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A 15-year climatology of wind pattern impacts on surface ozone in Houston, Texas

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ABSTRACT

Houston is recognized for its large petrochemical industrial facilities providing abundant radicals for tropospheric ozone formation. Fortunately, maximum daily 8-h average (MDA8) surface ozone concentrations have declined in Houston (-0.6 ± 0.3 ppbv yr^{-1}) during the summers (i.e., May to September) of 2000 to 2014, possibly due to the reductions in precursor emissions by effective control policies. However, it is also possible that changes in meteorological variables have affected ozone concentrations. This study focused on the impact of long-term wind patterns which have the highest impact on ozone in Houston. The analysis of long-term wind patterns can benefit surface ozone studies by 1) providing wind patterns that distinctly changed ozone levels, 2) investigating the frequency of patterns and the respective changes and 3) estimating ozone trends in specific wind patterns that local emissions are mostly involved, thus separating emissions impacts from meteorology to some extent. To this end, the 900-hPa flow patterns in summers of 2000 to 2014 were clustered in seven classes (C1–C7) by deploying an unsupervised partitioning method. We confirm the characteristics of the clusters from a backward trajectory analysis, monitoring networks, and a regional chemical transport model simulation. The results indicate that Houston has experienced a statistically significant downward trend (-0.6 ± 0.4 day yr^{-1}) of the cluster of weak easterly and northeasterly days (C4), when the highest fraction of ozone exceedances (MDA8 > 70 ppbv) occurred. This suggests that the reduction in ozone precursors was not the sole reason for the decrease in ozone exceedance days (-1.5 ± 0.6 day yr^{-1}). Further, to examine the efficiency of control policies intended to reduce the amount of ozone, we estimated the trend of MDA8 ozone in C4 and C5 (weak winds) days when local emissions are primarily responsible for high ambient ozone levels. Both C4 and C5 show a large reduction in the 95th percentile and summertime trends mainly due to effective control strategies. Based on the 5th percentile daytime ozone for C1 (strong southeasterly wind) in coastal sites, this study found that the cleanest air masses that Houston received became more polluted during the summer of 2000–2014 by 1–3 ppbv. Though this study focused on Houston, the analysis method presented could generally be used to estimate ozone trends in other regions where surface ozone is dominantly influenced by both wind patterns and local emissions.

1. Introduction

Tropospheric ozone (O_3) not only adversely affects human health, crop yields, and organic materials when they are exposed to high concentrations, but also acts as a greenhouse gas, directly contributing to global climate change (Seinfeld and Pandis, 2012). In addition, O_3 impacts concentrations of hydroxyl radicals (OH), thereby controlling the oxidation of many common trace gases. In the troposphere, O_3 forms photochemically from complex chemical reactions involving nitrogen oxides ($NO_x = NO + NO_2$), reactive volatile organic compounds (VOC), and OH (Sillman, 1995). Understanding the origins of surface ozone levels requires knowledge of meteorological factors (e.g., Banta et al., 2005) and emission sources (e.g., Li et al., 2016). The non-linearity of ozone production, variability in sources and sinks, and the impact of the ozone background (particularly from East Asia) have resulted in various trends across seasons and locations in the United States. Lefohn et al. (2010) analyzed surface ozone for different periods (i.e., 1980 to 2008 and 1994 to 2008) and found that the second highest annual 1-h average ozone and fourth highest daily maximum 8-h average in both rural and urban regions decreased largely during the summer. Cooper et al. (2012) found that during the summers of 1990–2010, most eastern rural regions experienced statistically significant decreases in the 95th and 50th percentiles of ozone, while the reduction in the western U.S. was minimal, especially during the springtime, possibly because of the elevated ozone levels hemispherically transported from Asia or deep stratospheric intrusions (Lin et al., 2015). More recently, during a period in which widespread reductions of NO_x and VOC anthropogenic emissions took place (1998–2013), Simon et al. (2014) found that ozone concentrations in the 95th percentile declined by 1–2 ppbv yr^{-1} in urban, suburban, and rural regions.

The Houston–Galveston–Brazoria (HGB) region is known for its large petrochemical industrial facilities and is located in a non-attainment region with respect to ozone pollution. Despite significant

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urbanization, governmental regulatory policies have lowered the emissions of ozone precursors. According to air pollutant emissions trend data from the National Emissions Inventory (NEI) of the US EPA (U.S. EPA, 2014) anthropogenic sources of NO_x from both stationary and mobile sources declined by 45% in the U.S. from 2000 to 2014. In addition, VOC anthropogenic emissions decreased by 16%. Although these numbers indicate a trend in the reduction of ozone precursors, comprehensive studies with supporting measurements (concentrations) need to be conducted to confirm such a trend. Due to the lack of sufficient in-situ observations of NO_2 and HCHO (a proxy for VOC reactivity), several studies have devoted themselves to the analysis of trends from satellite-based measurements (e.g., Tong et al., 2015; Choi and Souri, 2015a; Duncan et al., 2016). In the last decade, through the use of various satellites and retrieval methods, a reduction in tropospheric NO_2 in Houston has been detected by Choi et al. (2012), Russell et al. (2012), Hilboll et al. (2013), Tong et al. (2015), Choi (2014), Choi and Souri (2015b) and Duncan et al. (2016). De Smedt et al. (2010, 2015) and Choi and Souri (2015b) found that the reduction in the HCHO column over Houston was not as significant as the VOC anthropogenic emissions in Houston (Washenfelder et al., 2010) possibly resulting from biogenic emissions or climatic variabilities. An overview of NO_2 and HCHO trends seen from space is listed in Table 1.

There have been several studies devoted to examining ozone trends in Houston. In particular, Lefer et al. (2010) concluded, through the use of measurement data, that the MDA8 ozone in Houston between 1991 and 2009 decreased likely as a result of anthropogenic reductions. Zhou et al. (2014), using airborne observations from two field campaigns (2000 and 2006), found that ozone production declined by 40%–50% in the city; however, meteorological changes remain unknown. The biggest obstacle in the development of appropriate emission control policies that could mitigate the levels of ozone and the impact on consequent health and climate changes is the difficulty of quantifying the influences of long-term meteorology and emissions on changes in both ozone and its precursors. Therefore, this study is motivated by the need to understand the impact of meteorological changes on surface ozone concentrations. Among the many meteorological factors, wind fields have been proven to be the most prominent factor controlling the distribution of ozone precursors and the production rate in Houston. Although the impacts of wind patterns have been extensively studied in Houston (e.g., Darby, 2005; Banta et al., 2005; Rappenglück et al., 2008; Ngan and Byun, 2011), the time periods of these case studies were short. As far as we know, Davis et al. (1998) was the only study that used cluster analysis in a long-term study period (1981–1992) in Houston by using observations from the Houston International Airport. The study found that a majority of high daily 1-h maximum ozone events occurred during the summer months. Our work utilizes a cluster analysis in a regional-scale domain based on reanalysis data rather than sparse observations. This analysis also captures changes in the frequency of wind patterns and trends in ozone within the clusters, specifically in the summertime.

Clustering wind patterns can help us to estimate the baseline ozone (e.g., Chan and Vet, 2010) and ozone levels that are mainly governed by local emissions. Conventional methods for estimating baseline and regional background ozone (the definitions of which are presented in Berlin et al. 2013) have been based on the deployment of an isolated station, aircraft measurements (Kemball-Cook et al., 2009), or ozonesonde observations. However, these techniques are limited to short time periods or few sites. Additionally, the flat topography of Houston prevents the use of any elevated station to mitigate the effects of local emissions. Berlin et al. (2013) used principal component analysis (PCA) on MDA8 ozone, and defined the regional background as the principal component that correlates strongly with uniform ozone levels at continuous ambient monitoring stations (CAMS) operated by the Texas Commission on Environmental Quality (TCEQ). They concluded that between 1998 and 2012, the amount of regional background ozone in Houston declined dramatically (-0.92 ± 0.78 ppbv yr^{-1}) which should be considered to derive local emissions impacts on ozone trends. The goal of this study is 1) to cluster wind patterns that have distinctive impacts on surface ozone in Houston, 2) to examine the trend of wind pattern frequencies, 3) to investigate the trend of baseline ozone (i.e., from the Gulf of Mexico) in Houston and 4) to estimate the trend of ozone which was produced mainly by local emissions with the aid of the wind pattern clusters.

2. Measurements and modeling

2.1. Wind direction

Our delineation of wind patterns was mainly based on U- and V-wind components from the three-hourly National Centers for Environmental Prediction-North American Regional Reanalysis (NCEP-NARR) (Mesinger et al., 2006) with a spatial resolution of 32 km. The data analyzed for this study were gathered during the summers (i.e., May to September) of 2000 to 2014. Theoretically, winds at lower standard atmospheric levels of 900 hPa, 850 hPa, and 700 hPa were all possible choices because they were neither complicated by the surface topography nor uncorrelated with surface air pollution. Ngan and Byun (2011) used 850 hPa winds because this level was not subject to direct local influence. Nevertheless, we used 900 hPa winds which have stronger ozone-predicting capability because they are closer to the boundary layer, where the winds directly influence ozone concentrations. Lower wind levels were not considered because of the complexity and possible uncertainties of NARR surface winds. The averaged morning time data at 6:00 a.m., 9:00 a.m. and 12:00 p.m. local standard time (LST) were used to capture the main initial flow pattern, strongly affecting afternoon ozone concentrations (a peak around ~1300–1600 LST).

2.2. In-situ surface ozone and NO_2

In-situ surface data included regular measurements from the CAMS measurement network. The network collects hourly meteorology and chemistry data. The measured parameters vary from station to station.

Table 1
Overview of ozone precursor trends in Houston seen by remote sensing. Note that the spatial subset for Houston city and the radiometric error flags might be inconsistent in the literatures.

Variable	Period	Reference	Instrument	Trend
NO_2	2005–2011	Russell et al. (2012)	Berkley OMI[a]	$-4.7\%\ yr^{-1}$
	2005–2013	Choi and Souri (2015b)	NASA OMI	$-1.7\%\ yr^{-1}$
	2005–2012	Tong et al. (2015)	NASA OMI	$-3.4\%\ yr^{-1}$
	2005–2014	Duncan et al. (2016)	NASA OMI	$-3.8\%\ yr^{-1}$
HCHO	1997–2009	De Smedt et al. (2010)	GOME[b] and SCIAMACHY[c]	$-1.1\%\ yr^{-1}$
	2005–2013	Choi and Souri (2015b)	SAO OMI	$-0.6\%\ yr^{-1}$
	2005–2014	De Smedt et al. (2015)	BIRA-IASB OMI	$-1.1\%\ yr^{-1}$

[a] Ozone Monitoring Instrument.
[b] Global Ozone Monitoring Experiment.
[c] Scanning Imaging Absorption Spectrometer for Atmospheric Chartography.