors to tropospheric O_3 in Louisiana. Few major differences in the link between O_3 anomalies and synoptic patterns are identified between statewide anomalously high O_3 days and other days. Although drift from the southeastern part of the state is relatively important in contributing to SAODs, slight changes in the direction of drift from southeasterly to southerly can contribute to large differences in O_3 mixing ratios. Persistent surface and lower-tropospheric ridging are probably the main reason that the frequency of SAODs did not decline over the 1994–2001 study period.

Future work must also analyze the role of persistence of quasi-static weakly forced synoptic features on SAODs and consider an ''environment to circulation'' approach (Yarnal 1993) to analyze differences *within* SAODs. More specific, closer investigation of the distinguishing meteorological features of the various types of SAODs must be conducted, perhaps using objective methods. Field measurement of the vertical profile of O_3 mixing ratios during meteorological conditions that are not normally associated with high tropospheric O_3 (such as sea level rotated component 4) would assist in identifying the role of possible stratospheric–tropospheric exchange. In addition, more detailed time series analysis could be employed to identify nonlinear trends in PCA scores. Such an analysis might characterize the role of ENSO, the Pacific decadal oscillation, and other low-frequency teleconnections in pressure–geopotential height variability over the study area. However, the short time series of available data complicate such analyses at this time. Nevertheless, these and other analyses would provide a greater understanding of the forcing mechanisms associated with such events and would afford environmental planners an advantage in formulating policy designed to ensure that Louisiana complies with federal O_3 regulations.

Acknowledgments. The authors gratefully acknowledge the support of the Louisiana Board of Regents

Research Competitiveness Subprogram [LEQSF (2001-04)-RD-A-09] and the cooperation of Brian Blanchard, S. A. Hsu, Michael McDaniel, and Manop Vanichchagorn in the completion of this research. We also thank Clifford Duplechin for cartographic assistance and the anonymous reviewers for their helpful comments.

REFERENCES

Altshuller, A. P., 1986: The role of nitrogen oxides in non-urban ozone formation in the planetary boundary layer over North America, West Europe and adjacent areas of the ocean. *Atmos. Environ.,* **20,** 245–268.

Barna, M., and B. Lamb, 2000: Improving ozone modeling in regions of complex terrain using observational nudging in a prognostic meteorological model. *Atmos. Environ.,* **34,** 4889–4906.

Buell, C. E., 1975: The topography of empirical orthogonal functions. *Proc. Fourth Conf. on Probability and Statistics in Atmospheric Science,* Tallahassee, FL, Amer. Meteor. Soc., 118.

——, 1979: On the physical interpretation of empirical orthogonal functions. *Proc. Sixth Conf. on Probability and Statistics in Atmospheric Science,* Boston, MA, Amer. Meteor. Soc., 112–117.

Cattell, R. B., 1966: The scree test for the number of factors. *Multivariate Behav. Res.,* **1,** 245–276.

Chang, F. C., and E. A. Smith, 2001: Hydrological and dynamical characteristics of summertime droughts over U.S. Great Plains. *J. Climate,* **14,** 2296–2316.

Cheng, S. Q., and K. C. Lam, 2000: Synoptic typing and its application to the assessment of climatic impact on concentrations of sulfur dioxide and nitrogen oxides in Hong Kong. *Atmos. Environ.,* **34,** 585–594.

Chock, D. P., S. Kumar, and R. W. Herrmann, 1982: An analysis of trends in oxidant air quality in the South Coast Air Basin of California. *Atmos. Environ.,* **16,** 2615–2624.

Comrie, A. C., 1990: The climatology of surface ozone in rural areas: A conceptual model. *Prog. Phys. Geogr.,* **14,** 295–316.

——, 1992: An enhanced synoptic climatology of ozone using a sequencing technique. *Phys. Geogr.,* **13,** 53–65.

——, and B. Yarnal, 1992: Relationships between synoptic-scale atmospheric circulation and ozone concentrations in metropolitan Pittsburgh, Pennsylvania. *Atmos. Environ.,* **26B,** 301–312.

——, and E. C. Glenn, 1998: Principal component-based regionalization of precipitation regimes across the southwest United States and northern Mexico, with an application to monsoon precipitation variability. *Climate Res.,* **10,** 201–215.

Ellis, A. W., M. L. Hildebrandt, W. H. Thomas, and H. J. S. Fernando, 2000: Analysis of the climatic mechanisms contributing to the summertime transport of lower atmospheric ozone across metropolitan Phoenix, Arizona, USA. *Climate Res.,* **15,** 13–31.

Fovell, R. G., 1997: Consensus clustering of U.S. temperature and precipitation data. *J. Climate,* **10,** 1405–1427.

Greene, J. S., L. S. Kalkstein, H. Ye, and K. Smoyer, 1999: Relationships between synoptic climatology and atmospheric pollution at 4 U.S. cities. *Theor. Appl. Climatol.,* **62,** 163–174.

Groisman, P. Y., and D. R. Easterling, 1994: Variability and trends of total precipitation and snowfall over the United States and Canada. *J. Climate,* **7,** 184–205.

Heidorn, K. C., and D. Yap, 1986: A synoptic climatology for surface ozone concentrations in southern Ontario, 1976-1891. *Atmos. Environ.,* **20,** 695–703.

Hsu, S. A., B. W. Blanchard, J. M. Grymes, and R. V. Rohli, 2000: Development of short-range projection of the air quality index for the Baton Rouge area. Louisiana Department of Environmental Quality, 49 pp.

Jiang, G. F., B. Lamb, and H. Westberg, 2003: Using back trajectories and process analysis to investigate photochemical ozone production in the Puget Sound region. *Atmos. Environ.,* **37,** 1489–1502.

Keables, M. J., 1988: Spatial associations of midtropospheric circulation and upper Mississippi river basin hydrology. *Ann. Assoc. Amer. Geogr.,* **78,** 74–92.

Legates, D. R., 1991: The effect of domain shape on principal components analysis. *Int. J. Climatol.,* **11,** 135–146.

Leighton, R. M., and E. Spark, 1997: Relationship between synoptic climatology and pollution events in Sydney. *Int. J. Biometeor.,* **41,** 76–89.

Lennartson, G. J., and M. D. Schwartz, 1999: A synoptic climatology of surface-level ozone in eastern Wisconsin, USA. *Climate Res.,* **13,** 207–220.

Lettenmaier, D. P., E. F. Wood, and J. R. Wallis, 1994: Hydro-climatological trends in the continental United States, 1948–88. *J. Climate,* **7,** 586–607.

McGregor, G. R., and D. Bamzelis, 1995: Synoptic typing and its application to the investigation of weather air-pollution relationships, Birmingham, United Kingdom. *Theor. Appl. Climatol.,* **51,** 223–236.

McKendry, I. G., 1994: Synoptic circulation and summertime ground-level ozone concentrations at Vancouver, British Columbia. *J. Appl. Meteor.,* **33,** 627–641.

Moody, J. L., S. J. Oltmans, H. Levy, and J. T. Merrill, 1995: Transport climatology of tropospheric ozone: Bermuda, 1988–1991. *J. Geophys. Res.,* **100,** 7179–7194.

Muller, R. A., 1977: A synoptic climatology for environmental baseline analysis: New Orleans. *J. Appl. Meteor.,* **16,** 20–33.

O'Hare, G. P., and R. Wilby, 1995: A review of ozone pollution in the United Kingdom and Ireland with an analysis using Lamb weather types. *Geogr. J.,* **161,** 1–20.

Rao, S. T., I. G. Zurbenko, R. Neagu, P. S. Porter, J. Y. Ku, and R. F. Henry, 1997: Space and time scales in ambient ozone data. *Bull. Amer. Meteor. Soc.,* **78,** 2153–2166.

Richman, M. B., 1986: Rotation of principal components. *J. Climatol.,* **6,** 293–335.

Rohli, R. V., and K. G. Henderson, 1997: Winter anticyclone changes on the central Gulf Coast of the U.S.A. *Int. J. Climatol.,* **17,** 1183–1193.

——, S. A. Hsu, B. W. Blanchard, and R. L. Fontenant, 2003: Short-range prediction of tropospheric ozone concentrations and exceedances for Baton Rouge, Louisiana. *Wea. Forecasting,* **18,** 371–383.

Ryan, W. F., R. R. Dickerson, G. J. Huffman, and W. T. Luke, 1992: Tropospheric chemistry over the lower Great Plains of the United States. 1. Meteorology. *J. Geophys. Res.,* **97,** 17 963–17 984.

Seinfeld, J. H., 1989: Urban air pollution: State of science. *Science,* **243,** 745–752.

Shahgedanova, M., T. P. Burt, and T. D. Davies, 1998: Synoptic climatology of air pollution in Moscow. *Theor. Appl. Climatol.,* **61,** 85–102.

University Corporation for Atmospheric Research, cited 2002: Northern Hemisphere octagonal grid data. [Available online at http://www.dss.ucar.edu.]

Vega, A. J., 1994: The influence of regional-scale circulation on precipitation variability in the southern United States. Ph.D. dissertation, Louisiana State University, 280 pp.

Walsh, J. E., M. B. Richman, and D. W. Allen, 1982: Spatial coherence of monthly precipitation in the United States. *Mon. Wea. Rev.,* **110,** 272–286.

White, D., M. Richman, and B. Yarnal, 1991: Climate regionalization and rotation of principal components. *Int. J. Climatol.,* **11,** 1–25.

Yarnal, B., 1993: *Synoptic Climatology in Environmental Analysis: A Primer.* Belhaven Press, 195 pp.