Computers, Environment and Urban Systems 62 (2017) 222–232

Contents lists available at ScienceDirect

Computers, Environment and Urban Systems

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

A modelling system with adjustable emission inventories for cross-boundary air quality management in Hong Kong and the Pearl River Delta, China

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ARTICLE INFO

Article history:
Received 15 December 2015
Received in revised form 12 December 2016
Accepted 14 December 2016
Available online 19 December 2016

Keywords:
Air quality
Modelling management
Adjustable emission inventory
Cyberinfrastructure system
Pearl River Delta (PRD)

ABSTRACT

Air quality problems are attracting much attention in Hong Kong (HK) and the Pearl River Delta (PRD) in China. The complex and regional characteristics of air quality problems call for a comprehensive modelling system with a highly reliable simulation and effective communication tools for decision-makers and participants from multiple disciplines. In this paper, we used a modelling management method to develop a Cyberinfrastructure system that couples meteorological and air quality models with a visual analysis to improve the cognition and management of air quality problems. The database management of both the data and the modelling parameters is an innovative advantage of this system; this will be helpful not only for sharing modelling knowledge but also for improving the acknowledgement of modelling scenarios, which are usually conducted by various stakeholders. On the basis of 19 categories of emission inventories that provide detailed information about multiple pollutants in the 11 cities in the study area, this system provides an authoritative and adjustable emission inventory to draw an accurate scientific picture for decision-makers. We applied this system to a case study to investigate the effects of emission control of nitrogen dioxide from vehicles in HK and the PRD on air quality. The simulation showed that the air quality improvement from emission control was very limited and suggested that regional and super-regional co-operation involving the comprehensive emission control of multiple pollutants may be more effective in creating a better future.

1. Introduction

Air quality problems affect many highly developed cities worldwide, including the Hong Kong Special Administrative Region in China. To mitigate this crisis, the Hong Kong (HK) government has taken many measures to control air pollution emission sources, and dramatic achievements are evident from the emission trend statistics. However, air quality monitored by both general and road stations is not as satisfactory as the control of the emission sources (Clean Air Network, 2011). Such inconsistencies also cause conflicts among the government, organisations and the public regarding the management of this problem (Wang, 2005).

To explain the contrast between the decrease in emissions and continual poor air quality, a regional effect from the surrounding Pearl River Delta (PRD) region (nine cities in Guangdong province) has been identified as the predominant cause of the air quality problems. The PRD, which is geographically adjacent to HK and located in the southern part of China (Fig. 1), is 41,700 km^2 in size, with a population of approximately 65 million (Wang, Wu, & Liang, 2009a). Rapid urbanisation and high energy consumption have recently driven air pollution to harmful levels, which has been a growing concern for both HK and the PRD. It has long been recognised that the air pollution problem in HK is greatly affected by the PRD, particularly if the secondary products O_3 and $PM_{2.5}$ are considered instead of the classical primary pollutants, such as SO_2 and the total suspended particulate matter (Guo et al., 2006; Lam, Wang, Wu, & Li, 2005; Y. H. Zhang et al., 2008).

To address the different local and regional contributions to the air quality problem, extensive studies based on emission inventory data have been conducted during the past several years to analyse the relative individual contributions of the major emission sources in HK and the PRD. Yim, Fung, and Lau (2010) examined the contributions of sources such as major power plants, marine vessels and vehicles in the PRD and HK to the SO_2 concentrations observed at 11 HK

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http://dx.doi.org/10.1016/j.compenvurbsys.2016.12.004
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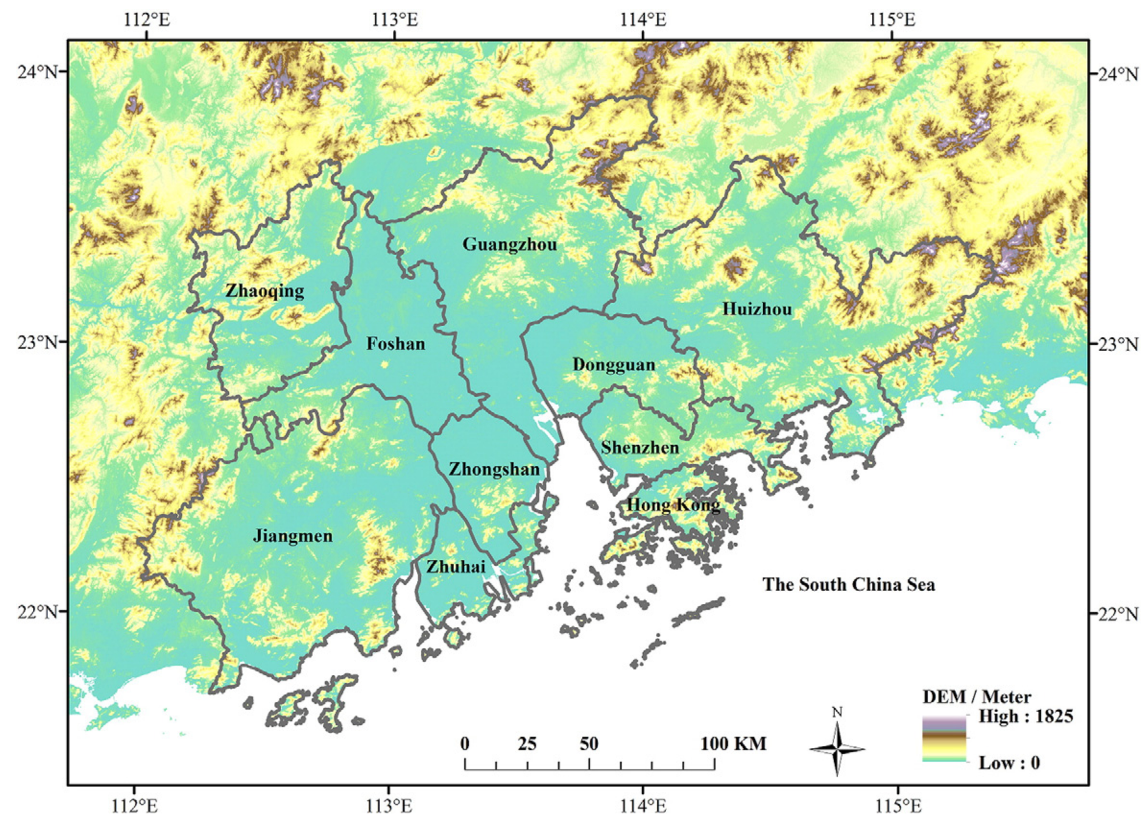

Fig. 1. Geographic location of HK and the PRD.

Environmental Protection Department general stations. Instead of focusing on HK, the impacts of emissions from transportation, industry and power generation on air quality in the PRD were addressed (Wang, Carmichael, Chen, Tang, & Wang, 2005). The scientific results of the contributions of various sources have provided the necessary evidence for government officials to take measures to manage the air quality problem. The findings also suggested that the government should take collaborative measures to manage these regional problems because the individual cities cannot achieve better air quality on their own (Kwok, Fung, Lau, & Fu, 2010; Lam et al., 2005; Nie, Wang, Wang, Wei, & Liu, 2013; Wang et al., 2009b; Wang et al., 2009a; Yim et al., 2010). On the basis of this scientific evidence, HK and the PRD have been collaborating to improve regional air quality since 2002, and a significant improvement in air quality was achieved by 2010 compared to 1997 (Environment Bureau, Transport, & Housing Bureau, Food, & Health Bureau, & Development Bureau, 2013).

To expand the positive effects of the collaborative measures, the two regions (HK and the PRD) are still actively calling for comprehensive studies to better understand the regional air quality problem because a greater understanding is needed to fine-tune the control policies (Environment Bureau et al., 2013). Therefore, an overarching and integral HK and PRD science platform has been proposed for the formulation of regional policy and control measures under the ‘one country, two systems’ principle to ensure continuous and concerted standards for the implementation of a regional control strategy (Yim et al., 2010; Zhong et al., 2013). Such a statement is concluded in regard of two aspects.

1) To provide a scientific foundation for air quality management policy making, many different scenarios concerning various sensitivity studies and potential policies must be considered (Wang et al., 2005; Yim et al., 2010). In addition, these scenarios are usually conducted by different research institutes or stakeholders, including the environmental protection department, universities in HK and scientific institutes in the PRD (EPDHK, 2014b; Kwok et al., 2010; Yim et al., 2010; Zheng et al., 2009a). Thus, the simulation results may not be widely accepted, and it can be difficult to reproduce a particular simulation given the limitations of the data source or the model setting (Environment Bureau et al., 2013; Jiang, Wang, Wang, Xie, & Zhao, 2008; Kwok et al., 2010; Zhong et al., 2013). Therefore, it is preferable to design an integral HK and PRD modelling system with a modelling management system that will manage the input data, modelling parameters and modelling results to improve the recognition and reproducibility of the modelling output (Zhang, Chen, Li, Fang, & Lin, 2016). Various government agencies can reproduce the simulation scenarios and obtain a consensus about the air quality situation, and then they can consolidate various standards to resolve the air quality problem. Unfortunately, such a requirement is rarely addressed by the current modelling systems (Kwok et al., 2010; Wang et al., 2005; Xu et al., 2010; Zheng et al., 2009a). Although the database system was applied for some support systems, management is still limited to data rather than modelling parameters, which has a considerable effect on the modelling results (Wu, Zhao, Zhu, & Jiang, 2015; Xu et al., 2011; Zhang, Lin, Chen, Li, & Zeng, 2014a; Zhang, Lin, Chen, & Yang, 2014b).
2) To make such a supporting system practical for decision-makers, in addition to the important requirement for integrated models, the emission inventory used for modelling should be comprehensive (multi-pollutants), reliable and acknowledged by all parties involved (i.e. HK and the PRD) (Zhong et al., 2013). Researchers and modellers are mostly focused on a single pollutant, source or specific region using the current systems; some of the parameters included SO_2 and point sources in HK and the PRD or volatile organic compounds (VOCs) and multiple sources in the PRD (Guo et al., 2006; Wang et al., 2005; Xu et al., 2011; Xu et al., 2010; Yim et al., 2010). Such a focus is inefficient for the provision of an integral and scientific picture for decision-makers because the pollutants may affect each other, particularly through chemical reactions (Sillman,

Logan, & Wofsy, 1990). Thus, a modelling system with an up-to-date emission inventory of multi-pollutants for both HK and the PRD should be the next step in developing systems used for decision-making.

In this paper, we developed an integral HK and PRD science platform, a type of Cyberinfrastructure (Arzberger et al., 2004; Convertino & Hedberg, 2014; Harris & Impelluso, 2008) to support cross-boundary air quality management in HK and the PRD. This system uses parallel computing to couple the Weather Research and Forecasting (WRF) model and the EPA Community Multiscale Air Quality (CMAQ) model to reproduce the meteorological conditions and estimate the air quality, respectively. A highly resolved temporal and spatial air pollutant emission inventory was prepared using the Sparse Matrix Operator Kernel Emissions (SMOKE) model, which can be adjusted for different pollutants, source categories and cities; these adjustments allow for different scenarios to be considered for potential policy-making. By applying the Linux-Apache-MySQL-Perl (LAMP) architecture in the implementation of the system, users from all locations can manage and retrieve simulations including both data and model parameterisation to help them reach a consensus on the simulation results and share modelling knowledge. In addition, a user-friendly interface and a set of visualisation methods have been implemented in the system. A graphical user interface (GUI) and multi-dimensional visualisations allow users from different backgrounds to interact with the system to set parameters, run models and conduct analyses.

The remainder of the paper is organised as follows. We present the system framework, database design and key technology of the system development in Section 2. In Section 3, we present the results of one application concerning the effects of vehicle emission control on air quality in HK and the PRD to demonstrate the system performance. Finally, in Section 4, we summarise the study with concluding remarks and propose future work.

2. System design and implementation

The system has three parts: the user interface, the data and modelling management system, and the numerical models. The user interface is a user-friendly GUI for users from multiple disciplines with different backgrounds, including government officials, researchers, businessmen and the public (Environment Bureau et al., 2013). The GUI provides users with an interface to set the modelling parameters and a multi-dimensional visualisation to improve their understanding of the air quality process.

The data and modelling management system is different from a traditional database designed only for data management; the present model-based system is designed to manage not only data but also the model setting, including the input data, modelling parameters and simulation results. Specifically, the input data and parameters are imported from the database. In addition, the corresponding simulation results from each modelling stage are stored in the database with the necessary data conversion to make each component compatible. This model-based design is helpful in two ways. On the one hand, it improves the credibility and acknowledgement of the simulation by users across disciplines and from different institutions because all the modelling parameterisations can be traced. On the other hand, because of the geographical dependence of the meteorological and air quality process, expert experience is highly important to the successful reproduction of the processes. This scenario management function allows new users to learn from experts by reviewing their simulation scenarios. Such efficient sharing of data and modelling knowledge are valuable for cross-boundary air quality management.

The numerical models include dynamic models such as WRF, SMOKE and CMAQ, which are widely used in this area of study and are high-performance models (CMAQ, 2010; Kwok et al., 2010; SMOKE, 2013; Wang et al., 2009a; WRF, 2012; Yu, Sokhi, Kitwiroon, Middleton, & Fisher, 2008). A high-resolution emission inventory is a significant modelling component that was re-allocated spatiotemporally using SMOKE on the basis of geographic data, statistical data and monitored data.

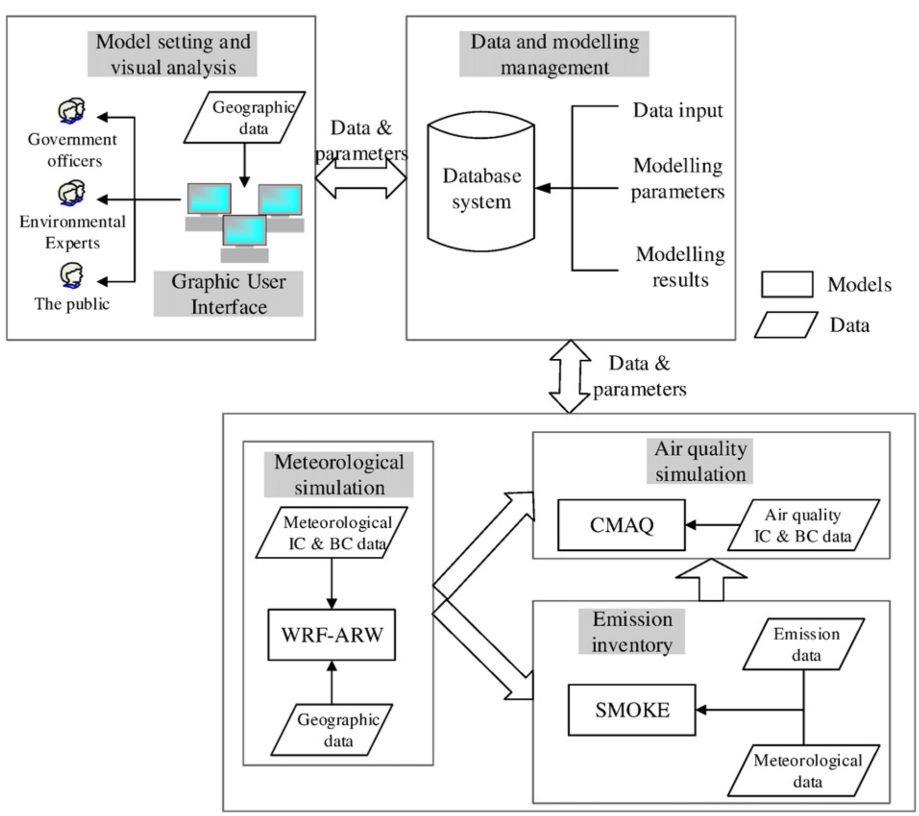

Fig. 2. System framework.

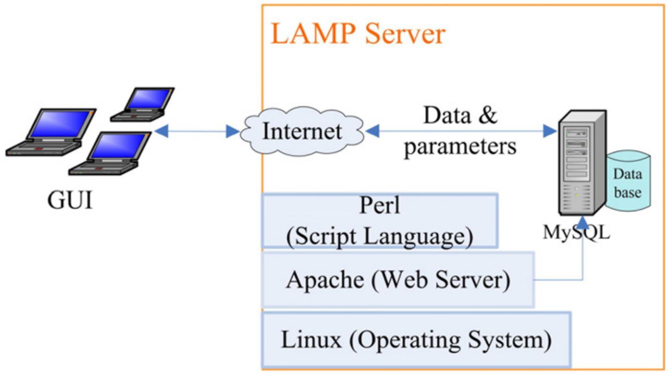

Fig. 3. LAMP architecture for modelling management.

Adjustable pollutant species and source types in the emission inventory allow the modelling system to estimate the effects of various emission control policies.

The three-part system framework is shown in Fig. 2.

2.1. LAMP for modelling management

The LAMP architecture provides a complete robust solution for the operating system, web server, database and scripting languages; therefore, it has become very popular as a way of deploying inexpensive, scalable and secure web applications (Arsan, Saka, & Sahin, 2010; Le Ru, Aron, Gerval, & Napoleon, 2015; Romano et al., 2016; Tsai & Luo, 2009). We implemented LAMP with parallel computing to manage both the data and modelling parameters. The server is built on the Linux operating system, and the MySQL database (version 14.14) is used to manage the data. In addition, Apache serves as the web server, and Perl can access the MySQL database (Fig. 3). Using this database, a user can set the model parameters and store those parameters in the database. In addition, the user can retrieve and preview the parameters, including the input files, output directories, domain setting, and physical setting, to ensure that they are set correctly or to learn from the stored simulation. Once this is performed, the simulation results and the parameters are stored accordingly in MySQL. In this way, a user can retrieve the simulation settings and the corresponding output.

2.2. Database design for modelling management

We designed the database system in physical mode on the basis of the conceptual and logical modes. This database system can effectively store and manage both the data and modelling parameterisation. Fig. 4 shows the crucial tables of the database and the foreign keys that link them, focusing on the modelling parameters and the corresponding output management because fundamental data management (geographic data, emission data source, etc.) is well explained in

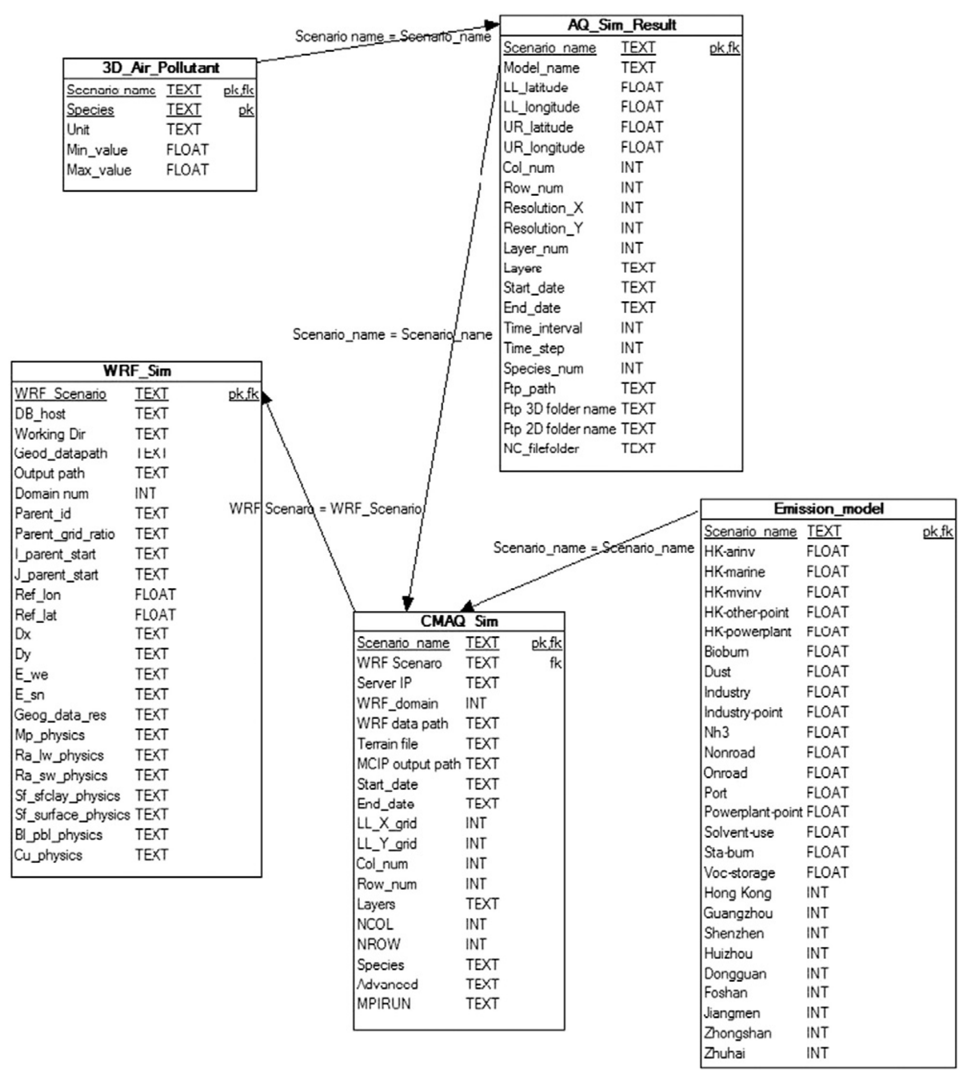

Fig. 4. Database design to manage the simulation data and modelling.

traditional database systems (Chaudhry & Mackaness, 2008; Xie, Zhang, & Gao, 2011). The table references are also illustrated along with the description of these tables to show the dependence of the models (Table 1). The user can retrieve a simulation concerning the input data, output data, model dependence and modelling parameters with this reference. Such design is valuable for the decision-makers to check the simulation configuration and collaboratively manage a cross-boundary air quality problem. Furthermore, such a database design allows a new model user to retrieve the model base to acquire modelling knowledge from experts through their modelling information.

2.3. Strategy for emission inventory

To allow the practical application of this system in decision-making, the emission inventory should be comprehensive and adjustable to estimate different policy scenarios for cross-boundary air quality management. This section illustrates the data organisation and strategy to adjust the emission inventory for HK and the PRD (Fig. 1) using specific factors to achieve this goal.

2.3.1. Data organisation

The emission inventory for CMAQ is complex given the large simulation domain, spatiotemporal allocation process and multiple pollutants (Zheng et al., 2009a; Zheng, Zhang, Che, Zheng, & Yin, 2009b). In this study, we used the SMOKE model to develop a comprehensive emission inventory for 2010 using both a bottom-up and a top-down approach (Zheng et al., 2009b). The emission data were organised into 19 categories (Table 2), including the major emission pollutants (i.e. SO_2, NO_X, CO, PM_{10}, $PM_{2.5}$, VOCs) in both HK and the PRD (Fig. 1).

2.3.2. Emission inventory adjustment

We developed a controller tool depending on the categories in the emission inventory listed above in four levels so that a user could efficiently navigate the emission inventory to assess different policy scenarios concerning emission types, pollutants, cities and factors. Fig. 5 is an example that explains the procedure for adjusting the emission inventory during a simulation. First, a user defines the emission types to be processed, such as the industry and the HK power plant. Second, the user selects the pollutants to regulate, such as SO_2, CO and VOC, and the factors for each pollutant, such as 0.9, 0.9 and 0.8, respectively, indicating that the emission of each pollutant is to be reduced by 10%, 10% and 20%. Third, the user chooses the cities where this regulation will be imposed, such as Guangzhou and Shenzhen. Similarly, the user can adjust the emission of certain pollutants from power plants in HK and other categories. Except for the adjusted pollutants, the remaining emissions are estimated by SMOKE in the simulation and left unchanged. Using this strategy, a user can generate a potential emission inventory for a specific scenario to assess the possible results of a trial policy. This controller tool was developed in Python scripts using the GeoFac and MRG Grid toolkits provided by the University of North Carolina at Chapel Hill (SMOKE, 2013).

Table 1
Description of the major tables in the database system.

Table	Description
WRF_Sim	This table manages the parameterisation of the meteorological setting using the WRF model.
CMAQ_Sim	This table manages the parameterisation of air quality model using the CMAQ model with the meteorological field from WRF_Sim and the emission source from the Emission_model.
Emission_model	This table manages the setting of 19 emission types and the PRD cities for policy control.
AQ_Sim_Result	This table manages the simulation results from the air quality models of CMAQ.
3D_Air_Pollutant	This table manages the air pollutant information from the air quality simulation results of the 3D visualisation.

Table 2
Nineteen types of the emission inventory.

Source category	Area/point	Description
HK-arinv	Area	Commercial source, non-road mobile and residential source in HK
HK-marine	Area	Marine source in HK
HK-mvinv	Area	Mobile source in HK
HK-other-point	Point	Airplane, gas station and other industry sources
HK-powerplant	Point	Power plant in HK
Bioburn	Area	Biogenic burning in the PRD
Dust	Area	Dust sources in the PRD
Industry	Area	Miscellaneous industry sources in the PRD
Industry-point	Point	Industry sources in the PRD
Nh3	Area	Agriculture and livestock sources in the PRD
Nonroad	Area	Non-road sources in PRD, including agricultural equipment, construction equipment, and marine
Onroad	Area	Vehicle source in the PRD
Port	Point	Airplane and port in the PRD (belong to non-road source)
Powerplant-point	Point	Power plant in the PRD
Solvent-use	Area	Solvent usage sources in the PRD
Sta-burn	Area	Stationary sources and fuel combustion in the PRD
Voc-storage	Area	VOC emitted from solvent/petroleum transportation and storage in the PRD
GD-nonPRD	Area	All anthropogenic sources in Guangdong province but outside the PRD area
Megan	Area	Biogenic sources in the simulation domain

2.4. System implementation

This system integrates dynamic models and visualisation with the key components illustrated above.

The current version of the system was developed and coded using C++ in a Microsoft Visual Studio 2010 environment. For the computing-intensive dynamic models, they were deployed in the Community Enterprise Operating System (CentOS) with 17 nodes, and each node had 16 cores. Specifically, WRF and CMAQ were compiled to support distributed and shared memory parallelisation. To run these models in parallel, the modelling domain can be decomposed into rectangular patches by setting the number of processers in the *x* and *y* direction with the product equal to the total number of processors for the computation (CMAQ, 2010; Grell, Peckham, Schmitz, & Mceen, 2005). The system activates dynamic models by calling Perl scripts as the Uniform Resource Locator in the C++ programme. In addition, a data convertor to link the data, model and a visual analysis was developed by nesting the NCAR Command Language in the Perl scripts to process the data in the Network Common Data Form. A box-based method was implemented for visualisation based on the OpenSceneGraph 3D graphics toolkit to express the dynamic air quality process.

Fig. 6 shows a system prototype in three panes. The top pane presents the menu in the ribbon style arranged in a logical manner, in which the user can find the functions for geographic data management, data conversion, spatial analysis, simulation results analysis and others. When a user clicks an icon to activate a function, such as data conversion from CMAQ for visualisation, a corresponding dialog box pops up so that the user can set the parameters for the function and complete it, as shown in Fig. 6. The system allows visual analysis by providing expression in multiple modes and abundant analysis methods, including a vertical sectional analysis, and a point profile. The left pane is for the management of the simulation scenario, in which a user can create a series of simulation events and define the simulation parameters in the parameter-setting dialog box. Once the setting is completed, the parameters are stored in the MySQL database, and the system can activate simulation models according to the setting. After the simulation is completed with a data format conversion, the user can conveniently activate the simulated events in the 'simulation management tree' for visualisation and comparison. The third pane is the main system window, in

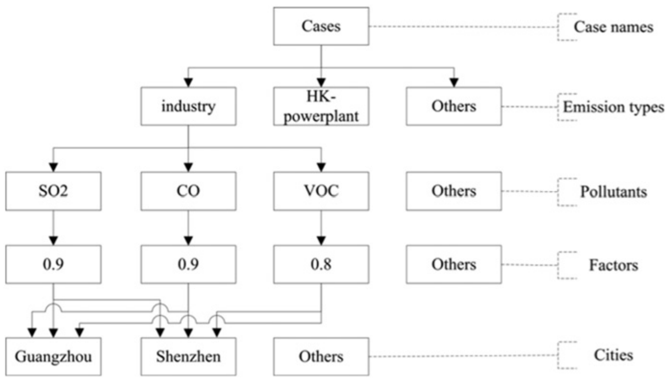

Fig. 5. Adjustment of the emission inventory for different scenarios.

which a user can view the study area, draw the simulation domain, visualise a simulated event and so on.

2.5. Workflow of the integrated system

Fig. 7 shows the workflow of the modelling system for an air quality problem with a model-base design. Along the green arrows, interdisciplinary experts and different stakeholders can set the modelling parameterisations according to their knowledge, and the data and modelling information will be stored in the database. We designed two ways to improve the interactivity and robustness of the modelling system in this stage. On the one hand, the system provides an information window for each parameter when it is activated in the GUI that shows the data type, format, range and so on. This allows the user to set an appropriate value for each parameter. On the other hand, the system validates the parameters before they are written to the database. For example, the nested simulation domain should be located in its parent domain; therefore, the system conducts a projection conversion and computes the domain co-ordinates to validate the parameter setting. If an error in the parameters is found, the system displays an error message. Then, the models can be activated with the parameter information from the database, and the simulation results can also be saved and managed in the database for further visual analysis. Moreover, the user can retrieve the model-base system to load a saved modelling parameterisation for reference or to reproduce a simulation scenario, as shown by the blue arrows.

The model-base design links the model inputs, parameterisation and outputs. This design is helpful for three reasons. First, new users from different disciplines can learn from the experienced and professional modellers by reviewing the model base for model settings (see Section 2.6). Second, the reproducibility of the model is improved by the detailed information about the modelling, which has been identified as one of the three primary challenges of simulation, such as in agent-based modelling for social behaviour (Crooks, Castle, & Batty, 2008). Third, the sharing of simulation output can be extended because simulation results from extensive modelling information should be more reliable. For example, the simulation results from WRF would always be employed as the initial and boundary conditions by a building designer who needs to examine a wind field for different building conditions. Thus, the modelling information enables the designer to have more confidence in the results of the evaluation.

2.6. User experiences of the integrated system

2.6.1. Participants

Participants were drawn from individuals in our college, as long as they were interested in earth science or air quality management. A total of 20 participants were recruited including 11 undergraduate students, 8 graduate students and one professor. All the participants' questionnaire responses were received after they applied the integrated system.

2.6.2. Procedure

We invited all the volunteers to our office having access to the modelling system and user guide. The authors briefly introduced the modelling system, such as the background of the system design, functions of data and modelling parameters management, simulation and

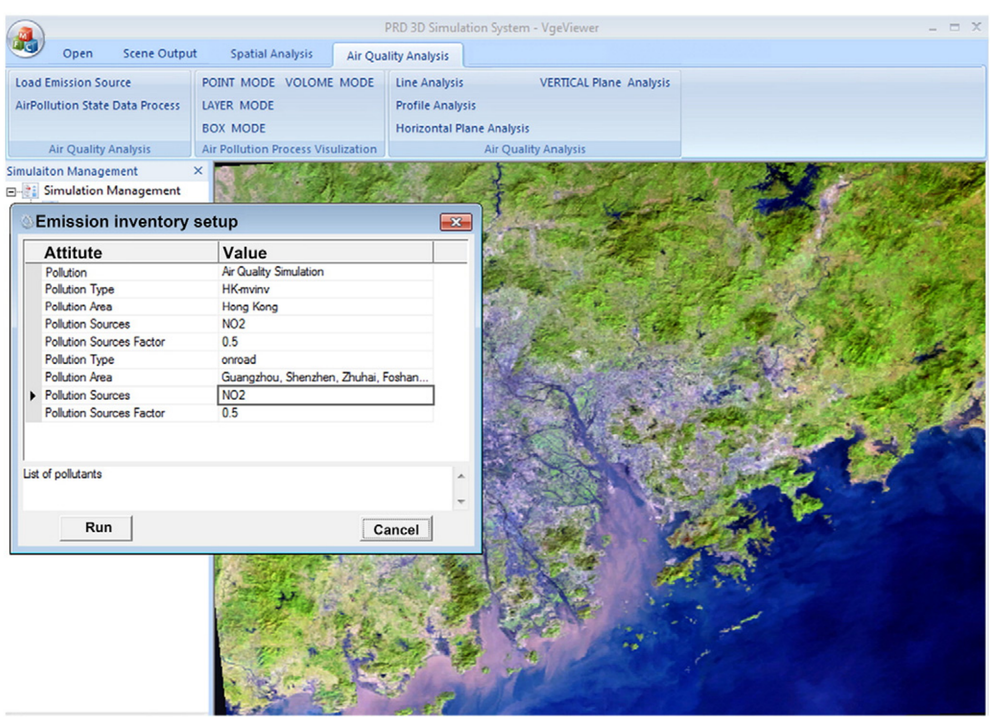

Fig. 6. Prototype of the system for decision-making.

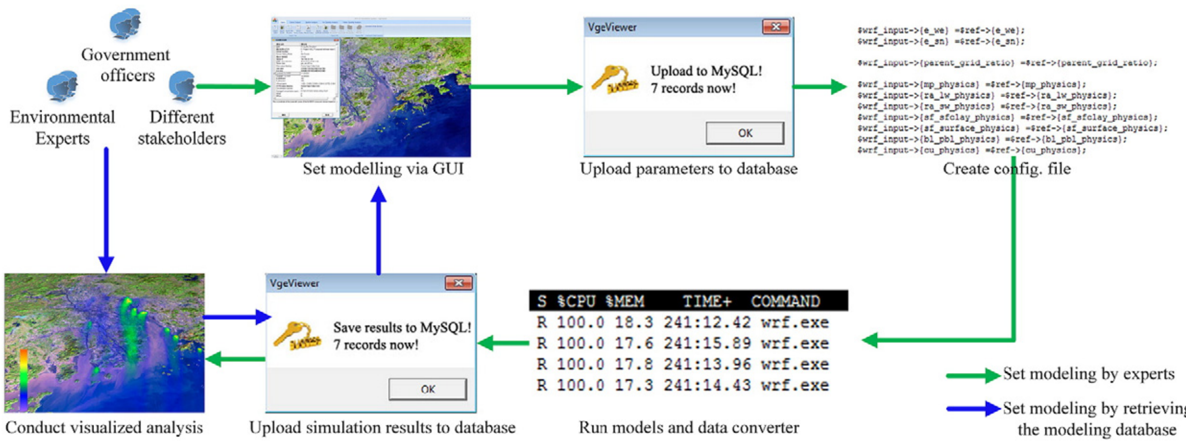

Fig. 7. Work flow using the decision-making system with model-base management.

visualisation. And then the participants were asked to simulate an air pollution event in 2010 concerning our emission inventory availability. After they applied the system, the questionnaire responses were collected. Selected key questions in our survey are listed in Table 3. Participants responded to these questions rating on a 10-point scale from "1 = Don't Agree" to "10 = Totally Agree".

2.6.3. Results of questionnaire

The survey results showed that 17 participants would first review the simulation scenarios conducted by experts and set their modelling parameters referring to those used in the scenarios, with scores larger than 6 for questions 3 and 4 in Table 3. The average score also support the conclusion that such model-base design is helpful for new users to learn from the experienced and professional modellers.

3. Application: investigation of a transport emission scenario

With regard to the recent severe roadside air quality problem, governments have taken many measures that have yielded some improvements (Environment Bureau et al., 2013). In HK, roadside concentrations of some of the major air pollutants were lower in 2011 than in 1999. However, roadside nitrogen dioxide (NO_2) increased by 23% during the same period. The rise in the roadside NO_2 level has recently resulted in an increase in the number of days with the roadside air pollution index (API) reaching the 'very high' level (API exceeding 100) (EPDHK, 2014b). In this context, because of the increasing trend in the roadside NO_2 concentration and the significant contribution of NO_2 from transportation, a policy to control vehicle emissions has attracted the attention of environmental officers (Environment Bureau et al., 2013; Wang et al., 2005). In January 2010, we applied the system that we developed to investigate the potential air quality and whether the NO_2 emissions were reduced by 50% from vehicles in HK and the PRD (Table 4). Such an emission-based simulation would be helpful for decision-makers to develop regional air pollution control strategies.

Table 3
Questionnaire response for critical questions.

Number	Critical questions	Averaged score
1	Are you clear about the instructions of this survey?	9.05
2	Do you think the user guide is useful?	9.55
3	Have you reviewed the model base for reference?	8.2
4	Do you set your modelling parameters referring to the model base?	7.8

3.1. Model setup and data

3.1.1. Model setup

The WRF model has a horizontal resolution of 3 km with 172 × 130 grids, 9 km with 223 × 163 grids and 27 km with 283 × 184 grids centred at 113.367°E, 24.716°N (Fig. 8). Its physical setting was determined by Jiang et al. (2012) and Ren and Xu (2011) on the basis of their successful application in the study area. For air quality, the simulation domain of CMAQ and SMOKE was set to 152 × 110 inside the third domain of WRF, with a resolution of 3 km and 18 vertical layers. The interface for the model setup is shown in Fig. 6, in which the parameters and the emission inventory for this case study have been defined and stored in the database for further application.

3.1.2. Data

1. Meteorology IC & BC data

The meteorological initial conditions and boundary conditions (IC and BC) for the model are from the National Centers for Environmental Prediction reanalysis data; the final analysis data (FNL) had a resolution of 1° × 1° every 6 h. The FNLs were produced with the same model as the Global Forecast System (GFS), but the FNLs were prepared approximately 1 h after the GFS was initialised. The FNLs were delayed so that more observational data could be used.

2. Air quality IC & BC data

The boundary condition was applied in CMAQ to account for a super-regional effect using the emission inventory from INTEX-B (Zhang et al., 2009), and the initial condition was prepared from averaged 10-day simulation results to minimise the effects of the spin-up.

3. Emission inventory

The emission inventory was processed by our system, and the vehicle emissions were adjusted using the basic emission inventory (Table 3). For example, for the emission at 9 am on 28th January 2010 (the highest level of NO_2 was observed in HK on that day), Fig. 9 shows a map of the

Table 4
Scenario design for policy assessment.

Emission category	Pollutant	Factor	City
HK-mvinv	NO_2	0.5	HK
Onroad	NO_2	0.5	Guangzhou, Shenzhen, Zhuhai, Foshan, Jiangmen, Zhaoqing, Huizhou, Dongguan, Zhongshan

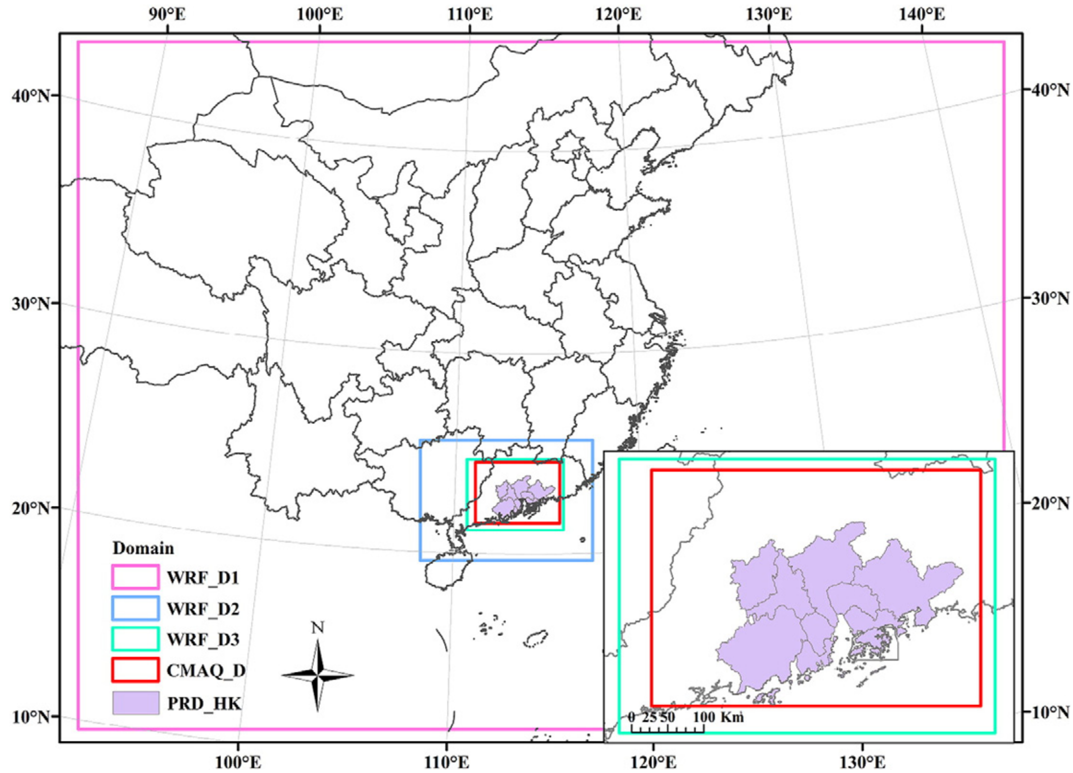

Fig. 8. Three nested domains in the WRF model with 27 km (pink line), 9 km (blue line) and 3 km (green line) resolution and the CMAQ domain (red line).

ratio between the emission inventory with and without emission control. The map demonstrates that the controlled emissions were clearly reduced. The total NO_2 emission during the simulation period was reduced on average by approximately 11% in the simulation domain. This percentage was generally consistent with the data reported by the environmental department and previous publications, which indicated that vehicles were a major NO_X emission source, accounting for 27%, 34.2% and 36% of the total emission in 2012 for HK and in 2001 and 2006 for the PRD, respectively (EPDHK, 2014a; Xuemei Wang et al., 2005; Zheng et al., 2009b).

3.2. Visual analysis

3.2.1. System validation

The modelling performance of the system was assessed before the analysis of the simulation results. Because the emission inventory without any reduction was expected to reflect the actual situation, we validated the simulation results from CMAQ against the observations. Statistical validation and a time series comparison indicated that the modelling system captured the background concentration and trends very well. Thus, it is feasible to apply our system and the emission

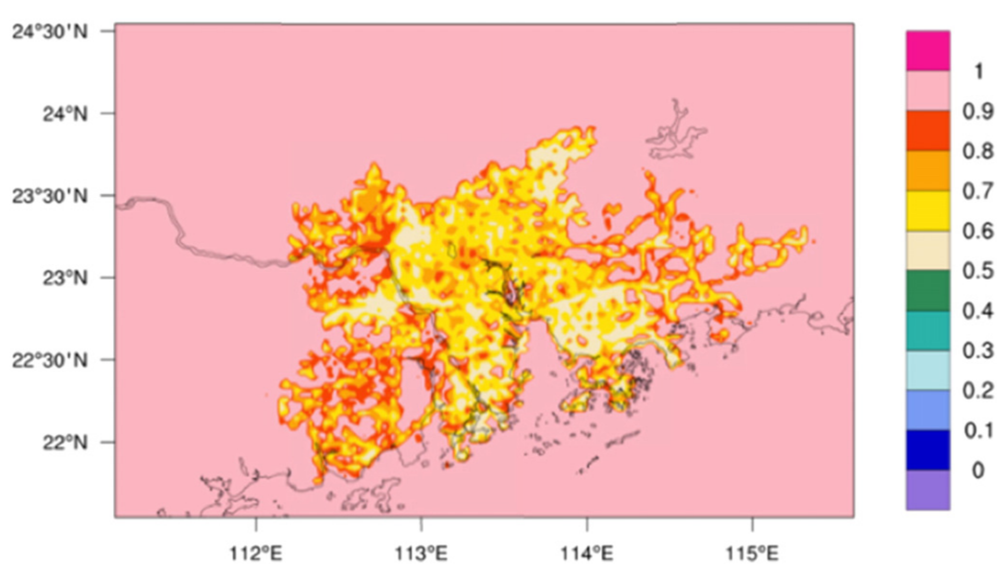

Fig. 9. Map of the ratio between the emission inventories with and without the reduction of NO_2 from vehicles in HK and the PRD at 9 am on 28th January 2010.

inventory to conduct air quality estimation. Our previous publications discuss the validation in detail (Zhang, 2014; Zhang, Chen, Li, Ding, & Lin, 2015; Zhang et al., 2014a).

3.2.2. Visualisation of simulation results

Using the two emission inventories with and without emission control, the air pollutant concentration was estimated in our system by running CMAQ in the integrated modelling system. After simulation, the system provides multi-dimensional visualisation for users to recognise the 3D dynamic processes. With NO_2 as an example, the NO_2 box for concentration expression is initialised and updated according to the time step to represent the dynamic process. The zoom in/out and drag functions enhance the human–computer interaction to provide a better understanding of the air quality process being investigated. The left side of Fig. 10 shows the dynamic air pollution dispersion process at different times with vertical sections and profiles. To improve the geographic analysis, additional geographic data can be loaded for further analysis, including boundary data and data for roads and other factors. In the simulation management pane (the right side of Fig. 10), the user can load cases with various scenarios concerning different pollutants, emission inventories and so on to compare the simulated results and improve the understanding of the air quality problem. Such multiple visualisation methods (Zhang et al., 2015) provide a tree structure of simulation management that is quite helpful for a user who is not an expert in air quality.

3.2.3. Results analysis

The modelling results demonstrate that for the simulation of NO_2 levels with emission control, the spatially averaged mean value was reduced only by approximately 5% in the simulation domain. A NO_2 reduction of approximately 1%; $PM_{2.5}$, SO_2 and CO reductions of less than 1%; and a slight increase of O_3 were also observed. These results were in conflict with our expectation that a noticeable decrease in air pollutant concentration should result from emission control. However, these results are supported by previous publications. In a study from January 2004, a comparison of simulated results based on basic emissions and no PRD emissions showed that without PRD emissions, the simulated NO_X was reduced by only approximately 50%, with a slight reduction of $PM_{2.5}$, SO_2 and so on, as shown in Figs. 15 and 16 in Kwok et al. (2010). With respect to the contribution of vehicles to NO_X (approximately 30% of the total NO_X emission) and 50% emission control, the limited NO_2 reduction in the simulated results agrees well with the previous study. This sensitivity study showed limited air quality improvement and revealed that tight emission control in both HK and PRD is only expected to have a limited effect on the air quality on a regional scale and that pollution sources beyond the PRD also contribute to air pollutant levels in both the PRD and HK, particularly during the winter (Kwok et al., 2010). This super-regional (beyond the PRD) effect has been increasingly acknowledged as an important factor affecting air quality because the monsoon system sometimes brings in pollutants from northern and eastern China (Wang et al., 2009a; Zhong et al., 2013), and air masses from long-range transport make a large contribution (approximately 80% for PM_{10} sulphate) to the air quality in HK (Guo et al., 2006; Nie et al., 2013; Wang et al., 2009a). Thus, traditional regional co-operation (including HK and PRD only) must be extended to super-regional co-operation in air quality management.

Concerning the ozone increase despite the reduced emission of NO_2 shown in this case study, Sillman et al. (1990) confirmed that a reduction in NO_X emissions often increases the ozone level, particularly when only the NO_X emissions are removed from certain regions of the computational domains, as shown by this study (Fig. 8). In this context, the chemical interaction of different air species should be considered when designing emission control policies.

Regarding inter-governmental co-operation and the interaction of multiple air pollutants, this case study informs government officials that regional and even super-regional co-operation for air quality problems addressing comprehensive emission control is more important and effective than rigid emission control on a local scale or for a single pollutant.

4. Conclusions and future work

From the research in model-based management, an integrated air quality modelling system that addresses regional and complex characteristics has been developed for decision-makers to use to help alleviate the air quality problems in HK and the PRD. Such a Cyberinfrastructure system has two major advantages. It provides a database design for the management of data and model parameters. The LAMP architecture of

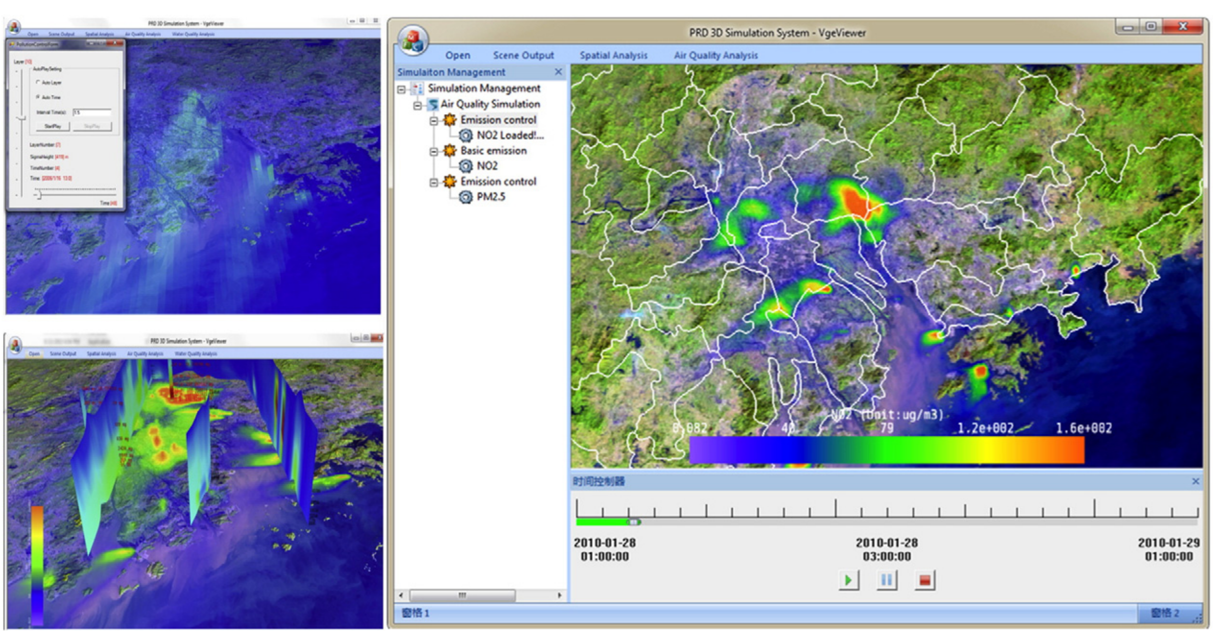

Fig. 10. Visualisation of air quality process with a tree structure of simulation management.

the database for model management allows different users the ability to retrieve the database to check the data, model settings and so on to achieve a consensus on the simulation results. Various government agencies can use this feature to reproduce simulation scenarios and arrive at a consensus concerning the air quality situation and then consolidate different standards to mitigate an air quality problem. For another, with respect to the important effect of the emission inventory on air quality modelling for decision-making, the system provides a reliable and comprehensive emission inventory that can be conveniently adjusted to create various emission scenarios for assessing the expected results from trial policies. The system has a user-friendly GUI and a set of visual analysis methods that aid the user in applying the system and understanding the air quality process. Finally, as a demonstration, the system was applied to assess the results when the NO_2 emissions from vehicles were reduced by 50% in HK and the PRD in January 2010. The simulation revealed that the improvement from the emission control was very limited and suggested that regional and super-regional co-operation with a comprehensive emission control of multiple pollutants may be a more effective way to achieve better results in the future.

Given the innovative modelling system and the results of the case study, certain limitations remain that will be considered in future research. The system is still under development as a professional platform for application. In the next stage, data assimilation with observations from the Cyberinfrastructure will be supported in modelling because HK and the PRD have a complex earth surface and coastline, which may pose challenges to numerical modelling and may require improvement from observation (Yim, Fung, Lau, & Kot, 2007). To support intergovernmental co-operation, collaborative simulations by interdisciplinary and geographically separated users will be considered in the next version of the modelling system (Zhang et al., 2016). Furthermore, we will conduct a more comprehensive study with emission adjustment for multiple pollutants and emission sources, a longer simulation period and station-based validation to provide more general knowledge for decision-makers.

Acknowledgements

We are grateful to Prof. Junyu Zheng and Dr. Zhijiong Huang for their help in processing the emission inventory data. The paper was supported by the National Natural Science Foundation of China (No. 41601432), the National Public Benefit (Land) Research Foundation of China (No. 201511010), China Postdoctoral Science Foundation (No. 2016M590117), the Fundamental Research Funds for the Central Universities (No. 2652015339) and the Key Laboratory of Spatial Data Mining & Information Sharing of Ministry of Education, Fuzhou University (No. 2017LSDMIS06).

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