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Relationship of ground-level ozone with synoptic weather conditions in Chicago

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ABSTRACT

This study investigates the relationship between ground-level ozone variability and synoptic weather conditions in the Chicago area in the summertime over the period 1990–2014. It shows that the occurrence of dry tropical (DT) weather conditions is most likely to lead to high ozone concentrations. Both the 95th percentile of summertime daily maximum 8-hour-average ozone concentrations and the number of days >70 ppb are shown to have a greater and more significant correlation with DT weather in recent years (2004–2014) than in the preceding period (1990–2003), indicating an increased dependence of ozone on DT weather. The DT weather is shown to be associated with increased geopotential height, warmer temperature, and slower eastward wind at 500 hPa and also with warmer temperature and increased northward wind near the surface. The results have implications for the likely effect of future climate change on ozone as a result of modified synoptic weather conditions. More frequent episodes of high ozone concentrations can be expected, leading to worsened effects on public health and the environment. It will also make it increasingly challenging for Chicago to attain the National Ambient Air Quality Standard for ozone, which has recently been tightened by the U.S. Environmental Protection Agency.

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1. Introduction

Ground-level ozone (O_3) is an important air pollutant. Breathing O_3 can trigger a variety of health problems, particularly for children, the elderly, and people of all ages who have lung diseases such as asthma (Bell et al., 2004; Bell et al., 2007; Lippmann, 1993). It can also have harmful effects on sensitive vegetation and ecosystems (Fishman et al., 2010; Heagle, 1989; Kline et al., 2008). Ground-level O_3 is formed through photochemical oxidation of carbon monoxide and volatile organic compounds (VOC) by the hydroxyl radical (OH) in the presence of nitrogen oxides (NO_x). Ozone is removed from the atmosphere by its chemical reaction with NO_x and its photolysis in the presence of water vapor, as well as by dry deposition (Jacobson, 2002). The production of ground-level O_3 is affected not only by the emissions of its precursors (i.e., NO_x and VOC), but also by meteorological conditions. Ozone production is greater on warm, sunny days when the air is stagnant than on days when it is cool, cloudy, and windy (Cox and Chu, 1996; Lee et al., 2012). The influences of meteorology on O_3 include the transport of O_3 and its precursors (i.e., NO_x and VOC) by air flow, as well as the temperature and amount of sunlight, which both affect the chemical reaction rates of O_3 production and destruction.

The U.S. Clean Air Act of 1970 requires the U.S. Environmental Protection Agency (US EPA) to set National Ambient Air Quality Standards (NAAQS) for O_3 and other pollutants that are considered harmful to public health and the environment (so-called "criteria" pollutants). The primary NAAQS for O_3 (to protect public health) and the secondary NAAQS (to protect public welfare) had both been set at the level of 75 ppb, measured as the annual fourth–highest daily maximum 8-hr concentration, averaged over three years. After an extensive review of the health effects of O_3 by the Clean Air Scientific Advisory Committee, the US EPA tightened the ambient standard to 70 ppb in October 2015, with the intention to extend the health protection to people at higher risk of O_3 pollution (e.g., people with respiratory conditions) and sensitive ecosystems (US EPA, 2015).

Ozone levels are usually limited by the supply of NO_x, but O_3 can also be VOC-limited in highly-polluted urban areas (Jacob and Winner, 2009). Ozone control strategies include reducing VOC and NO_x emissions. NO_x emissions come mainly from combustion activities, while VOC have both anthropogenic and biogenic sources (Jacobson, 2002). Efforts in the U.S. since 1998 have focused on controlling NO_x emissions. Because of the effects of regulatory actions since the passage of the Clean Air Act and its 1977 Amendments, national average O_3 concentrations in the U.S. decreased by 22% from 1983 to 2002. The number of high surface O_3 events was also reduced in most cities during this period (US EPA, 2003). Both of these achievements reflect the success of efforts made by the US EPA and state and tribal agencies to drive down emissions of the O_3 precursors, NO_x and VOC. Nevertheless, the rate of improvement in O_3 levels slowed in the recent decade (a decrease of only 13% in national average O_3 concentrations from 2000 to 2010), and many metropolitan areas of the U.S. continue to violate the NAAQS for O_3, including Chicago (US EPA, 2012). The diminishing returns of emission reductions on O_3 concentrations at least partly reflect the growing importance of weather.

It has been known for many years that ground-level O_3 is highly dependent on weather (see, e.g., Bloomfield et al., 1996; Camalier et al., 2007; Cox and Chu, 1996; Lee et al., 2012; Shen et al., 2015). Several studies have attempted to quantify the effect of meteorological variability on O_3 concentrations, with values such as 53% for the Chicago area (Jing et al., 2014), 56–80% for 39 eastern U.S. urban areas (Camalier et al., 2007), and 50–80% for 74 areas across the eastern U.S. (Davis et al., 2011). Because of this sensitivity to weather, it follows that climate change should influence O_3 (Bell et al., 2007; Holloway et al., 2008; Jacob and Winner, 2009; Oswald et al., 2015). Warmer temperatures can be expected to lead to higher O_3 concentrations due to a greater O_3 production rate, as well as to increased production of biogenic emissions of VOC and NO_x (Lin et al., 2007). In addition, anthropogenic emissions of NO_x in summertime are expected to increase in a warmer climate due to greater energy consumption for summertime cooling (Hadley et al., 2006; Lin et al., 2010; McDonald et al., 2012).

Climate change could also affect O_3 through modifications of synoptic-scale weather systems. It has been shown that climate change has resulted in decreased frequency of mid-latitude cyclones (Key and Chan, 1999; Knapp and Soulé, 2007). It has also been found that summertime O_3 concentrations are negatively correlated with mid-latitude cyclone frequencies; the decreased frequency of mid-latitude cyclones between 1980 and 2006, which resulted in more stagnant weather, largely offset the improvement in O_3 in the eastern U.S. that was obtained by reducing anthropogenic emissions (Leibensperger et al., 2008). It has also been predicted that cyclone activities will continue to decrease in the future due to climate change (Turner et al., 2013)

and that stagnation events will increase (Horton et al., 2014). It can therefore be expected that future climate change will make it harder and harder to bring U.S. urban areas into compliance with the new O_3 NAAQS, especially if further reductions in precursor emissions are of diminishing value (Downey et al., 2015). In concert with the increasing role of weather in determining O_3 levels, it would seem that any predictive capability (see, e.g., Santurtún et al., 2015) could potentially be used for implementing pollution alert protocols on the basis of synoptic weather forecasts.

Chicago is the third largest metropolitan area in the U.S. In 2012, the US EPA made final designations on compliance with the previous 75 ppb O_3 standard. The greater Chicago area—consisting of eight Illinois (IL) counties (two of them partial), two northwest Indiana (IN) counties, and one southeast Wisconsin (WI) county (partial)—was designated to be in marginal nonattainment (i.e., having a design value of 0.076 ppm up to but not including 0.086 ppm), based on monitoring data, state recommendations, and related technical information. Under the new 70 ppb NAAQS standard for O_3, additional areas might have to be designated as nonattainment in the future.

While the reduction of NO_x emissions in recent years has lowered the NO_2 concentration in the region, the mean O_3 concentration has shown no obvious decrease in the past decade and may even have increased since 2009 (Jing et al., 2014). This indicates that O_3 in Chicago has become less sensitive to NO_x and may have become more sensitive to VOC. The trends in precursor emissions and resulting O_3 concentrations also suggest that weather is becoming an increasingly important determinant of O_3 formation. There have been previous modeling studies to project O_3 in the Chicago area under the effect of climate change (Hayhoe et al., 2010; Holloway et al., 2008; Lin et al., 2010). Because O_3 is a regional pollutant, not directly tied to point sources of emissions, this present study examines how O_3 concentrations are influenced by regional-scale weather phenomena (as distinct from local-scale meteorological conditions). This study focuses on synoptic weather types, which can be defined as characterizations of the weather occurring over a wide area—typically ranging from 500 to 10,000 km—on a time scale >12 h.

The objectives of this study are therefore: (1) to investigate the relationships between O_3 and different synoptic weather conditions from 1990 to 2014, and (2) to assess how the impact of weather on O_3 changed during the period 1990 to 2014. This analysis provides insight into the sensitivity of O_3 to present-day weather and to potential future modifications to weather arising from climate change. The results have implications not only for the Chicago area but for all major metropolitan areas of the U.S. that have similar problems attaining the O_3 NAAQS today and in the future.

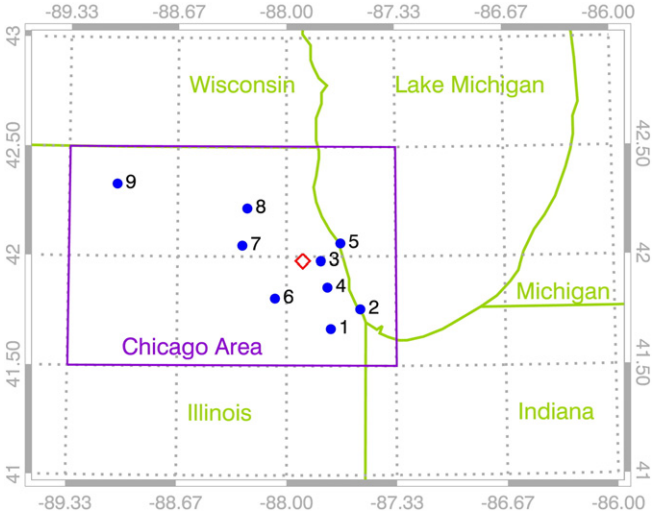

Fig. 1. Locations of the nine US EPA O_3 monitoring sites (blue dots) used in this study and the weather station at O'Hare International Airport (red diamond). The purple box defines the region of interest—the Chicago area. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2. Data and methods

Summary air quality data are obtained for the period 1990–2014 from the US EPA Air Quality System (AQS), a repository of ambient air quality measurements from >10,000 monitors nationwide (http://www.epa.gov/ttn/airs/airsaqs/). Daily maximum 8-hour-average (DMA8) O_3 values are retrieved for the nine monitoring sites that have continuous O_3 observations in the Chicago area throughout the period 1990–2014. The locations of these nine monitoring sites are shown in Fig. 1 as solid blue circles. The site codes of the nine O_3 monitoring sites are: 1. 17-031-0001; 2. 17-031-0032; 3. 17-031-1003; 4. 17-031-4002; 5. 17-031-7002; 6. 17-043-6001; 7. 17-089-0005; 8. 17-111-0001; 9. 17-201-2001. Using the DMA8 O_3 values, we calculate the summertime (May to August) 95th percentile of O_3 and the number of days when O_3 concentrations exceeded 70 ppb for each monitoring site. The summertime 95th percentile is used because it is closest to the 4th highest DMA8 value, which the US EPA uses to assess the status of ozone attainment.

In order to analyze the relationship between O_3 and synoptic weather conditions, this study employs the results of the Spatial Synoptic Classification (SSC) (http://sheridan.geog.kent.edu/ssc.html). The SSC method is a hybrid classification scheme based solely on surface observations of meteorological variables at an individual weather station, and, as such, it provides a convenient tool for classifying ambient weather conditions into useful categories (Sheridan, 2002). The six basic SSC weather types are: dry moderate (DM), dry polar (DP), dry tropical (DT), moist moderate (MM), moist polar (MP), and moist tropical (MT). Using surface-based observations of temperature, dew point, cloud cover, sea-level pressure, and south-north and west-east wind components, the SSC method classifies the weather at a given location on a daily basis into one of the six types, or as a transition (TR) between two weather types. Upper-level conditions are not taken into account. In a sense, the SSC method develops a weather "calendar" for a given location. The results are available for 327 stations in North America with an average length of 45 years. This study uses the SSC data for the station at O′ Hare International Airport (shown as the red diamond in Fig. 1) for the period 1990–2014 to represent the synoptic weather conditions in the Chicago area, which is defined by the purple box in Fig. 1.

The SSC method only uses surface-based meteorological observations to define the synoptic weather type. However, surface weather is largely driven by and associated with atmospheric conditions aloft. This study therefore further analyzes the relationship between O_3 and meteorological conditions both near the surface (at 10 m altitude) and in the middle troposphere (at 500 hPa pressure surface). The 500 hPa surface is chosen because it is often referred to as the "steering level" of surface weather. Air flow at 500 hPa is normally used to locate troughs and ridges that are associated with surface cyclones and anticyclones (Eagleman, 1985). Surface weather systems move in the same direction as the winds at 500 hPa, and surface weather conditions are highly correlated with those at 500 hPa (Lynch and Cassano, 2006). The meteorological variables used in this study consist of pressure, temperature, specific humidity, and winds at 10 m and at 500 hPa (as listed in Table 1). These data are obtained from the Incremental Analysis Updates (IAU) 2-D atmospheric single-level diagnostics data of NASA's Modern Era Retrospective Analysis for Research and Applications (MERRA) reanalysis (http://gmao.gsfc.nasa.gov/merra/). The MERRA dataset has been shown to have good accuracy in representing climate variability and jet stream dynamics (Manney et al., 2014; Rienecker et al., 2011). MERRA IAU 2-D atmospheric single-level diagnostics are available globally at 0.5° latitude by 0.67° longitude grids every hour from 0:30 to 23:30 GMT. The MERRA data for the Chicago area are extracted for the 1990–

Table 1
Meteorological variables used in this study.

Variable name	Description	Units
H1000	Geopotential height at 1000 hPa	m
T10M	Temperature at 10 m	K
Q10M	Specific humidity at 10 m	kg/kg
U10M	Eastward wind at 10 m	m/s
V10M	Northward wind at 10 m	m/s
H500	Geopotential height at 500 hPa	m
T500	Temperature at 500 hPa	K
Q500	Specific humidity at 500 hPa	kg/kg
U500	Eastward wind at 500 hPa	m/s
V500	Northward wind at 500 hPa	m/s

2014 period, and the MERRA grids are shown in Fig. 1. Using these hourly data, daily mean values are calculated for every variable listed in Table 1 within the Chicago area.

For every summer (May to August) in 1990–2014, we calculated the frequency of different SSC types, the mean values of the MERRA meteorological variables, and the 95th percentile of EPA DMA8 O_3. Linear regressions were used to examine the trends of O_3, the relationship between O_3 and SSC weather, and the relationship between SSC and meteorological variables.

3. Results

This study examines the relationship between O_3 concentrations and SSC weather types in the Chicago area during the period 1990–2014. It focuses on the summer months (May to August) when high O_3 episodes occur.

3.1. Relationship of O_3 with SSC weather types

We first examined the frequency of occurrence of the different SSC types in summer in Chicago, segmenting the data into five-year periods. The results are shown in Fig. 2. This bar chart shows that, as would be expected, Chicago is influenced in the summertime by warm weather (i.e., the MT, DM, and MM types) more frequently than by cold weather (DP and MP). The occurrence of warm and moist MT weather is the most frequent weather type, which is caused by arrival into the Chicago area of air masses that originated in the Gulf of Mexico or the tropical Atlantic Ocean. The warm, moist air masses from the Gulf region can frequently penetrate deep into the central U.S. in summer months when there is a general sea-to-land air flow over southeastern North America (Lutgens et al., 2015). The presence of MT weather is usually associated with the warm sector of a mid-latitude cyclone or the western edge of an anticyclone. The second highest occurrence is mild and dry DM weather, which is usually the result of cold, dry DP air modified by the warmer surface as it travels southward from Canada. It should be noted in Fig. 2 that dry and hot DT weather occurs least frequently among all the SSC types. There are no dramatic changes in the frequency of occurrence of different weather types over the 25-year time period, but it does appear that the relative frequency of occurrence of DT weather increased during the period 2000–2014, which may be important (see later discussion).

We next assigned measured summertime O_3 levels to the seven different SSC types for the nine O_3 monitoring stations that had continuous observations in the Chicago area from 1990 to 2014. The results are shown in Fig. 3. This graphic shows that summertime DMA8 O_3 mixing ratios are the highest in DT weather conditions, averaging approximately 60 ppb with excursions up to 100 ppb. This is because the driest and hottest DT air is usually associated with high pressure systems that produce clear-sky conditions, which permit stronger solar radiation for greater photochemical production of O_3. Fig. 3 also shows that, generally speaking, warmer weather (DT and MT) is associated with higher O_3 concentrations than colder weather (DP and MP). It is rare that the O_3 mixing ratio exceeds 70 ppb under DP, MM, MP, or TR conditions; it is only likely for DM, DT, and MT. The MM weather, although warm, usually occurs with high cloud cover in summertime, which inhibits photochemical O_3 production (Davis et al., 2010). It is therefore associated with relatively low O_3 concentrations. There are no significant differences of this O_3–SSC relationship across the nine monitoring sites.

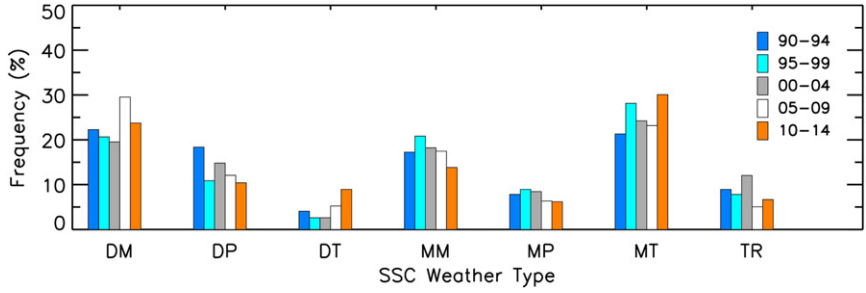

Fig. 2. Frequency of occurrence of different SSC weather types in Chicago in the summertime in five-year bins from 1990 to 2014.

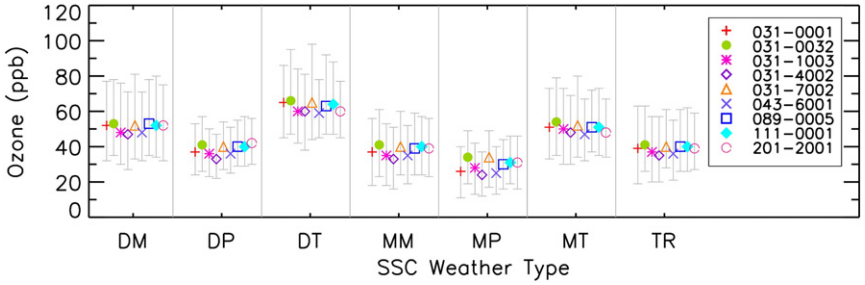

Fig. 3. Median DMA8 O_3 mixing ratios by SSC air mass over the nine monitoring sites in the Chicago area in summertime for the period 1990–2014. Error bars are 5th and 95th percentiles.

This is consistent with the spatial homogeneity of data among the O_3 monitoring sites in the Chicago area (Jing et al., 2014) and the fact that O_3 is a regional air pollutant.

We next counted the number of days when the DMA8 O_3 mixing ratios were greater than the equivalent of the new NAAQS of 70 ppb for the different SSC types. A day is considered to be a "high-O_3" day for Chicago if the DMA8 O_3 value is >70 ppb at any of the nine sites. The results of this analysis are shown in Fig. 4. It can be seen that the number of high-O_3 days (solid blue portions of the histograms) are mainly associated with warm, clear SSC types (MT, DM, and DT) and rarely with cold (MP and DP), high-cloud (MM), or transitional (TR) types. In general, the number of high-O_3 days has decreased during the 1990–2014 period, reflecting the effectiveness of regulatory efforts during the past two decades to reduce emissions of the O_3 precursors, NO_x and VOC. Only the DT weather type does not appear to be associated with a decrease in the number of high-O_3 days; in fact, it seems to be associated with an increase since 2000.

According to Fig. 4, the number of high-O_3 days overall was greatest in MT air, followed by DM air. This, of course, is primarily due to the fact that summertime weather in Chicago is under the influence of these two weather types more than any others, as was shown in Fig. 2 and is indicated by the relative sizes of the histograms in Fig. 4. In order to examine which SSC type is most prone to the occurrence of high-O_3 days, we calculated the percentage of SSC days that had DMA8 O_3 > 70 ppb. These results are shown by the pink lines with open squares in Fig. 4. Among the SSC types, the percentage of high-O_3 events in DT air is the highest. In the past 25 years, when DT weather arrived in Chicago, the chance that the O_3 mixing ratio would exceed 70 ppb was 56%–88%. Therefore, DT weather clearly demonstrates the greatest susceptibility to high-O_3 events among all SSC types. The percentage of high-O_3 days associated with each SSC weather type has generally

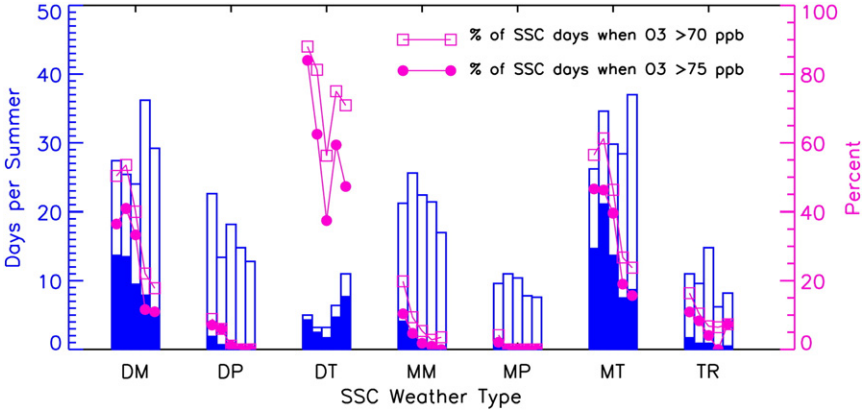

Fig. 4. The occurrence of SSC air mass types and high-O_3 days (when DMA8 O_3 > 70 ppb) for different SSC air mass types in five-year bins from 1990 to 2014. The histograms are the frequencies (in days per summer) for each SSC type that were associated with high-O_3 (filled) or non-high-O_3 (empty) days. The percentages of SSC that had O_3 exceeding 70 ppb and 75 ppb are shown as squares and circles, respectively.

decreased during the period 1990–2014, even for DT, which again reflects the effectiveness of emission controls in lowering O_3 concentrations. However, we can see that for each SSC weather type the decrease is not so marked in recent years as in earlier years. For comparison to the old NAAQS standard for O_3, we also calculated the percentage of days >75 ppb; the results are shown by the pink lines with solid circles in Fig. 4. Tightening the threshold value from 75 ppb to 70 ppb increases the chances of O_3 exceedances in all SSC types, and that increase is most significant in DT. This indicates that it will be challenging for Chicago to attain the new NAAQS standard for O_3.

Because of its clear association with high-O_3 occurrences, the DT weather type was investigated further. In order to statistically analyze the association between high-O_3 occurrence and DT weather, we analyzed the relationship between the 95th percentile of DMA8 O_3 and the number of DT days during the summer months from 1990 to 2014 for the nine different O_3 monitoring sites. The results are shown in Figs. 5 and 6. According to Fig. 5, there are good correlations of O_3 95th percentile values among different monitoring sites, and they all demonstrate a decreasing trend from 1990 to 2014; by average, they decreased at a rate of 0.30 ± 0.18 ppb/year over the 25-year period (dashed blue line). This means that the general trend of O_3 concentrations has been decreasing, again indicating that reducing emissions had been successful in reducing the occurrence of high O_3 values in the Chicago area.

Fig. 5 also shows that the number of DT days increased at a rate of 0.26 ± 0.18 days/year from 1990 to 2014 (orange dashed line). However, it is apparent that this increasing trend is largely driven by the exceptionally hot year of 2012, when there were 35 days of DT weather. Removing 2012 from the trend analysis reduces the rate of DT increase to 0.03 ± 0.09 days/year. Although there is no significant trend in the DT frequency after the 'outlier' year 2012 is removed, we should still recognize the strong role that DT played in causing O_3 concentrations to increase in that year: values recorded at each of the nine monitoring sites in 2012 lie above the long-term average concentration line. Values of the 95th percentile O_3 concentrations approaching 90 ppb were recorded in 2012, exceeding any of the 95th percentiles that had been experienced in the preceding ten years. The extremely large number of DT days in 2012 in Chicago is related to the record-high temperatures and drought in 2012 in the Midwest, which was caused by a combination of meteorological conditions: (1) reduced moisture transport from the Gulf of Mexico and reduced cyclone activities in late spring; and (2) high pressure anomalies that remained in the region in summer, which not only produced clear-sky weather but also inhibited the inflow of colder air from Canada (Hoerling et al., 2014).

Fig. 6 shows that there is a stronger and more significant linear correlation between DT days and mean O_3 95th percentile values in the more recent 2004–2014 period (correlation coefficient $R = 0.832$, p-value $= 0.001$) than in the previous 1990–2003 period ($R = 0.415$, p-value $= 0.141$). Excluding the year of 2012 in the analysis results in an even stronger correlation ($R = 0.967$, p-value $= 0.000$) for the 2004–2014 period.

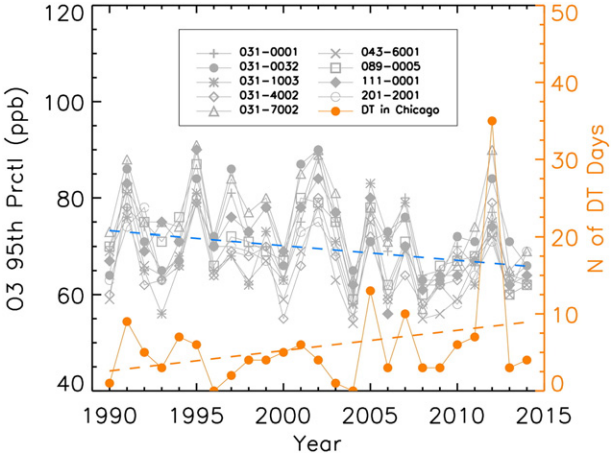

Fig. 5. The summertime 95th percentile values of DMA8 O_3 concentrations at the nine monitoring sites versus the number of DT days in Chicago in summertime during the period 1990–2014.

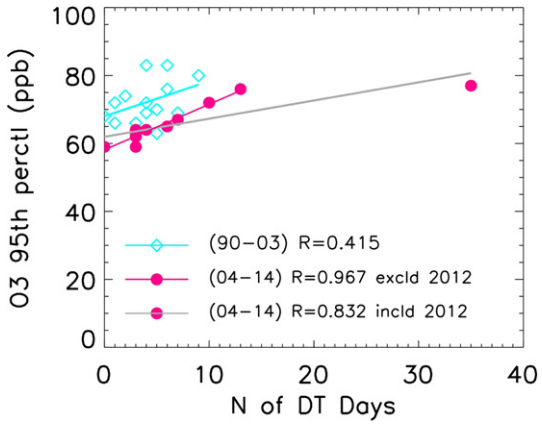

Fig. 6. Correlation between the mean summertime 95th percentile of DMA8 O_3 averaged across the nine sites and the number of DT days in Chicago in 1990–2003 (blue diamonds) and in 2004–2014 (pink circles). The R values represent the Pearson correlation coefficients of the two variables in 1990–2003, in 2004–2014 excluding 2012, and in 2004–2014 including 2012. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

These results indicate a greater dependence of 95th O_3 percentile values on DT weather in the recent 11 years, which is not driven by the unusually hot year of 2012.

We examined the homogeneity of DT weather in the Chicago area by calculating the Pearson correlation coefficients of DT frequency between the O′Hare International Airport station—which we have selected as the basis for our SSC classifications in this work—and four other weather stations in the extended Chicago region for which SSC data are available. The results are shown in Table 2. There is a significant positive correlation between DT frequencies at the O′Hare station and the four other SSC stations, as indicated by the high correlation coefficients (ranging between 0.831 and 0.917) and low *p*-values (<0.05). Therefore, we conclude that the designations of DT synoptic weather type for the Chicago region are well represented by the O′Hare station.

In order to test the sensitivity of the results to the definition of "high-O_3" concentration, we repeated the above analysis using the 4th highest value, the summertime 98th percentile of O_3, and the summertime 90th percentile of O_3. The results, shown in Table 3, demonstrate that using different definitions of "high-O_3" concentration does not change the conclusion that O_3 in the Chicago area has become increasingly dependent on DT weather in the most recent 11 years. On average, a one-day increase in DT weather would result in a 1 ppb increase in the average O_3 mixing ratio in summertime in Chicago. It should also be noted that excluding the data for 2012, when the number of DT days was the highest, causes O_3 concentrations to increase more rapidly with DT days in the 2004–2014 period.

We used 2004 as the beginning year of the second period because there have been strengthened efforts to further reduce the vehicle and power-plant emissions of NO_x since 2004, which is an important precursor of O_3 formation. We tested using 2003 and 2005 to divide 1990–2014. They did not change the conclusion that there was a greater O_3–DT correlation in the more recent period than in the preceding period.

Table 2
Correlation of DT frequency between the O′Hare International Airport weather station (41.84°N, 87.68°W) and four other SSC stations in the extended Chicago region.

	Milwaukee, Wisconsin (43.05°N, 87.95°W)	South Bend, Indiana (41.67°N, 86.26°W)	Rockford, Illinois (42.26°N, 89.06°W)	Springfield, Illinois (39.70°N, 89.62°W)
Pearson correlation coefficient (*R*)	0.831	0.883	0.917	0.904
p-Value	0.000	0.000	0.000	0.000

Table 3
Statistical parameters for the O_3–DT relationship using the linear regression model: $y = b_0 + b_1x$, in which y is O_3 mixing ratio in ppb and x is the number of DT days. The Pearson correlation coefficient is given by R in the table.

	DT and O_3 95th percentile	DT and O_3 4th highest	DT and O_3 98th percentile	DT and O_3 90th percentile
1990–2003	R = 0.415	R = 0.431	R = 0.436	R = 0.461
	$b_1 = 1.03 \pm 0.66$	$b_1 = 1.12 \pm 0.68$	$b_1 = 1.28 \pm 0.76$	$b_1 = 0.99 \pm 0.55$
	$b_0 = 68.00 \pm 3.11$	$b_0 = 71.66 \pm 3.21$	$b_0 = 76.57 \pm 3.62$	$b_0 = 61.20 \pm 2.59$
2004–2014	R = 0.832	R = 0.817	R = 0.804	R = 0.809
	$b_1 = 0.53 \pm 0.12$	$b_1 = 0.55 \pm 0.13$	$b_1 = 0.60 \pm 0.15$	$b_1 = 0.46 \pm 0.11$
	$b_0 = 61.65 \pm 1.45$	$b_0 = 64.57 \pm 1.57$	$b_0 = 68.60 \pm 1.81$	$b_0 = 57.29 \pm 1.35$
2004–2014, excluding 2012	R = 0.967	R = 0.941	R = 0.874	R = 0.948
	$b_1 = 1.34 \pm 0.13$	$b_1 = 1.37 \pm 0.18$	$b_1 = 1.41 \pm 0.28$	$b_1 = 1.18 \pm 0.14$
	$b_0 = 58.13 \pm 0.80$	$b_0 = 60.65 \pm 1.12$	$b_0 = 64.74 \pm 1.77$	$b_0 = 53.86 \pm 0.89$

In order to test the implication of DT weather for Chicago's attainment status relative to the new NAAQS standard for ozone, we also studied the relationship between the number of $O_3 > 70$ ppb days and the number of DT days. The results are shown in Fig. 7 and Table 4. For all sites except 17–031-1003 the correlation coefficients are greater and the corresponding p-values are smaller for the period 2004–2014 than for the preceding period 1990–2003 (Table 4), indicating a much stronger and more significant dependence of high-O_3 days on DT weather in the past 11 years. The site (17-031-1003) is located near the O'Hare International Airport and is also closest to the weather station. The fact that it has a relatively weaker correlation with DT weather may be because there is some influence of NO_x from aircraft emissions on O_3 concentrations at that site.

As previously shown in Fig. 3, O_3 values are relatively high not only in DT but also in DM and MT weather conditions. To be thorough, therefore, we also investigated the relationships between 95th percentile O_3 values and the other two SSC types, DM and MT. The results in Table 5 show that the relationships of O_3 with DM and MT are much weaker and less significant than with DT.

These results indicate that O_3 in Chicago has become more dependent on the hot DT weather. This raises concerns about the potential effect of a warmer climate in the future on O_3 concentrations in the Chicago area, as will be discussed in the next section.

3.2. Relationship of DT weather with atmospheric conditions

In order to understand what atmospheric conditions facilitate the formation of DT weather, we analyzed the frequency distributions of the ten meteorological variables listed in Table 1 in DT weather and in non-

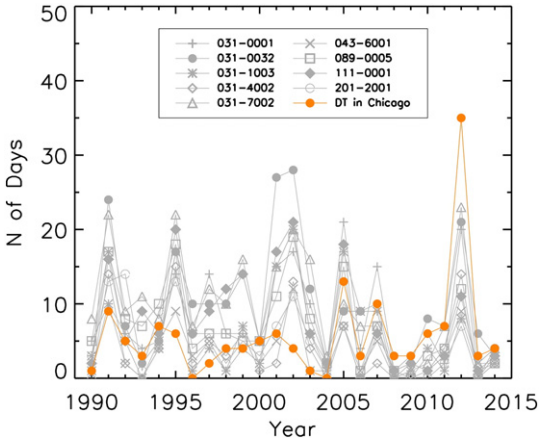

Fig. 7. The number of O_3 days >70 ppb at each of the O_3 monitoring sites versus the number of DT days in Chicago in the summertime during the period 1990–2014.

Table 4
Pearson correlation between the number of high-O_3 days and the number of DT days in the summertime in Chicago for the nine monitoring sites considered.

Site code	Correlation between $O_3 > 70$ ppb Days and DT days (R is the correlation coefficient and p is the p-value)		
	1990–2014	1990–2004	2005–2014
17-031-0001	$R = 0.576$; $p = 0.003$	$R = 0.129$; $p = 0.202$	$R = 0.794$; $p = 0.004$
17-031-0032	$R = 0.385$; $p = 0.057$	$R = 0.421$; $p = 0.134$	$R = 0.911$; $p = 0.000$
17-031-1003	$R = 0.300$; $p = 0.145$	$R = 0.538$; $p = 0.047$	$R = 0.471$; $p = 0.143$
17-031-4002	$R = 0.545$; $p = 0.005$	$R = 0.496$; $p = 0.071$	$R = 0.959$; $p = 0.000$
17-031-7002	$R = 0.447$; $p = 0.025$	$R = 0.400$; $p = 0.156$	$R = 0.944$; $p = 0.000$
17-043-6001	$R = 0.510$; $p = 0.009$	$R = 0.531$; $p = 0.051$	$R = 0.886$; $p = 0.001$
17-089-0005	$R = 0.393$; $p = 0.052$	$R = 0.606$; $p = 0.021$	$R = 0.765$; $p = 0.006$
17-111-0001	$R = 0.281$; $p = 0.174$	$R = 0.481$; $p = 0.082$	$R = 0.658$; $p = 0.028$
17-201-2001	$R = 0.265$; $p = 0.201$	$R = 0.569$; $p = 0.034$	$R = 0.710$; $p = 0.014$

DT weather. Using the daily mean values of these variables derived from the NASA MERRA datasets for the Chicago area, the Gaussian fits of the frequency distributions were derived for each of the variables in DT and non-DT weather in 1990–2014, 1990–2003, and 2004–2014. The results of the Gaussian fits are listed in Table 6. To test if there is a significant difference between the frequency distribution of a meteorological variable in DT weather and the distribution of the variable in non-DT weather, we employed the z-statistic, $z = \frac{\overline{y}_1 - \overline{y}_2}{\sqrt{\frac{S1^2}{N_1} + \frac{S2^2}{N_2}}}$, in which $\overline{y}_1$, S_1 and N_1 are the average, standard deviation, and sample size of the variable in DT weather, respectively; $\overline{y}_2$, S_2 and N_2 are the average, standard deviation, and sample size of the variable in non-DT weather, respectively. The results of two-sided z-tests are also listed in Table 6.

As noted in the table, for the 1990–2014 data seven of the 10 variables are significantly different (with p-values < 0.05) in DT weather than in non-DT weather. They are H500, T500, U500 and V500 at 500 hPa, and T10M, U10M, and V10M at 10 m. The 500 hPa geopotential height is a measure of the thickness of the atmosphere below the 500 hPa level. The thickness of this layer is proportional to the average temperature of the layer between the surface and 500 hPa (Holton, 1992). Therefore, significant differences in the atmospheric conditions between DT and non-DT weather are essentially caused by changes in temperature and winds. Specific humidity does not seem to vary significantly between DT and non-DT weather. Results for the seven variables that demonstrate significant differences in their frequency distributions between DT and non-DT weather (H500, T500, U500, V500, T10M, U10M, and V10M) are plotted in Fig. 8.

As shown in Fig. 8, temperatures (both T500 and T10M) are warmer in DT weather than in non-DT weather; H500, which is temperature-dependent, is also higher in DT weather. The increase of H500 is associated with the formation of surface anticyclones, which produce clear-sky conditions and increase the probability of DT weather during summer. Low H500 values, on the other hand, are associated with surface cyclones, which produce clouds and precipitation and therefore do not facilitate the formation of DT weather. Fig. 9 shows that the number of DT days and the mean H500 are positively correlated. In the 25-year period from 1990 to 2014 of this study, no significant trend of H500 was found over the Chicago area. Other studies of cyclones over longer periods have shown significantly declined frequencies of mid-latitude cyclones in the Northern Rockies from 1900 to 2000 (Knapp and Soulé, 2007) and across 40°–50° latitude in North America over the 1980–2006 period (Leibensperger et al., 2008). Both the average summer temperatures and days

Table 5
Pearson correlation between the average O_3 95th percentiles among the nine sites and the number of DM and MT days in the summertime in Chicago. R is the correlation coefficient and p is the p-value.

O_3 and DM			O_3 and MT		
1990–2014	1990–2003	2004–2014	1990–2014	1990–2003	2004–2014
$R = 0.097$	$R = 0.454$	$R = 0.189$	$R = 0.188$	$R = 0.378$	$R = 0.060$
$p = 0.644$	$p = 0.102$	$p = 0.577$	$p = 0.367$	$p = 0.183$	$p = 0.860$

Table 6
Statistical parameters for the Gaussian fits to the frequency distributions of meteorological variables in DT and non-DT weather in different periods.

	1990–2014			1990–2003			2004–2014		
	DT $N_1 = 179$ $(\bar{y}_1 \pm S_1)$	non-DT $N_2 = 3646$ $(\bar{y}_2 \pm S_2)$	*p-Value*	DT $N_1 = 75$ $(\bar{y}_1 \pm S_1)$	non-DT $N_2 = 2220$ $(\bar{y}_2 \pm S_2)$	*p-Value*	DT $N_1 = 104$ $(\bar{y}_1 \pm S_1)$	non-DT $N_2 = 1426$ $(\bar{y}_2 \pm S_2)$	*p-Value*
H500 (m)	5856 ± 59	5811 ± 74	0.000	5835 ± 73	5810 ± 77	0.003	5867 ± 44	5812 ± 72	0.000
T500 (K)	263.5 ± 3.1	262.8 ± 3.2	0.009	262.7 ± 3.0	262.8 ± 3.2	0.711	264.2 ± 3.1	262.9 ± 3.3	0.000
U500 (m/s)	7.2 ± 6.0	11.2 ± 7.8	0.000	7.8 ± 6.3	11.1 ± 7.9	0.000	6.7 ± 5.7	11.4 ± 7.5	0.000
V500 (m/s)	0.0 ± 6.6	−2.8 ± 6.6	0.000	0.1 ± 6.1	−2.6 ± 6.5	0.000	0.1 ± 6.9	−3.1 ± 7.0	0.000
Q500 (kg/kg)	0.8 ± 0.7	0.8 ± 0.9	0.603	1.0 ± 0.6	0.8 ± 0.9	0.017	0.7 ± 0.8	0.8 ± 0.9	0.129
H1000 (m)	130 ± 34	128 ± 41	0.490	137 ± 34	131 ± 41	0.121	125.1 ± 33.5	124.0 ± 39.5	0.749
T10M (K)	298.3 ± 4.0	295.4 ± 4.2	0.000	297.2 ± 3.8	295.3 ± 4.2	0.000	299.2 ± 3.8	295.5 ± 4.2	0.000
U10M (m/s)	1.6 ± 2.6	0.5 ± 2.9	0.000	2.1 ± 2.4	0.6 ± 2.9	0.000	1.2 ± 2.6	0.4 ± 3.0	0.003
V10M (m/s)	3.2 ± 2.9	0.1 ± 3.2	0.000	3.3 ± 2.8	0.2 ± 3.2	0.000	3.2 ± 3.0	0.1 ± 3.2	0.000
Q10M (kg/kg)	10.6 ± 3.4	10.4 ± 3.8	0.430	10.2 ± 3.2	10.3 ± 4.0	0.631	11.0 ± 3.5	10.6 ± 3.7	0.258

above 95 °F are projected to increase in the next 50 years in the Chicago region (Pryor et al., 2014). As such, the future frequency of DT weather in Chicago may increase.

DT weather is also shown to be associated with winds. Both the northward and eastward components of the near-surface winds are significantly stronger in DT weather, indicating surface air blowing from the relatively hot southwest region, which contributes to the development of DT weather. The occurrence of DT weather is also shown to be negatively correlated with the mean zonal wind speed at 500 hPa (see Fig. 10).

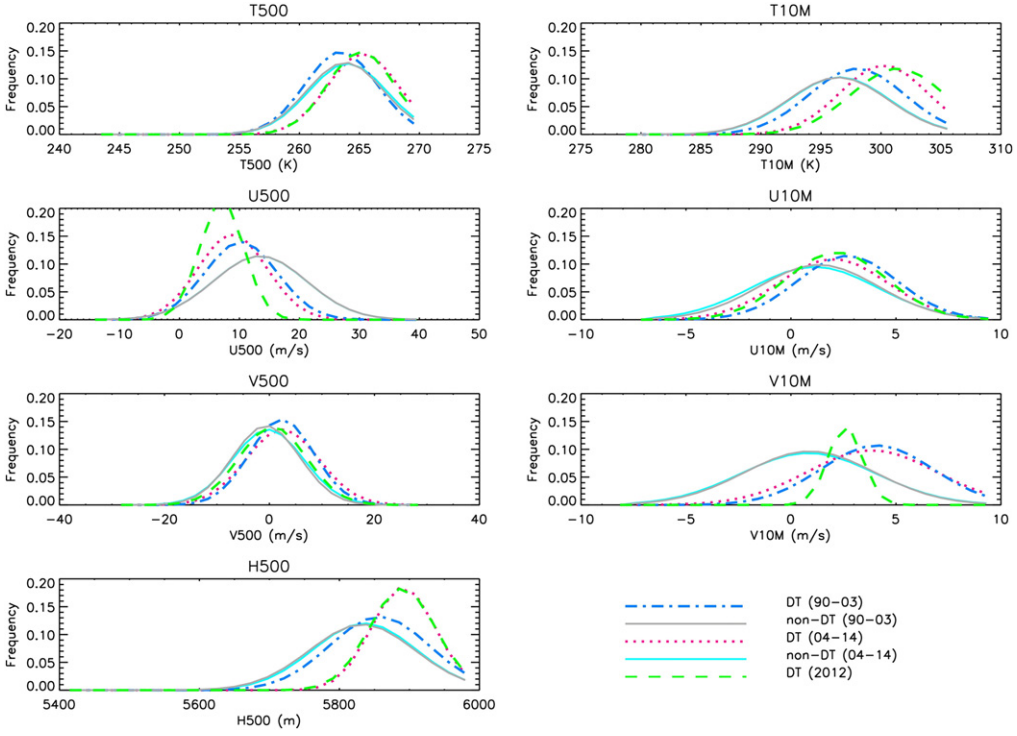

Fig. 8. Frequency distributions of meteorological variables (T500, U500, V500, H500, T10M, U10M and V10M) in summertime in Chicago on DT days and non-DT days in 1990–2003 and in 2004–2014. The distributions on DT days in 2012 are shown as green dashed lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

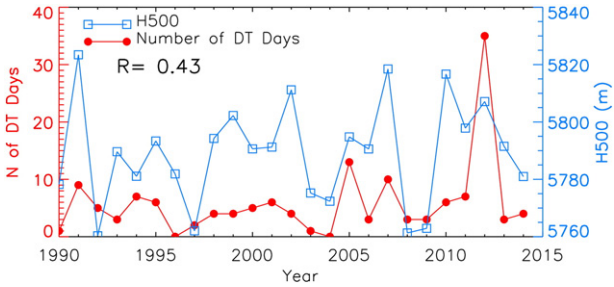

Fig. 9. The number of DT days versus the mean geopotential height of 500 hPa in May-to-August over Chicago, in which R is the Pearson correlation coefficient of the two time series.

The average speed of U500 is 4.0 m/s slower in DT weather than in non-DT weather. Slower mean zonal winds aloft (U500) result in slower progression of the Rossby waves, which consequently leads to more stagnant surface weather conditions (Holton, 1992). This facilitates the formation of hot DT weather. Under conditions of an enhanced greenhouse effect, especially enhanced Arctic warming relative to the mid-latitudes, there has been a growing thickness of the 1000-to-500 hPa layer and slower wind speeds aloft from 1970 to 2010 in mid-latitude regions (Francis and Vavrus, 2012). In this study, the average U500 wind speed in DT weather in 2004–2014 was 1.1 m/s weaker than that in 1990–2003, but the decrease of U500 is not significant (p-value = 0.115). However, future climate change may bring more significant changes in the air flow aloft. The Midwest region is projected to experience weaker winds aloft (Winkler et al., 2014).

The differences between the DT and non-DT frequency distributions are greater in the later 2004–2014 period than in the earlier 1990–2003 period (Fig. 8). The non-DT distributions show no discernable differences between the two periods. The DT distributions, on the other hand, indicate warmer average T500 and T10M and higher H500 in the latter period (p values < 0.05). The average H500 in DT not only became 32 m higher in 2004–2014 but also showed smaller standard deviation.

The distributions for 2012 (the green dashed lines in Fig. 8) show that the extraordinarily hot year of 2012 was associated with even weaker U500 wind. An anticyclone that formed in Mexico moved north into the central U.S. in June 2012. Because of the weak steering U500 winds aloft, the anticyclone then was trapped in the central U.S., including the Chicago area (Hoerling et al., 2014). The air was stagnant, as shown by the slow near-surface V10M. The average V10M in DT was 2 m/s weaker in 2012 than in other years (Fig. 8). The hot, cloud-free conditions produced by the anticyclone extended and resulted in the observed 35 DT days in the Chicago area. Consequently, the mean O_3 value in DT weather was also higher in 2012 than the mean in 2004–2014 (Fig. 11). Fig. 11 also confirms that O_3 mixing ratios in DT weather are significantly higher than in non-DT weather; the chances of O_3 exceeding 70 ppb (represented by the area under the curves to the right hand side of the orange line) are also significantly higher in DT than in non-DT weather. Hot summers like 2012 are expected to become more common in the future due to increasing temperature and weaker 500 hPa winds. This will greatly increase the chances of high O_3 events.

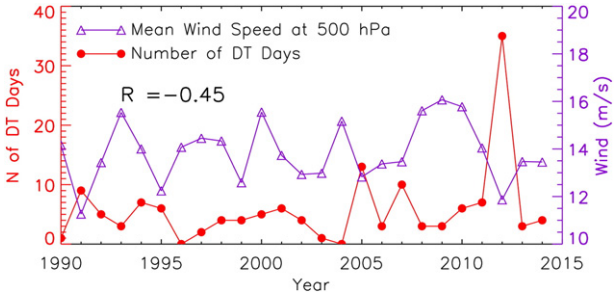

Fig. 10. Same as Fig. 7 but for the number of DT days versus the mean zonal wind speed at 500 hPa.

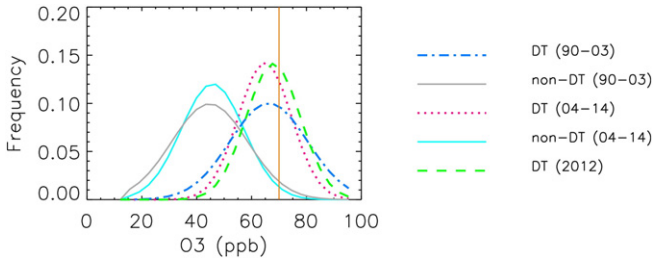

Fig. 11. Similar to Fig. 8 but for O_3 concentrations. The orange vertical line marks the 70 ppb NAAQS O_3 value.

4. Discussion and conclusions

In this study we have described the ground-level O_3 concentration variability and its relationship with synoptic weather conditions in summer months from May to August during the period 1990–2014 in Chicago. The SSC method, by taking into account surface weather conditions such as temperature, humidity, and pressure, provides a very convenient and useful discriminator of O_3 concentrations. Among the six different types of SSC weather, O_3 concentrations are highest in DT weather, although DT occurrence is the least frequent. The summertime O_3 95th percentile has become increasingly correlated with the occurrence of DT weather since around 2003/2004.

This study also demonstrates that DT weather (which is closely associated with high O_3 events) is well correlated with weather conditions aloft. The increase in the number of DT days is associated with the increase of 500 hPa geopotential height (H500) and slower zonal wind speeds at 500 hPa (U500). In addition, the observed enhanced warming in the Arctic region relative to the mid-latitudes (the so-called Arctic Amplification) has been linked to weaker zonal upper-level flow and slower progression of Rossby waves at 500 hPa, which in turn may cause more frequent extreme weather conditions such as drought and heat waves (Francis and Vavrus, 2012). Under the effect of future climate change, H500 is projected to increase and U500 to decrease in the Midwest region (Winkler et al., 2014), which may result in the increase of DT weather in Chicago.

We employ a linear regression model to analyze the relationship between O_3 and DT weather separately for the two periods 1990–2003 and 2004–2014. The results indicate that there was a greater contribution of DT weather to O_3 concentrations in the period 2004–2014 than in 1990–2003. The variation in O_3 seems to have become more strongly associated with DT weather conditions in 2004–2014 than in 1990–2003. We think there are two reasons for this. One is that the O_3-NO_2 relationship was weaker in 2004–2014 than before. Jing et al. (2014) showed that O_3 became insensitive to NO_2 in about 2008/2009, especially for high O_3 concentrations (>75 ppb). Another reason is that, as the climate becomes progressively warmer, temperature-related variables (i.e., H1000, T10M, H500, and T500) become more dominant in determining the occurrence of DT weather, and temperature is highly correlated with O_3. Both reasons result in a stronger O_3–DT correlation in the more recent period 2004–2014.

The combined effects of increasing greenhouse-gas emissions, climate change, and globally enhanced O_3 suggest a strong likelihood of increasing O_3 concentrations in the U.S. in the future. Using a regional coupled chemistry-transport model, Pfister et al. (2014) estimated that the 95th percentile for daily 8-hour-maximum surface O_3 would increase from 79 ppb to 87 ppb by 2050 under the IPCC A2 scenario. Tao et al. (2007) projected an increase of about 4% in U.S. Midwest average O_3 concentrations under the IPCC A1Fi scenario. Murazaki and Hess (2006) projected that about 12 additional days per year would exceed 80 ppb by the end of the century. The results of this present study suggest that because O_3 has become increasingly correlated with DT weather, and because Chicago is projected to become warmer in the future, O_3 concentrations will also increase in Chicago.

The US EPA has tightened the NAAQS standard for O_3 from 75 ppb to 70 ppb (US EPA, 2015). Based on this present work, which shows that O_3 is becoming increasingly dependent on DT weather, and previous work, which demonstrated that O_3 in Chicago is no longer NO_x-sensitive (Jing et al., 2014), the ability to achieve further decreases in O_3 concentrations through NOx emission control in Chicago is reduced. This ability will be

further inhibited should a warmer climate prevail in the future. Emissions of NO_x are predicted to increase due to greater energy consumption for summertime cooling (Hadley et al., 2006; Lin et al., 2007; Lin et al., 2010; McDonald et al., 2012). This will have the effect of reducing O_3 concentrations, as O_3 has become VOC-limited in Chicago. However, because VOC emissions from both biogenic and anthropogenic sources are also predicted to increase, the overall effect of a warmer climate will still enhance ozone concentrations (Lin et al., 2007; Lin et al., 2010). This will further contribute to the stronger correlation between O_3 and temperature. We conclude that it will be extremely challenging for Chicago to attain the 70 ppb O_3 NAAQS level.

The ability to project the long-term O_3 trend in cities is important for the protection of public health. The strong O_3–DT correlation demonstrated in this paper provides a potentially convenient tool for local policy makers to design action plans against expected O_3 pollution in a warmer future climate (without having to conduct complex chemistry-transport modeling). Our future work will examine the relationship between O_3 and DT weather in other U.S. cities. We will also establish a statistical model to predict future O_3 trends using the O_3–DT relationships by making use of downscaled climate forecasts for weather variables after the climate modeling community has made them available both at the surface and aloft, especially at 500 hPa.

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References

Bell, M.L., McDermott, A., Zeger, S.L., Samet, J.M., Dominici, F., 2004. Ozone and short-term mortality in 95 US urban communities, 1987–2000. J. Am. Med. Assoc. 292, 2372–2378.
Bell, M.L., Goldberg, R., Hogrefe, C., Kinney, P.L., Knowlton, K., Lynn, B., Rosenthal, J., Rosenzweig, C., Patz, J.A., 2007. Climate change, ambient ozone, and health in 50 US cities. Clim. Chang. 82, 61–76. http://dx.doi.org/10.1007/s10584-006-9166-7.
Bloomfield, P., Royle, J.A., Steinberg, L.J., Yang, Q., 1996. Accounting for meteorological effects in measuring urban ozone levels and trends. Atmos. Environ. 30, 3067–3077.
Camalier, L., Cox, W., Dolwick, P., 2007. The effects of meteorology on ozone in urban areas and their use in assessing ozone trends. Atmos. Environ. 41, 7127–7137.
Cox, W.M., Chu, S.-H., 1996. Assessment of interannual ozone variation in urban areas from a climatological perspective. Atmos. Environ. 30, 2615–2625.
Davis, R.E., Normile, C.P., Sitka, L., Hondula, D.M., Knight, D.B., Gawtry, S.P., Stenger, P.J., 2010. A comparison of trajectory and air mass approaches to examine ozone variability. Atmos. Environ. 44, 64–74.
Davis, J., Cox, W., Reff, A., Dolwick, P., 2011. A comparison of CMAQ-based and observation-based statistical models relating ozone to meteorological parameters. Atmos. Environ. 45, 3481–3487.
Downey, N., Emery, C., Jung, J., Sakulyanontvittaya, T., Hebert, L., Blewitt, D., Yarwood, G., 2015. Emission reductions and urban responses under more stringent US standards. Atmos. Environ. 101, 209–216.
Eagleman, J.R., 1985. Meteorology: the Atmosphere in Action. second ed. Wadsworth Pub.
Fishman, J., Creilson, J.K., Parker, P.A., Ainsworth, E.A., Vining, G.G., Szarka, J., Booker, F.L., Xu, X., 2010. An investigation of widespread ozone damage to the soybean crop in the upper Midwest determined from ground-based and satellite measurements. Atmos. Environ. 44, 2248–2256.
Francis, J.A., Vavrus, S.J., 2012. Evidence linking Arctic amplification to extreme weather in mid-latitudes. Geophys. Res. Lett. 39, L06801. http://dx.doi.org/10.1029/2012GL051000.
Hadley, S.W., Erickson III, D.J., Hernandez, J.L., Broniak, C.T., Blasing, T.J., 2006. Responses of energy use to climate change: a climate modeling study. Geophys. Res. Lett. 33, L17703. http://dx.doi.org/10.1029/2006GL026652.
Hayhoe, K., Sheridan, S.C., Kalkstein, L.S., Greene, J.S., 2010. Climate change, heat waves, and mortality projections for Chicago. J. Great Lakes Res. 36, 65–73.
Heagle, A.S., 1989. Ozone and crop yield. Annu. Rev. Phytopathol. 27, 397–423.
Hoerling, M., Eischeid, J., Kumar, A., Leung, R., Mariotti, A., Mo, K., Schubert, S., Seager, R., 2014. Causes and predictability of the 2012 Great Plains drought. Bull. Am. Meteorol. Soc. 95, 269–282.
Holloway, T., Spak, S.N., Barker, D., Bretl, M., Moberg, C., Hayhoe, K., Van Dorn, J., Wuebbles, D., 2008. Change in ozone air pollution over Chicago associated with global climate change. J. Geophys. Res. 113, D22306. http://dx.doi.org/10.1029/2007JD009775.
Holton, J.R., 1992. An Introduction to Dynamic Meteorology. third ed. Academic Press.
Horton, D.E., Skinner, C.B., Singh, D., Diffenbaugh, N.S., 2014. Occurrence and persistence of future atmospheric stagnation events. Nat. Clim. Chang. 4, 698–703.
Jacob, D.J., Winner, D.A., 2009. Effect of climate change on air quality. Atmos. Environ. 43, 51–63.
Jacobson, M.Z., 2002. Atmospheric Pollution, History, Science, and Regulation. Cambridge University Press.
Jing, P., Lu., Z., Xing, J., Streets, D.G., Tan, Q., O'Brien, T., Kamberos, J., 2014. Response of the summertime ground-level ozone trend in the Chicago area to emission controls and temperature changes, 2005–2013. Atmos. Environ. 99, 630–640.
Key, J.R., Chan, A.C.K., 1999. Multidecadal global and regional trends in 1000 mb and 500 mb cyclone frequencies. Geophys. Res. Lett. 26, 2053–2056. http://dx.doi.org/10.1029/1999GL900367.

Kline, L.J., Davis, D.D., Skelly, J.M., Savage, J.E., Ferdinand, J., 2008. Ozone sensitivity of 28 plant selections exposed to ozone under controlled conditions. Northeast. Nat. 15, 57–66.
Knapp, P.A., Soulé, P.T., 2007. Trends in midlatitude cyclone frequency and occurrence during fire season in the northern Rockies: 1900–2004. Geophys. Res. Lett. 34, L20707. http://dx.doi.org/10.1029/2007GL031216.
Lee, C.C., Ballinger, T.J., Domino, N.A., 2012. Utilizing map pattern classification and surface weather typing to relate climate to the air quality index in Cleveland, Ohio. Atmos. Environ. 63, 50–59.
Leibensperger, E.M., Mickley, L.J., Jacob, D.J., 2008. Sensitivity of US air quality to mid-latitude cyclone frequency and implications of 1980–2006 climate change. Atmos. Chem. Phys. 8, 7075–7086.
Lin, J.-T., Patten, K.O., Hayhoe, K., Liang, X.-Z., Wuebbles, D.J., 2007. Effects of future climate and biogenic emissions changes on surface ozone over the United States and China. J. Appl. Meteorol. Climatol. 47, 1888–1909.
Lin, J.-T., Wuebbles, D.J., Huang, H.-C., Tao, Z., Caughey, M., Liang, X.-Z., Zhu, J.-H., Holloway, T., 2010. Potential effects of climate and emissions changes on surface ozone in the Chicago area. J. Great Lakes Res. 36, 59–64.
Lippmann, M., 1993. Health effects of tropospheric ozone: review of recent research findings and their implications to ambient air quality standards. J. Expo. Anal. Environ. Epidemiol. 3, 103–129.
Lutgens, F.K., Tarbuck, E.J., Tasa, D.G., 2015. The Atmosphere: An Introduction to Meteorology. 13th ed. Pearson.
Lynch, A.H., Cassano, J.J., 2006. Applied Atmospheric Dynamics. Wiley.
Manney, G.L., Hegglin, M.I., Daffer, W.H., Schwartz, M.J., Santee, M.L., Pawson, S., 2014. Climatology of upper tropospheric–lower stratospheric (UTLS) jets and tropopauses in MERRA. J. Clim. 27, 3248–3271.
McDonald, B.C., Dallmann, T.R., Martin, E.W., Harley, R.A., 2012. Long-term trends in nitrogen oxide emissions from motor vehicles at national, state, and air basin scales. J. Geophys. Res. 117, D00V18. http://dx.doi.org/10.1029/2012JD018304.
Murazaki, K., Hess, P., 2006. How does climate change contribute to surface ozone change over the United States? J. Geophys. Res. 111, D05301. http://dx.doi.org/10.1029/2005JD005873.
Oswald, E.M., Dupigny-Giroux, L.-A., Leibensperger, E.M., Poirot, R., Merrell, J., 2015. Climate controls on air quality in the northeastern U.S.: an examination of summertime ozone statistics during 1993–2012. Atmos. Environ. 112, 278–288.
Pfister, G.G., Walters, S., Lamarque, J.-F., Fast, J., Barth, M.C., Wong, J., Done, J., Holland, G., Bruyère, C.L., 2014. Projections of future summertime ozone over the U.S. J. Geophys. Res. 119, 5559–5582. http://dx.doi.org/10.1002/2013JD020932.
Pryor, S.C., Scavia, D., Downer, C., Gaden, M., Iverson, L., Nordstrom, R., Patz, J., Robertson, G.P., 2014. In: Melillo, J.M., Richmond, T.C., Yohe, G.W. (Eds.), Ch. 18: Midwest. Climate Change Impacts in the United States: The Third National Climate Assessment. U.S. Global Change Research Program, pp. 418–440.
Rienecker, M.M., Suarez, M.J., Gelaro, R., Todling, R., Bacmeister, J., Liu, E., Bosilovich, M.G., Schubert, S.D., Takacs, L., Kim, G.-K., Bloom, S., Chen, J., Collins, D., Conaty, A., da Silva, A., Gu, W., Joiner, J., Koster, R.D., Lucchesi, R., Molod, A., Owens, T., Pawson, S., Pegion, P., Redder, C.R., Reichle, R., Robertson, F.R., Ruddick, A.G., Sienkiewicz, M., Woollen, J., 2011. MERRA: NASA's modern-era retrospective analysis for research and applications. J. Clim. 24, 3624–3648.
Santurtún, A., González-Hidalgo, J.C., Sanchez-Lorenzo, A., Zarrabeitia, M.T., 2015. Surface ozone concentration trends and its relationship with weather types in Spain (2001 – 2010). Atmos. Environ. 101, 10–22.
Shen, L., Mickley, L.J., Tai, A.P.K., 2015. Influence of synoptic patterns on surface ozone variability over the eastern United States from 1980 to 2012. Atmos. Chem. Phys. 15, 10925–10938.
Sheridan, S.C., 2002. The redevelopment of a weather-type classification scheme for North America. Int. J. Climatol. 22, 51–68.
Tao, Z., Williams, A., Huang, H.-C., Caughey, M., Liang, X.-Z., 2007. Sensitivity of U.S. surface ozone to future emissions and climate changes. Geophys. Res. Lett. 34, L08811. http://dx.doi.org/10.1029/2007GL029455.
Turner, A.J., Fiore, A.M., Horowitz, L.W., Bauer, M., 2013. Summertime cyclones over the Great Lakes storm track from 1860 to 2100: variability, trends, and association with ozone pollution. Atmos. Chem. Phys. 13, 565–578.
United States Environmental Protection Agency, 2003. National Air Quality and Emissions Trends Report, Special Studies Edition. Chapter 2. Criteria Pollutants. EPA Publication No. EPA 454/R-03-005.
United States Environmental Protection Agency, 2012. Our Nation's Air – Status and Trends through 2010. EPA Publication No. EPA-454/R-12-001.
United States Environmental Protection Agency, 2015. National Air Quality Standards for Ozone, Final Rule, in: 40 CFR Parts 50, 51, 52, and 58. Register, Federal.
Winkler, J.A., Andresen, J.A., Arritt, R.W., Beecher, J.A., Gronewold, A.D., Hall, K.R., Hatfield, J.L., Handler, S.D., Lofgren, B., Mackey, S.D., Nicholls, S., Patz, J., Posey, J., Pryor, S.C., Swanston, C.W., 2014. An introduction to the synthesis report. In: Winkler, J.A., Andresen, J.A., Hatfield, J.L., Bidwell, D., Brown, D. (Eds.), Climate Change in the Midwest: A Synthesis Report for the National Climate Assessment. Island Press, pp. 1–7.