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Trans-boundary air pollution in a city under various atmospheric conditions

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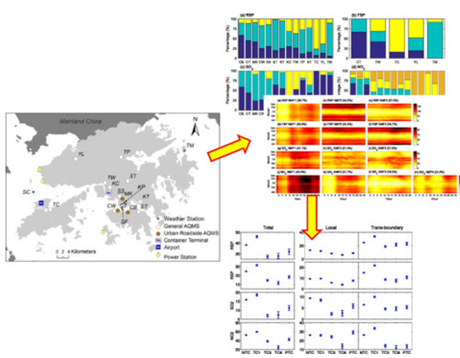
HIGHLIGHTS

- An integrated statistical scheme is developed and applied for source apportionment.
- The contributions of trans-boundary air pollution and local sources to air pollutants in a city are estimated.
- Contribution of trans-boundary air pollution increases by 17%–46% when a tropical cyclone is approaching.

GRAPHICAL ABSTRACT



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ABSTRACT

Trans-boundary air pollution (TAP) is a crucial factor affecting air quality, and its contribution may vary over time and differ under various atmospheric conditions. This study firstly applies an integrated statistical scheme to estimate the contributions of TAP and local sources to air pollutants in a city, and then investigate the influences of tropical cyclones (TC) on TAP. Hong Kong is chosen as an example because of its significant and special TAP characteristics. This study focuses on four major air pollutants, namely, respirable and fine suspended particulates (RSP/PM_{10} and $FSP/PM_{2.5}$), sulfur dioxide (SO_2), and nitrogen dioxide (NO_2), from 2002 to 2013. Our results show that, on average, TAP is the major contributor of the annual RSP, FSP, SO_2, and NO_2 in Hong Kong. We estimate that when a TC is approaching, the increase in pollutant concentration in Hong Kong is mainly due to the increase in TAP contribution by the strengthened northerly wind at higher level of atmosphere (≥900 hPa). These changes are accompanied by decreases in precipitation and increases in northerly/north-easterly wind, which may prolong the lifetime of pollutants, enhancing pollutant transport from mainland China to Hong Kong.

1. Introduction

Air pollution is a serious threat to people all over the world, especially to people living in cities (Donaldson et al., 2001; Tian et al., 2013; WHO, 2006; Wilson et al., 2004; Wong et al., 2002; Wong et al., 1999). In many cities, such as Hong Kong, air pollution is attributable to not only local sources but also pollutants transported from outside the city

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(Chan and Chan, 2000; Colvile et al., 2001; Yuan et al., 2013), which is one of the major causes of air pollution problem in Hong Kong (Chan and Chan, 2000). Trans-boundary air pollution (TAP) in Hong Kong is mainly from mainland China (e.g., the Pearl River Delta, hereafter PRD) or Taiwan during winter with northerly wind (Chan and Chan, 2000; Yuan et al., 2013). However, source identification of gaseous species such as SO_2 and NO_2 in the PRD region or Hong Kong needs to be better understood. To address air pollution problems in a city, understanding the contribution and spatio-temporal characteristics of TAP to air pollutants is of great significance albeit a challenging task (Berge et al., 1999; Lam et al., 2005; Park et al., 2006).

The air quality of a city is not only affected by local emission sources and TAP (intrinsic factors) but also related to meteorological conditions (extrinsic factors). A number of studies have analyzed the influences of wind, temperature, and relative humidity on the concentrations of air pollutants (Chan and Chan, 2000; Fung and Wu, 2014; Wang et al., 2001). Furthermore, air quality is affected by temporary weather conditions, and it might also be influenced by the variability of large-scale climate systems, e.g., tropical cyclones (TCs), monsoons, and El Niño-Southern Oscillation (ENSO). To tackle air pollution, the impacts of TCs on the contributions of TAP and local sources to air pollutants need to be studied, especially in Hong Kong, which is directly affect by at least 6 TCs every year from China Seas or the western North Pacific (Lee and Cheng, 2012). Nevertheless, very few studies have comprehensively analyzed the variation in contribution of various sources to air quality during TC events.

Many approaches, such as receptor modeling (Fung and Wong, 1995), principal component analysis (PCA), UNMIX (Song et al., 2006), and positive matrix factorization (PMF) (Hu et al., 2010; Shi et al., 2009), have been employed to apportion sources to air pollutants in a city. These methods provide valuable information for air quality management. Nevertheless, they typically require measured chemically speciated data (i.e., data showing the chemical composition of particulates) which are not always available. Furthermore, these methods are on the basis of chemical speciation, and they are thus inapplicable to gaseous pollutants, e.g., SO_2 and NO_2.

Non-negative matrix factorization (NMF), a modified version of PMF, is a method that factorizes a non-negative matrix into two matrices with non-negative elements (Lee and Seung, 1999); hence NMF gives a decomposition into parts (Donoho and Stodden, 2003). Compared with traditional methods, NMF results are more interpretable and its matrices are easier to be inspected (Brunet et al., 2004; Lee and Seung, 1999). Moreover, NMF does not require a large amount of chemically speciated data. NMF can be applied to identify contributions of different emissions sources to air pollutants, including both gaseous species and particulate matter. For instance, NMF has been applied to classify source types to ozone concentration datasets for the period 1991–2010 in Europe (Malley et al., 2014) and to identify the daily patterns of particulate air pollution in Beijing (Thiem et al., 2012). Compared with the conventional methods, NMF provides a more effective and economic way to identify the sources of air pollutants. We note that the NMF method is based on statistical procedure. It is therefore required to integrate the NMF method and other appropriate ways to provide a robust source identification.

In this study, we propose a scheme by integrating the NMF approach with air pollution-rose and backward trajectory model to estimate the contribution of trans-boundary air pollution and to then study the influences of meteorological phenomena (e.g., local wind, TCs events) on trans-boundary components.

The rest of the paper is organized as follows. Section 2 introduces the data used in this study. Section 3 introduces the integrated identification scheme. The results of source identification and the effects of various weather and climatic conditions on different contributions are given in Section 4. Section 5 provides a discussion of the implications of our findings and a conclusion of this study.

2. Materials

2.1. Study area

To analyze the TAP of a city, Hong Kong serves as a good example due to its significant magnitude and seasonal variations of TAP. Hong Kong is located on the sub-tropical south coast of China and in the southern part of the PRD region, one of the most densely urbanized regions in the world and one of the main hubs of China's economic growth. The climate of Hong Kong is characterized by the East Asian monsoon (Leung et al., 2004) exhibiting two main seasons: a warm wet summer season, and a cool dry winter season. Prevailing synoptic wind is south-westerly in summer and north-easterly in winter, and the latter is always favorable to the transport of air pollutants (i.e., the TAP) from mainland China to Hong Kong.

2.2. Air quality monitoring stations

In this study, we focus on four major air pollutants in Hong Kong, i.e., respirable suspended particulates (RSP or PM_{10}), fine suspended particulates (FSP or $PM_{2.5}$), sulfur dioxide (SO_2), and nitrogen dioxide (NO_2). Hourly measurement data of RSP, NO_2, and SO_2 recorded from 2002 to 2013 are collected from the air quality monitoring network operated by the Hong Kong Environmental Protection Department (HKEPD) (Fig. 1). FSP has been reported since 2005 in Hong Kong, and thus the data before 2005 are not included. The characteristics of the air quality monitoring network are described in the supporting information (SI), and the details about the monitoring stations are listed in Table S1.

2.3. Meteorology and climate data

Local hourly wind direction and speed recorded from 2002 to 2013 at four stations, i.e., Sha Chau (SC), Star Ferry (SF), Tap Mun (TM), and King's Park (KP), in Hong Kong are used to study the relationship between air pollution and the local weather conditions. These four stations represent the general wind conditions in different parts of Hong Kong (Fig. 1). For instance, SC represents wind conditions in western Hong Kong; SF and KP represent wind in central urban areas (e.g., northern Hong Kong island, and southern Kowloon peninsula); and TM indicates wind in north-eastern Hong Kong.

TC records are obtained from the Hong Kong Observatory (HKO) warnings and signals database at http://www.hko.gov.hk/wxinfo/climat/warndb/warndb1_e.shtml. According to the warning signals of TCs reported by the HKO, we categorize the TC influential episodes into different phases, namely, TC1, TC3, TC8, and Post-TC (PTC). TC1, TC3, and TC8 are the periods when a TC is affecting Hong Kong with warning signals of NO.1, 3, and 8 in force, respectively. Refer to HKO (2012) for details of definition of Hong Kong's tropical cyclone warning signals. PTC is the period when a TC is leaving Hong Kong, and a warning of No.1 or No.3 signals is in force after TC8. We also compare these periods with the normal summer period when there is no TC signal issued, namely, TC0.

3. Methodology

In this study, we develop and apply an integrated statistical scheme to identify sources to air pollutants in a city. This scheme integrates NMF, pollution-wind rose, the Hybrid Single — Particle Lagrangian Integrated Trajectory (HYSPLIT), and the concentrations weighted trajectory (CWT) analysis. Firstly, the measured data at all stations are classified by NMF into different groups (i.e., NMF factors) through the statistical identification of intrinsic features of the data, and the contributions from each group to each station are calculated. The derived groups, with similar component abundances to the known source signatures, are regarded as source profiles. Secondly, contributions of TAP and