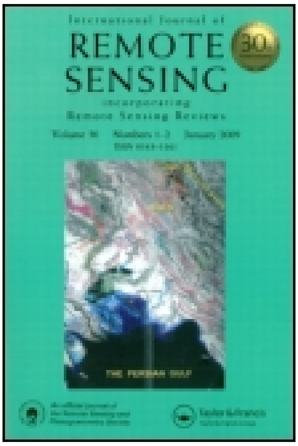

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Estimation of aerosol sources and aerosol transport pathways using AERONET clustering and backward trajectories: a case study of Hong Kong

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Estimation of aerosol sources and aerosol transport pathways using AERONET clustering and backward trajectories: a case study of Hong Kong

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Hong Kong, located adjacent to the rapidly growing urban-industrial region of south China, provides a case of mixed aerosol types (urban, industrial, marine, and long-distance, including dust) from diverse activities and has suffered many serious air pollution episodes over the last decade. However, the sources and transport pathways of aerosols measured and recorded in Hong Kong have not been well researched due to the lack of air quality monitoring stations in east Asia. Here, an integrated method combining Aerosol Robotic Network (AERONET) data, backward trajectories, and Potential Source Contribution Function (PSCF) modelling is used to identify probable transport pathways and magnitudes of source contributions for four characteristic aerosol types. These types, which are dominant in Hong Kong during defined climatic and environmental conditions, are urban fine aerosols, urban mixed aerosols, dust, and heavy pollution. They were defined by clustering a total of 730 AERONET data sets between 2005 and 2008. Results show that aerosol types 1 and 2 (urban fine and urban mixed) are associated with regional fine particulate urban emissions and predominantly local urban emissions, respectively, suggesting that mitigating measures taken within Hong Kong itself would be partially effective. Heavy pollution and dust (types 4 and 3) are more associated with short- and long-distance sources, notably heavy industries in nearby southern Guangdong and the Pearl River Delta region, and desert dust from arid regions in north China. The PSCF map representing dust aerosol type shows a wide range of eastward and southeastward trajectories from northwest China to Hong Kong. Although the contribution of dust sources is small compared to anthropogenic aerosols, a serious recent dust outbreak observed in Hong Kong was associated with an elevation of the air pollution index to 500, compared with 50–100 on normal days. The combined use of clustered AERONET, backward trajectories, and PSCF model can help to resolve long-standing issues about source regions and characteristics of pollutants carried to Hong Kong.

1. Introduction

Hong Kong is a city in southeast China with a service-based economy, but it has suffered many severe air pollution episodes over the last decade. Many reports and scientific works suggest that the greater part of Hong Kong pollution originates in the adjacent rapidly industrializing areas of the Chinese mainland including the Pearl River Delta (PRD) region

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(CH2M 2002; Business Environment Council 2005; Civic Exchange 2007). Lo et al. (2006) emphasize the importance of cross-boundary air pollution from the Chinese mainland, and Yuan et al. (2006) affirm that 60–70% of PM10 (particles measuring equal to or less than 10 μm) originates outside Hong Kong. Obtaining evidence of the specific locations of pollutant sources outside Hong Kong is challenging, since air pollution varies temporally and spatially. Regional emissions from the neighbouring industrialized PRD region often appear to be dominant over local ones, but dust plumes from north China are sometimes experienced.

In recent years, a variety of numerical models such as the Pennsylvania State University/National Center for Atmospheric Research (PSU/NCAR) mesoscale model (known as MM5) have been developed for modelling air pollutant transportation. The MM5 model can simulate air flow at spatial resolutions of 1–100 km, with domains of twenty to thousands of square kilometres, but it is highly computer demanding. Numerical models of air mass trajectories from air quality models are widely used for studying the source–receptor relationships of pollutants (Miller 1981; Ashbaugh, Malm, and Sadeh 1985; Collett and Dyuyemi 1997; Hsu, Holsen, and Hopke 2003; Perkauskas 2004; Zannetti and Puckett 2004). These include the three-dimensional Atmospheric Environment Service (AES) trajectory model (Olson, Oikawa and Macafee 1978) and the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Draxler and Hess 1997, 1998). The HYSPLIT model calculates advection and dispersion using puff or particle approaches under a Lagrangian framework (Draxler 2003). These models can help to calculate air mass distribution and paths at regional and global scales, as well as the long-distance dispersion of pollutants such as PM10. The model trajectories provide information on movement of air parcels in both the horizontal and vertical directions, thus the backward trajectories can help to locate the sources of pollutants.

The Potential Source Contribution Function (PSCF) model simulates the potential probability of source areas from designated receptors. Our model presented here does this automatically by linking the trajectory data mathematically with pollutant clustering data, to show high-potential source areas. Many studies have used the PSCF model in recent decades to locate pollutant sources (Zeng and Hopke 1989; Gao, Cheng, and Hopke 1993; Hopke et al. 1995; Cheng and Lin 2001; Liu, Hopke, and Vancuren 2003; Salvador et al. 2004; Pekney et al. 2006; Hwang and Hopke 2007). Determination of the pollutant types can be achieved by a range of available clustering algorithms (Kaufman and Rousseeuw 1990; Omar et al. 2005; Gobbi et al. 2007). For example, Omar et al. (2005) used cluster analysis to classify aerosol types based on a set of aerosol optical thickness (AOT) and inversion data derived from 200 Aerosol Robotic Network (AERONET) stations around the world. They recognized and classified six aerosol types geographically, namely desert dust, biomass burning, polluted continental, clean continental, polluted marine aerosols, and dirty pollution. The clustering technique groups and partitions the data based on the suggested variables. They used 26 parameters of aerosol optical properties from AERONET, and the relative errors were computed to check the accuracy of each model. Kaskaoutis et al. (2007a) demonstrated the use of AOT and the Ångström exponent to classify different aerosol types (biomass burning-urban, clean maritime, desert dust, and mixed aerosol types) based on optical and microphysical data from four AERONET stations around the world. Barnaba and Gobbi (2004) and Kaskaoutis et al. (2007b) showed a method for distinguishing the main aerosol types such as urban/industrial, maritime, and desert dust based on the combination of Moderate Resolution Imaging Spectroradiometer (MODIS) AOT data and MODIS fine-mode fraction data. The rationale of this method is based on sensitivity of these two parameters to different microphysical properties. However, to date, no research has used clustering of AERONET data along with backward trajectories to establish the PSCF model. Since the backward trajectories are constructed hourly from aerosol (AERONET) data with 15 minute temporal resolution, the modelling of sources is very sensitive to changes in aerosol characteristics or changes in wind direction and thus in sources. Moreover, since the linking of backward trajectories with AERONET gives data every hour, a large volume of data for construction of accurate and robust models is given (our data archive goes back to 2005).

This project runs a HYSPLIT trajectory model with the AERONET cluster data to generate PSCF maps, representing the likely source areas of different aerosol types in Hong Kong. Although many other studies have used PSCF models, none have attempted any validation of their accuracy; however, this study validates the PSCF maps by comparison with Asia emission data. A dust event which occurred on 19–22 March 2010 is also used to evaluate the PSCF map representing the dust aerosol type.

2. Study area and data collection

Hong Kong is a coastal city immediately south of the heavily industrialized regions of the PRD and Guangdong Province in southern China (Figure 1). It is therefore susceptible to air pollutants from this region, as well as other types of pollutants such as desert dust from long-distance sources. These regional and distant pollutants are more likely to affect Hong Kong during the winter and spring dry season due to northerly and northeasterly winds bringing long-distance dust and anthropogenic pollutants from neighbouring

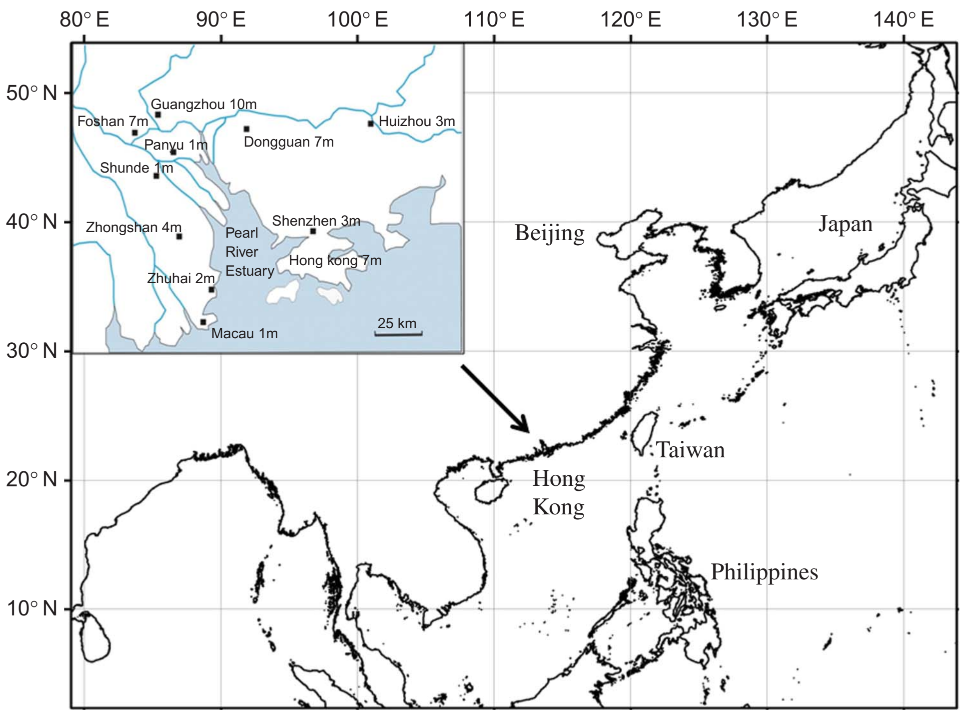

Figure 1. Location of Hong Kong in the Pearl River Delta (with populations given in millions) and east Asia.

provinces southward and southeastward to Hong Kong. The summer monsoon winds from the south carry a large percentage of ocean sea salts (often associated with regional pollutants) to Hong Kong. The northerly and northeasterly winds account for 56% of all winds in Hong Kong, whereas the southern onshore winds only account for 31% of the winds in a year. The maximum northerly wind speed can achieve over 10 m s^{-1}, particularly in windy conditions. Recently, Wong, Nichol and Holben (2010) demonstrated an integrated technique using remote sensing, backward trajectory modelling, and *in-situ* PM10 measurements to identify the presence of two major dust storms in Hong Kong, with source areas in north China. They also observed 20 dust events between January 2006 and May 2009, mostly during the spring season using AERONET data.

The HYSPLIT model by the National Oceanic and Atmospheric Administration (NOAA) has been used in many applications such as trajectory, dispersion, and volcanic ash modelling. The model outputs can be saved in image, geographic information system (GIS), and text formats. Since running the HYSPLIT model is time and resource consuming, an Interactive Data Language (IDL) program was written for processing the hourly trajectory data from 2005 to 2008. In addition, AERONET data (Holben et al. 1998) from 2005 to 2008 were acquired from the Hong Kong Polytechnic University station. The AERONET is a federated network of ground sun photometers with more than 400 sites around the world. An AERONET station consists of a Cimel sun photometer (Cimel, Paris, France), which measures AOT every 15 minutes using multiple wavelengths. The sun photometer observes aerosol radiance remotely from the ground upwards through an atmospheric path to the sun. It calculates atmospheric absorption and scattering from radiances observed in different wavebands and derives AOT. In addition, it also measures radiances at scattering angles away from the sun. These sky radiances coupled with AOT and estimations of land and water surface reflectance can be used to derive aerosol optical properties after processing by a radiative transfer model. The inversion data include size distribution, single scattering albedo (SSA), and refractive index. Three levels of data, namely 1, 1.5, and 2, represent the raw, cloud-screened, and cloud-screened and quality-assured data, respectively, as well as inversion data. Our local aerosol and microphysical data were acquired from the level 2 AOT and inversion data, and they consist of 730 readings over the mentioned period.

The 2006 Asia emission inventory (Woo et al. 2002; Streets et al. 2003) developed by the Decision and Information Sciences Division, Argonne National Laboratory, was used for validation in this study. This emission inventory recognizes four sectors (power, industry, residential, and transportation) and eight pollutants (SO_2, NOx, CO, VOC, PM10, PM2.5, BC, and OC), and the data are stored in $0.5° \times 0.5°$ grid cells. The 2006 inventory data are considered to be a reference database for anthropogenic emission over Asia and were used here to evaluate the quality and accuracy of the PSCF output maps. In addition, a Global Self-consistent, Hierarchical, High-resolution Shoreline Database (GSHHS; Wessel and Smith 1996) was used to plot the coastlines in Asia.

3. Methodology

3.1. Cluster analysis

In this study, *k*-means cluster analysis is adopted for classifying the aerosol optical and microphysical properties from AERONET AOT and inversion data from 2005 to 2008. This was carried out in SPSS statistical software with 24 selected parameters from the AERONET inversion data, which include AOT at 500 nm ($AOT_{500\ nm}$), Ångström exponent in the waveband 440–870 nm ($\alpha_{440–870}$), SSA at four wavelengths ($SSA_{439\ nm}$, $SSA_{676\ nm}$,

Table 1. Distances between cluster centroids of the four aerosol types using *k*-means clustering.

Cluster	Type 1	Type 2	Type 3	Type 4
Type 1		0.734	2.086	0.773
Type 2	0.734		1.370	0.630
Type 3	2.086	1.370		1.735
Type 4	0.773	0.630	1.735	

Note: Types 1, 2, 3, and 4 represent urban fine aerosols, urban mixed aerosols, dust, and heavy pollution, respectively.

$SSA_{869\ nm}$, $SSA_{1020\ nm}$), real and imaginary parts of the refractive index at the same four wavelengths, asymmetry factor, mean radii, standard deviations, and the total volumes of coarse- and fine-mode particles. The rationale of *k*-means clustering (MacQueen 1967) is to un-supervise the data set through a number of clusters and define their centroids. The data points belong to certain groups according to their associations with the nearest centroid. In this study, the number of clusters was first tested by Ward's method (Ward 1963) under an automated hierarchical clustering method. The distance between each step from 0 to 730 (number of samples) was calculated. The 'elbow' or 'saturation' point was found at step 726; therefore, the number of clusters was set to four (730–726 = 4). Sensitivity tests were also conducted by calculating the distances between cluster centres (Table 1), the variability of cluster membership, and the scatter plots (Figures 2(*a*) and (*b*)). Table 1 shows that cluster 3 is significantly different to the other clusters. Clusters 2 and 4 also appear dissimilar, but the pairs of clusters 1 and 2 and clusters 1 and 4 are similar. Figure 2(*a*) shows the three-dimensional scatter plot using SSA at 439 nm ($SSA_{439\ nm}$), $AOT_{500\ nm}$, and coarse-mode mean radius. Four clusters are designated, which are quite discrete with only small overlaps. Cluster 3 appears dissimilar from the others in terms of distance between the coarse- and fine-mode mean aerosol radii and its wide scatter (Figure 2(*b*)). The number of outlier points (with 4, 4, 2, and 5 outliers points in clusters 1, 2, 3, and 4, respectively, that go beyond 2 standard deviations of the mean) is small, so they are not classified as another unique class.

After the clustering using AERONET data, the aerosol optical and microphysical properties of each aerosol type were known, and these were used for linking with backward trajectories to establish the PSCF model.

3.2. Trajectory and PSCF analysis

The NOAA HYSPLIT trajectory model and global meteorological data were used to generate three-dimensional air mass movements in this study. The trajectories can be plotted as endpoints of segments with latitude, longitude, and height information. Backward trajectories over a 5 day period were calculated for every hour on every day in the period 2005–2008. This is because long-distance pollutants take almost 5 days to reach Hong Kong. For example, Asian dust from Inner Mongolia travels in a curved trajectory via Beijing and Taiwan over a 5 day period, before reaching Hong Kong (Lin 2001; Cao et al. 2003; Wong, Nichol, and Holben 2010). Four different heights (500, 1000, 2000, and 4000 m) were calculated for each trajectory, and the Reanalysis 1 surface pressure data (Kalnay et al. 1996) of the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) with 17 pressure levels (mb) were input to the model. After the backward trajectories were generated, the PSCF model could be

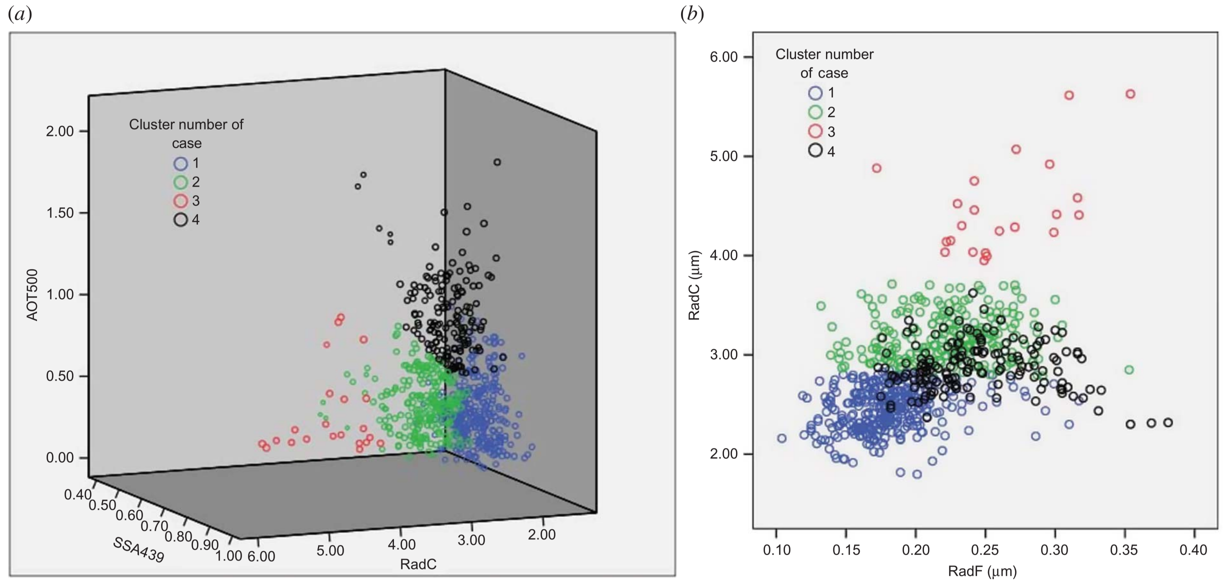

Figure 2. Scatter plots of four clusters, (*a*) three-dimensional scatter plot with parameters: AOT at 500 nm, SSA at 439 nm, and coarse-mode mean radius (RadC); (*b*) two-dimensional scatter plot with parameters: fine-mode mean radius (RadF) and coarse-mode mean radius.

established. If a trajectory endpoint lies at a cell with coordinates (x, y), this cell is regarded as a potential contributor of pollutants that are assumed to be transported to the receptor site (Hong Kong: latitude 22.303° N and longitude 114.180° E). The cumulative probability of endpoints, $P(x, y)$, can be calculated as:

$$P(x,y) = \frac{m(x,y)}{n(x,y)}, \tag{1}$$

where $n(x, y)$ is the total number of endpoints falling within cell (x, y), and $m(x, y)$ is the number of endpoints that fall within cell (x, y) that are associated with samples that exceed the threshold criterion. An AOT value larger than 0.2 ($AOT_{500\ nm}$ observed from AERONET station > 0.2) for each aerosol type was used for the threshold criterion for application of the PSCF model. The cumulative probability of endpoints, $P(x, y)$, represents the potential probability of pollutants transported to Hong Kong from this cell (i.e. higher PSCF $P(x, y)$ indicates higher potential contributions for the pollutant). The model is statistically stable if large values of $n(x, y)$ are observed (Polissar et al. 1999; Wang, Zhang, and Arimoto 2006). Therefore, for improving the data quality, an arbitrary weight function $W(x, y)$ was assigned to multiply the $n(x, y)$ values for reducing the small values of $n(x, y)$ (Polissar et al. 1999). $W(x, y)$ takes the form as follows:

$$\begin{aligned} &W(x,y) = 1, \text{ when } n(x,y) > 120, \\ &W(x,y) = 0.7, \text{ when } n(x,y) > 40 \text{ and } n(x,y) \leq 120, \\ &W(x,y) = 0.42, \text{ when } n(x,y) > 10 \text{ and } n(x,y) \leq 40, \\ &W(x,y) = 0.17, \text{ when } n(x,y) \leq 10. \end{aligned} \tag{2}$$

Therefore, Equation (1) becomes

$$P(x,y) = \frac{m(x,y)}{n(x,y) \cdot W(x,y)}. \tag{3}$$

For incorporating the aerosol cluster data (four aerosol types) into the trajectory data, a customized IDL program was developed. This program first reads the day and time of each aerosol type based on the cluster results. Then it searches for the corresponding day and time from the hourly HYSPLIT database; the HYSPLIT endpoints and trajectory data are loaded to the computer memory, and the PSCF model is formed (Equation (3)). Finally, the PSCF map of each aerosol type is plotted and saved as an image and as a GIS point file.

4. Results

4.1. Results of clustering

The clustering identified four aerosol types using a total of 730 cases between 2005 and 2008, and the classes are markedly distinct (Figure 2). These were defined by their optical and microphysical properties (Table 2), as (i) urban fine aerosols, (ii) urban mixed aerosols, (iii) dust, and (iv) heavy pollution.

Type 1 (urban fine aerosols) has the largest number (45% of total) and type 3 (dust) has the smallest number of records (3% of total). This suggests that the Hong Kong AERONET station is more exposed to urban pollution and only a few observations represent dust. Heavy urban pollution (type 4) accounts for 22% of records, and type 2 (urban mixed aerosols) accounts for 30% of the records.

Table 2. Summary of the cluster analysis results, with 24 selected parameters from AERONET inversion data.

Aerosol optical parameter	Type 1	Type 2	Type 3	Type 4
$AOT_{500\ nm}$	0.451	0.518	0.510	1.065
$SSA_{439\ nm}$	0.876	0.869	0.885	0.894
$SSA_{676\ nm}$	0.889	0.874	0.871	0.911
$SSA_{869\ nm}$	0.878	0.857	0.855	0.899
$SSA_{1020\ nm}$	0.872	0.844	0.848	0.888
Real refractive index (676 nm)	1.470	1.452	1.500	1.452
Imaginary refractive index (676 nm)	0.014	0.022	0.016	0.015
$\alpha_{440–870}$	1.363	1.316	0.952	1.286
Asymmetry factor (676 nm)	0.643	0.665	0.683	0.682
Fine-mode total volume ($\mu m^3\ \mu m^{-2}$)	0.064	0.081	0.070	0.155
Fine-mode mean radius (μm)	0.181	0.222	0.262	0.244
Geometric standard deviation (fine)	0.478	0.562	0.644	0.542
Coarse-mode total volume ($\mu m^3\ \mu m^{-2}$)	0.055	0.038	0.148	0.066
Coarse-mode mean radius (μm)	2.458	3.177	4.484	2.892
Geometric standard deviation (coarse)	0.672	0.592	0.504	0.594
Number of records	332	216	22	160

Notes: Parameters from AERONET inversion data include AOT at 500 nm, Ångström exponent ($\alpha_{870–440}$), SSA at four wavelengths, real and imaginary refractive index at the same four wavelengths, asymmetry factor, mean radii, standard deviations, and the total volumes of coarse- and fine-mode particles.

Type 1 (urban fine aerosols) has moderate absorption properties ($SSA_{439\ nm} = 0.876$) and is dominated by both coarse and fine particles (fine and coarse total volumes are 0.064 and 0.005, respectively) (Table 2). The moderate absorption properties of this type could be due to the proportion of carbonaceous particles that have high absorption properties in urban pollutants (Torres et al. 2005; Bergstrom et al. 2007) and correspond to regional haze from urbanization, biomass burning, and other human activities. This type of aerosol is usually present in the atmosphere in Hong Kong and is more predominant during periods of low wind speed, e.g. 1–2 m s^{-1}, which favour the formation of secondary aerosols by photochemical reactions, especially in summer, and from biogenic volatile organic compounds (BVOCs) emitted from surrounding forested areas. Type 2 (urban mixed aerosols) also has moderate absorption properties ($SSA_{439\ nm} = 0.869$) and shows a similar size distribution to type 4 (heavy pollution), although type 2 generally has lower AOT values. Type 2 is found during windier conditions (e.g. 4–7 m s^{-1}), and has coarser particles than type 1 (fine-mode radius of 0.222 μm). These coarse particles are probably due to industrial constructions, dust transport, and marine aerosols (few places in Hong Kong are more than 5 km from the coast) mixed with fine particles from local urban pollution, namely traffic and light industry. Thus, we refer to this type as urban mixed aerosols. Type 3 (dust) is associated with relatively high AOT ($AOT_{500\ nm} = 0.51$) and a large number of coarse particles. The coarse-mode aerosols are approximately four times larger in volume than the other three types, and the coarse-mode radius at 4.484 μm is also much larger. Type 4 (heavy pollution) is characterized by aerosols with AOT readings almost double those of the other three types ($AOT_{500\ nm} > 1$), comprising a large volume of fine particles (70%), and a visibly polluted atmosphere over Hong Kong. It represents high aerosol concentrations from fossil fuel burning by oil-and coal-powered industries supporting hundreds of thousands of factories in the PRD region, including chemicals, plastics, paints, and furniture as well as power plants, and this type of aerosols consists of sulphate particles having low absorption properties ($SSA_{676\ nm} = 0.91$, Table 2).

4.2. Results of trajectory and PSCF analysis

Figure 3 is a typical example of trajectory data and endpoints showing two major pathways to Hong Kong. It indicates that any pollutants may be transported from central and northern China at lower elevations (blue and purple lines), whereas those from the west and southwest China are carried at higher elevations (green and yellow lines).

Although Cheng, Hopke, and Zeng (1993) demonstrated that increasing the number of trajectory endpoints does not improve the quality of PSCF results significantly, this study generated 484 endpoints (each of 4 elevations has 121 endpoints) for each hourly trajectory. The study area extends from 10° N to 60° N and 80° E to 150° E, and each cell size was set to 0.5° × 0.5° grid cells. Figure 4 shows the PSCF maps calculated using backward trajectories for each aerosol type. Cells with red colour (probability approaching 1) represent a greater source potential and therefore high probability of transport to Hong Kong. The air masses associated with aerosol types 2 and 4 (urban mixed aerosols and heavy pollution) appear to come from the industrialized Guangdong province and PRD region (Figures 4(*b*) and (*d*)). But these source areas for types 2 and 4 extend to the whole of southern China if the moderate probabilities for PSCF are adopted (yellow colour). Aerosol type 4 (heavy pollution) with greater potential than 0.5 (moderate-potential pollutant source) has a more compact spatial coverage and is mainly located in Guangdong province, whereas the source areas for aerosol type 2 (urban mixed aerosols) include Guangxi, Guangdong, and Fujian provinces. The air masses associated with aerosol type 1 (urban fine aerosols) have larger spatial coverage for PSCF, larger than 0.8 (high-potential pollutant source),

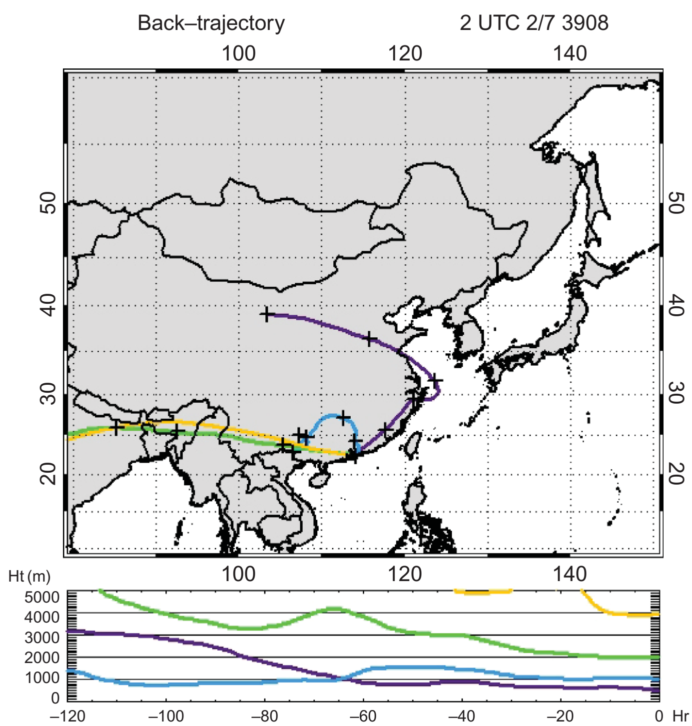

Figure 3. HYSPLIT trajectory map on 7 February 2008 02:00 UTC (four different colours represent four different atmospheric heights).

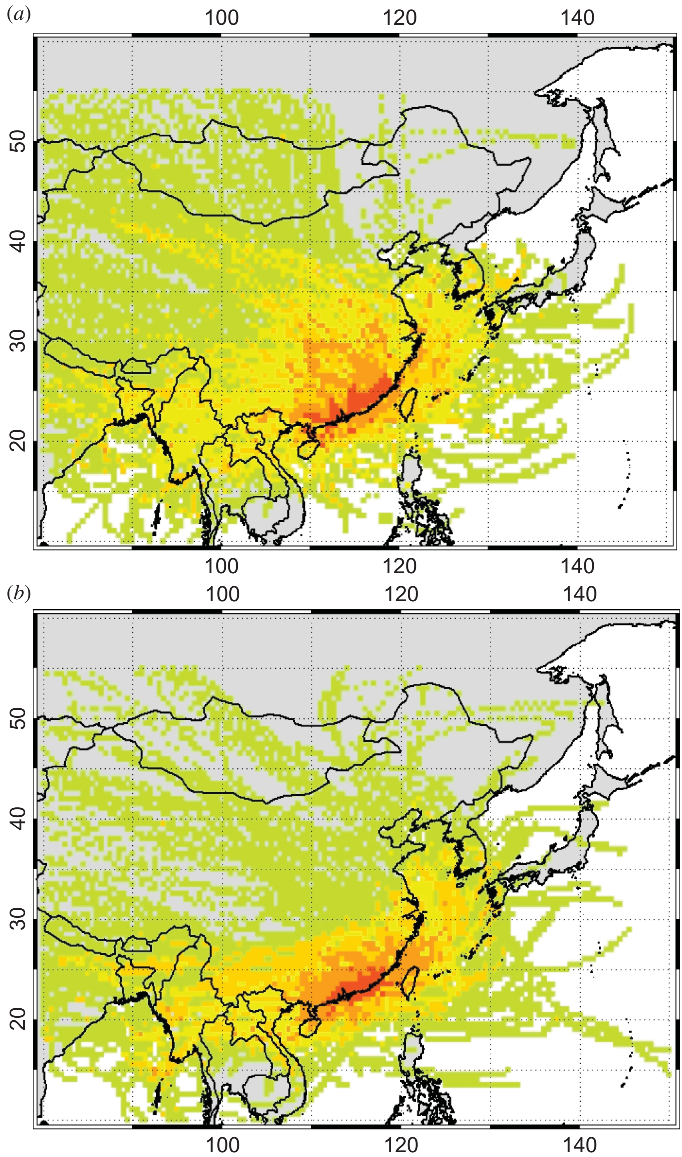

Figure 4. PSCF maps of (*a*) type 1 (urban fine aerosols), (*b*) type 2 (urban mixed aerosols), (*c*) type 3 (dust), and (*d*) type 4 (heavy pollution).

than those for types 2 and 4, including the large urbanized regions of southern China such as Shenzhen, Guangzhou, Wuhan, and Chongqing. Aerosol type 3 (dust), in contrast, has a less concentrated and smaller source area distribution and follows the main trajectory paths southeastwards, southwards then southwestwards from Mongolia and north China to Hong Kong (Wong, Nichol, and Holben 2010). It was also found that some dusts may be sourced from the west, including India and southwest China, but these have low PSCF values.

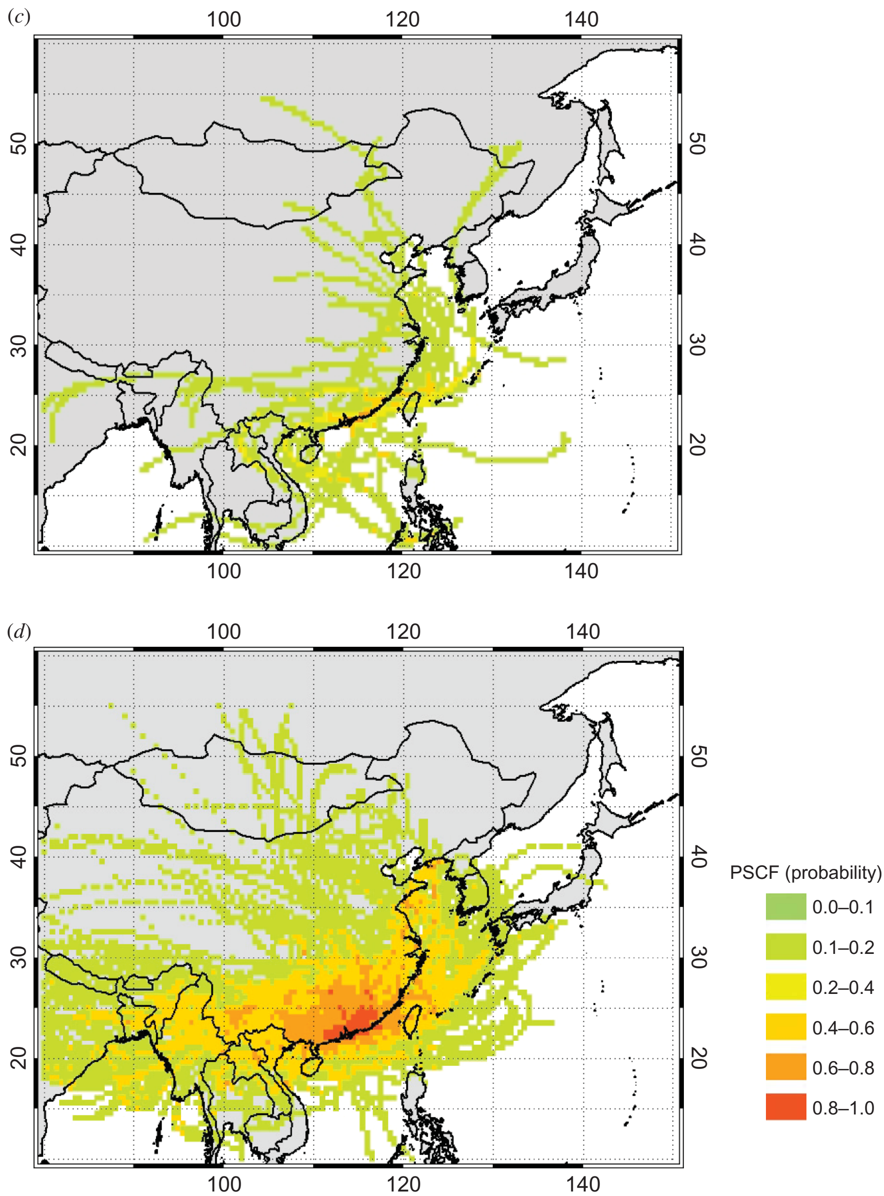

Figure 4. (*Continued*).

5. Validation

The PSCF results are somewhat difficult to validate as precise locations of emission sources would ideally be required. Because approximately two-thirds of Hong Kong's aerosols are fine particles (Ho et al. 2003; Cheng, Chan, and Yang 2006), we decided to use the PM2.5 emission inventory database, which represents the total PM2.5 emissions from four sectors, namely power, industry, residence, and transportation. Figure 5(*a*) shows the PSCF type 2 data overlaid with PM2.5 emission data, which are given in $0.5° \times 0.5°$ grid cells. The dot symbol represents a PSCF value larger than 0.8 (a high-potential of pollutant

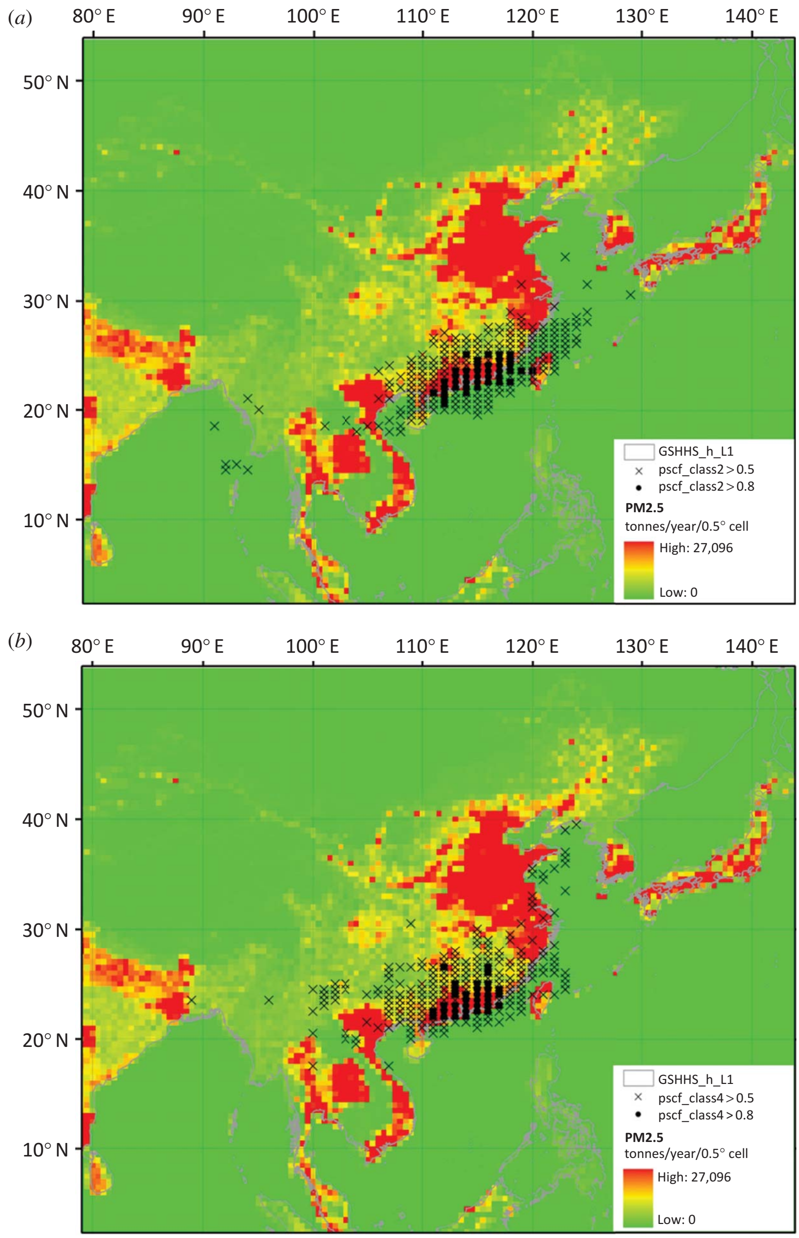

Figure 5. (*a*) PSCF type 2 data and (*b*) PSCF type 4 data (dot represents PSCF value > 0.8 and cross represents PSCF value > 0.5) overlaid with emission data (PM2.5) in 0.5° × 0.5° grid cell.

source), while the cross symbol represents a PSCF value larger than 0.5, i.e. moderate potential. The PSCF values in Figure 5(*a*) indicate that the sources of urban mixed pollutants (type 2) are likely to be Hong Kong itself and the PRD region, which corresponds to the highest class (red colour) on the emission inventory map.

The potential sources of higher PSCF values for heavy pollution (type 4) are also located mainly on the land surfaces of the PRD region. For Hong Kong, PSCF values greater than 0.8 are always observed occurring downwind (northerly wind) of the industrial regions. A correlation above 90% is found between high PSCF values for type 4 (>0.8) and high PM2.5 emissions (red colour) in the PRD region (Figure 5(*b*)). This indicates a good agreement between the modelled PSCF sources of heavy pollution and the PM2.5 emission data.

Type 1 data could not be validated because it results from the formation of both primary and secondary aerosols, by photochemical reactions, especially in summer, and from BVOCs emitted from surrounding forested areas. There is no emission inventory data representing biogenic aerosols.

6. Case study

A severe dust storm was reported by media in Hong Kong, Beijing, Korea, and Taiwan on 19–22 March 2010, and high AOT levels ($AOT_{500\ nm} > 0.8$) were observed on MODIS AOT images and at the Hong Kong AERONET station. The dust storm crossed the Yellow Sea and spread towards South Korea and Taiwan on 20–21 March 2010. Figure 6 shows the dust (brown colour) on the MODIS true colour satellite image, spread wide over southern China. On 22 March 2010, the AERONET station at Hong Kong recorded a high volume of coarse particles (>1 μm), while on the day before, fine-mode particles typical of a normal day were dominant. Such dust storms from Mongolia and north China have been reported previously in Hong Kong (Wong, Nichol, and Holben 2010). In this dust event, high levels

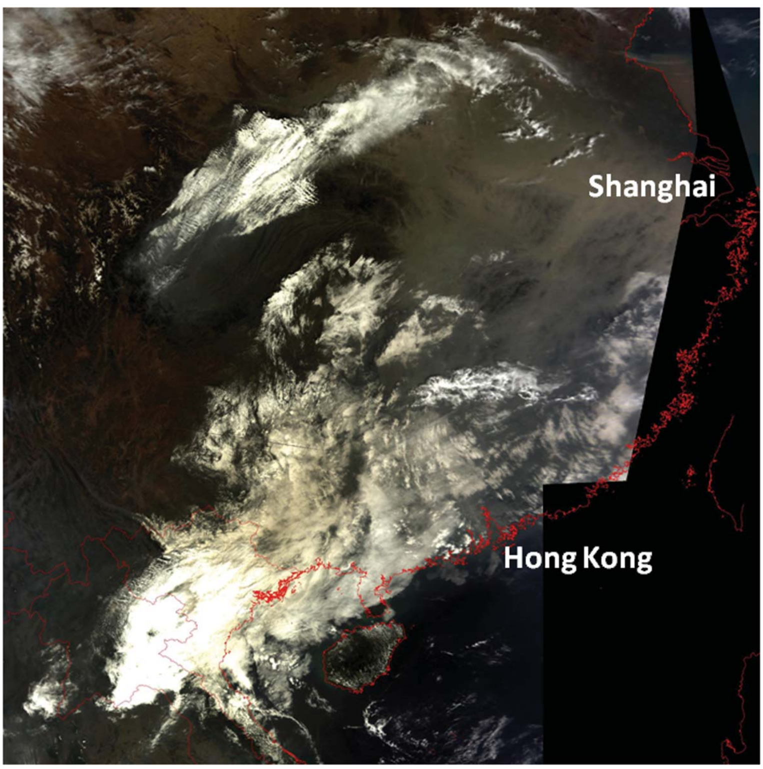

Figure 6. True colour MODIS image on 20 March 2010, 02:30 UTC.

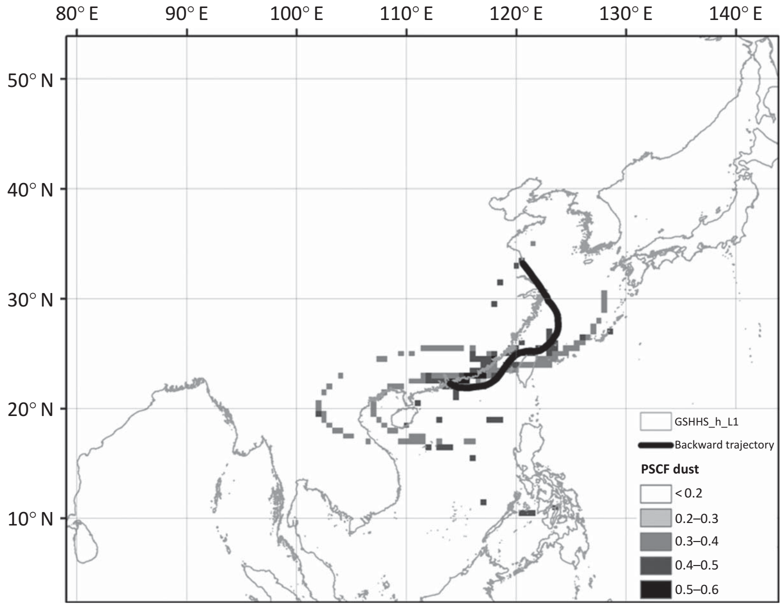

Figure 7. Three days of backward trajectory data (black line) for the dust event of 19–22 March 2010 (500 m height, 22 March 2010, 00:00 UTC) overlaid with PSCF type 3 data (with probability values larger than 0.2).

of respiratory suspended particles and a record-breaking air pollution index were observed, with pollution levels 5 and 10 times higher than those on polluted non-dust days and clean days, respectively. The 3 day backward trajectory indicates an offshore transport path for the lower level winds below 500 m to Hong Kong (Figure 7). In Figure 7, the backward trajectory (black line) is overlaid on the PSCF dust map, indicating that this dust event follows the higher potential pathways of dust transported to Hong Kong.

7. Discussion and conclusion

Four aerosol types representing the dominant aerosols observed in Hong Kong were identified by clustering. These aerosol types were coupled with backward trajectories and PSCF modelling to identify the sources and pathways of pollutants to Hong Kong. The aerosol types: urban fine aerosols, urban mixed aerosols, dust, and heavy pollution accounted for 45%, 30%, 3%, and 22% of all AERONET data, respectively, between 2005 and 2008. Results showed that the source areas for urban fine aerosols (type 1) include all of the large urban areas in southern China (Shenzhen and Guangzhou; Figure 1), as well as more distant ones such as Wuhan and Chongqing, and this type could be defined as a semi-persistent fine regional haze comprising both primary and secondary aerosols. This aerosol type is likely to be derived from combustion of fuels in light industries, biomass and vehicular sources, as well as BVOCs. Although this aerosol type is frequently occurring and is recognized as regional pollution with the largest spatial coverage, local sources such as types 2 and 4 are likely to be equally important. The source areas for urban mixed aerosols (type 2) are mainly local, including Hong Kong itself and the neighbouring PRD region. This aerosol type is a mixture of coarse particles from marine salts, industrial dusts, and fine particles from traffic and light industries. Both aerosol types 1 and 2 are present all year round, independent of wind direction. However, type 3 (dust) and type 4 (heavy pollution) are mostly observed during the winter and spring periods with northerly and northeasterly winds, which bring dust and high concentrations of heavy pollutants from Guangdong province to Hong Kong. The source areas for type 4 (heavy pollution) include power plants, and oil and coal-burning industries located in the PRD region and Guangdong province. Type 3 (dust) originates from arid regions of Mongolia and northwest China. In this study, the case of a dust storm on 19–22 March 2010 was investigated and compared with the PSCF dust map. The backward trajectory of a recent dust storm plotted over the PSCF dust map agreed well with the potential paths of dust to Hong Kong.

The combined use of clustered AERONET, backward trajectory data, and PSCF models can help to identify the source areas of aerosol types carried to Hong Kong, and this provides an objective method for resolving the long-standing issue about the sources of Hong Kong pollution. Environmental authorities may use the aerosol-type characteristics and derived PSCF maps to devise realistic emission control targets. For example, type 1, which is dominant for 45% of the time and corresponds to regional haze affecting south China, can be mitigated by local emission controls in individual southern Chinese cities. This is the most urgent situation since type 1 is dominant most frequently and represents fine aerosols whose adverse health effects have recently been identified (Dominici et al. 2006). Type 4 (heavy pollution) is also a serious situation (although occurring only 22% of the time), since it is associated with very high AOT levels. As its source corresponds to the heavily urbanized and industrialized belt of southern Guangdong, with a rapidly growing population of 70 million, its control depends on regional cooperation and may only evolve along with economic development, as heavy industries are moved to less populated regions (a trend already seen). For this type as well as type 3 (dust from long-distance sources), action in the short term may be limited to prediction and forecasting. For type 2 (mixed urban), as with type 1 (fine urban), Hong Kong can improve air quality by regulating its own emissions with immediate effect.

The method used in this study only describes the aerosol-type sources by their own properties; further improvement may include mapping the sources of aerosol type mixtures. For example, dust (type 3) coming from rural arid regions may be mixed with heavy pollution (i.e. type 4), including pathogenic and toxic substances, if it passes through industrialized regions; a situation described by Chan et al. (2007) as causing a sharp rise in morbidity and hospital admissions in Taipei. It should be noted that the method described is potentially of more benefit to non-coastal cities, where a larger proportion of the backward trajectories generated would correspond to land areas, which have higher probabilities of being pollution sources.

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