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Spatial Pattern of Ground-Level Ozone Concentration in Dallas-Fort Worth Metropolitan Area

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ABSTRACT: The objective of this study was to analyze spatial patterns of ground-level ozone concentration in the Dallas-Fort Worth, Texas metropolitan area. Average daily maximum eight-hour ozone concentration, number of days with concentrations exceeding 75 ppb, average outside air temperature, and resultant wind direction at 20 monitoring stations were compiled for January-December, 2013. Recent estimates of population and vehicle miles traveled were also compiled for 12 counties with ozone monitoring station(s). Ozone levels and resultant wind directions were mapped for representative months in each season. On several days from May-October, eight-hour ozone measurements exceeded 75 ppb. September, followed by August, produced the highest ozone concentrations, as well as the most observations exceeding 75 ppb. Late spring and summer months also showed the greatest range in ozone concentrations; during this time period, sustained southeasterly winds caused distinct clusters of high ozone concentration at the northern perimeter of the study area. However, ozone concentrations at individual monitoring stations were not associated with population or vehicle miles traveled in counties occupied by those stations.

Key words: Ozone, Dallas, Fort Worth,Texas

INTRODUCTION

Air pollution from natural and human sources is a significant environmental hazard in many parts of the world. A primary ingredient of ground-level smog, ozone often accumulates to high levels in urban areas with heavy automobile traffic and warm outside air temperatures. Areas with high solar radiation (clear skies), stagnant air (slow wind speeds), and emissions of nitrogen oxides, carbon monoxide, and volatile organic compounds (VOCs) are especially prone to hazardous ozone conditions. Nitrogen oxides, carbon monoxide, and VOCs from various sources react with sunlight to produce ground-level ozone. Major sources for these gases include motor vehicle exhaust, industrial facilities, electrical utilities, gas-powered yard equipment, gasoline vapors, chemical solvents, and biogenic sources. Ozone concentrations often peak in mid-afternoon to early evening (EPA, 2003). Children, older adults, and people with lung disease are particularly sensitive to ozone. Exposure to high ozone levels may impair functional lung development (Murphy *et al*., 2013), as well increase the frequency of respiratory disease in children (Fanucchi *et al*., 2006). In all people, breathing in high levels of ozone may irritate or damage cells in the respiratory system; decrease the elasticity of lung tissue; cause coughing, congestion, chest pain, eye irritation, and throat irritation; and aggravate symptoms of asthma, bronchitis, and emphysema (EPA, 2003).

High ozone concentrations may also lead to reduced agricultural crop and commercial forest yields; reduced survival and growth of trees; and increased plant susceptibility to disease, pests, and other stresses such as harsh weather. In the United States alone, ground-level ozone is responsible for an estimated $500 million in reduced crop production each year. Crops especially sensitive to ozone include lettuce, grapes, and corn, among others (Keller, 2011). Ground-level ozone also damages the foliage of trees and other plants, affecting the landscapes of cities, national parks and forests, and recreation areas (EPA, 2003). In addition to harming plants and animals, ozone can damage rubber, paint, and textiles (Keller, 2011). Many urban and suburban areas throughout the United States experience high ozone levels. Rural areas may also experience adverse ozone conditions,

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as winds carry precursor emissions and ozone away from their original sources (EPA, 2003). The Dallas-Fort Worth metropolitan area (DFW) has experienced high ozone concentrations in recent decades. Over the last decade, the problem has actually improved despite a large increase in population, through multi-faceted programs including emissions control programs (TCEQ, 2014a).

The United States Environmental Protection Agency has set air quality standards for major air pollutants including ozone. For an eight-hour averaging time, the standard for ozone is 75 parts per billion (ppb) (EPA, 2011). Higher ozone concentrations are considered unhealthy for sensitive people. A region is non-compliant if, among its monitoring stations, the annual fourth-highest daily maximum eight-hour ozone concentration, averaged over three years, exceeds 75 ppb. Recently, the EPA (2014) classified ten counties in DFW (Wise, Denton, Collin, Parker, Tarrant, Dallas, Rockwall, Kaufman, Johnson, and Ellis) as a moderate non-attainment area (Figure 1). While previous studies of DFW examined temporal ozone concentration trends and the application of predictive models, this study portrays and evaluates spatial patterns of ozone concentration, including associations with wind direction, outdoor air temperature, population, and vehicle miles traveled. Ground-level ozone in DFW tends to reach high levels periodically between May and October (Cox and Chu, 1996), although the magnitude of this problem has decreased in recent years. Sather and Cavender (2012) analyzed eight-hour ozone data in the south-central United States. In DFW, 88% of the annual four highest eight-hour ozone daily maxima for 2006-2010 occurred from June-August. Ambient ozone concentrations showed a notable decrease over this five-year period, despite more favorable meteorology for ozone production. At the highest-concentration site in the monitoring network, the three-year average of the annual fourth highest eight-hour ozone concentration dropped from 95 ppb in 2003-2005 to 86 ppb in 2008-2010. These trends reflect a decrease in precursor gases through emission reduction measures. Mean concentrations of VOC precursors (total non-methane organic compounds, ethylene, propylene, and m/p xylene) at one Dallas monitoring site were down 39-61% for 2006-2010 compared to 1996-2000, and mean concentrations of nitrogen oxide precursors were down 54% for 2006-2010 compared to 1991-1995 (Sather and Cavender, 2012).

Previous investigators also used models to predict ozone concentrations in DFW and surrounding areas, comparing predictions with measured concentrations. For example, Temiyasathit *et al.* (2009) used multi-scale and functional data analysis to predict time series at several ozone monitoring stations over a three-year period. Recently, Digar *et al.* (2013) developed probabilistic estimates of ozone sensitivity to nitrogen oxide emissions by incorporating uncertainties into photochemical modeling.

Others used models to identify probable sources of ozone. For example, Wilczak *et al.* (2009) found that, while commonly-used models under-predicted the full range of observed ozone concentrations in east Texas, a combination of regional anthropogenic and natural

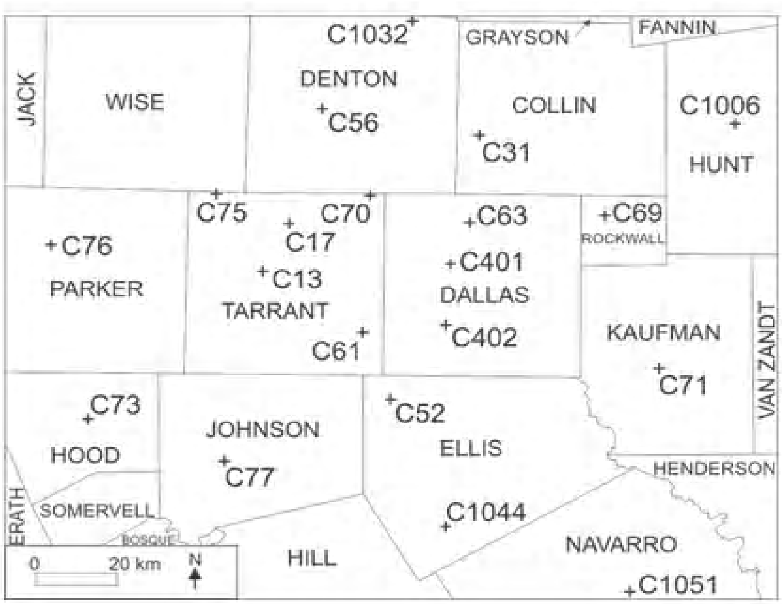

Fig. 1. Ozone monitoring stations and counties in study area.

emission sources influenced observed ozone levels. In addition to forming within the region, ozone and its precursors also moved into the region from distant sources. Similarly, Kim *et al.* (2009) concluded that local, intrastate, and neighboring state emissions of nitrogen oxides all contributed significantly to daytime ozone concentrations during summer episodes featuring east-northeasterly winds. Local nitrogen oxide emissions exerted the strongest impact on local ozone concentrations, although this impact was highly variable temporally and spatially within the region. Nitrogen oxide emissions from areas outside DFW, but within Texas, contributed on average about 10 ppb to daytime ozone in DFW. Collectively, four nearby states (Oklahoma, Arkansas, Louisiana, and Mississippi) also contributed about 10 ppb to DFW ozone. In contrast, anthropogenic emissions of VOCs from outside DFW had negligible impact on DFW ozone (Kim *et al.*, 2009). Previously, Stoeckenius and Yarwood (2004) showed that, while local sources contributed most, emissions from Louisiana, Oklahoma, and Arkansas also contributed to ozone in DFW. However, based upon data from a research flight on one high-ozone day, Kemball-Cook *et al*. (2009) concluded that 72% of DFW ozone was transported into the region. Research flights also indicate the relative contributions of mobile and stationary sources toward ozone buildup in DFW. Based upon data from 12 research flights in 2005, Luria *et al.* (2008) concluded that precursor gases from mobile sources contributed more stationary sources toward elevated ozone concentrations in DFW (Luria *et al*., 2008).

While several studies, including those outlined above, evaluated temporal trends and sources for ozone, fewer have focused on spatial patterns of ozone concentration. Casado et al. (1994) mapped and analyzed hourly ozone from 29 stations in the southeastern United States. They concluded that during daytime hours, local factors are dominant over the ozone production process, whereas in evening hours, regional factors become more dominant in the ozone depletion process. Wind and topography exerted significant influence on patterns of ozone concentration. The present study evaluates spatial patterns of ozone concentration in DFW, considering different seasons, as well as the influence of wind direction, population, and vehicle miles traveled.

MATERIALS & METHODS

The study area includes 12 counties with ozone monitoring stations in DFW (Fig. 1). Total human population of the 12 counties is approximately 6.7 million (Table 1). Dallas and Tarrant are the most populated counties, with approximately 2.5 million and 1.9 million residents, respectively. The next most populated counties, Collin and Denton, have approximately 835,000 and 707,000 residents, respectively. Other counties in the study area have considerably smaller populations, ranging from approximately 48,000 to 154,000 people (Table 1). Each day, automobiles travel approximately 107 million miles within the 12 counties, with the greatest activity in Dallas and Tarrant counties (Table 1). Daily vehicle miles traveled by county reflect population and proximity to work. At 20 monitoring stations, several variables were compiled for each month of 2013: average daily maximum eight-hour ozone concentration; number of days with eight-hour ozone concentration(s) above 75 ppb; average outdoor air

Table 1. Population and Daily Vehicle Miles Traveled

County	Population[a]	Daily Vehicle Miles Traveled[b]
Dallas	2,453,843	37,704,794
Tarrant	1,880,153	29,987,190
Collin	834,642	8,724,618
Denton	707,304	10,139,214
Ellis	153,969	4,361,790
Johnson	153,441	2,853,939
Parker	119,712	2,913,629
Kaufman	106,753	3,529,744
Hunt	87,079	2,453,379
Rockwall	83,021	1,756,402
Hood	52,044	911,775
Navarro	47,979	1,759,397
Total	6,679,940	107,095,871

[a]U.S. Census Bureau (2014)
[b]Texas Department of Transportation (2014)

Table 2. Average Daily Maximum Eight-Hour Ozone Concentration (ppb), Number of Days Exceeding 75 ppb (Parentheses), and Average Outdoor Air Temperature (°C), 2013[a]

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg
C13	28	37	44	44	43	46	51 (3)	55 (4)	59 (4)	36	28	24	41
C17	28	37	42	48	44	47	53 (4)	56 (3)	60 (5)	37	30	24	42
C31	31	39	47	49	47	49	52 (1)	58 (3)	59 (4)	38	29	25	44
C52	29	38	46	45	44	45	48	51 (1)	55 (2)	38	31	28	42
C56	30	38	45	48	47 (1)	51 (1)	56 (4)	61 (4)	65 (9)	40	31	27	45
C61	29	36	ND	45	41	40	44	46 (1)	50	33	28	25	38
C63	28	37	45	45	43	45	51 (2)	56 (2)	58 (2)	37	29	24	42
C69	31	39	47	47	46	44	49 (1)	53	56	40	32	28	43
C70	30	39	46	46	44	47	53 (3)	57 (3)	61 (6)	37	29	24	43
C71	32	39	47	45	45	43 (1)	46	50	54 (2)	39	32	29	42
C73	32	40	45	46	44	45	48 (1)	49 (1)	54 (1)	37	31	28	42
C75	27	37	43	46	42	42	48	51 (2)	56 (2)	36	29	25	40
C76	34	41	45	49	43	43	49 (1)	51	53 (2)	39	33	30	43
C77	30	39	44	41	44	47	48	50 (2)	56 (3)	39	31	29	42
C401	27	37	45	44	43	45 (1)	52 (2)	55 (3)	58 (2)	35	30	22	41
C402	27	37	43	42	39	39	45	47 (1)	53 (1)	33	28	24	38
C1006	32	38	46	46	44	41	47	51	55	37	32	29	42
C1032	30	37	46	48	48	53	54 (3)	61 (3)	61 (4)	40 (1)	33	28	45
C1044	30	38	46	44	41	41	44	48	52 (1)	36	29	26	40
C1051	32	38	45	44	44	43 (1)	45	50	54 (1)	38	31	28	41
Temp	9.1	10.4	13.2	16.7	22	27.8	28.2	30	27.2	19.1	11.2	5.7	18.4

[a]Data compiled from TCEQ (2014b)

[b]ND: No data

temperature; and resultant wind direction (Table 2). A rank correlation was computed between (a) average annual daily maximum eight-hour ozone concentration in a county and (b) county population. A second rank correlation was computed between variable (a) and average daily vehicle miles traveled in a county. Average daily maximum eight-hour ozone concentrations, the number of days exceeding 75 ppb, and resultant wind direction were mapped over the study area for each of four representative months, one for each season: February, May, August, and November.

RESULTS & DISCUSSION

Average monthly temperature for all monitoring stations in the study area ranged from 5.7 °C in December to 30 °C in August (Table 2). August also produced relatively high ozone concentrations, reflecting the influence of outside air temperature on ozone formation. In August, average daily maximum eight-hour ozone concentrations ranged from 46-61 ppb. At 14 of 20 monitoring stations, concentrations exceeded 75 ppb on at least one day; at two stations, concentrations exceeded 75 ppb on four days (Table 2). However, September produced the highest ozone concentrations, ranging from 50-65 ppb. At 17 monitoring stations, concentrations exceeded 75 ppb on at least one day; at one station, concentrations exceeded 75 ppb on nine days. July produced the third highest ozone concentrations, ranging from 44-56 ppb. At 11 monitoring stations, concentrations exceeded 75 ppb on at least one day; at two stations, concentrations exceeded 75 ppb on four days (Table 2). At least one eight-hour ozone concentration exceeded 75 ppb in each month from May-October; concentrations peaked from July-September. During these peak months, Station C56 in Denton County consistently registered the highest average daily maximum eight-hour ozone concentration and the most days with concentrations above 75 ppb (Table 2). In September, this single station registered nine days with readings above 75 ppb. July-September also showed the greatest range in ozone concentration across the study area (Table 2). Results outlined above reflect a tendency for ozone to buildup given warm outside temperatures, as well as the influence of prevailing wind direction. Prevalent southeasterly winds in late spring and summer create an ozone concentration gradient, with generally higher concentrations building up on the downwind perimeter of the study area; this pattern is especially strong in late summer, during peak ozone season. Thus, ozone concentration maps for May and August show clustering of similar ozone concentrations, especially for August; however, months with variable wind conditions, such as February and November, show more random concentration patterns (Figs 2-3).

Rank correlation coefficients were -0.10 between county average ozone concentration and population; and -0.16 between county average ozone concentration and vehicle miles traveled. These associations are statistically insignificant; there was no relationship between county average ozone concentration and population, nor county average ozone concentration and vehicle miles traveled. In fact, the most populated county (Dallas) had the lowest average ozone concentration, whereas the fourth-most populated county (Denton) had the highest average ozone concentration, although these associations were statistically insignificant.

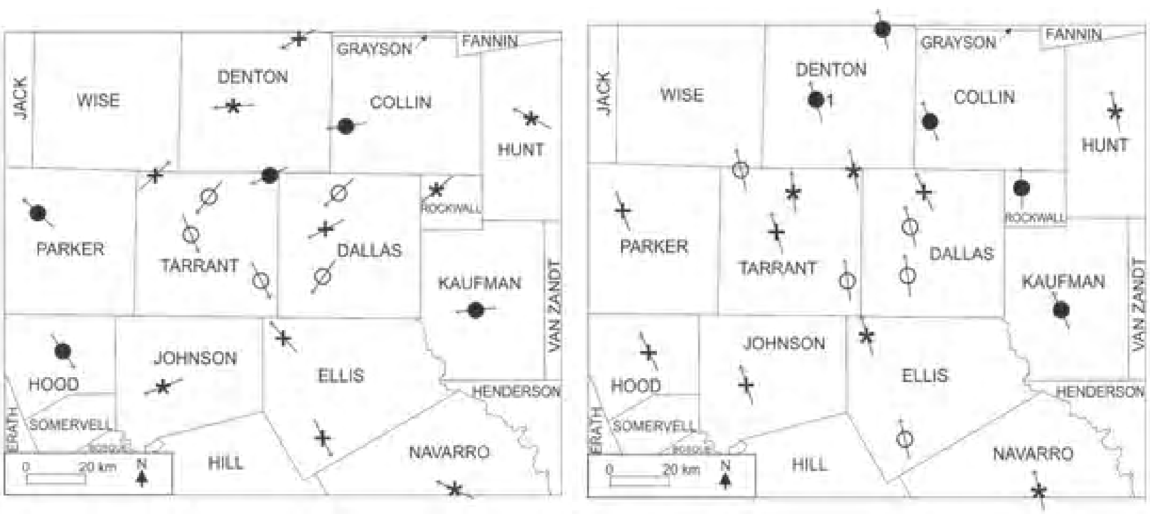

Fig. 2. First (•), second (*), third (+), and fourth (o) highest quartile average daily maximum eight-hour ozone concentrations in February 2013 (top) and May 2013 (bottom); numbers (if any) denote number of days with concentration(s) exceeding 75 ppb; arrows – resultant wind direction

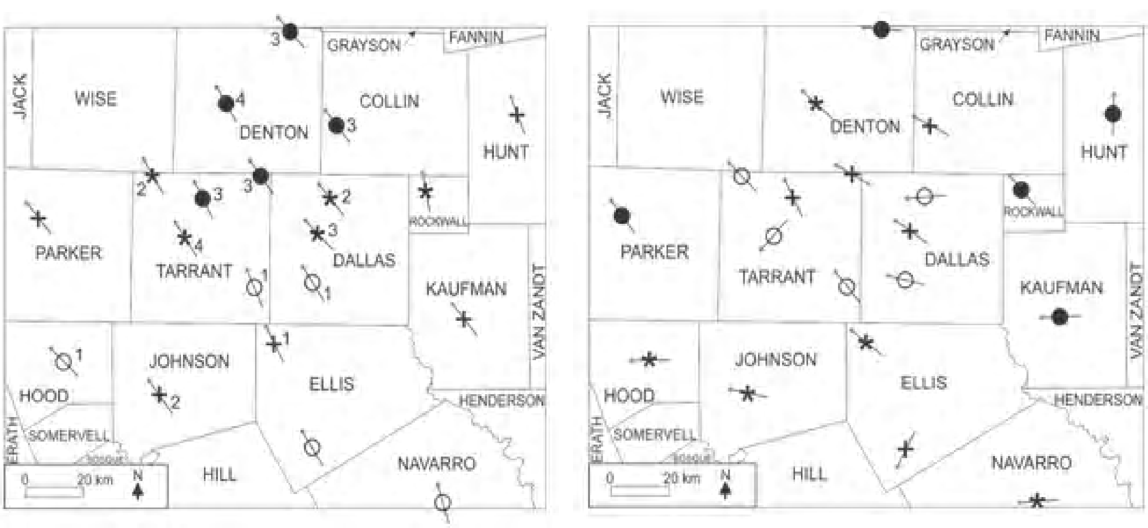

Fig. 3. First (•), second (*), third (+), and fourth (o) highest quartile average daily maximum eight-hour ozone concentrations in August 2013 (top) and November 2013 (bottom); numbers (if any) denote number of days with concentration(s) exceeding 75 ppb; arrows – resultant wind direction.

CONCLUSION

High outside air temperatures and consistent southeasterly winds during the late spring and summer of 2013 produced clusters of similar ozone concentration, with generally higher concentrations in northern DFW. This time interval also showed the greatest range in ozone concentrations across the study area. Lower air temperatures and variable winds in other months produced more random patterns of ozone concentration. There was no association between county ozone concentration and population, nor county ozone concentration and vehicle miles traveled. While various sources contribute to ozone formation in DFW, wind direction exerts a dominant control on the spatial organization of ozone concentration in the study area. Results of this study may have implications for predicting patterns of ozone buildup, as well as further documenting such patterns with additional monitoring stations in the study area.

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