# Air Quality Forecasting: A Review and Comparison of the Approaches used Internationally and in Australia

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### ABSTRACT

Poor air quality poses a risk to human health, particularly to those people suffering cardio-vascular illness. In this paper, we survey a range of techniques used in Australia and internationally to forecast air quality. The levels of technology used in Australia appear to be comparable to those used internationally and the accuracy of the best Australian forecast results is comparable to the best internationally. Based on this survey, we recommend that future work in Australia should be directed towards unifying the methods of displaying and reporting the forecast results. Secondly, techniques need to be developed to blend different types of forecasts using fuzzy neural network techniques. Thirdly, we need to consider the use of ensemble forecasts and model–data fusion to reduce forecast uncertainty and to provide an estimate of forecast error. The implementation of such a major program would require a nation-wide, coordinated research effort to develop new models and to provide improved methodologies of assessment of the impacts of pollution (such as directly predicting rates of mortality); to develop strategies for reduction of pollution; and to strengthen the interface between air quality science and those charged with the responsibility for air quality regulation and downstream clients.


### INTRODUCTION

The deleterious impact of poor air quality on human health has been the subject of numerous epidemiological studies in recent years (c.f. Bunekreef and Holgate 2002 and references therein; Morgan et al. 1998; Simpson et al. 1997; EPA Victoria 2000). The levels of excess mortality resulting from daily changes in air pollution loading are estimated to be significant. Using an excess risk of death of 0.5% per 10 μg $m^{-3}$ for PM10, Brunekreef and Holgate (2002) calculated that 2,100 premature deaths would occur in the Netherlands each year (total population of 16 million). This is nearly double the number due to motor vehicle accidents. A similar exercise has been undertaken in Australia (Department of Environment and Heritage 2001), where it is estimated that, on the average, 2,400 of the 140,000 Australian deaths per year are linked to air pollution and health issues. By contrast, an average of 1,700 Australians die in motor vehicle related accidents.

Over the short term (i.e. hours to days), the mitigation of health impacts due to air pollution is addressed through the collection and dissemination of information about the current and forecast state of air pollution within designated regions. The aim of this approach is two-fold — 1) to proactively restrict activities which may result in increased pollutant dosage within an airshed (e.g. banning open air burning on days of high fine particle loading); 2) by communicating this information through appropriate media outlets (viz the web, printed media, television and radio) to provide at-risk members of the population with contextual air quality data, thus giving them the capacity to take appropriate remedial action to offset the effects of high pollutant dosage (e.g. restricting periods of intensive outdoor exercise, and taking preventative medications).

Such approaches have been found to be effective at reducing health impacts. For example, a study recently conducted in southern California estimated that air quality alerts were responsible for a 4-7% reduction in hospital admissions on poor air quality days for children with asthma (Wayland et al., 2002). This suggests that a useful set of measures to curtail the health effects of short term air pollution events are: 1) measure and disseminate to the public real-time data about the status of criteria air pollutants; and 2) on a daily (or more frequent) basis, generate and disseminate to the public limited time horizon (i.e. 6–48 h forwards in time) air quality forecasts.

Access to real-time air pollution data is readily achieved in Australia via the internet. In particular, EPAs in New South Wales, South Australia, Queensland, Victoria and Western Australia all provide tables of current (i.e. last hour) air pollution data on their web sites. Thus we turn our attention to the second measure listed above, viz the methods used to generate short-term air quality forecasts. This is an area of atmospheric science which is currently in a stage of rapid change, primarily triggered by an increasing availability of cost effective, high performance computing capacity which allows the ready application of complex numerical modelling systems to air pollution forecasting.

In the next section, we provide a brief introduction into the hierarchy of methods which are used to generate air quality forecasts. We then go on to sample some of the forecasting systems which are used in the international arena. This is followed by a discussion of the systems which are used in Australia. The Australian and international approaches are contrasted in the final section, and consideration is given to possible further directions for forecast system development in this country.

### AIR QUALITY FORECASTING TECHNIQUES

A useful classification of air quality forecasting techniques was given by Wayland et al. (2002).

***Criteria schemes*** use rules-of-thumb or thresholds to predict the future state of air quality. Criteria schemes are based on simple threshold requirements, such as that a photochemical smog event will occur tomorrow if the temperature is forecast to exceed 30$^0$C. Persistence is a simple and often very robust example of a criteria scheme – the air quality tomorrow will be similar to the air quality observed for today. In the USA, persistence is able to forecast next day ozone events with an accuracy of about 85% (Davidson et al., 2003). By contrast, in Melbourne Victoria, we have found that persistence delivers a detection rate of <15% (based on observations of bushfire-filtered peak 1-h ozone of 60 ppb or greater for the 2001/2002 and 2002/2003 summer smog seasons). The 'hit rate' for Melbourne is so low because a majority of the observed events don't extend beyond a single day.

***Parametric Methods (statistical, neural networks, fuzzy logic)***. This popular approach makes predictions based on patterns in past meteorological, traffic and air quality data, using regression or trained neural network systems. The chemical and physical processes determining air quality are not directly considered. For example, multiple linear regression relations for radiation and temperature might be used to predict the peak ozone concentration. Or perhaps nonlinear regression relations, such as radiation and temperature multiplied by traffic density or wind speed, are used. This method has the advantage that it is quick and simple to use.

Neural networks, which act in a rudimentary way to simulate the thought processes of the brain, are another example of a parametric forecasting method. This approach uses parallel nets of nonlinear units called neurons. Each neuron has an activation number associated with it and is connected to other neurons by a numerical weight representing the strength of the synapse. The activation of the neuron depends on the activation and weight of the neurons connected to it, and the pattern of neuron firing adapts until it simulates the pattern of the data used for training. The method is robust even in the presence of noise and failure of some components (i.e. a fuzzy

Table 1. Examples of forecasting systems used by agencies in Europe, U.S., Canada and Japan.

| Institution | Region | Scale | Pollutant | Methodolgy |
|---|---|---|---|---|
| Institute for Geophysics and Meteorology, University of Cologne | Europe, Central Europe, Germany, North Rhine-Westphalia | Forecasts on large-scale and regional scale (urban scale under development). Forecast for today and tomorrow and the next day. | $O_3$, $NO_2$, $SO_2$, CO, PM10, $C_6H_6$ | Deterministic (3-D Eulerian photochemical smog). |
| Meteo France et al. | Global, Europe, France | Forecasts on large-scale and regional scale. Forecast for today, tomorrow and the day after. | $O_3$, $NO_2$, PM10 | Deterministic (3-D Eulerian photochemical smog). |
| Tropical Environmental Research, Institute for Meteorology, Free University of Berlin | Central Europe, Germany, local | Regional scale (urban scale under development). 72-h forecast starting with the previous day. | $O_3$ | Deterministic/Parametric hybrid (3-D Eulerian numerical regional model; statistical; neuro-fuzzy model). |
| Swedish Meteorological and Hydrological Institute | Europe | Regional scale. | $O_3$, $NO_2$, $SO_2$ | Deterministic (3-D Eulerian photochemical smog). |
| Norwegian Institute for Air Research, Norway et al. | Northern Hemisphere | Routine forecasts on large scale. Regional scale nesting available. | $O_3$, $NO_x$, $NO_y$ + others | Deterministic (3-D Eulerian hemispherical photochemical model). |
| European Union and Czech Republic | Central Europe and Czech Republic | Regional scale. Forecast is for today and tomorrow. | $O_3$, NO, $NO_2$, $SO_2$, CO, PM10, | Deterministic (3-D Eulerian regional-scale photochemical smog). |
| Ircel-celine | Belgium + surrounding regions | Regional and urban scales. Forecast is for today, tomorrow and the next day. | $O_3$ - regional PM10 - urban | Parametric (statistical). |
| National Environmental Research Institute | Denmark, Copenhagen and Aalborg | Regional, urban and local scales. Forecast is for today, tomorrow and the next day. | $O_3$, $NO_2$, $NO_x$, CO | Deterministic Eulerian (regional, urban and local scales). |
| Netcen and Met Office | UK and Europe and 11 cities | Regional and urban models. Forecast is for tomorrow. | $O_3$, NO, $NO_2$, $SO_2$, CO, PM10 | Deterministic. Regional Lagrangian model and urban box model. |
| Environmental Research Consultants | Many UK cities, NE Somerset, UK, SW Wales, Budapest, Hungry | Urban model. Forecasts for 3-5 days. | $O_3$, $NO_2$, $SO_2$, CO, PM10 | Statistical model for rural background; Gaussian model for urban areas. |
| AIRNOW (U.S EPA) | 250 cities | Mainly urban scale. Next day forecasts. | $O_3$, PM10 PM2.5 | Mainly parametric models. |
| NOAA-EPA | NE of USA | Regional model. Forecast for 48 h. | $O_3$ | Deterministic 3-D Eulerian model. |
| Environment Canada, Meteorològical service of Canada | Canada | Regional model forecast for 48 h. | $O_3$, $SO_4^{2-}$, Organic aerosols | Deterministic 3-D Eulerian model. |
| National Institute for Environmental Studies. | Osaka, Japan | 10 day regional scale forecasts. | $O_3$, $NO_x$, $SO_2$, PM10 | Deterministic 3-D Eulerian model. |

neutral net), but like all parametric methods the forecast results are highly dependent on the predictive variables chosen and the representativeness of the training data set for general conditions. Neural networks are an example of data mining (Thurling 2004) and they employ pattern recognition techniques to explore large data sets.

***Deterministic Methods***. These methods attempt to simulate the underlying chemical and physical processes of air pollution production and generally require greater computer resources than parametric methods. The meteorological conditions, gaseous and particle emissions, chemical reactions, as well as the nature of the surface, are taken in account. The simplest method is the box model in which inputs and outputs are considered for a volume represented by a box. Within the box, the air is assumed to be well-mixed. The next simplest approach is the Gaussian model in which the concentration of a pollutant is prescribed according to a normal probability distribution from a point source. Limited meteorological information, such as a single wind speed for the transport, is used. Usually the chemistry, if included, is highly simplified. A third, more complex approach is to use Lagrangian models which follow an air parcel in time. Lagrangian puff models prescribe the growth of a puff of a pollutant and the concentration within the puff is given by a Gaussian or other probability distribution. The total concentration is determined by summing up the contributions of the many puffs. Lagrangian particle models are based on the release of a large number of particles which are transported by the mean flow and a random turbulent component to the wind. These models are driven by three-dimensional meteorological data and the chemistry is solved within the puffs/particles. A fourth method is the Eulerian model which employs a fixed three-dimensional grid. In this model, the meteorological and chemical equations are solved at the grid points and often comprehensive chemistries are used. Sometimes a separate model for the emissions resulting from traffic or variables dependent on meteorological conditions, such as particle emissions from wind-blown dust, is included. Lastly, there are hybrid models – e.g. models with particles in the vertical direction and puffs in the horizontal direction, or Lagrangian model features for transport and Eulerian model features for calculation of the concentrations – which attempt to combine the advantages of different model approaches.

### INTERNATIONAL APPROACHES

The availability of cost-effective high performance computers, ranging from personal computers to supercomputers, has spurred a wave of activity in high-resolution, three-dimensional meteorological modelling over the last five years. This research and the recognition of the health and economic benefits that forecasting air quality offers the community has led to air quality forecasting programs being set up in many countries around the world. Table 1 shows a sample of this forecasting effort. The Table is not

**Figure 1. Verification of ozone predictions from the NETCEN-Met Office (see Table 1) Lagrangian trajectory model for 6 June 1996. Air parcel trajectories used to construct the forecast are shown in the right hand plot (after NETCEN-Met Office, UK http://www.airquality.co.uk/archive/uk_forecasting/forecast_is_made.php).**

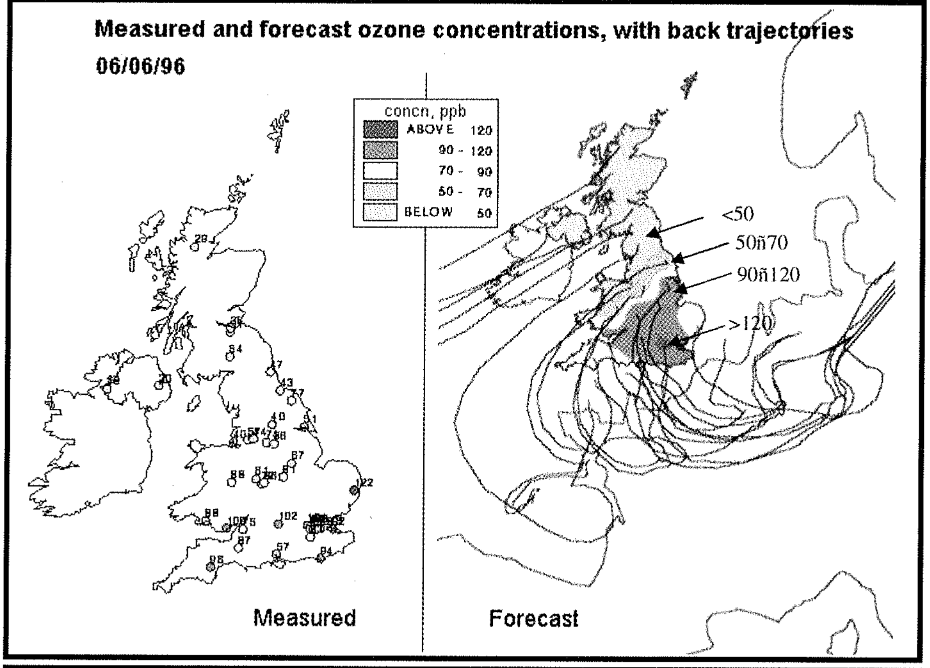
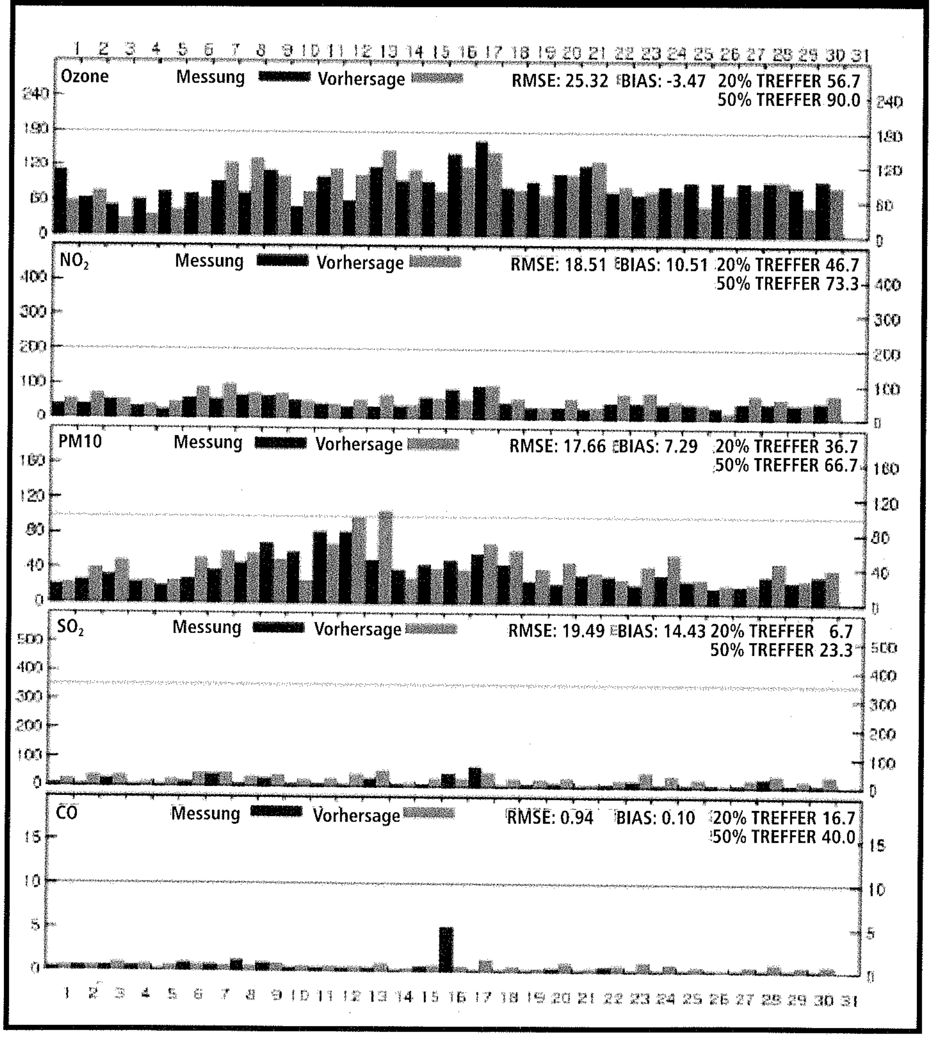



**Figure 2. Verification of the EURAD (see Table 1) Eulerian model forecasts for (top to bottom) $O_3$, $NO_2$, PM10, $SO_2$ and CO for Cologne for May 2002; forecast values are shown as light bars and measured values as dark bars. (After Institute for Geophysics and Meteorology, University of Cologne, Germany: http://www.eurad.uni-koeln.de/index_e.html )**




comprehensive in scope, but focuses on some of the major centres in Europe, North America and one in Asia. Most of the effort so far has been on regional-scale forecasting with horizontal resolution of ~25–50 km. However, increasing attention is being paid to the development of higher resolution regional-scale models, urban-scale models and local (street canyon) models.

We now examine some of the different approaches to air quality forecasting being used by the international community. The IRCEL-CELINE centre in Belgium issues 3-day forecasts for ozone and PM10 each day. The ozone forecasts use a model called SMOGSTOP and the PM10 forecasts use a model called OVL; both models were developed at the Flemish Institute of Technology. SMOGSTOP consists of several independent statistical models, based on regression, stratified pattern-matching and neural networks. OVL utilises neural networks and is based on historical data of PM10 measurements for 1998–2002, and a limited number of forecast meteorological fields from a mesoscale numerical weather prediction model. At present, the PM10 forecasts are limited to 11 stations because of the short length of the historical records, but the area of coverage will be expanded to encompass all of Belgium as more historical data become available.

The Cambridge Environmental Research Consultants produce three day to five day forecasts for certain urban centres in the UK. They do this by combining a statistical approach with a Gaussian model. They use a statistical regression model to compute correlations between historical meteorological variables and pollutant concentrations. These relations are used to predict the rural background concentrations of pollutants. This information and local emissions are fed into a sophisticated Gaussian model along with forecast meteorological variables to produce an air quality forecast for urban areas.

A Lagrangian forecasting approach is used by NETCEN and the (UK) Met Office. A sophisticated Lagrangian particle dispersion model called NAME is used to compute particle trajectories. The latest emission inventories, including area and large point sources and daily traffic flow, are included. Emissions and meteorology within the UK are modelled at ~11 km resolution and outside the UK at ~60 km resolution. The PM10 forecast includes both primary particles and secondary sulfate particles. Forecasts for 0-47 hours for $NO_x$, CO, $SO_2$ and PM10 are issued twice a day. The ozone trajectory model is run each day and provides a three day forecast for 20 monitoring sites. Figure 1 shows an example of verification of an ozone forecast and back trajectories from the monitoring sites.

The EURAD model, operated by the Institute for Geophysics and Meteorology at the University of Cologne, is a three-dimensional Eulerian model covering Europe with 125 km horizontal resolution. Within this grid, there is a nested sub-grid covering central Europe with a resolution of 25 km, and a second nested grid covering the North Rhine-Westphalia region with a resolution of 5 km. The meteorological data are obtained

Table 2. Examples of forecasting systems used by agencies in Australia.

| Institution | Region | Scale | Pollutant | Methodolgy |
|---|---|---|---|---|
| Environment Protection Authority of Victoria (EPAV) | Melbourne/Geelong | Urban scale - summer/winter, forecast is for the following day. | $O_3$, PM10 (visibility) | Parametric: statistical/expert system. |
| EPAV + Bureau of Meteorology (Bureau) | Melbourne/Geelong/ Victoria | Urban and regional. Same day and next day forecasts. | $O_3$, $NO_2$, CO, PM10, $SO_2$, Bscat | Deterministic: 3-D Eulerian photochemical model. |
| New South Wales Department of Environment and Conservation (NSW DEC) | Sydney/Newcastle/ Wollongong | Regional. Same day and next day forecasts. | $O_3$, PM10 | Parametric: statistical. |
| NSW DEC + Bureau of Meteorology | Sydney/Newcastle/ Wollongong | Urban and regional. Same day and next day forecasts. | $O_3$, $NO_2$, CO, PM10, $SO_2$, Bscat | Deterministic: 3-D Eulerian photochemical model |
| Queensland Environmental Protection Agency (QEPA) | Brisbane, south-east air quality region | Urban/regional Same day and next day forecasts.Trialling forecasts of up to seven days. | $O_3$, PM10 | Parameteric: hybrid of statistical/neural network/long-memory time series modelling. |
| Western Australia Department of Environment (WA DEP) and Bureau of Meteorology | Perth | Urban. Same day, next day forecasts. | Haze (Bscat) | Parameteric: statistical. |
| Bureau of Meteorology | Australia | Regional, same day; next day forecasts. | Smoke | Deterministic: puff/particle model. |
| As above | Launceston | Urban, next day forecast. | PM10 | Parametric: statistical. |

Table 3. Performance of original and revised versions of the Haze Robot for haze events observed in Perth in 1999 (from Rye 1999).

| Event | Alert issued | Alert not issued | Alert issued | Alert not issued |
|---|---|---|---|---|
| | Revised scheme | | Orginal scheme | |
| Haze Event | 8 | 3 | 9 | 2 |
| No Haze Event | 3 | 101 | 8 | 96 |

from the MM5 mesoscale model nested in the NOAA AVN global model. The chemical model, RADM2, comprises 63 active species and 158 chemical reactions. The aerosol model, MADE, is based on modal dynamics. A three day forecast is issued once a day. Many pollutant species are forecast, including $O_3$, $NO_2$, CO, $SO_2$ and PM10. An example of the model performance is given in Figure 2.

The National Environmental Research Institute in Denmark operates a comprehensive air quality forecasting system called THOR. This system produces 3-day air quality forecasts based on Eulerian models for regional scales, urban scales and individual street canyons on the local scale. The meteorological forecast uses the US National Center for Environmental Prediction mesoscale ETA model, which has a horizontal resolution of 10 km and covers Europe. This is nested in the AVN global model. The system also includes a Eulerian long-range transport model, DEHM, with the same chemistry, which can also forecast sand/dust storms. The urban model has a spatial resolution of 1 km and is run for the central city of Copenhagen and Aalborg, Denmark, four times a day. The output from this model is used as input for the street canyon model, OSPM, which forecasts NO, $NO_2$, $NO_x$, $O_3$, CO and benzene on both sides of the street. There is a multi-point source model for regulation applications and a Lagrangian model, RIMPUFF, for near-source transport and dispersion, with a Eulerian model, DREAM, for far-field transport and dispersion for accidental releases. An example of the street canyon model performance for the street Vesterbro, Aalborg, is given in Figure 3.

In the USA, real-time ozone air quality data from 1,200 monitors, real time PM2.5 data from 200 monitors and next day air quality forecasts for 250 cites are collated and presented in a common, colour-coded air quality index format (Wayland et al., 2002) on the U.S Environment Protection Agency's (USEPA) AirNow web site (www.epa.gov/airnow.htm). Because the density of observing sites is so high for ozone, real-time data are able to be displayed visually as contours. The USEPA and National Oceanic and Atmospheric Administration (NOAA) have recently signed a memorandum of agreement to develop a national air quality forecasting system for ozone, which will then be enhanced to include forecasts for PM2.5 (http://www-frd.fsl.noaa.gov/aq/beta/). This initiative includes the development of an advanced three dimensional Eulerian modelling system and provides for significant research and development components in the fields of numerical weather forecasting, chemical transport modelling, inverse modelling, emission inventory development and remote sensing. The program of research is projected to extend for more than a decade.

## AIR QUALITY FORECASTING IN AUSTRALIA

In Australia, air quality forecasting is undertaken by state environment authorities in New South Wales, Queensland, Victoria and Western Australia, with supporting data and guidance provided by the Bureau of Meteorology. The Bureau also issues fine particle forecasts for Launceston, provides regional forecasts for smoke and, in collaboration with the NSW and Victorian EPAs and CSIRO, runs a three-dimensional Eulerian forecast model.

A list of the systems operating in Australia is given in Table 2. It can be seen that the majority of the systems are parametric, and are used to provide 6–24 h forecasts of photochemical smog or poor visibility/fine particle loading. We now consider some of these systems in more detail.

### *Haze predictions for Perth for Western Australia Department of Environment Protection, conducted by the Bureau of Meteorology.*

The Bureau of Meteorology began issuing forecasts of poor visibility (as typified by a light scattering coefficient Bscat $> 2.1 \times 10^{-4}$ $m^{-1}$ [~ 20 km visibility]) in support of the WA DEP 'Halt the Haze' campaign, which promoted the efficient use of domestic wood burning for heating during the winter months in Perth. However, the original scheme had a poor hit rate and a parametric system was developed based on an analysis of the relationship between selected meteorological variables and the observed backscatter (Bscat) (Rye, 1999). Important meteorological determinants were found to include the predicted near-surface potential temperature gradient, the minimum overnight temperature, and wind speed and direction (in particular, the presence of a light onshore flow). Forecast variables, such as the minimum overnight temperature, are obtained from the Bureau of Meteorology.

Table 4. Probability of detection and false alarm rate for Brisbane ozone forecasts (based on 3 years of data, and without any re-training). From Killip et al. 2000.

| Time of day | $O_3$ > 60ppb | | $O_3$ > 100ppb | |
|---|---|---|---|---|
| | POD | FA | POD | FA |
| Morning | 0.41 | 0.32 | 0.28 | 0.45 |
| Afternoon | 0.45 | 0.18 | 0.23 | 0.33 |

Table 5. AAQFS probability of detection for regional and sub-regional peak 1 h ozone concentration for Sydney and Melbourne for the 2001/2002 and 2002/2003 photochemical smog seasons (there is insufficient data to accurately calculate a POD for Melbourne $O_3$ > 80 ppb).

| POD | Sydney | | Melbourne |
|---|---|---|---|
| | $O_3$ > 60ppb | $O_3$ > 80ppb | $O_3$ > 60ppb |
| **6–12h forecast** | | | |
| Regional | 0.89 | 0.42 | 0.53 |
| Sub-regional | 0.65 | 0.48 | 0.21 |
| | | | |
| **24–36h forecast** | | | |
| Regional | 0.89 | 0.53 | 0.73 |
| Sub-regional | 0.66 | 0.37 | 0.33 |

The system runs in an automated mode (the 'Haze Robot'), emailing a conditional haze forecast to the Bureau at 15 h each day. This is followed up with haze observations at 3 h and 7 h on the forecast day. Forecasters at the Bureau review the Haze Robot forecast and include other data (e.g. 900 hPa temperature and smoke observations) and, if necessary, issue a haze alert as a part of their 16:30 h public forecast. The alert covers the evening of the current day.

The scheme was revised prior to the 2000 winter season through the inclusion of an improved methodology to predict the development of the land breeze. The performances of the original and revised versions of the Haze Robot (i.e. prior to any corrections from the Bureau) for the 1999 haze season are presented in Table 3. Defining the 'probability of detection' (POD) as the number of alerts issued divided by the total number of observed events, and the 'false alarm rate' (FA) as the number of alerts incorrectly issued divided by the total number of alerts issued, it can be seen that the scheme has a POD of 0.78 and 0.74 for the original and revised scheme respectively, and a FA of 0.47 and 0.27 for the original and revised schemes respectively. Thus the revised scheme has been able to significantly reduce the number of false alarms.

### New South Wales Department of Environment and Conservation (NSW DEC)

NSW DEC issues air quality forecasts in the form of a 'No Burn Notice', a 'Don't Light Tonight Unless Your Heaters Right' advisory, and an indicator as to whether the afternoon regional pollution index is likely to improve, get worse or remain the same (the regional pollutant index [RPI] is a linear combination of the concentrations of ozone, nitrogen dioxide and light scattering coefficient divided by their respective standards). The 'No Burn Notice' is a legislative requirement which prohibits outdoor fires under conditions of prevailing poor air quality. A 'Don't Light Tonight' advisory is issued for similar conditions, and for forecast conditions of poor dispersion. In addition, a forecast is issued for a high regional pollutant index resulting from photochemical smog.

The forecasting system was originally developed more than 25 years ago at the Bureau of Meteorology (Spark 1973) and consisted of a simple decision tree based on surface wind speed, rainfall, temperature inversion strength, gradient wind speed and gradient wind direction. The methodology was expanded in the 1980s (Hawke et al. 1983) to provide separate schemes for summer photochemical smog and winter brown haze (particle) events. This system continues to be used, although it has now been modified to generate a trend, i.e. the RPI tomorrow will be better/worse/similar to today. Some guidance is also given by the Australian Air Quality Forecasting System (AAQFS, see below), which is run twice daily for Sydney. The final forecast issued to the public is also weighted by the experience of the forecaster.

### Victorian Environmental Protection Agency (EPA)

Air quality forecasting has been undertaken at the Victorian EPA since the 1970s, with one of the earliest schemes being set up to forecast ozone and nitrogen dioxide as part of a proposed reactive pollution control system for the Newport power station (EPA Victoria 1985). The scheme was then expanded in the 1980s (Morgan 1986) to consider poor visibility events and underwent further review in the 1990s (Cook 1995), before developing into the semi-automated expert system which is used at the current time (Dewundege 2001). Since 2000, the predictions of this scheme have been complemented by the forecasts of AAQFS.

The scheme is used to issue 'Smog Alerts' for days when (during the warmer months) photochemical smog is forecast to exceed 100 ppb and for days when (during autumn and winter months), the airborne particle index (API) is forecast to exceed 2.35 (corresponds to a visual distance of less than 20 km). Parameters used by the scheme are listed in Dewundege (2001) and include the forecast pressure gradient and geostrophic wind direction, the forecast minimum and maximum temperature, trends in the upper level wind speed and direction and (for winter smog) observed API for the current day. The forecast parameters are taken from Bureau of Meteorology weather forecasts. Each of the parameters is assigned a numerical weighting factor which has been derived from a correlation of the major meteorological determinants and the observed concentrations of API and ozone. A categorical test is then conducted to see whether each of the observed or forecast parameters lies within a designated range. If a forecast parameter passes the test, then its weighting factor is accumulated into a 'smog potential' score. A Smog Alert may be issued if the forecast smog potential exceeds 75/100 for API and 85/100 for ozone. The system has been evaluated and found to yield a probability of detection of 0.67 for winter smog days (API) and 0.57 for summer (ozone) smog days (Dewundege 2001).

### Queensland EPA

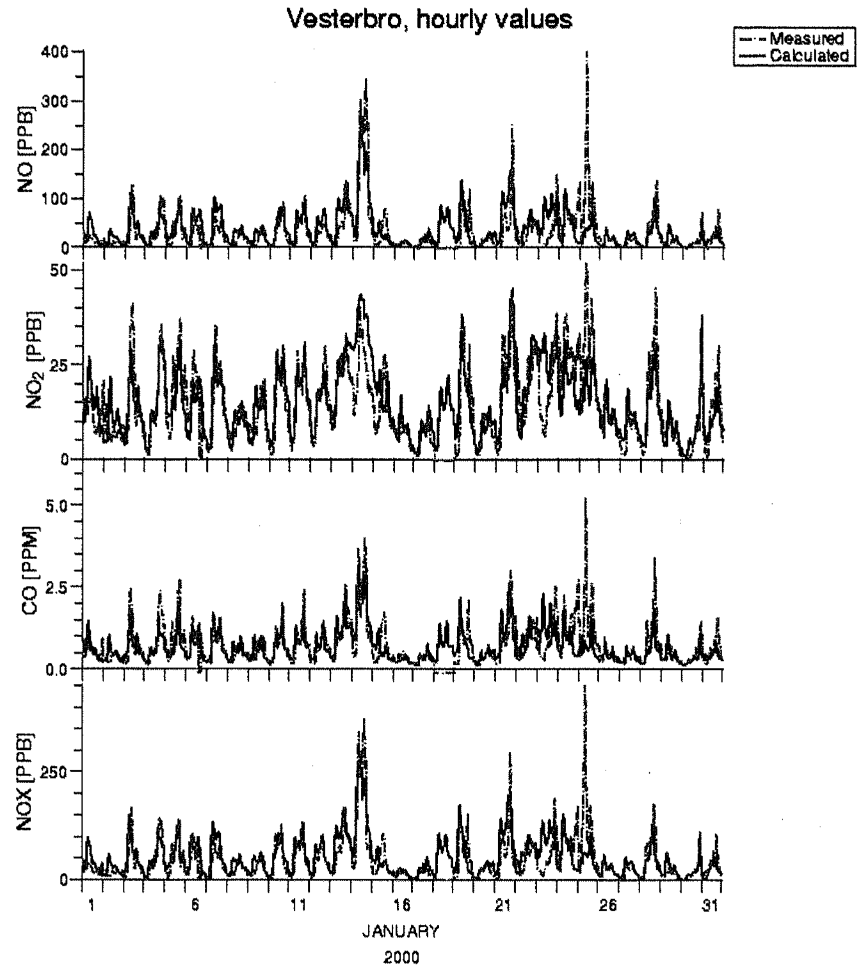
Air quality forecasting in Brisbane has historically been undertaken using an 'Air Quality Decision Support System (AQDSS)' which is briefly described in Killip et al. (2000). Using this scheme, forecasts are generated for ozone and backscatter, and are disseminated to the public as a three–tier air quality index (low, medium and high).

The basis of the system is as follows:

- A set of 63 synoptic weather types with associated probability distributions of pollutant concentration has been generated from the analysis of an extensive historical air quality and meteorological database. This information and forecast weather parameters (available from the Bureau of Meteorology) provide a forecast of synoptic type for the following day, and a first guess as to the spatial pattern of pollutants that will occur within the forecast period.
- A hybrid, long-memory time series approach is used to model pollutant time series (based on monitoring station observations for the previous few days). When combined with the forecast synoptic type, the approach yields predictions of hourly pollutant concentrations for each monitoring site for the duration of the forecast period.

The two methods, together with indicators of bushfire and rainfall likelihood are then combined to provide a regional air quality index. Preliminary results from the AQDSS for a three-year period prior to June 2000 are presented in Table 4. It can be seen that the afternoon forecast for ozone exceeding 60 ppb currently has the most favourable combination of detection probability and false alarm rate. A recent upgrade to the system to include additional spatial detail, on-the-fly re-training and the capability of providing forecasts up to seven days ahead is currently being evaluated.

**Figure 3. Verification of the street canyon model for the THOR system (see Table 1) for the street Vesterbro, Aalborg for January 2000; forecast values are shown as blue lines and measured values as red lines. (After National Environmental Research Institute, Denmark: http://www2.dmu.dk/AtmosphericEnvironment/thor/).**




### Australian Air Quality Forecasting System

The Australian Air Quality Forecasting System (Manins et al., 2002) is a deterministic (three-dimensional Eulerian model) system which solves the fundamental equations of the atmosphere to provide detailed 24-36 hour forecasts of meteorology and pollutant concentration fields for Melbourne and Sydney. Forecasts are provided for photochemical smog, urban aerosol, wind-blown dust and bushfire plume impacts. Meteorological forecasts are generated by the Bureau of Meteorology Limited Area Prediction System (Puri et al., 1998) running at a grid spacing of 5 km. Anthropogenic emissions are taken from inventories provided by the respective Environment Protection Authorities. Wind-blown dust and biogenic emissions are calculated on-the-fly during the forecast of chemical transport. Spot-fire locations for smoke plume envelope forecasting are downloaded from the CSIRO Sentinel hotspot site (http://www.sentinel.csiro.au) prior to the commencement of each forecast simulation. Chemical transformation is modelled using the Generic Reaction Set (Azzi et al. 1992) or more complex chemical transformation mechanisms if required. The Victorian forecasts are available from the Victorian EPA web site (see Table 2). An example of a forecast of peak 24-h PM10 for Melbourne is shown in Figure 4.

The forecast and observed time series of 1-h ozone for a Sydney seven day ozone episode (21-27 January 2001) is shown in Figure 5 (a composite of 24-h forecasts). It can be seen that although AAQFS is able to forecast extreme concentrations of ozone during this period, the system can have difficulty in forecasting the location of the maximum concentrations (this can be seen from the time series plots in Figure 5, where observed peaks are sometimes strongly over predicted and sometimes strongly under predicted). Such behaviour results from difficulties in correctly forecasting the location and timing of sharp mesoscale transitions (e.g. the location of a sea-breeze front under conditions of blocking synoptic flow).

Probability of detection performance figures for regional scale and sub-regional scale AAQFS ozone forecasts are given in Table 5 for 6-12 h (same day) forecasts and 24-36 h forecasts. The performance figures are provided for regional and sub-regional areas (i.e. Melbourne/Geelong is divided into east-Melbourne, west-Melbourne and Geelong). It can be see that the POD is not strongly dependent on the length of the forecast (with POD sometimes increasing as the forecast period increases from 6–12 to 24–36 h). However, it is dependent on the choice of regional or sub-regional spatial coupling, with the regional scale forecasts exhibiting a higher POD than the sub-regional scale forecasts.

AAQFS is also used to predict the onset of wind-blown dust. For the 2002/2003 summer period for the Victorian region, AAQFS was able to predict the onset of dust storms with a probability of detection of 0.58 and a false alarm rate of 0.48. This compared well with the results of a data-based persistence model (0.37, 0.63).

### Smoke forecasting using HYSPLIT

HYSPLIT, a hybrid Lagrangian-Eulerian puff/particle model, is used by the Bureau of Meteorology to predict the relative smoke concentrations for the States' Fire Authorities (Draxler and Hess 1997). The model also employs Sentinel hotspot satellite data, updated three times daily at 3 h, 6 h and 12 h (Eastern Standard Time). The hotspots are downloaded in the form of ESRI shape files and the latitude, longitude and brightness temperature are extracted. A crude filter is applied to eliminate multiple sources within 10 km and the resulting sources are grouped by state. HYSPLIT is used to produce a smoke trajectory and dispersion forecasts. Smoke behaviour advice is also provided from the Bureau for prescribed-burns planning. A link to examples of HYSPLIT smoke forecasts is given in Table 2.

**Figure 4. Example of AAQFS air quality forecast for Melbourne. (http://www.epa.vic.gov.au/Air/AAQFS/default.asp).**

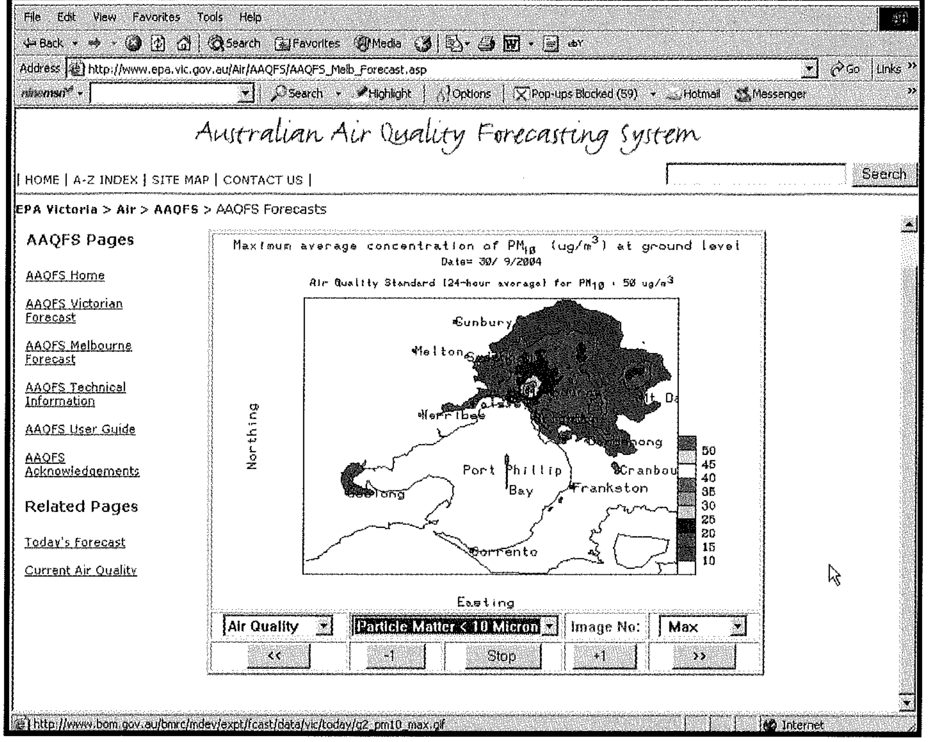
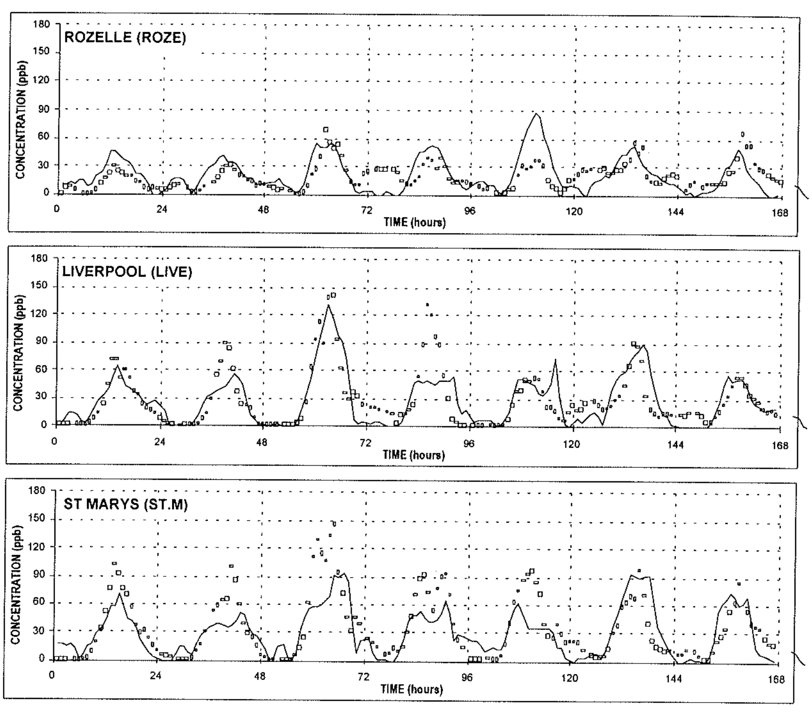



**Figure 5. Time series of AAQFS forecast ozone concentrations (solid lines) with observations (squares) for various monitoring stations in the Sydney region for a seven-day ozone event 21–27 January 2001.**




## DISCUSSION

It can be seen from the content of the previous two sections that a wide variety of air quality forecasting systems are used internationally and in Australia. Photochemical smog (primarily as ozone) and fine particles (either as PM2.5, PM10 or poor visibility/backscatter) are the two pollutant groups of most concern. Forecast periods typically extend from a few hours to a few days. There are various levels of sophistication available, ranging from experience, simple rule-of-thumb systems, to sophisticated three-dimensional numerical modelling systems. In this regard, the level of technology used in Australia is comparable to those used internationally and the accuracy of the best Australian forecast results is comparable to the best internationally.

A common linkage in the Australian systems is the Bureau of Meteorology, which provides either routine or specific meteorological data for use by the systems. It is also responsible, together with participating EPAs and CSIRO, for the operation of AAQFS, and other modelling systems for forecasting the large-scale transport of smoke and wind blown dust.

Resources continue to be applied to improving air quality forecasting in Australia, at both the state and commonwealth level. For example, the EPA Queensland system has recently been upgraded; the South Australia EPA recently commissioned a scoping study to investigate the implementation of a forecasting system in that state; the Bureau of Meteorology, CSIRO and participating EPAs continue to refine components of AAQFS. In this regard, Victoria EPA has upgraded its air emissions inventory and plans to incorporate the revisions into the forecasting system; operation of the system in Victoria is currently being reviewed and streamlined; and a continental-scale version of AAQFS with a horizontal resolution of 25 km is being tested over the 2004/2005 summer.

The Bureau is developing a non-hydrostatic version of LAPS, its operational numerical weather prediction system. When completed, the system will be able to generate very high–resolution forecasts for selected regions (i.e. 1 km horizontal grid spacing), which potentially can be used to provide more accurate input to the current suite of Australian forecasting schemes.

One of the deliverables for the Cooperative Research Centre for Bushfires (http://www.bushfirecrc.com/PDF%20Files/BfCRC%20Handbook.pdf) is a module which can be used for estimating the trace gas and aerosol species emitted from bushfires, for forecasting purposes. Such a module will provide more refined estimates of the heat flux and the speciated aerosol and trace gas emissions. When applied within numerical models this should yield improved predictions of plume rise, fine particle concentrations and the influence of bushfire-generated photochemical smog precursors on photochemical smog production within regional airsheds.

CSIRO, in collaboration with researchers at Australian National University, have commenced a study to investigate the potential for directly forecasting changes in daily hospital admission rates using forecast meteorological and pollution fields and health response factors derived from local epidemiological time-series studies. This approach is an extension of a system which is currently being trialled in the United Kingdom (http://www.meto.gov.uk/weather/europe/uk/heat_health.html ).

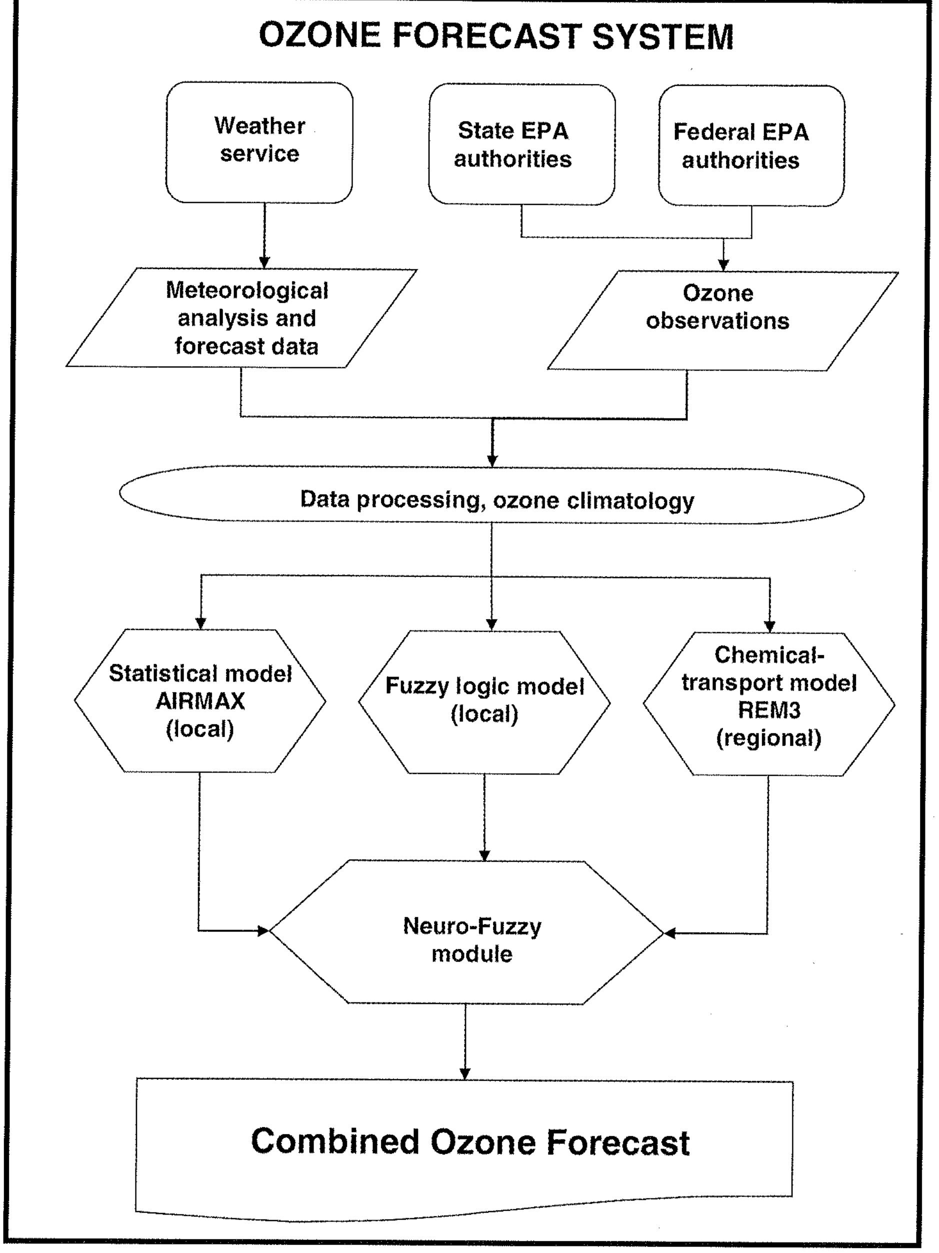
Europe and the United States of America have programs in place which unify the reporting of observed and forecast data. For example, the US Environment Protection Authority has partnered with state and local air authorities to provide real time and forecast air quality through the EPA's AirNow program (Wayland et al. 2002). AirNow uses a single air quality index to relate pollution concentration and health impact to a set of colour codes. For example, code orange corresponds to days on which peak 1 h ozone concentrations are observed or forecast to lie in the range 125–164 ppb (125 ppb corresponds to exceeding a threshold of 120 ppb, when the data are rounded to the nearest 5 ppb). A code orange day corresponds to an air quality index in the range 101–150 and carries the health impact summary 'unhealthy for sensitive group'. The European Union mandates a more detailed scheme. Some of the Australian EPAs have adopted a similar approach, at least for reporting real time data (i.e. Queensland, South Australia, Victoria, New South Wales), and in the case of AAQFS, for reporting forecast data. Unfortunately, the methodologies for calculating the air quality indices and the associated colour mappings are not always comparable. For the most part, the Australian forecasting systems are able to generate continuous indices which can be mapped to a set of discrete ranges, and thus it should be possible to present the forecasting results within the same framework.

The majority of the Australian forecasting systems represent a blending of more than one methodology to achieve an optimal forecast. For example, the Western Australian haze forecasting system consists of an automated conditional forecast that is delivered to forecasters at the Bureau who add in other data (i.e. the proximity of bushfire plumes), and finally apply their own experience before issuing a forecast. In Victoria, the forecast results from the blending of an in-house expert system, AAQFS and operator experience. Where more than one automated system is involved, the possibility exists for blending the results using techniques based on neural networks or fuzzy logic. An example of what this might look like is given in Figure 6.

In addition to very high-resolution forecasting and blended forecast results, the other major future direction in air quality forecasting will be the introduction of ensemble forecasting and model-data fusion. The former will involve multiple forecasts with perturbations in the meteorological, chemical and emissions fields. Uncertainties in each of these fields can lead to errors in the forecast. By combining many forecasts with perturbed initial fields the forecast errors can be reduced. Also, an estimate of the error of the forecast can be obtained.

There are major national cooperative efforts (e.g. in the United States) and multi-national cooperative efforts (e.g. by the European Union) to develop far-reaching integrated air quality forecasting programs. It is recommended that an integrated research and development program similar to the CLEAR projects in Europe (see: http://www.nilu.no/clear/) be implemented in Australia. This program would provide increased scientific understanding of the sources and processes involved in air quality forecasting, enabling the development of improved models; provide improved methodologies of assessment of the impacts of pollution; develop strategies for reduction of pollution; strengthen the interface between air quality science and those charged with the responsibility for air quality regulation. The challenges to be faced are significant. If Australia is to provide the public with the leading-edge information for the social and economic welfare of the community, the small isolated human and material resources in the field of air quality need to be pooled. This would have the added benefit of providing a nation-wide uniform approach to air quality data collection and assessment. We note that preliminary discussions are underway within a Subgroup of the Air Quality Working Group of the Environment Protection and Heritage Council on the development of a unified air quality forecasting/strategic modelling system for potential application by the state environment agencies and their partners.

**Figure 6. Schematic flow diagram representing local and regional forecasts from statistical regression, fuzzy and numerical models blended with a neuro-fuzzy model and combining input data from the Weather Bureau and Environment Protection authorities to produce an ozone forecast. (After Tropical Environmental Research, Institute of Meteorology, Free University of Berlin, Germany http://trumf.fu-berlin.de/ozonprognose/ozonprognose_e/index.htm )**




We complete this review by noting that our discussion has been directed towards the science and application of short-term forecasting. However, there are also multi-national cooperative efforts underway to forecast long-term air quality (i.e. under greenhouse warming scenarios – see Patz et al. 2004). Perhaps environmental agencies in Australia should also consider including this area of research in their air pollution science programs.

## ACKNOWLEDGEMENTS

The authors would like to thank Peter Rye, Piya Dewundege, Michael Johnson, David Wainwright, Peter Best, Doug Shepard and Barry Cook for their help in providing information for this review.

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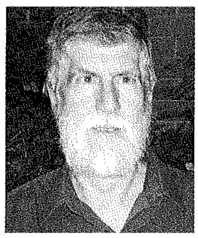


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*Editor's note: We are continuing to have occasional problems with diagram quality in technical articles, and hope to resolve these in the very near future.*