The Challenges of Modelling Air Quality in Hong Kong

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Abstract

Only a numerical air pollution modelling system can link together all the processes involved in determining air quality coherently to provide a science-based picture. The PATH (Pollutants in the Atmosphere and their Transport over Hongkong) modelling system was set up in the year 2000 and has since provided useful information on the various aspects of air pollution in and around Hong Kong. The system has also been enhanced to make short-term forecast of air quality. Further upgrade of the system to meet new challenges is continuing.

1. The Basics of Air Pollution – Processes to Simulate

Air pollution can be described as a “source to receptor” relationship. Between the emission sources and what is experienced at the receptors are the transport, transformation and removal of the pollutants.

The emissions contributing to Hong Kong’s air pollution come from many sources: power plants, cars, ships, cooking, solvent and chemical usage in industrial and domestic activities as well as nature – vegetation … etc. Ad hoc emissions like fireworks, hill fires and lightnings also impact air quality. All these sources are distributed widely in different areas and the pollutants are released at different heights. When these chemicals mix in the air, chemical reactions take place and transformation occur. These reactions can either be helped or inhibited by the weather. For example, ozone in and around the city is formed through the chemical reactions between nitrogen oxides (main from cars and power stations) and volatile organic compounds (VOCs – a class of many compounds released by solvent use, incomplete combustion as well as vegetation) in the presence of sunlight in moderately high temperature (~20^{o}C or above). In these transformations, new pollutants, e.g. ozone, can be formed from precursors that in themselves are not considered pollutants like VOCs from plants. Simultaneously, all these chemicals are transported by the wind. The weather in Hong Kong is complicated by the many scales of interactions: the monsoonal flow resulting from seasonal differential heating of the large Asia landmass, the local non-uniform distribution of land and water surfaces leading to land and sea breezes, local hilly topography and varied landuse types which significantly modify the winds … etc. At the same time, some of the pollutants are removed by various processes – chemical reactions, precipitation in form of rain or snow, absorption by vegetation, deposition to sticky surfaces …etc. What is left is experienced by the ecosystem, including humans.

Attempts have been made to quantify the various processes in air pollution’s source-receptor relationship. Comprehensive emission inventories covering most chemical species and their distributions in space and time have been attempted. Meteorological parameters – wind, sunshine, relative humidity, temperature … etc. – have been extensive measured. Chemical transformations and the removal processes have been studied individually and in combination in various laboratories and field experiments around the world. A number of air quality monitoring stations have been routinely taking measurements of a number of pollutants in and around Hong Kong. Yet none of the above alone, or even in combination, is up to the task of answering the basic policy questions: which emission sources are contributing to which receptor and by how much, and how would the air pollution pattern respond to a change in the emission pattern? The intricacy of these problems can be illustrated by the well-researched and well-documented fact that reducing a precursor of ozone, e.g. nitrogen oxides, can frequently lead to higher ozone formation because of the non-linear chemistry that interacts with other parameters on different scales.

By representing all the above processes and their interactions as linked equations on a digital computer, a numerical model is the only tool that can give science-based answers to the above questions. It also avoids the need to involve the whole society in a very costly and potentially destructive experiment. It is because of this ability to look into the future as well as accounting for factors far and wide (winds and emissions from tens to thousands of kilometers away) that numerical air pollution models are used around the world to inform policy makers. Positioning itself to meet the air pollution challenges in the region, the Environmental Protection Department set up a modelling system called Pollutants in the Atmosphere and their Transport over Hongkong (PATH) in 2000 through a consulting contract (ERM 2000) to study regional air quality issues.

2. The Modelling System

PATH comprises three main modules (Figure 1): an emission model (EMS-95; Emigh and Wilkinson J.G. 1995); a prognostic meteorological model (MM5; Grell et al. 1994) and an Eulerian transport and chemistry model (SAQM; Chang et al. 1997). These modules are interfaced together and set up on a series of nested domains to account for influences outside HK. The grid spacings of successive domains are 40.5, 13.5, 4.5, 1.5 and 0.5 km. Each domain of the air quality module has 49 x 49 grid cells while the domains of the meteorological and emission modules are identical and cover a larger area. The outermost domain stretches from the Himalayas (west), to central China (north) to the mid-western Pacific (east) and to the Philippines (south) to account for flow development and emissions from outside HK (Figure 2). The domains zoom into Hong Kong with the 1.5km resolution domain covering all of HK. The system currently uses 15 to 25 unevenly spaced layers (thinner closer to ground) in the vertical to represent the relevant parameters up to some 25km above ground. About 30 chemical species (some representing groups of compounds) are represented in about a hundred chemical reactions. Emission, meteorological and air quality data have been collected for validating the performance of the system.

3. Various Applications of PATH – Real Time Simulations

When the development of PATH was started, limited computer power and experience have only allowed it to simulate a number of pre-selected air pollution scenarios to represent typical air pollution situations in HK. But the pollution pattern never repeats exactly and a system providing real-time air quality simulation would help advance the science. By seeking cooperation with the Hong Kong Observatory for real-time access to meteorological data and bring in the most recent advances in computer technology (grid computing, computer clusters …etc.) we developed PATH further into a real-time air pollution simulation system (Rt. PATH) making hourly projections of air pollution for the next 48 hours. These daily forecasts are invaluable to understanding Hong Kong's air pollution in a more comprehensive manner.

Though air pollution is most acutely and directly felt where it is emitted, our awareness of inter-regional transport is growing with the deterioration of air quality in Hong Kong. The Pearl River Delta (PRD) is now understood to be a major source of HK's air pollution under certain meteorological conditions. However, little has been said about air pollution beyond the PRD. Here PATH, given its wide spatial coverage, can put things in better perspective. Figure 3 illustrates the complex interactions of the physical and chemical processes on different scales. The wind at the largest scale (upper left) is seen carrying pollutants from the Yangtze River Delta down along the eastern coast of China, passing the Taiwan Strait to the south of Hong Kong and producing significant ozone values over the

South China Sea. The same pattern amplified over HK (upper right and lower left) shows that the ozone values over HK and the PRD are depressed with respect to the values in the South China Sea because local emissions of nitrogen oxides have destroyed the ozone from the sea through chemical reactions. When there is no such depletion, the ozone concentration to PRD's east, being forced onto land by the wind, is significantly higher. The highest resolution pattern (lower right hand) shows that the local wind direction to the west of HK has reversed direction due to the effect of the sea breeze. The pollutant in question, ozone, has been suppressed over a streak starting at Victoria Harbour and following the wind to the north. This type of interactions, between physical factors (wind, sunlight … etc.) and chemical factors (creation and destruction of ozone), to produce a dynamic pattern with many fine structures is very common and cannot be ignored since our receptors experience air pollution on that scale.

How well PATH is performing is illustrated in Figure 4 which gives a comparison of model output with averaged measurements from monitoring stations for the year 2004. All of the emitted species show under-prediction, suggesting that the emission input has been under-represented in general. Ozone itself is not an emitted species and it show over prediction at the lower concentration end of the distribution. This diagnosis, coupled with other detailed statistical analyses of the meteorological conditions, can be a very powerful tool in backward engineering the component of greatest uncertainty in our air pollution problem – emissions. Starting with species that are least affected by chemical conversion, hence most likely to indicate a direct link between emissions and concentrations, one asks how the emissions can be changed (magnitude, location, sector …etc.) to produce better agreement between model and measurements. Modelling experiments are then performed to answer these questions. After prioritizing the findings, one can then try to improve the emission representation.

4. A Look to the Future

The above illustrates the powerful dynamic between the three basic components of air pollution science – emission inventorying, monitoring and modelling. Based on monitoring data, the model feeds back to the emission estimates leading to improvements in our understanding and representation of our pollution problems. This dynamic is particularly important to our rapidly changing region as emissions – both the pattern and magnitude – change very rapidly without giving emission researchers time to get an accurate snapshot of the situation. But a model, though still subject to uncertainties, can give the best informed direction for improvements to other components. This interaction between the three components will be pursued further to benefit air quality science in the region.

The science of air pollution is also changing emphasis and new models are being developed to simulate processes like particulates in the air which is a far more complex phenomenon than the interactions among gaseous pollutants. This is receiving more detailed treatment in newer models. The government has approved funding to upgrade PATH to incorporate the best available science and technology into the system to improve our diagnostic capability in service of the community.

References

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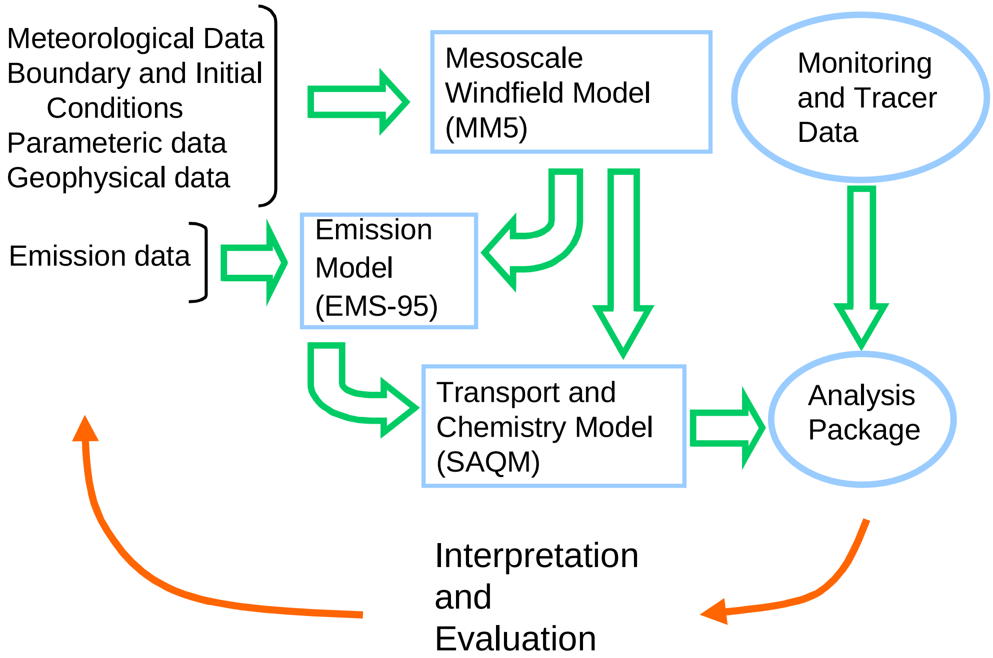

Figure 1. Schematic representation of PATH

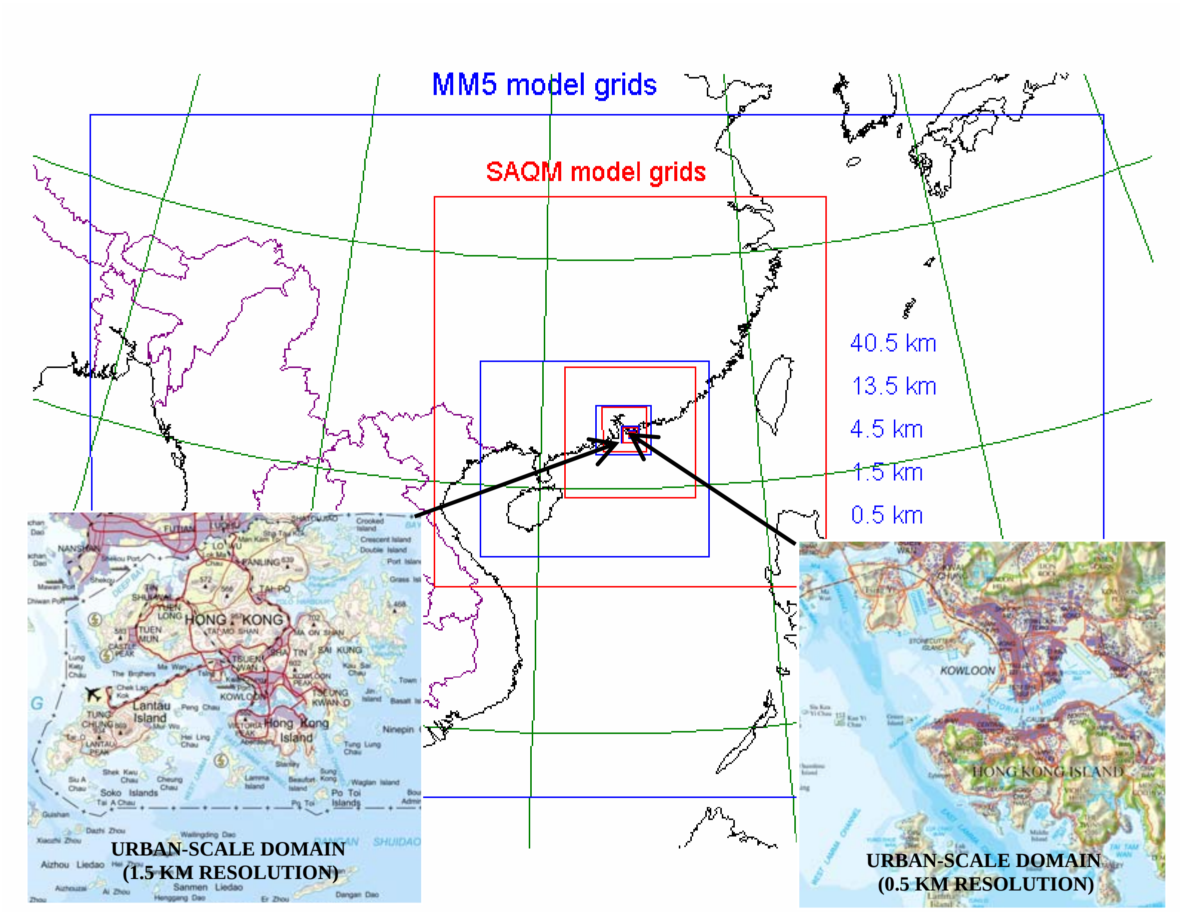

Figure 2. The domains of the PATH modelling system

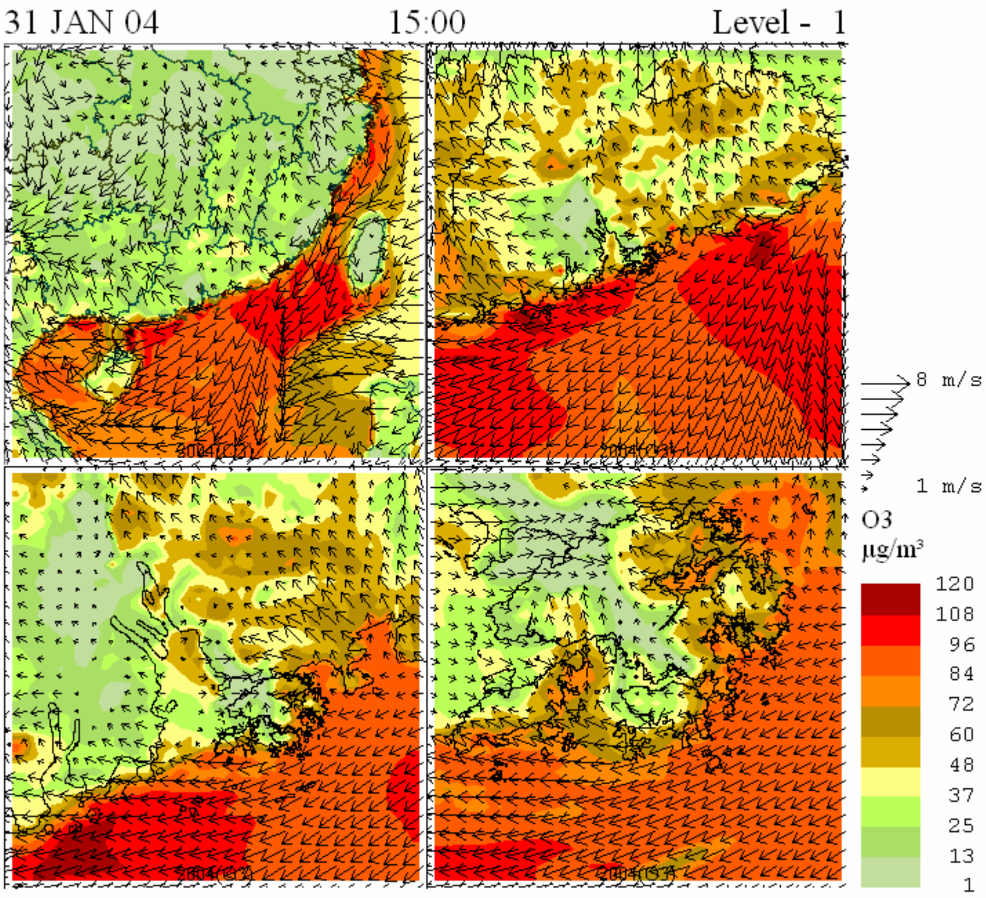

Figure 3. An illustration of PATH's predictions on different scales for ground level ozone concentrations (horizontal grid resolutions are 40.5, 13.5, 4.5 and 1.5km for the upper left, upper right, lower left and lower right panels, respectively)

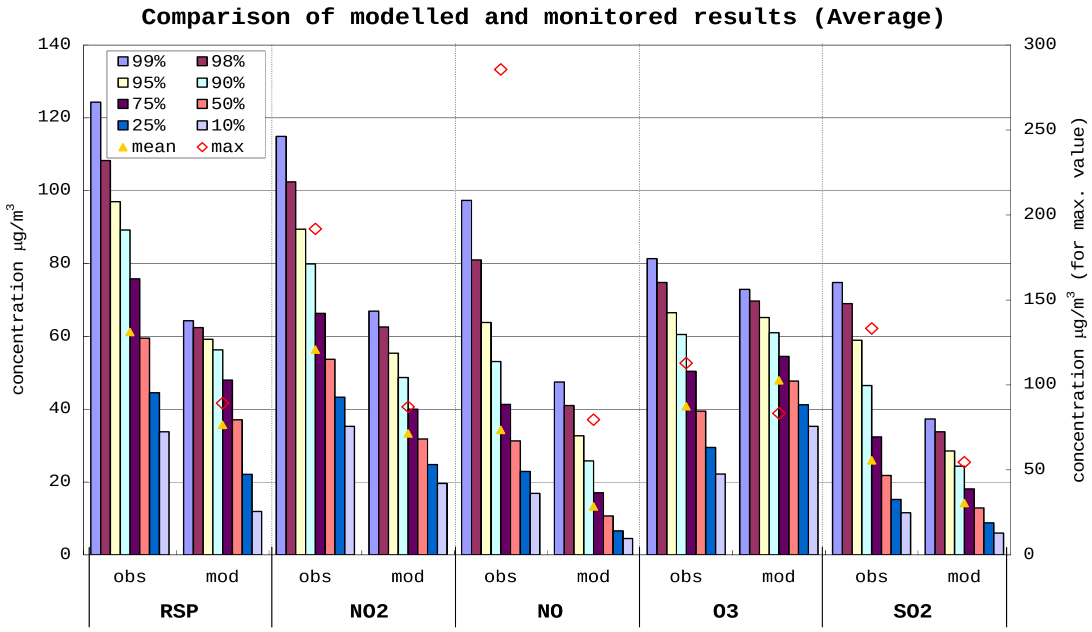

Figure 4. Comparison of model predictions against measurements for different pollutants. Data for the year 2004 are averaged over all the monitoring stations of Hong Kong. Data for the model are extracted from the grid cell in the model domain containing the monitoring station and averaged accordingly.