Developments in Environmental Science, Volume 8 535
A. Bytnerowicz, M. Arbaugh, A. Riebau and C. Andersen (Editors)

ISSN: 1474-8177/DOI:10.1016/S1474-8177(08)00023-5

# Chapter 23

# Managing Smoke from Wildfires and Prescribed Burning in Southern Australia

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## Abstract

In Australia the responsibility for management of forests and other public lands rests largely with state governments, and multiple government agencies may be involved in fire management. Whether resulting from wildfire, fuel reduction, or silvicultural operations, biomass burning often stimulates community concerns about hazards from fine particulates and chemical compounds contained in smoke. Management practices and community perceptions of smoke from biomass burning differ from region to region according to social and environmental factors. Recognition of the need for a response to concerns has led to the development of a smoke management research program within the Bushfire Cooperative Research Centre, in conjunction with fire and land management agencies and the Australian Bureau of Meteorology (the Bureau). This program aims to assist land management planning by predicting where smoke from scheduled burns would be transported, thus providing the opportunity to avoid burning in situations where there is potential for adverse community impact. The primary tool provided is a dispersion model forecast using input from the Bureau's operational mesoscale numerical weather prediction (NWP) models. Decision tools are applied in a similar manner for prescribed burning and wildfires and have been used by agencies to provide community advice and to avoid smoke hazards during aircraft operations. We investigated strategies used by land management agencies to minimize community impact of smoke from prescribed burns, and studied the way in which the dispersion model forecasts are integrated into their decision support systems. Included

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are details of HYbrid Single Particle Lagrangian Integrated Trajectory's (HYSPLIT) configuration, several examples of its use in prescribed and wildfire events, and the research direction being pursued to improve both the quality of the dispersion forecasts and to enhance the use of these forecasts in agency planning.

## 23.1. Introduction

We describe the development and implementation of smoke dispersion forecasting in southern Australia representing areas of the continent below latitude 30°S including the southern third of Western Australia, most of South Australia and New South Wales (NSW), and all of Victoria and Tasmania (Fig. 23.1). We focus on this region because it includes six of the nation's capital cites, the majority of Australia's population, and much of the transport and industrial infrastructure on which the nation depends. The socio-economic setting of southern Australia, in combination with the generally fire-prone nature of the landscape, results in a situation where management of smoke from fires in native vegetation is an important and topical issue for land managers, the

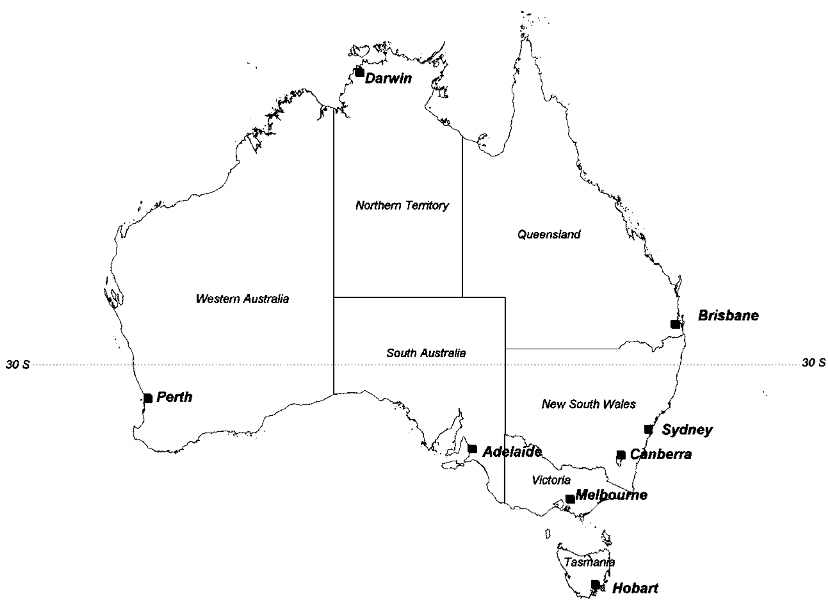


*Figure 23.1.* Map of Australia showing state boundaries and capitals.

community, and governments. Notwithstanding this, fires in the vast rangelands and tropical savannas of northern Australia contribute the majority of Australia's fire-related emissions of greenhouse gases, particulates, and volatile organic compounds (Australian Greenhouse Office, 2006; Meyer et al., 2004).

Large areas of southern Australia are managed for agricultural land uses including dryland cereal cropping, grazing, and irrigated horticulture. Agricultural landscapes are typically flat to gently undulating with small remnants of the original woodland vegetation dispersed amongst broadacre paddocks of introduced crops and annual grasses. Pastoralism for sheep and cattle production is also widespread in semi-arid areas with annual rainfall below 350 mm. Tall forests, comprised predominantly of eucalypts, occur in association with the Great Dividing Range that rises to elevations above 2000 m and extends northeast from Melbourne, through the Australian Capital Territory and into northern New South Wales, where it forms a distinct escarpment separating elevated tablelands from coastal lowlands. Much of Tasmania is mountainous and heavily forested, with eucalypt forests giving way to temperate rainforest in high rainfall areas on the western half of the island. Eucalypt forests also occur in the southwest corner of Western Australia extending southwards from Perth to Albany in areas where annual rainfall exceeds 600 mm.

The climate of southern Australia is dominated by the subtropical band of high pressure that migrates north and south across the southern half of the continent with the change of seasons. During the winter months, cold fronts embedded within moist westerly and southerly winds on the southern side of the subtropical ridge bring rainfall to areas up to several hundred kilometers inland. Annual rainfall declines and becomes more variable with increasing distance from the coast, although occasional heavy summer rainfall may result from decaying tropical cyclones. Southerly areas experience a summer/autumn fire season with fire danger highest from December to March, whereas much of eastern NSW experiences peak fire danger during spring (Luke & McArthur, 1978). Fire regimes in forested landscapes of southern Australia have recently been reviewed by Gill and Catling (2002).

State government agencies are responsible for managing a high proportion of the forest and other remaining native vegetation in southern Australia (National Forest Inventory, 2003). Multiple-use forestry is practiced on state forests, with national parks and other categories of land reserved for nature conservation and recreation. Land management agencies operate within a framework of state legislation governing fire protection and emergency response in rural landscapes and are responsible for integrating fire with land uses and for responding to unplanned fire events (wildfires).

Prescribed fire is used for a range of purposes, including regenerating forests after timber harvesting, managing wildlife habitat, and limiting the accumulation of flammable litter and understorey fuels in order to reduce the intensity and suppression difficulty of unplanned fires. Forest regeneration burning is generally confined to harvested areas and adjacent buffer strips that may be on a scale of tens, and sometimes hundreds, of hectares. Burning is often conducted under dry conditions at the end of the summer in order to maximize consumption of large woody debris and creation of ashbeds favorable for eucalypt seedling establishment. Ignition techniques and burning conditions conducive to strong convective activity may be used to generate intense fires (Tolhurst & Cheney, 1999).

In contrast, prescribed fires implemented to reduce fuel loads in forests and other vegetation types are typically of low to moderate intensity ($<$ 3000 kW m$^{-1}$; Cheney, 1980) and are lit under stable atmospheric conditions. The scale of prescribed fires used to reduce fuel loads varies from limited burning around high value built assets and urban interface zones to landscape scale application of strategic burning programs. Prescribed fire can be applied to thousands of hectares in a single day using aerial incendiaries under suitable conditions of weather, terrain, and forest type. Aerial ignition was introduced in the late 1960s following a period of intensive research and development into fire behavior prediction and aerial ignition technology (McCaw et al., 2003; Packham & Peet, 1967). The extent of prescribed burning conducted for fuel and habitat management purposes varies considerably from year to year according to seasonal conditions. Typically, 150,000–200,000 ha per annum are burnt in southwest Western Australia, predominantly during the spring months (October to December). In the southeastern states including Tasmania prescribed burning tends to be undertaken during autumn (March to May) with an aggregate area of 100,000–150,000 ha per annum across Victoria, NSW, and Tasmania. Until recently, the use of prescribed burning in land management has been very limited in South Australia. Increasingly, burning prescriptions are seeking to create mosaics of burnt and unburnt vegetation within a designated management area to better accommodate biodiversity conservation objectives (Burrows, 2004). This may require ignition to be conducted in a dispersed pattern over a large area and staged over a period of days or weeks to optimize burning conditions for fuel types that dry at different rates.

Australia's population is concentrated in large coastal cities, and the proportion of the population living in traditional rural communities continues to decline. At the same time, major cities are experiencing rapid growth of peri-urban communities at the interface with agricultural lands and native vegetation under public or private ownership (Cottrell, 2005). This trend has important implications for fire management, including an increasing risk to peri-urban communities from wildfires and changing community expectations in relation to environmental factors including air quality and visibility. Rural communities dependent on agriculture or forestry tend to be more tolerant of occasional inconvenience from smoke than do peri-urban communities sustained by manufacturing and service industries. Smoke haze events from prescribed burning that affect major urban centers can also provide a catalyst for broader debate within the community about the perceived impacts of prescribed fire on the environment and its effectiveness in reducing the scale and severity of wildfires (Esplin et al., 2003). Away from the urban interface, other rural land users including viticulturalists and tourism operators may have an expectation that smoke from prescribed burning will not unduly impact their activities at critical periods of the year. Currently, there is no attempt to regulate or manage smoke dispersal from burning on agricultural lands or private forests even though it may contribute substantially to the volume of smoke in the atmosphere in some years, particularly during late autumn when stubble is burnt prior to sowing of cereal crops.

The importance of managing smoke from prescribed burning was realized at the outset of the aerial burning program in Australian forests, with initial research seeking to characterize the composition of bushfire smoke, its dispersal, and its ultimate fate in the environment (Vines et al., 1971). Further studies quantified the amounts of nitrogen dioxide ($NO_2$) and sulfur dioxide ($SO_2$) in smoke and the extent of ozone formation on the top of the smoke plume (Evans et al., 1976), the latter being of potential concern because of its role in photochemical smog (Evans et al., 1974; Rye, 1995). Recognizing the need to avoid smoke accumulation over airports and major population centers, some agencies developed decision models based on basic weather factors (current and future wind direction, inversion strength), scale of proposed burning, and distance from the proposed burn to the impact area (Sneeuwjagt & Smith, 1995). Preliminary research by the Australian Bureau of Meteorology (the Bureau) also demonstrated that useful forecasts of smoke transport could be achieved by combining mesoscale numerical weather predictions (NWPs) with a transport model (Mills et al., 1996). This led to an initial agreement in 2000 between the Australasian Fire Authorities Council and the Bureau for a project to develop a system to aid decision making for smoke management from prescribed burning. This chapter describes the subsequent research conducted by the Bushfire Cooperative Research

Centre to integrate dispersion model forecasts into fire management support systems.

## 23.2. Forecasting smoke dispersion

The smoke dispersion forecasting system developed for southern Australia consists of a 12-hour dispersion forecast based upon meteorology from a mesoscale NWP model delivered via the World Wide Web (WWW). Smoke forecasts began as a trial program in three states during 2001 and were expanded to a national coverage in 2004.

### *23.2.1. Meteorology*

The meteorological information required for the smoke dispersion forecasts is obtained from NWP model fields. The Bureau operates a hierarchical suite of limited area NWP systems over Australia, with latitude/longitude grid resolutions ranging from 0.375° to 0.05°. These are all variations of the Limited Area Prediction Scheme (LAPS) system described by Puri et al. (1998). Until March 2006, smoke dispersion forecasts for all Australian states utilized the 0.125° grid version of meso-LAPS, this being the highest resolution configuration covering the entire continent. Having 29 levels, with some 10 levels below 1500 m above the surface, 48-hour forecasts are calculated twice daily at 0000 and 1200 UTC. The full atmospheric state is output every 3 h of the model integration. In March 2006 the staged implementation of the 0.05° grid version began. This model version is available for limited areas of Australia on independent grids generally co-incident with capital cities. Its initial conditions are derived from the 0.375° LAPS, and the operational version currently has 29 vertical levels, with the horizontal grid spacing of 0.05° equating to a distance of approximately 5 km. Areas not covered by the 0.05° meso-LAPS will continue to use data from the 0.125° version.

### *23.2.2. Transport-dispersion model*

The transport and dispersion model used is version 4 of the HYbrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) modeling system (Draxler & Hess, 1997). This model is a hybrid Lagrangian/Eulerian transport and dispersion model, with the advection and diffusion calculations performed in a Lagrangian framework, and the concentrations calculated on an Eulerian grid. Diffusion is modeled in a combined particle/puff formulation to take advantage of the increased accuracy in the vertical diffusion calculation of the particle formulation, and of the efficiency of the puff formulation in the horizontal diffusion.

The HYSPLIT model is highly configurable. For operational smoke forecasts the concentration grid is specified with a horizontal spacing of $0.05^\circ$ and four levels at 10, 150, 500, and 1500 m. While near-surface concentrations are most important for determining possible adverse community impact, it was found that the most useful product for verification, particularly when comparing forecasts with remote sensing data, was given by the average concentration through the four vertical levels of the concentration grid. To provide quantitative forecast guidance it is necessary to specify a source plume for the prescribed burn, both in terms of a source concentration and of an initial plume rise. It quickly became apparent that the current degree of uncertainty in the amount of fuel to be burnt and its moisture content made the calculation of plume rise from any individual planned burn unrealistic. In addition, emissions models for these burns were not available, meaning that source particulate concentrations could not be specified. Accordingly, for the first version of the system, an arbitrary source concentration of one dimensionless unit was specified. Forecast concentrations are relative to that arbitrary value. Contour intervals for concentration plots were then selected such that the outermost contour roughly coincided with the "edges" of the visible smoke plume based on some early field observations provided by participating agencies, and the forecast relative concentration plots are interpreted in this way by the agencies. The plumes are specified to be 1500 m in height, chosen because this approximates the typical height of the subsidence inversion that is a common feature during the ideal prescribed burning conditions of clear-sky conditions with light winds. Case studies (Wain & Mills, 2006) indicate some more problematic forecasts could be improved if the height of the smoke plume is set to the depth of the diurnally varying mixed layer from the meso-LAPS model. An amended version of HYSPLIT, which contains this formulation, has been tested and implemented in selected states. However, the latest revision of the software, HYSPLIT 4.8, contains provision for plume rise calculations that utilize the buoyancy terms of Briggs' equations and the total heat output of a fire. While testing of this new feature is in progress, the lack of fuel data noted earlier may limit its usefulness to research applications.

### 23.2.3. Timing

Each state has determined a number of locations representative of forest management areas where prescribed burns are planned. Dispersion forecasts are prepared based on each of these potential fire locations, with three ignition times each day spanning the times during which fires would normally be lit. These times have been chosen by each state to suit their operational practices, with the earliest ignition time being 1000 local time (0000 UTC), and the latest 1600 local time (0600 UTC) with either 2 or 3 h between each time. Forecasts are grouped regionally, but with only two or three source points on each display panel in order to minimize the possibility of overlapping plumes reducing the clarity of the guidance. The number of source points per state ranges from 8 to 12. In the early afternoon, forecasts based on the 1000 local time NWP model run are prepared for ignition times "tomorrow." This guidance is intended for use in broad decision making regarding the next day's burning program. As the forecast is already some 24 h in the future at the initiation of the modeled smoke plume, and with the expectation of a later forecast generally being more accurate than an earlier one, a later set of runs based on the 2200 local time NWP model forecast, is prepared overnight. These are available at the commencement of final planning in the early morning, and are intended to be used for final "yes or no" decisions at particular sites. A feature of the system is that an agency can interactively change the coordinates of a source point to a particular location of interest before the 1200 UTC NWP forecast is run. Thus, if a planned burn of particular interest lies between two of the standard ("fixed") points and it is considered that these points may not be representative of the desired point, then the source position can be amended via the submission of a Web-based form.

### *23.2.4. Operational products*

The smoke dispersion forecasts are provided as a set of graphical products delivered via the WWW from a secure section of the Bureau's Web server to which only user agencies have access.

The basic forecast product (Fig. 23.2) shows multiple smoke plumes that are contoured according to their relative concentration levels and each contour is shaded to aid in discrimination. The contours overlay a reasonably detailed map background containing the locations of major roads, coastline, and built-up areas. The initial display is currently in the form of an animated gif file. Manual controls are provided to allow users to step through the forecast. Navigation buttons provide access to alternate start times and locations, other information pages, and forecast atmospheric profiles that are generated for each starting point.

The latter are aerological diagrams of the skewT-logP form (tephigrams) (Fig. 23.3). These are provided for each source location at 3-hour intervals through the forecast period. Derived from the meso-LAPS

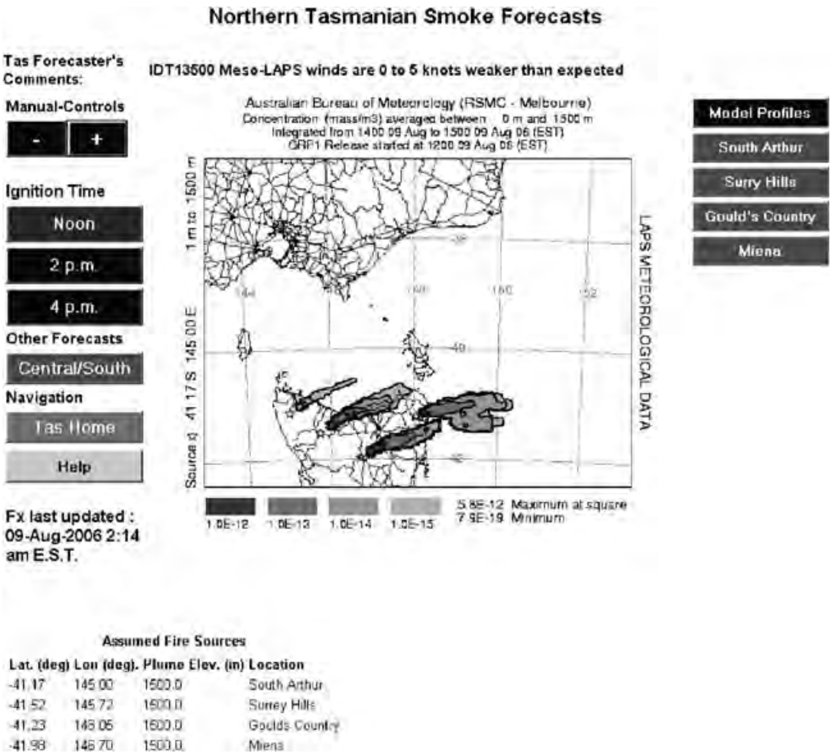


*Figure 23.2.* Operational smoke forecasts for Northern Tasmania.

model, the forecast vertical profiles shown in these diagrams provide users with forecasts of additional fire weather information, such as stability, inversion height, and vertical profiles of wind speed and direction and temperature. A ventilation index is also calculated and printed in the top right of the diagram. Derived from a similar U.S. index (Ferguson, 2001), this provides users with an indication of the expected ability of the atmosphere to disperse any smoke (or other pollutant) at the time of the forecast.

Forward trajectories track the projected route followed by a hypothetical parcel of air. Since the inception of the smoke forecasting system, Victoria has utilized forward trajectory forecasts from 18 locations across the state. The path followed by a forward trajectory is equivalent to the centerline of a plume dispersion forecast calculated from the same point. Trajectories require much shorter computation times, an attractive feature when considering many source points.

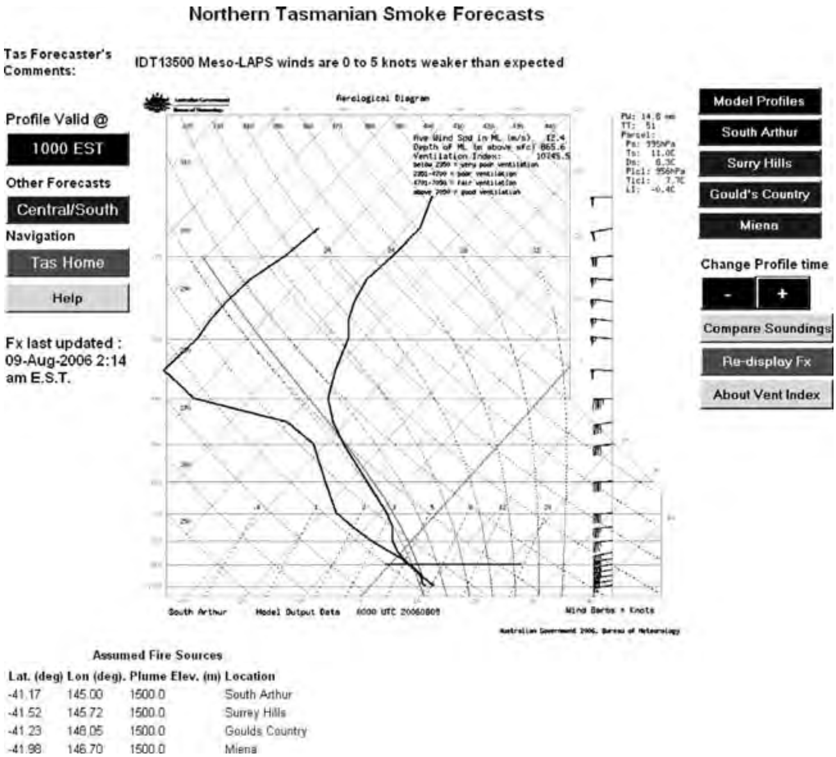


*Figure 23.3.* Aerological diagram of smoke forecasts for Northern Tasmania derived from model data.

While not part of the basic smoke dispersion forecasting system, backward trajectories have been widely used in air pollution studies to identify potential pollutant source regions, and as such are a very useful aid to decision making. During the Melbourne Commonwealth Games forecast back trajectories were calculated for several vertical levels at 3-hourly intervals from all major games locations (Fig. 23.4). This assisted in planning for prescribed burns by identifying where the air reaching the games venues was coming from over the forecast period.

Perhaps the most important aid to informed decision making is suitable training. A recent survey of land managers highlighted the need for general meteorological and smoke-specific training within their organizations. An html-based modular instruction guide has been designed to provide users information on basic meteorology, stability, and the models used to create the forecasts. In the final section all this information is used

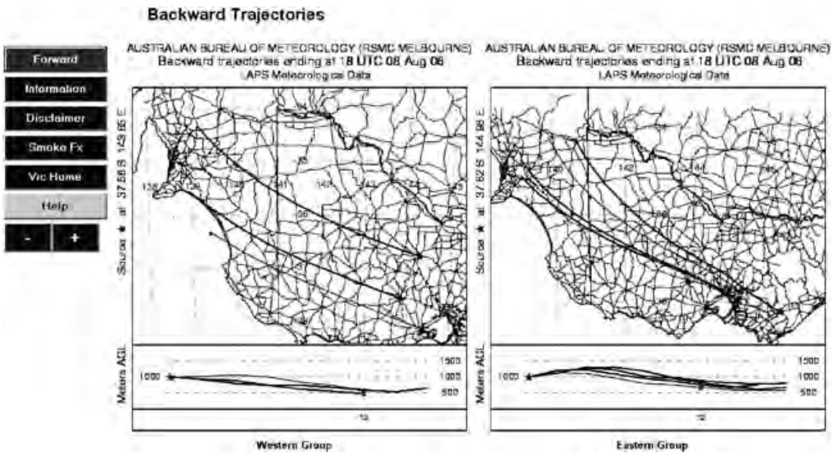


*Figure 23.4.* Backward trajectories from Commonwealth Games venues in Victoria.

to demonstrate to the user how the various products should be used and interpreted. The wider dissemination of this guide via the Web together with more formal training sessions is planned.

Another forecast aid end-users have identified as invaluable is the comment by operational weather forecasters regarding the validity of the underlying meso-LAPS model data. Initially these were very brief descriptions, such as ‘‘Meso-LAPS winds are 5–10 knots stronger than expected.’’ However the inclusion of more detailed comments including details of inversion heights and wind shifts has made them a very useful aid to users in assessing the likely accuracy of smoke forecasts.

### *23.2.5. Wildfires*

Land managers can do little to control smoke from wildfires. Nonetheless, smoke dispersion forecasts can assist them with providing information to the community about the likely presence of smoke in their vicinity. This information can be important to vulnerable groups within the community such as asthmatics, particularly in situations where smoke plumes contain toxic compounds released by the combustion of industrial or agricultural chemicals (Wain & Mills, 2006). Forewarning of reduced visibility on major roads can also minimize disruption to transport networks and commuters. Interruptions to transport networks caused by smoke from wildfires are by no means restricted to the present day; Foley (1947) reported a notable haze event in Western Australia in

February 1924 when dense smoke from bushfires in coastal shrubland around Perth disrupted shipping movements over several days and caused a ship to run aground in Fremantle Harbor.

While improvements in dispersion forecasting have been impressive, smoke from prescribed fires may still accumulate over population centers in situations where a burn has been commenced and must be completed prior to the expected onset of severe fire weather conditions. This is most likely to occur with burns containing several vegetation types with different rates of fuel drying, as is the case in the southern karri (*Eucalyptus diversicolor*) forests of Western Australia and the foothill forests of southeastern Australia where the meteorological aspects exert a strong effect on fuel drying.

Knowing where the smoke is going to be is of great interest to the general aviation industry and to fire aviation controllers whose fire support aircraft operate under visual flight rules and need good visibility for take-off and landing. This was highlighted during the Alpine Fires in Eastern Victoria during January to February 2003 when large areas were blanketed by thick smoke for extended periods. Normal smoke forecast points were relocated to correspond with the going fires. Also, at this time hotspot data from the MODerate resolution Imaging Spectroradiometer (MODIS) instrument became readily available and daily smoke forecasts were made from all hotspots.

Most recently an automated system was implemented for the Commonwealth Games that queried the Department of Sustainability and Environment's (DSE) database for active fires at frequent intervals and ran smoke forecasts from the fire locations every 3 h (Fig. 23.5).

### 23.3. Future directions

Smoke management in southern Australia has progressed from its beginnings of a basic forecast of the path traveled by a smoke plume to the current system that includes

- Model aerological diagrams
- Forward and backward trajectories
- Forecasts from MODIS hotspots
- Ventilation Index

Impetus for further development is coming from increasing community concerns for public health and "global warming," two factors likely to

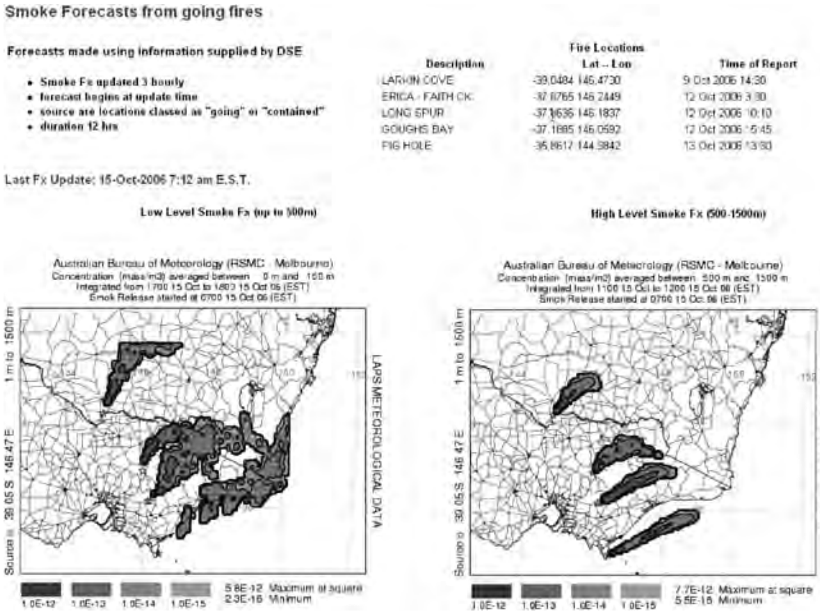


*Figure 23.5.* Smoke forecasts from wildfires in Victoria.

impinge upon future prescribed burning operations. Already there is increasing pressure from regulators to meet tougher emission standards for respirable particles. Current Australian regulations lag behind the U.S. standards. However, we foresee this changing in the near future, thus increasing the requirement for more sophisticated smoke management tools.

To assist in the determination of future directions, a survey of users was initiated in June 2006 (Wain et al., 2008). Sixteen staff in five agencies were interviewed and questioned about their experiences with the current smoke forecasts and their vision for future requirements. Areas of focus included usefulness, requirements, standards, other needs, and barriers to use. While generally satisfied with the usability of the current system, respondents indicated a desire for:

- More accurate quantitative forecasts
- Better visualization including 3-dimensional views
- Longer forecast outlook
- Integration with other available meteorological data
- Inclusion of pre-existing smoke.

The survey also addressed the future use of probabilistic ensemble forecasts, if and when they were available, which had received a positive user response. The exact type of ensemble to be used is unclear. Draxler (2003) utilized a perturbed source location to generate an ensemble of 27 dispersion members using a single meteorological dataset. Straume (2001) used meteorological data from both individual ensemble members and ensemble forecast cluster means as input for a dispersion model. In addition to perturbations to the meteorological fields, there is considerable merit in using variations in plume rise (varying fire intensities) or varying emission factors in future systems to provide greater ensemble spread in the concentration forecasts.

Improved meteorology and transport models should assist in achieving the end-user's desires for a more accurate forecast. The smoke forecasts in several states are already using a finer resolution NWP model than previously available. Future needs will necessitate finer scales to capture topographic/local-scale influences. An experimental version of meso-LAPS with 51 vertical levels is currently being assessed. Most of the additional levels are within the region of most interest to users of the smoke dispersion forecasts: the atmospheric boundary layer. The Bureau is also testing a rapid update version of meso-LAPS with new model runs available at 6-hourly intervals rather than the current 12 h. The increased temporal resolution should reduce errors later in the forecast period.

The current version of HYSPLIT is 9 years old with essentially only minor revisions made to the source code since the last major rewrite in 1997. It is a transport and dispersion model not an air quality model and as such does not perform sophisticated chemistry calculations required for deterministic concentrations. One initial aim of the project was to conduct a gradual move from HYSPLIT to a full atmospheric chemistry model, the Australian Air Quality Forecasting System (AAQFS; Cope et al., 2004). The current smoke dispersion forecast system does not provide quantitative results, while AAQFS does not include emissions from prescribed burns in its pollutant inventory. This is largely because of the lack of a suitable emissions model to provide "realistic" estimates of the pollutants produced during the combustion of Australian biomass. Such a model will require up-to-date vegetation mapping and some form of growth and litter accumulation model to calculate fuel loads. At present significant uncertainty exists in the available estimates for emissions such that quantitative forecasts are not attempted. The development of such vegetation mapping, growth, and emissions models will enable smoke forecasting in Australia to progress to a level where useful quantitative forecasts can be provided not only to the land managers but also to the general public.

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