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Assessing the impacts of seasonal and vertical atmospheric conditions on air quality over the Pearl River Delta region

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ABSTRACT

Air pollution is an increasingly concerning problem in many metropolitan areas due to its adverse public health and environmental impacts. Vertical atmospheric conditions have strong effects on vertical mixing of air pollutants, which directly affects surface air quality. The characteristics and magnitude of how vertical atmospheric conditions affect surface air quality, which are critical to future air quality projections, have not yet been fully understood. This study aims to enhance understanding of the annual and seasonal sensitivities of air pollution to both surface and vertical atmospheric conditions. Based on both surface and vertical meteorological characteristics provided by 1994–2003 monthly dynamic downscaling data from the Weather and Research Forecast Model, we develop generalized linear models (GLMs) to study the relationships between surface air pollutants (ozone, respirable suspended particulates, and sulfur dioxide) and atmospheric conditions in the Pearl River Delta (PRD) region. Applying Principal Component Regression (PCR) to address multi-collinearity, we study the contributions of various meteorological variables to pollutants' concentration levels based on the loading and model coefficient of major principal components. Our results show that relatively high pollutant concentration occurs under relatively low mid-level troposphere temperature gradients, low relative humidity, weak southerly wind (or strong northerly wind) and weak westerly wind (or strong easterly wind). Moreover, the correlations vary among pollutant species, seasons, and meteorological variables at various altitudes. In general, pollutant sensitivity to meteorological variables is found to be greater in winter than in other seasons, and the sensitivity of ozone to meteorology differs from that of the other two pollutants. Applying our GLMs to anomalous air pollution episodes, we find that meteorological variables up to mid troposphere (~700 mb) play an important role in influencing surface air quality, pinpointing the significant and unique associations between meteorological variables at higher altitudes and surface air quality.

1. Introduction

Air pollution is strongly influenced by meteorological conditions. For example, previous studies have reported that heat waves and droughts have a significant contribution on ozone (O_3) and particular matter and air-quality-related mortality (Fischer et al., 2004; Filleul et al., 2006). There is a rising concern that as a result of climate change, air quality in cities will degrade in the future (IPCC, 2014), but the mechanisms driving these changes have yet to be fully understood. Previous work has studied the relationship between air pollution and various meteorological conditions, but findings vary among different studies. For instance, the formation and removal of surface O_3 are enhanced by increases in temperature and ultraviolet radiation. Previous studies have adopted air quality models to examine the influence of meteorological conditions on increases in O_3 concentration (Sillman and Samson, 1995; Sillman, 1999). The magnitude of this influence is however still uncertain (Cuchiara et al., 2014). On the other hand, concentration of respirable suspended particulates (RSP) was revealed to be strongly correlated with low relative rainfall and humidity (Chan and Kwok, 2001), while other studies found that RSP concentration is associated with wind direction (Chan and Kwok, 2001; Cheng and Lam, 1998; Peng et al., 2011). Some studies have combined theoretical interactions between meteorology and air pollutants to investigate the overall correlation, but the occurrence and magnitude of these

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interactions have yet to be well understood (e.g., Samet et al., 1998).

Correlations between meteorological and air quality variables can vary from region to region because of differential meteorological patterns in terms of synoptic, mesoscale, and turbulent scales (Pielke and Uliasz, 1998), as well as changing spatial patterns of pollutant emissions (Fiore et al., 2012). IPCC (2014) reported that there are insufficient studies focusing on the Asia and Pacific regions, where regional monsoons dominate seasonal climate variability. The Pearl River Delta (PRD) region, which accommodates tens of millions of inhabitants in major urban areas, has suffered from complex regional air pollution problems due to escalating anthropogenic emissions and its unique geography and climatology settings (Wang et al., 2003; Wu et al., 2005; Zhang et al., 2015). Several studies have highlighted a relationship between atmospheric conditions and air quality over the region (Cheng and Lam, 1998; Zhao et al., 2016). Given that the climate is projected to change, to investigate how climate change impacts on air quality requires a systematic and clear understanding of the current meteorology-air quality relationship.

While statistical approaches were commonly applied to understand influences of meteorology on air quality, majority of them focused on the sensitivity of air quality to surface meteorological conditions (Li et al., 2014; Luo et al., 2017; Ramsey et al., 2014; Tai et al., 2012; Zhang et al., 2015). Only few of them have explored the sensitivity of air quality to vertical atmospheric profiles i.e. temperature and wind profiles and developed regression models based on both surface and vertical meteorological characteristics, and comprehensively described influences of surface and upper level meteorology on various pollutants in different seasons. Atmospheric stability, normally quantified by meteorological characteristics among different altitudes, has a significant influence on re-circulating polluted air within the PRD and it mixes pollutants emitted from varying sources (Lo et al., 2006), as well as allows pollutants to accumulate and chemically react under stagnant airflow conditions (Wu et al., 2005). The Bulk Richardson Number, an atmospheric stability metric, has been shown to be associated with surface stability (Zoumakis and Kelessis, 1991), and has been applied to examine its effect on air quality through vertical mixing (Jeričević and Grisogono, 2006). However, none of them have applied separately the component of these metrics, which are the meteorological variables at different altitudes, to investigate how meteorology influences the vertical transport of air pollutants and thus impacts air quality.

Furthermore, literature commonly focused on the effects of meteorology on O_3 and particulate matters, or indices that are used to represent air quality. A comprehensive analysis of influences of meteorology on various pollutants has yet to be available. For example, while sulfur dioxide – an important particulate matter precursor – is strongly influenced by atmospheric characteristics (Cheng and Lam, 1998; Meng et al., 2010). How meteorology at different attitudes affects sulfur dioxide has yet to be fully understand. A multi-pollutant analysis is necessary to provide vulnerable information for policy makers and atmospheric scientists.

The aim of this study is to develop linear models using dynamic downscaling meteorological data along with air quality observations, and to evaluate the sensitivity of each air pollutant to surface and upper level meteorological variables. This allows us to understand the sensitivities of O_3, RSP and SO_2 concentration to both surface and vertical atmospheric conditions in the densely populated PRD region, and particularly to explain recently observed extreme anomalies of air quality in the PRD region.

2. Data and methods

2.1. Site selection

The PRD region is selected in this study due to two primary reasons: it has a large population living under rising concerns about air pollution, and it has a complicated air quality–meteorology relationship due to unique geographical and climatic conditions. The PRD region is a large low-lying area surrounded by the hilly coast of southern China. The region is often regarded as an emerging megacity and is considered a fast-growing economic area (Wang et al., 2014). It features nine major cities and two special administrative regions (SARs), Hong Kong and Macao. The climate of PRD is influenced by the Asian monsoon, with prevailing winds from the northeast in winter, from the east in spring and autumn, and from the southwest in summer (Wang et al., 2001). Most rainstorms occur during the warm period of April to September. Air pollution in the PRD is typically attributed to emission sources at alternating spatial scales (local, regional in PRD and beyond the PRD region) under certain synoptic conditions (Huang et al., 2005; Luo et al., 2017; Wang et al., 2009). Local pollution is caused by intensive air pollutant emissions from different sources such as power plant, industry and mobile sources (Zheng et al., 2009). Additionally, monsoons sometimes transport pollutants along the coastline from adjacent areas into the PRD region.

Air pollution in the PRD region has a significant *trans*-boundary nature (Gu and Yim, 2016; Lee and Savtchenko, 2006). This study includes three air quality monitoring stations in Hong Kong due to their air quality characteristics and a better representation of regional air quality (see Fig. 1). The monitoring stations include Yuen Long (22.4440 °N, 114.0224 °E), Tung Chung (22.2886 °N, 113.9431 °E) and Tap Mun (22.4714 °N, 114.3608 °E). These stations represent different land-use types and have different surrounding geographic landscapes. Yuen Long station is located in a new town at the northwest of Hong Kong, with immediate exposure to *trans*-boundary air pollution. The sampling height of Yuen Long station is 25.0 m above ground. Tung Chung station is situated within a residential area in a new town on the north-western coast of Lantau Island. Tung Chung is surrounded by mountains on three sides (west, south and east), including Lantau Peak (934.0 m, second highest peak in Hong Kong) and Sunset Peak (869.0 m, third highest peak in Hong Kong). The sampling height of Tung Chung station is 27.5 m above ground. Tap Mun is a rural station located on Grass Island in north-eastern part of Hong Kong. The highest point of Grass Island is 125.0 m above sea level and the sampling height of Tap Mun station is 11.0 m above ground.

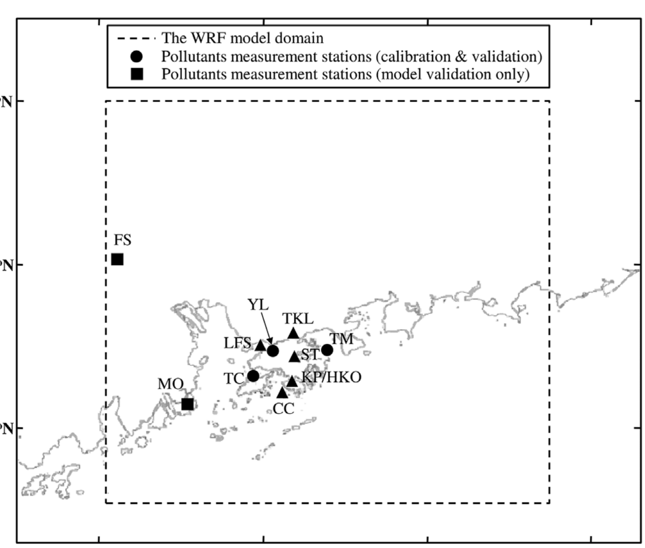

Fig. 1. The WRF model domains. The circle labels show the locations of air pollution measurements [Yuen Long (YL), Tung Chung (TC) and Tap Mun (TM)] for model calibration and validation. The square labels show the location of air pollution measurements [Foshan (FS) and Macau (MO)] outside Hong Kong used for model validation only. The triangular labels show the locations of weather stations [Lau Fau Shan (LFS), Shatin (SHA), Ta Kwu Ling (TKL), Cheung Chau (CC) and Kings Park/Hong Kong Observatory Headquarter (KP/HKO)] for our WRF validation.