Synoptic-Scale Meteorological Variability and Surface Ozone Concentrations in Vancouver, British Columbia

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(Manuscript received 19 January 1994, in final form 1 June 1994)

ABSTRACT

The Lower Fraser Valley of British Columbia is currently experiencing rapid population growth and episodically suffers elevated oxidant concentrations, the frequency of which is linked to meteorological conditions on the synoptic scale. This study is a first step toward developing and validating a methodology for "declimatizing" air quality data so that postulated effects of changing emissions patterns can be addressed. Principal component analysis of gridded fields at three atmospheric levels (sea level-reduced surface pressure, 850-mb height, and 500-mb height) yields four principal components (or modes of the atmospheric circulation) that account for over 83% of geophysical dataset variance. Daily component scores from these components are used as independent parameters in a regression equation of the daily maximum ozone concentrations at a site (Rocky Point Park) in Vancouver over five summers (1984–88, inclusive). The coefficients in this equation are used to construct another algorithm that is used to predict maximum daily ozone concentrations at this site during the summers of 1989–92 on the basis of synoptic-scale meteorology. The algorithm correctly predicts the low frequency of ozone episodes in the July 1989–July 1992 period but cannot account for the reduction in daily maximum ozone concentrations on nonexceedance days at Rocky Point Park over this period. The implications of these findings are that during the summers of 1989–92 meteorological conditions on the synoptic scale were not conducive to the occurrence of ozone exceedances but that the reduction in average daily maximum ozone concentrations cannot be accounted for on the basis of synoptic-scale meteorological variability as parameterized by the component scores.

1. Introduction

The Lower Fraser Valley (LFV) of British Columbia (BC) is currently experiencing rapid population growth. The metropolitan area of Vancouver, located in the western reaches of the valley (Fig. 1), is the fourth most rapidly expanding city of over 1 million people (in terms of population growth) in Canada and the United States (Greater Vancouver Regional District 1992). The LFV is also perceived to suffer from reduced air quality, specifically, impaired visibility and summertime exceedances of the National Ambient Air Quality Objective (NAAQO) for ozone of 82 ppb. The summer of 1993 saw the continuation of a multiyear, multiagency study into oxidant levels in the LFV (Bottenheim et al. 1993). This study will ultimately contribute to air quality management initiatives and combines detailed and intensive field measurement programs with numerical modeling of mesoscale meteorology and photochemistry. Research efforts such as *The Lower Fraser Valley Oxidant Study* offer highly detailed but temporally limited information, the utility of which may be greatly enhanced by work that addresses conditions on a longer temporal scale.

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Previous studies of air quality in the Vancouver region have shown the following:

1) Ozone concentrations occasionally exceed 82 ppb (e.g., Steyn et al. 1990). The 82 ppb NAAQO was exceeded for at least 1 h at 1 or more of the 24 monitoring sites in the LFV on 70 of the 828 days (8.5%) during July–September, 1984–1992.

2) There is a strong relationship between meteorological conditions on the synoptic scale and daily maximum ozone concentrations in the region (e.g., McKendry 1994).

3) Exceedances of the NAAQO are typically single-day events. McKendry (1994) showed that approximately 60% of the exceedances of the 82 ppb level at Rocky Point Park (Fig. 1) did not have exceedances 1 or 2 days before.

Other studies have further indicated the following:

4) The frequency of occurrence of midlatitude circulation patterns is variable on interannual and interdecadal timescales (e.g., Agee 1991).

5) Variations in synoptic-scale meteorological patterns significantly impact temporal variability of air quality parameters. For example:

(a) The frequency and severity of acid deposition events in northern Europe has been linked to variations in the frequency of Lamb weather

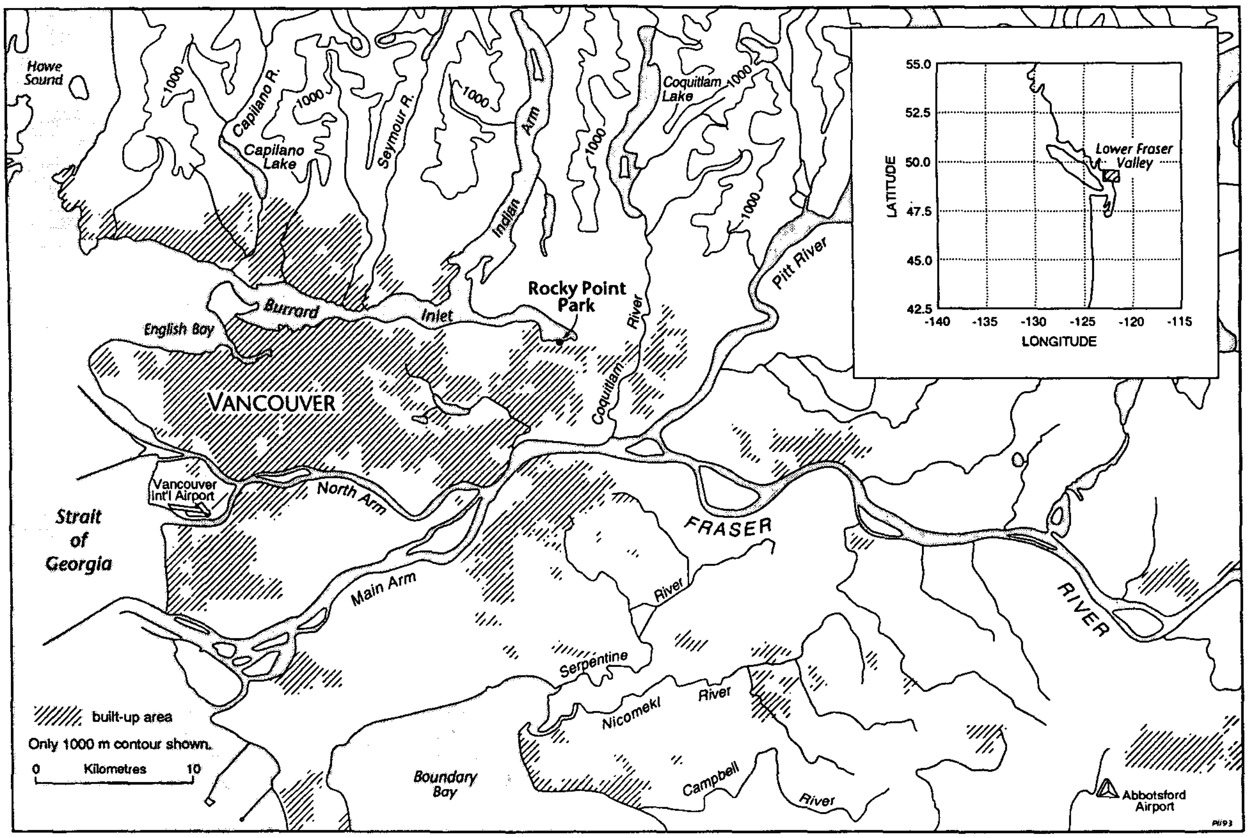


FIG. 1. The location of the Vancouver metropolitan area and Rocky Point Park (RPP) in the Lower Fraser Valley (LFV). The inset shows the domain used in the synoptic typing. The location of the LFV (as depicted in the main frame) is indicated on the inset by the hatched box.

types, leading researchers to suggest that climatic change and synoptic-scale meteorological variability be considered in "the assessment of emission control strategies" implemented to reduce acidic deposition in this region (Davies et al. 1986).

(b) The mean daily surface ozone concentration at a number of rural sites in Europe show significant correlations with "subregional surface pressure gradient" (wind speed index calculated over an area of 5° × 10°), which Davies et al. (1992) define as an "objective indicator of atmospheric circulation."

These conclusions and work by Davidson (1993) in the Los Angeles region prompted this study, which examines the impact of changes in the frequency of dominant atmospheric circulation patterns on ozone concentrations at a site in Vancouver using multivariate statistical techniques. It is a first step toward developing and validating a methodology for removing the influence of large-scale meteorological variability on air quality (specifically daily maximum ozone concentrations at a single site in Vancouver). Such a methodology would aid analysis of the effect of changing emissions patterns, such as might occur as a result of air quality initiatives and legislation (e.g., the *Air Care Program* to reduce vehicular emissions) and/or industrial/population growth, and may be viewed, as Comrie (1992a) describes, as "declimatizing" environmental data. This work can also provide a framework for the interpretation of data collected during intensive studies.

2. Data sources

Although the spatial and temporal scale of the meteorological data used in this study is synoptic/subsynoptic, clearly, the occurrence of ozone episodes in Vancouver is not solely dependent upon meteorological conditions on this scale. The state of the atmosphere in terms of local flows (meters to kilometers), mixed-layer depth, wind speed, temperature, and UV intensity play an important role in determining whether ozone formation is inhibited or enhanced, in addition to factors such as the temporal variability of precursor emissions. Although these meteorological variables are not treated explicitly in this analysis, a wide range of meteorological variables are implicitly contained within each mode of the atmospheric circulation identified using principal component analysis (PCA).

Meteorological data used in this study were obtained from the National Meteorological Center (NMC) of the United States of America. Gridded fields of 1) sea level-reduced surface pressure, 2) 850-mb height, and 3) 500-mb height, at 1200 UTC, were extracted for a region encompassing southwestern Canada and the northwestern United States (Fig. 1). The fields are composed of a rectangular grid 2.5° latitude by 5° longitude. Data were extracted for a region extending from 42.5° to 55°N and from 115° to 140°W, and so the resulting data matrix (at each level) is a 6 × 6 grid of resolution 2.5° × 5°. Because ozone exceedances in the Vancouver region are almost entirely a summertime phenomenon (Robeson and Steyn 1990), only data from the summer months of July to September (July 1963–July 1992, inclusive) were used in the PCA. Prior to undertaking the analysis a number of quality control checks were performed upon the NMC gridded fields used herein, including checks for temporal and spatial consistency and extreme value validation.

Ozone concentrations at a single station, Rocky Point Park (RPP) in Vancouver (Fig. 1), are presented here as the dependent air quality variable. RPP is located east of the major population center of Vancouver, near the "center" of highest ozone (O_3) concentrations in the LFV (Joe et al. 1993). This station was selected from a much larger network because the following:

1) RPP has been diagnosed as a national air pollution survey class I station.

2) RPP has a relatively high frequency of exceedance of the 82-ppb objective.

3) RPP has the longest and most reliable record of the stations in the LFV (Robeson and Steyn 1990).

4) Although RPP represents a local maximum of ozone concentrations, its pattern of exceedances is typical of other stations in the region. Hence, although this site represents a "worst case" scenario, the qualitative behavior of the site is similar to that of surrounding sites.

5) It provides continuity with the study by McKendry (1994).

Figure 2a shows the frequency distribution of daily maximum ozone concentrations at RPP during July–September 1984–92. From this figure it is evident that the 82-ppb objective is exceeded on less than 1 day in 20. Daily maximum ozone concentrations by year (Fig. 2b) show marked interannual variability, as well as a tendency for lower frequency of ozone exceedances during the period July 1989–July 1992 than during the earlier portion of the dataset. Joe et al. (1993) speculate that expansion of Vancouver and the surrounding communities has resulted in shifts in ozone precursor and "scavenger" emissions and a relocation of the urban plume, which is manifest in the ozone time series

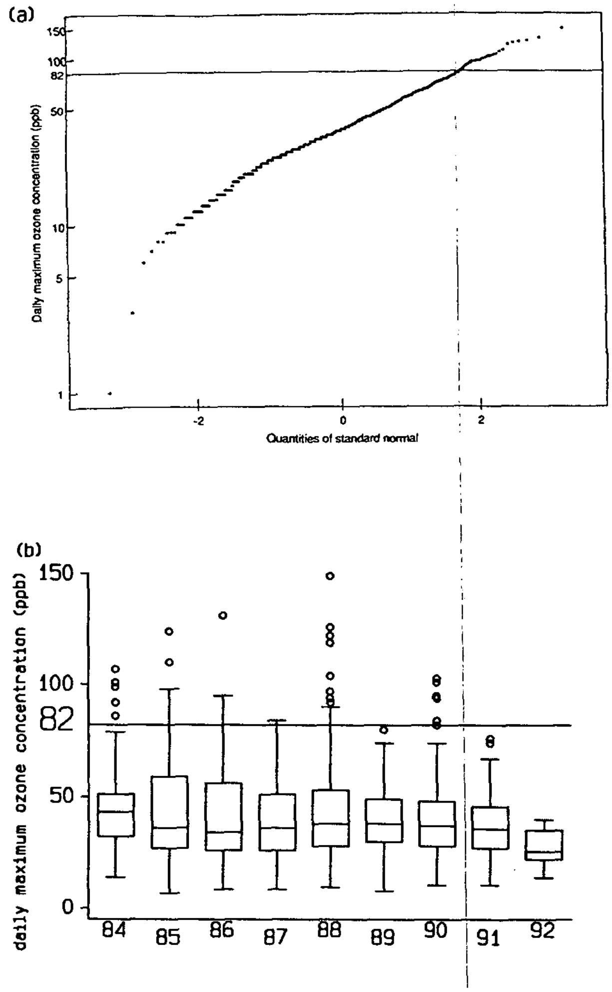


FIG. 2. (a) The daily maximum ozone concentrations at RPP during July–September of 1984–92 plotted against the quantiles of a normal (Gaussian) distribution. Normally distributed data would lie along a straight line on such a graph. These data are positively skewed, the 50th percentile value is 37 ppb, and the mean is 41 ppb. The number of observations is 717, and the number of 82-ppb exceedances in this dataset is 31 (82 ppb is denoted by the horizontal line). (b) A box plot of daily maximum ozone concentration by year. The line in the middle of the box represents the 50th percentile of the data. The box extends from the 25th percentile to the 75th percentile—the interquartile range. The lines extending vertically from the box extend to the upper and lower adjacent values (three halves the interquartile range "rolled back" to where there are data). Observed points more extreme than the adjacent values (outside values) are individually plotted. The data from 1992 should be interpreted with care due to the comparatively small number of data values in the sample. Using a chi-squared test, it was determined that there is no statistically significant difference between the distribution of the data by 10-ppb "bins" between the 1984–88 and 1989–92, inclusive, periods. However, the number of exceedance to nonexceedance days is significantly different: in the 1984–88 period there were 27 exceedance days and 383 nonexceedance days; during the 1989–92 period there were 6 exceedance days and 301 nonexceedance days. The result of the nonparametric Mann-Kendall test for trend as applied to the annual 50th percentile daily maximum ozone values (from the summers of 1984–91, 1992 was excluded due to the comparatively small number of values used to calculate the 50th percentile) was 16 negative values and 12 positive values indicating a downward trend (Rao et al. 1992).

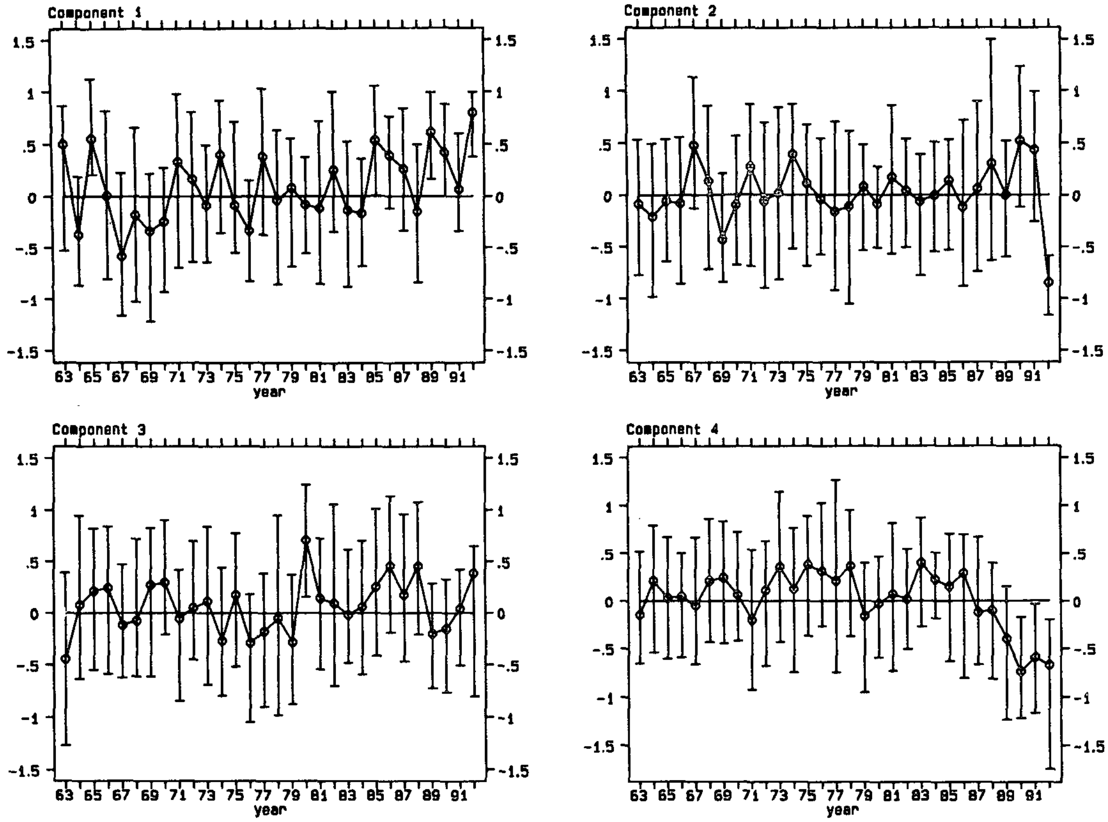


FIG. 3. The 50th, 25th, and 75th percentiles of the daily component scores from component 1–4 by year. In each frame, the "middle" line represents the 50th percentile of the data. The vertical lines extend from the 25th percentile to the 75th percentile—the interquartile range. The data from 1992 should be interpreted with care due to the comparatively small number of data values in the sample.

from RPP as a decrease in the extreme values of ozone concentrations. Removal of the meteorological signal from this data may clarify the interpretation of such trends (Rao et al. 1992).

The maximum daily ozone concentration at RPP is used rather than an average daily value because the maximum daily ozone concentration is more variable than the average daily concentration and has been identified by Comrie (1992b) as a sensitive indicator of "limiting environmental conditions."

3. Methodology and results

Principal component analysis of the three levels of the NMC gridded fields was used to generate an index of synoptic-scale meteorology using the following procedure (and routines from the IMSL Statistics Libraries). The data were arranged in a matrix such that each column was one of the parameters for a single grid point: sea level–reduced pressure or the height of the 850- or 500-mb level (i.e., 3 × 36 grid points, 108 in total). Each row contained data from 1 of the 2579 days of observations. From this matrix the correlation matrix was determined and used in a multifield S-mode PCA. Four principal components were extracted and rotated using Varimax (orthogonal) rotation (Richman 1986). These four components passed the two significance tests applied—the *N* rule (Overland and Preisendorfer 1982) and North et al.'s (1982) test for "degenerate couplets"—and are physically meaningful. Because the mean is removed from a correlation matrix, the principal components reveal information concerning deviations from the mean, and so, contours of component loadings are analogous to dominant anomaly patterns. The four components extracted here account for 83% of the total dataset variance.

The relationship between each of the observations (each day of gridded data) and each component was calculated using the magnitude of the variables in that observation and the contribution of each component to the variance in those variables. These daily component scores [calculated using the regression method, which yields the factor scores most highly correlated with true factor scores (Harman 1976)] indicate the approximation of observed atmospheric conditions on each day to the principal components. Figure 3 shows time series of the daily component scores and indicates significant variability of occurrence of these modes of atmospheric circulation from summer to summer during 1963–92. Note that the components derived here are characteristic of similar spatial patterns of isolines and not the intensity of those patterns; hence, daily component scores provide information concerning the "proximity" to the principal components and not the intensity of the conditions upon that day.

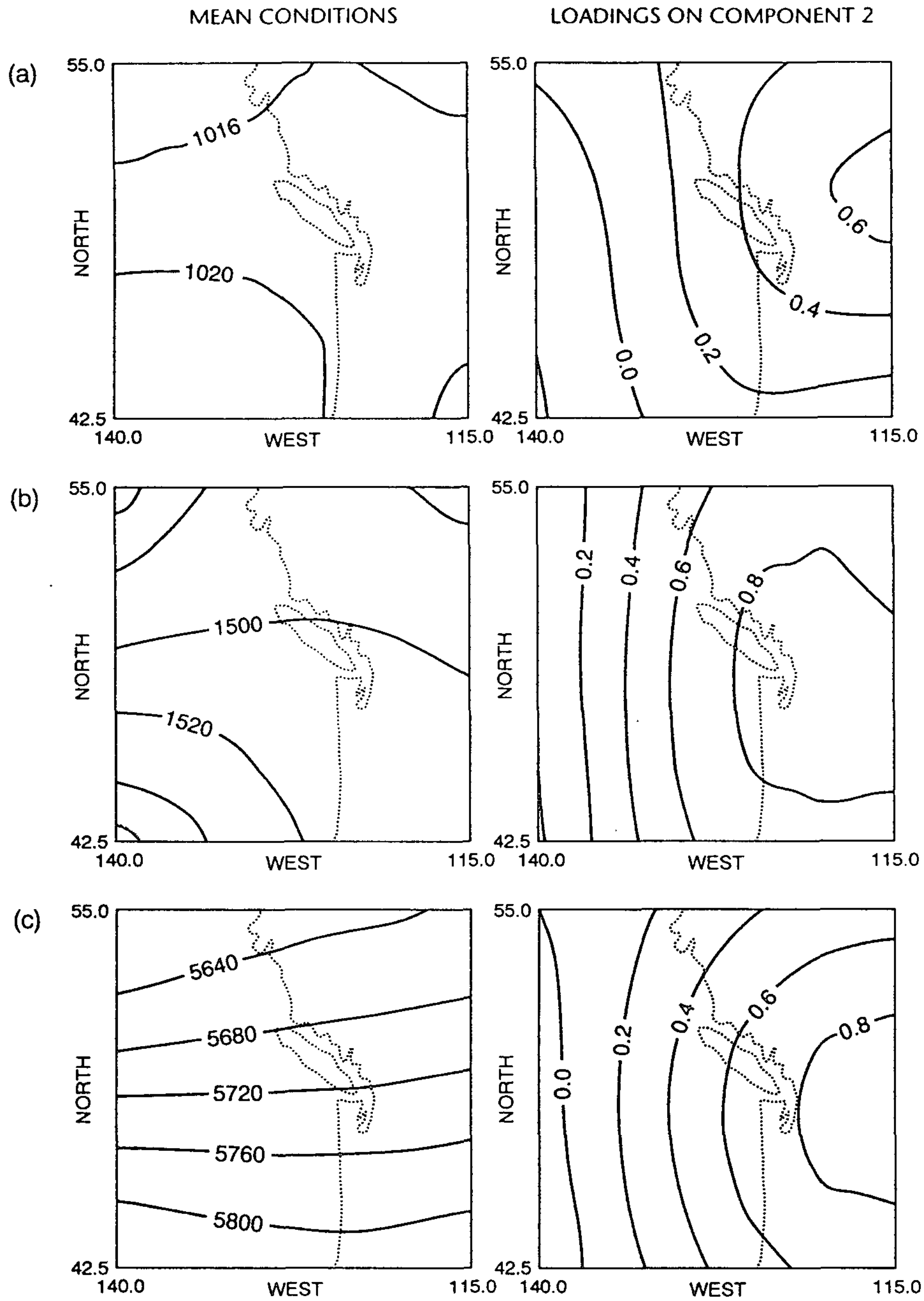
The purpose of developing these indices of synoptic-scale circulation was to test the dependence of daily maximum ozone concentrations at RPP on the prevailing synoptic-scale conditions, and then to test whether temporal variations in ozone concentrations are due to meteorological variability on the synoptic scale. The first five years of the datasets, 1984–88, inclusive, were selected for use in developing the equation for predicting daily maximum ozone concentrations as a function of the synoptic indices. The remaining three years and one month were set aside to use as the independent test case. Daily component scores were used to construct a multiple least-squares-fit regression equation of summertime daily maximum ozone concentrations at RPP as a function of prevailing synoptic conditions as represented by the daily component scores during the period 1984–88, inclusive (Table 1). As shown, 51% of the variance of the ozone time series dataset during this period may be "explained" on the basis of variability of the synoptic indices. The loading coefficients c_n on each of the daily component scores indicate the control exerted by each synoptic index (as defined by the daily component scores) on the predicted ozone concentration. From coefficients shown in Table 1, it was inferred that the synoptic conditions associated with component 2 (Fig. 4) are conducive to ozone formation. To understand meteorological conditions identified by these components, the loadings should be interpreted with reference to mean conditions over the entire dataset (of 2579 observations) at each atmospheric level (also shown in Fig. 4). These frames indicate that the mean summertime circulation pattern is characterized by a shallow ridge to the southwest and zonal flow aloft. Component 2 is defined by high positive loadings at all levels over the eastern portion of the domain, which are interpreted as being indicative of a ridge over the interior of British Columbia. An upper-level ridge over the east of the region was also identified by McKendry (1994) using the Kirchhofer technique as being conducive to elevated ozone concentrations at RPP. Two strategies were used to further test the hypothesis that this principal component (mode of atmospheric circulation) is associated with elevated ozone concentrations:

1) First, the median, 25th, and 75th percentiles of the daily component scores were calculated for 10-ppb ozone concentration bins. Figure 5 indicates that large and positive scores on component 2 are associated with higher daily maximum ozone concentrations. The correlation coefficient between component scores from component 2 and the daily maximum ozone concentration is 0.57 (n = 386).

TABLE 1. A regression equation of the daily maximum ozone concentration at RPP (ozone concentration) and prevailing synoptic-scale meteorological conditions as parameterized by the daily component scores (c_1–c_4). The daily component scores have been normalized to the maximum value and so vary between −1 and 1: Ozone concentration = $1.27c_1 + 36.7c_2 - 15.5c_3 + 19.1c_4 + 43.4$. Note: the r^2 value is adjusted for the number of parameters. The daily component scores generated using the least-squares method from the Varimax rotated components are uncorrelated and can be used as independent parameters in a regression equation.

r^2 = 0.51 Number of observations: 386			F statistic: 99.54	
Statistics of the coefficients and constant	Coefficient	Standard error	95% confidence interval	
c_1	12.7	2.1	8.54	16.8
c_2	36.7	2.1	32.6	40.8
c_3	−15.5	2.1	−19.5	−11.4
c_4	−19.1	2.4	−23.8	−14.4
Constant	43.4	0.87	41.7	45.1

2) Second, time series of the daily component scores and daily maximum ozone concentration were examined during (a) the most severe ozone episode (defined on the basis of number of days of the ozone standard exceedance and maximum record hourly ozone concentration at RPP) in the summertime record (1984–88, inclusive), 26 August–5 September 1988, and (b) the entire summer of 1988. From Figs. 6a,b it is clear that during 26–28 August, and then again during 1–5 September 1988, daily maximum ozone concentrations were elevated and loadings are high and positive on component 2 (indicating that the atmospheric conditions closely approximated those identified by this component). However, during the intervening period, meteorological conditions were dissimilar to those parameterized by component 2 and ozone concentrations were lower. Figure 6c shows the strong positive correlation between the daily maximum ozone concentration and component score during the summer of 1988 throughout a range of ozone concentration values and not just during severe episode periods. This supports the hypothesis that the conditions identified by component 2 are associated with elevated concentrations of ozone. It is particularly important that good agreement between these parameters (the daily component score on component 2 and daily maximum ozone concentration) is seen during this summer because 1988 appears to have been characterized by an anomalously high-ozone summer across Canada and the United States at both urban and rural sites (e.g., Lefohn and Lucier 1991; Rao et al. 1992; U.S. Environmental Protection Agency 1990), which implies a synoptic- (and/or larger) scale meteorological cause. (Note: Trenberth and Branstator (1992) present a full



(a) = SEA LEVEL REDUCED SURFACE PRESSURE
(b) = 850 mb HEIGHT
(c) = 500 mb HEIGHT

FIG. 4. Contours of the component loadings from component 2 and mean conditions during the 1963–92 period. The mean conditions indicate a high pressure area to the southwest at the (a) surface and (b) 850-mb levels, and near zonal flow aloft at (c) 500 mb. Component 2 is defined by high positive loadings at all levels over the eastern portion of the domain, which are indicative of a ridge over the interior of BC. The other three components identified by the PCA defined the following conditions: 1—slackening of pressure gradients at all levels (most notably a reduction of the zonal flow aloft), 3—a deepening and strengthening of the ridge in the southwest of the domain, and 4—a storm track in the north of the domain.

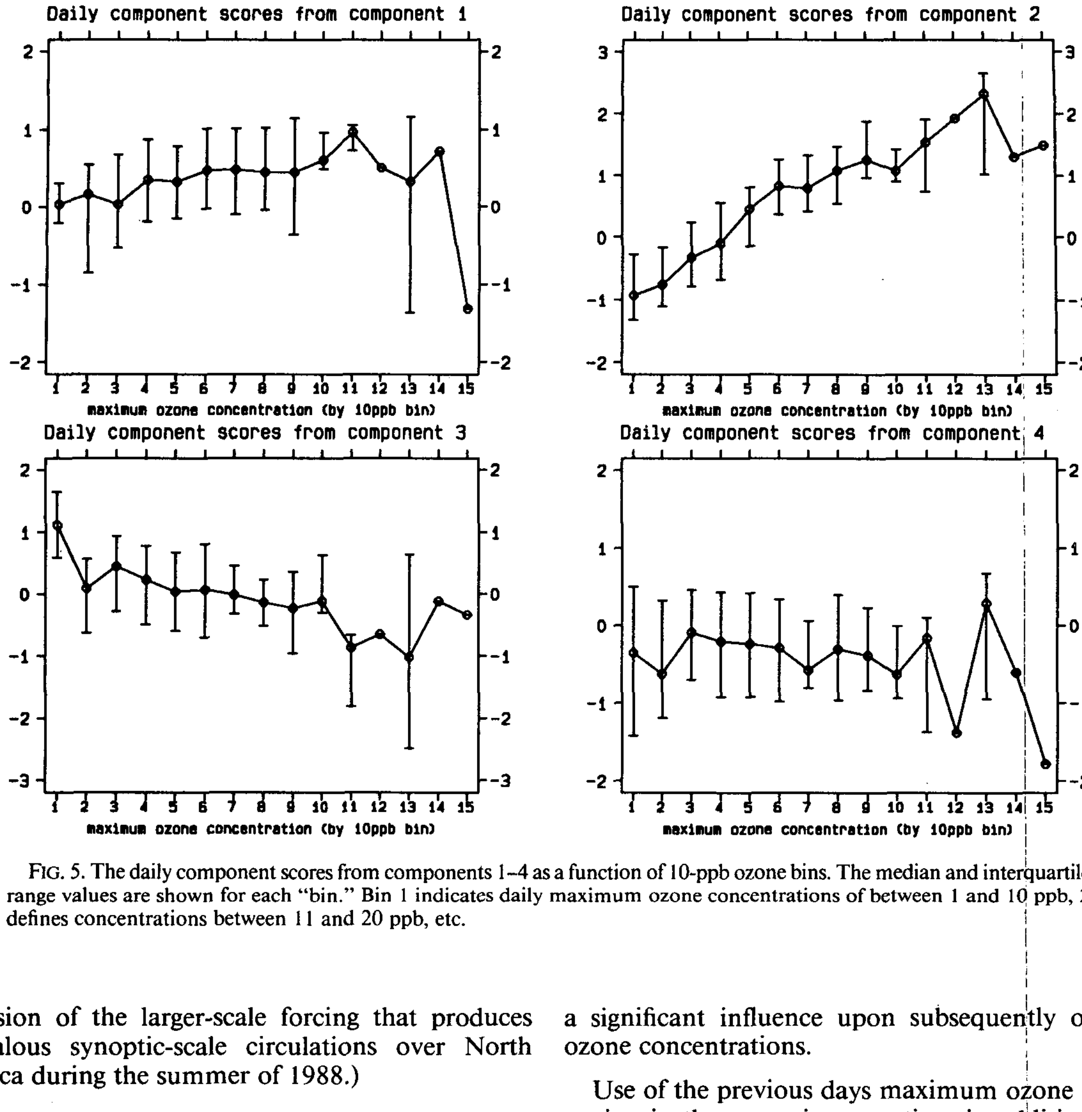


FIG. 5. The daily component scores from components 1–4 as a function of 10-ppb ozone bins. The median and interquartile range values are shown for each "bin." Bin 1 indicates daily maximum ozone concentrations of between 1 and 10 ppb, 2 defines concentrations between 11 and 20 ppb, etc.

discussion of the larger-scale forcing that produces anomalous synoptic-scale circulations over North America during the summer of 1988.)

Comrie (1992b) showed that sequenced synoptic typing was able to offer greater explanation of daily maximum ozone concentrations in Pittsburgh over a "static" synoptic typing. The applicability of sequencing in the current study was examined by incorporating the previous days component scores in the regression equation shown in Table 1. Interestingly, the variance explanation of the dependent variable (ozone concentrations) was not enhanced (adjusted $r^2 = 0.50$). This may be due to

1) correlation of the independent variables (the daily component scores) in the temporal domain,
2) the slow evolution of circulation patterns during ozone episodes in Vancouver (McKendry 1994), or
3) the soundings, which are used here, taken at 1200 UTC, which corresponds to 0400 LT (local time). Hence, "the previous days" conditions are typically 36 h prior to the ozone maxima. This may be too large a time differential for meteorological conditions to exert a significant influence upon subsequently observed ozone concentrations.

Use of the previous days maximum ozone concentration in the regression equation, in addition to the component scores, increases the variance explanation (adjusted $r^2 = 0.55$), but this may be due to temporal autocorrelation of the daily maximum ozone concentrations rather than reflecting a physical cause, such as increasing concentrations of the precursor species. Robeson (1987) investigated temporal autocorrelation of ozone concentrations from RPP and found it to be strong for $\Delta T = 1$ day but weak for larger lags.

To examine whether temporal variability of synoptic-scale meteorology might be responsible for the comparatively low frequency of ozone episodes during the summers of 1989–92, the regression equation from Table 1 was used to predict ozone concentrations during this period. Figure 7 shows the predicted maximum daily ozone concentration based upon the daily component scores and the actual record maximum daily ozone concentration by the two time periods—(a) 1984–88 and (b) 1989–92. During the summers of 1984–88, although the ozone concentration on days

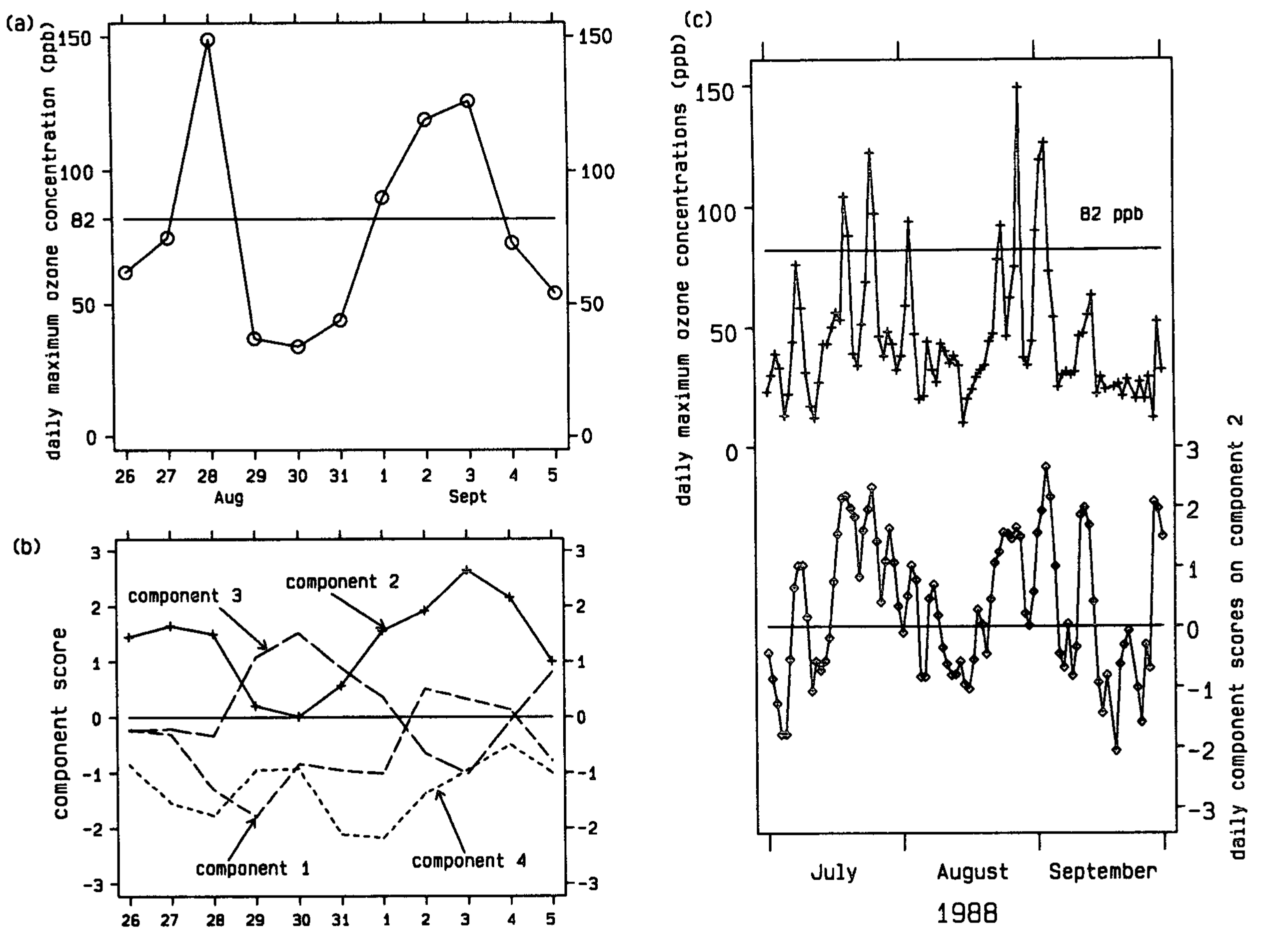


FIG. 6. (a) The daily maximum ozone concentration for the period 26 August–5 September 1988. (b) The daily component scores from components 1–4 for the period 26 August–5 September 1988. (c) The daily maximum ozone concentration (upper trace) and daily component scores from component 2 (lower trace) during the summer of 1988.

when the ozone standard was exceeded is not predicted correctly (in part because of the nature of regression analysis), the algorithm is fairly accurate. However, when the algorithm is applied to the later period (1989–92), it typically overestimates ozone concentrations.

4. Discussion

The implication of Figure 7 is that at this site recent trends in the average daily maximum ozone concentration on nonexceedance days cannot be explained on the basis of variability of the most common modes of synoptic-scale circulation (principal components). One possible explanation is that ozone concentrations are responding to changing emissions patterns. The city of Vancouver is rapidly expanding, and there may have been an increase in ozone scavenging or decrease in ozone formation at this site. However, this is speculation as this study does not explicitly consider precursor emissions or atmospheric chemistry. The inability of the algorithm to predict accurately the magnitude of exceedances in the 1984–88 period (the occurrences are predicted) is not unexpected in a regression analysis but may reflect an underlying physical process. For example, it may indicate that the exceedance days are controlled by emissions variability, or meteorological variability on a smaller scale [Steyn et al. (1990) showed that reduced mixed-layer depth is observed during periods of ozone exceedances], or synoptic-scale meteorological conditions not parameterized by these four components. In terms of predicting the low frequency of exceedance days in the 1989–92 time frame, the regression equation performs well. The implication may be that two factors resulted in the dissimilar pattern of ozone concentrations in the two time periods:

1) A reduction in the frequency of the synoptic-scale meteorological conditions that favors the occurrence of ozone episodes. Using a chi-squared test, it was determined that there is no statistically significant difference between the distribution of daily component

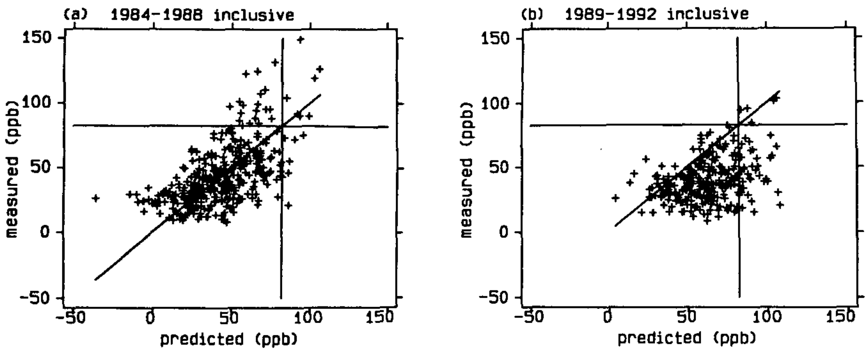


FIG. 7. Scatter diagrams of the observed maximum ozone concentration (*y* axis) and that predicted (*x* axis) using the regression equation in Table 1 for (a) 1984–88 and (b) 1989–92. The vertical and horizontal lines indicate the 82-ppb level. The diagonal line represents a one-to-one relationship. Note: the daily component scores used in the regression equation used to generate the predicted values are normalized by the maximum value such that they vary between −1 and 1.

scores from component 2 (grouped in unit bins, that is, values of −2 to −1, −1 to 0, 0 to 1, 1 to 2, etc.) between the 1984–88 and 1989–92, inclusive, periods. However, extreme values (both negative and positive) were statistically biased toward occurring during the 1984–88 period.

2) Temporally and spatially shifting emissions patterns reduced the potential for ozone formation or increased ozone scavenging (Joe et al. 1993).

If, as Davis and Gay (1993) contend, most day-to-day variations in air quality may be accounted for on the basis of changing meteorology, and so, "it is impossible to make any definitive statements regarding air quality of a region without accounting for the underlying meteorology or climatology," then clearly, the same must be true for the implementation of air quality initiatives and legislation under the *Green Plan* (initiative developed to address a number of policy issues including air quality objectives) for the Lower Fraser Valley. Meteorological variability must be accounted for in any analysis regarding the success of such initiatives. The goal of this study was to determine the relationship between the indices of the most common meteorological circulation patterns over southwestern British Columbia and ozone concentrations at a site in Vancouver. PCA is ideal for this purpose as it produces a manageably small number of representative principal components that account for over 83% of the dataset variance. It has been shown that synoptic-scale meteorological variability parameterized by daily component scores is "responsible for" a significant amount of the interannual variability of ozone concentrations. This signal could be partly removed using the following methodology: The resultant of observed [O_3] minus predicted [O_3] (see Table 1 caption) is the variability of ozone concentrations not associated with the parameterized meteorological variability. The correlation coefficient of this residual from the data collected at RPP with a continuous time variable is −0.49 ($n = 676$).

Using the four principal components defined herein, it has been shown that the recent downward trend in daily maximum ozone concentrations on *nonexceedance days* at this site cannot be accounted for on the basis of synoptic-scale meteorological variability. However, the following should be noted:

1) The predictive algorithm developed based on the daily components scores correctly (but possibly coincidentally) predicted the low frequency of ozone episodes in the July 1989–July 1992 period. This period was characterized by a statistically significant reduction in the frequency of the synoptic-scale meteorological conditions that favor the occurrence of ozone episodes relative to the summers of 1984–88, inclusive.

2) The principal components defined here represent dominant anomaly patterns. The modes of atmospheric circulation may not correlate with pollution events because singularly polluted days may occur under synoptic conditions that do not occur frequently enough or are not long lived enough to generate a data cluster within this analysis. If the goal of future studies is purely to explain the conditions under which ozone formation is enhanced, either a Procrustes target analysis or PCA, including the ozone concentration as a parameter, would be more appropriate.

It is hypothesized herein that recent trends in the average daily maximum ozone concentration at RPP on nonexceedance days may have a nonmeteorological cause. That is, ozone concentrations are responding to changing emissions patterns. This hypothesis could be tested by examining a number of sites within the Vancouver region. If the trend is consistent between sites, this implies a "regional" causation; however, if ozone concentrations are responding to the speculated spatial and temporal variations of emissions, then sites in the urban core, at the periphery of, and external to the city, should exhibit different trends.

Acknowledgments. This research was supported by a grant from the Natural Science and Engineering Research Council of Canada. The authors gratefully acknowledge the constructive criticism offered by Dr. R. Barthelmie, Mr. B. Thomson, Ms. J. Pottier, and three anonymous reviewers. Thanks also to Mr. P. Jance for drafting three of the figures presented herein.

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