An ozone climatology: relationship between meteorology and ozone in the southeast United States

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Abstract: A statistical analysis of ozone (O_3) concentrations and meteorological parameters was performed to determine the relationship between meteorological changes and ambient O_3 concentrations in the Southeast United States. The correlation between average daily maximum O_3 concentration and various meteorological variables was analyzed on a monthly basis from April through October during 1980-1994. The correlations were strongest during the summer months, particularly June, July, and August. Analysis of long term O_3 concentration trends indicates increasing trends during the 1980s and decreasing trends during the early 1990s.

Keywords: ozone; climatology; seasonal trends; meteorological variables; regional analysis.

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1 Introduction

Photochemical oxidants such as O_3 in the troposphere may be responsible for damage to plants, decline of forests both in the Southeast USA and in Europe (Schutt and Cowling, 1985; Woodman and Cowling, 1987) and crop damage in the USA (Heck et al., 1982; Logan, 1985). Elevated O_3 exposure causes changes in lung capacity, flow resistance and bronchial efficiency in humans (Logan, 1985; Lippmann, 1989). In addition, tropospheric O_3 is a greenhouse gas and can lead to global warming by trapping infrared radiation emitted by the earth's surface (National Research Council, 1991). Although it has been shown that the concentrations of ozone precursors such as NO_x ($NO_x = NO + NO_2$) and hydrocarbons have decreased with respect to time in recent years (Logan, 1985), ambient concentrations of O_3 have failed to fall below the NAAQS and in fact have increased in several areas (Aneja et al., 2000; Logan, 1985; Walker, 1985; Oltmans and Komhyr, 1986; Rao et al., 1996; Volz and Kley, 1988). Implementing a plan for urban areas to meet the EPA's guidelines for O_3 attainment continues to be a problem, particularly in the southeastern USA where vast spans of natural forest areas emit greater concentrations of biogenic hydrocarbons than in other areas of the country.

2 Experimental methods

Ozone records were studied during the photochemically active season (i.e., April–October) for a 15 year period from 1980–1994 at nine sites located in and around five major cities in the Southeastern USA (i.e., Atlanta, GA; Charlotte, NC; Nashville, TN; Raleigh, NC; and Greensboro, NC). Meteorological data include daily maximum temperature, and daily averages (from 10:00 am to 4:00 pm only) for wind speed, wind direction, temperature, pressure, dewpoint temperature, dewpoint temperature depression, and relative humidity. The effects of lower tropospheric stability and regional high pressure stagnation on O_3 concentrations were also studied.

Ozone data was retrieved from the USEPA Aerometric Information Retrieval System (EPA-AIRS) database in Research Triangle Park, NC. Meteorological data were retrieved from the Air Force Combat Climatology Center (AFCCC) located at Scott AFB, IL.

The complete data set was scrutinised to ensure that >85% data capture efficiency was achieved for the entire period of study, each ozone season (April–October) during 1980–1994. The Pasquill Index (Pasquill, 1961) was used to characterise lower tropospheric stability. High pressure stagnation was based on a modification to Korshover's (1976) definition. A stagnation day was determined from hourly surface observations with mean sea level pressure greater than 1,014 mb, surface wind speed less than 8 knots (~4.1 m/s), less than 5/8ths cloud coverage, and only short lived (<2 hours) convective shower activity. Stagnation count indicates the consecutive number of days meeting stagnation day criteria; a stagnation event requires four consecutive days meeting the stagnation day criteria.

The complete data-set was divided into 105 (7 × 15) smaller data subsets, each one representing the data for one month of one year throughout the study period. In cases, data gaps present in the complete data-set became more pronounced when the data-set was broken down into smaller subsets since there were cases in which nearly an entire month of data was missing for a given site. Consequently, each of these 105 data subsets was scrutinised to ensure that it contained at least 80% of the data site-days possible to exist for the period. That is, for each April, June, and September the maximum possible data site-days was 270 (9 sites × 30 days), while for each May, July, August, and October the maximum possible was 279 (9 sites × 31 days) data site-days. Elimination of those data subsets that had less than 80% data capture efficiency resulted in the loss of 9 of the 105 data subsets, resulting in 96 data subsets with >80% data capture efficiency.

Monthly means for maximum daily O_3 and each of the meteorological parameters were computed for each month during each year of the study. Correlation coefficients were then calculated between the monthly means for maximum daily O_3 and the monthly means for each of the meteorological parameters, to provide a quantitative estimate of the association between the two data-sets, similar to an analysis performed by Vukovich (1994). Note that no more than fifteen (one for each year in the study, less years deleted due to data capture efficiency falling below 80%) pairs (one each of O_3 variable and meteorological variable) of numbers are represented in each of the Pearson correlation coefficients presented in the discussion text that follows. In order to be statistically significant at the 95% confidence level with $n = 15$, the absolute value of the Pearson correlation coefficient must be greater than 0.515. Boldface type in the tables throughout the paper highlights the statistically significant Pearson correlation coefficients, while the correlation coefficients that are not statistically significant are given standard typeface.

3 Discussion

3.1 Climatological analysis

This study focuses on attempting to gain an understanding of what combination of external influences (Table 1) lead to O_3 exceedences in atmospheric air quality, as defined by the US Environmental Protection Agency (EPA). Nine sites throughout the Southeast USA were analysed for O_3 and meteorological trends during a 15 year climatology (1980–1994). Means and interannual variability are presented in an attempt to discern the relationship between the meteorology and the ambient O_3 concentration. The effect of stagnating high-pressure systems is studied using Korshover's (1976)

definition of high pressure stagnation, as well as our own surface observation-based stagnation parameter. The relationship between O_3 and stability was also studied using the Pasquill Stability Index.

Table 1 Correlation coefficients between daily average maximum O_3 concentration and meteorological variables by month

	Month (n)						
Parameter	*April* (14)	*May* (13)	*June* (14)	*July* (14)	*August* (15)	*September* (15)	*October* (11)
Max. temp. (°F)	0.53	0.17	0.68	0.83	0.94	0.42	0.19
Average temp. (°F)	0.32	–0.11	0.24	0.66	0.91	0.04	–0.04
Wind speed (knots)	–0.19	–0.32	0.12	–0.23	–0.10	–0.63	0.07
Relative humidity (%)	–0.53	–0.39	–0.85	–0.85	–0.90	–0.52	–0.45
Dewpoint temp. (°F)	0.02	–0.23	–0.50	–0.08	0.61	–0.24	–0.19
Dewpoint depression (°F)	0.56	0.43	0.87	0.85	0.92	0.53	0.47
Pressure (mb)	–0.05	–0.26	0.45	0.02	–0.40	–0.42	0.70
Average Pasquill Index	0.63	0.79	0.44	0.79	0.50	0.49	0.34
Minimum Pasquill Index	–0.77	–0.62	–0.77	–0.88	–0.77	–0.64	–0.59
Stagnation parameter	0.37	0.70	0.35	0.50	0.35	0.62	0.42
Stagnation events	0.52	0.62	0.02	0.21	0.19	0.40	0.18
Stagnation count	0.53	0.69	0.34	0.38	0.32	0.54	0.38

Unless otherwise indicated, the parameters are averages based on hourly observations from 10:00 a.m. to 4:00 p.m. EST. The number in parentheses after each month's name indicates the number of pairs of averages that went into the calculation of each correlation coefficient.

Many researchers (Korshover, 1976; Vukovich, 1994; Warmbt, 1979; Wolff et al., 1977; Aneja et al., 1994, 2001) have noted the correlation between higher temperatures and higher ambient O_3 concentrations. As shown in Table 1, the correlation between daily maximum temperature and daily maximum O_3 for this data-set is very strong during June–August, while the correlation is much lower during the other months. Meteorological conditions during these months produce the greatest amount of photochemical activity in the region, which results in more O_3 formation. In addition, this study found relatively dry conditions for a given month, compared to the same month in other years, are well correlated with higher ambient O_3 concentrations.

Lower tropospheric stability is also significantly correlated with occurrences of high O_3. Lindsay and Chameides (1988) and Chu and Doll (1991) point out that high O_3 events occur when convection is suppressed. The minimum daily Pasquill Index demonstrates strong negative correlation for all months in the study, indicating that instability resulting from strong solar radiation and low wind speed is correlated with

increased O_3. However, the average daily Pasquill Index is positively correlated with O_3 concentration. The seemingly contradictory correlations arising from considering two different interpretations of the Pasquill stability index could indicate that a short time of moderate instability can lead to elevated O_3 levels while extended periods of instability are likely to result in thunderstorms which would in turn wash out the precursors to O_3 before it (O_3) can be formed. In addition, extended periods of instability may tend to ventilate the lower troposphere due to larger mixing heights, resulting in lower concentrations near the surface. McNider et al. (1993) noted a peculiarity similar to ours: that maximum surface O_3 concentrations were highest near an old frontal boundary in an area of convective instability. He measured relatively high O_3 in Atlanta coincident with regional scale deep convective mixing, generally thought to be destructive of high O_3 concentrations at the surface. Other researchers (Logan, 1989; Lindsay and Chameides, 1988; Vukovich, 1994) note that elevated O_3 levels are most often found on the back side of weak, slow moving, persistent high pressure systems; summertime convective activity in the Southeast USA is often embedded in weak high pressure systems along an old frontal boundary.

Research has shown that high O_3 episodes are associated with persistent high pressure systems (Buntz et al., 1974; Stasuik and Coffey, 1974; Ludwig et al., 1977; Vukovich et al., 1977; Ripperton et al., 1977; Wolff et al., 1977; Vukovich, 1979; Wolff and Lioy, 1980; Chu and Doll, 1991; Lindsay and Chameides, 1988; Logan, 1989; Vukovich, 1994). However, average mean sea level pressure does not show significant correlation with O_3 for this data. Instead, O_3 concentration was found to be moderately associated with high-pressure stagnation, consistent with Chu and Doll's findings (1991) and with Logan's findings (1989) that half of O_3 episodes occurred during high pressure stagnation, as defined by Korshover (1976). Table 1 shows that positive correlation exists between each stagnation parameter (day, count, and event) and O_3 concentration for every month in the study, although only a few months are statistically significant.

3.2 Seasonal analysis

Averages for the season consisting of the months of July and August were computed and compared with the results obtained by Vukovich (1994). Strong positive correlation with O_3 was found for temperature (both daily maximum and daily average; $r = 0.94$ and $r = 0.87$, respectively), dewpoint temperature depression ($r = 0.91$), average Pasquill Index ($r = 0.76$), and stagnation count ($r = 0.54$). Strong negative correlation with O_3 was found for relative humidity ($r = -0.90$) and minimum Pasquill Index ($r = -0.88$). Table 2 demonstrates that the results obtained here are very similar to Vukovich's results. Recall that the Pasquill Stability Index is not only a measure of tropospheric stability, but also a measure of sky cover since the index is based primarily on incoming solar radiation and wind speed. Therefore, comparison of the minimum Pasquill Stability parameter with Vukovich's sky cover parameter yields consistent results. The analysis of mean sea level pressure performed here did not yield the same results as Vukovich's analysis, however the analysis of high pressure stagnation and stagnation 'count' does yield results similar to Vukovich's. Our results are consistent with those of Korshover (1976), Vukovich et al. (1977), King and Vukovich (1982), Mukammal et al. (1982), Meagher et al. (1987) and Chu and Doll (1991). The absolute pressure is not necessarily as good of a predictor of O_3 concentrations as is the persistence of high pressure, commonly called 'high pressure stagnation'. As high

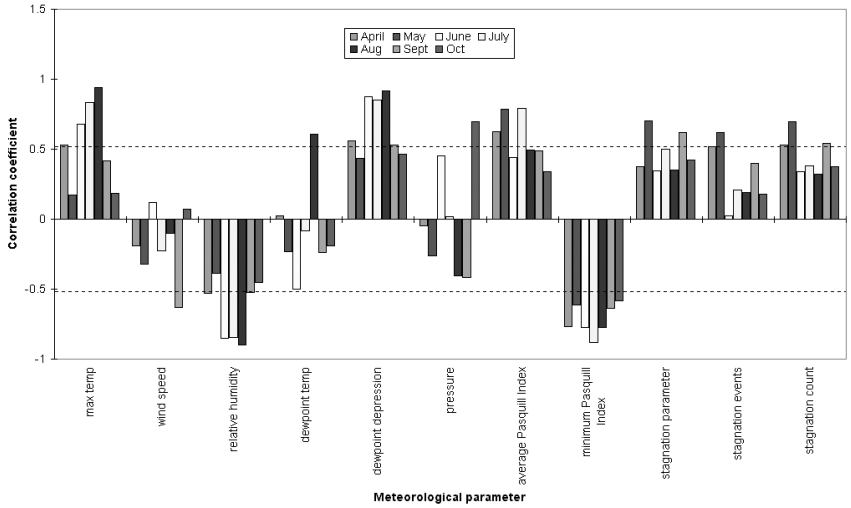
pressure persists, O_3 levels continue to rise from one day to the next due to the increased photochemistry that is associated with the clear skies, light winds, and warm temperatures under the high pressure.

Table 2 Comparison between correlation coefficients found by Vukovich and those found in this work. Results are based on a two-month ozone season (July and August only)

	Researcher	
Parameter	*Vukovich*	*This work*
Temperature	0.91	0.94
Pressure		
Mean sea level pressure	0.33	–0.30
High pressure stagnation	–	0.49
Stagnation 'count'	–	0.54
Wind speed	–0.42	–0.14
Solar radiation		
Sky cover	–0.87	–
Min. Pasquill Index	–	–0.88
Atmospheric moisture		
Dewpoint temperature	0.31	0.25
Dewpoint temp. Depression	–	0.91
Relative humidity	–	–0.90
Precipitation	–0.91	–

Ozone season length was extended to 3–7 months by adding June, September, May, April, and October, respectively to the previous season length's analysis. As months were added, the correlation between O_3 and the meteorological parameters became less obvious for each of the parameters that were previously determined to demonstrate very high correlation coefficients (Figure 1). Statistically significant positive and negative correlation coefficients in Figure 1 are highlighted by the bars that cross the dashed horizontal lines drawn at 0.515 and –0.515. Analysis of days exceeding 0.120 ppmv showed that over 90% of the exceedence days recorded for the data set occurred during June–August. In addition, the correlation between O_3 concentration and the meteorological parameters, when analysed on the monthly basis, was strongest during June, July, and August. This indicates that this three-month 'ozone season' is adequate to capture the meteorological variation present on high ozone days and thus analyse the relationship between ambient O_3 concentrations and meteorological parameters. Consequently, the three month timeframe was used to study the ozone season climatology.

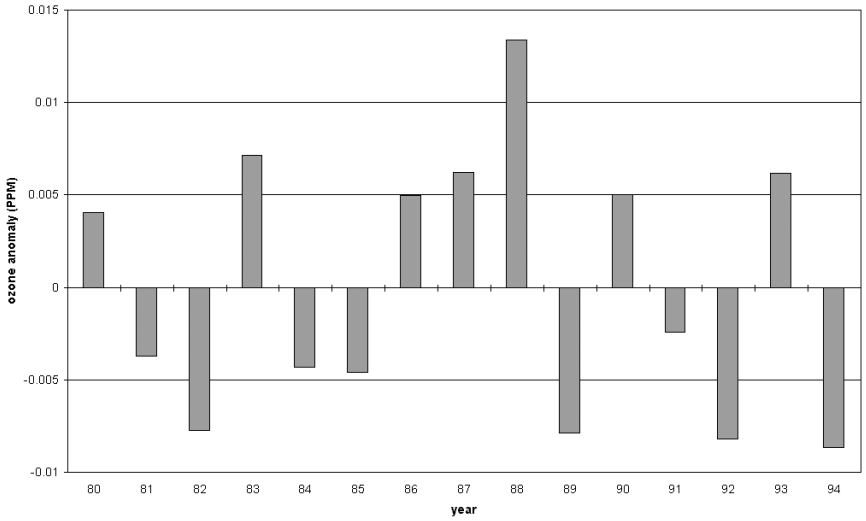
Figure 1 Correlation between daily average maximum ozone concentration and meteorological parameters, by length of ozone season



4 Analysis for the three-month ozone season

The months of June–August define the three-month ozone season, as discussed above. Figure 2 illustrates O_3 anomalies by year for the three-month ozone season, similar to an analysis performed by Vukovich (1994) which were computed by subtracting the climatological average O_3 concentration from the annual average O_3 concentration for each year. The figure indicates that the mean daily maximum O_3 concentration was higher than the climatological average in 1980, 1983, 1986–1988, 1990, and 1993 during the three month period of each of those years.

Figure 2 The anomaly of the surface daily maximum ozone concentration (ppm) for each ozone season (June-August) in the 15-year period averaged over all sites



The anomaly of the average daily maximum temperature correlates best with O_3 concentration ($r = 0.89$) (Figure 3). Among the indicators of atmospheric moisture (Figure 4), relative humidity generally displays negative anomalies while dewpoint temperature depression displays positive anomalies during years which had positive O_3 anomalies, and vice versa. Both relative humidity and dewpoint temperature depression have strong correlations over the three-month ozone season ($r = –0.90$ and $r = 0.92$, respectively). The dewpoint temperature anomalies are much more random in nature and generally smaller than the anomalies for the relative humidity or dewpoint temperature depression, and the correlation between dewpoint and O_3 concentration is not strong ($r = –0.24$). Given that the correlation between O_3 and the minimum Pasquill Stability Index (Figure 5) is stronger than that for the average Pasquill Stability Index ($r = –0.84$ vs. $r = 0.68$), it is therefore a better indicator of high O_3 probability. The stagnation parameters display positive correlations with O_3 concentration (Figure 6). Each of the high-pressure stagnation parameters demonstrates more consistent correlation with O_3 than the mean sea level pressure. For approximately 2/3 of the years analysed, positive (negative) annual deviations for the high pressure stagnation parameters correspond to positive (negative) annual deviations for O_3 concentrations. Logan (1989) reported similar findings, noting that half of high ozone episodes occurred during high-pressure stagnation events, as defined by Korshover (1976).

Figure 3 The anomaly for the daily maximum temperature (°F) for each ozone season (June–August) in the 15-year period averaged over all sites

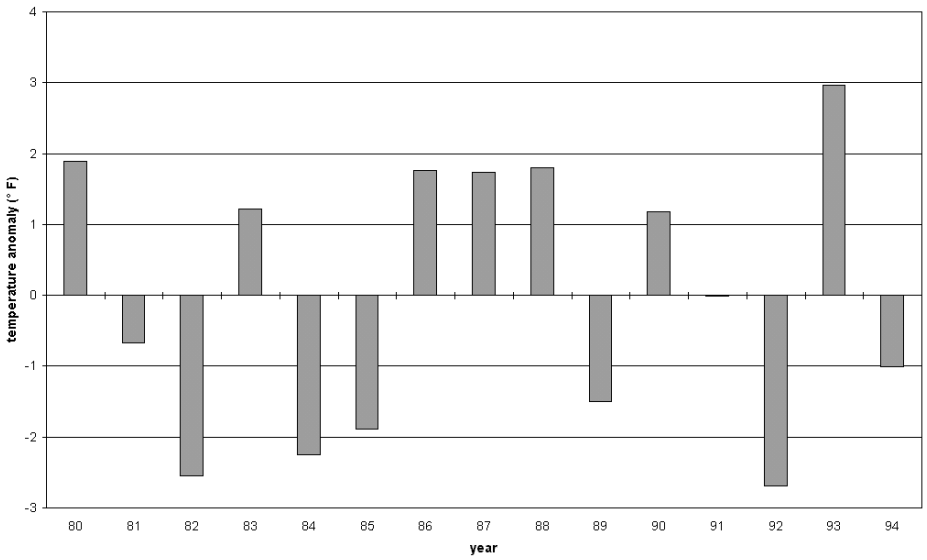


Figure 4 Anomalies for indicators of atmospheric moisture for each ozone season (June–August) in the 15-year study period averaged over all sites

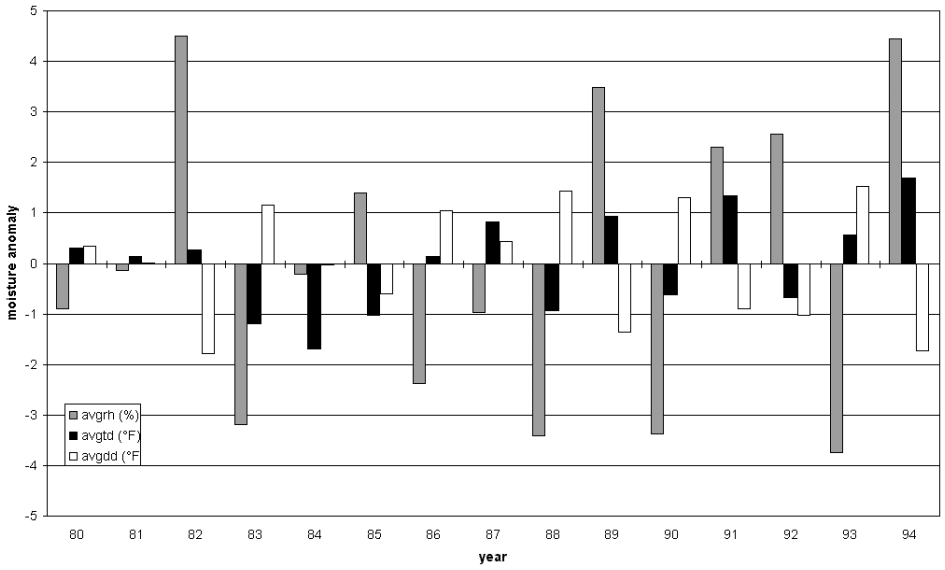


Figure 5 Anomalies for Pasquill Stability Index for each ozone season (June–August) in the 15-year study period averaged over all sites

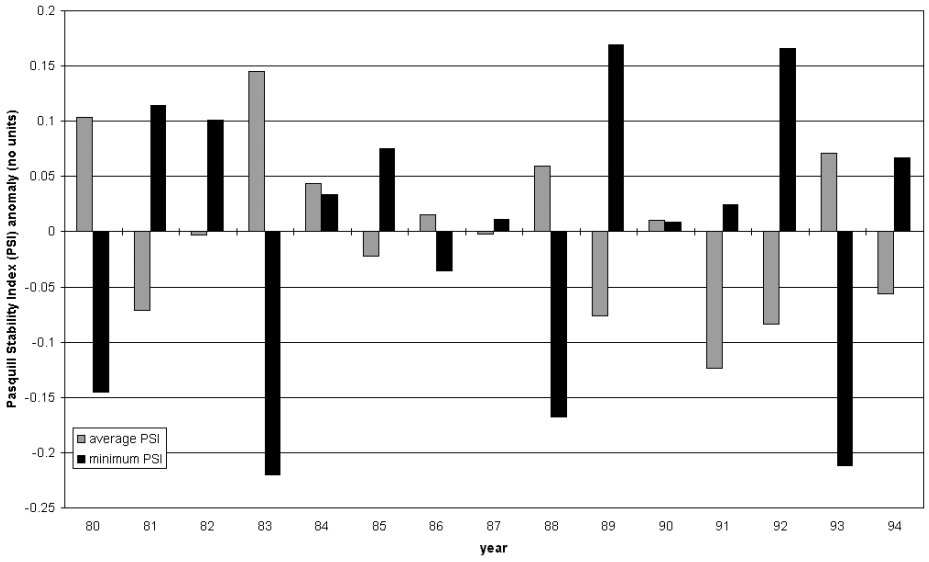
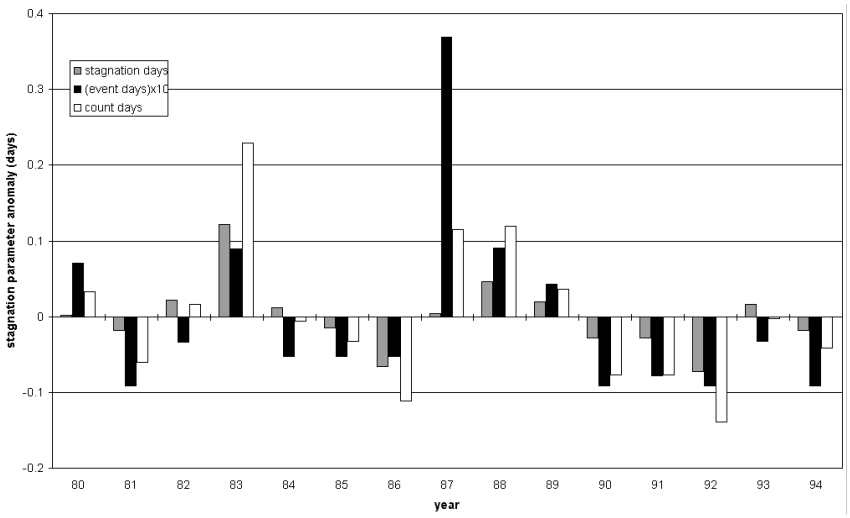


Figure 6 Anomalies for stagnation parameters for each ozone season (June–August) in the 15-year study period averaged over all sites



5 Ozone trends and analysis

Trends for O_3 concentration at each site were determined by simple linear regression of the annually averaged daily maximum O_3 concentration for the three-month season and are presented in Table 3. In general, each site demonstrated an upward trend during the 1980s and a downward trend during the 1990s. Researchers, however, have indicated that trends in ambient O_3 concentrations do not necessarily indicate the effects of O_3 control strategies (Chameides et al., 1988; Lindsay, et al., 1989; Logan, 1989).

Average daily maximum temperature and average daily dewpoint temperature depression both had upward trends in the 1980s (0.07 ± 0.25%/yr. and 0.38 ± 1.60%/yr.) and downward trends in the 1990s (-0.16 ± 0.89%/yr. and -4.88 ± 6.58%/yr., respectively). In addition, the average daily relative humidity trend was downward in the 1980s (-0.05 ± 0.40%/yr.) and upward in the 1990s (1.23 ± 1.60%/yr.). These findings reinforce the likelihood that the fluctuations of meteorological parameters play an important part in the fluctuations of the ambient O_3 concentration.

The trends for the indicators of lower atmospheric stability do not correspond to the trend for O_3 concentration. Recall that the minimum daily Pasquill Index was found to be highly inversely correlated with maximum O_3 concentration, while the average Pasquill Index was strongly positively correlated with O_3 concentration, even though we expected both variations of the parameter to be inversely correlated. However, analysis of the trends for these parameters reveal that the minimum Pasquill Stability Index is positively correlated with the trend in O_3 concentration (0.21 ± 0.52%/yr. in the 1980s,-0.41 ± 1.69%/yr. in the 1990s), while the average daily Pasquill Stability Index is negatively correlated with the trend in O_3 concentration (-0.15 ± 0.17%/yr. in the 1980s, 0.13 ± 0.60%/yr. in the 1990s). An explanation for this apparent reversal of correlation is not readily apparent; further analysis is necessary to determine how atmospheric stability is correlated with ambient O_3 concentrations and their trends, and which parameter is best suited to represent the correlation.

Table 3 Trends for daily maximum O_3 concentration for nine urban and semi-urban sites in the Southeast USA

Site	*Trend in daily maximum ozone concentration*					
Site code	*1980–1989*			*1990–1994*		
Location Lat. (°N)/Long (°W) Elevation (m)	Avg. daily max. conc. (ppbv)	Trend (ppbv/yr)	Trend (%/yr.)	Avg. daily max. conc. (ppbv)	Trend (ppbv/yr.)	Trend (%/yr.)
ATL089 Atlanta, GA 33.691/84.273 305	73.9	0.91 ± 1.20	1.23 ± 1.63 1.7 ± 1.6*	71.3	–4.15 ± 3.26	–5.82 ± 4.57
ATL247 Atlanta, GA 33.586/84.067 219	74.3	1.09 ± 0.97	1.47 ± 1.31 0.3 ± 1.5*	75.3	–3.32 ± 2.95	–4.40 ± 3.91
BNA037 Nashville, TN 36.205/86.745 165	57.5	–0.02 ± 1.25	–0.04 ± 2.18	52.3	–1.43 ± 2.55	–2.73 ± 4.88
BNA165 Nashville, TN 36.298/86.653 143	71.5	2.40 ± 0.68	3.36 ± 0.95	76.2	–0.46 ± 2.25	–0.60 ± 2.96
CLT119H Charlotte, NC 35.247/80.764 239	73.9	0.47 ± 0.79	0.63 ± 1.07	70.4	– 1.92 ± 2.17	– 2.73 ± 3.08
CLT119I Charlotte, NC 35.113/80.919 195	71.6	0.39 ± 1.16	0.55 ± 1.62	67.5	– 3.00 ± 2.43	– 4.45 ± 3.60
CLT119J Charlotte, NC 35.348/80.693 255	77.4	–0.27 ± 0.95	–0.35 ± 1.23	74.5	– 2.42 ± 2.37	– 3.25 ± 3.19
GSO081 Greensboro, NC 36.113/79.704 229	70.9	0.40 ± 0.86	0.56 ± 1.21	69.4	–0.40 ± 2.93	–0.57 ± 4.22
RDU183 Raleigh, NC 35.971/78.491 87	71.0	see text	see text	66.0	see text	see text
Entire region Avg.	71.3	0.45 ± 0.83	0.64 ± 1.17	69.3	–1.87 ± 2.34	–2.69 ± 3.37

The trends for Atlanta sites marked with an asterisk (*) are those determined by Lindsay et al. (1989) at the same sites for the period 1979–1987.

6 Analysis of stagnation

Korshover (1976), using a pressure gradient technique as a basis of determining areas of stagnation, related high-pressure stagnation with occurrences of high O_3 concentration, particularly in the Southeast USA. Using the same criteria, Korshover and Angell (1982–1985, and 1987) reported annual summaries of the high-pressure stagnation through 1985. Through personal communication with Angell (November 1995), the raw data indicating which grid points met the Korshover stagnation criteria for days during 1980–1984 were obtained.

The stagnation parameter (as defined here) demonstrated positive correlation with daily maximum O_3 concentration ($r = 0.07$ to $r = 0.70$) for all sites (Table 4). The count parameter also showed similar correlations for each site, demonstrating slightly stronger correlation with O_3 concentration ($r = 0.14$ to $r = 0.76$) than the basic stagnation parameter did for most sites. Neither site in Atlanta had any occurrences meeting stagnation event criteria, therefore correlations for that parameter for those sites could not be calculated. However, the remaining sites all showed positive correlation between meeting event criteria and O_3 concentration; with correlation coefficients ranging from $r = 0.09$ to $r = 0.78$. Korshover's stagnation event parameter generated very strong positive correlations for all sites except the Nashville site (BNA165, $r = 0.10$); the range of correlation coefficients for the other sites was $r = 0.50$ to $r = 0.99$. The homogeneity of the correlation coefficients was tested across sites for each parameter. The χ^2 test of homogeneity failed to find statistically significant differences between sites for each of the parameters' correlation coefficients. Upon verification that each parameter gave statistically equivalent correlation coefficients across sites, another test was performed to determine if the correlation coefficients between O_3 and each of the stagnation parameters determined for the seasonal analysis were statistically equivalent. All four of the stagnation parameters were compared and found to be statistically equivalent. In addition, each of the stagnation parameters defined in this work were compared to Korshover's stagnation event parameter on a one-to-one basis, with the result that each of them is independently statistically equivalent to Korshover's parameter.

Table 4 Correlation coefficients comparing two methods of defining high-pressure stagnation, based on a three month ozone season

		Parameter			
Site	*n*	*Stagnation parameter*	*Stagnation event*	*Stagnation count*	*Korshover stagnation*
ATL089	5	0.42	–	*0.56*	*0.79*
ATL247	4	0.11	–	0.30	*0.79*
BNA037	4	*0.70*	0.19	*0.76*	*0.99*
BNA165	4	*0.64*	0.09	0.47	0.10
CLT119H	4	*0.53*	*0.55*	*0.52*	*0.80*
CLT119I	5	0.07	*0.54*	0.14	*0.96*
GSO081	5	*0.63*	0.17	*0.54*	*0.62*
RDU183	5	*0.53*	*0.78*	*0.68*	0.50

The number of days meeting stagnation criteria were plotted for the entire Southeastern US (over 130 sites) and isoplethed to further analyse occurrences of high-pressure stagnation for the region. By simple subjective analysis of the isopleths on the maps, we found that 1983, 1986–1988, 1990, and 1993 generally have more high pressure stagnation days regionwide than a climatologically averaged map. Other years (particularly 1985, 1989, 1991, 1992, and 1994), in general, have fewer than the climatological average of days meeting the high-pressure stagnation criteria. Notice by comparison with Figure 2 that the years with more (fewer) high-pressure stagnation days were previously noted as years that had anomalously high (low) O_3 concentrations throughout the ozone season. Regions with a large number of high pressure stagnation days may also play an important part in determining which years have abnormally high (or low) O_3 concentrations on an average. For example, examination of the high-pressure stagnation maps for 1986–1988 showed that all three years have more than the climatological average overall of high pressure stagnation days and all three years had higher than average O_3 concentrations. However, 1988's O_3 anomaly was much higher than that for either 1986 or 1987. This may be due in part to the fact that the greatest concentration of high pressure stagnation during 1988 was further north in the more industrial states along the Ohio River Valley, while the greatest concentration of high pressure stagnation during 1986 and 1987 was in the less industrial Gulf Coast States. Other authors (Vukovich et al., 1977; Altshuller, 1978; Wolff and Lioy, 1980; King and Vukovich, 1982; Lindsay and Chameides, 1988) have noted that high-pressure stagnation in conjunction with larger emissions of NO_x and VOC's result in high ambient O_3 concentrations. Ozone precursors emitted in more industrial areas may lead to elevated O_3 concentrations in the Southeast US region via transport of the precursors as high pressure systems migrate south and east. Further analysis into the location of concentrated areas of high pressure stagnation and the direction of the high pressure centre's migration may lead to a better understanding of the effect that high pressure stagnation has on increasing ambient O_3 concentrations.

7 Conclusions

An extensive statistical analysis of O_3 concentrations and relevant meteorological parameters was performed to examine the relationship between meteorological changes and ambient O_3 concentrations in the Southeast USA. The correlation between average daily maximum O_3 concentration and various meteorological variables was analysed on a monthly basis from April through October during the years from 1980 to 1994. The correlations (both positive and negative) were found to be the strongest during the summer months, particularly June–August. These findings are consistent with others (Warmbt, 1979; Meagher et al., 1987; Logan, 1989; McNider et al., 1993; Vukovich, 1994; Chameides and Cowling, 1995), who noted that O_3 concentrations are highest during periods characterised with warm, dry, and sunny conditions. To verify the hypothesis that a three-month 'ozone season' from June to August of each year adequately defined the period in each year that most O_3 concentrations above the NAAQS occurred in, a seasonal analysis of correlation was also performed for the region. It was also noted that, climatologically, over 90% of the O_3 exceedence site-days for the region occurred during the 'ozone season' from June to August of each year. As the potential ozone season was extended beyond the three month timeframe the

strength of the correlations between O_3 concentration and the meteorological variables diminished slightly, but remained statistically significant. Based on the results obtained from this analysis, future O_3 studies for the Southeast USA should be based on a three month 'ozone season' from June to August of each year. In addition, changes in O_3 concentration are well correlated with changes in meteorological indicators of temperature, lower tropospheric moisture, and lower tropospheric stability. Among the various parameters studied to represent these atmospheric variables, daily maximum temperature, average daily relative humidity, average daily dewpoint temperature depression, and minimum Pasquill Stability Index, were found to demonstrate the strongest correlation.

Although high-pressure stagnation was positively correlated with daily maximum O_3 concentration, the correlation between O_3 concentration and high-pressure stagnation was not found to be statistically significant for those sites analysed during the period of time covered by this study. The high-pressure stagnation parameters used in this analysis were examined further and compared with that defined by Korshover (1976). The correlation between O_3 concentration and each of the parameters was found to agree well for the limited dataset (five years) that was available for intercomparison. Absolute pressure is not necessarily as good predictor of O_3 concentrations as is the persistence of high pressure, commonly called 'high pressure stagnation'. As high pressure persists, O_3 levels continue to rise from one day to the next because of the increased photochemistry that is associated with the clear skies, light winds, and warm temperatures under the high pressure. Analysis suggests that not only the presence of high-pressure stagnation, but also the location of concentrated areas of high-pressure stagnation may play an important role in whether or not ambient O_3 levels are increased. Further study is needed to determine what effect high-pressure stagnation has toward elevating O_3 concentrations above the NAAQS.

Long-term trends of O_3 were also studied. Although statistical significance was not found, O_3 concentrations were found to have increased slightly ($+0.45 \pm 0.83$ ppb/yr., $+0.64 \pm 1.17$%/yr.) during the 1980s and decreased slightly (-1.87 ± 2.34 ppb/yr., -2.69 ± 3.37%/yr.) during the 1990s. The observed trends in O_3 concentration may be caused by reduction of chemical precursor emissions, as brought about by the 1990 Amendments to the Clean Air Act; however, the role of meteorology cannot be ignored. The trends in O_3 concentration correspond very well with trends in meteorological variables calculated for the same sites over the same period. The trend for meteorological variables that demonstrated positive correlation with O_3 concentration (i.e., daily maximum temperature and dewpoint temperature depression) had the same sign as that for O_3 concentration during both decades, while the trend for a meteorological variable that demonstrated negative correlation with O_3 concentration (i.e., relative humidity) had the opposite sign as that for O_3 concentration during both decades. Correlation of trends in O_3 concentration and meteorological variables in this manner reinforces earlier findings that higher ambient O_3 concentrations occur more often during summers that are warmer and drier (Warmbt, 1979; Meagher et al., 1987; Vukovich, 1994; Chameides and Cowling, 1995). However, this study cannot place a causal relationship between the O_3 and meteorological parameters' trends calculated.

The interaction between the meteorology and chemistry that leads to high concentrations of O_3 in the lower troposphere is what makes compliance with the NAAQS for O_3 a challenge. Although exceedences of the NAAQS for O_3 do not result from any one of these relationships, some combination of the meteorological factors,

along with the proper proportions of emissions of O_3's chemical precursors (NO_x and VOC's), will lead to ambient O_3 concentrations in excess of the NAAQS. Further research is needed to determine how the interaction between the chemistry of O_3 precursors and physics of the atmosphere lead to ambient O_3 concentrations that may be hazardous to the health and welfare of plants and animals exposed to high concentrations of O_3.

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