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RESEARCH ARTICLE

A building-based data capture and data mining technique for air quality assessment

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Abstract Recently, a building-based air quality model system which can predict air quality in front of individual buildings along both sides of a road has been developed. Using the Macau Peninsula as a case study, this paper shows the advantages of building-based model system in data capture and data mining. Compared with the traditional grid-based model systems with input/output spatial resolutions of 1–2 km, the building-based approach can extract the street configuration and traffic data building by building and therefore, can capture the complex spatial variation of traffic emission, urban geometry, and air pollution. The non-homogeneous distribution of air pollution in the Macau Peninsula was modeled in a high-spatial resolution of 319 receptors·km^{-2}. The spatial relationship among air quality, traffic flow, and urban geometry in the historic urban area is investigated. The study shows that the building-based approach may open an innovative methodology in data mining of urban spatial data for environmental assessment. The results are particularly useful to urban planners when they need to consider the influences of urban form on street environment.

Keywords traffic air pollution, spatial distribution, high resolution, geographic information system

1 Introduction

The method and accuracy of data capture dominate air quality assessment. Due to limited budget, installation space and labor resource, permanent or temporary air pollution monitoring sites are very scattered. Air quality assessment of a city based on scattered monitoring sites may not be sufficient to capture the spatial variation of air pollution exposures. Therefore, a number of model systems have been developed to estimate urban air quality at unsampled sites, such as the Atmospheric Dispersion Modeling System (ADMS-urban) [1], the Air Quality Information System (AirQUIS) [2], the Environmental Management (EnviMan) [3], and the Urban Simulation Model (Urban SIM) [4].

The traditional air quality model systems are designed for applications in regional scale with input/output resolutions in kilometers, regardless of the complexity of urban geometry within the urban areas. The air quality monitoring studies co-conducted by the author in the Macau Peninsula, an urban area with highly compact urban forms, have shown the significant spatial variation of air pollution within kilometer squares. In an area of 1 km× 4 km, the roadside polycyclic aromatic hydrocarbons levels of dustfall samples at 11 sites varied from 2.72 to 24.83 μg·g^{-1} [5]. Even in a neighborhood scale of 670 m × 200 m, toxic volatile organic compounds such as benzene, toluene, ethylbenzene and xylene (BTEX) at 18 sampling sites varied to a great extent, i.e., the highest total BTEX was 136 times higher than that of the lowest value [6]. It is obvious that regional scale model systems with input/output resolution in kilometers cannot precisely predict the complex spatial variation of air quality in an urban area with complex urban geometry.

In recent years, the scale or spatial resolution has been an important research topic in disciplines involving geographic information. Researches in environmental and urban management have shown that the outcomes can be altered with different selections of scale in the studies [7–9]. The importance of scale issues has led some researchers to propose a new science of scale, which includes the studies of measures or properties which are invariant with respect to scale, the studies of the influences of scale as a

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parameter in process models, and the implementation of multi-scale approaches [10,11].

Some researchers have developed high temporal/spatial resolution systems for modeling air quality [12–19]. In particular, Jensen [12,13] developed a prototype air quality model system based on a Geographic Information System (GIS) to support local authorities in air quality management for big Danish cities. The system integrated digital maps, administrative databases, an Operational Street Pollution Model (OSPM) [20], an urban landscape model and ArcView GIS for air quality and exposure estimation at the street address level. Compared with existing urban air quality management tools such as the ADMS-urban, Jensen's model system has higher spatial resolution, makes use of digital maps and administrative databases for automatic generation of street configuration data, adds standard GIS features, and provides improved exposure assessment [13].

Building on the work of Jensen [12,13], Tang [18] has developed a building-based air quality model system for Macau. The building-based approach further increases the spatial resolution of input/output data for the modeling of urban air pollution. Applying the developed model system, Tang and Wang [19] performed a preliminary study of the influences of urban forms on vehicle transport and street environment in the Macau Peninsula. Related conference papers have been awarded by the Hong Kong Society for Transportation Studies [18], the International Association of Chinese Professionals in Geographic Information Sciences of the United States [21], and the Urban and Regional Information Systems Association of the United States [22].

Using the Macau Peninsula as a case study, this paper shows the advantages of building-based model system in data capture and data mining. In Sect. 2, the building-based approach is illustrated to show how it takes account of the exact variation of building heights. In Sect. 3, the data capture of urban geometry by the building-based model system is described in details. Applying the building-based model system, Sect. 4 shows an air pollution map with a high-spatial resolution in the Macau Peninsula. The spatial relationship among air quality, traffic flow, and urban geometry in the historic urban area is investigated in Sect. 4. Finally the conclusions are given in Sect. 5.

2 Building-based approach

To capture the complex spatial variation of air quality in an urban area with complex urban geometry, a model system with higher spatial resolution is necessary. Building on the work of Jensen [12,13], Tang [18] has developed a prototype building-based air quality model system for Macau. As shown in Fig. 1, the model system integrates the Operational Street Pollution Model (OSPM), digital maps of the road network, building layout and topographic

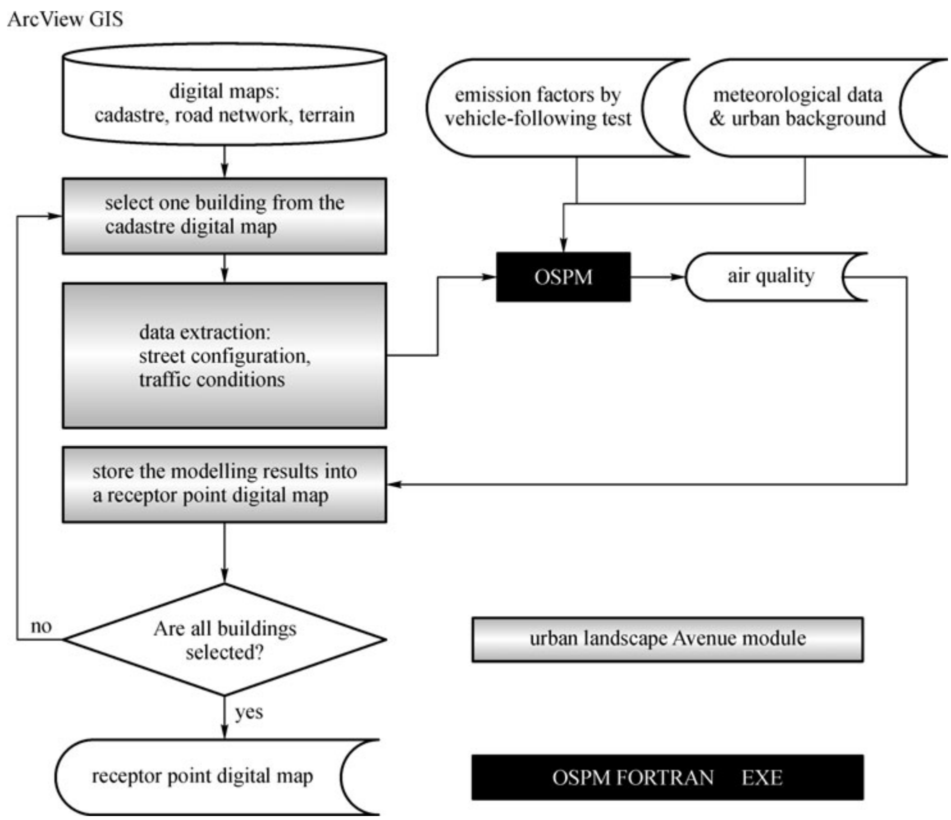


Fig. 1 Structure of air quality model system

information, and an urban landscape model.

The air quality in front of a building is determined by use of the OSPM. The OSPM is a practical street pollution model, developed by the Department of Atmospheric Environment, National Environmental Research Institute, Denmark [20]. Concentrations of exhaust gases are calculated by a combination of a simple plume model for the direct contribution and a box model for the recirculation part of the pollutants in the street. Chemical transformations inside the street canyon are ignored for most of the pollutants emitted from traffic due to the very short distances between the sources and receptors. However, for nitrogen oxides, the chemical reactions involving nitric oxide (NO), nitrogen dioxide (NO_2), and ozone (O_3) are taken into account to model the formation of NO_2 in the street air. Exchange with the background air is modeled taking into account the residence time of pollutants in the street [20].

In the model system, the OSPM programmed in FORTRAN is compiled into an executable module for integration with ArcView. ArcView is a commercially available, desktop GIS. The required input parameters such as traffic conditions and street configurations are extracted from digital maps in ArcView format, namely themes.

The air quality model OSPM requires detailed input of spatial data for buildings (e.g. locations, heights) around the predicated point, so that wind characteristics and thus dispersion of air pollution can be calculated accurately. To increase the spatial resolution of input/output data for the modeling of urban air pollution, Tang [18] has designed a building-based procedure to extract street configuration data automatically by using GIS technique. As shown in Fig. 2, the description of street configuration around a center point on the road is handled by wind sectors. Each wind sector is defined with the origin at the road center and the upper and lower bounds pointing from the origin to the two vertices of building boundary segment. As the boundary of each wind sector is defined by the exact location of each building or open space, the building and the associated building height within the wind sector can be identified. The distance from the center point to the building in each wind sector can be also calculated.

The building-based approach can take account of the exact variation of building heights, so that the OSPM can calculate more accurately the transport distance of the emission plume for the direct contribution and the length of vortex for the recirculation of the emission plume, and thus can predict the air quality in a more realistic setting.

3 Data capture of the building-based model system

As shown in Fig. 1, the air quality model OSPM is integrated with ArcView GIS by a prototype urban landscape model programmed in Avenue which is a scripting language of ArcView. The data capture of the model system is conducted by the urban landscape model. When the urban landscape model is executed, a target building polygon is selected from the cadastral map in ArcView (see Fig. 2). Based on the coordinates of the vertices of the target building polygon, the boundary segments of the building polygon are obtained. If the boundary segment faces a street aligning parallel to it, it is treated as a building façade which is exposed to direct

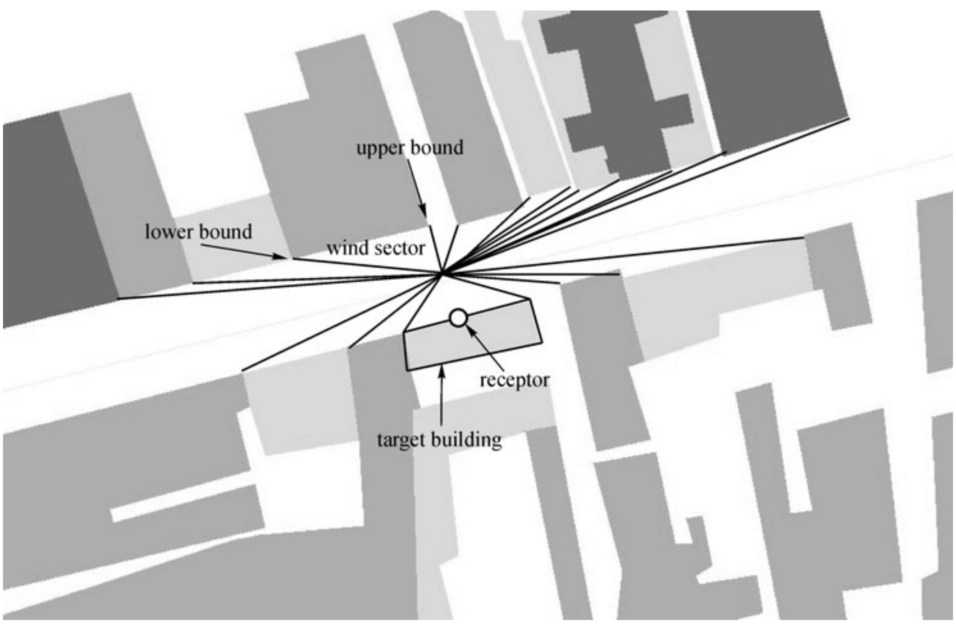


Fig. 2 Wind sectors generated from the urban landscape model

traffic air pollution and a target receptor point is created in the middle of the boundary segment. During this process, the distance from a boundary segment to a street is determined based on their locations in the cadastre map and the road network map, which share a common coordinate system. The target receptor point is stored in a receptor point map.

The spatial-related input data around the target receptor point are then extracted from the cadastre, road network, and terrain maps for the OSPM. The spatial-related input data include the street configuration data and traffic data. For a building polygon around the target receptor point, the coordinates of its vertices can be extracted from the cadastre map. Its position relative to the target receptor point can be described by a parameter of wind sector. As shown in Fig. 2, the wind sector of a building polygon is defined with the origin at the road center and the upper and lower bounds pointing from the origin to the two vertices of the building boundary segment.

The height of the building polygon is calculated by subtracting the elevation of the road surface in front of the building from that at the top of the building. The elevation at the top of the building is extracted from the attribute table of the cadastre map. The elevation of the road surface is extracted from the terrain map in ArcView. With the heights and the relative positions of the building polygons around the target receptor point, the distribution of the building heights around the receptor point can be obtained to determine the height of recirculation zone for the air quality modeling.

The other two-dimensional street configuration data required in the air quality modeling, such as the length, width, and orientation of the street in front of the target receptor point and the distance between the source line and the target receptor point can be determined by the urban landscape model based on the coordinates of the related features extracted from the cadastre map. The traffic data on the street in front of the target receptor point can be extracted from the attribute records of the street in the attribute table of the road network map.

As shown in Fig. 1, the spatial-related data extracted from the digital maps in ArcView are input into the OSPM to simulate the air pollution at the target receptor point. Since the OSPM is integrated with ArcView as an executable module, the spatial-related input data extracted from the digital maps are stored in ASCII input files for the OSPM. The non-spatial input data required by the OSPM such as traffic emission factors, meteorological data and urban background concentrations, which have been prepared before the execution of the urban landscape model, are also stored in ASCII input files.

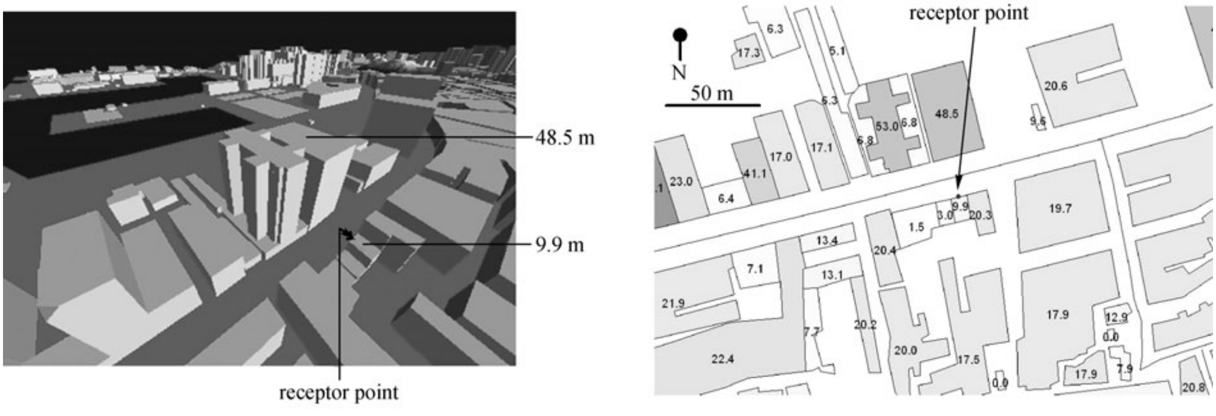
The modeling results of the OSPM, which include the gaseous concentrations of CO, NO, NO_2, and benzene are then stored in the attribute fields of the target point feature created in the receptor point map. Spatial-related input variables such as street configurations, traffic data and vehicular emissions are also stored in the attribute fields of the receptor point. When all the buildings in the cadastral map are selected and manipulated, the urban landscape model stops the execution. All the modeling results in front of the building façades at roadside can then be accessed from the receptor point map in ArcView. The statistical/spatial relationships of the input values and output results can also be investigated.

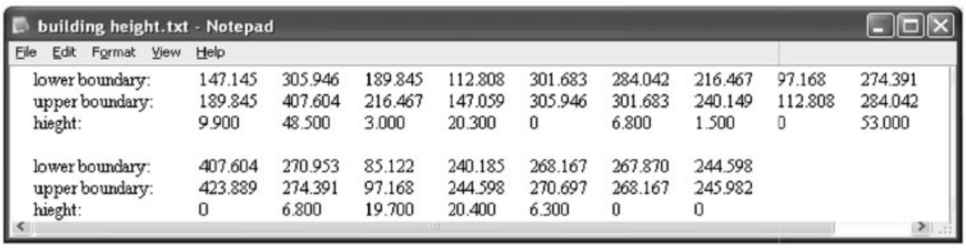
As an illustration of data capture of the model system, a receptor point is created in a typical urban trunk road Rua da Ribeira do Patane in the Macau Peninsula. The immediate neighborhood is given in Fig. 3(a), which shows that the receptor point is located in a street segment with complex building structures on both sides. The building heights around the receptor point is given in Fig. 3(b). The extracted building heights and building locations (wind sectors in degrees) are stored in an ASCII input file and shown in Fig. 3(c). By manual inspection, these extracted spatial-related input data are all correct. The data extraction by the urban landscape model has taken less than one second, which is much faster than the manual inspection.

4 Data mining by the building-based model system—A case study

Applying the developed model system, the spatial relationships among air quality, traffic flow and urban geometry in the Macau Peninsula are investigated. The urban forms in the Macau Peninsula are highly compact due to the high population density (49763 inhabitants$\cdot$km^{-2}) and mixed-used development (i.e., a mixture of residential, commercial, industrial, or other land uses in a building or set of buildings) [23]. In the modeling, pedestrian exposure to traffic air pollution is assessed in a traffic scenario using real traffic data. The traffic data including traffic volume, composition and speed on each road segment have been obtained by on-street traffic surveys conducted during the evening peak period (18:00–19:00) on working days in 2010. Typical meteorological conditions and urban backgrounds in the wind sector 280°–300° are chosen, i.e., wind direction 290°, wind speed 1.8 m$\cdot$s^{-1}, temperature 31.0°C, background nitrogen dioxide (NO_2) 21.2 ppb and background ozone (O_3) 88.3 ppb. The data are the average of measurements during the peak hour 18:00–19:00 on 4 days in 2010.

The vehicle emission factors are essential input parameters in air quality modeling. In this study, the emission factors for five categories of vehicles, i.e., motorcycle, passenger car, taxi, truck, and bus, are obtained from vehicle following measurement conducted in the urban hot spots in the Macau Peninsula in 2004. The details of the vehicle following measurement and the calculation of the emission factors have been reported in [24]. Compared with the emission factors obtained by modeling methods





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lower boundary:	147.145	305.946	189.845	112.808	301.683	284.042	216.467	97.168	274.391
upper boundary:	189.845	407.604	216.467	147.059	305.946	301.683	240.149	112.808	284.042
hieght:	9.900	48.500	3.000	20.300	0	6.800	1.500	0	53.000
lower boundary:	407.604	270.953	85.122	240.185	268.167	267.870	244.598		
upper boundary:	423.889	274.391	97.168	244.598	270.697	268.167	245.982		
hieght:	0	6.800	19.700	20.400	6.300	0	0		

(c)

Fig. 3 (a) 3D view of street configuration around a receptor point in Rua da Ribeira do Patane; (b) building heights around the receptor point; (c) extracted building heights (m) and building locations (wind sectors in degrees) stored in an ASCII input file

(e.g. MOBILE5) [25], Tang and Wang [24] showed that the emission factors obtained from the vehicle following measurement can better represent real-world situations in the Macau Peninsula.

4.1 Air pollution map with high-spatial resolution

The regional scale model systems with input/output resolution in kilometers are not suitable for the study of air pollution distribution in the Macau Peninsula, which has only 9.3 km^2. In the previous studies co-conducted by the author in the Macau Peninsula, a higher resolution of 300 m $\times$ 300 m grids have been used in data capture of traffic emissions (see Fig. 4(a)) and the subsequent modeling of annual nitrogen oxides (NO_x) distribution (see Fig. 4(b)) [25,26]. The modeling of NO_x distribution was accomplished by a steady-state, Gaussian plume model (ISCST3) [26] for transportation distance up to 50 km. NO_x concentrations are modeled at 110 receptor points located in the center of the 300 m $\times$ 300 m grids. The height of the receptors was set to 1.5 m, which is approximately equivalent to the human respiration height. The emission and NO_x distributions in Figs. 4(a) and (b) show a directly perceived conclusion that higher air pollution exposures can be found in the areas with higher traffic emissions. However, the influence of urban geometry (i.e., street configuration) on NO_x dispersion inside a grid or between different grids were not taken into account because the characteristics of urban geometry was only described by a highly simplified parameter — surface roughness.

With the building-based approach invoked by the present model system, a total of 2615 receptor point entities are created automatically in front of individual buildings along both sides of the streets in ArcView GIS. The modeled NO_2 concentrations at 2615 receptor points are shown in Fig. 4(c). As the area of lands in the Macau Peninsula is only 8.2 km^2 (excluding the 1.1 km^2 of a reservoir and two lakes), the average spatial resolution is 319 receptors$\cdot$km^{-2}, which is much higher than the previous studies with grid-based approach. In addition, as the street configuration and traffic data can be extracted building by building, the influence of the complex urban geometry and traffic conditions on the NO_2 exposures at human respiration height can be taken into account. Human exposures in a city can then be investigated at the address level, which is more precise than those based on the unrealistic assumption of homogeneous distributions of urban geometry and air pollution inside the grids with resolutions of kilometers.

With the ArcView's 3D-Analyst extension, spatial relationship between air quality and urban geometry can be presented in a 3D view by the present model system (see Fig. 4(d)). Such 3D visualization is useful to urban planners when they need to consider the influences of urban form on street environment. Particularly, the highly compact urban forms in the Macau Peninsula may make the findings very relevant to urban planners as they prepare for higher population densities in cities throughout the world.

4.2 Spatial analysis of urban form and air pollution in historic area

Urban geometry and urban land use are two basic characteristics of urban form. With the present building-based model system, the influences of urban geometry and urban land use on transport and air quality in the historic

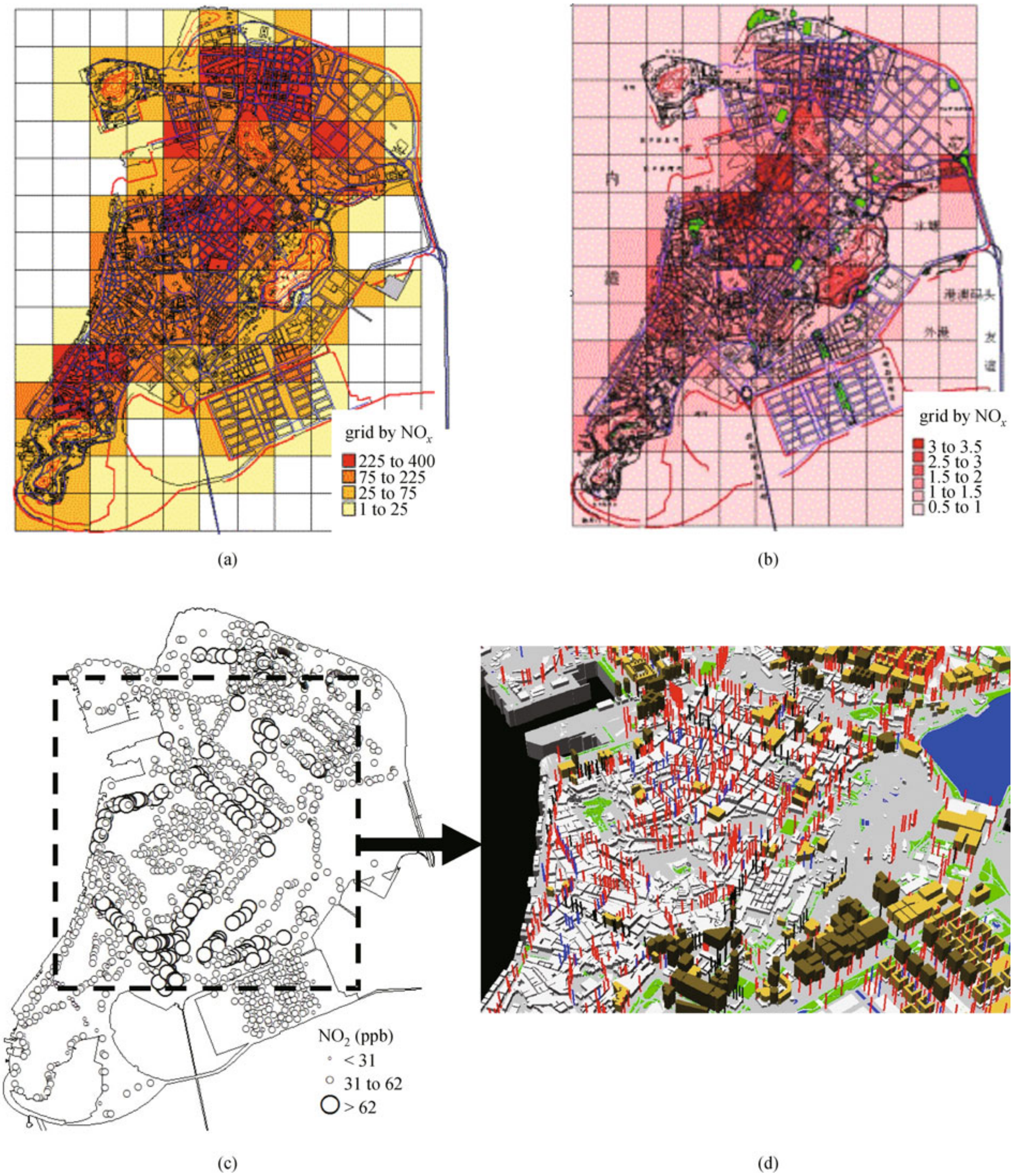

Fig. 4 (a) Distribution of NO_x emission by 300 m × 300 m grids [25]; (b) modeled NO_x concentrations based on 300 m × 300 m grids [25]; (c) modeled NO_2 concentrations by the building-based approach; (d) 3D view of modeled NO_2 concentrations by the building-based approach (columns represent NO_2 concentrations: blue < 31 ppb, red 31–62 ppb, and black> 62 ppb)

area of the Macau Peninsula are investigated. Figure 5 shows the road network, traffic volume, and air pollution in the historic area. In the historic area, the building lot space covers 71% of the urban area. While the road space, green space and water coverage cover only 8%, 2%, and 0%, respectively. Comparing with the other urban areas, the historic area has the most intensive land use as it has been developed since 1557. Besides residential houses, the Central Business District (CBD) lies in this area. The most famous historic landmarks are within walking distance of each other. In 2005, the historic center was awarded "World Cultural Heritage" status by the United Nations Educational, Scientific and Cultural Organization, citing the "dramatic mixing of eastern and western buildings in this jewel" [23].

As shown in Fig. 5(b), the layout of the road network is in complex curvature style which was originally designed for pedestrian transport and human-powered transport such as litters and sedan chairs. Study shows that about 66% of the roads are less than 10 m wide in this historical urban area. About 79% of the buildings are 10–20 m in height and 94% of the buildings are lower than 30 m. The ratio of the building height with respect to the street width (namely the aspect ratio H/W) along 68% of the roads is larger than 0.7. According to Oke [27], the aspect ratio H/W governs the wind flow regimes, which in turn governs dispersions of traffic emissions in the street. For an aspect ratio larger than 0.7, the street is so narrow that a stable circulatory vortex may be formed in the street, leading to an adverse dispersion condition for traffic emissions.

On the other hand, the complex curvature of the road network and the high percentage of narrow roads limit the traffic speed, traffic capacity, and parking capacity in the historic area. As shown in Fig. 5(c), the traffic volumes on most roads in the historic area are very few (around 200–400 $\mathrm{vehicles \cdot h^{-1}}$) as drivers lack the motivation to drive vehicles into the area. As a result, 87% of the modeled NO_2 concentrations at the 298 receptor points in this urban area do not exceed the National Ambient Air Quality Standard for Scenic Spot of 0.12 $\mathrm{mg \cdot m^{-3}}$ (GB3095–1996), which is equivalent to 62 ppb for the present meteorological conditions, see Fig. 5(d).

The receptor points where the modeled NO_2 concentrations exceed the National Ambient Air Quality Standard for Scenic Spot are mainly located in two busy straight roads. As shown in Fig. 5(c), two straight roads cutting across the historic area in the central and south-east part attract vehicle drivers to use as shortest paths to their destinations of the other urban areas. The great traffic demands (> 2000 $\mathrm{vehicles \cdot h^{-1}}$) on the two straight roads lead to higher NO_2 concentrations of over 62 ppb than the other roads, as shown in Fig. 5(d).

Particularly, the longest straight road (namely the New Road) passing through the heart of the historic area was designed for vehicle use in the early 1900s, which does not match the morphology of complex curved road network originally designed for pedestrian use during 1557–1794. Consequently, today's drivers select the straight New Road rather than the other complex curved roads to pass through the heart of the historic area. It leads to a significantly higher traffic volume on the New Road and hence, higher pedestrian exposure to NO_2 concentrations of 76–89 ppb, which are 1.2 to 1.4 times of the National Ambient Air Quality Standard for Scenic Spot (i.e. 62 ppb). In addition, the NO_2 concentrations along the pedestrian sidewalks on the two sides of the road show observable difference of around 13%. The average NO_2 concentration along the pedestrian sidewalk on the windward side is 76.5 ppb, while that on the leeward side is as high as 86.7 ppb. This can be explained by the formation of a stable circulatory vortex in the New Road which has an aspect ratio H/W of 1.0. The pedestrian sidewalk on the windward side is exposed to the NO_2 concentration from the recirculation plume of the vortex while the leeward side is exposed to the combination of NO_2 concentration from the recirculation plume of the vortex and the direct emission plume of the traffic. Noticeably, NO_2 acts mainly as an irritant affecting the mucosa of the throat, nose, eyes, and respiratory tract. The high pedestrian exposure to NO_2 on the New Road may reduce the comfort of tourists walking in the historic center and ruin the reputation of the area as a World Cultural Heritage site.

5 Conclusions

The data capture and data mining of urban air pollution by an innovative building-based approach are introduced in the paper. In a case study in the Macau Peninsula with only 8.2 $\mathrm{km^2}$ of land area, the street configuration data in front of 2615 receptors have been extracted automatically and the air pollutant concentrations have been modeled with a high-spatial resolution of 319 $\mathrm{receptors \cdot km^{-2}}$. As the street configuration and traffic data can be extracted building by building, the complex spatial variation of traffic emission, urban geometry, and air pollution can be captured. Human exposure to traffic air pollution in a city can then be investigated at the address level, which is more precise than those obtained by the traditional grid-based approach based on the unrealistic assumption of homogeneous distributions of urban geometry and air pollution inside a grid of 1–2 km. Based on the high-spatial resolution of input/output data, the spatial relationship among air quality, traffic flow and urban geometry in the historic urban area of the Macau Peninsula have been investigated. The study shows that the building-based approach may open an innovative methodology in data mining of urban spatial data for environmental assessment. The results are particularly useful to urban planners when they need to consider the influences of urban form on street environment.

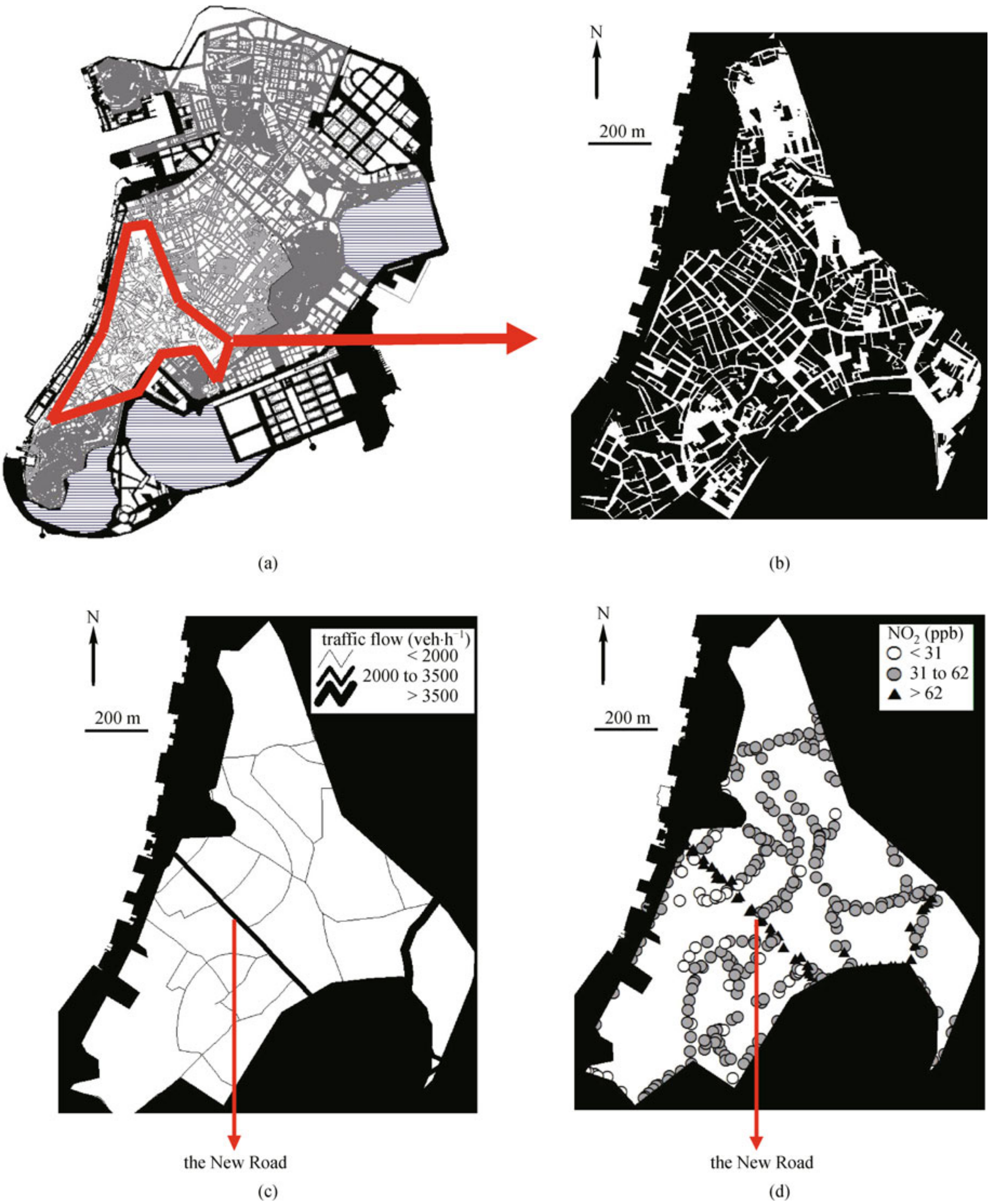

Fig. 5 Spatial relationships of urban form, traffic flow, and air pollution in the historic area: (a) historic area in the Macau Peninsula; (b) road network in the historic area; (c) traffic flow in the historic area; (d) air pollution (NO_2) in the historic area

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