LAPS and the Australian Air Quality Forecasting System

G. D. HESS[1], M. E. COPE[2,3], S. LEE[2], and K. TORY[1]

[1]Bureau of Meteorology Research Centre, Melbourne, Victoria, Australia
[2]CSIRO Atmospheric Research, Aspendale, Victoria, Australia
[3]CSIRO Energy Technology, North Ryde, New South Wales, Australia

Introduction

The Australian Air Quality Forecasting System (AAQFS) is being developed with funding from the Air Pollution in Major Cities Program. The project's short-term goal is to develop, validate and trial an accurate, next-day (24-36 hour) numerical air quality forecasting system for a three-month demonstration period in Sydney, which includes the 2000 Olympics. Currently forecasts are produced in both Melbourne and Sydney. After the Olympics, the AAQFS will be available for forecasting health- and visibility-related air quality metrics in the other major population centres of Australia. Principal project partners are the Bureau of Meteorology (BoM), CSIRO, Environment Protection Authority of Victoria (EPA-VIC) and the Environment Protection Authority of New South Wales (EPA-NSW).

The project has a number of specific goals: to provide the ability to generate 24-36 hour air quality forecasts twice per day (available 9 am and 3 pm); provide forecasts for a range of air pollutants including oxides of nitrogen (NO_x), ozone (O_3), sulfur dioxide (SO_2), benzene (C_6H_6), formaldehyde (CH_2O) and particulate matter (PM10 and PM2.5); provide forecasts at a resolution sufficient to consider suburban variations in air quality; and to provide the ability to generate simultaneous forecasts for a 'business-as-usual' emissions scenario and a 'green emissions' forecast. The latter may correspond to a minimal motor vehicle-usage scenario and will be used to indicate the reduction in population exposure that could result from a concerted public response to a forecast of poor air quality for the next day.

In this paper, we provide a brief description of the AAQFS and present a case study of an ozone pollution event in Melbourne.

Description of the Forecast System

The AAQFS consists of five major components (Fig. 1): a numerical weather prediction system (LAPS), an emissions inventory module, a chemical transport module (CTM) for air quality modelling, an evaluation module, and a data archiving and dissemination module (data package). The development of the AAQFS is proceeding in two phases: 1) the construction and operation of a pilot system using components that were available at the time of study inception; and 2) the development of a demonstration system, through the enhancement of components in the pilot system, and where necessary, through the construction of new modules (Cope, et al. 1999). We note that resources were allocated to first implement a pilot system in order to provide a preliminary indication of system performance. This has enabled important areas of development to be identified prior to the design and construction of the demonstration system.

As indicated in Fig. 1 the principal difference between the pilot and demonstration systems is the number of processes that are run online (i.e. as modules that are called directly by LAPS). For example, in the demonstration system (Fig. 1b), a large component of the emissions modelling, and all of the chemical transport modelling, are conducted online. This contrasts with the pilot system (Fig. 1a), where a meteorological forecast is first completed, stored and post processed prior to the execution of the chemical transport model.

LAPS constitutes the NWP system in both the pilot and demonstration versions of the AAQFS. LAPS is a hydrostatic model with state-of-the-art numerics and physics packages, and has been used by BoM to generate operational meteorological forecasts since July 1996 (Puri, et al. 1998). Meteorological forecasts will be provided at a horizontal resolution of 0.05° (LAPS05). Special attention will be paid to the

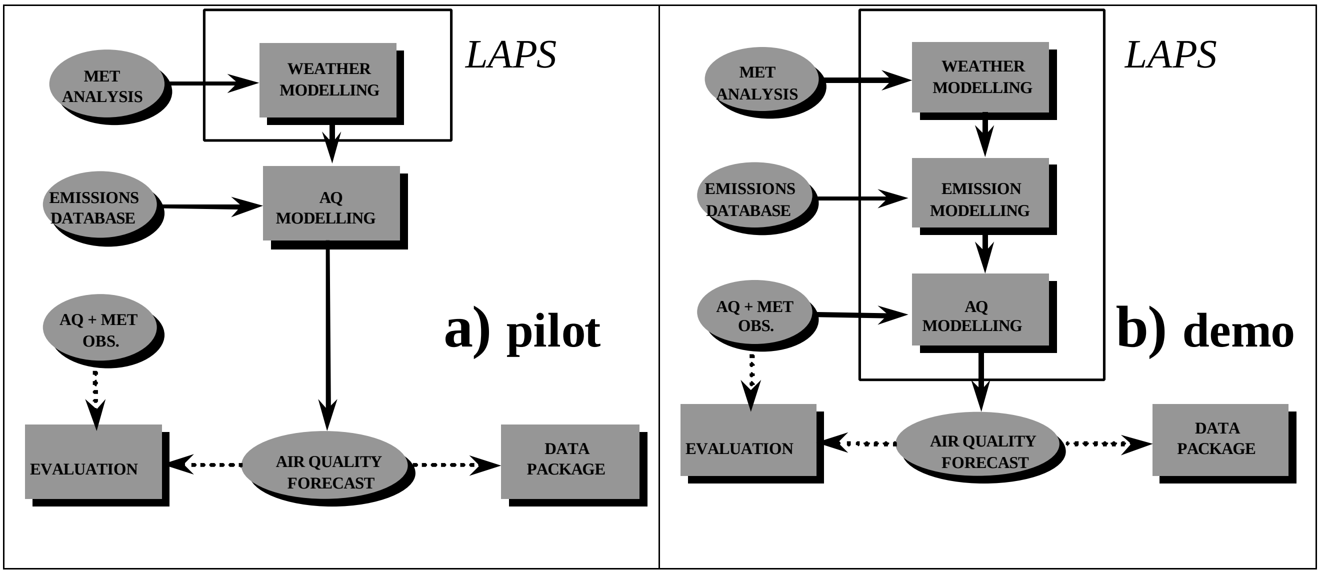

Fig. 1: Schematic diagram of (a) the pilot and (b) the demonstration forecasting systems. Note that modules located within the bounding-box labeled 'LAPS' correspond to components that are run online during a meteorological forecast.

resolution and treatment of surface processes in an effort to improve representation of local and mesoscale flows and boundary-layer growth. Accurate representation of these processes is crucial for realistic, high-resolution forecasting of air pollution dynamics.

EPA-VIC and CSIRO, with support from EPA-NSW, are undertaking emission inventory development. All emissions processing for the pilot system is undertaken offline with a resolution of 6 km with no allowance made for week/weekend or seasonal/local meteorological dependencies. The demonstration system will use size-fractionated and speciated particle emissions, 0.01° gridded area sources over the densely population regions and meteorologically dependant emissions that are generated online during LAPS operation (see Fig. 1b). A power-based vehicle emissions model, being developed at CSIRO, will be used to generate road-specific vehicle emission fluxes for the purpose of near-road impact modelling.

The Carnegie Mellon/California Institute of Technology (CIT) photochemical airshed model comprises the pilot CTM (Cope and Ishtwan, 1996; Cope, et al. 1998, 1999). A notable modification is the implementation of the compact GRS photochemical mechanism, which enables rapid turn-around times for the CTM modelling. The domain is divided into 10 non-uniform levels in the vertical (extending to 2000 m above ground level). The pilot system has been used to generate 24-hour air quality forecasts (NO_x, O_3 and SO_2) using the 1100 UTC (2100 EST) LAPS05 forecasts. In the demonstration system, the CTM modelling will be conducted online using LAPS05 transport fields that are updated at 5-10 minute intervals. Note that the CTM simulations use a 0.05° outer grid, with nested inner 0.01° grids for major urban areas. Photochemical smog production will be simulated using an enhanced version of the GRS mechanism and particle transformation will be modelled using a modal-based particle scheme. A more comprehensive treatment of both processes will also be available in an offline version of the CTM.

Both the meteorological and air quality forecasts are the subject of on-going and case-specific validation. This has already commenced for the pilot system through comparison of LAPS meteorological fields with METAR/SYNOP (near-surface) and AMDAR (vertical profile) data and meteorological observations from the EPA monitoring networks. Air quality forecasts are compared against 1-hour EPA observations for NO_x (both as NO and NO_2) and O_3. This will be expanded for the demonstration system to include SO_2, PM10, PM2.5, CO and (where available) non-methanic hydrocarbons. Critical to the validation process has been the availability of EPA data sets by the end of each forecast period, enabling the on-going validation to be substantially automated.

Data archiving will evolve from use of native system formats in the case of the pilot system (already NetCDF in the case of LAPS) to unified NetCDF data packets, which will be accessible via GUI-driven Q&A software. Sufficient information will be available in a data packet to enable the CTM to be run offline at a later time. The EPAs will have access to the daily forecasts via the AAQFS Web Site and will control the dissemination of the forecast data.

Photochemical Smog Event in Melbourne

The highest concentration of ozone in the Melbourne Airshed during the 1998/99 summer ozone season was observed to occur on 10 December 1998. A maximum concentration of 122 ppb was observed at Mt Cottrell with 107 ppb observed at Point Cook (i.e. the maximum concentrations occurred on the western side of Port Phillip Bay). The meteorological situation this day was typical of many pollution events for Melbourne. There was an anticyclone located southeast of Melbourne in the Tasman Sea. During the 24-hour period the centre of the anticyclone drifted northeastward and then eastward. In the early morning the near-surface winds over the Melbourne Airshed were light northerlies. However as the morning heating increased a bay breeze developed, producing winds perpendicular to the bay shoreline and opposing the larger-scale northerly flow. By mid-afternoon the Bass Strait sea breeze with its southeasterly winds replaced the bay breeze. It is this delicate balance between opposing wind fields that must be accurately modelled; this includes accurately modelling the timing, direction and penetration of the bay breeze and the sea breeze.

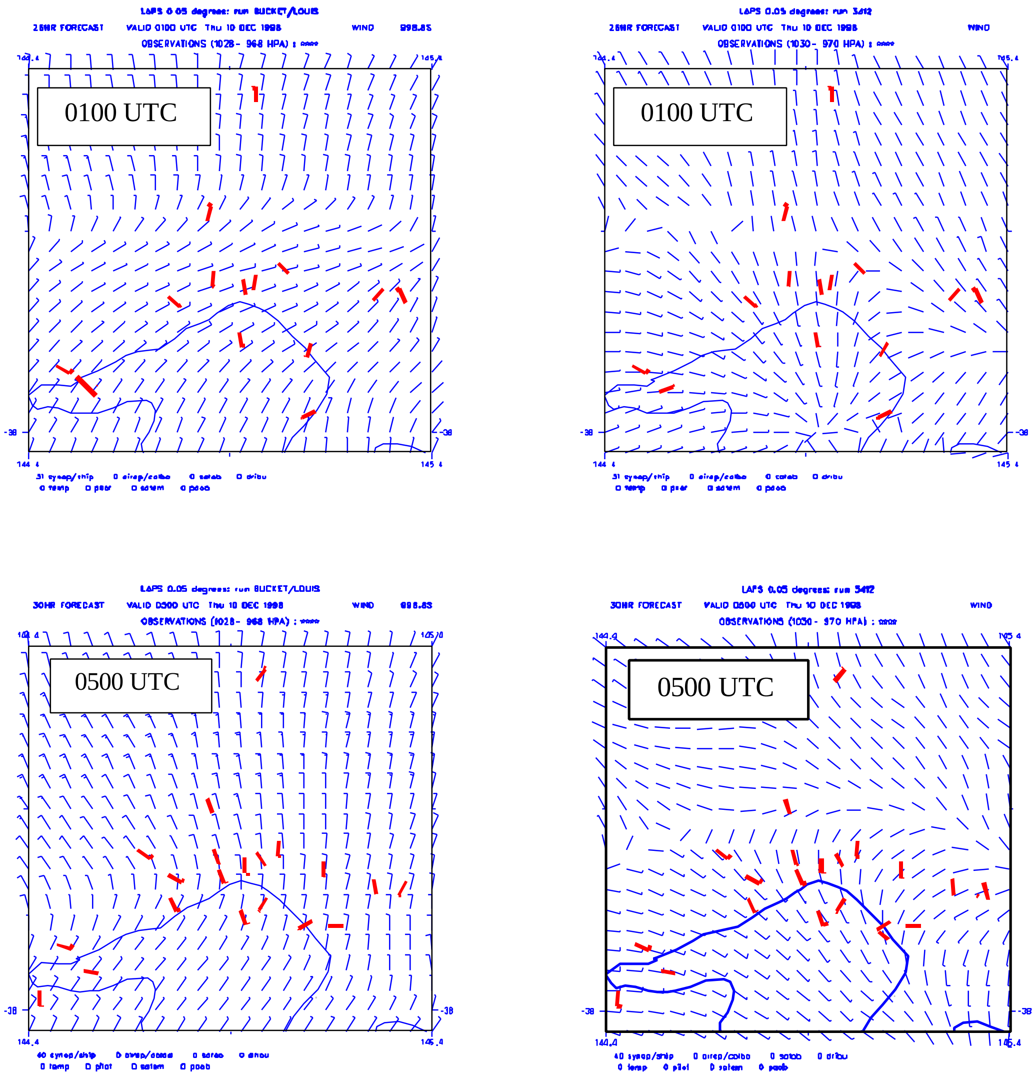

Fig. 2. Comparison of 10-m wind fields for LAPS with bucket hydrology and Louis scheme surface fluxes and vertical diffusion (left column) and the Viterbo-Beljaars land-surface scheme and vertical diffusion, and directly calculated Monin-Obukhov surface fluxes (right column). Observations are in bold.

In Fig. 2 we show examples of the modelled wind fields for two versions of LAPS05. In the first version (left column of Fig. 2) the original pilot scheme physics was employed: bucket hydrology and Louis scheme surface fluxes and vertical diffusion; however, the vertical resolution of the model had been enhanced from the original 19 levels to 29 levels (Puri, et al. 1998). The second version (right column of Fig.2) used the Viterbo-Beljaars land-surface scheme and vertical diffusion, and direct calculation of the Monin-Obukhov surface fluxes (Viterbo and Beljaars, 1995). In addition, a number of higher resolution modifications were made: topography was changed from 1^{o} degree to 30-sec resolution; SST from 1^{o} degree (spatial resolution) and weekly to 0.25^{o} and daily; soil texture and hydrological properties from constant values to 0.05^{o} resolution; momentum roughness length and fractional vegetation coverage from 1^{o} to 0.05^{o} resolution.

In Version 1 of LAPS the modelled northerlies are too strong and prevent the bay breeze from developing. In Version 2 a bay breeze develops in good agreement with the observations in direction and penetration. The timing of the onset (not shown) is also in good agreement. The source point (where the flow begins its divergent pattern over the bay) is clearly identifiable. The sea breeze also shows good agreement with the observations for Version 2, but in Version 1 the northerlies still prevail and there is no sea breeze.

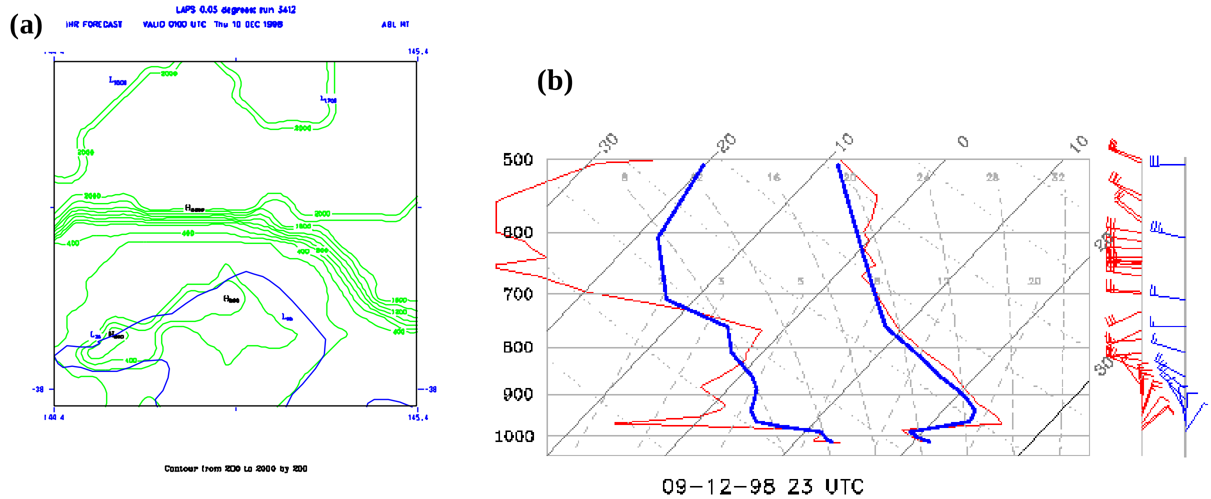

Fig. 3. (a) Mixed layer height at 0100 UTC 10 December 1998 for the LAPS model with the Viterbo-Beljaars land-surface and vertical diffusion schemes and directly calculated Monin-Obukhov surface fluxes; (b) comparison of model vertical profiles (bold lines) for temperature, dew point temperature and winds with Laverton rawinsonde data for 2300 UTC 9 December 1998 (24-hour forecast).

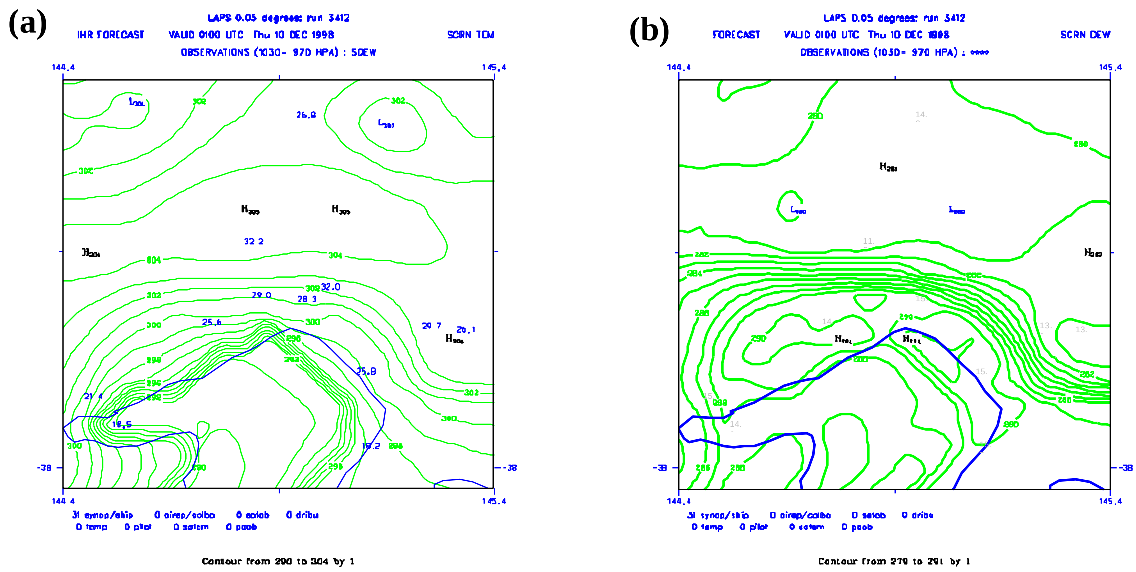

Fig. 4. (a) Screen temperature and (b) screen dew point temperature for 0100 UTC 10 December 1998. The strong gradient in the temperature corresponds to the land-sea contrast; the outer edge of the temperature gradient and the strong gradient in the dew point temperature (the dry line) corresponds to the bay breeze advance and mixed layer gradient. Numbers in degrees C are the observations. Laverton is the station to the west and near the top of Port Phillip Bay in (a).

The height of the mixed layer (i.e. the height of the turbulent mixing) is another important meteorological variable. Figure 3a shows the variation of the mixed layer height over the airshed at the time of the mature bay breeze (0100 UTC) for Version 2. The strong gradient shows the extent of the bay breeze penetration. In Fig. 3b we present a comparison of the model's vertical structure (winds, temperature and dew point temperature) with observed values (for a time two hours earlier than Fig. 3a). The agreement is very good, particularly for the winds and temperature.

Another way to look at the effect of the bay breeze penetration is examine the pattern of screen temperature and dew point (see Fig. 4a,b, respectively). The strong gradient for screen temperature shows the land-sea contrast; the outside edge of the gradient shows the bay breeze penetration, as does the dry line for the screen dew point temperature (cf. Fig.3a for comparison with the mixed layer pattern).

The sensitivity of forecast air quality to the alternative meteorological forecasts is illustrated in Fig. 5 a,b where observed and forecast concentrations time series of nitrogen dioxide (NO_2) and O_3 are shown for selected monitoring stations in the EPA-VIC network. Forecast concentrations are shown for cases where the CIT model was driven by meteorological fields from Version 1 and Version 2 for LAPS. It can be seen that the forecast NO_2 concentrations (Fig. 5a) generally show a significantly improved level of agreement with the observations when Version 2 meteorological fields are used. This is clearly evident at Footscray and Point Cook where NO_2 forecasts based on Version 1 of LAPS are seen to have significant phase and amplitude errors.

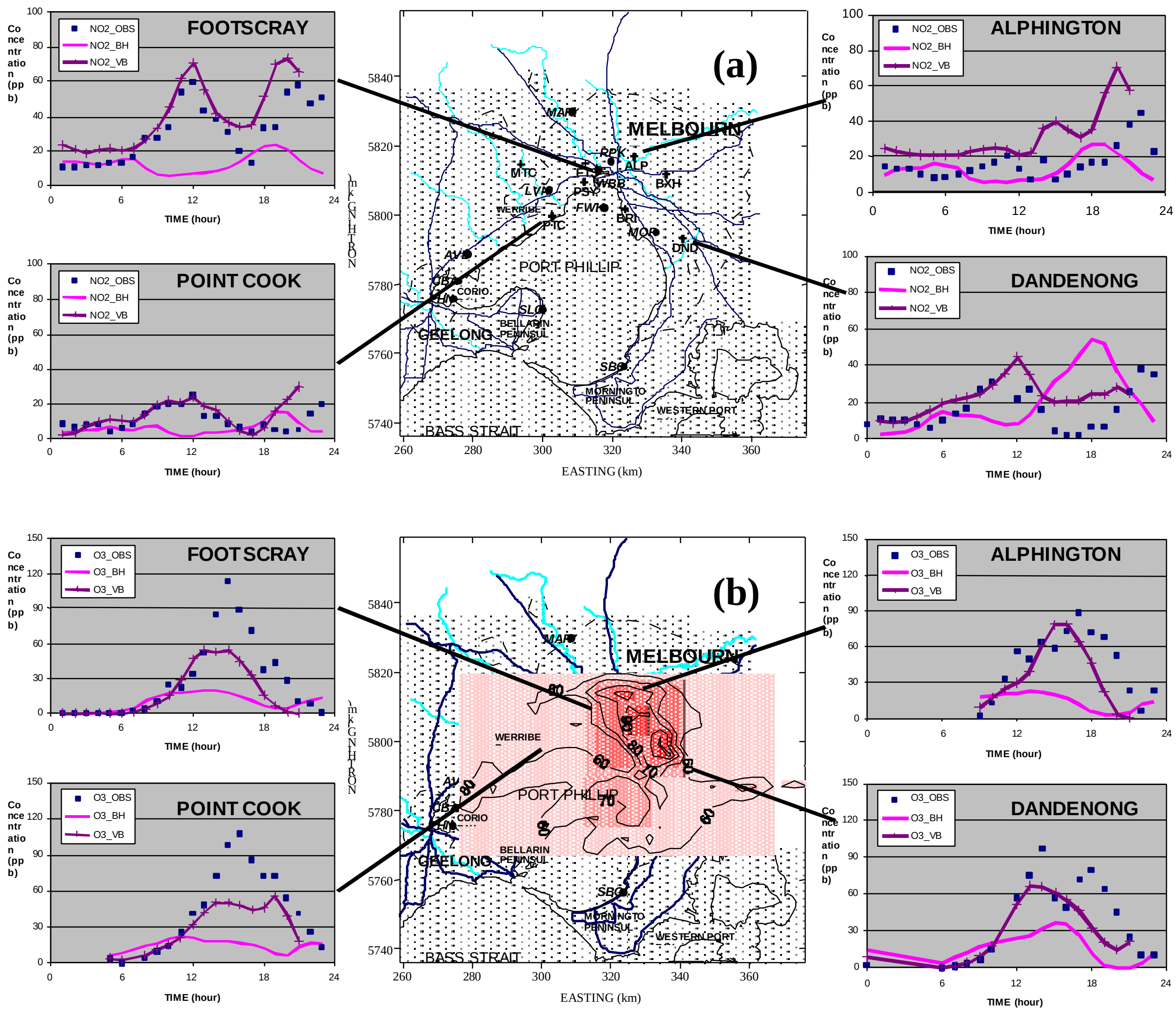

Fig. 5. Observed and forecast 1-hour concentration time series of (a) NO_2 and (b) O_3 for 10 December 1998. Two forecasts are shown, generated using meteorological fields from LAPS with bucket hydrology (BH) and LAPS with the Viterbo-Beljaars land-surface scheme (VB).

For example, failure of Version 1 LAPS to predict bay breeze activity and the related recirculation of primary and photchemically produced NO_2 is the principal cause for the omission of the NO_2 peaks observed at the EPA-VIC monitoring stations at hour 12. However, this peak has been well simulated when Version 2 LAPS meteorology is used and the bay breeze activity is better simulated. A second peak in NO_2 is observed near midnight local time. This peak is due to the recirculation of the aged air mass (with primary and secondary NO_2 concentrations), and possibly due to the titration of the O_3 plume by local emissions of NO. The model also forecasts a second peak, although the amplitude is too high and the phase is too early, in general.

Forecast ozone concentrations also show a significantly improved level of agreement with observations when Version 2 LAPS meteorological fields are used in the air quality forecast (Fig. 5b). A major O_3 peak occurs in mid-afternoon due to the photochemical transformation and recirculation of O_3 precursors in the bay breeze and this is seen in the model results. However, it is also clear that further improvements should be sought, given that peak ozone concentrations are still underpredicted by the forecasting system at stations on the western side of Port Phillip Bay. Nevertheless, as can be seen from the spatial plot the maximum O_3 in Fig. 5b is in good agreement with maximum observed value for the airshed (100 ppb from the model compared to 122 ppb observed). A secondary peak is also observed in the early evening (and is weakly shown in the model at Point Cook). This peak is associated with transport of pollution within the Bass Strait sea breeze.

Given the demonstrated capabilities of the Version 2 LAPS forecast for this event, emphasis has now shifted to investigating the relative performance of the photochemical transformation mechanism, and the emissions inventory.

Conclusions

The AAQFS is evolving from the pilot stage to the demonstration stage. Improvements in LAPS model physics and resolution have resulted in improved meteorological forecasts. The air quality forecasts reflect the presence of both the bay breeze and the sea breeze, and the general diurnal variations of forecast pollutant concentrations are fair to very good; for the case study considered the forecast maximum ozone concentration for the airshed is in good agreement with observations. However, even with a good meteorological forecast, accurately determining the location of pollutant maxima is an extremely difficult problem for a complex site like Melbourne. Our efforts to improve the simulation of this event now centre on improvements in photochemical modelling and the emission inventory. The limits of predictability have not yet been established.

References

Cope, M. E. and Ischtwan, J. 1996. Metropolitan Air Quality Study: Airshed modelling, *Final report to New South Wales Environment Protection Authority*, Bankstown, NSW, Australia.

Cope, M. E., Manins, P., Hess, D., Mills, G., Puri, K., Dewundege, P., Tilly, K. and Johnson, M. 1998. Development and application of a numerical air quality forecasting system. *Proc. 14th International Conf. Clear Air & Environment*, Melbourne, 18-22 October 1998, Clean Air Society of Australia and New Zealand, 353-8.

Cope, M., Hess, D., Lee, S., Azzi, M., Carras, J., Wong, N. and Young, M. 1999. Development of the Australian Air Quality Forecasting System: Current Status. *Proc. International Conf. Urban Climatology, Sydney*, 8-12 November 1999, in press.

Puri, K., Dietachmayer, G., Mills, G. A., Davidson, N. E., Bowen, R. A. and Logan, L. W. 1998. The new BMRC Limited Area Prediction System, LAPS. *Aust. Met. Mag.*, 47, 203-33.

Viterbo, P. and Beljaars, A. C. M. 1995. An improved land surface parametrization scheme in the ECMWF model and its validation. *Tech. Report 75*, Research Department, ECMWF, Shinfield Park.