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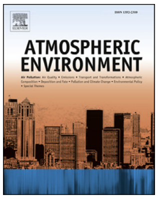

Climate controls on air quality in the Northeastern U.S.: An examination of summertime ozone statistics during 1993–2012

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HIGHLIGHTS

- We model surface ozone concentrations using meteorological and climate variables.
- Meteorological-driven statistical models could improve ozone season predictions.
- Teleconnection-driven statistical models were only insightful.
- Precipitation, temperature and solar radiation were strong predictors.
- Pacific Decadal, Quasi-Biennial and Arctic Oscillations were superior predictors.

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ABSTRACT

The goal of this study is to better understand the linkages between the climate system and surface-level ozone concentrations in the Northeastern U.S. We focus on the regularity of observed high ozone concentrations between May 15 and August 30 during the 1993–2012 period. The first portion of this study establishes relationships between ozone and meteorological predictors. The second examines the linkages between ozone and large-scale teleconnections within the climate system. Statistical models for each station are constructed using a combination of Correlation Analysis, Principal Components Analysis and Multiple Linear Regression. In general, the strongest meteorological predictors of ozone are the frequency of high temperatures and precipitation and the amount of solar radiation flux. Statistical models of meteorological variables explain about 60–75% of the variability in the annual ozone time series, and have typical error-to-variability ratios of 0.50–0.65. Teleconnection patterns such as the Arctic Oscillation, Quasi-Biennial Oscillation and Pacific Decadal Oscillation are best linked to ozone in the region. Statistical models of these patterns explain 40–60% of the variability in the ozone annual time series, and have a typical error-to-variability ratio of 0.60–0.75.

1. Introduction

Tropospheric ozone is primarily formed in the atmosphere as the result of photochemical reactions between precursor species of nitrogen oxides (NO_x) and volatile organic compounds (VOCs). Meteorology plays a major role by influencing chemical reaction rates of ozone formation and destruction; emission rates of VOC and NO_x precursors; as well as atmospheric mixing, the accumulation and transport of ozone and precursors to downwind receptor locations. Establishing the controls on ozone is difficult since long-term ozone observations are sparse and uncertainties associated with emissions and meteorological conditions can be substantial. This constrains air quality professionals in their need to provide both short-term forecasts and long-term planning.

Early ozone control strategies focused primarily on reducing urban VOC emissions. Increasing recognition of the importance of ozone transport led to a concerted effort to reduce NO_x emissions – for example as recommended by the multi-state Ozone Transport Assessment Group after years of modeling and data analysis (LeClair, 1997). Such work led the U.S. Environmental Protection

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Agency (EPA) to enact the “NO_x SIP Call” in 1998, requiring reduced emissions in 22 states by 2003. The general consensus is that anthropogenic NO_x emissions reductions are the best way to reduce surface ozone, and that modern NO_x reductions have driven a substantial decline in surface ozone concentrations (Baldridge, 2005).

Daily maximum air temperatures correlate well with ozone concentrations in the Eastern (Rao et al., 2003; Rasmussen et al., 2012) and Northeastern U.S. (Bloomer et al., 2009). Of all the individual meteorological variables, it is generally believed that temperature has the strongest relationship with ozone (Jacob and Winner, 2009). Other meteorological variables related to ozone include wind speed (Vukovich, 1994; Rao et al., 2003; Chan, 2009), mixing layer height (Rao et al., 2003), boundary layer ventilation (Rao et al., 2003), surface pressure (Vukovich, 1994) and surface radiation flux (Vukovich, 1994; Rao et al., 2003). Atmospheric moisture content is another meteorological variable linked to surface-level ozone (Chan, 2009; Rao et al., 2003), as are frontal passages (Leibensperger et al., 2008) and stagnation events (Vukovich, 1995).

In the Northeastern U.S., ozone is also dependent upon regional transport, making the wind direction an integral factor in ozone concentrations (Husar and Renard, 1997; Schichtel and Husar, 2001). Unlike most regions where low wind speeds are associated with high ozone levels, higher wind speed typically aids in effective transport and is positively correlated with ozone levels (Husar and Renard, 1997; Schichtel and Husar, 2001).

It is well known that modes of climate system variability, or “teleconnections”, across the Northern Hemisphere play a significant role in climate changes on interannual to interdecadal time scales. Thus, when investigating changes in tropospheric ozone, teleconnections should also be considered (Lin et al., 2014). Recent work has linked teleconnections and surface-level ozone (e.g. Lin et al., 2015; Lin et al., 2014). Here an exploratory approach was taken and the physical mechanisms were discussed only for teleconnection patterns found to have statistical relationships with ozone.

This study contributes to existing literature on the influence of weather and climate on ozone by examining:

- the upper tail of the ozone distribution via the 60 ppbv threshold
- a large suite of meteorological variables, previously unanalyzed simultaneously
- meteorological variables not previously examined
- the physical mechanisms underlying the meteorology-ozone relationship, thereby moving beyond previous work on the removal of the influence of meteorology (e.g. Milanchus et al., 1998)
- the linkages between ozone and hemispheric teleconnections

In this study, research questions focus on the interplay among ozone, meteorological variables and teleconnections. Can empirical models of meteorological predictors and NO_x emissions explain ozone changes over time? What meteorological predictors drive the majority of these models? Can similar models built on teleconnections and NO_x emissions explain ozone changes over time? Which teleconnections are important predictors?

2. Material and methods

2.1. Focus region

The Northeastern U.S. region is downwind of the majority of the continental U.S. and marks the exit region of the Polar Jet Stream. The region is topographically complex, extensively borders the Atlantic Ocean and frequently features a low level jet. The general pattern of NO_x emissions in the region decreases from higher to lower values moving in the northeast direction.

2.2. Ozone data

Ozone observations were acquired from the EPA's Air Quality System. Tools on the Datafed.net website (Husar et al., 2008) facilitated the spatial delineation and extraction of the 1993–2012 time series of daily maximum 8-hour average values of ozone (MDA8O3) for all available (253) stations in the Northeastern U.S. region (39.4°-45.4°N, 69.5°-80.2°W). To minimize the influence of missing data, each station used was required to have at least 80% of the years during the 1993–2012 period with 80% of the dates in each year's “season” (defined as May 15-August 30). We chose this period over the April 1-September 30 period because the smaller window generally had higher ozone levels. Stations meeting our completeness criteria constituted the set of stations (83) used in this study (Fig. 1).

Two metrics were derived from the ozone observations. The primary metric to quantify ozone for this analysis was the percent of the season with the MDA8O3 $\geq$60 ppbv. This will be referred to as the “60 ppbv” metric. While the 60 ppbv level is well below the level of the current (2008) U.S. National Ambient Air Quality Standard (NAAQS) of 75 ppbv, it is within the range recommended by the EPA's Clean Air Scientific Advisory Committee during the last two rounds of ozone NAAQS review (e.g. Frey, 2014). The second metric was the MDA8O3 value corresponding to the 80th percentile over the season and is referred to as “80 pctl”. The 60 ppbv concentration level was chosen to better reflect human and ecological health-relevant exposures, and the 80th percentile correlated with the 60 ppbv metric better than other percentile levels. Using two ozone metrics instead of one allowed for more concrete conclusions about the relationships between high ozone concentrations and predictor metrics.

2.3. Meteorological and climate data

Gridded meteorological data in this study were from one of three climate data products, depending upon the variable and geographical location. Within the U.S., daily total precipitation, daily maximum and minimum temperatures were extracted from the 4 km resolution PRISM AN81d dataset (Daly et al., 2008). The same variables were extracted from the DAYMET dataset (Thornton et al., 1997) for the Canadian provinces. DAYMET is a 1 km resolution daily dataset that was aggregated to 4 km resolution and regridded to that of the PRISM dataset for use in this study.

The North American Regional Reanalysis (NARR) (Mesinger et al., 2006) provided the other meteorological variables, including daily average relative humidity, 40–100 cm volumetric soil moisture, downwelling shortwave radiation flux, 10m above ground wind speed and direction, 850 mb geostrophic wind speed and direction, mean sea level pressure and 500 mb geostrophic wind speed. NARR data consist of daily values on a 30 km resolution grid, which were regridded to the PRISM grid via inverse distance weighting.

The teleconnections indices were preferentially acquired from the NOAA's Physical Science Division <http://www.esrl.noaa.gov/psd/data/climateindices/list/>, followed by the National Weather Service's (NWS) Climate Prediction Center <http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml>.