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Projecting the impacts of atmospheric conditions under climate change on air quality over the Pearl River Delta region

Cheuk Hei Marcus Tong[a], Steve Hung Lam Yim[a,b,c,*], Daniel Rothenberg[d], Chien Wang[d], Chuan-Yao Lin[e], Yongqin David Chen[f,b,b], Ngar Cheung Lau[a,b]

[a] Department of Geography and Resource Management, The Chinese University of Hong Kong, Hong Kong, China
[b] Institute of Environment, Energy and Sustainability, The Chinese University of Hong Kong, Hong Kong, China
[c] Stanley Ho Big Data Decision Analytics Research Centre, The Chinese University of Hong Kong, Hong Kong, China
[d] Center for Global Change Science, Massachusetts Institute of Technology, Cambridge, MA, USA
[e] Research Center for Environmental Changes, Academia Sinica, Taipei, Taiwan
[f] School of Humanities and Social Science, The Chinese University of Hong Kong, Shenzhen, Hong Kong, China

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ABSTRACT

Anthropogenic climate change has been increasingly confirmed by weather observation and scientific literature in recent decades. Atmospheric stability, which has strong effects on vertical mixing of air pollutants and thus air quality, may be affected under climate change. This study aims to statistically assess the impacts of climate change alone on the future air quality in the Pearl River Delta region in the near future (2030–2039) and the far future (2090–2099) under two Representative Concentration Pathways (RCP) scenarios, i.e., RCP 4.5 and RCP 8.5, based on the future surface and upper level meteorological data projected by one regional climate model (RCM): WRF, and by four general circulation models (GCMs): CanESM2, MIROC, MRI-CGCM3 and MPI-ESM-LR. The arithmetic means of projections reveal an increase in the levels of air pollutants [ozone (O_3), respirable suspended particulates (RSP) and sulphur dioxide (SO_2)] in various seasons, even though a decrease is projected to occur in June-July-August. These changes in projected mean concentration are more significant in the far future, and under the RCP8.5 scenario. Among difference meteorological variables, surface temperature is most associated with the projected change in the three pollutants, with a range from 56.9% to 65.2% in all seasons and for all pollutants, relative to all contributions in RCP8.5 for example. Other notable associations include positive effects of vertical temperature gradient and the temperature–dew point difference on pollutant concentration. We found an increase in frequency of high pollution levels in December–January–February and March–April–May, as the occurrence proportion of pollutant concentration greater than the recent 95th percentile is 9.5%–9.6% and 6.4%–9.2%, respectively. We conclude that climate change alone is projected to have significant effect on air quality in the Pearl River Delta region in future, implying the necessity of more stringent air pollutant emission control policies to mitigate air pollution in the future.

1. Introduction

Air pollution is strongly influenced by weather conditions, and is therefore sensitive to climate change. The Intergovernmental Panel on Climate Change (IPCC) projected that air quality in cities will be degrading in the future (IPCC, 2014), with some studies attributing the effect to increase in anticyclonic conditions (e.g. Hulme and Jenkins, 2002). Particularly, many previous studies have adopted air quality models to investigate the influence of climate change on the increase in O_3 concentrations (Morris et al., 1989, 1995; Penner et al., 1989; Sillman and Samson, 1995; Sillman, 1999). Particularly, Dawson et al. (2007) and Hedegaard et al. (2008) suggested that temperature is one of the greatest contributors among the meteorological parameters. Some studies have also highlighted that both the increases in temperature and radiation contribute the most to projected O_3 increase in the 21st century (Krüger et al., 2008). On the other hand, changes in circulation patterns at synoptic and global scales due to climate change can also affect pollution levels (e.g., Collins et al., 2003; Stevenson et al., 2006). Most previous studies have focused on the projection of O_3 concentration only, whereas a few studies have highlighted the role of wet deposition on the removal of particulate matters and SO_2 through increased precipitation (e.g. Tagaris et al., 2007). Yet, projecting air

* Corresponding author. Department of Geography and Resource Management, The Chinese University of Hong Kong, Hong Kong, China.
E-mail address: steveyim@cuhk.edu.hk (S.H.L. Yim).

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quality for future years is challenging because of its complex nature. Air quality is influenced by different factors that often interfere one another that masking effects make the understanding to processes and contribution of each factor separately difficult.

Furthermore, the impacts of climate change on air quality vary from region to region due to the change of the pollutant emission patterns (Fiore et al., 2012), and the differential meteorological pattern in terms of synoptic, mesoscale, and turbulent scale (Pielkea et al., 1998). Most of these outcomes mentioned were obtained in Europe or in the US. Yet, studies focusing on the Asia and Pacific region where regional monsoons determine seasonal meteorological variability are insufficient (IPCC, 2014). The Pearl River Delta (PRD) region has been accommodating tens of millions of inhabitants in major urban areas. The rapid urbanization and economic development in the PRD have contributed to complex regional air pollution problems associated with rising anthropogenic emissions (Wang et al., 2003; Wu et al., 2005; Zhang et al., 2008a). In addition to global scale climate change, notable effects of urbanization have also contributed to the regional climate change in the PRD. Wang et al. (2014) has found a rise of surface temperature, but a drop of surface absolute humidity and wind speed in the PRD in recent years, which is pointed to the reduction in vegetation and irrigated cropland. Projections by Liu et al. (2013) have suggested a climate change induced increase in afternoon mean surface O_3 by 1.5 ppb from 2000 to 2050. Studies have been focused mostly on O_3 which is associated with various chemical interactions in the atmosphere. A clear and comprehensive study on the sign and magnitude of climate change impacts on air quality in the PRD region still requires further investigations.

We note that previous studies have projected future air quality based on surface meteorological factors alone. Yet, vertical atmospheric stability, which is often defined by various meteorological factors such as temperature, humidity and wind speed along the vertical profile (e.g. George, 1960; Miller, 1967; Shir and Shieh, 1974), has played an important role on mixing pollutants emitted from different sources (Lo et al., 2006), as well as allowing accumulation and chemical reaction of pollutants under stagnant airflow conditions (Wu et al., 2005). Previous studies have run general circulation model (GCM) or regional climate model (RCM) simulations to study climate change's effect on mixing depth for the 21st century, but both increases and decreases of mixing depths are found in different regions without consistent patterns (Hogrefe et al., 2004; Mickley et al., 2004; Leung and Gustafson, 2005; Murazaki and Hess, 2006; Lin et al., 2008; Wu et al., 2008). Notable model uncertainty has also implied that the projected trends are not robust (Murazaki and Hess, 2006). Moreover, none of these studies have applied meteorological variables measured at different altitudes to project the role of climate change on the vertical transport of air pollutants and hence the air quality.

Above all, our aim of this study is to project the sole effects of climate change on future air quality with various GCM & RCM meteorological data based on linear models, and to evaluate the contribution of each of these meteorological variables on the future projection.

2. Data and methods

2.1. Site selection

The PRD region has been selected as the focus of this study. This area is a large flatland surrounded by the Nanling Mountains which isolate the air pollution in the PRD from that in central China (Zhang et al., 2008b). Nonetheless, the arrival of the northeast monsoon during winter period sometimes transports pollutants from eastern and northern China along the coastline to the PRD region (Yim et al., 2010; Gu and Yim, 2016). Under stagnant airflow conditions, the basin-shaped PRD limits pollutant dispersion. Some local-scale meteorological patterns like urban heat islands, land–sea breezes, and mountain–valley winds are associated with mixing and re-circulating air pollutants emitted from different places within the PRD region (Lo et al., 2006). The topographic and meteorological features have combined altered the processes of pollutant accumulation and reaction (Wu et al., 2005; Yim et al., 2007) in terms of various spatial scales (local, PRD regional or beyond the PRD region) depending on the specific synoptic conditions (Huang et al., 2005Wang et al., 2009).

The PRD, which is consisted of nine major cities and two special administrative regions – Hong Kong and Macao, has contributed approximately 70% of the gross domestic product (GDP) in Guangdong Province (Wang et al., 2014). Rapid urbanization is witnessed in the PRD over the past few decades, with a 72.7% of the total land has been designated as urban land use as of 2010 (Wang et al., 2014). Besides, the absolute population has multiplied from 24.0 million in 1990 to 56.1 million in 2014. Serious air pollution associated with massive urbanization and industrialization remains to be a critical problem in the region. Local emissions are contributed by the intensive industrial activities and facilities which produce intensive pollutant emissions in various categories (Zheng et al., 2009). While both the fraction of urbanized land and region population are projected to continue to increase in the future, the pollution problem is projected to remain significant in the next decades.

2.2. GLM models for air quality projections

The projection models adopted in this study are derived by Tong et al. (2018). They developed generalized linear models (GLM) which correlate the meteorological variables along altitudes with the surface air quality at several selected measuring stations in the PRD. The predictor meteorological variables in the model, derived by the basic meteorological parameters of classical stability indices like K-index (George, 1960) and Bulk Richardson Number (Baklanov et al., 2002; Borge et al., 2008; Shir and Shieh, 1974), includes temperature at surface level, and vertical temperature difference, temperature–dew point difference, north-south and east-west wind components along four vertical levels up to 700 mb, approximately 3000 m where anthropologic aerosol typically exists below this level (see Table 1). Regarding the response of air quality variables, our study focuses on the projection of ozone (O_3), respirable suspended particulates (RSP) and sulphur dioxide (SO_2). These pollutants are considered as major air pollutants in the PRD region, and produced from both local and non-local emission sources (Che et al., 2011; Luo et al., 2018; Wang and Lu, 2006). They are usually adopted as indicators to assess the ambient air quality in the PRD such as the Air Quality Health Index due to their adverse impacts on human health and plants (Wong et al., 2013). These pollutants can be potentially transported over long distances (Fiore et al., 2009), thus their ambient concentrations can be significantly altered by variability in atmospheric conditions.

2.3. Future meteorological projection data

The future meteorological data are simulated by a monthly ensemble of various GCMs & RCM [hereafter referred to as climate models]. The climate models include MPI-ESM-LR (Giorgetta et al., 2013), MRI-CGCM3 (Yukimoto et al., 2012), MIROC5 (Watanabe et al.,

Table 1
Meteorological variables used in the study.

Temperature (°C)	2 m (**T_{2m}**)
Temperature Difference (°C)	2 m–925 mb (**T_{2m}**), 925 mb–850 mb (**$T_{925\text{-}850}$**), 850 mb–700 mb (**$T_{850\text{-}700}$**)
Temperature–Dew Point Difference (°C)	2 m (**T-D_{2m}**), 925 mb (**T-D_{925}**), 850 mb (**T-D_{850}**), 700 mb (**T-D_{700}**)
U wind component (m/s)	10 m (**U_{10m}**), 925 mb (**U_{925}**), 850 mb (**U_{850}**), 700 mb (**U_{700}**)
V wind component (m/s)	10 m (**V_{10m}**), 925 mb (**V_{925}**), 850 mb (**V_{850}**), 700 mb (**V_{700}**)