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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)