ARTICLES

Air Quality, Climate, and Policy: A Case Study of Ozone Pollution in Tucson, Arizona

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This article addresses the need to better understand the complex interactions between climate, human activities, vegetation responses, and surface ozone so that more informed air-quality policy recommendations can be made. The impacts of intraseasonal climate variations on ozone levels in Tucson, Arizona from April through September of 1995 to 1998 are determined by relating variations in ozone levels to variations in atmospheric conditions and emissions of ozone's precursor chemicals, volatile organic compounds (VOCs) and nitrogen oxides (NO_x), and by determining month-specific atmospheric conditions that are conducive to elevated ozone levels. Results show that the transport of ozone and its precursor chemicals within the Tucson area causes the highest ozone levels to be measured at a downwind monitor. The highest ozone levels occur in August, due in part to the presence of the North American monsoon. Atmospheric conditions conducive to elevated ozone concentrations differ substantially between the arid foresummer (May and June) and the core monsoon months (July and August). Transport of pollution from Phoenix may have a substantial impact on elevated ozone concentrations during April, May, and June, while El Paso/Ciudad Juarez–derived pollution may contribute significantly to elevated ozone concentrations in August and September. Two broad policy implications derive from this work. Regional pollutant transport, both within the U.S. and between the U.S. and Mexico, is a potential issue that needs to be examined more intensively in future studies. In addition, spatiotemporal variations in sensitivities of ozone production require the adoption of both NO_x and VOC control measures to reduce ozone levels in the Tucson area. **Key Words: air pollution, climate, environmental policy, ozone, Southwest.**

Introduction

Air pollution is an intrinsically geographical problem. Understanding it involves describing and explaining interactions among and between human and environmental variables. Surface (ground-level) ozone is a good example of these interactions, as it depends on the interplay of pollutant emissions and atmospheric conditions. Ozone, which is a secondary pollutant (i.e., one not emitted directly by sources), can be present at high concentrations in both urban and rural locations, and its adverse effects on human health, crops, and forest ecosystems have become a major environmental concern (Sillman 1999). Significant associations have been found between respiratory-related hospital admissions and ambient ozone levels, with stronger relationships occurring in areas with higher ozone concentrations (Cody et al. 1992; Burnett et al. 1994). More specifically, White and colleagues (1994) suggest that asthma among children from low-income families may be exacerbated following periods of high ozone pollution. In California's San Bernardino and Sierra Nevada Mountains, decreased sizes of and increased foliar injuries among pines have been linked to increased ambient ozone concentrations (Peterson et al. 1987; Miller et al. 1989). In addition, substantial seasonal crop reductions (>30 percent) have occurred when alfalfa has been exposed to ambient ozone (Thompson, Kats, and Cameron 1976). The recognition of increasing ozone levels in the United States and the realization of its adverse effects on people and vegetation initiated the establishment of a national ambient air quality standard (NAAQS) for ozone in the early 1970s and the subsequent enforcement of the standard by the U.S. Environmental Protection Agency (EPA). Consequently, most metropolitan areas have one or more monitors that continuously measure ambient ozone concentrations to ensure the protection of public health and welfare—e.g., crops, forests, and materials—from elevated ozone concentrations.

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Despite its proven deleterious effects, ozone's behavior over space and time in some metropolitan areas is insufficiently known and explained. Understanding the link between climate and ozone is critically important to air quality planners and managers; they rely on this information when facing policy issues such as selecting optimal ozone reduction strategies to bring ozone levels below the federal standard or ensuring that the standard is not violated. These strategies involve reducing emissions of volatile organic compounds (VOCs) and nitrogen oxides (NO_x), which are ozone's precursor chemicals. Deciding whether or not to reduce VOC emissions, NO_x emissions, or both depends on the availability of detailed spatiotemporal information concerning the sensitivity of ozone production to either of the ozone precursors, knowing what atmospheric conditions are conducive to ozone concentrations that might exceed the federal ozone standard, and determining the total amount of ozone and its precursors that are regionally transported into an area.

Aims and Objectives

This article aims to examine the complex interactions between intraseasonal variations in climate and ozone levels so that relevant processes can be understood more fully, thereby enabling better air quality policy decisions. This is accomplished by determining the synoptic-scale circulation features and associated surface and upper-level atmospheric variables that significantly affect ozone pollution. Climatic factors are investigated with respect to both direct and indirect effects on VOC and NO_x emissions and ozone levels. The article's major objectives are to link month-to-month variations in ozone levels with variations in atmospheric conditions and associated ozone precursor chemical emissions, to determine month-specific atmospheric conditions (including long-distance transport of pollution via upper-level winds) that are conducive to elevated ozone levels, and to discuss the policy implications of the results. We present a case study of Tucson, Arizona, a rapidly growing metropolitan area in the southwestern U.S. that has the potential for exceeding the federal ozone standard in the near future. Our results and selected aspects of our methodological framework might be applicable to other urbanized areas in the Southwest.

Impacts of intraseasonal climate variations on ozone precursor emissions and ozone levels are examined using an ensemble averaging approach rather than the common episode-specific approach, which typically involves in-depth examinations of meteorological conditions over the course of one to several days. Averaging removes day-to-day meteorological variations by pooling days for each month over several years, thereby revealing the overall impacts of intraseasonal climate variations on ozone levels. Graphical and statistical analyses of the pooled observations yield air quality information that can be critically important from both scientific and policy perspectives. This information improves deterministic ozone modeling (e.g., predictive spatial mapping, temporal forecasting, and regulatory modeling), enables an increased understanding of ozone's effect on sensitive receptors such as humans and certain types of vegetation, provides a foundation upon which results from episode-specific studies can build, and improves air quality policy decisions.

Overview of Surface Ozone

Production

Surface ozone can be formed by the oxidation of VOCs in the presence of NO_x and sunlight (Chameides et al. 1992). To facilitate later discussion, a greatly simplified description of the ozone-formation process, involving just NO_x and VOCs, is as follows:

- During daylight hours, ultraviolet (UV) radiation photolyzes nitrogen dioxide (NO_2).

$$NO_2 + UV \rightarrow NO + O$$

- The oxygen atom (O) reacts with an oxygen molecule (O_2) to form ozone (O_3).

$$O_2 + O \rightarrow O_3$$

- O_3 reacts rapidly with NO produced in the photolysis reactions, resulting in no significant ozone formation.

$$O_3 + NO \rightarrow NO_2 + O_2$$

- VOCs break down in the presence of O_2. This results in extremely reactive hydroxyl (OH) radicals.

- The VOC-derived radicals are involved in reactions that oxidize NO to NO_2, resulting in the accumulation of ozone and other photochemical oxidants.

Ultimately, the production of ozone is controlled by the availability of VOCs, even though nitrogen oxides are required to initiate the reactions (Elsom 1992). In addition, the rate of ozone production is a nonlinear function of the mixture of VOCs and NO_x (Cardelino and Chameides 1995). VOCs essentially suppress ozone scavenging by nitric oxide (NO), thereby enabling the accumulation of ambient ozone concentrations. Meteorology also affects ozone formation and transport. Ozone accumulation in the lower troposphere is critically dependent upon the physical parameters that characterize the planetary boundary layer, such as temperature, wind speed, wind direction, and mixing height (i.e., the depth of the atmosphere directly above the surface through which pollutants may be mixed) (Cardelino and Chameides 1995). Generally, hot, sunny, and calm conditions are conducive to elevated ambient ozone concentrations.

Transport

Peak ozone concentrations usually occur at significant downwind distances (i.e., 30 to 150 km) from emission source areas (Seinfeld 1989; Imhoff, Valente, and Meagher 1995). Within an airshed, such as California's South Coast Air Basin (i.e., Los Angeles), coastal breezes and mountain winds, which are generated by strong daytime heating of land surfaces, can transport and distribute pollutants across the basin (Lu and Turco 1996). Up-slope flows are thought to be an important mechanism whereby pollutants can be transported from source areas into forests and wilderness areas located in mountainous terrain, such as the transport of pollutants from the San Joaquin Valley to the Sierra Nevada Mountains (King, Shair, and Reible 1987). On a regional scale, ozone and its precursors generated near urban areas can slowly accumulate within high-pressure cells and be transported long distances (Vukovich et al. 1977; Comrie 1990). For example, NO_x emissions in the lower Ohio and middle Mississippi River valleys have a high likelihood of contributing to high ozone air masses arriving in western Pennsylvania (Comrie 1994).

Urban versus Rural Ozone

The characteristics of ozone concentrations differ noticeably between urban and rural areas. Ozone production at a location can be described as VOC-sensitive, NO_x-sensitive, or transitional. In urban atmospheres, where NO_x concentrations can be extremely high, the rate of ozone production can actually become depressed by additional NO_x (i.e., NO-scavenging), and can essentially be limited solely by the availability of VOCs. If NO_x concentrations are held constant and VOC concentrations are increased, ozone concentrations increase. Increases in ambient VOC concentrations can enhance ozone production significantly (Chameides and Lodge 1992). In this predominantly urban situation, ozone production is described as VOC-sensitive.

In contrast to most urban situations, ozone in rural air depends strongly on NO_x concentrations but is almost independent of VOCs (Sillman, Logan, and Wofsy 1990; Sillman 1999). High biogenic VOC (BVOC) emissions (i.e., VOCs emitted by vegetation) are a major cause of this NO_x-sensitivity. Nevertheless, increasing some VOC concentrations can increase the rate of ozone destruction, due to the reaction between ozone and VOCs (Chameides and Lodge 1992). Ozone production in rural areas may also be more efficient than in urban areas, for production efficiencies are highest at low NO_x concentrations even when VOC concentrations are assumed to increase with increasing NO_x concentrations (Lin, Trainer, and Liu 1988; Lefohn 1992).

Finally, areas that have transitional atmospheres are often intermediate points, both geographically and chemically, between VOC-sensitive urban centers and NO_x-sensitive rural areas. These transitional areas often have the highest ozone concentrations in a region (Sillman 1999), and when located on the edges of urban areas present policy questions concerning the control of emissions of VOC, NO_x, or both to reduce ozone levels and the subsequent impacts of these changes on ozone levels in other parts of the area.

The Study Region

Geographical Location and Pollutant Emissions

Tucson (~32° N, ~111° W) is located approximately 700 m above sea level (a.s.l.) in a basin

surrounded by four mountain ranges (Rincon, Santa Catalina, Tortolita, and Tucson Mountains) (Fig. 1). Tucson is a low-density, urbanized area with a population density drastically different than that of eastern U.S. areas with similar population totals. Syracuse, New York has a similar population total, but the population densities of Syracuse and Tucson in 1990 were 107 and 28 people per square kilometer, respectively (U.S. Census Bureau 1999). Tucson's population total expanded from approximately 265,000 in 1960 to over 800,000 people in the late 1990s (PAG 1996). The population growth occurred in concert with the expansion of the metropolitan area, which in this article is denoted as a contiguous portion of the region that has been developed for residential, municipal, commercial, or industrial purposes. Consequently, the average daily vehicle miles traveled (VMT) increased during that time period from approximately 1 million to over 20 million (PAG 1998). Tucson's dependence on motor vehicles and its relative lack of major industrial facilities have resulted in motor vehicles emitting a majority of the area's ozone precursor pollutants, VOCs and NO_x (Diem and Comrie forthcoming). In this way, Tucson is typical of most western U.S. cities.

Climate and Pollutant Transport

Pollutant emissions, transport, chemistry, dispersion, and accumulation are all affected strongly by atmospheric conditions on several scales. In winter, Tucson lies at the southernmost extreme of the polar front jet stream; hence, midlatitude storms move through the region (Comrie 1996). In addition to cyclonic storms, this situation also results in quasistationary anticyclones centered over the Great Basin, which bring light winds and shallow mixing heights to the region (Holzworth 1962). These anticyclones have been found to be the most likely synoptic features conducive to poor air quality (Holzworth 1962; Comrie 1996; Comrie and Diem 1999). During July and August, the North American monsoon brings moist, hot conditions and thunderstorms to the region (Adams and Comrie 1997). Similar to wintertime pollution potential, ozone levels during the summer months are highest under upper-level anticyclones in many locations, including the Tucson area, due to higher temperatures and greater ultraviolet radiation (Comrie 1996).

Local circulations, superimposed on the global and synoptic scale circulations, are important with respect to pollution transport within the Tucson area. The region is affected by a mountain-valley circulation on most days. Nearly all months show a diurnal reversal in wind direction with down-slope winds (southeasterlies) occurring during the early morning hours and up-slope winds (northwesterlies) occurring during times of maximum surface heating (Frenzel 1963; Comrie 2000). Up-slope winds transport pollutants eastward/southeastward across the Tucson metropolitan area during the afternoon and early evening, while down-slope winds transport pollutants westward/northwestward during the late evening and early morning.

Data

Hourly ozone concentrations were obtained from the EPA's Aerometric Information Retrieval System (AIRS) for Tucson's five long-term ozone monitors (i.e., monitors that were in operation from 1995 to 1998). Scattered throughout the metropolitan area (Fig. 1), these monitors were placed in varying environments, including a semirural, upwind area in northwest Tucson (Tangerine Road [TANG]), a city center area (Downtown [DT]), an urban/suburban area (22nd and Craycroft [22&C]), and two semirural, downwind areas (Saguaro National Park East [SNP] and Fairgrounds [FG]). AIRS also provided hourly wind speed and direction data for the TANG and 22&C monitors. Hourly NO_x concentrations from 1995 to 1998 at 22&C were acquired from the Pima County Department of Environmental Quality (PDEQ). Hourly temperature, relative humidity, and insolation data were obtained from an Arizona Meteorological Network (AZMET) site located at the University of Arizona's Campus Agricultural Center in midtown Tucson. Daily temperature, wind speed, relative humidity, and atmospheric pressure measurements at Tucson International Airport (TIA) were obtained from the National Climatic Data Center (NCDC). Upper air data (geopotential heights, temperatures, dew point temperatures, wind speed, and wind direction) acquired via radiosonde twice daily (0Z and 12Z) at TIA were also obtained from NCDC. Estimates of daily VOCs and NO_x emissions are described in Diem and Comrie (2000) and Diem and Comrie (forthcoming).

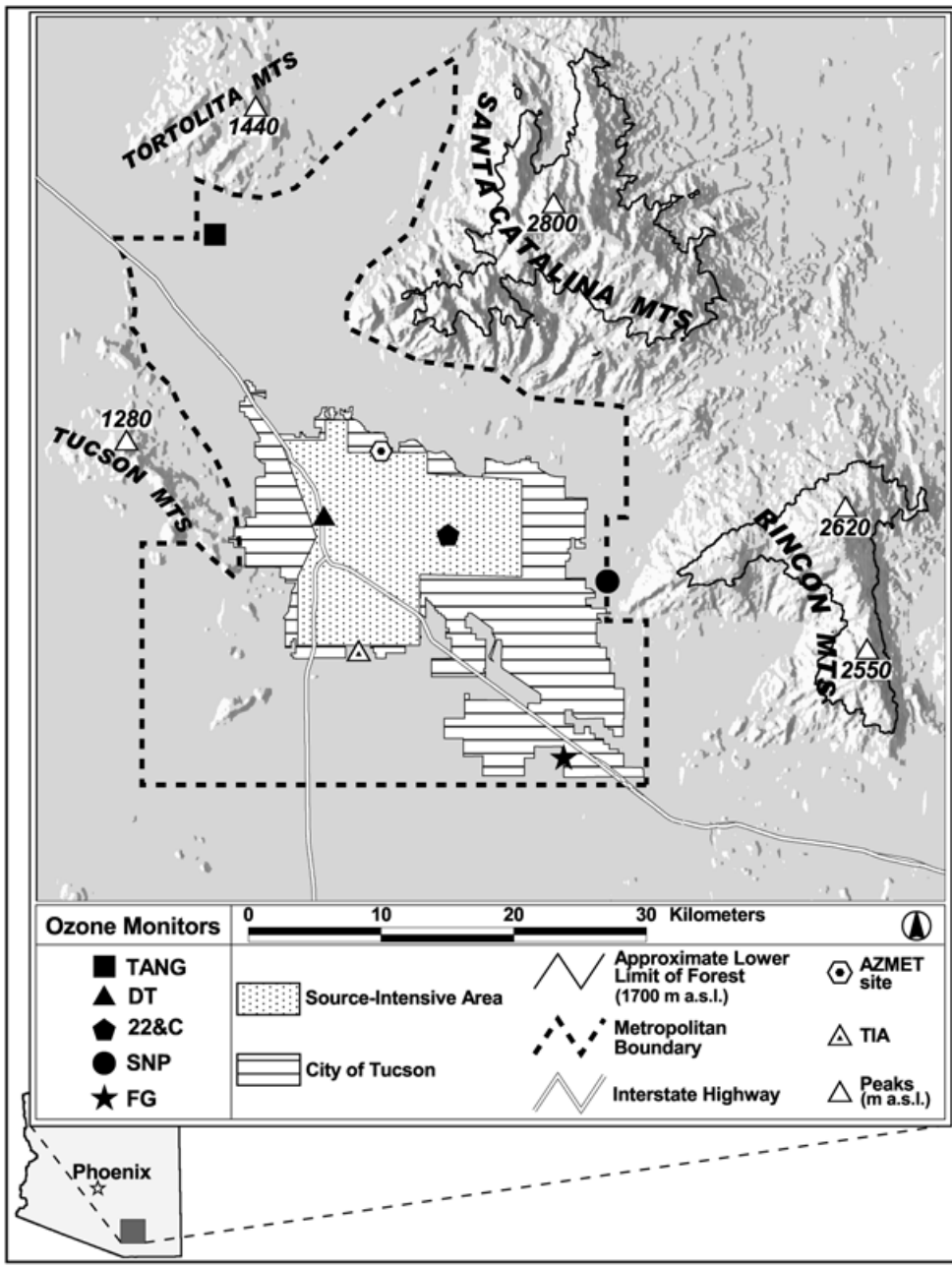

Figure 1 *Map of the Tucson area showing its location within Arizona as well as five long-term ozone monitors, meteorological stations, topography, and the area's developed portions (i.e., source-intensive area, city of Tucson, and metropolitan area).*

Methods

Methods were targeted toward (1) determining month-to-month changes in ozone precursor emissions and associated spatiotemporal variations in ozone production sensitivity, (2) determining and explaining intraseasonal variations in ozone levels by examining intraseasonal climate variations, and (3) creating a month-specific climatology of high ozone concentrations.

First, intraseasonal variations in area-wide VOC and NO_x emissions from all sources were determined and subsequently compared with results from other research (Diem 2000) to obtain better estimates of precursor emissions. Second, average daily maximum ozone concentrations (i.e., daily maximum one-hour and eight-hour average concentrations) and average daily ozone exposure values (i.e., SUM06 and W126) were calculated for each month. Due to uncertainties pertaining to the adoption of either the one-hour or eight-hour average federal ozone standard, both standards are presented in this study. Values of the four ozone metrics served as typical ozone levels to which other variables (i.e., climate and emissions) could be related. SUM06 is an ozone exposure index that is the sum of all hourly concentrations greater than or equal to 0.06 ppm (parts per million). In this study, the average monthly SUM06 was calculated at each monitor. This index and other cumulative standards have been used to quantify human exposure to ozone pollution (Blanchard, Byrne, and Ziman 1997). W126 is a sigmoidally weighted exposure index that gives more weight to higher hourly average concentrations and less weight to less biologically-effective concentrations (Lefohn and Runeckles 1987). Hourly ozone concentrations were weighted using the following equation:

$$W_i = \left[1 + M * e^{(-A * C_i)}\right]^{-1} \quad (1)$$

where M and A were assigned values of 4403 and 126 ppm^{-1}, respectively. W_i is the weighting factor for concentration i, and C_i is the concentration of i (Lefohn and Runeckles 1987). Using the above values, minimal weight was given to values less than 0.04 ppm, while maximum weight was given to values greater than 0.1 ppm. Along with the SUM06 index, this index has been used to relate vegetation effects to ozone exposure (Lefohn, Laurence, and Kohut 1988).

Third, a month-specific climatology of high ozone concentrations was developed. The climatology focused on the upper tail of the daily maximum ozone concentration distribution because peak ozone concentrations are strongly influenced by meteorological conditions (Rao et al. 1991). This climatology was constructed for the SNP and TANG stations by determining the average atmospheric conditions present on days that had the top 20 percent of daily maximum ozone concentrations at each monitor during each month. Therefore, the goal of the climatology was to determine the direct and indirect impacts of atmospheric conditions on high ozone concentrations. Student's *t*-tests were used to test for differences between atmospheric conditions during high ozone days (HODs) and the rest of the days (non-HODs). The top 20 percent of days translated into a substantially robust number of observations, enabling the use of the above statistical tests. These methods facilitated a climatological comparison of upwind and downwind locations as well as month-to-month comparisons.

Results and Discussion

Overview of Spatiotemporal Variations in Ozone Precursor Chemical Emissions

The three major types of ozone precursor chemicals emitted in the Tucson metropolitan area are anthropogenic VOCs and NO_x (AVOCs and ANO_x), which are emitted by stationary and mobile sources, and BVOCs. Monthly variations in AVOC and ANO_x emissions are caused primarily by changes in human activities and atmospheric conditions (Fig. 2a). For example, increased air conditioner use during the monsoon causes an increase in NO_x emissions from a local power plant in July and August (Diem 2000). Temporal variations in BVOC emissions are a function of leaf biomass, temperature, light intensity, relative humidity, and various phenological factors such as blooming (Dement, Tyson, and Mooney 1975; Arey, Corchnoy, and Atkinson 1991; Guenther et al. 1993, 1995; Monson et al. 1995). Over the course of Tucson's ozone season, BVOC emissions are lowest during the arid foresummer (May and June) and highest during the core monsoon months (July and August) (Fig. 2b).

Spatially, the highest AVOC and ANO_x emissions occur in the source-intensive area,

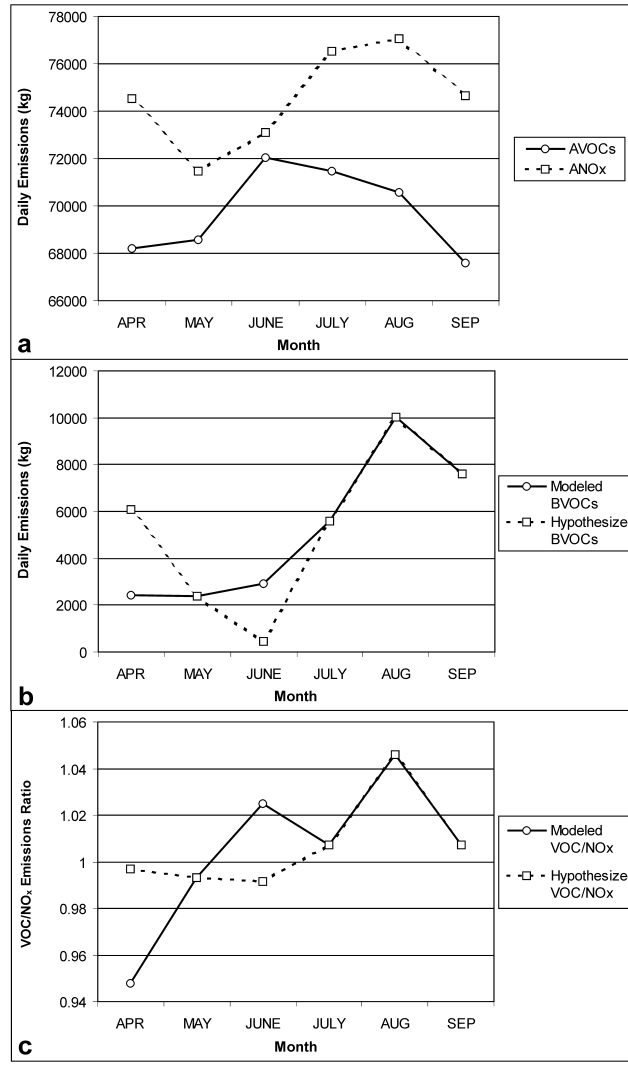

Figure 2 *Month-to-month changes in (a) anthropogenic VOC (AVOC) and anthropogenic NO_x (ANO_x) emissions, (b) BVOC emissions, and (c) VOC/NO_x emissions ratios within the Tucson metropolitan area. Modeled BVOC emissions are estimated with month-specific coefficients presented in Guenther et al. (1995). Hypothesized BVOC emissions are estimated by adjusting modeled emissions by various factors. It is assumed that April's emissions are 2.5 times higher than estimated due to increased emissions from blooming and bud-break. In addition, it is assumed that June's emissions are 85 percent lower than estimated due to stomatal closure during dry conditions. The hypothesized values are constructed based on findings presented in Diem (2000).*

while low emissions occur in nonmining and nonhighway areas outside the metropolitan boundary (refer to Fig. 1). The urban forest, which exists almost entirely within the city of Tucson, and the forested areas of the Santa Catalina and Rincon Mountains have the highest BVOC emissions, while the desert lands have relatively moderate BVOC emissions (Diem and Comrie 2000).

Month-specific estimates of VOC/NO_x emissions ratios within the metropolitan area provide insight concerning temporal variations in the sensitivity of ozone production (Fig. 2c). Due to month-to-month variations in BVOC emissions, the sensitivity of ozone production changes dramatically between the months (Diem 2000). Minimal BVOC emissions in June contribute to that month's relatively small VOC/NO_x emissions ratio. Monsoon-induced increases in BVOC emissions cause August to have the largest VOC/NO_x emissions ratio. Therefore, the monsoon can take ozone production from VOC-sensitive in May and June to transitional/NO_x-sensitive in July and August. On average across the metropolitan area, April has transitional sensitivity, May is VOC-sensitive,

June is VOC-sensitive, July is transitional/NO_x-sensitive, August is transitional/NO_x-sensitive, and September is VOC-sensitive.

Superimposed on the temporal variation is spatial variation. There is a progression from VOC-sensitive to NO_x-sensitive chemistry as the urban pollution plume moves downwind. The plume is anchored on the west by the western boundary of the urban/source-intensive area and extends eastward toward the Rincon Mountains (Fig. 1). The downtown area and other upwind source-intensive areas are nearly always VOC-sensitive, while downwind, "urban-fringe" areas such as SNP are nearly always transitional/NO_x-sensitive throughout the ozone season (Diem 2000). Ozone production is probably always NO_x-sensitive in the BVOC-intensive, coniferous forests of the Rincons. Spatiotemporal variations in the sensitivity of ozone production result in monitor-to-monitor and month-to-month variations in ozone levels.

Intraseasonal Ozone Variations

Ambient ozone levels in the Tucson area are a function of VOC and NO_x emissions, atmospheric ventilation, ambient VOC/NO_x concentration ratios, photochemistry, and local and regional pollution transport. These controlling factors vary over time and thus cause intraseasonal variations in ozone levels, with high levels during the summer months (April through September) and low levels during the rest of the year (Figs. 3 and 4).

Nearly all monitors show the highest daily maximum one-hour and eight-hour average values occurring in August (Fig. 3). SNP and 22&C have the highest overall ozone levels, while DT has the lowest values. Ozone levels at TANG and FG behave similarly, even though the two monitors are relatively distant from each other. These two monitors are located on the outskirts of the metropolitan area and are not directly impacted by the urban pollution plume.

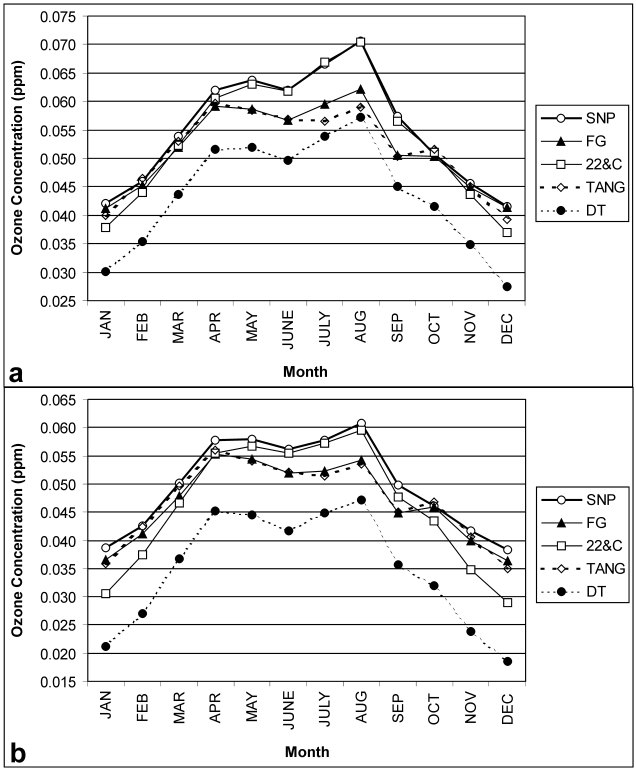

Figure 3 *Month-to-month changes in (a) average daily maximum one-hour average ozone concentrations and (b) average daily maximum eight-hour average ozone concentrations at five ozone monitoring sites in the Tucson area. Refer to Figure 1 for monitor locations.*

Month-to-month variations in ozone exposure values are considerably different from variations in daily maximum values. SUM06 and W126, which in this study are proxies for the magnitude of human and vegetation exposure respectively, have nearly identical variations (Fig. 4). All monitors have the highest exposure levels in April/May or August and a noticeable decrease in either June or July.

In general, SNP, being a downwind and "urban-fringe" monitor that is within the urban pollution plume, has the highest daily maximum ozone concentrations among the monitors, followed by 22&C, TANG, FG, and DT. Considerably higher values occur at SNP and 22&C than at the other three monitors. Downwind, plume-affected monitors have higher ozone exposure levels than do upwind monitors. Semirural and suburban monitors (e.g., SNP, TANG, and FG) always have higher levels than do urban monitors (e.g., DT).

Monitors within the urban/source-intensive area have relatively large diurnal ranges in hourly ozone concentrations due to NO-scavenging, especially during rush hour periods (e.g., 7 a.m). Conversely, monitors outside of the source-intensive area have relatively small ranges (Fig. 5). Since daily maximum one-hour average ozone concentrations depend only on a single hourly concentration, the one-hour average value is the least affected of the four ozone metrics by NO-scavenging. Consequently, heavy NO_x emissions in June cause a smaller drop in daily maximum ozone concentrations compared to ozone exposure levels, which are more sensitive to NO-scavenging. The relatively high ozone exposure levels in April and May at TANG and FG (Fig. 4) presumably result from increased ozone production efficiencies (Lin, Trainer, and Liu 1988) and decreased NO-scavenging, which result in turn from low NO_x emissions (Fig. 2a).

Pollution transport at upper atmospheric levels from Phoenix and other nearby urban areas might also add substantially to ozone levels at TANG and FG during April, May, and June.

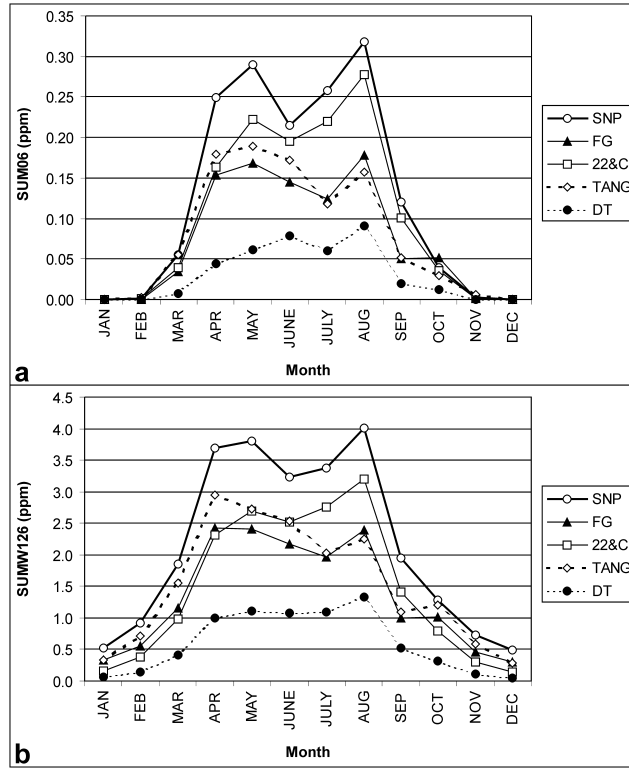

Figure 4 *Month-to-month changes in (a) daily SUM06 values and (b) total daily W126 values at five ozone monitoring sites in the Tucson area. Refer to Figure 1 for monitor locations.*

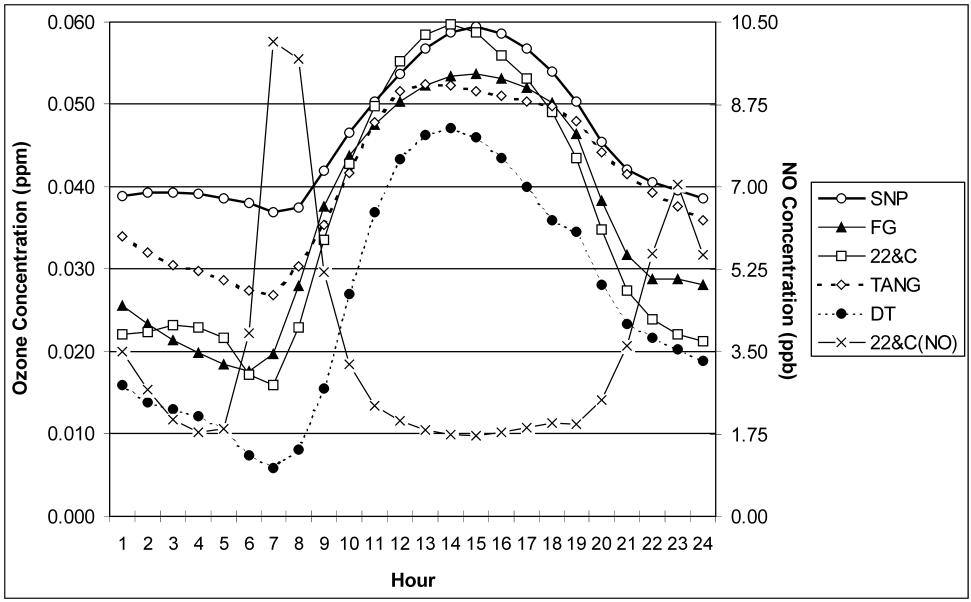

Figure 5 *Diurnal variations in ozone concentrations at the five ozone monitors and NO concentrations at the 22&C monitor.*

Ozone is relatively stable above the mixed layer, and its lifetime is thought to be between ten days (Liu et al. 1980) and sixty days (Hough and Derwent 1990). Thus, Tucson may be affected by ozone with distant origins. This ozone can be entrained to the surface by convection and the subsequent deepening of the mixed layer (Neu, Kunzle, and Wanner 1994; McKendry et al. 1997). Regional pollution transport is discussed in more detail in the next section.

With respect to ozone air quality standards, human exposure, and vegetation exposure, August is the most severe month at most of the monitors because of high VOC and NO_x emissions in addition to decreased ventilation (i.e., light winds and shallow mixed layer). Increased BVOC emissions associated with the North American monsoon result in the high VOC emissions and VOC/NO_x emissions ratio. High NO_x emissions, which result from increased electricity production, increase the ozone formation potential (Wakamatsu et al. 1999), thereby generating high daily maximum ozone concentrations, especially in downwind, plume-affected areas. Since ozone is a photochemical pollutant, it might be expected that, among the summer months, the highest levels should occur in June, a month with high AVOC emissions, high insolation values, and high temperature values (Figs. 2a, 6a). However, low VOC emissions, decreased ozone production efficiency and increased ozone removal caused by increased NO_x emissions, and increased ventilation resulting from increased wind speeds and a deep mixed layer (Fig. 6b) cause ozone levels at most monitors to be considerably lower in June than in August.

These month-to-month changes in the four ozone metrics illustrate the influence of complex interactions between nonlinear chemistry and physical processes on ambient ozone levels (Cardelino and Chameides 1995; Sillman 1999).

Climatology of High Ozone Concentrations

Monthly high ozone concentrations were examined to reveal the temporally varying characteristics of climatic controls on high ozone concentrations (i.e., the top 20 percent of daily maximum eight-hour average concentrations for each month). In this study, important determinants of HODs are those atmospheric conditions that are significantly different ($\alpha = 0.05$ by a Student's *t*-test) between HODs and non-HODs (Tables 1 to 4). Month-specific HOD

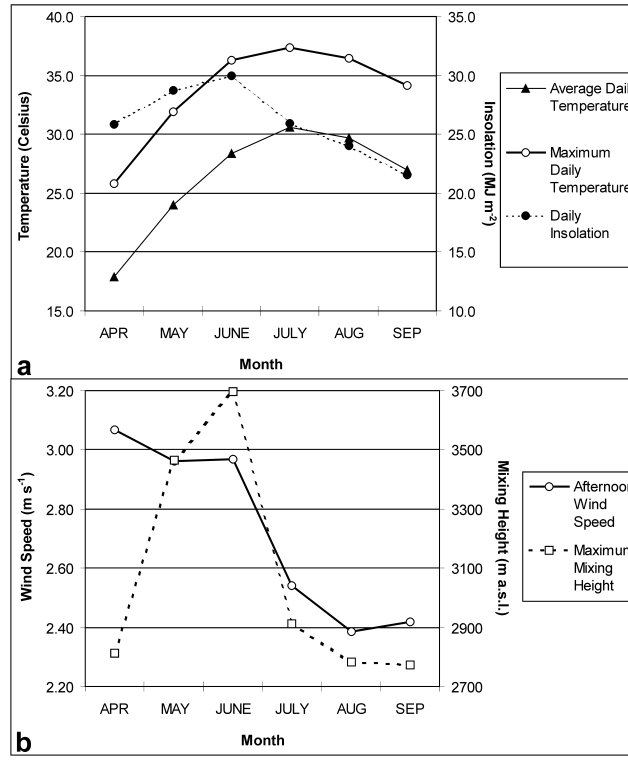

Figure 6 *Month-to-month changes in (a) temperature and insolation and (b) average afternoon wind speed and average maximum mixing height. Temperature, insolation, and wind speed were measured at the AZMET site. Mixing heights were calculated using the Holzworth (1962) method, in which the mixing height is where the adiabatic lapse rate from the daily maximum surface temperature intersected the observed temperature profile.*

versus non-HOD atmospheric differences are presented for both an upwind (TANG) and a downwind (SNP) monitor. HOD conditions are described relative to non-HOD conditions for each month.

Examination of Tables 1 to 4 reveals that HODs during April, May, and June are sunnier, calmer, and have higher atmospheric pressure at the surface than non-HODs. These HODs have light and westerly to northwesterly upper-level winds. An exception is that 850 mb winds in June are northerly. HODs during July, August, and September are not as dependent on surface pressure; rather, they are associated more with temperature-related conditions. They are hotter, drier, and sunnier than non-HODs. In contrast to those in July and September, August HODs have relatively high pressure at the surface as well as light 850 mb winds.

Summary of HODs. HODs during all summer months are typically associated with upper-level, synoptic-scale anticyclones and ridges (Figs. 7 and 8). These high-pressure areas vary in location and magnitude depending on the summer month, and indirectly produce elevated ozone concentrations in the Tucson area by creating optimal conditions for in-situ ozone production, regional transport of ozone and its precursors, or both.

Each month has a unique set of conditions that are conducive to high ozone concentrations. Considering both HODs and non-HODs, April does not have optimal afternoon atmospheric conditions with respect to photochemical pollutant production and dispersion. It has the lowest temperatures, least intense insolation, and windiest conditions of all months of the ozone season. Therefore, nearly all of the HODs occur during the second half of the month. These HODs are dependent on the co-occurrence of hot, sunny, and calm conditions at the surface that are associated with an upper-level ridge that covers the Tucson area (Fig. 7a). This system also creates calm, westerly/northwesterly, upper-level winds that might transport pollutants from Phoenix to Tucson and thus contribute to elevated ozone concentrations. Ozone

Table 1 *Average Surface Atmospheric Conditions for TANG's HODs and Typical Days during Each Month*

	MAXT[a]	MINRH[b]	PRESS[c]	INSOL[d]	WS_{Daily}[e]	$WS_{Afternoon}$[f]	$WD_{Afternoon}$[g]
APR							
HOD	***30.2***	***11.9***	***925.5***	***28.0***	***3.2***	***3.0***	***271***
AVG	26.9	15.2	923.9	25.8	3.7	3.3	259
MAY							
HOD	34.0	11.3	***924.1***	29.1	3.3	3.1	267
AVG	33.2	11.6	923.4	28.8	3.6	3.1	266
JUNE							
HOD	38.1	9.2	***924.2***	***31.3***	***2.9***	3.1	260
AVG	37.8	10.0	922.9	30.0	3.6	2.9	265
JULY							
HOD	***40.4***	***17.1***	924.5	***27.5***	3.6	3.0	259
AVG	38.1	21.6	924.9	26.0	3.5	3.1	263
AUG							
HOD	***38.5***	***22.1***	***923.5***	***25.8***	3.5	2.7	268
AVG	36.9	27.7	924.6	24.0	3.5	2.7	266
SEP							
HOD	***36.3***	24.7	922.1	22.3	3.2	2.6	***241***
AVG	33.3	25.8	923.1	21.6	3.3	2.7	264

Note: HOD values in bold, italicized type are significantly different ($\alpha = 0.05$) from non-HOD values.
[a] *MAXT = daily maximum temperature (°C).*
[b] *MINRH = daily minimum relative humidity (%).*
[c] *PRESS = average daily pressure (mb).*
[d] *INSOL = total daily insolation (MJ m^{-2}).*
[e] *WS_{Daily} = average daily wind speed (m s^{-1}).*
[f] *$WS_{Afternoon}$ = average afternoon wind speed (m s^{-1}).*
[g] *$WD_{Afternoon}$ = average afternoon wind direction (°).*

aloft is entrained to the surface as the mixing height increases throughout the day. Interestingly, Tables 3 and 4 and Figure 7b indicate that some of Tucson's pollution on typical days in April might originate from southern California (e.g., San Diego and Los Angeles) and/or northwestern Mexico (e.g., Tijuana and Mexicali) rather than from Phoenix.

Ozone production at TANG and SNP is transitional to VOC-sensitive in May and June. Production during these months is critically dependent on high atmospheric pressure at the surface as well as light, northwesterly, 850-mb winds. These HODs are neither hotter nor drier than the rest of the days. Extremely high temperatures and dry conditions in the arid foresummer

Table 2 *Average Surface Atmospheric Conditions for SNP's HODs and Typical Days during Each Month*

	MAXT	MINRH	PRESS	INSOL	WS_{Daily}	$WS_{Afternoon}$	$WD_{Afternoon}$
APR							
HOD	***29.6***	***12.4***	***925.3***	***28.1***	***3.1***	***2.6***	***285***
AVG	26.9	15.2	923.9	25.8	3.7	3.0	276
MAY							
HOD	34.1	10.9	***924.3***	***29.6***	***3.2***	3.0	***276***
AVG	33.2	11.6	923.4	28.7	3.6	2.9	264
JUNE							
HOD	38.1	10.2	***923.7***	***31.6***	***3.0***	***2.9***	***286***
AVG	37.8	10.0	922.9	30.0	3.6	2.5	259
JULY							
HOD	***40.6***	***16.3***	924.6	***27.9***	3.4	2.5	***294***
AVG	38.1	21.6	924.9	25.9	3.5	2.7	284
AUG							
HOD	***38.0***	***24.5***	***923.8***	***25.8***	3.5	2.3	262
AVG	36.9	27.7	924.6	24.0	3.5	2.7	271
SEP							
HOD	***36.1***	27.7	923.8	***23.0***	3.2	2.8	***293***
AVG	33.3	25.8	923.1	21.5	3.3	2.7	264

Note: HOD values in bold, italicized type are significantly different ($\alpha = 0.05$) from non-HOD values. Variable descriptions are presented in the caption for Table 1.

Table 3 *Average Upper-Level Atmospheric Conditions for TANG's HODs and Typical Days during Each Month*

	500 H[a]	500 T[b]	500 DP[c]	500 WD[d]	500 WS[e]	700 H[a]	700 T[b]	700 DP[c]	700 WD[d]	700 WS[e]	850 H[a]	850 T[b]	850 DP[c]	850 WD[d]	850 WS[e]	8550 H[f]	8570 H[g]
APR																	
HOD	***5748***	***−13.6***	−37.6	***304***	***12.8***	***3107***	***3.7***	−16.7	***273***	***6.1***	***1498***	***15.4***	***−8.3***	***49***	***4.2***	***4250***	***1609***
AVG	5695	−15.3	−35.2	273	18.7	3071	1.3	−16.2	246	9.8	1477	12.6	−5.8	246	5.4	4218	1593
MAY																	
HOD	5794	−11.0	−27.8	***264***	***14.4***	3121	6.4	−11.4	***252***	***7.6***	***1495***	18.7	−1.9	***311***	4.1	4299	1626
AVG	5779	−11.3	−29.7	249	17.0	3110	6.3	−14.4	233	9.5	1487	17.8	−2.2	237	4.8	4292	1623
JUNE																	
HOD	5848	−8.5	−30.5	***263***	***8.7***	3150	9.7	−11.5	***223***	***5.4***	***1505***	21.9	−1.6	***352***	***4.5***	4343	1645
AVG	5841	−8.6	−29.1	232	12.8	3142	10.3	−9.8	221	9.2	1493	22.3	−0.9	223	5.4	4347	1648
JULY																	
HOD	***5922***	−6.9	−17.9	91	6.7	***3195***	***13.9***	0.4	57	***3.9***	1519	***26.8***	4.8	***60***	***4.1***	***4403***	***1676***
AVG	5902	−6.9	−18.3	151	6.7	3183	12.2	1.0	144	5.0	1519	24.4	7.6	225	4.7	4383	1664
AUG																	
HOD	***5916***	−6.6	−18.8	***94***	5.8	***3194***	***12.9***	***2.7***	***51***	5.1	1524	***25.0***	***9.5***	105	***3.8***	***4392***	***1670***
AVG	5902	−6.6	−16.2	130	5.8	3183	11.9	4.1	94	4.9	1520	23.7	11.7	114	4.7	4382	1663
SEP																	
HOD	***5872***	−6.8	***−22.6***	***174***	***8.2***	3159	***11.6***	0.5	***149***	***6.1***	1498	***23.8***	7.5	***83***	4.4	***4373***	***1661***
AVG	5858	−7.0	−27.0	234	10.0	3153	10.0	−0.4	196	7.2	1501	22.2	8.6	149	4.6	4357	1651

Note: HOD values in bold, italicized type are significantly different ($\alpha = 0.05$) from non-HOD values. Variable descriptions are as follows:

[a] *500H, 700H, 850H = heights (m) at the three levels.*
[b] *500T, 700T, 850T = temperatures (°C).*
[c] *500DP, 700DP, 850DP = dew point temperatures (°C).*
[d] *500WD, 700WD, 850WD = wind directions (degrees).*
[e] *500WS, 700WS, 850WS = wind speeds (m s^{-1}).*
[f] *8550H = 500 mb minus 850 mb height difference (m).*
[g] *8570H = 700 mb minus 850 mb height difference (m).*

might suppress BVOC emissions and increase NO_x emissions from power plants, thereby resulting in depressed ozone concentrations.

Unlike April's HODs, which have both high upper atmospheric pressure and anomalous upper-level winds, HODs in May and June are only associated with the latter. Consequently, the singular presence of light, northwesterly winds at the 850-mb level, which are associated with slight ridging (Fig. 7c, e), during May and

Table 4 *Average Upper-Level Atmospheric Conditions for SNP's HODs and Typical Days during Each Month*

	500 H	500 T	500 DP	500 WD	500 WS	700 H	700 T	700 DP	700 WD	700 WS	850 H	850 T	850 DP	850 WD	850 WS	8550 H	8570 H
APR																	
HOD	***5736***	***−13.4***	−35.2	***291***	***15.1***	***3097***	***2.7***	−15.3	***277***	***4.9***	***1495***	***14.4***	−6.6	***49***	***4.2***	***4242***	***1603***
AVG	5695	−15.3	−35.2	273	18.7	3071	1.3	−16.2	246	9.8	1477	12.6	−5.8	246	5.4	4218	1593
MAY																	
HOD	5792	−10.9	−27.6	***256***	***14.9***	***3120***	6.2	−11.7	232	***8.2***	***1495***	18.4	−3.4	***270***	4.1	4297	1625
AVG	5779	−11.3	−29.7	249	17.0	3110	6.3	−14.4	233	9.5	1487	17.8	−2.2	237	4.8	4292	1623
JUNE																	
HOD	5844	−8.3	−30.6	***269***	***9.1***	3145	9.7	−10.7	***233***	***5.1***	1500	21.7	−1.6	***351***	***4.4***	4344	1644
AVG	5841	−8.6	−29.1	232	12.8	3142	10.3	−9.8	221	9.2	1493	22.3	−0.9	223	5.4	4347	1648
JULY																	
HOD	***5925***	−6.9	−17.6	***82***	6.1	***3196***	***14.3***	−0.7	2	4.6	1519	***26.9***	***5.0***	358	4.8	***4406***	***1677***
AVG	5902	−6.9	−18.3	151	6.7	3183	12.2	1.0	144	5.0	1519	24.4	7.6	225	4.7	4383	1664
AUG																	
HOD	***5908***	−6.6	−14.4	123	5.8	3185	***12.8***	3.5	72	4.2	1517	24.5	***10.6***	112	***3.2***	***4391***	***1668***
AVG	5902	−6.6	−16.2	130	5.8	3183	11.9	4.1	94	4.9	1520	23.7	11.7	114	4.7	4382	1663
SEP																	
HOD	5857	−7.3	−25.1	***180***	7.7	3153	10.6	***2.1***	***121***	6.9	1495	***23.4***	8.9	***59***	***5.9***	4362	1657
AVG	5858	−7.0	−27.0	234	10.0	3153	10.0	−0.4	196	7.2	1501	22.2	8.6	149	4.6	4357	1651

Note: HOD values in bold, italicized type are significantly different ($\alpha = 0.05$) from non-HOD values. Variable descriptions are presented in the caption for Table 3.

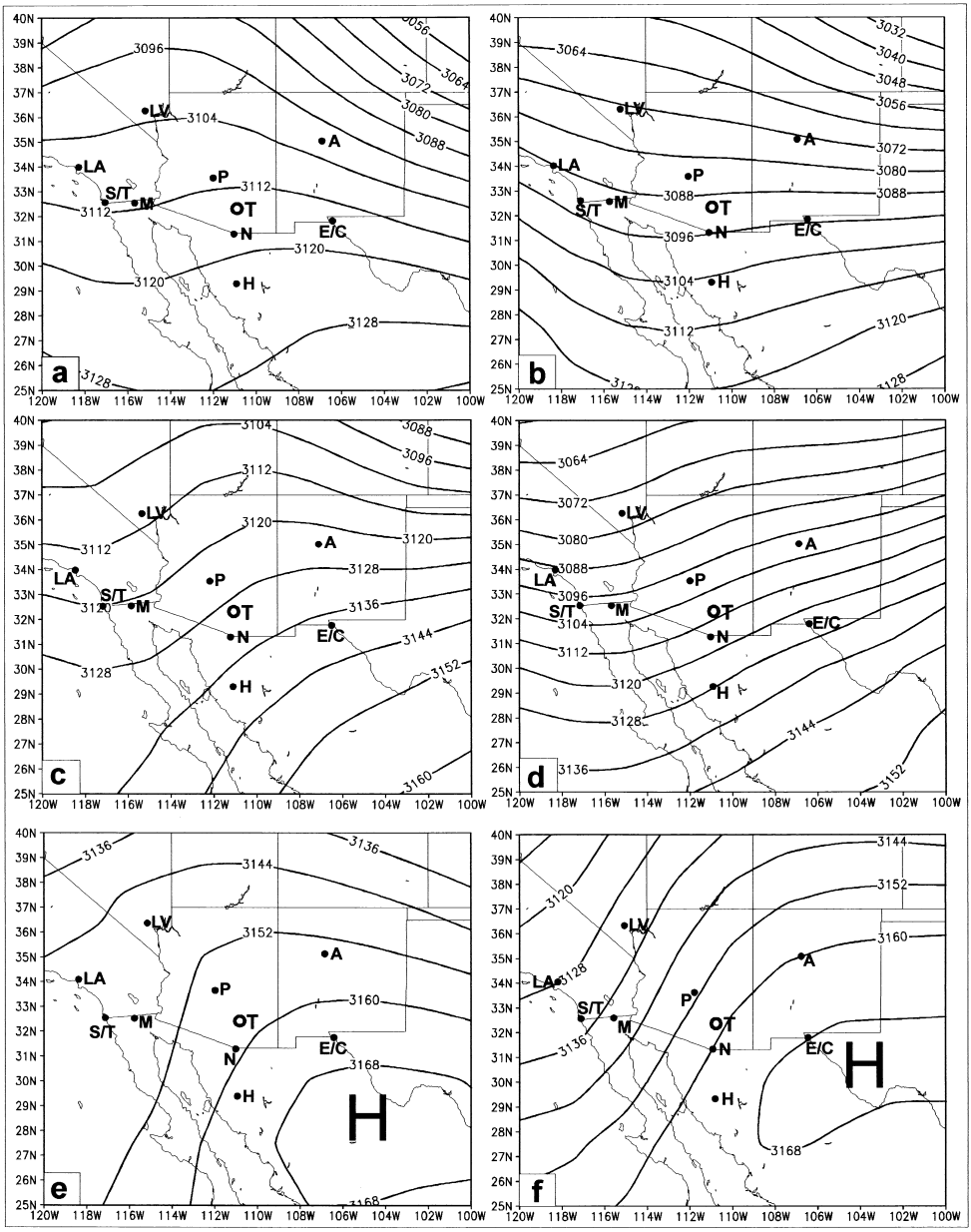

Figure 7 *Height (geopotential meters) of the 700 mb isobaric surface at 12Z over the southwestern U.S. for typical TANG HODs in (a) April, (c) May, and (e) June and for average days in (b) April, (d) May, and (f) June. Each HOD composite shows the presence of anomalous ridging over Arizona. Descriptions of abbreviations of cities from which a portion of the area's pollution might originate are as follows: A (Albuquerque); E/C (El Paso/Ciudad Juarez); H (Hermosillo); LA (Los Angeles); LV (Las Vegas); M (Mexicali); N (Nogales); P (Phoenix); and S/T (San Diego/Tijuana).*

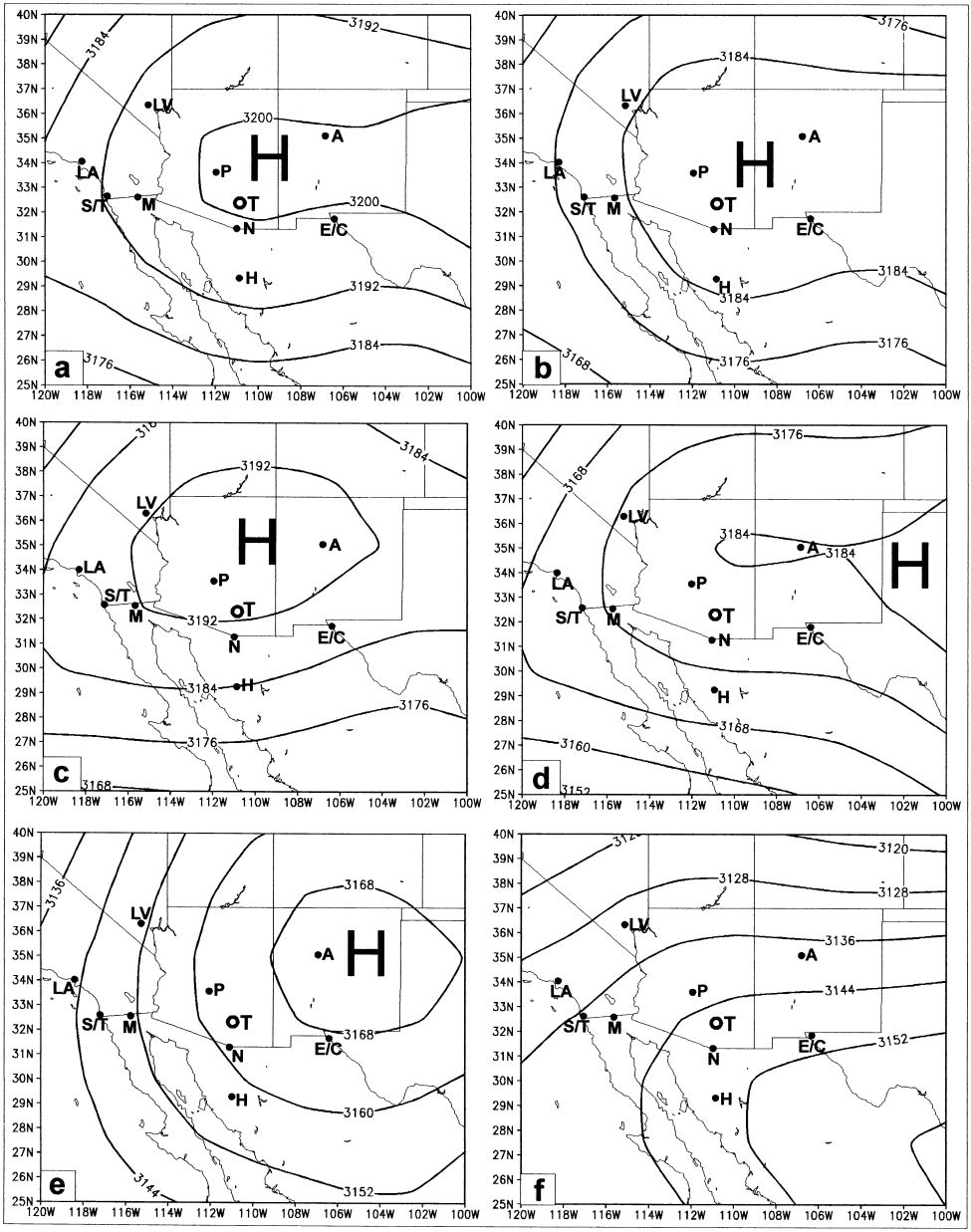

Figure 8 *Height (geopotential meters) of the 700 mb isobaric surface at 12Z over the southwestern U.S. for typical TANG HODs in (a) July, (c) August, and (e) September and for average days in (b) July, (d) August, and (f) September. Each HOD composite shows a northward and/or westward displacement of high-pressure cells. Refer to caption of Figure 7 for descriptions of city abbreviations.*

June's HODs, indicates a potential for regional pollution transport. Although this transport most likely involves Phoenix and possibly Las Vegas, frequent upper-level southerly winds might advect pollution from northern Mexico (e.g., Hermosillo and Nogales). In addition, even though both TANG and SNP have relatively low ozone concentrations on typical days in June (Fig. 3b), the two monitors have relatively high ozone concentrations on June's HODs (Fig. 9a). Coefficients of variation of ozone concentrations are also statistically similar at TANG and SNP on both typical days and HODs (Fig. 9b); TANG's values are typically much larger than SNP's values. Similarities in diurnal variability suggest that ozone aloft is supplementing the surface ozone budget, with the largest impact occurring at TANG. Therefore, both monitors have relatively flat diurnal curves on June HODs (Fig. 10). This also implies a constant entrainment of ozone from upper levels throughout the convection period (i.e., sunrise to sunset). In addition, although it is related to local transport rather than regional transport, SNP has an increase in ozone concentrations between 1 a.m. and 6 a.m., probably due to cold air drainage from the Rincon Mountains and associated low-level temperature inversions (Kirby and Sellers 1987; Comrie 2000). An increase in ozone concentrations during the early morning hours is unusual, for ozone is not produced nocturnally and low-level temperature inversions increase the removal of ozone at the surface. However, during most June HODs, easterly to southeasterly drainage winds most likely transport ozone-rich air down from the Rincons into the eastern portion of the metropolitan area. This convergence of circumstantial evidence points towards the injection of regionally transported pollution into Tucson's atmosphere during May and June.

A warm, quasistationary, upper-level, high-pressure cell positioned over southern Arizona (Fig. 8a, c) and associated surface temperature

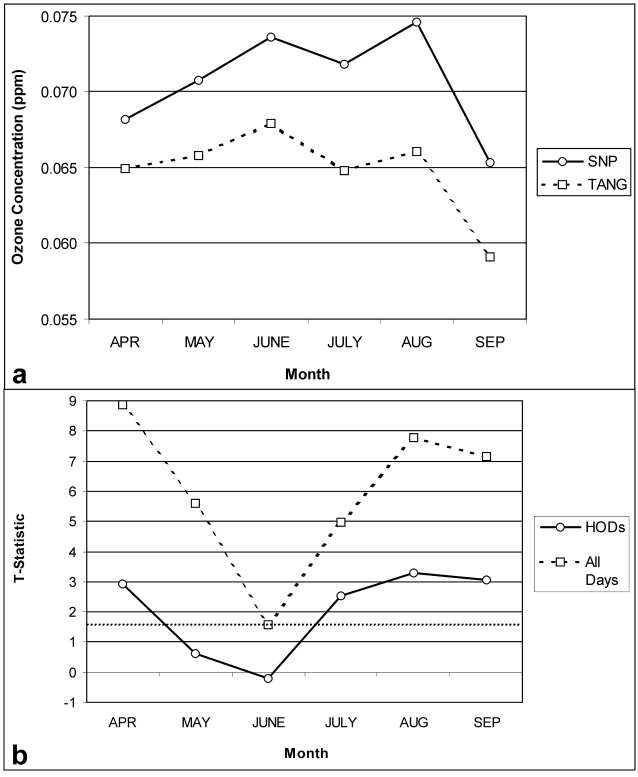

Figure 9 *Month-to-month changes in (a) daily maximum eight-hour average ozone concentrations on HODs at TANG and SNP and (b) differences in coefficients of variation of hourly ozone concentrations between TANG and SNP. In Figure 9b, values below the dashed line indicate that differences between the two monitors are not significant ($\alpha = 0.05$).*

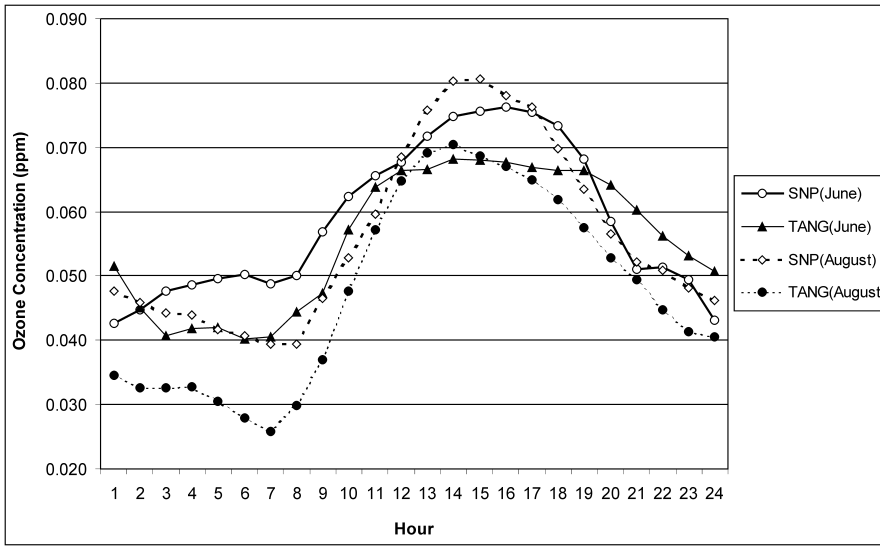

Figure 10 *Diurnal variations in ozone concentrations at TANG and SNP during HODs in June and August.*

and humidity are important factors during July and August. Similar to HODs in April, July's HODs occur primarily toward the end of the month—that is, when conditions are comparable to those in August. High surface and aloft temperatures, especially in July, as well as a dry lower troposphere, are conducive to high ozone concentrations in July and August. Contrary to the situation during May and June, these NO_x-sensitive months presumably need increased NO_x emissions and/or decreased BVOC emissions, along with hot and sunny conditions, to yield high ozone concentrations. Phoenix-derived pollution may still impact Tucson in July, for July's HODs have northerly to northeasterly upper-level winds. A smaller potential source region in July is Albuquerque. The situation changes in August, for upper-level winds during HODs are mostly easterlies, implicating the El Paso, Texas/Ciudad Juarez, Mexico metropolitan area as the most plausible source region. However, with the Tucson area located almost directly under the center of an upper-level, high-pressure cell during July and August, the resultant light and variable winds may only have a small potential for pollution transport. This notion is supported by strongly statistically different coefficients of variation between the two monitors (Fig. 9b) as well as large diurnal fluctuations in ozone concentrations (Fig. 10).

Finally, high ozone concentrations in September are associated with high temperatures, both at the surface and aloft, a warm troposphere, and intense insolation resulting from the northward displacement of a high-pressure cell (Fig. 8e, f). These conditions are needed to increase photochemical activity and subsequent ozone formation. Since most of September's HODs occur in the first half of the month, the above conditions reflect the final stages of the monsoon. More so than in July and August, September's HODs might be influenced by pollution from the El Paso/Ciudad Juarez area based on the easterly to southeasterly wind directions at the 850- and 700-mb levels.

Atmospheric conditions that are conducive to elevated ozone concentrations do not vary considerably between upwind and downwind locations in the Tucson area. Both SNP and TANG are located in "urban-fringe" environments and have similar precursor-sensitive atmospheres during each month. However, there are slight differences resulting from SNP being in the Tucson pollution plume and TANG being on the upwind boundary of the plume. For instance, Phoenix's pollution should theoreti-

cally impact TANG's ozone levels more noticeably than those at the other monitors, since TANG is the most upwind monitor and is thus the least affected by Tucson-derived emissions. This article's results, such as high ozone exposure levels in April, May, and June and the occurrence of exceedingly high and temporally stable ozone concentrations in June, indicate that TANG is indeed probably more affected than SNP by regional pollution transport, especially from the Phoenix area. Another major difference is that SNP's HODs during most months are dependent on westerly to northwesterly afternoon winds at the surface, while TANG's HODs are not. Locally transported ozone and its precursors contribute heavily to ambient ozone concentrations at SNP. Westerly to northwesterly surface winds maximize SNP's upwind local pollution source area; consequently, ambient VOC, NO_x, and ozone concentrations are also maximized.

To summarize, the sensitivity of ozone production at a site and—to a lesser degree—the site's relative upwind or downwind location determine which atmospheric conditions are conducive to elevated ozone concentrations in the Tucson area. Regional pollution transport via upper-level winds is another factor that might contribute to high ozone concentrations. This particular meteorological phenomenon is mostly independent of ozone production sensitivity and location within an urban area. It should be noted that Tucson's pollution can be transported to one or more of the aforementioned urban areas and thus add to their ozone levels. Intensive research (e.g., back trajectory analyses, joint examinations of wind variables and ozone concentrations, and so on), which is beyond the scope of this article, is needed to verify the existence of and determine the overall importance of regional pollution transport. Results presented in this article merely suggest the strong possibility of regional pollution transport.

Policy Implications

Air quality policy implications associated with ozone pollution in the Tucson region relate to the NAAQS for ozone, various ozone reduction strategies, and regional pollution transport that occurs both within the U.S. and between the U.S. and Mexico. These matters are interrelated and therefore must be considered simultaneously when devising strategies to improve air quality in Tucson.

The current NAAQS for ozone involves the daily maximum one-hour average ozone concentration. However, an eight-hour average concentration may soon be adopted depending on the outcome of current litigation. The eight-hour standard is designed for longer exposure periods and should thus more adequately protect public health and welfare against adverse effects of ozone (Rombout, Lioy, and Goldstein 1986). An exceedance of the one-hour standard occurs when the fourth-highest daily maximum one-hour average concentration at a monitor over a three-year period reaches 0.125 ppm. An exceedance of the eight-hour standard occurs when a monitor's three-year average of each year's fourth-highest daily maximum eight-hour average concentration reaches 0.085 ppm. The values to which these exceedance threshold values are compared are known as design values.

Tucson has a much higher likelihood of exceeding the eight-hour standard than the one-hour standard. Tucson's one-hour design values in 1997 and 1998 were 0.101 ppm and 0.094, respectively. During those same years, the eight-hour design values were 0.080 and 0.079. These design values occurred at SNP. The one-hour values were between 75 percent and 81 percent of the exceedance threshold values, while the eight-hour values were between 93 percent and 94 percent of the exceedance threshold values. In fact, modeling results (Diem and Comrie in review) indicate that Tucson may have violated the eight-hour standard in 1997 in an unmonitored area between the 22&C and SNP monitors. Approximately 1,500 people may have been exposed to federally determined "unhealthy" ozone levels (Diem and Comrie in review).

If the eight-hour standard was promulgated in the near future and Tucson were to violate it, the region would be classified as an ozone nonattainment area. Tucson would acquire either marginal, moderate, serious, severe, or extreme nonattainment status. With marginal status, which appears to be the most likely, state and local agencies would be forced to apply reasonable available control technology (RACT) to a wide range of stationary sources (Chang et al. 1992). Acquiring moderate status would force the agencies to develop plans to reduce VOC

emissions (and NO_x emissions, if necessary) by 15 percent within six years. In addition, the agencies would have to apply RACT on stationary sources, establish motor vehicle refueling regulations (e.g., secondary vapor recovery at gasoline stations), and establish a motor vehicle inspection/maintenance (I/M) program (Chang et al. 1992). Only if Tucson were to be labeled as a serious, severe, or extreme nonattainment area would it have to employ photochemical grid models in simulations designed to demonstrate that proposed air pollution control measures would bring the area into ozone attainment status (Saylor, Chameides, and Chang 1999).

The selection of a specific ozone reduction strategy is a complicated procedure, whether it is done for regulatory purposes or not. In addition to the aforementioned RACT application, I/M program, and vehicle refueling regulations, other strategies include the introduction of reformulated gasoline, the employment of traffic control measures (TCMs), and the modification of the urban atmosphere. TCMs are intended to control congestion and VMT growth (Hawthorn 1991). Specific TCMs include employer-based trip reduction rules, management of parking supply and pricing, regional high-occupancy vehicle system plans, and land development policies that seek to reduce vehicle trips and promote mass transit use by reconnecting transport with land use through such means as the establishment of transit-oriented development consisting of higher density, mixed-use areas built around high-quality transit systems (i.e., New Urbanism) (Chang et al. 1992; Newman and Kenworthy 1996). The modification of the urban atmosphere involves the lowering of urban temperatures, which can be accomplished by the widespread planting of ozone-tolerant, xerophytic, and low-BVOC-emitting trees and shrubs. This concept has been modeled for the Los Angeles area, and the reduced temperature effect has been shown to significantly improve air quality (Taha, Konopacki, and Akbari 1998). Lowered temperatures decrease chemical reaction rates and reduce precursor emissions (e.g., BVOCs, AVOCs from evaporated gasoline and solvents, and NO_x from power plants due to decreased cooling demand). In addition, more vegetation increases the surface deposition area for the removal of ozone.

Spatiotemporal variations in the sensitivity of ozone production prohibit the adoption of a singular NO_x or VOC control measure to reduce ozone levels. Reducing NO_x emissions (VOC emissions) is only effective when NO_x-sensitivity (VOC-sensitivity) occurs at a particular time and place. As an example, reducing NO_x emissions might decrease ozone levels during the predominantly NO_x-sensitive months (July and August), especially in downwind rural areas such as coniferous forests in the Rincon Mountains. However, ozone exposure levels in the urban/source-intensive area might increase due to reduced NO-scavenging effects. Consequently, human exposure to harmful ozone levels might increase, while the exposure of sensitive, downwind forests to harmful ozone levels might decrease. Selecting a reduction strategy involves deciding between various consequences.

Regional pollution transport changes the complexion of Tucson's ozone pollution problem. Tucson could be designated a transport region if its ozone levels are not caused completely by sources in the region (Chang et al. 1992). Therefore, if Tucson has a serious or worse nonattainment status, it would be treated as a moderate nonattainment area. Additionally, a regional oxidant model (ROM) could be applied to central and southern Arizona to determine the regional impacts of pollutants from Tucson and Phoenix. Phoenix is currently a serious ozone nonattainment area and is also the most likely source area of regionally transported pollutants in Tucson.

Tucson's ozone levels may also be influenced by Mexican air pollution. As mentioned previously, Tijuana, Mexicali, Hermosillo, Nogales, and Ciudad Juarez are Mexican urban areas that might be source areas for regionally transported pollutants. *Maquiladoras*—foreign-owned manufacturing facilities that were stimulated by the adoption of the North American Free Trade Agreement (NAFTA) in 1993—are major pollutant emitters in and around border towns. The proliferation of maquiladoras has been accompanied by rapid urban growth: the population of Mexican border cities increased by 20 percent from 1995 to 2000, and it will more than double in the next two decades if moderate growth continues (Mumme 1999).

Transboundary air quality issues and other environmental issues are addressed by binational technical working groups established under the

La Paz Agreement in 1983. In addition, NAFTA created several new institutions charged with managing the border environment (Liverman et al. 1999). Similar to what has been done for the El Paso/Ciudad Juarez area (Hays and Malkus 1996), the La Paz Agreement and its predecessor, the U.S-Mexico Border XXI Program (associated with NAFTA) may need to be addressed with respect to ozone pollution in the Tucson area if a substantial amount of Tucson's air pollutants is deemed to have originated in Mexico.

Summary and Conclusions

Spatiotemporal variations in ozone levels in the Tucson area result from dynamic human-environment interactions. Intraseasonal climate variations play a large role in directly and indirectly controlling ambient ozone levels. Variables such as temperature and insolation directly affect the nonlinear chemical reactions involved in ozone production. As an indirect effect, the appearance of the North American monsoon in July causes a dramatic increase in BVOC emissions, thereby taking ozone production at most locations from a mostly VOC-sensitive situation in June to a transitional/NO_x-sensitive situation in August. Overall, the highest ozone levels usually occur at downwind locations where ambient concentrations of both VOCs and NO_x are high. This is especially true during the monsoon, when both VOC and NO_x emissions are usually at a maximum. Finally, upper-level synoptic scale circulation features (e.g., high-pressure cells) and mesoscale circulations (e.g., mountain-valley winds) directly affect pollutant transport processes regionally and locally.

The occurrence of high ozone concentrations during each summer month is a function of the overall sensitivity of ozone production, the presence of atmospheric conditions that provide optimal in-situ ozone production conditions with respect to the different precursor-sensitive situations, and the presence of upper-level circulation features that might transport ozone and its precursors to Tucson from other urbanized areas. Atmospheric conditions conducive to elevated ozone concentrations differ substantially between the arid foresummer (May and June) and the core monsoon months (July and August). High ozone levels during May and June, which have mostly VOC-sensitive ozone production, depend on high atmospheric pressure at the surface as well as light northwesterly winds aloft. Upper-level winds during HODs of April, May, and June have some potential for transporting ozone, mostly from Phoenix to Tucson. During the monsoon and early fall, high surface and upper-level temperatures as well as a dry lower troposphere are conducive to high ozone concentrations. Upper-level winds during most of the monsoon and early fall have some potential for contributing to elevated ozone concentrations in Tucson by transporting pollution, mostly from the El Paso/Ciudad Juarez area.

The above results can facilitate more informed decisions regarding air quality policy. If the eight-hour ozone standard is promulgated, Tucson may become an ozone nonattainment area and thus be forced by the EPA to reduce ozone precursor emissions. There is evidence that ozone-induced damage has already occurred in high-elevation coniferous forests (Duriscoe and Selph 1985). Consequently, it seems imperative that some ozone control measures be implemented to reduce ozone levels in both urban and rural areas. Reducing ozone levels in the Tucson area involves controlling VOC emissions, NO_x emissions, or both through strategies such as inspecting and maintaining important pollutant sources, switching to less polluting fuels, implementing traffic control measures, and planting additional trees in urbanized areas. Increased cooperation with other urban/industrial areas in the southwestern U.S./northern Mexico border zone is also needed to quantify the impacts of regional pollutant transport and to subsequently formulate strategies to reduce ozone levels throughout the entire zone. Detailed chemical modeling studies are needed to assess the impact of all major changes to precursor emissions and the urban atmosphere on ozone levels in the Tucson area and in the border zone. Many of these policy recommendations are appropriate for other urban areas in the southwestern U.S. ■

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