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Development and case study of a science-based software platform to support policy making on air quality

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ABSTRACT

This article describes the development and implementations of a novel software platform that supports real-time, science-based policy making on air quality through a user-friendly interface. The software, RSM-VAT, uses a response surface modeling (RSM) methodology and serves as a visualization and analysis tool (VAT) for three-dimensional air quality data obtained by atmospheric models. The software features a number of powerful and intuitive data visualization functions for illustrating the complex nonlinear relationship between emission reductions and air quality benefits. The case study of contiguous U.S. demonstrates that the enhanced RSM-VAT is capable of reproducing the air quality model results with Normalized Mean Bias <2% and assisting in air quality policy making in near real time.

Introduction

Continued economic development has led to air quality degradation in urban areas throughout the world. Air pollution is a result of complex interactions among air pollutant emissions, meteorological conditions and a wide variety of atmospheric processes including transport, chemical transformation and deposition. To improve air quality without impairing economic development, strategies of air pollutant emission control must be carefully formulated by assessing the fate of air pollutant emissions in the atmosphere. Typically, such assessments are achieved by air quality modeling using science-based atmospheric models, such as the Community Multi-scale Air Quality (CMAQ) model (Byun and Schere, 2006; Wang et al.,

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2014a, 2014b), for multiple emission scenarios. However, the high computational cost associated with the modeling effort often becomes the bottleneck of the assessment process. In addition, most atmospheric models used in air quality management lack a user-friendly interface that can synthesize the model results produced from different air pollutant emission inputs, and do not offer adequate data visualization for supporting policy making.

To improve the efficiency of data synthesis in air quality management, it is necessary to develop a tool to translate the massive amount of model data to policy-relevant visualization. Ideally, such policy decision support tools should be efficient, easy-to-use, and capable of estimating air quality changes for given emission reduction scenarios. In addition, the tools should offer intuitive policy-related visualizations. Some earlier prototypes, such as: the IMPAQT — Integrated Modular Program for Air Quality Tools (Lim et al., 2005) and the GIS-CALPUFF coupled air quality decision support system (Fraser et al., 2013), have demonstrated the benefits of a decision support tool for urban air quality assessment with limited visualization features. To our knowledge, there has not been a comprehensive package that has been demonstrated to support air quality management at both urban and regional scales. Since many air quality problems are of regional scale (Wang et al., 2014a, 2014b), for example regional haze and trans-boundary transport, an efficient and powerful tool for supporting decision making in regional air quality is in great need.

To address this need, we rewrote the code of the response surface model (RSM) (Lao et al., 2012) with C# using the high-dimensional Kriging techniques (Mohammadi et al., 2012; Xiao et al., 2009) to interpolate the model results of CMAQ for policy making support. The RSM serves as a statistical metamodeling interface for rapid assessment of the massive data of atmospheric model results (Ashok et al., 2013). Following the data assessment, it is essential to couple the model results in a graphical user interface such as USEPA's Visual Policy Analyzer (VPA), which allows using slider bars and a mouse to change emission factors for visualizing the air quality response (U.S.EPA, 2006). However, VPA has incurred user-friendliness and data accuracy issues. At this moment, the development and support of VPA have been discontinued.

In this work, an enhanced response surface model-visualization and analysis tool (RSM-VAT) is developed for better understanding and analyzing the established statistical relationship (RSM) between air pollution emission reductions and air pollutant concentrations. The statistically generalized RSM surface by the method of MPerK (MATLAB Parametric Empirical Kriging) reported in our previous work has demonstrated that the nonlinear relationship between emission sources and air quality concentration of $PM_{2.5}$ (Wang et al., 2011) or O_3 (Xing et al., 2011) can be well analyzed by RSM. The established nonlinear relationship is not only a foundation of decision making, but also critical for formulating emission control strategies. The development of enhanced RSM-VAT is the extension of our previous work, it aims to provide a series advanced visualization and analysis functions for validating RSM prediction results and for examining the nonlinear interactions among multiple air pollutant precursors, in addition to instantly generate the air pollutant concentration surface response to air pollutant emission changes.

1. Methodology

Fig. 1 shows the block diagram of the development and application of the RSM-VAT. The modules of control matrix, RSM, and quality assurance (QA) are designed to guide the users through the RSM development and accuracy validation. Most end users (policy makers) would directly use the RSM data analysis module for policy decisions. It greatly improves the user interface and visualization accuracy of VPA for the RSM results. The design of control matrix, response surface modeling, quality assurance, and RSM data analysis are described here.

1.1. *Design of emission control matrix*

RSM aggregates the results of pre-specified CMAQ simulations into a multi-dimensional "response surface" that also incorporates the acceptable uncertainties in environmental decision-making. This allows a rapid assessment of air quality impacts caused by different combinations of emission sources. These sources are selected as emission control factors as shown in Table 1. The CMAQ simulations are performed at a defined set of distributed emission inventories (control scenarios) in a high-dimensional experimental design space. For example, as one of the source targets subject to emission control, Electricity Generating Units (EGUs) NO_x emission is set at 0–120% of the base-year level. The response surface of the CMAQ results attempts to maintain the model accuracy while minimizing the computationally expensive CMAQ run at a given emission scenario within the experimental design space. The RSM method uses statistical techniques to relate a response variable (*e.g.*, the annual $PM_{2.5}$ at multiple U.S. receptor sites) to its influencing factors (*e.g.*, the emission of a pollutant precursor, NO_x) from local and regional emission sources.

The control matrix module (Fig. 1) is to create the experiment design of emission control matrix. The matrix is created by sampling the control factors in the design space (*e.g.*, from 0.00 to 1.20) using Latin Hypercube Sampling — LHS (Hirabayashi et al., 2011). LHS is often applied to generate the experimental design for a Kriging model (Kleijnen, 2009). It is a statistical method for generating a sample of plausible collections of parameter values from a multidimensional distribution which is more efficient than random sampling for a large number of factors. Table 2 shows an example of emission control matrix created by LHS. The base-year emission inventory is factored by the weight shown in the matrix (Table 2), forming 181 emission control scenarios for CMAQ model runs. These emission inventory factors, together with the identical meteorology and other model input, are applied in CMAQ simulations to provide the annual $PM_{2.5}$ concentration estimates for the 181 emission control scenarios. In order to reduce computational time for such a large number of annual model runs, the results of 4-monthly (February, April, July, and October 2001) CMAQ runs over the contiguous US are utilized in the response surface modeling. These months were chosen based on greatest predictability of the quarterly mean in US. The emission projections for three future years (2010, 2015 and 2020) together with 2001 meteorology data (U.S.EPA, 2005) are used in the CMAQ runs (U.S.EPA, 2006).