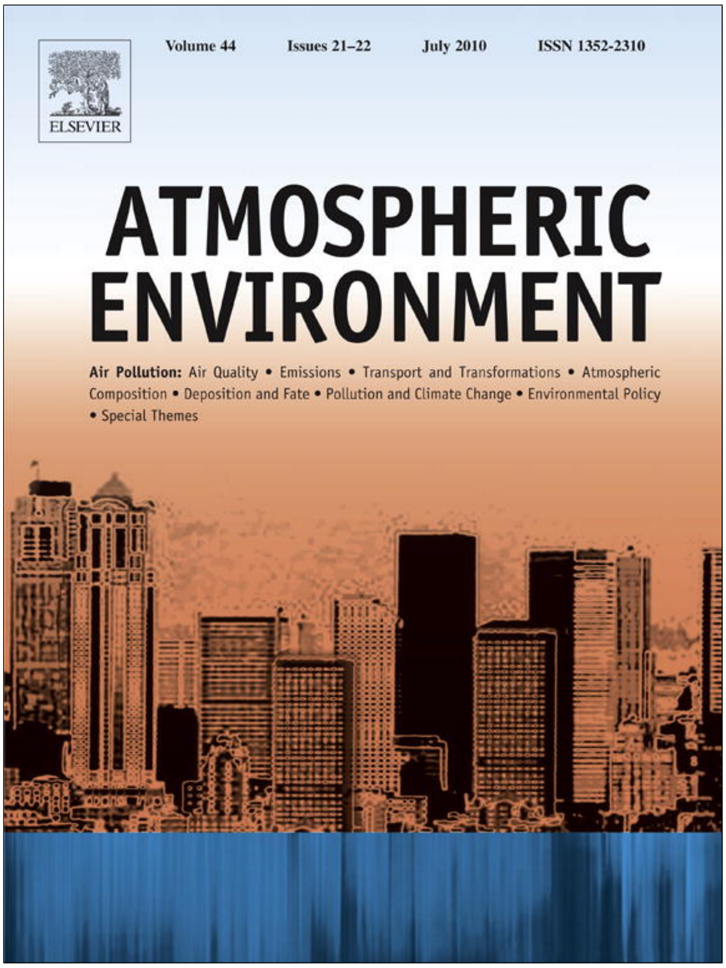
Volume 44
Issues 21–22
July 2010
ISSN 1352-2310
ELSEVIER
ATMOSPHERIC ENVIRONMENT
Air Pollution: Air Quality • Emissions • Transport and Transformations • Atmospheric Composition • Deposition and Fate • Pollution and Climate Change • Environmental Policy • Special Themes

Atmospheric Environment 44 (2010) 2501–2506

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

A 3D aerosol and visibility information system for urban areas using remote sensing and GIS

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ARTICLE INFO

Article history:
Received 8 February 2010
Received in revised form
17 April 2010
Accepted 19 April 2010

Keywords:
Aerosol Optical Thickness
Visibility
GIS
Remote sensing

ABSTRACT

Currently, the depiction of urban air quality at boundary layer scale uses modelled climatic and land cover data. However, such models are difficult to verify, and only low to moderate accuracy may be achieved due to the complexity of the input data required and the reliance on assumptions about dispersion patterns. The provision of comprehensive air quality data to urban residents in city districts, at a level of detail commensurate with other Location-Based Services (LBS) which are time- and place-sensitive, has therefore not been possible. A method for urban air quality monitoring over cities at boundary layer scale, other than by the use of air quality models is presented here. The system presented uses empirical Aerosol Optical Thickness (AOT) data in near-real time, combining AOT data from AERONET with aerosol vertical profiles computed from twice-daily MODIS satellite images at 500 m resolution, to give three dimensional (3D) air quality data over the urban landscape. There has been no previous attempt to project the horizontal spatial distribution of aerosols from satellite image pixels into a vertical dimension to give a spatially comprehensive three dimensional record of air quality. The paper describes the sources and accuracy of the AOT data input to the system as well as its storage and retrieval on a Geographic Information System (GIS) platform, to provide air quality and visibility information according to user query at any 3D geographical location, including individual buildings or building floor.

1. Introduction

Aerosols are fine particles which are ubiquitous in air in either liquid or solid form, and are often observed as dust, smoke and haze. Atmospheric haze is now a semi-permanent feature of large cities worldwide, caused by the emission of fine aerosols from industrial and vehicular sources. In Hong Kong, for example, visibility lower than 8 km, which may affect transport safety, now occurs approximately 20% of the time, having risen at 6% per decade since 1980. Apart from low visibility and its negative impacts on tourism and transport, international companies are increasingly reluctant to deploy staff, and the local population is concerned about long term health effects.

Multispectral satellite sensors such as the MODerate resolution Imaging Spectroradiometer (MODIS) can now provide estimates of aerosol amounts for the whole atmospheric column as a unitless measure, Aerosol Optical Thickness (AOT), over a horizontal area corresponding to the satellite field of view. Most satellite-based aerosol retrieval algorithms however have been at coarse resolution for global studies, such as the MODIS collection 4 and collection 5 AOT product at 10 km resolution (Kaufman et al., 1997; Kaufman and Tanré, 1998; Levy et al., 2004; Remer et al., 2005; Hsu et al., 2004). Stated accuracies of collection 4 and 5 products are within 20% (Remer et al., 2005), when compared with data from ground-based AERONET sunphotometers (Holben et al., 1998). As with most satellite-based aerosol retrieval techniques, however, the algorithm operates only over surfaces with low reflectance such as vegetation and not over bright, and mixed urban surfaces. Recently Wong et al. (2009a, in press) presented a modified Minimum Reflectance Technique (MRT) for use over mixed urban surfaces at the relatively high resolution of 500 m which is adequately detailed to depict spatial variations of air quality within densely urbanised regions such as Hong Kong and the Pearl River Delta (PRD) region. This is able to show aerosol concentrations in urban districts at meso-scale (Fig. 1). However there has been no attempt to decompose the satellite-derived (whole column) AOT into a vertical profile, to give three dimensional aerosol concentrations over whole cities. This is important in high rise cities and those with steeply sloping terrain such as Hong Kong, where particulate concentrations especially fine particulates (PM2.5) at lower levels are usually significantly higher than at roof levels or on upper slopes and ridgetops (Chan and Kwok, 2000; He et al., 2008). Vertical aerosol

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1352-2310/$ – see front matter
doi:10.1016/j.atmosenv.2010.04.036

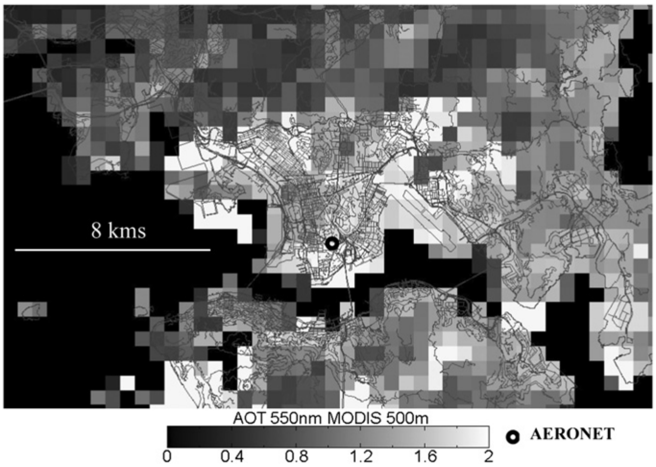

Fig. 1. AOT image of Hong Kong urban areas on October 20th 2007, derived from MRT technique at 500 m resolution. The study area, the Kowloon Peninsula, with a high density road network, is near the centre of the image.

profiles are also important for understanding the radiative effects of aerosols and for air quality modeling. In Hong Kong, the Hong Kong International Airport is in need of comprehensive horizontal and vertical visibility data, whereas currently visibility is measured one-dimensionally as a single column by Lidar, and by forward scatterers on runways.

The favoured urban planning model in future decades is likely to be high rise and compact, to ensure energy efficiency. For example, China is predicted to have 15 high rise mega-cities of at least 25 million population by 2030. Thus to ensure maximum sustainability of future cities, the environment at levels well above the ground in terms of noise, temperature, visibility and air quality will become more important, as well as the quality and use of natural light and ventilation at these elevations, which require fresh air.

For the depiction of air quality over large regions such as a whole city, air quality models rather than empirical measurements have been used, since it is assumed that the spatial and temporal coverage of model data exceeds that of measured data. Two common types of urban air quality models are regression models, and Gaussian dispersion models. The former derive a relationship between air quality parameters measured at points, and urban parameters such as traffic volume, land cover and terrain (Briggs et al., 1997, 2000), whereas the latter estimate pollutant concentrations dispersed from known sources, based on distance to nearest road or point sources (Hoek et al., 2001) or traffic volume on nearby roads (Janssen et al., 2003). Limitations of such modeling are evident from the only moderate accuracies obtained e.g. $r^2 = 0.58-0.76$ for the regression-based model (Briggs et al., 2000), and consistent over-predictions often exceeding double the measured amounts, by dispersion models (Wanjura et al., 2005). Reasons include the complexity and abundance of input data required, as well as the reliance on assumptions about dispersion patterns.

The approach used in our study avoids problems of air quality modeling by the use of measured data, which has previously only been available either from ground stations or from remote sensing at coarse resolution. There has been no previous attempt to use vertical profiles in combination with satellite images, and previous satellite-based aerosol products were at a coarse resolution unsuitable for the analysis of urban areas. The horizontal and vertical aerosol components in our 3D model are from twice-daily MODIS satellite images at 500 m resolution, and the higher temporal resolution is derived from an AERONET sunphotometer near the centre of Hong Kong's urban area (Fig. 1), which operates every 15 min during daylight hours.

2. Study area

The study area corresponds to the densely urbanised Kowloon peninsula of Hong Kong which contains an AERONET station at the Hong Kong Polytechnic University near the centre of the peninsula (Fig. 1). The AERONET (Holben et al., 1998) is a multi-channel Cimel sunphotometer which senses aerosols upward through the atmospheric column and thus derives AOT every 15 min during daylight hours. Air quality in Hong Kong has deteriorated over the last decade, and the Hong Kong PolyU AERONET station shows aerosol levels to be high, compared with other urban stations worldwide. For example, data from AERONET sites (NASA, 2010) show a mean AOT of 0.69 for the 440 nm band, compared with 0.57 for Beijing, 0.55 for Singapore, 0.22 for Rome, and 0.24 for Goddard Space Flight Centre. Surface visibility data, needed for computation of extinction profile are acquired from the Hong Kong Observatory which is only 800 m from the AERONET site, and the paired AOT and visibility readings are within a 30-min time difference.

3. Aerosol Optical Thickness (AOT) database

3.1. MODIS 500 m AOT algorithm

Two major limitations of MODIS collection 4 and 5 data for aerosol retrieval over complex urban regions include the inapplicability of the algorithm over bright urban surfaces, and low (10 km) spatial resolution. Therefore a new aerosol retrieval algorithm for the MODIS 500 m resolution bands has been developed using a modified Minimum Reflectance Technique (MRT) (Wong et al., 2009a, in press). The rationale is to estimate the aerosol reflectances by decomposing the Top-of-Atmosphere (TOA) reflectance from surface reflectance and Rayleigh path reflectance. The MRT technique determines surface reflectance by creating a composite image of the lowest value pixels over a number of different dates. The 500 m MRT aerosol retrieval algorithm shows good results, with strong correlations with AERONET ($r^2 = 0.86$) and a Mean Absolute Difference (MAD) error of 10% in the 8-month dry season. This result, is slightly better than that obtained from MODIS collection 5 operational product at 10 km resolution ($r^2 = 0.72-0.85$) (Chu et al., 2002). The high accuracy of the 500 m AOT algorithm may be surprising given the lower signal-to-noise ratio (SNR) using the smaller (500 m) pixel size, However, only small or negligible changes in aerosol retrieval with increasing

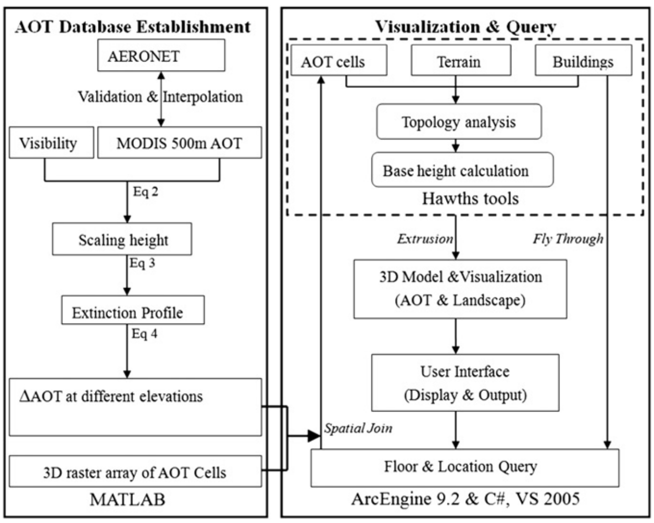

Fig. 2. Methodology of 3D aerosol information system.

pixel sizes have been reported (Henderson and Chylek, 2005) and any loss of accuracy due to a decreased signal-to-noise ratio of the 500 m AOT is thought to be compensated by increased accuracy due to the higher resolution when validated against AERONET data. For more details of the MRT technique, see Wong et al. (in press).

3.2. Computing the aerosol vertical profile using MODIS and climatological data

While Lidar measurements do provide height dependent extinction values, and thus AOT for different atmospheric layers (Ansmann et al., 1990; Spinhirne et al., 1995), the high instrument cost and its complicated installation prohibit its widespread use. Recent work demonstrates that accurate aerosol profiles can be derived by ground-based sensing of the properties of the atmospheric column using a pyrheliometer (Qiu, 2003) or a multi-channel sunphotometer such as AERONET. Wong et al. (2008) used Qiu's method to examine the accuracy of vertical profiles computed from AERONET. They observed an absolute error of the extinction coefficient (σ_a) of just 0.004, from an average σ_a of 0.324, i.e. an error of 1% between AERONET and a co-located MPLNET Lidar using 164 paired readings in a normal urban atmosphere in Taipei.

The extinction coefficient at surface level (σ_a) can be derived from the visibility (or "visual range") according to (Koschmieder, 1924)

$$\sigma_a\ (z = 0) = 3.912/\mathrm{Vis}\ (\mathrm{km}) \quad (1)$$

Furthermore, since the integrated extinction coefficient over a vertical column of unit cross section corresponds to AOT, the aerosol extinction at each altitude ($\Delta\sigma_a$) can be calculated using a known AOT value and its rate of decrease with altitude (aerosol scaling height (z_0)) (Elterman, 1970). The latter can be estimated from the surface visibility, along with AOT values from MODIS 500 m images (AOT_{550nm}).

The aerosol scaling height (z_0) is defined as the height of an exponential profile at which the value is decreased to 1/e of the value at ground level ($\sigma_a\ (z = 0)$). Thus

$$(z_0) = AOT_{550nm}/\sigma_a \quad (2)$$

Given the extinction coefficient at the surface (σ_a), and that the hygroscopic growth effect is negligible when relative humidity (RH) is less than 70% (Hanel, 1976; Fitzgerald et al., 1982), the extinction profile can be obtained from

$$\Delta\sigma_a = \sigma_a \times \exp(-z/z_0) \quad (3)$$

Lastly, the extinction coefficient is converted to ΔAOT (difference in AOT over an atmospheric level) by multiplying the extinction coefficient profile $\Delta\sigma_a$ with the difference in height over that level (Δz) (Equation (4)).

$$\Delta AOT_{(550nm,\Delta z)} = \Delta\sigma_a \times (\Delta z), \quad \text{where } \Delta z = z_2 - z_1 \quad (4)$$

This is a better way of analyzing urban aerosols than using only the whole column aerosol measure of AOT derived from satellite images. In a similar way it is possible to calculate the visibility at different heights from the extinction profile by inverting the Koschmeider equation by

$$\mathrm{Vis}\ (\mathrm{km}) = 3.912/(\Delta\sigma_a) \quad (5)$$

3.3. Temporal interpolation to near-real time using AERONET

Since AERONET sunphotometers are calibrated annually by NASA they are recognized as the standard reference for validation of satellite AOT (Holben et al., 1998; Kaufman and Tanré, 1998). Therefore, in this study, after obtaining MODIS AOT at 500 m, the AOT pixel corresponding to the AERONET site is compared to AERONET AOT obtained within 15 min of MODIS overpass time (Fig. 2). Any difference in AOT between the MODIS pixel and AERONET is applied to adjust the whole image to the AERONET reading. The scaling height, extinction profile and ΔAOT for every MODIS pixel at the image time are then computed. Subsequently, at 15-min intervals corresponding to AERONET observations, the ΔAOT of each image pixel is adjusted according to changes in the difference between AERONET and the AERONET site pixel. This method is obviously subject to spatial and temporal errors, since AOT changes at the AERONET site are expected to be less applicable to pixels far from AERONET, as well as with increasing time following the image overpass. However, the AERONET values have been observed to be highly correlated with temporal changes in AOT from MicrotopsII hand-held sunphotometers deployed at locations across the urban area, namely a common response to morning peak traffic times as well as to the onset and decline of regional pollution events (Wong and Nichol, in press). Therefore the significant increase in temporal resolution from, twice-daily to every 15 min, is thought to be valid and relevant.

4. GIS database for visualisation and query

4.1. Data model

ArcGIS™ (ESRI®) is the basic data model selected for interactive 3D visualisation and data querying by location, such as streets or buildings, over the 3D urban landscape. Most buildings in Hong Kong are high rise, and in the data model each building is associated with its cadastral footprint polygon, which has attributes including height, number of floors, floor depth and floor elevation (building height/number of floors). The individual floors of a building are not stored explicitly but a floor can be related to the outdoor AOT concentrations at its elevation. The AOT data are represented for each building by tabular linkage through the relational database, using the polygon-in-polygon function of the Hawth's extension (Beyer, 2004) for ArcGIS (i.e. building inside pixel).

The AOT grid data layer is created by importing the 500 m twice-daily MODIS AOT images in HDF4 format into Matlab™ as an XY grid georeferenced to the Hong Kong 1980 grid coordinate system. The vertical aerosol profile (Section 3.2) is computed for each MODIS pixel in Matlab™, and adjusted by direct input from an AERONET sunphotometer and visibility data from the Hong Kong Observatory for calculation of aerosol scaling height (z_0), the aerosol extinction profile ($\Delta\sigma_a$) and from these, the AOT at different heights (ΔAOT) (see supplementary material computation code).

4.2. Implementation

ArcGIS Engine is used for integrating the landscape objects including spatial join between the terrain model, building polygons and AOT data, extrusion of the building polygons and raster pixels after their base heights are established by the Digital Elevation Model (DEM), and rendering of the 3D raster atmospheric layers corresponding to 500 m pixel columns, using a transparent colour scheme. The functionality permits near-real time fly-through, giving a realistic representation of aerosol concentrations across the urban area at different scales from whole city to an individual building floor, whose associated AOT level can be retrieved by direct query. Since the system is aimed at visualising the built environment within the city, only seven AOT/visibility layers, each 75 m deep, are created up to the height of the tallest building, the International Commerce Centre (ICC) in south-west Kowloon at 503 m (currently the world's 3rd tallest building). This avoids unnecessary higher atmospheric layers masking the lower layers nearer the ground which vary more horizontally from the observer point of view.

4.3. Model operation

Fig. 3a is a close-up of the ICC tower on the February 1st weekday. At this time and date the total column AOT_{550nm} of the MODIS 500 m pixel at the AERONET site is 0.72 and is adjusted downwards to correspond to AERONET's AOT value of 0.68. The visualisation shows the ICC to be surrounded by a highly-polluted environment, with high AOT_{550nm} values of 0.029 for the lowest 75 m atmospheric layer near ground level (Fig. 3a) and with slow decrease toward the top of the building. On the other hand, for February 4th 2007 (a weekend) the visualisation (Fig. 3b) shows only moderate pollution (represented by AERONET and MODIS AOT_{550nm} values of 0.46 and 0.47 respectively) and much greater difference in AOT between ground level and the top of the ICC. Fig. 3 also demonstrates retrieval of AOT and visibility which may change every 15 min, for a particular building floor.

5. Discussion

AOT retrievals in the model appear accurate to within 10% for horizontal (Wong et al., 2009a, in press), and 7% for vertical dimensions (Wong et al., 2008, 2009b). The horizontal accuracy is higher than that achievable from other satellite-based AOT algorithms, and the higher resolution is more suitable for complex urbanised regions where more spatial variation due to local pollution sources would be expected. Lower accuracies for both horizontal and vertical retrievals however would be expected during the 4-month rainy season due to the growth in size of aerosols in a humid atmosphere. Issues of accuracy will remain for the foreseeable future in the retrieval of AOT from satellite images (Nichol et al., 2007). Furthermore, although the retrieval of vertical

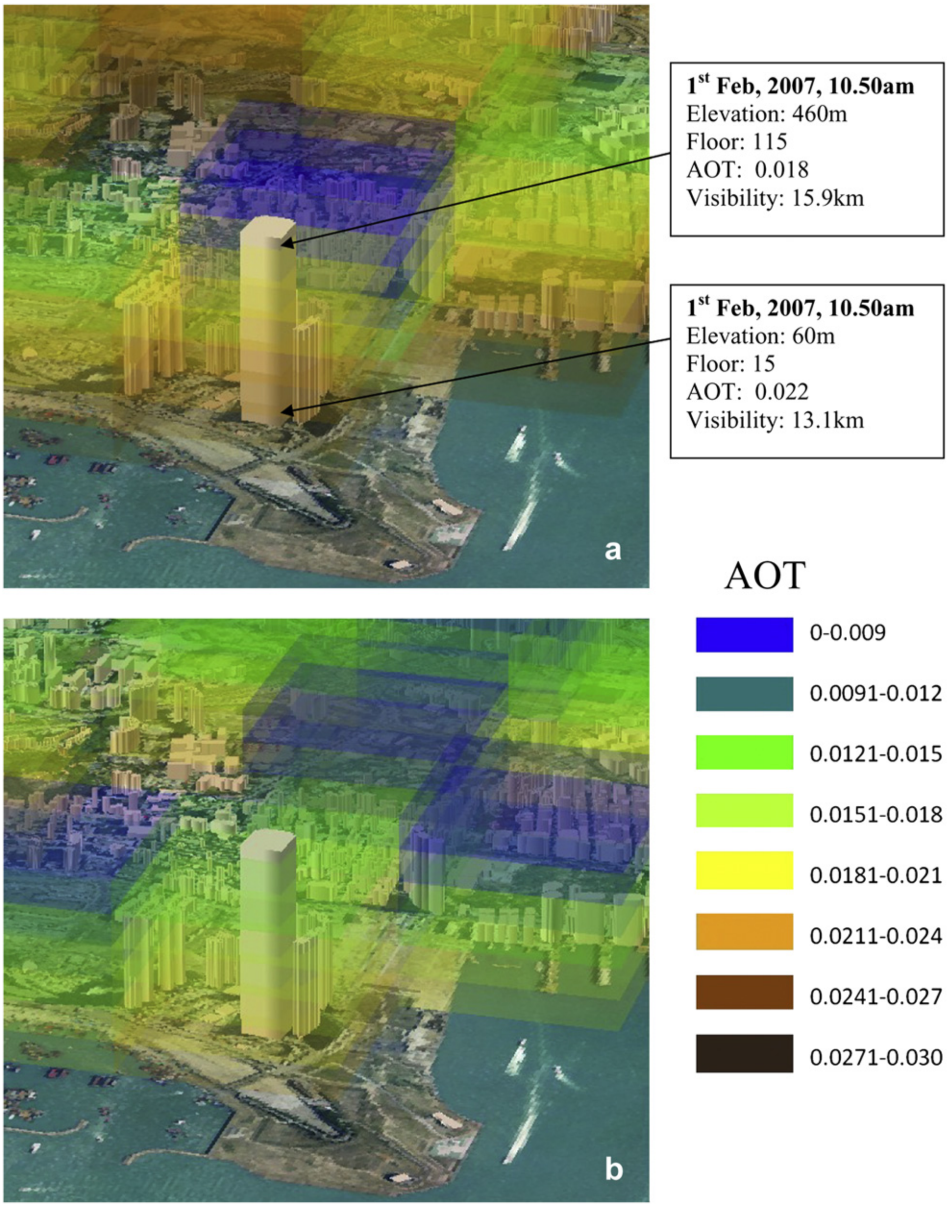

Fig. 3. Derived AOT for different atmospheric layers, 3D view from across Victoria harbour to the high rise buildings on Kowloon Peninsula on (a) February 1st 2007 (local time 10:50 am.), and (b) February 4th 2007 (local time 10:25 am). Example of floor query for AOT and visibility.

aerosol profiles from AOT and visibility data as described here appears accurate in a normal urban atmosphere, it has been shown less accurate during dust events (Wong et al., 2008, 2009b) and in hazy conditions. The spatial and temporal uncertainties due to the use of a single point for calibration and temporal interpolation can be overcome by the deployment of more fixed AOT stations including sunphotometers and Lidars over the urban area, permitting spatial interpolation of the near-real time AOT values between stations.

The extension of this methodology to impacts of air quality on tourism and transport can be achieved by a conversion of AOT to visibility (Lai and Sequiera, 2001; Baumer et al., 2008) (Equation (5)). Thus query by horizontal coordinate, individual building or floor level can be replaced by query at view points or transport hubs. Currently the Hong Kong Observatory carries out assessment of visibility around the Hong Kong International Airport by one vertical Lidar whose accuracy below 1500 m is less satisfactory than at higher levels, and forward scatterers along two runways. This gives visibility along restricted pathways. Query according to the 3D position of an aircraft approaching the runways can be accommodated by the system presented here. Visibility along any 3D line of sight such as a flight path, is a function of the cumulative extinction values in the 3D pixels along the line. In the case of high AOT cells such as those containing a smoke plume, the cumulation along the line is greater and the visibility degradation curve steeper.

The system presented here operates at the scale of the urban boundary layer, and ignores spatial variations due to detailed urban morphology such as street canyons (Chan and Kwok, 2000) as the 500 m horizontal resolution is clearly unable to resolve street and building scales. However, even if such detailed air quality data within street canyons can be collected using hand-held instruments (Chan and Kwok, 2000) this would be difficult to extrapolate to city scale due to the different scales of climatological processes. Although current urban boundary layer models are able to operate within, or nested into regional climate models such as MM5, at similar resolutions to the 500 m data described in this study, accuracy assessment is difficult due to complexities of urban land use and urban climatology, and often relies on plausibility of outputs rather than on direct comparison with reference variables (e.g. Tong et al., 2005). This study, which uses empirical data to model urban air quality is able to avoid the uncertainties of modeling in the complex urban environment, and to retrieve 3D aerosol information at the image time, within stated accuracy levels. The prospects for improved accuracy in the future are good, given the forthcoming new global satellite sensors in the National Polar Operational Environmental Satellite System (NPOESS) program (Hutchison et al., 2009), and future geostationary satellites with higher temporal resolution.

Acknowledgements

This research was funded by the Sustainable Urbanisation Research Fund of the Faculty of Construction and Land Use, The Hong Kong Polytechnic University.

Appendix. Supplementary material

Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.atmosenv.2010.04.036.

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