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A novel method to construct an air quality index based on air pollution profiles

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ABSTRACT

Background: Air quality indices based on the maximum of sub-indices of pollutants are easy to produce and help quantify the degree of air pollution. However, they discount the additive effects of multiple pollutants and are only sensitive to changes in highest sub-index.
Objectives: We propose a simple and concise method to construct an air quality index that takes into account additive effects of multiple pollutants and evaluate the extent to which this index predicts health effects.
Materials and methods: We obtained concentrations of four criteria pollutants: particulate matter with aerodynamic diameter ≤ 10 μm (PM_{10}), sulphur dioxide (SO_2), nitrogen dioxide (NO_2) and ozone (O_3) and daily admissions to Hong Kong hospitals for cardiovascular and respiratory diseases for all ages and those 65 years or older for years 2001–2012. We derived sub-indices of the four criteria pollutants, calculated by normalizing pollutant concentrations to their respective short-term WHO Air Quality Guidelines (WHO AQG). We aggregated the sub-indices using the root-mean-power function with an optimal power to form an overall air quality index. The optimal power was determined by minimizing the sum of over- and under-estimated days. We then assessed associations between the pollution bands of the index and cardiovascular and respiratory admissions using a time-stratified case-crossover design adjusted for ambient temperature, relative

1. Introduction

The rapid rate of industrialization and urbanization, notably in low- and middle-income countries, has led to deteriorating air quality and increasing risk of adverse effects on human health (PAPA, 2011; Wong et al., 2010). This development has brought about the need to have reliable, valid and up-to-date information on air quality conditions to support environmental policy and, in particular, to inform members of the public. To this end, air quality indices are used to monitor ambient concentrations in real-time to ensure that the air we breathe is clean and safe, a basic requirement of human health and well-being. A long-standing subject of research in air quality assessment has been the specification of what constitutes a valid index for air quality. For it to be valid, an index should be accurate, in the sense that it should be carefully balanced between (1) not raising unnecessary alarm by overestimating the level of pollution and (2) not providing a false sense of security by underestimating the level of pollution (Ott, 1978). In addition, it should be possible to validate such an index with a set of health outcome data to test the extent to which the index predicts health effects. These criteria are important in a proposed air quality index in that they strengthen the validity of the index with respect to environmental policy and public health.

The features of a valid air quality index outlined above should also be clearly communicated to members of the public. This is normally achieved by grouping into ranges, with each range assigned a number and/or a colour. A standardized public health message is also often provided for each range.

The most common air quality index, the Pollutant Standard Index (PSI), was developed by the US Environmental Protection Agency (EPA), taking into account five major criteria air pollutants: particulate matter with aerodynamic diameter ≤ 10 μm (PM_{10}), sulphur dioxide (SO_2), nitrogen dioxide (NO_2), ozone (O_3), and carbon monoxide. The indexing system was further revised and replaced by the Air Quality Index (AQI) (USEPA, 2006). Particulate matter with aerodynamic diameter ≤ 2.5 μm ($PM_{2.5}$) and 8-h mean of O_3 concentrations were also included in the AQI.

Abbreviations: AQI, Air Quality Index; DAQI, Daily Air Quality Index; EPA, Environmental Protection Agency; HKAQI, Hong Kong Air Quality Index; IQR, interquartile range; IT, interim targets; max, maximum; min, minimum; NO_2, nitrogen dioxide; O_3, ozone; p, power; PM_{10}, particulate matter with aerodynamic diameter ≤ 10 μm; $PM_{2.5}$, particulate matter with aerodynamic diameter ≤ 2.5 μm; PSI, Pollutant Standard Index; SD, standard deviation; SO_2, sulphur dioxide; WHO AQG, World Health Organization Air Quality Guidelines

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Despite its extensive use over time as the basis of several air quality indices worldwide such as the China AQI and the UK Daily Air Quality Index (DAQI), the USEPA AQI has its own limitations (China AQI, 2016; DEFRA, 2016; USEPA, 2016). First, it is only based on the pollutant with the highest sub-index, which discounts the additive effects of multiple pollutants. Second, it is not sensitive to variations in the sub-indices of pollutants, that is any change other than the highest sub-index is not reflected in the aggregate index (Ott, 1978). Last, in terms of risk communication, its use of the sub-indices' maxima would result in frequent alarm in highly polluted areas leading to risk fatigue. Thus, the public health warnings about air pollution harms are more likely to be ignored by members of the public with few or no precautions taken during hazardous air quality episodes.

In view of these limitations, we set out to develop a method of constructing an air quality index that accounts for multiple pollutants using air pollution profiles. We then applied this method to data from Hong Kong. We also undertook a comprehensive empirical study to evaluate the extent to which the index predicts health effects.

2. Material and methods

2.1. Hong Kong air quality and meteorological data

We obtained hourly concentrations of PM_{10}, SO_2, NO_2, and O_3 from 1st January 2001 to 31st December 2012 from ten fixed-site general monitoring stations operated by the Hong Kong Environmental Protection Department (HKEPD, 2016). The measurement/analytical methods for PM_{10}, SO_2, NO_2, and O_3 were tapered element oscillating microbalance, fluorescence, chemiluminescence, and ultraviolet absorption, respectively. We averaged the hourly concentrations of air pollutants across the ten monitoring stations to represent hourly concentrations of the whole territory of Hong Kong. We then derived daily concentrations of air pollutants by taking the maximum of 3-h mean (the mean of the current and two previous hours) for the four pollutants. In calculating hourly and daily data, we required there to be at least 2 out of 3 hours available for running 3-h mean and at least 18 out of 24 hours available for daily maximum. Meteorological data, including daily mean temperature and mean relative humidity, were provided by the Hong Kong Observatory (HKO, 2016).

2.2. Hospital admissions data

The *Clinical Management System* computerized hospital data used in this study were based on principal discharge diagnoses from 1st January 2001 to 31st December 2012 from the 19 hospitals within the Hospital Authority which managed over 95% of hospital bed-days in Hong Kong (Leung et al., 2005). The disease rubrics retrieved from these records were based on the International Classification of Diseases, Ninth Revision, Clinical Modification (ICD-9-CM). The principal discharge diagnoses included were cardiovascular (ICD-9-CM: 390–459) and respiratory (ICD-9-CM: 460–519) for all ages and those 65 years or older. Control conditions included injury, poisoning and external causes (ICD-9-CM: 800–999) and were available only for persons aged 65 years or older.

2.3. Construction of an air quality index

Three primary steps were followed in developing the Hong Kong Air Quality Index (HKAQI):

(1) select pollutants of interest, (2) normalize all the selected pollutants into their corresponding sub-indices, and (3) aggregate these sub-indices to form an overall air quality index.

Step 1. Selected air pollutants

The HKAQI was formulated to include four criteria pollutants: PM_{10}, SO_2, NO_2, and O_3. We used PM_{10} in place of $PM_{2.5}$ because PM_{10} data were available in all ten monitoring stations during the study period.

Step 2. Conversion of pollutant concentrations into sub-indices

The sub-index s_i of pollutant i is expressed as the ratio of pollutant concentrations q_i to the recommended short-term World Health Organization Air Quality Guidelines [WHO AQG] (WHO, 2006), Q_i. That is, s_i can be written as:

$$s_i = 100 \times \left(\frac{q_i}{Q_i}\right) \tag{1}$$

A value of the sub-index s_i greater than 100 indicates that the pollution level has exceeded the WHO AQG. The WHO AQG are based on a comprehensive review of the evidence on the relationships between air quality and adverse health effects, and provide guidance to support actions to achieve clean air. The short-term WHO AQG are defined as concentrations with averaging times of 24-h means of 50 $\mu g/m^3$ for PM_{10} and 20 $\mu g/m^3$ for SO_2; 1-h mean of 200 $\mu g/m^3$ for NO_2; and running 8-h mean of 100 $\mu g/m^3$ for O_3.

2.4. Maximum 3-h mean WHO AQG of PM_{10}, SO_2, and O_3

Since the average times of the short-term WHO AQG are 24-h means for PM_{10} and SO_2, 1-h mean for NO_2 and running 8-h mean for O_3, it is necessary to derive the equivalent maximum 3-h mean WHO AQG of the four pollutants. To do this, for simplicity, we adopted the same WHO AQG 24-h means of 50 $\mu g/m^3$ for PM_{10}, 20 $\mu g/m^3$ for SO_2, and running 8-h mean of 100 $\mu g/m^3$ for O_3 as the maximum 3-h mean of these three pollutants. This is because the limits with averaging times of maximum 3-h mean would have been higher than those of 24-h means for PM_{10} and SO_2 and of the running 8-h mean for O_3. Shorter averaging times of pollutant concentrations would produce higher values than longer averaging times (Larsen, 1969).

2.5. Maximum 3-h mean WHO AQG of NO_2

For the equivalent maximum 3-h mean WHO AQG for NO_2, we estimated this limit by means of a simple linear regression method (Noll and Miller, 1997). First, we calculated the daily maximum 3-h mean and 1-h mean NO_2 concentrations for the whole territory of Hong Kong over the years 2001–2012. Second, we regressed the dependent variable, the maximum 3-h mean NO_2 concentration against the independent variable, the 1-h mean NO_2 concentration. Last, the equivalent maximum 3-h mean WHO AQG for NO_2 was obtained by setting the maximum 1-h mean NO_2 concentrations at 200 $\mu g/m^3$.

Step 3. Aggregation function

After normalizing air pollutant concentrations to their respective WHO AQG, the individual pollutant sub-indices are aggregated into a single index to produce an overall air quality index. For an aggregation function F to have a unique interpretation, it should follow that

$$F(0, 0, \ldots, 0, s_i, 0, \ldots, 0) = s_i \tag{2}$$

That is, if all of the sub-indices except one are zero, they should not affect the aggregation process and the aggregation function should return to the non-zero sub-index. In addition, the aggregation should be sensitive to the high-pollutant sub-index, that is,

$$F(s_1, s_2, \ldots, s_{i-1}, \infty, s_{i+1}, \ldots, s_n) = \infty \tag{3}$$

Also, an increase in the sub-indices from 0 to s in Equation (2) should increase the aggregation index, as F is an increasing function of sub-indices, that is,

$$F(s, s, s, \ldots, s, s, s) \geq s \tag{4}$$

For the construction of an air quality index, the proposed root-sum-power for the aggregation function is free from eclipsing (situations where an index indicates highly polluted air as less polluted) and satisfies the requirements of Equation (2) to (4) (Ott, 1978; Swamee and Tyagi, 1999):

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