DEVELOPMENT AND APPLICATION OF A NUMERICAL AIR QUALITY FORECASTING SYSTEM

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Summary

In this paper we describe a project to develop a numerical air quality forecasting system for application in major airsheds throughout Australia. Named the Australian Air Quality Forecasting System (AAQFS), the project is a collaborative undertaking between CSIRO Atmospheric Research, CSIRO Energy Technology, the Bureau of Meteorology, the Environment Protection Authority of Victoria, and NSW Environment Protection Authority. Following a two-year period of development and testing in Victoria and NSW, the AAQFS will be used to generate twice daily, 24-36 hour forecasts of air quality at a resolution of a few kilometres. A range of air pollutants will be considered including photochemical smog, fine particulate matter, oxides of nitrogen, air toxics, sulfur dioxide and volatile organic compounds. Output from the AAQFS will be made available to state environment authorities.

Keywords: Air pollution, forecasting, numerical modelling, urban air quality modelling, regional modelling, mesoscale, meteorological.

1. INTRODUCTION

In this paper, we describe a project to develop and implement a numerical air quality forecasting system suitable for operation in the major Australian airsheds. Known as the Australian Air Quality Forecasting System (AAQFS), the project was initiated following recent advances in high-resolution numerical mesoscale weather forecasting at the Bureau of Meteorology (BoM), and the commissioning of a new CSIRO/BoM super computer. In combination, these two events have made it practical for an operational numerical forecasting system to accurately simulate air pollution transformations within an urban area.

1.1 Background

The requirement for air quality forecasting follows from the recognition that poor air quality can potentially have a deleterious impact on sensitive members of our population (Morgan *et al*. 1998). Advanced warning of such occasions may enable appropriate mitigating action to be taken, with a resultant reduction in the risk of an adverse reaction.

Contemporary operational air quality forecasting systems can be broadly categorised as empirical/statistical, numerical or hybrid. Empirical and/or statistical forecasting systems are currently operated by a number of state authorities in Australia. For example, the Environment Protection Authority of Victoria (EPAV), has been generating air quality forecasts for Melbourne and Geelong since 1982 using an expert system which attempts to predict the confluence of key meteorological and air quality factors which lead to a reduction in air quality. This system is soon to be replaced by a multi-variate statistical model. The NSW Environment Protection Authority has also used an expert system for air quality forecasting for more than 20 years. More recently, the Queensland Department of Environment has begun operating a three-stage system for forecasting air quality in the South Eastern Queensland Region.

Numerical air quality forecasting systems develop meteorological and air quality predictions by solution of the conservation equations for momentum, energy, moisture, and the mass for various species. Numerical systems are currently in operation, or under development in a number of countries, including Japan, Germany, U.S.A and Canada. An indicative example is given by a Japanese system (Ohara *et al*. 1997), where a coupled, multi-scale meso-meteorological model and a chemical transport model are used to generate 48 hour forecasts of nitrogen dioxide and photochemical oxidant concentrations for the Tokyo region. The Japanese Meteorological Agency operational forecast model provides boundary conditions for the meteorological model. The chemical transport model is initialised using air quality observations from 130 monitoring stations. The system has been in operation since April 1996 and has been shown to forecast peak daily air pollution concentrations with good skill.

1.2 AAQFS- project description and status

The Australian Air Quality Forecasting System is in the initial stages of a two-year program of development and testing. Following this period, the AAQFS will be used to operationally generate air quality forecasts for the Port Phillip Control Region (PPCR) and regional centres of Victoria (see Figure 1), and a region in NSW which includes the Metropolitan Air Quality Study Region (MAQSR; see Figure 1). It is planned that the AAQFS will have the following features.

- Air quality forecasts will be made twice per day, and will be for a period of 24-36 hours.

- The forecasting system will operate at an effective maximum horizontal resolution of about 5 km, thus enabling the forecast to discriminate between different regions of a city.

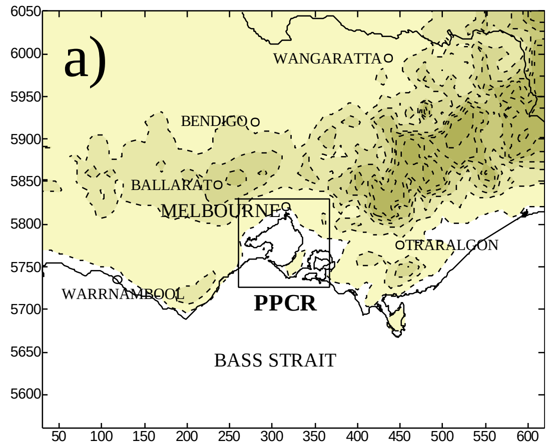
- The AAQFS will simulate a wide range of air pollutants including photochemical smog, particulate matter (PM_{10}), air toxics, oxides of nitrogen (NO_x), carbon monoxide, sulfur dioxide and volatile organic compounds (VOCs).

- The AAQFS will provide the ability to generate air quality forecasts simultaneously for a ' business as usual' emissions base case, and for alternative cases in which emissions are perturbed to represent environmentally friendly scenarios such as increased patronage of public transport systems.

- An archive of forecasts will be available for a number of applications including the determination of long-term population exposure metrics, the development of an optimal network design, and regulatory planning.

The system will go operational in time to provide air quality forecasts for the Sydney 2000 Olympics. Forecasts will be managed by the environment department of each state, and will be made available to the media and general public.

As discussed in the next section, system development is being undertaken in two stages, with the first stage involving the operation of a pilot system in Melbourne, and Sydney. The pilot system, which commenced operation in Melbourne early May 1998, is being used to investigate the computational and practical issues arising from the generation of an air quality forecast on a daily basis. During the second stage of the project, key components of the emissions inventory sub-system, the numerical weather prediction system, the chemical transport model, the evaluation sub-system, and the air quality display package will be refined until an acceptable level of performance is achieved.



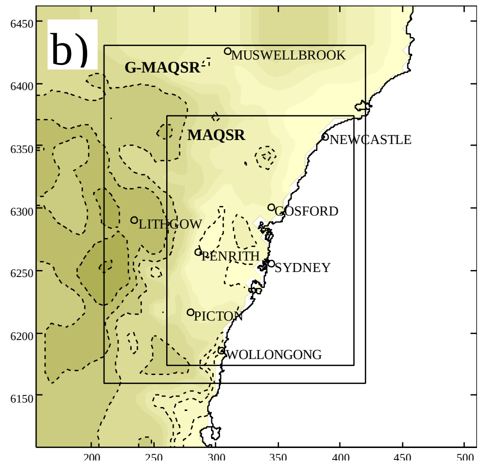


Figure 1. (a) Domain to be used for air quality forecasting in Victoria (domain of the PPCR is also indicated). (b) Domain to be used for air quality forecasting in NSW (GMAQSR- GREATER MAQS study region). Note that distances are given in units of kilometres.

2. System overview

A schematic diagram of the forecasting system is presented in Figure 2. Principal components of the system are the numerical weather prediction system (NWP), the emissions inventory module (EIM), the initial and boundary condition module (BCM), the chemical transport model (CTM), the evaluation module (EVM), and the display module (DSM). A brief description of the current status and the planned stages of development is now given for a number of the key system components.

2.1 Numerical weather prediction system

The purpose of the NWP is to provide accurate, high-resolution (both spatial and temporal) forecasts of the vector wind field, temperature, humidity and radiation fields, and surface-layer stability parameters. The meteorological forecasts are used by the CTM to drive the processes of pollutant transport and deposition, and to provide radiation, temperature and moisture fields for the simulation of chemical transformation processes.

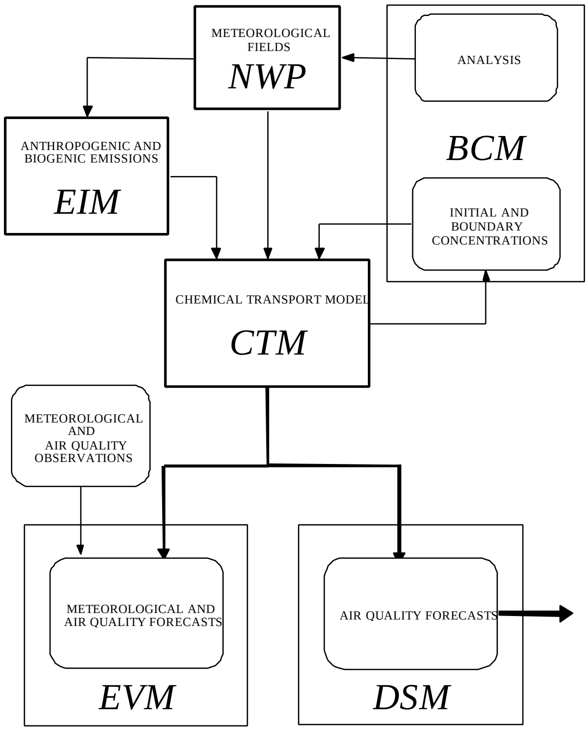


Figure 2. Schematic diagram of the Australian Air Quality Forecasting System.

Meteorological forecasts will be generated by the Bureau of Meteorology's Limited Area Prediction System (LAPS; Puri *et al.* 1998) a state-of-the-art numerical weather model, which began operational forecasting at a resolution of 0.75° in July 1996 (the system has also been generating operational forecasts at a resolution of 0.25° over two smaller regions since May 1997). The LAPS model uses a latitude/longitude grid and solves the primitive equations of momentum, mass, temperature and moisture on a non-staggered Arakawa A grid. Physical processes in the model include: a parameterization that approximates a Monin Obukhov constant flux layer at the surface; turbulent diffusion above the boundary-layer based on a stability dependant mixing length formulation; a Tiedtke convection scheme (with an option for a Kuo scheme); and a Fels-Schwarzkopf radiation scheme. The model is initialised from a limited-area version of the global multi-variate statistical interpolation analysis, using data which comprise available surface pressure data, radiosondes, radar winds, cloud drift winds, AMDAR (commercial airline) winds and temperatures, and satellite temperatures.

In the pilot air quality forecasting system, LAPS has been configured to generate twice daily (commencing hour 11 and 23 UTC) 36 hour forecasts at a horizontal grid spacing of 0.05° (approximately 5 km).

2.1.1 NWP- development work.

A considerable amount of ongoing and specifically targeted development work will feed directly into the operational version of the forecasting system. Key aspects of the development work include:

- Improved parameterisations of physical processes, with emphasis on land surface moisture and energy exchange processes, higher order turbulence closure, cumulus convection and gravity wave drag.

- Improved analysis methodologies targeted specifically for high resolution modelling, including a refined soil moisture initialisation scheme, and improved usage of data from polar orbiting and GMS-5 satellites. A mesoscale analysis scheme will also be developed, which is able to handle all data types included in the meso-network deployed in the modelled region. Consideration will also be given to alternative analysis formulations such as the use of variational methods and the development of improved methods of data assimilation to ensure that the extra details provided by the meso-network are retained by the model.

- Implementation of semi-implicit and semi-Lagrangian numerical integration formulations, in order to improve the computational efficiency of the NWP at high resolution.

2.2 Emissions Inventory Module

The EIM provides daily forecasts of emissions for a wide range of pollution species including, oxides of nitrogen, carbon monoxide, sulfur dioxide, PM_{10}, air toxics and a number of volatile organic compounds (VOCs). As discussed in Section 1.2, the emission forecasts will be for a ' business as usual' base case, and for one or more scenarios in which transport usage patterns are perturbed.

The pilot forecasting system uses the PPCR emissions inventory (Carnovale *et al.* 1991) for the Melbourne modelling and intends to use the MAQSR inventory (Carnovale *et al.* 1996) for the NSW modelling. Both inventory databases provide hourly-varying emissions on a 3 km grid for a range of source categories (including motor vehicle, industrial, commercial, natural and biogenic).

2.2.1 EIM- development work

The PPCR inventory will be extended to cover the Victorian forecasting domain (Figure 1). Computational and storage efficiencies will be achieved through the use of high-resolution grids (1-3 km) over the more populous regions (such as Melbourne and regional centres), while a coarser grid (9-27 km) will be used for the other areas within the forecasting domain.

Emission forecasts will be improved through the use of day-specific variations in source groups subject to meteorological influences.

•Biogenic emissions will be calculated for each day on the basis of predicted solar flux and diurnal temperature.

•The rate of domestic wood combustion will be based on correlations developed from a research project recently conducted by EPAV into the usage patterns of wood heating within Melbourne. The resultant emissions will be determined as a function of predicted temperature.

•The emissions of wind blown dust and sea-salt aerosol will be estimated using the forecast surface shear-stress and (in the case of dust), the near-surface soil moisture content.

•The impact of day-specific variations in vehicle use will be investigated with a view to account for days of non-average use. This will be of particular importance for forecasting on public holidays, weekends, and special events (particularly the Olympics). Temperature effects on motor vehicle evaporative emissions will be considered.

2.3 Chemical Transport Model

A modified version of the Carnegie Mellon, California Institute of Technology model (CIT; Harley *et al.* 1993) comprises the CTM in the pilot system. Originally developed in its basic form at the California Institute of Technology for the simulation of photochemical smog within the Los Angeles region, the model has since been applied to other airsheds in the Americas and in Europe.

The CIT model features a Cartesian grid in the horizontal and a non-uniform sigma-height coordinate system in the vertical. Sub-grid scale transport is simulated using the gradient transfer approximation. Dry deposition at the surface is modelled using the multiple-path resistance analogue. Photochemical transformation processes in CIT are simulated using an extended version of the Lurmann, Carter, Coyner mechanism (LCC; Harley *et al.* 1993 and references therein).

The model has been extensively modified and applied to the simulation of photochemical smog production in a number of major Australian airsheds (for example, see Cope and Ischtwan 1996). A significant modification for AAQFS is the replacement of LCC by the Generic Reaction Set (GRS; Azzi *et al.* 1992). The highly condensed GRS mechanism (7 reactions and 7 species) has the advantage of being computationally more efficient (the GRS version of CIT typically runs 5-10 times faster), yet can be configured to reproduce the predictions of the more detailed mechanism. In addition to the other enhancements documented in Cope and Ischtwan (1996), we have also modified CIT to simulate the transport and deposition of PM_{10} emissions.

2.3.1 CTM- development work.

The CTM will be developed as an online/offline module that can run within LAPS. Other planned development work addresses research issues which are currently the focus of attention of the air quality modelling community, as work continues towards the development of next (3^{rd}) generation regional air quality modelling systems. Areas of particular importance are as follows.

•Treatment of primary and secondary aerosols. Particulate matter is increasingly being considered a potential health risk (Morgan *et al.* 1998). Moreover, visibility degradation due to scattering by fine particles, is the primary indicator used by the public to ascertain the state of air quality. In order to adequately address these issues, it is essential that the CTM have the capability of efficiently modelling the transport and transformation of size-segregated primary and secondary aerosol species.

•Treatment of sub-grid scale emission sources. A series of sub-models will be developed which will estimate sub-grid scale variations of air pollution concentrations in the presence of strong gradients in the local source distribution. This is a particularly critical requirement if population exposure estimates are to account for the presence of large, local sources such as roads.

•Sensitivity analysis. An extremely useful outcome from the forecasting system is the ability to predict differences in air pollution levels (and exposure) which may result if a coordinated response (such as a 25 % increase in the use of public transport) resulted from a forecast of imminent air quality reduction. Such an outcome could be forecast by running the EIM and CTM with multiple emission scenarios. Alternatively, there are now techniques available which enable such an outcome to be predicted by a single CTM simulation.

2.4 Evaluation.

Evaluation of forecast accuracy is a critical on-going task of the project. The evaluation will comprise two components.

1. A daily evaluation of model performance using routinely available data sets. The evaluation will target performance of the NWP, and the coupled NWP, EIM and CTM systems.

2. A detailed diagnostic investigation of system component performance for selected extreme- and/or data-rich events.

The evaluation will make use of quantitative and qualitative comparison methodologies. Quantitative evaluation metrics will be based on the differences between hourly observed and predicted variables and will include measures of bias, variance and gross error. The qualitative comparisons will use diurnal and spatial plots of observed and predicted variables to determine whether critical characteristics, such as the timing and strength of important mesoscale features, have been correctly reproduced.

Components of the pilot system have already been the subject of extensive evaluation studies (Puri *et al.* 1998; Cope and Ischtwan 1996). Two examples follow.

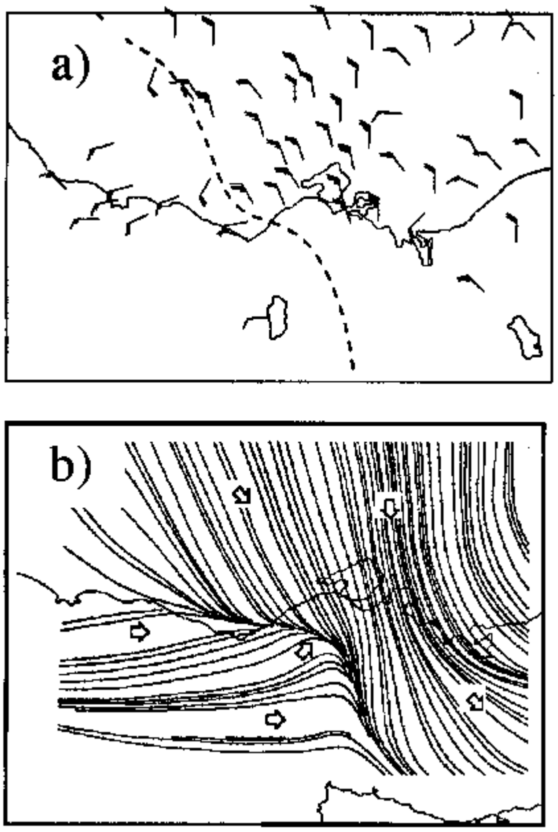
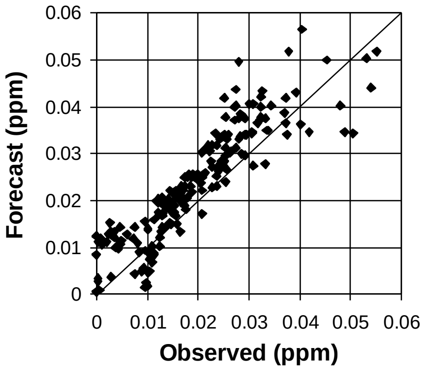


Figure 3. (a) Surface wind observations for 0500 UTC 21 January 1997 at the time of uncontrolled bushfires in the Dandenong Ranges. The dashed line indicates the wind shear line associated with a cold front approaching Melbourne. (b) Predicted streamline field from the LAPS model run at approximately 5 km horizontal resolution. The arrows indicate the wind direction.

•An important objective for LAPS is to accurately forecast the passage of cold fronts across southern Australia during the summer months. An accurate prediction of the timing and strength of the front becomes even more critical when bushfires are present, given that the passage of the front is accompanied by a wind shift and possibly rain. An example of model performance is given in Figure 3, for a day when firefighters were attending a large bushfire near Dandenong to the east of Melbourne. It can be seen from the figure that the position of the front along the coastal region has been extremely well forecast by LAPS.

•A proof of concept study for the forecasting system was recently conducted in Perth. A preliminary system was exercised in a ' hands-off' mode for a 72 hour period which was covered by an intensive measurement campaign in the Perth Photochemical Smog Study (Cope and Hess 1997). Results shown in Figure 4 for the last 24 hours of the period, and other comparisons discussed in the cited paper demonstrated the potential for a numerical system to generate accurate, high resolution meteorological and air quality forecasts.

Figure 4. Scatter plot of observed and forecast one-hour ozone concentration (matched in space and time)



for monitoring stations in the Perth region (Western Australia) on 4 February 1994.

An evaluation of the pilot system performance is also under way following the commencement of system testing for Melbourne in early May 1998. Although the system is forecasting both primary and secondary species, the emphasis is currently on the ability of the system to predict the diurnal variation, and peak 1-hour concentrations of NO_x during the autumn and winter smog season. NO_x was selected as the test pollutant because it is quasi-conserved over the time scales of interest and thus provides an indication of NWP performance. Moreover, NO_x is currently one of the most accurately inventoried and extensively monitored gaseous species in the PPCR.

An indication of system performance is given in Figure 5 where forecast peak 1-hour NO_x concentrations for the Melbourne region are compared against the range of peak concentrations observed by EPAV urban monitoring stations (sited in Alphington, Melbourne C.B.D, Box Hill, Brighton, Dandenong, Paisley and Footscray). It is apparent from Figure 5 that the pilot system has generally been able to forecast the day-to-day trend of increasing or decreasing peak NO_x, which is in response to the passage of high pressure systems over the study area. Further improvements in forecasting skill may be expected once the program of system refinements has been completed.

2.4.1 EVM- development work.

Future development work on the evaluation task will primarily consist of the following.

•Location of additional instrumentation in the field to

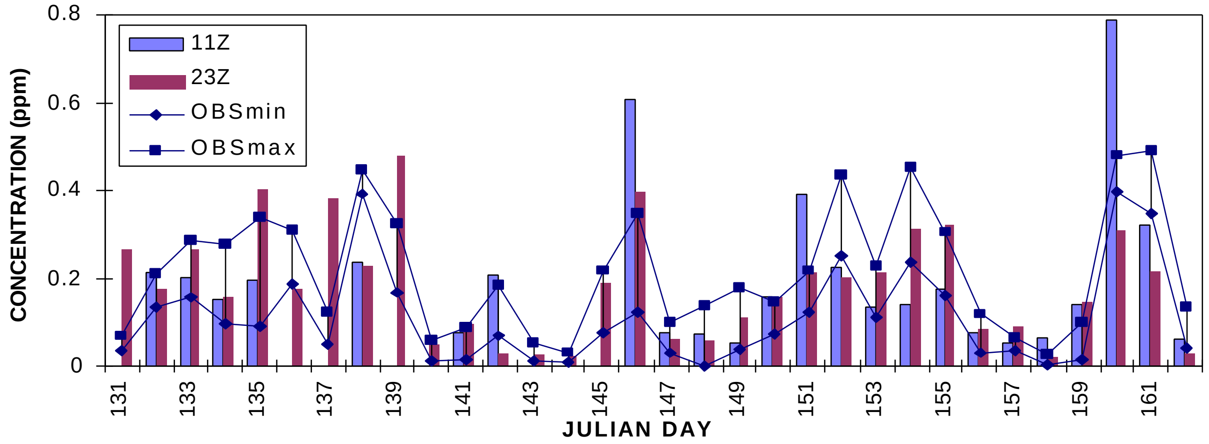


Figure 5. Forecast (bar plots) and observed (line plots) peak 1-hour concentrations of NO_x for Melbourne- May 13-June 11, 1998. Note that the line plots show the range of peak concentrations observed at urban monitoring sites.

aid with ongoing system evaluation. For example, the EPAV has recently installed five automatic meteorological observation stations and a phased-array sodar (range 2.5 km) to aid with the evaluation of the NWP.

- The development of robust quantitative metrics that provides improved measures of model performance. Experience gained in the evaluation of photochemical airshed models (Cope and Ischtwan 1996) suggests that the current recommended suite of statistical evaluation measures do not provide the best indicators of model performance.

4. Conclusions

The AAQFS is a project to develop operational numerical air quality forecasts for large coastal and regional population centres. A pilot system is currently in operation in Victoria, and will shortly be applied in NSW. When a two year development phase is completed, the system will be used to routinely generate 24-36 hour air quality forecasts for a range of air pollutants. The maximum effective resolution of the system will be about 5 km, thus enabling the forecast to discriminate between different areas of a city.

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