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Development of a Rapid Assessment Tool for Evaluating the Effectiveness of Emission Control Policies on Ozone Reduction

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***Abstract*:** *The emission control approach has been traditionally used to mitigate air pollution in atmospheric science and environmental management. The effectiveness of each emission policy especially those for reducing secondary pollutants such as ozone (O3) has not been fully understood, and thus a clear reference has yet to be provided for future policy formulation. An emission-concentration approach should be therefore used to assess the effectiveness of different emission control scenarios for formulating the most appropriate emission policies, especially when the evaluation of a wide range of policy scenarios is necessary. This study aimed to develop a rapid assessment tool based on an adjoint approach, which computed O3 sensitivities to a unit of emission perturbation. The Pearl River Delta (PRD) region of China was taken as an example due to its substantial emission strength. This paper introduced the development of the rapid assessment tool, and its potential applications in emission control policy evaluations. We also analyzed the annual O3 sensitivity to nitrogen oxides emissions in the PRD region.*

Keywords: *adjoint sensitivity; air quality; climate change; emissions*

1. Introduction

Surface ozone (O_3) pollution is one of the most serious air pollution problems in urban areas. Previous studies reported that ozone exposure can result in a number of health effects including the induction of respiratory and cardiovascular symptoms [1]–[2]. It is important to reduce ozone concentrations to safeguard public health in urban areas.

In policy formulation, an emission control approach has been traditionally used to mitigate urban air pollution problems. For example, the Pearl River Delta (PRD) region implemented a number of emission control policies in the past decade to improve its regional air quality, such as retrofitting existing coal-fired power generation units with emission reduction devices. As opposed to primary pollutants, O_3 is a secondary pollutant formed through photochemical reactions from precursor gases including nitrogen oxides (NO_x − NO + NO_2) and hydrocarbons. The relationships between the emissions of precursor gases and the final concentration of O_3 are highly nonlinear and also depend significantly on other factors such as weather conditions. The emission control approach may not capture the expected effectiveness of each emission control policy. To complicate the issue more, the likelihood of acute emission reductions are strongly sensitive to other factors such as the level of policy enforcement and implementation. An emission-concentration approach should instead be used to assess emission control scenarios.

To understand the effectiveness of an emission policy, the resultant long-term changes in pollutant concentration should be investigated, as suggested by Chong et al. [3] who examined the annual changes in ozone due to different bus technologies. For formulating emission policies, a range of scenarios always need to be assessed. Runtime consideration is particularly acute when modeling long-term mean concentration levels for all possible scenarios. Previous study [4] applied a forward emission-concentration approach to estimate the annual $PM_{2.5}$ concentration due to different aviation emission scenarios and reported that the expensive computational time of an annual simulation for each scenario. Moreover, the emission uncertainties should be quantified when assessing the effectiveness of an emission policy, but this could cause an exponential increase of computational time.

Previous studies have found that changes in meteorological conditions may heavily affect O_3 concentrations [5]–[9]. It is thus critical to understand the influence of meteorological conditions on O_3 formation, which typically requires simulations for at least several years to capture the inter-annual climate variability. This would further increase the computational time for policy analysis.

Due to the expensive computational requirement, it is not practical to assess all the potential policy scenarios. In the U.S., the Federal Aviation Administration (FAA) developed a rapid assessment tool to rapidly evaluate different aviation emission policy scenarios [10]–[11]. The tool was highly useful to reduce the environmental impacts of aviation with respect to air quality, climate change and noises due to aircraft engines. Therefore, to develop effective emission control policies for mitigating ozone pollution, an assessment tool should analogously be developed for HK and PRD. The rapid assessment tool is anticipated to provide a useful tool for policy makers to assess the effectiveness of a wide range of policy scenarios for improving ozone air quality in a reasonable time frame.

2. Method

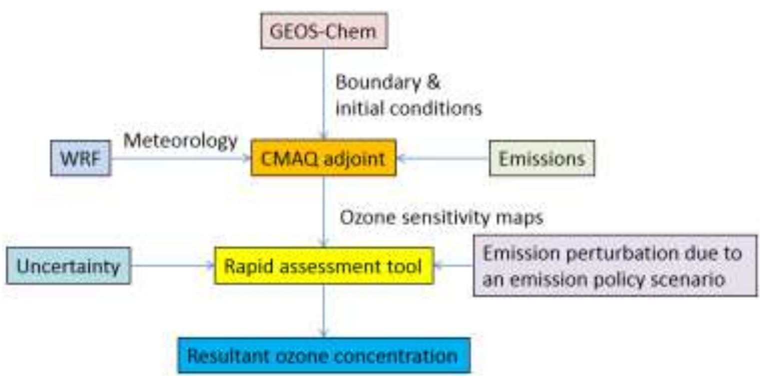

Fig. 1 Schematic diagram of our model framework. WRF refers to Weather Research and Forecast, while CMAQ refers to the Community Multiscale Air Quality Modeling System.

2.1. Meteorological Modeling

We applied the Weather Research and Forecasting Model (WRF) (Version 3.7) to simulate the meteorology in the PRD region. The model was configured to have three nested domains with a spatial resolution of 27 km, 9 km and 3 km. The model domains are shown in Fig. 1. The meteorological data at six-hour intervals provided by the National Centers for Environmental Prediction/Final (NCEP/FNL) were used to provide initial and boundary conditions.

2.2. Air Quality Modeling

We applied the Community Multi-scale Air Quality modelling system in version 4.7.1 [15] to simulate the air quality in China and downscale to southern China and the PRD region. The boundary conditions were provided by the GEOS-Chem model. Chemical speciation and reaction regulation were defined by the updated Carbon Bound mechanism (CB05).

2.3. Adjoint Sensitivity Modeling

Based on the CMAQ adjoint model v4.5.1 (CMAQ_ADJ_V4.5.1), we implemented the gas phase process of adjoint sensitivity calculation in the CMAQ v4.7.1 [16]. We note that the calculated adjoint sensitivity provides sensitivity of O_3 in a defined receptor area to changes in emissions of each grid in the model domain. This study used the revised model to calculate the sensitivity of O_3 in Hong Kong (HK – as a defined impact region) to NO_x emissions in the PRD region. Positive O_3 sensitivity at one grid indicates an increase (decrease) in O_3 in HK when NO_x emission is increased (reduced) at the grid.

3. Results

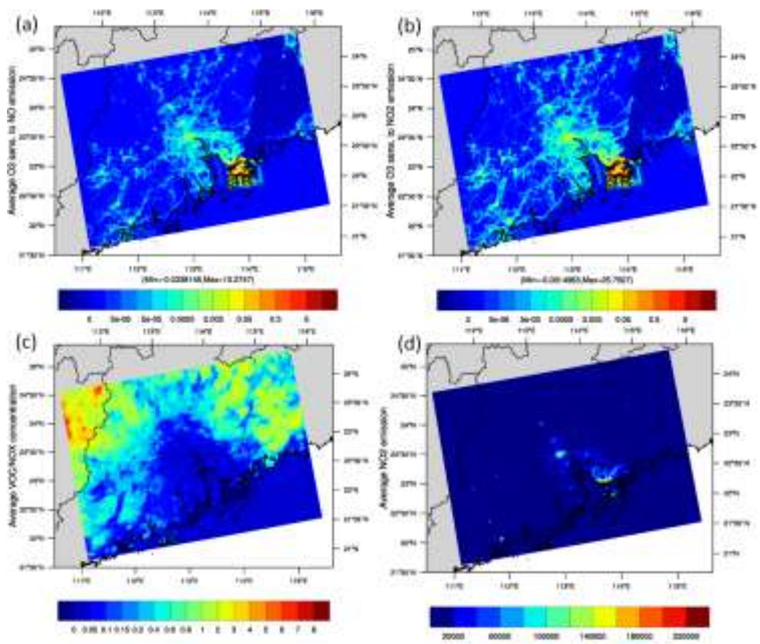

Fig. 2 (a) O_3 sensitivity to (a) NO and (b) NO_2 emissions (μg/m^3), (c) VOC-NO_x concentration ratio, and (d) NO_2 emissions (μg/m^3).

Fig. 2 (a) and (b) depict the annual sensitivity of O_3 to emissions of NO and NO_2, respectively. Our results show that the PRD NO_x (NO + NO_2) emissions lead to increases in annual O_3 in HK in general. It is expected that the O_3 in HK is more sensitive to local emissions, showing larger sensitivity results (>0.5 μg/m^3). The O_3 sensitivity is relatively less sensitive to NO_x emissions in other cities in the PRD region compared to HK.

The annual O_3 sensitivity varies with VOC-NO_x ratio. Urban areas (with low VOC/NO_x ratio values as shown in Fig 2. (c) are typically VOC-limited regions. They show a positive ozone sensitivity with respect to NO_x emissions. This result indicated that reducing NO_x emissions at such areas may reduce annual O_3 in HK. We note that there are two pathways that could influence O_3 in HK from an emission grid. The primary possible pathway is that O_3 may form outside of HK and be then transported to HK; The second possible pathway is through transport of precursors, i.e. NO_x, to HK that may then react with other species to influence O_3 in HK. The positive O_3 sensitivity in the PRD region and even HK may go through the first pathway. The PRD cities have substantial emissions including NO_x and Volatile Organic Compounds. The emitted NO_x may immediately react with other species to form O_3 locally that may directly influence O_3 in HK.

Our results also show that the O_3 sensitivity to NO_x emission are negative in remote areas at northeastern Guangdong province. It suggests that emitted NO_x emissions from such areas would reduce annual O_3 in HK. The negative O_3 sensitivity occurs in winter and is most likely through the second pathway. While the prevailing wind in winter is due northeast, the emissions in the remote areas is relatively low such that the emitted NO_x can be transported to HK directly. The marginal NO_x may titrate O_3 in HK which is a VOC-limited area.

4. Conclusion

This paper introduced the development of a model framework that allows a rapid assessment of evaluating effectiveness of emission control policies to mitigate air pollution. The results of annual O_3 sensitivity in HK to emissions in the PRD region were discussed. Future analyses will be conducted to understand the annual O_3 sensitivity in PRD region to emissions in present and future years.

5. Acknowledgment

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