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Bureau of Meteorology Research Centre and
Bushfire Cooperative Research Centre

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The work presented in this report has been completed as part of Project B2.1 (Management of Smoke Plumes and Hazes from Urban and Rural Fires) of the Bushfire Cooperative Research Centre (www.bushfirecrc.com). More details of the project aims and its relation to other Bushfire CRC projects can be found on this website.

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Abstract

In order to assist land management agencies to plan prescribed burns in a way that minimises the impact of the resulting smoke on population centres, the Bureau of Meteorology Research Centre, with funding from the Australasian Fire Authorities Council and subsequently the Bushfire Cooperative Research Centre, has developed a smoke management guidance system for land management agencies in all States of Australia. The system uses mesoscale NWP model forecasts to provide the meteorological forecast fields on a 0.125° latitude longitude grid covering all of Australia, and the HYSPLIT_4 transport and dispersion code to simulate the dispersion of smoke plumes.

Source points are specified at locations chosen by the agencies to represent major planned operations in their areas, but there is the facility for the agency staff to interactively modify the locations of these points. Two sets of forecasts are computed each day, each for a range of ignition times. The first set of forecasts is prepared in the early afternoon, based on the morning run of the NWP model, and is for ignition times “tomorrow”: these forecasts are for broad planning purposes. A second set of forecasts is prepared overnight, based on the evening model runs, and provides updated information available at the commencement of work in the morning: these forecasts are used to confirm (or otherwise) decisions made the previous afternoon, prior to the prescribed burns being lit. The forecast products are provided via a password-protected website, and are integrated with the Bureau’s other fire weather forecast products to maximise forecast consistency.

The design of the system is described in this report, and examples of its performance for a range of case studies for which verification data are available are presented. Some of these cases are for prescribed burns, some for wildfires, one industrial accident, and two long-range transport applications. The performance of the system will be discussed and evaluated, and future directions discussed.

Introduction

Land management agencies use prescribed burning to achieve fuel reduction, flora and fauna management, or commercial forest management (reestablishment of harvested forests) (Tolhurst 2003). However, many of the higher priority fuel reduction areas are near population centres, and it is desirable that the smoke from these fires does not adversely affect the amenity or health of these communities. Indeed there are air quality standards specified in the National Environmental Protection Measures (http://www.ephc.gov.au/nepms/air/air_nepm.html) that should not be exceeded. In addition, smoke can be a traffic hazard if it blows across highways, and can adversely affect aviation operations and safety if visibility is reduced near airports. In response to requests from land management agencies it was demonstrated in the mid 1990's that useful forecasts of smoke transport could be achieved using the Bureau of Meteorology's (hereafter the Bureau) emerging mesoscale NWP models in combination with a transport model (eg Mills et al 1996). This led to an agreement between the Australasian Fire Authorities Council (AFAC) and the Bureau of Meteorology Research Centre in 2000 for a two-year project to develop a system by which land management agencies could be provided with forecasts to aid their planning of prescribed burns with the aim of reducing the community impact of smoke from these fires. This project commenced in late 2000, was subsequently extended to the end of June 2003, and then formed the basis for a project within the Bushfire Cooperative Research Centre's research program from July 2003.

The first purpose of this report is to describe the numerical systems that are used to provide the smoke guidance system, and to describe the strategies used to deliver the guidance products to the agencies. An important part of the design process was the inclusion of both Bureau forecasters and agency users in the development of the delivery system, and so the guidance products are designed to meet both the needs and the timing of the land management agency's decision-making process. The second part of this report presents examples of the smoke management guidance forecasts and observations of smoke from prescribed burns and wildfires where good validation data are available, and some sensitivity studies in these cases are presented to demonstrate the applicability or otherwise of the particular transport model

configuration initially used for these forecasts, and to indicate directions for future improvements to the system.

System configuration

Numerical systems

The need for the system to produce forecasts of smoke transport from a relatively large number of possible ignition points, for any point in Australia, and in a timely manner, precludes the use of a more computationally complex atmospheric chemistry model, such as the Australian Air Quality Forecast System (AAQFS, Cope et al. 2004) at this time.¹ The Bureau operates a hierarchy of limited area numerical weather prediction systems over Australia, with grid resolutions ranging from 0.375° to 0.05° latitude/longitude grids. These are all configuration variations of the LAPS system described by Puri et al. (1998), and the particular version selected to provide the atmospheric state forecasts for the smoke management forecasts is the 0.125° grid version, meso-LAPS, this being the highest resolution configuration that covers the entire continent. It has 29 levels, with some 10 levels below 1500 m above the surface. The full atmospheric state is output every three hours of the model integration, with 48-hour forecasts being run twice daily and initiated at 0000 and 1200 UTC. The transport and dispersion model used is the HYSPLIT_4 modelling system (Draxler and Hess 1998). 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 modelled 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 the operational forecasts the concentration grid is specified with a horizontal spacing of 0.05°, and four levels at 10, 150, 500, and 1500 m. While near-surface concentrations are the most important for 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. It is necessary to specify a source plume for the prescribed burn,

¹ Although expected advances in computing power may allow this in the near future.

both in terms of a source concentration and of an initial plume rise. It became quickly 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, and for the first version of the system, an arbitrary source concentration (1 unit) was specified, and the forecast concentrations are relative to that arbitrary value. Contour intervals for concentration plots were then selected such that the outermost contour plotted roughly coincided with the “edges” of the visible smoke plume, based on some early field observations provided by participating agencies. The plumes are specified to be 1500 m in height in this first version of the system, chosen because this is of the order of the typical height of the subsidence inversion that is a common feature during the ideal prescribed burning conditions of fine conditions with light winds. Some implications of this choice will be discussed later.

Forecast presentation

Forecasts are presented to agencies via password-protected websites. Each State has determined a number of locations representative of their major forestry management areas in which 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, and the latest 1600 local time, and with either 2 or 3 hours between each time. Forecasts are grouped regionally, but with only two or three source points on each display panel in order to reduce the possibility of overlapping plumes reducing the clarity of the guidance, and the number of source points per State ranges from 6 (Tasmania) to 16 (Northern Territory). In the early afternoon, forecasts based on the 0000 UTC model run are prepared for ignition times “tomorrow”. This guidance is used for broad decision-making regarding the next day’s burning program. As the forecast is already some 24 hours in the future at the initiation of the modelled smoke plume, and with the expectation that a later forecast will generally be more accurate than an earlier one, a later set of runs, based on the 1200 UTC model forecast, is prepared overnight. These are available at the commencement of final planning in the early morning, and are used for final “yes or no” decisions at particular sites. A

particular 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 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.

After logging on to the website, the first choice for a user is to select their respective State. When this is done, a page similar to Fig. 1 is seen. This is the Western Australian page, and the user has the choice of selecting one of the buttons to either display the forecasts for the Southwest, Lower West, or Perth area source groupings, to go to the on-line background information ("Product Information"), or to go to the link to amend the source location. An important feature here is the provision of the facility for the Regional Forecast Centre fire weather meteorologist to provide comment on the dispersion forecasts in the event that later observations may indicate that the forecast may not be perfect. In this way the smoke dispersion forecasts and the other fire weather forecasts should not present inconsistent information to the user.

Selecting one of the source location icons leads then to the page shown in Fig. 2, which lists the individual source locations within each regional sub-set, and an ignition time button. Clicking on (say) the Southwest Region and 3pm ignition time brings up an animated gif file showing the growth of the forecast smoke plumes from the three source points in that region. There is the interactive provision to stop the animation and select an individual time or step through the time sequence, and a typical still frame product is shown in Fig. 3, where the forecast smoke plumes are shown some 4 hours after the hypothetical ignition time.

Verification

The routine verification of these smoke forecasts is difficult, as in most cases the fires are not lit at the source locations, either due to the forecast transport indicating that the day is not suitable, or due to other management decisions made by agencies. At some prescribed burns, however, the fire agencies have deployed aircraft and ground-based observations to delineate both the horizontal and vertical extent of the resultant smoke plumes. Meteorological satellite imagery has been a powerful tool in verifying smoke from larger prescribed burns and wildfires, so long as the atmosphere is clear (no cloud), and that the underlying surface and the smoke plume have different

radiative properties. The best results using these techniques are often when the smoke plume is transported over the ocean, although there is certainly some uncertainty between the minimum smoke concentration that a ground-based observer can discern, and the visible smoke plume in the imagery. There are also various aerosol products from polar orbiting satellites such as the Total Ozone Mapping Spectrometer (TOMS, http://toms.gsfc.nasa.gov/aerosols/aerosols_v8.html), the Advanced Very High Resolution Radiometer (AVHRR) and the Moderate Resolution Imaging Spectrometer (MODIS, <http://modis.gsfc.nasa.gov/>) that can be extremely valuable to compare with the smoke forecasts, but these sensors are better-suited for long-distance estimates of mid-tropospheric aerosol, and have their deficiencies near the ground (eg Nordgren 2003). In the examples and case studies presented in the next sections several of these data sources will be used, with the particular verification depending on the individual case characteristics.

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Smoke Dispersion Forecasting (Western Australian Trial)

Quick Links

PRODUCT INFORMATION	DISCLAIMER	These forecasts are provided for use by land managers on a trial basis. The calculations are based upon the premise that a vertical smoke source, usually extending from the surface to 1500 metres, is located at each source point. Smoke is assumed to be emitted from these sources for the entire duration of the forecast.
SOUTHWEST	LOWER WEST	
PERTH AREA	Amend Forecast Locations	The dispersion maps represent the pollutant concentration distribution averaged from the ground level up to 1500 metres and are based on meteorological data from the mesoLAPS numerical weather prediction model.

Forecasts are in three groups. The southwest group contains dispersion forecasts from 3 starting points in the Southern Forest Region and in the southern part of the Central Forest Region. The lower west group comprises 2 starting points in the Swan Forest Region and one in the Central Forest Region. The Perth group contains two starting points, the RAAF base at Pearce and the outer Perth suburb of Bickley.

Forecasts were last updated : 05-Dec-2004 11:55 pm Western Standard Time

W.A. Region Forecaster's Comments

CALM SMOKE PLUME COMMENTS. Issued at 8:00am WST on Monday the 6th of December 2004

Fig. 1: Header page for the Western Australian state smoke management advice forecasts.

Lower West Region

Lat. (deg / min)	Lon (deg / min).	Plume Elev. (m)	Location
-32.1167	116.2500	1500.0	Occidental
-32.5167	116.1333	1500.0	Torrens
-33.1167	116.1833	1500.0	Ross

Ignition Time

11 A.M.

1 P.M.

3 P.M.

Southwest Region

Lat. (deg / min)	Lon (deg / min).	Plume Elev. (m)	Location
-33.7667	116.1167	1500.0	Catterick
-34.0333	115.4667	1500.0	Layman
-34.6167	116.3667	1500.0	Westcliffe

Ignition Time

11 A.M.

1 P.M.

3 P.M.

Perth Region

Lat. (deg / min)	Lon (deg / min).	Plume Elev. (m)	Location
-31.66	116.0167	1500.0	Pearce
-32.00	116.0833	1500.0	Bickley

Ignition Time

11 A.M.

1 P.M.

3 P.M.

Site Navigation

Fig. 2: Second page of the Western Australia smoke management forecast website. The source locations are specified for each of the regional groupings, with a separate set of choices for the three ignition times.

Case studies

The selection of these case studies was opportunistic rather than systematic. The prescribed burn case studies were selected in some cases because the responsible agency deployed aircraft and ground spotters at those events to provide accurate plume rise and perimeter data. Such cases are the MJ019, MJ035 and the SWC053 (see below) burns in Western Australia (WA) and the central Tasmanian fire. Other cases were used because circumstances brought them to our attention, and such cases are the Butler Block fire, the smoke from which affected Perth and other towns in

southwestern WA, or the fire near Erica, Victoria, the plume from which was observed by one of the authors (AGW) while driving along the Princes Highway. The wildfire and industrial events were generally selected because of their community impact together with good (generally satellite) verification data.

In many of these cases the HYSPLIT runs were re-computed, rather than using the operational forecasts, in order to explore the sensitivity of the forecasts to system configuration and input data, with the intent of determining priorities for later upgrades to the operational configurations, and these issues are noted in each case study, and will be further addressed in the final section of this report.

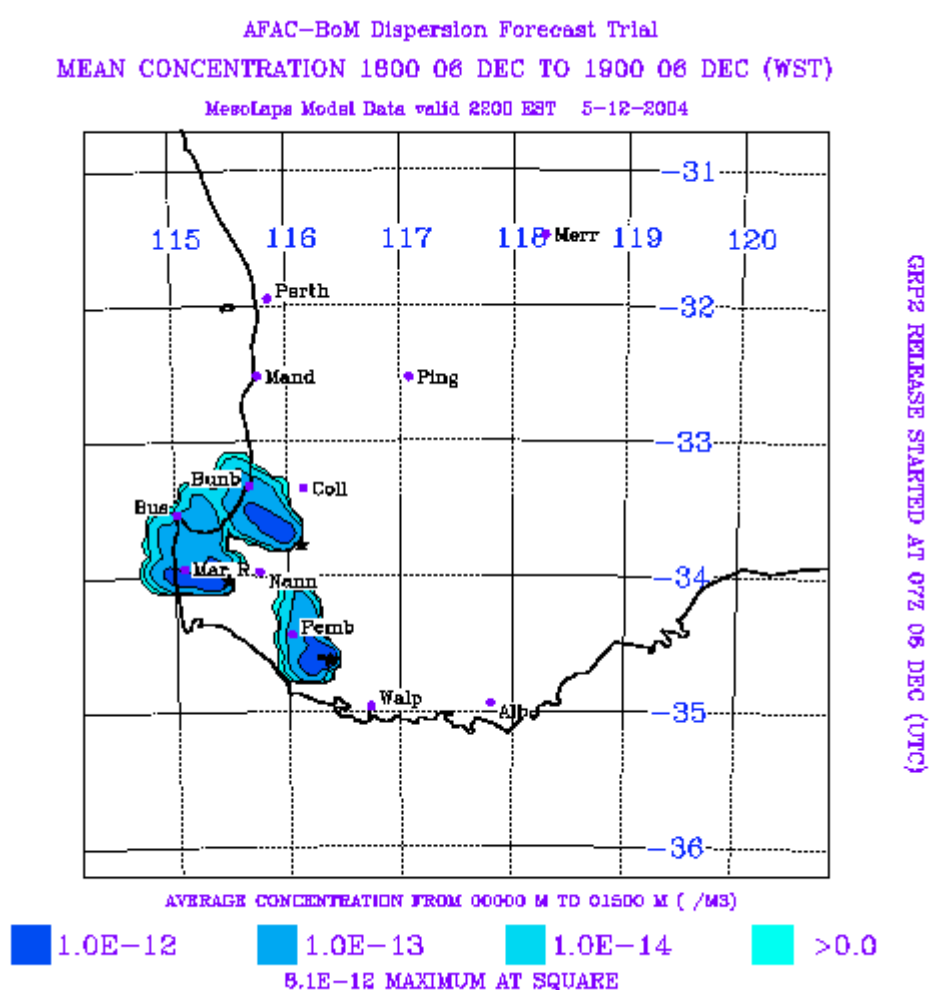


Fig. 3: Sample frame from the animated gif loop showing the forecast dispersion from hypothetical fires ignited at 3 pm (local time) for the Southwest grouping in Western Australia.

CALM prescribed burn: Butler Block – 31 October 2001

On 31 October 2001, the Western Australian Department of Conservation and Land Management (CALM) planned a prescribed burn in the Butler block, about 20 km west of Nannup, and approximately 10 km north of the regular dispersion forecast source point at Layman (the western of the three source points shown in Fig. 4). The operational HYSPLIT forecast for that day, based on the 1200 UTC 30 October 2001 meso-LAPS forecast, predicted that a smoke plume from Layman would cross the coast near Bunbury and then move northwards to reach Perth around 10.00pm Western Standard Time (WST) as indicated in Fig. 4.

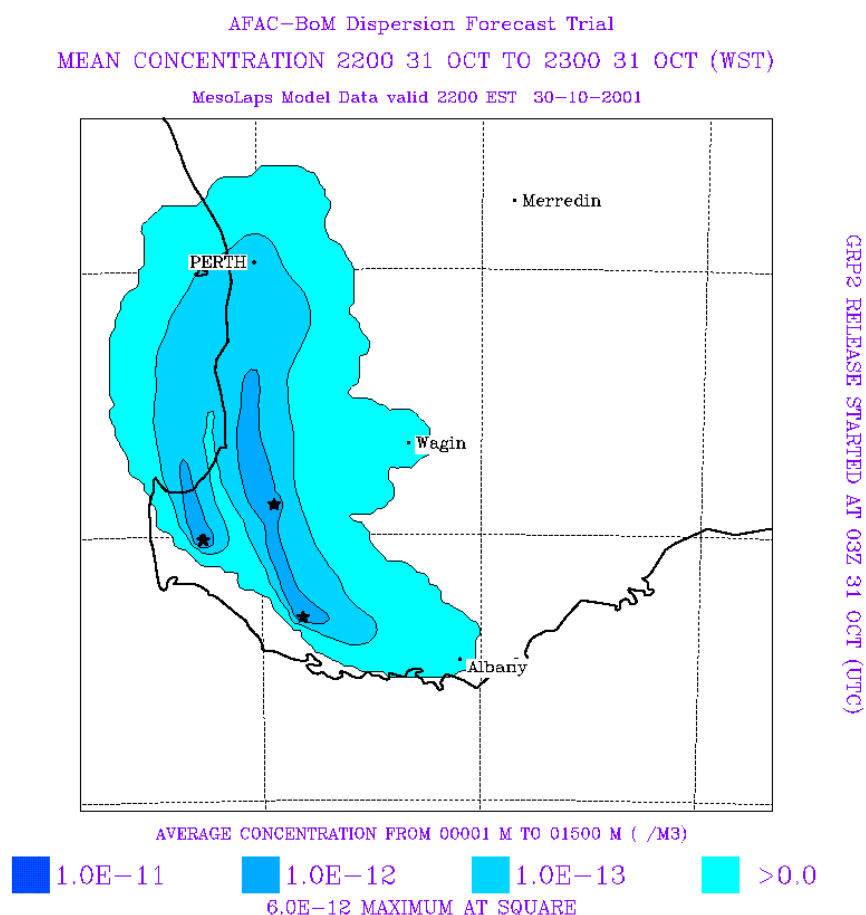


Fig. 4: Rerun of operational forecast for southwest Western Australia showing potential impact on Perth around 10 pm WST on Oct 31. The westernmost point, Layman, is approximately 10 km from the Butler block.

AVHRR satellite imagery at 2:24pm Western Standard Time (WST) (Fig. 5) and at 5:16pm WST, and surface observations of smoke at coastal towns, are used to assess the quality of the forecast. For this case study the smoke dispersion forecasts presented have been made from the actual fire location in the Butler block, but using the same wind-field forecasts that were used operationally (1200 UTC 30 October 2001 base-time). Figure 6 shows the HYSPLIT dispersion forecasts at the times of the AVHRR satellite imagery, with the outlines of the smoke plumes as seen in the imagery overlaid. Despite the presence of smoke emanating from several other prescribed burns on the area, there is a very good agreement between the plume visible in the satellite images and the forecasts. In Fig. 6a, some 2.5 hours after ignition, the visible plume extends 60 km from the source point and is more than 45 km wide at its mid-point. The forecast plume has travelled almost the same distance but is more widely dispersed being some 67 km across at the mid-point. Three hours later (Fig. 6b) the observed plume has reached almost to Mandurah and is 160 km from the source; the forecast plume is only a short distance (20 km) behind that observed, but again more widely dispersed.

The smoke plume was observed to reach Bunbury between 4 and 4.30pm WST, Mandurah at approximately 6:30pm WST, and Perth around 9-9.30pm WST. It is a moot point what concentration contour best represents visible concentrations, given that these concentrations are only relative to an arbitrary source. However, examination of these forecasts showed that the second concentration contour most-closely matched the observed times of smoke arrival at the four coastal stations, and this comparison is shown schematically in Fig. 7. On this basis the forecast plume is a little early arriving in Bunbury and a little late arriving in Mandurah, but given the imprecise nature of the reported arrival times and the pragmatic selection of the contour that best represents forecast arrival time, this is excellent agreement.

On this occasion the HYSPLIT forecast has produced an excellent forecast of the passage of the smoke plume from the southwest capes region of WA north to Perth. While the outer extent of the forecast plume provides a good fit with the satellite observations, the second lowest contour matches quite well with the observed passage of the smoke plume. It is of interest that the next day smoke was noted in Geraldton some 375 km north of Perth and 590 km from the Butler block, the smoke having been trapped in a stable marine boundary layer during its northward transport. An extended HYSPLIT forecast (not shown) replicated this transport very well

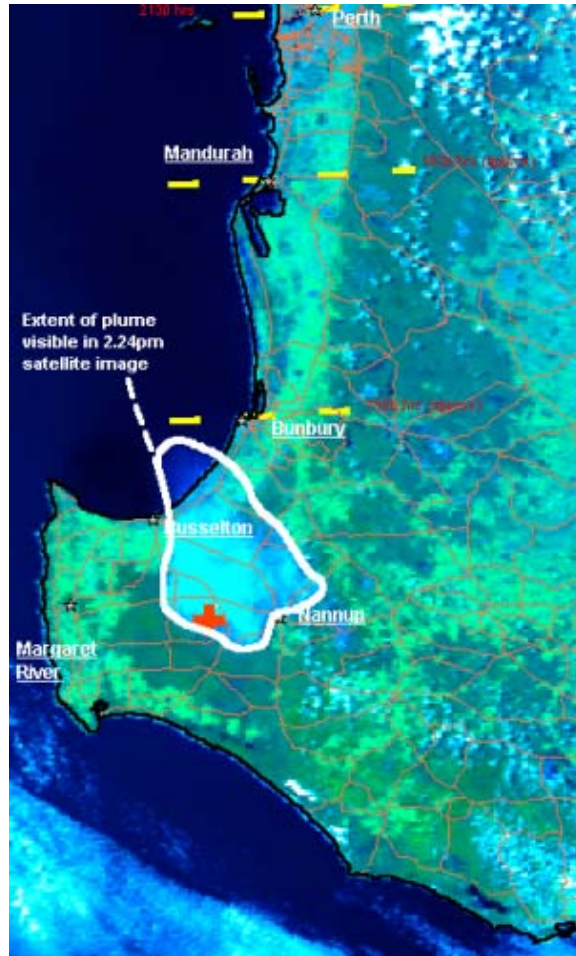


Fig. 5: AVHRR satellite image at 0224 WST 31 October 2001, with the edges of the smoke plume outlined.

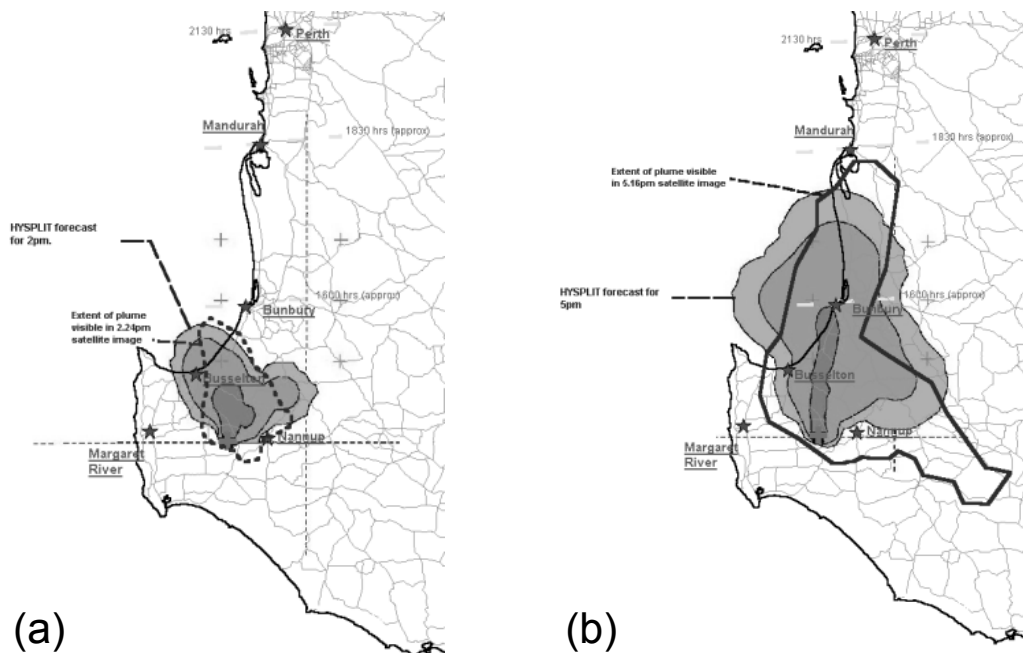


Fig. 6: Comparison of HYSPLIT dispersion forecasts with plume extent obtained from AVHRR satellite imagery. (a) – 2.24 pm WST, (b) - 5.16 pm WST 31 October 2001. The observed smoke plume includes contributions from other fires burning to the east.

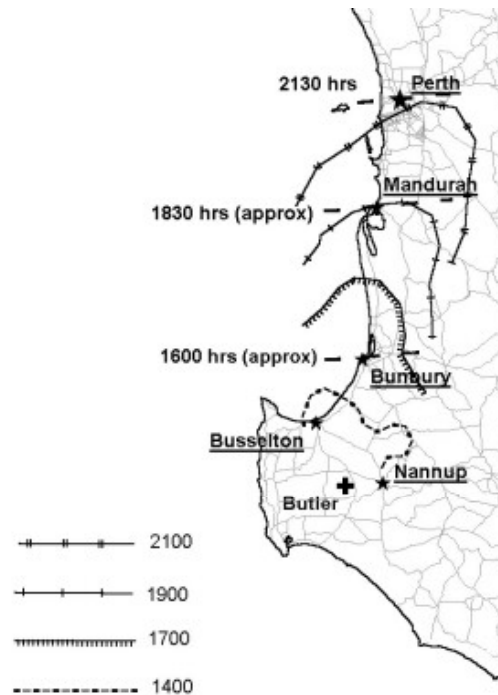


Fig. 7: Comparison of the position of 2nd lowest contour in the HYSPLIT forecast with reported arrival times (WST) at various coastal locations of the smoke plume from the prescribed burn at the Butler block.

DSE prescribed burn: Erica – 10 March 2002

On 10 March 2002 the (then) Victorian Department of Natural Resources and Environment (NRE) conducted a prescribed burn near Erica ($37^{\circ} 967' S$ $146.367^{\circ} E$). The smoke plume was observed to rise almost vertically above the fire to an estimated height of over 2000 m before extending southward over the Latrobe Valley from Erica to Wilson's Promontory. Significant light extinction was observed beneath the plume that was at least 20 km wide as it passed over the Princes Highway, 40 km south of the fire, but near the surface visibility was relatively unaffected. The plume was clearly visible in images from the GMS-5 satellite from 0230 – 0530 UTC 10 March 2002 (e.g. Fig. 8), and these images are used as validation of the forecasts in this case.

As the subjective observations of the plume indicated that it extended considerably higher than the operationally specified 1500 m, some sensitivity experiments varying the plume specification were conducted. The opportunity was also taken to use the high resolution meteorological fields from successive runs of the 0.05° grid Victorian domain meso-LAPS, based at 1200 UTC 9 March 2002 and 0000 UTC 10 March 2002, to explore the issue of accuracy versus forecast lead time. For

all experiments the HYSPLIT concentration grid was configured with 12 vertical levels up to 5000 m and the actual ignition time of 1030 local time (AEDT) used.

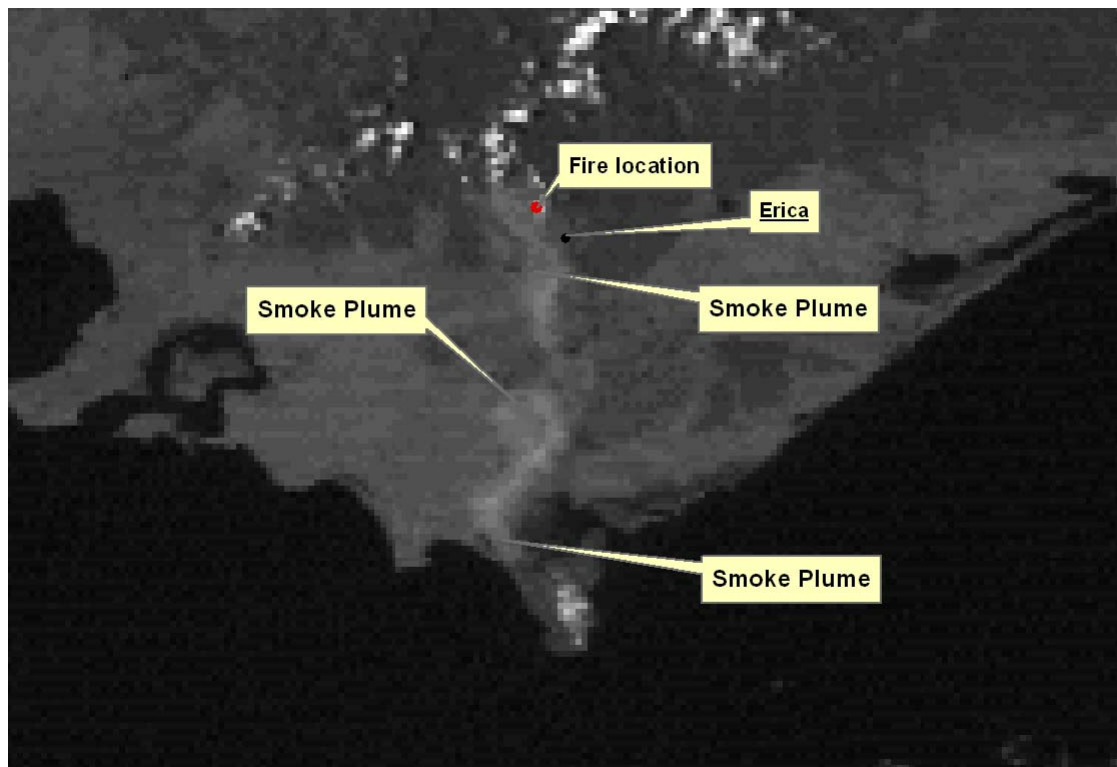
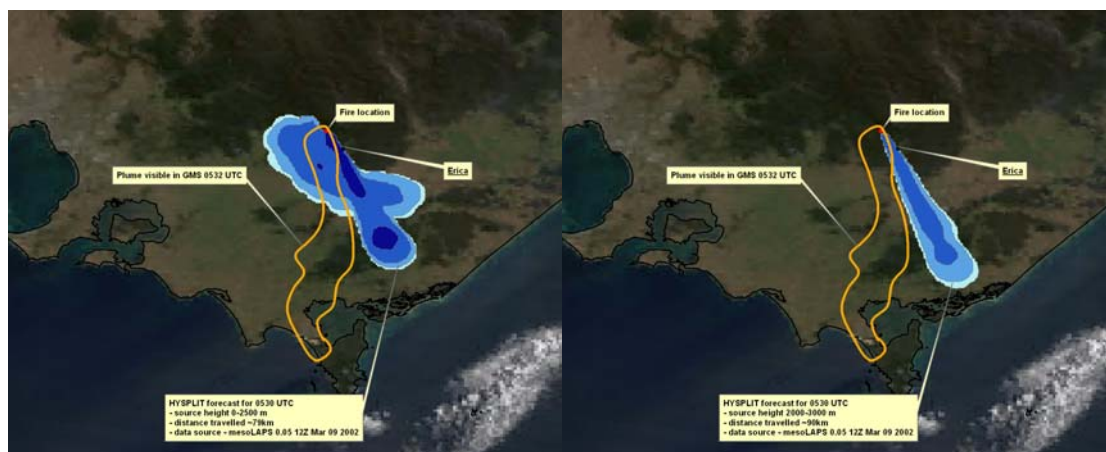


Fig. 8: Visible GMS-5 imagery at 0532 UTC 10 March 2002.

The first plume rise scenario assumed a plume height of 2500 m, and was based on a subjective estimate of the height of the plume. Comparisons of the plume observed in the 0530 UTC satellite image and the HYSPLIT forecast plumes from the two forecast base times are shown in the left hand panels of Fig. 9a and b. Both these forecasts include a significant amount of dispersion in an east-west direction as well as a well-defined plume section extending towards the coast, albeit in different directions in the two forecasts. This latter area is reflecting the influence of northerly winds at levels above 2000 m.

In the forecast based on the 1200 UTC meso-LAPS the plume has travelled approximately 79 km from the fire site in 5.5 hours in a southeasterly direction. The measured travel distance (along the centreline) of the observed plume at this time was 125 km. Error in forecast direction was approximately 24° . The east-west spreading occurs in light variable winds below 1500 m where turbulent dispersion processes dominate, resulting in the very wide forecast plume, appears to be excessive based on the visual observations from the south, and is not resolved in the GMS imagery. In the later 0000 UTC HYSPLIT forecast (Fig. 9b) the dispersion at lower levels is similar

to that in the previous forecast but reflects somewhat more easterly forecast winds, supported by the observations from Latrobe Valley Airport. The upper part of the plume extends southwestward, with a calculated travel distance of only 65 km.



(a) Forecasts made using 5km mesoLAPS data valid 1200 UTC March 9 2002.



(b) Forecasts made using 5km mesoLAPS data valid 0000 UTC March 10 2002

Fig. 9: HYSPLIT smoke dispersion forecasts for 0530 UTC (1630 AEDST). The orange lines show the outline of the smoke plume as seen in the GMS satellite imagery. Images on left show the forecast made using plume height from surface to 2500 m. Images on right show forecasts made specifying a plume height 2000-3000 m.

Given that the visual observations suggested that there was very little horizontal dispersion of the plume until it had reached some 2000 m, a second forecast was run, with the plume specified to rise to 3000 m, but with dispersion only commencing above 2000 m. These forecasts (right hand panels Fig. 9) show more elongated smoke plumes extending towards the Gippsland coast. The slightly greater depth of the plume has resulted in a greater distance travelled, reflecting increasing wind speeds with height in the 2000-3000 m layer. The forecast based on the 1200 UTC data again travels to the southeast some 90 km, while the 0000 UTC based forecast has also transported the plume approximately 90 km but in a southwesterly direction. The

plume direction in the later forecast is slightly improved with an error of approximately 22°.

At both forecast times the 2000-3000 m forecast plume provided a much better representation of the actual smoke plume (at least as is visible in a GMS satellite image) than the 0-2500 m forecast plume. This case highlights the sensitivity of the forecasts to accurate plume rise specification in conditions of marked wind shear, and also perhaps points to the need to examine the forecast winds and diffusion in light wind conditions.

CALM prescribed burn: 12 February 2002 (MJ019)

This prescribed burn was ignited at approximately mid-day local time, in the southwest of WA at 34.273S 116.027E. Qualitative observations by CALM spotter aircraft described the plume as initially spreading northwards below an inversion at 4500-5000 ft. A cumulus cloud developed above the fire source around one hour after ignition. Southward movement of the plume at elevations above 5000 ft under the influence of a “strong upper wind reversal” was noted at 1605, but this southern extension dissipated rapidly. In addition the CALM aircraft flew transects across the plume (Fig. 10 for details) obtaining data to describe the visible perimeter of the plume, and completed five sequences at hourly intervals beginning 20 minutes after ignition (1220, 1320, 1420, 1520, and 1620 WST). The first three measurements are shown by the coloured polygons (M1, M2, and M3) in Fig. 11.

Also shown in Fig. 11 is the mean concentration forecast at valid at 1230 WST, 30 minutes after ignition, and based on the meso-LAPS forecast initialised at 1200 UTC 11 February 2002. The forecast plume spreads in two directions, one almost due north and one to the southeast. If only the low-level concentrations are plotted (Fig. 12), then the comparison with the aircraft reports is improved. The direction of transport at the low levels is to the north, and while the low-level forecast plume has moved a little too far, the winds are quite light and the forecast would not be seen as grossly misleading. Examination of the meso-LAPS wind fields at 0200 UTC (10 am WST) shows a significant vertical wind shear between the 900 hPa and 875 hPa levels. South-southeast winds are forecast up to 900 hPa (1000 metres approx), at the 875 hPa (1240 m) level, winds are from the north-northeast, while at 850 hPa (1450 m) winds are from the north-northwest. This shear is consistent with the spotter aircraft observations reported above, although the level at which the shear

is simulated in the model is probably a little lower in the atmosphere than that reported by the aircraft. With the specified source plume height of 1500 m the modelled plume penetrates the model inversion, and so the forecast plume shows a bifurcation, with northward transport below the inversion, and southward transport above the inversion. The aircraft did, however, report a period when the plume penetrated the inversion, and the smoke above that level was transported southwards.

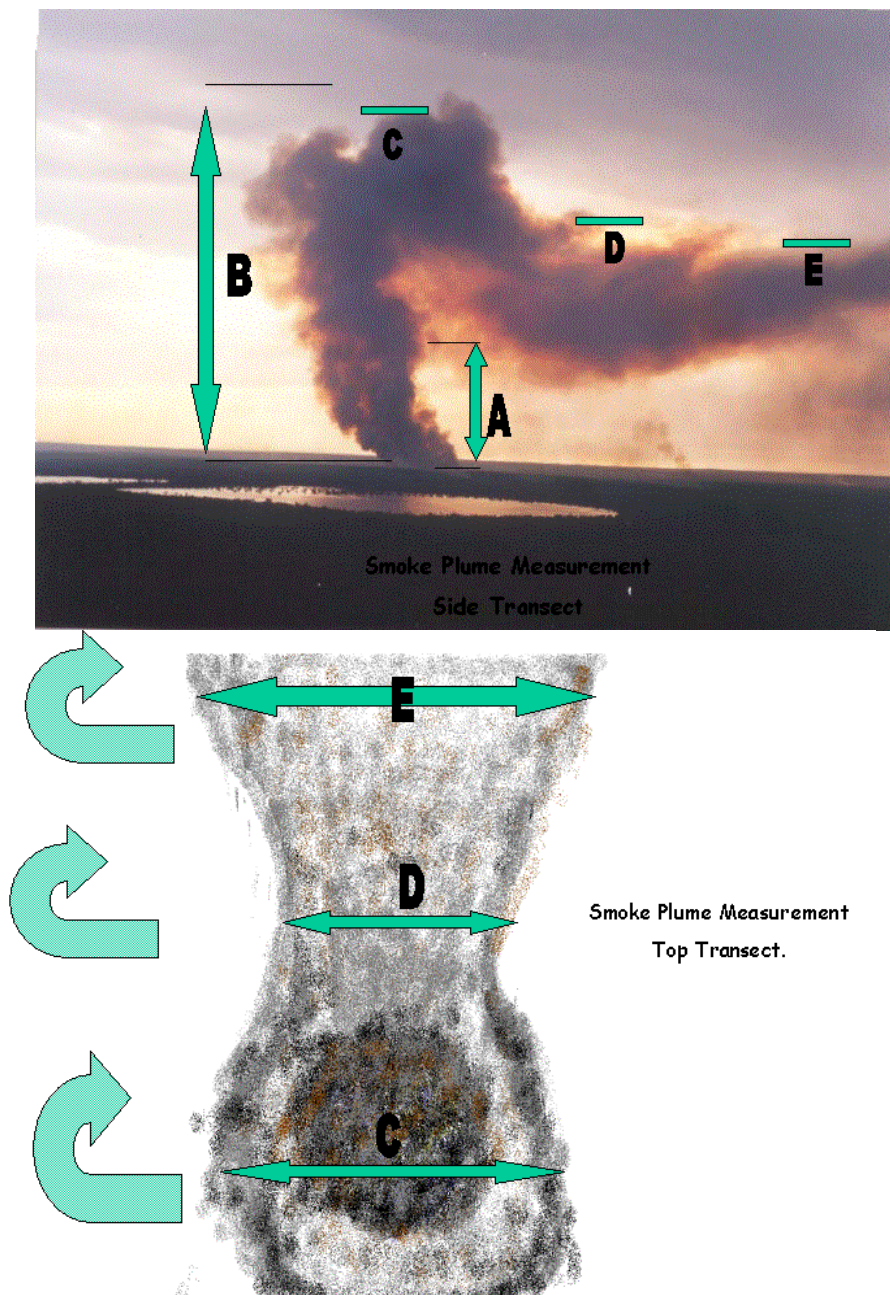


Fig. 10. Graphic showing measurements taken by airborne CALM observers of smoke plumes from prescribed burning operations. Distances A and B describe the height of the plume while transects C, D, and E describe the horizontal extent of the smoke.

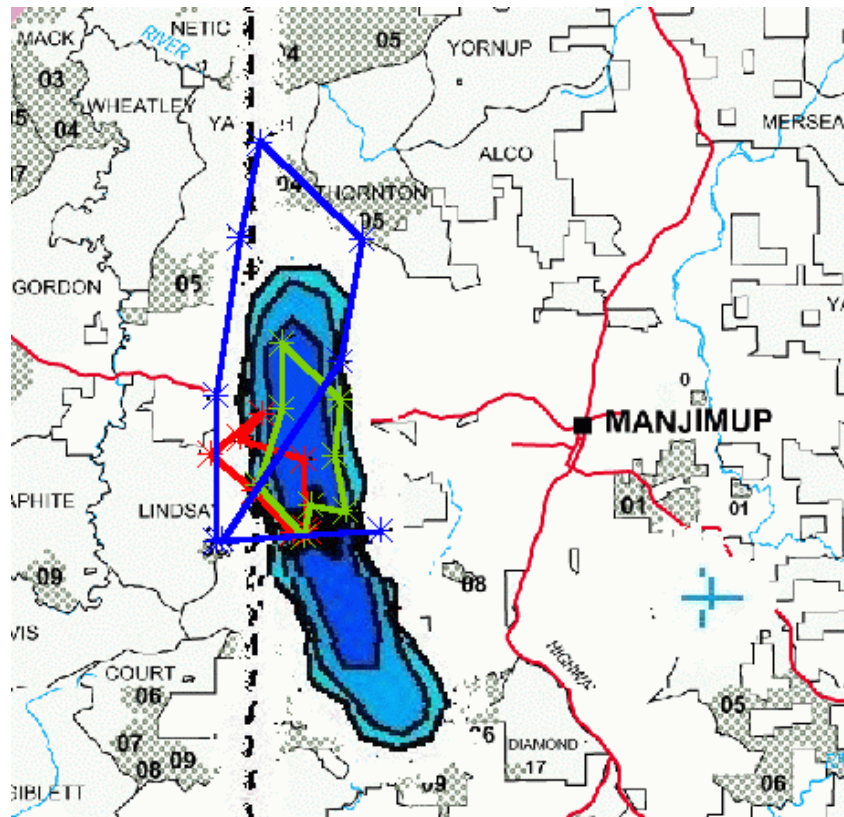


Fig. 11: Coloured polygons outlining the CALM spotter aircraft observations of the smoke plume from prescribed burn MJ019 at 1220 (red), 1320 (green) and 1420 (blue) WST 12 February 2002. The shaded contours show the forecast mean concentration at 1230 WST, approximately 30 minutes after ignition.

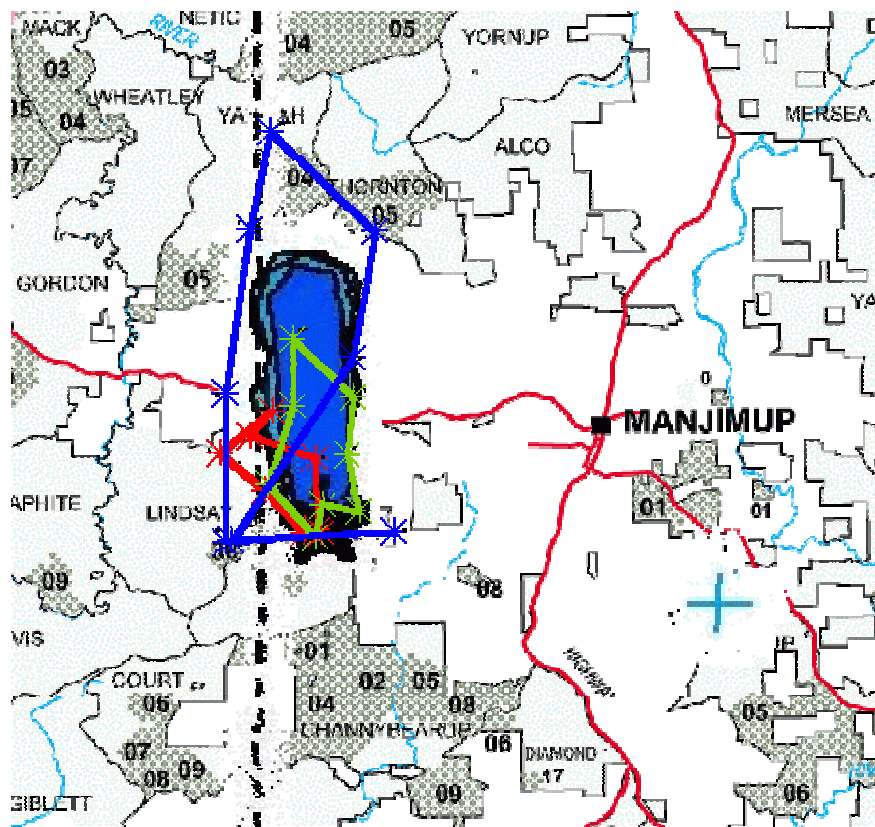


Fig. 12: 150 m concentration forecast at M1 (1230 WST) together with the observed plume outlines as in Fig. 11.

This example shows some interesting features. The meteorological conditions are extremely benign, with light surface winds and a subsidence inversion. These features, though, make the forecast dispersion very sensitive to small errors in wind speed, and it is known that the model forecast winds are slightly over-predicted (on average) in very light wind conditions, while the accurate specification of inversion height is a difficult problem that is compounded by the use of a fixed model plume height that may penetrate an inversion, while the actual smoke plume may not.

CALM prescribed burn: 13 November 2001 (Donelly Mill – MJ035)

CALM provided the following spotter report for this fire : *“Ignition occurred at 1400 hours, point of origin was 34° 05.507' S 115° 58.934' E. Total area of the burn was approximately 30 hectares. Fire behaviour was mild and a defined plume did not develop until 1630 hours (approx). The plume was under the influence of a NNE wind at this time. At 1700 hours plume was a very thin hazy smoke, the majority of the defined plume being vertical, extending to an estimated 10,500 feet (500 feet above the aircraft's max ceiling). By 1800 hours the wind had shifted to the west while the fire behaviour had moderated. The end point of the smoke plume at this time was estimated only, due to operational commitments. At 1810 a southerly wind was observed and smoke was spreading to the north of the fire.”*

Figure 13 shows the forecast dispersion based on the meso-LAPS model forecast from the previous evening (base-time 1200 UTC 12 November 2001) at the times corresponding to the overlayed spotter-defined plume perimeters. The forecast plume is more extensive than the observed smoke limits in the early stages of the forecast, with the possible reasons being an over-forecast of wind speed, or an inappropriate source specification, given that the observed fire, as reported above, exhibited only mild behaviour. However, Fig. 13d does show that the forecast plume was beginning to expand north of the source by 1815 WST, consistent with the observed southerly wind change at around that time.

A feature of the synoptic conditions under which prescribed burns are undertaken is that they are quite benign in a fire-weather sense, and this is the case in this burn as indicated by the mean-sea-level pressure analysis for that afternoon (Fig. 14). In such light wind situations only very small errors in wind speed or direction may cause large *relative* errors in forecast dispersion, although the extent of that

dispersion may be small. In addition there is a possibility in this case that the source specification may not be appropriate for this relatively low-intensity burn. It is also of note that, broadly speaking, these benign conditions do allow local circulation features, such as sea-breezes, to develop, and the quite accurate forecast of the southerly wind change in the late afternoon is both encouraging and operationally highly relevant information.

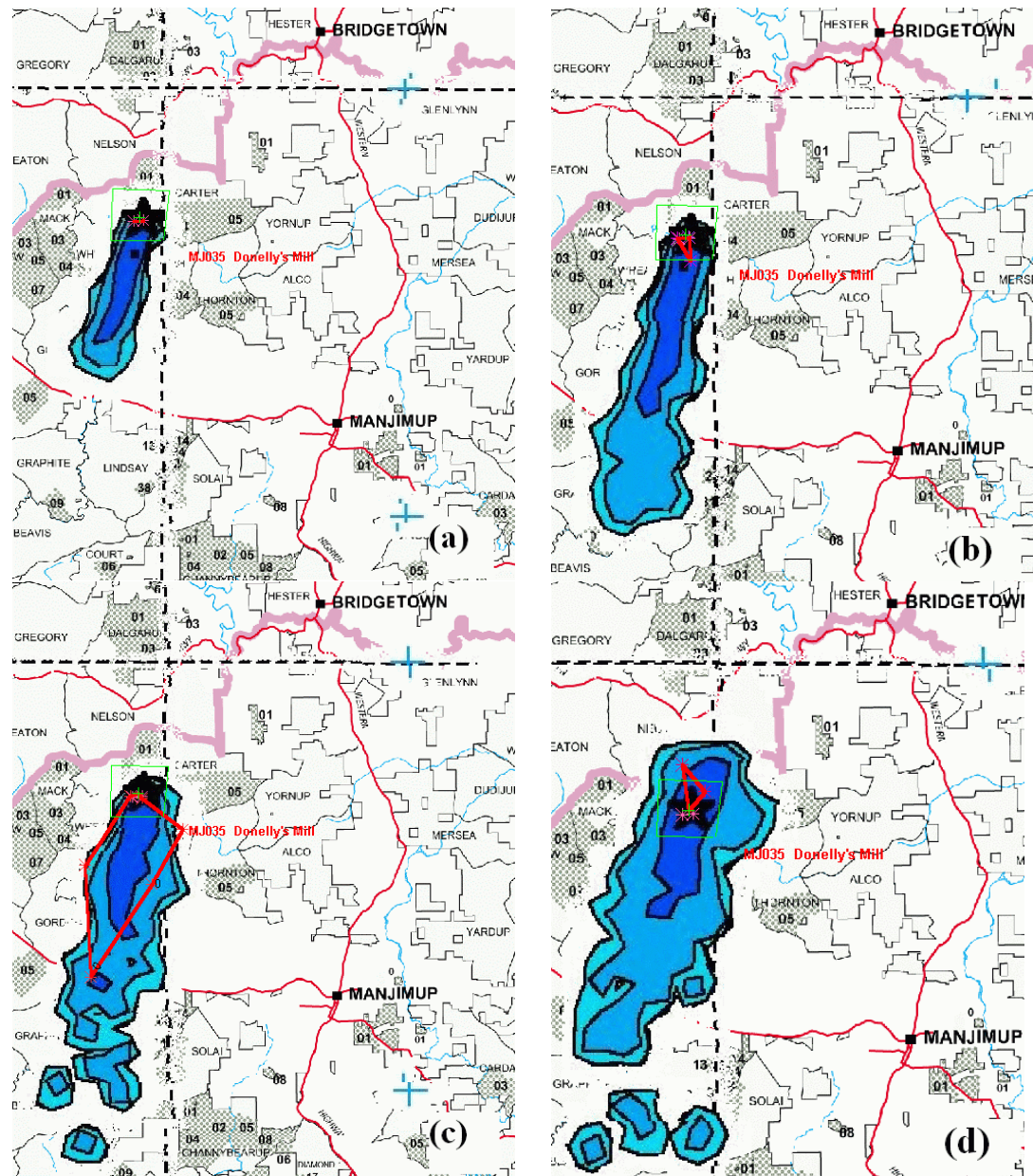


Fig. 13: Coloured polygons outlining the CALM spotter aircraft observations of the smoke plume superimposed upon dispersion forecasts from prescribed burn MJ035. Based on the meso-LAPS forecast initialised at 1200 UTC 12 November 2001. The forecasts are valid at (a) 1500 WST, (b) 1615 WST (c) 1715 WST and (d) 1815 WST.

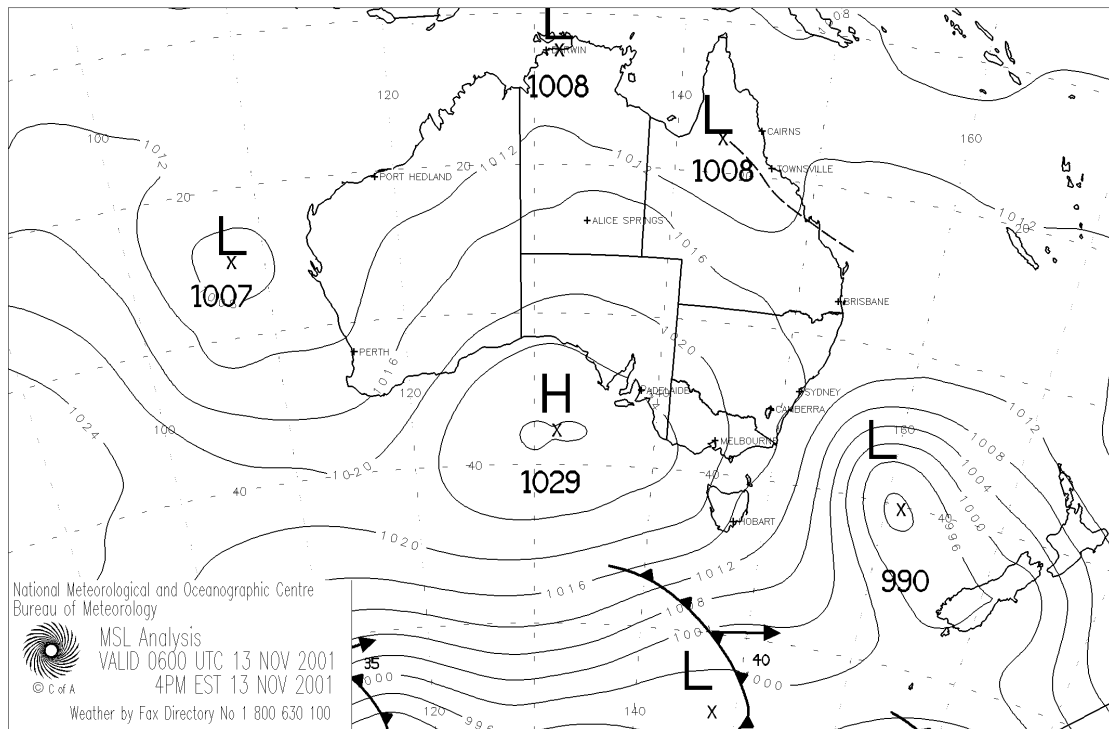


Fig. 14: MSLP analysis at 0600 UTC 13 November 2001 (MJ035).

CALM prescribed burn: 25 October 2001 (SWC 053)

The CALM spotter's report for this fire was *"First measurement was made at 1200 WST, while lighting up was still occurring. Smoke was rising from all ignition areas but collapsing back to ground within 3 km and was quite diluted. Even at the third measurement, two hours later, the plume was on the ground 10 km from the source continuing at a low level to a point 5 km south of Nannup where it rose to 7000 feet diluting and mixing with cloud to the Pemberton area. By 1530 the smoke was becoming layered, presumably an indication of the sea breeze, which had arrived by 1630 WST."*

In common with the previous case, meteorological conditions were very benign, as indicated by the mean-sea-level pressure analysis for that afternoon (Fig. 15). The dispersion forecasts are shown in Fig. 16, with the spotter aircraft plume perimeters shown by the polygons. In the early stages the plume is forecast to move southwards, but the observed plume outline describes very slow transport to the east (Fig. 16b). However, the later forecast times show quite good agreement between the observed plume outline and that forecast, with both the observed and forecast plumes crossing the coast east of Cape Leeuwin by the final time. Again in the light wind conditions early in the forecast, small absolute errors in forecast wind speed and direction can cause large relative errors in the dispersion forecast. In this case the

model might be interpreted as having forecast the shift to north-northwesterly winds a little earlier than they actually occurred, although in absolute terms an error of perhaps 2-3 hours in a forecast lead time of some 18 hours might not be considered a bad forecast. In addition, the implications of the shift to northerly winds on the likely burn behaviour would become evident if the three different ignition times were examined – while the exact timing of the wind change may have been in error, the range of ignition times would have provide a “before change” and an “after change” scenario.

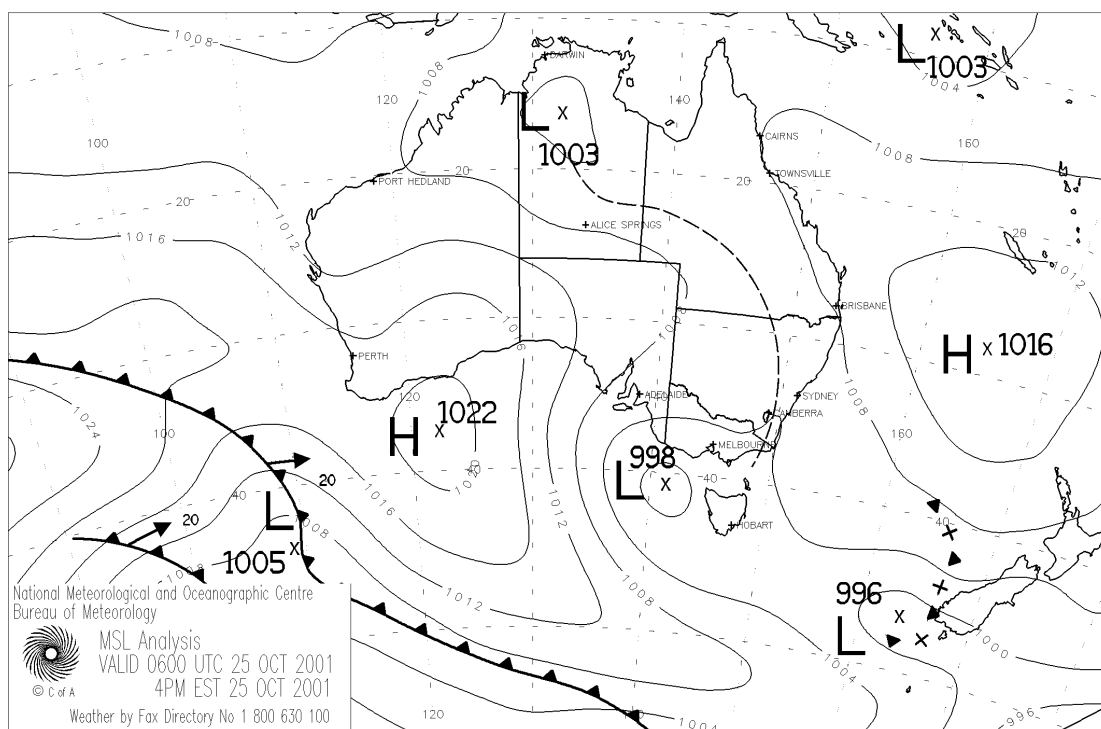
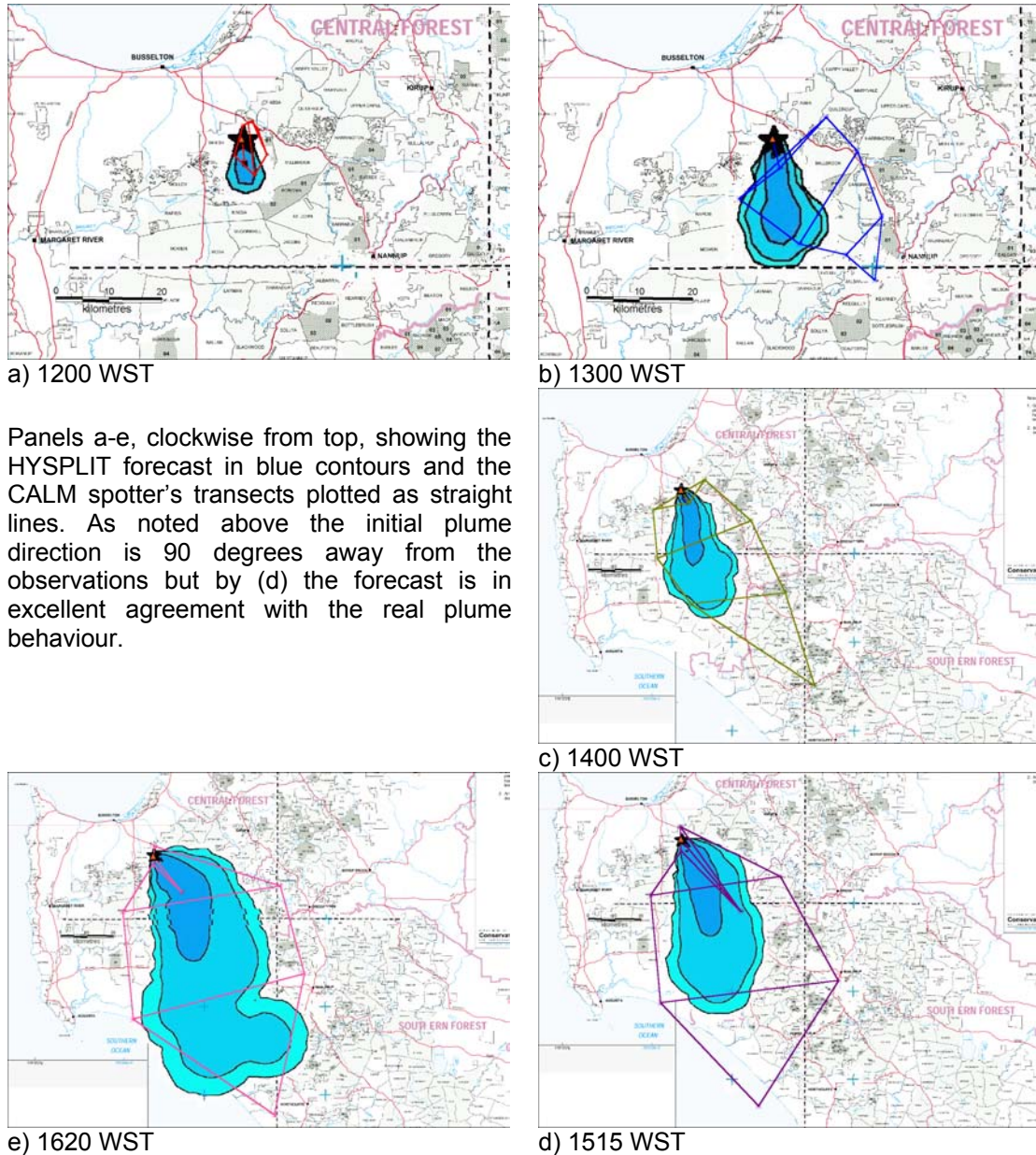


Fig. 15: MSLP analysis at 0600 UTC 25 October 2001 (SWC 053).

QDPI prescribed burn: Bribie Island - 10 August 2004

The smoke plume from a prescribed burn on Bribie Island on 10 August 2004 could be observed on both radar (Fig. 17) and geostationary satellite imagery (Fig. 18), although the radar does not detect the downwind extension of the plume seen in the satellite imagery where concentrations, and thus radar returns, are weaker. What the radar does show, though, is the vertical extent of the plume near its source (lower panel, Fig. 17), and it is seen that the plume rose to around 6 km before its downwind transport.



Panels a-e, clockwise from top, showing the HYSPLIT forecast in blue contours and the CALM spotter's transects plotted as straight lines. As noted above the initial plume direction is 90 degrees away from the observations but by (d) the forecast is in excellent agreement with the real plume behaviour.

Fig. 16: Dispersion and observation forecasts for SWC053 showing approximate observed plume outlines and equivalent HYSPLIT forecasts at indicated times.

Two forecasts are presented for this event (Fig. 19). Both were made using data from the 0000 UTC meso-LAPS 0.125° model run on 10 August. In both cases the concentration grid has 12 levels from the surface to 6000 m while the grid point interval is 0.05° . The “Normal” forecast used the default 1500 m initial plume height. Comparison with observed smoke visible in the GOES-9 image at 0413 UTC shows a significant difference in travel distance in the short period since the forecast was initialised (Fig. 19, left). The second forecast utilising the actual plume height observed by the radar (6000 m), provides a much better description of the smoke

transport (Fig. 19, right). The lobe of smoke extending to the southeast, visible at the eastern extremity of the observed plume at 0413 UTC, is replicated by the “Normal” forecast two hours later, (0600 UTC Fig. 20), perhaps indicating that mesoLAPS correctly forecast the processes influencing the plume transport but underestimated their intensity.

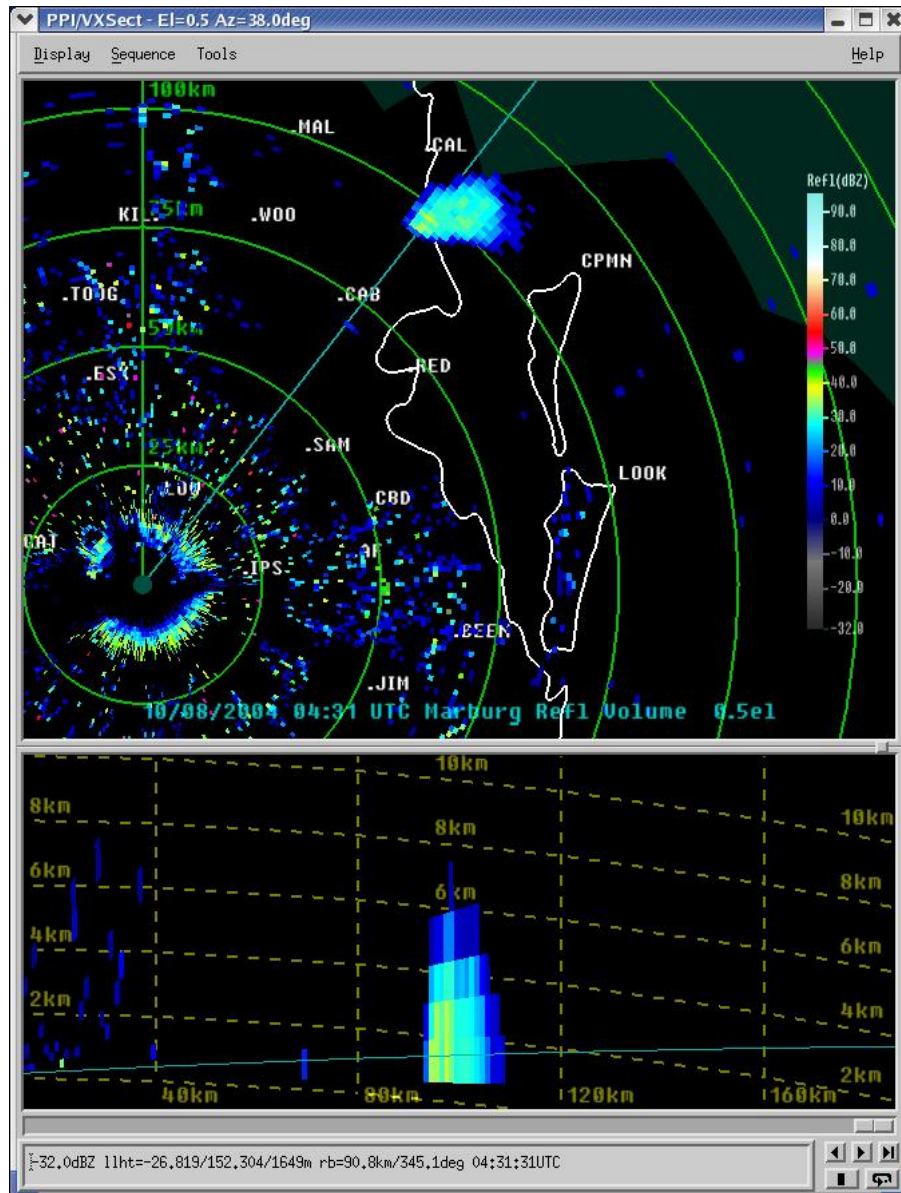


Fig. 17: Marburg radar image at 0431 UTC 10 August 2004 showing PPI (plan) and vertical cross-section presentations of the smoke plume from the fire on Bribie Island.



Fig. 18: Geostationary satellite imagery at 0413 UTC 10 August 2004 showing the smoke plume from the Bribie Island fire.

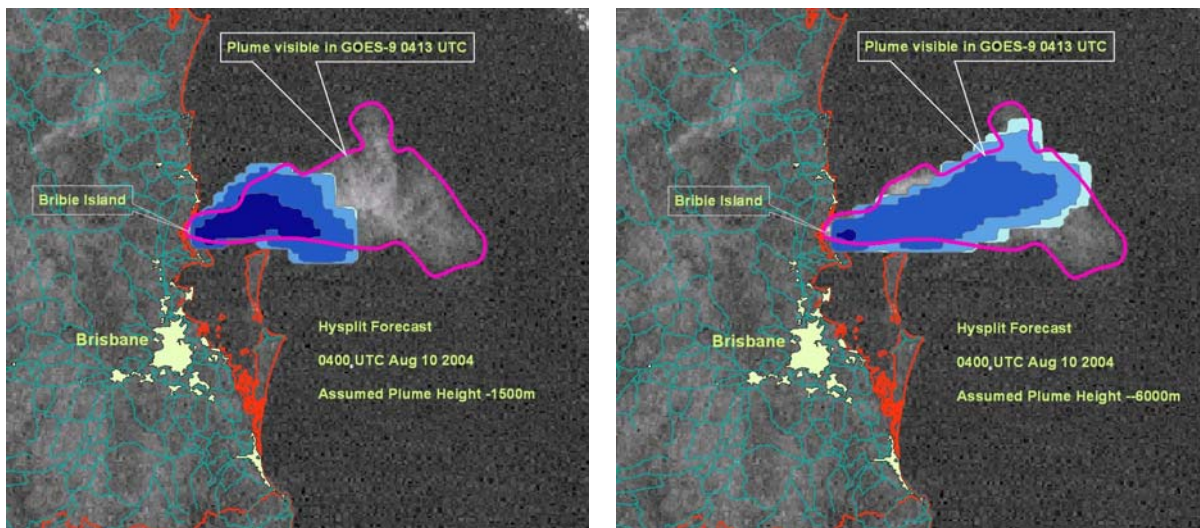


Fig. 19: The HYSPLIT dispersion forecast valid at 0400 UTC based on the meso-LAPS model run initialised at 0000 UTC 10 August 2004 with an ignition time at 0000 UTC. The outline of the smoke plume as seen in the visible satellite imagery is overlaid for comparison. The left hand panel shows the dispersion forecast made with an initial plume rise of 1500 m. The right hand panel shows the forecast made using the plume height obtained from radar images.

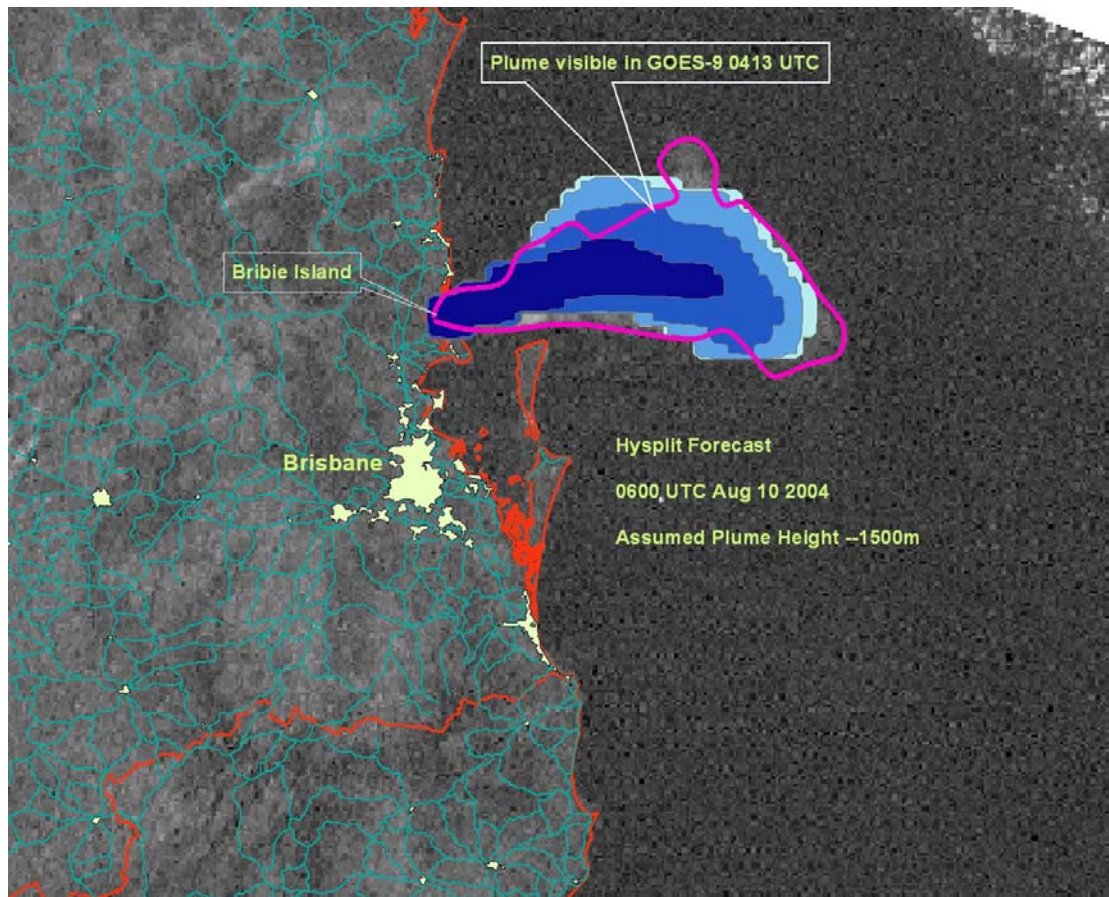


Fig. 20: “Normal” forecast for Bribie Island prescribed burn valid at 0600 UTC 10 August 2004 compared with observation for 0413 UTC.

Central Tasmania - low intensity prescribed burn BD331 : 30 March 2001

This 59 ha Forestry Tasmania controlled burn was ignited by aerial helitorch at 12:50 pm (AEDT) and burned for a total duration of 200 minutes. The average fuel moisture content was calculated as 17%, the wind speed at the surface was 0-5 km h⁻¹ from the WSW, and the inversion height was reported as 1300 m.

The height of the plume downwind of the fire 70 minutes after ignition was determined, by aircraft observation, to be 1705 m. The lower level of the plume was observed at 1190 m. For this forecast HYSPLIT was configured to produce output at 15 minute intervals on a 5 level concentration grid (normal 4 plus one at 2000 m) with a grid point interval of 0.005° (~500 m). The initial plume height was set at 1700 m. Figure 21 shows the position of the HYSPLIT forecast at 14:00 AEDT together with the observed plume outline as plotted from aircraft GPS observations. As can be seen from Fig. 21 the HYSPLIT forecast is transporting the smoke too quickly. The forecast plume has travelled 35.6 km from the source while the actual plume has only

travelled 23 km, a 55% over-estimate. The forecast wind direction appears to be approximately 30° in error.

This is not a particularly good forecast from a direction or distance of transport point of view, although again in an absolute sense the errors are not great. As noted earlier the light synoptic winds favoured for the ignition of these burns allow the development of mesoscale circulations which may not be resolved by the NWP model, and there may be deficiencies in the initial state specification that allow greater relative errors in these benign conditions.

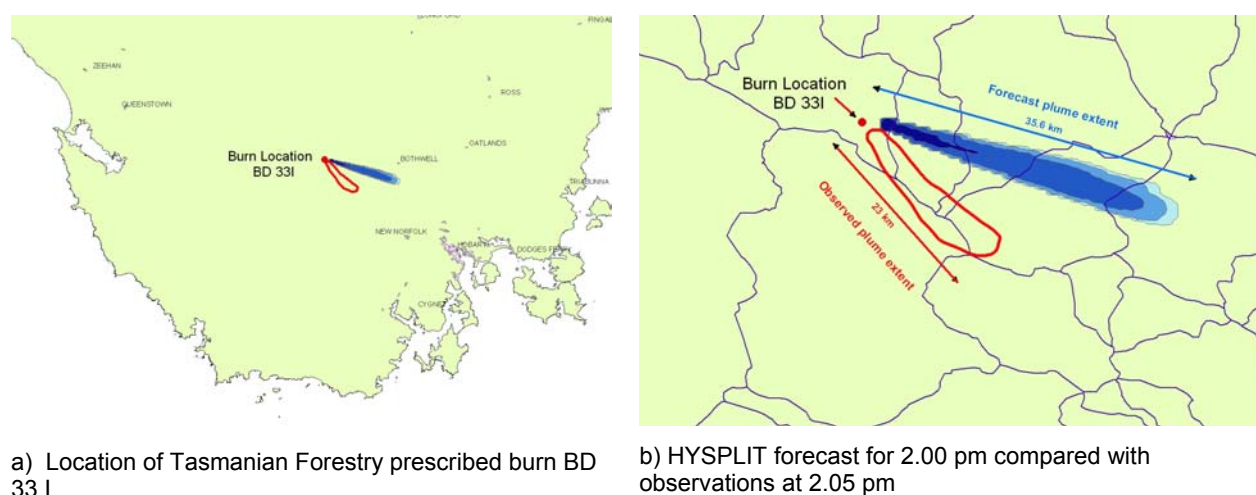


Fig. 21: Forestry Tasmania low intensity prescribed burn, Central Tasmania, 30 March 2001.

Fireworks magazine explosion – Carmel, WA, 6 March 2002

Early on 6 March 2002 an explosion occurred at a fireworks magazine in the Perth suburb of Carmel. The resulting fire produced a smoke plume that was clearly visible in satellite images. Routine HYSPLIT guidance was available to CALM from a nearby location at Bickley (32.00 S 116.08 E). Subsequent comments from CALM indicated that the HYSPLIT forecast gave a good indication of the plume's behaviour. CALM also provided a spatially registered Landsat-7 image of the event and a 250 m resolution MODIS (MODerate Resolution Imaging Spectroradiometer) image (<http://rapidfire.sci.gsfc.nasa.gov>) taken approximately 30 minutes later was also available. HYSPLIT was run from the meso-LAPS dataset with a concentration grid point interval of 0.005° (about 500 m) and the output interval was 15 minutes, and used data from the 1200 UTC 5 March 2002 meso-LAPS model run. The Perth Airport radiosonde sounding for 2300 UTC 5 March 2002 showed a mixed layer

depth of 600 m, and this was selected as the height of the vertical line source, rather than the default 1500 m used in operational forecasts.

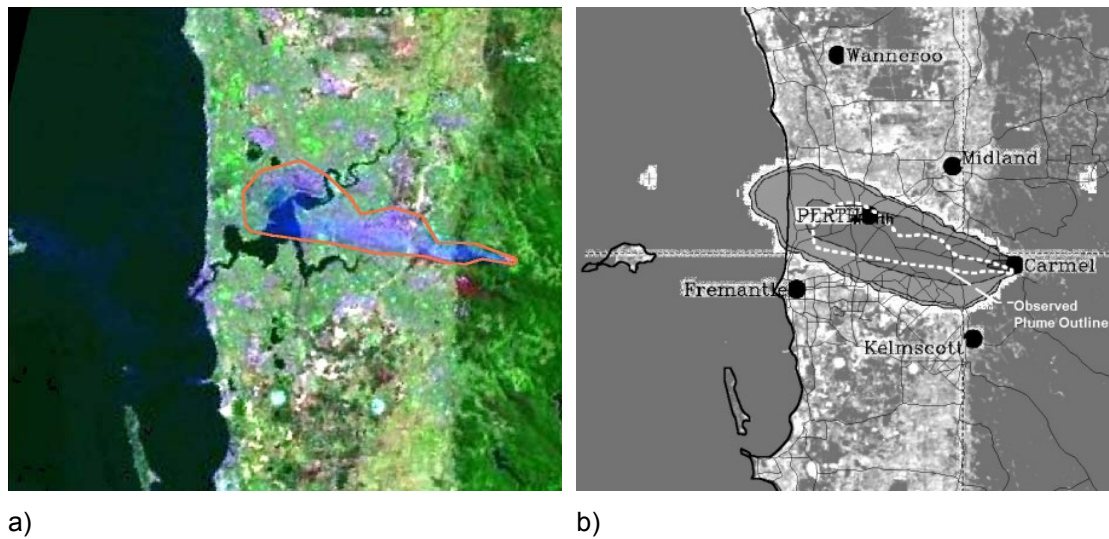


Fig. 22: Left panel: Landsat 7 image 0954 WST with plume outlined. Right panel: as left, with addition of HYSPLIT forecast for 1000 WST using 1200 UTC mesoLAPS winds.

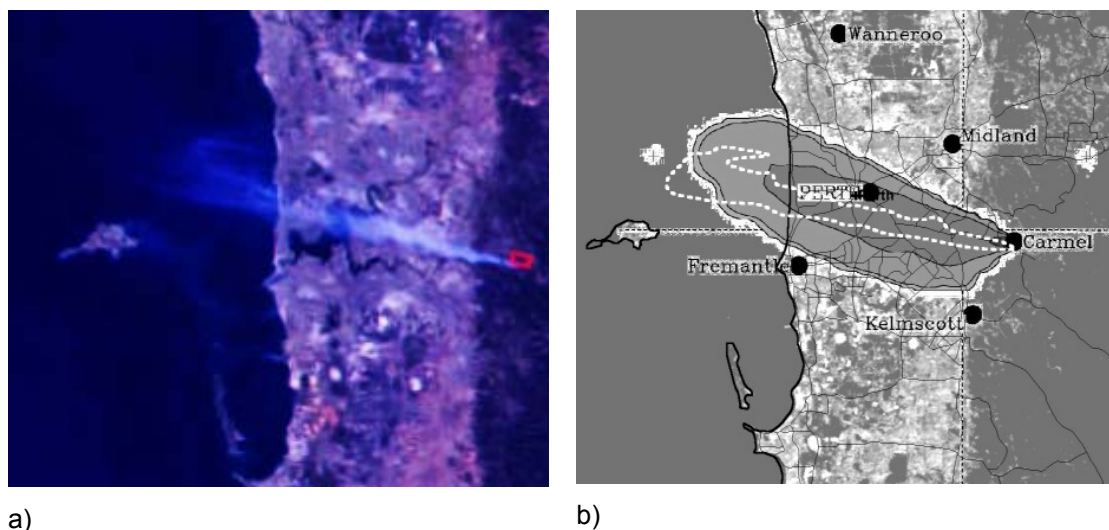


Fig. 23: (a) MODIS image taken at 0220 UTC (1020 WST) showing smoke plume and “hotspot”. (b) Outline of smoke from MODIS image overlaid on HYSPLIT forecast based on 1200 UTC mesoLAPS winds.

Figure 22a shows the Landsat image with the edges of the visible smoke plume outlined. In Fig. 22b the HYSPLIT forecast for the corresponding time is added. The comparison is excellent in respect of direction (3 degrees between the plume centrelines) and only a 9 km overestimate in distance travelled. This forecast, particularly the two higher concentration contours, would have provided excellent guidance. The MODIS image in Fig. 23 was taken only 30 minutes after the Landsat image and shows the plume extending further out to sea in a relatively thin band. At this time the visible plume extended for 49 km. The HYSPLIT forecast (Fig. 23b)

appears to give reasonable guidance, although the forecast plume is much wider than the observed plume. However, the difference in width of the observed smoke plumes may rather reflect the different sensitivities and properties of the two satellites than a change in the width of the plume over a 30-minute interval.

Wildfire: Whiteman Park, W.A. – 14 February 2001

14 February 2001 was a day of extreme fire danger in Perth, with easterly winds gusting 45 km h^{-1} . According to the West Australian newspaper, a fire began in Whiteman Park (Fig. 24) around noon, and subsequently consumed approximately 1100 ha of banksia scrub before being contained. The smoke plume was clearly visible in several geostationary satellite images (e.g. Fig. 24). Based on this report two HYSPLIT dispersion forecasts were calculated, one using data from the meso-LAPS model initialised the previous evening (1200 UTC 13 February), the other from the 0000 UTC 14 February meso-LAPS. The concentration grid was amended to a 1.8 km grid point interval to capture the full extent of the plume, and the concentration fields were output at 15-minute intervals. Calculating the mixed layer depth using the meso-LAPS model data produced a figure of 1900 m in both cases. This was used as the height of the vertical line source in the forecast initialisation. The forecast concentrations shown in this case are averaged from the surface to 2500 m. The first visible appearance of the plume in a satellite image occurred at 1430 WST, when the leading edge of plume was approximately 40 km west of Whiteman Park. As Fig. 25 shows, both the HYSPLIT forecasts based on the noon starting time appear poor. The forecast made with the later (0000 UTC) data shows evidence of a slightly higher wind speed but otherwise both forecasts are essentially the same and the distance travelled by the plume is grossly overestimated in both cases if the satellite imagery is used as the benchmark.

Initially this was thought to be because the meso-LAPS model winds were too strong. Surface winds at Pearce RAAF base at midday were 100 degrees at 18 knots (33.3 km h^{-1}). The 7.00am upper level soundings at Perth Airport reported surface winds of 27.7 km h^{-1} and a 900 m wind speed of 72.4 km h^{-1} . The wind direction varied from 105° to 85° . However there is a 130 km difference between the distances travelled in the 0730 UTC (1530 WST) GMS (Geostationary Meteorological Satellite) image (Fig. 24) and the forecast position for the same time, and this difference remains fairly constant in subsequent comparisons. The differences between the

actual winds and those in the meso-LAPS model are of the order of 10 km h^{-1} , not enough to account for a 130 km error in only 3.5 hours. Plausible explanations for this inconsistency could include that the fire began later or that the amount of smoke produced in the early stages of the fire was insufficient to be detected in the visible band GMS imagery. Subsequent information obtained from CALM showed the fire was first reported at 1230 WST.

Figure 25d shows a comparison of revised forecasts with the fire beginning at 1400 WST. The distances travelled are quite well forecast but the wind direction is in error by about 18 degrees. The high coincidence between the forecasts starting at 1400 and the satellite observations makes plausible the hypothesis that approximately 1.5 hours was required before a sufficient concentration of smoke was produced as to be visible to the satellite. This sensitivity analysis indicates the difficulty of obtaining “perfect” forecasts when there may be uncertainty in the source specification, and, of course, the unknown correlation between what is discernable in satellite imagery and the forecast concentrations remains an unresolvable issue in all these comparisons.

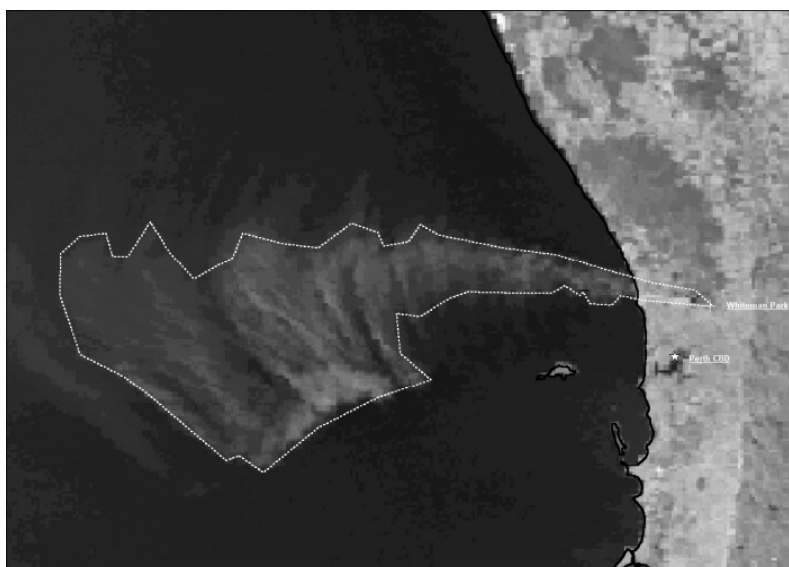


Fig. 24: GMS satellite image at 0830 UTC 14 February 2001 with the edges of the visible smoke plume outlined.

Wildfire: King Island – 11 January 2001

On the evening of 11 January 2001 many Melbourne residents noted the smell of smoke in the air and there were a large number of calls to emergency services reporting fires (The Age 12 January 2001). For much of the next 36 hours Melbourne was covered in a pall of smoke, with significant reductions in visibility. There were two peaks of reduced visibility recorded in the Air Quality Index (AQI) at the

Victorian Environment Protection Agency's Melbourne metropolitan monitoring stations on the evening of 11 January 2001 (Fig. 26). The initial peak (~1800 AEDT), also noted at Geelong South, is attributed to a grass fire that burnt around 320 ha of grass (estimated fuel load 6t/ha) near Winchelsea (approx. 100 km SW of Melbourne, Fig. 27). This fire began at approximately 1600 AEDT, immediately after the passage of a southwesterly change. The local temperature at the time was around 30 C and the wind was from the southwest at between 30-40 km h⁻¹. A strong inversion was also noted at 1000 m (Country Fire Authority (CFA) personal communication 2001).

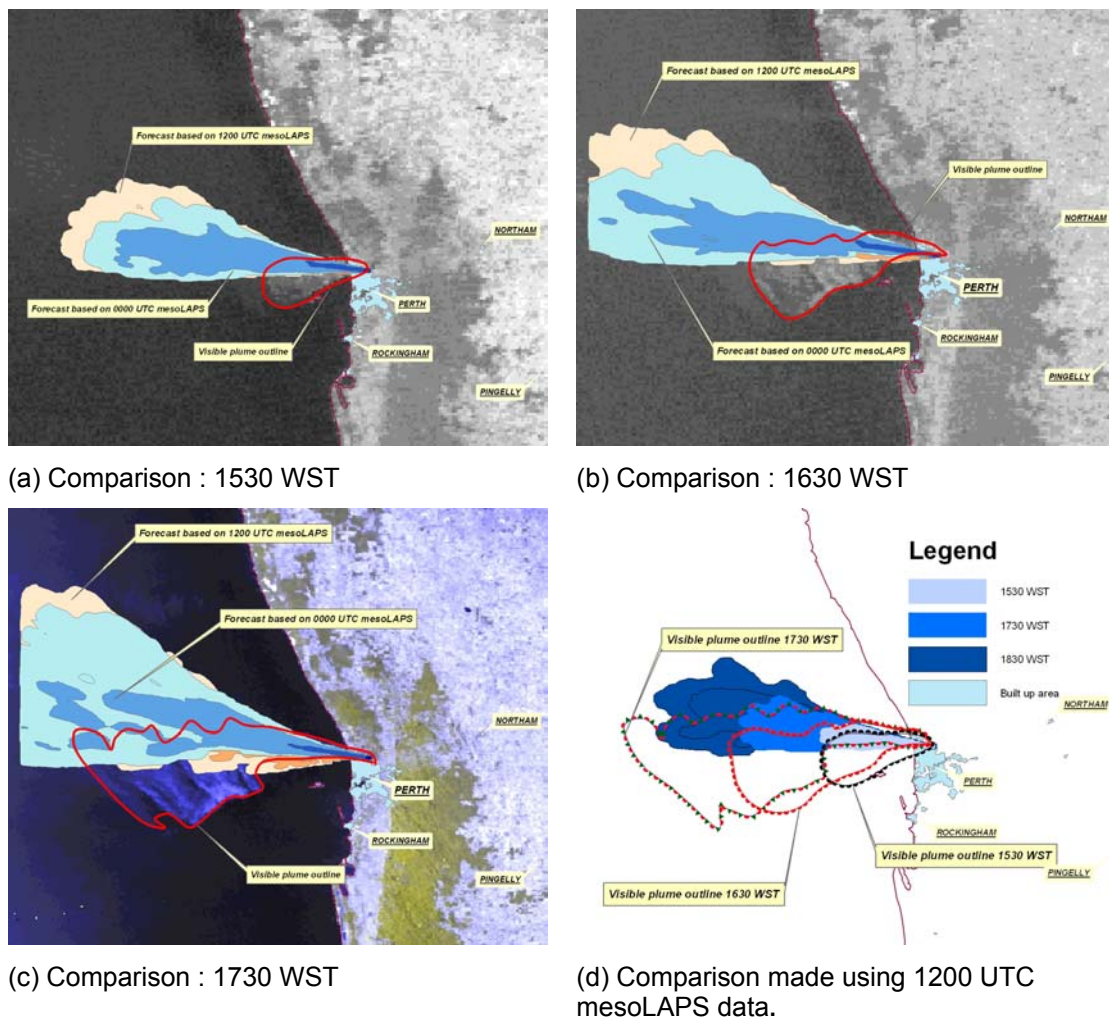


Fig. 25: Comparisons of the observed position of the smoke plume from the Whiteman Park fire with successive HYSPLIT forecasts, made using mesoLAPS data from 1200UTC 13 February and 0000 UTC 14 February 2001. Panels (a), (b), and (c) have an ignition time at 1200 WST, while (d) compares three successive forecast times, made with an ignition time two hours later, with the observed positions.

The main reduction in visibility, indicated by the subsequent peaks in Fig. 26, was due to a fire burning in the Lavinia Nature Reserve in the northeast corner of

King Island, approximately 300 km SSW of Melbourne (Fig. 27). This fire, started by a lightning strike on 1 January, had been burning for several days in scrub overlying a peat swamp. The meteorological conditions associated with the passage of the change noted above allowed the smoke plume from this fire to enter the Melbourne airshed.

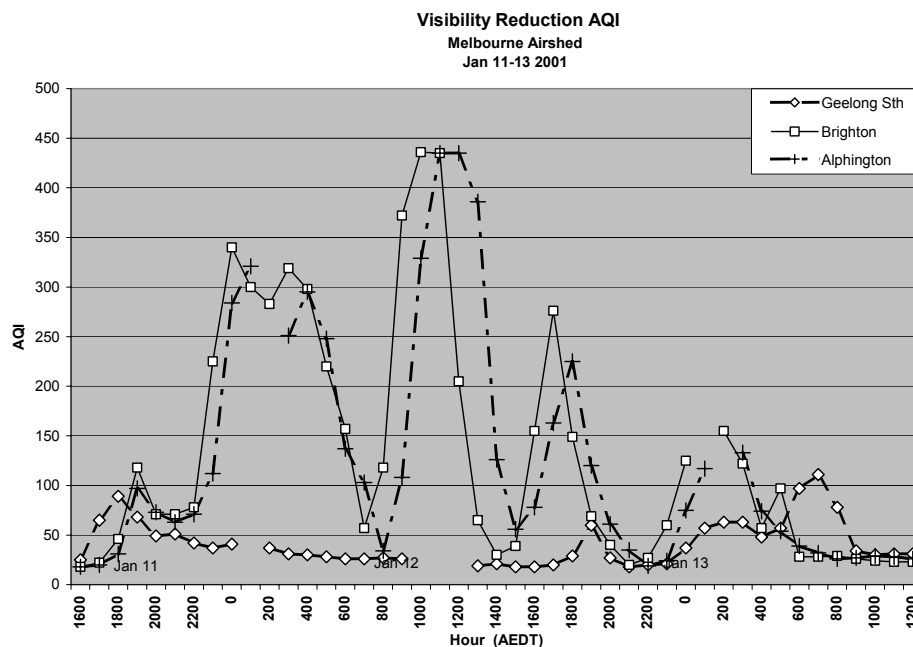


Fig. 26: The Visibility Reduction Air Quality Index (AQI) for 3 Victorian EPA monitoring stations January 11 –13, 2001 (Data: EPA 2001).

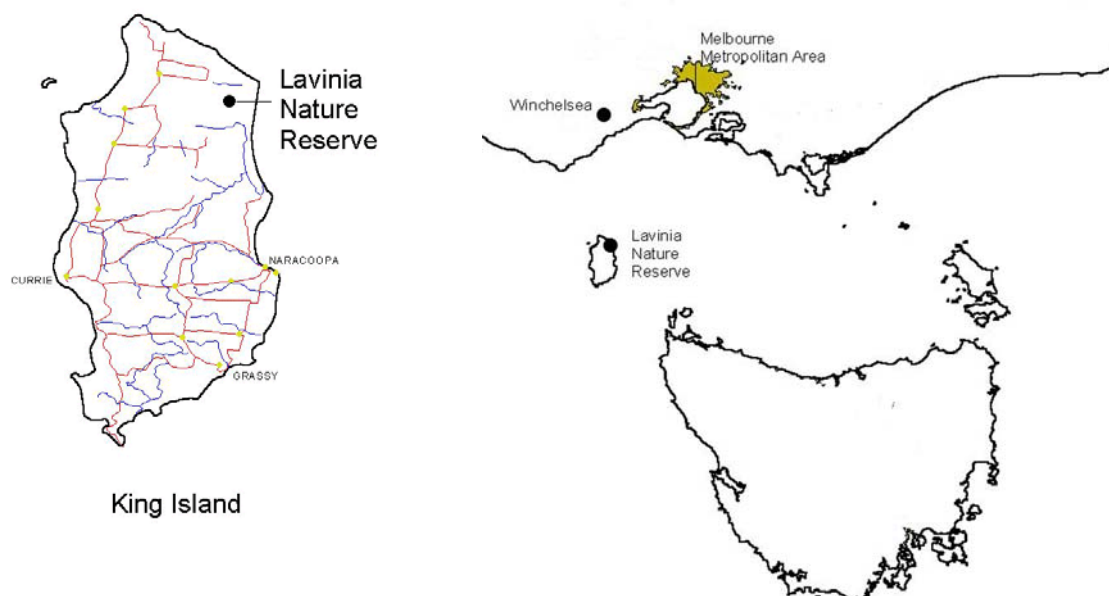


Fig. 27: Location of Winchelsea and King Island fires relative to the Melbourne Metropolitan area.

To study this episode HYSPLIT was used with meteorological input from both the 0.05° and 0.125° meso-LAPS numerical weather prediction models. In the initial studies undertaken the two fires were treated separately. For the Winchelsea fire a plume height of 1000 m was used based on the CFA report of a strong inversion at this height. A 12-hour forecast, starting at 1600 AEDT was produced using meteorological data from the 0000 UTC 11 January 2001 run of the 0.125° meso-LAPS numerical weather prediction model. The forecast showed the smoke plume moving across Geelong, over Port Phillip, and then impacting on the Melbourne metropolitan area before moving on to the northeast. Figure 28 shows two extracts from the dispersion forecast begun at 1600 hours AEDT from the Winchelsea fire. The forecast shows good agreement with the initial peak in the AQI at Geelong South at 1800 hours (Fig. 26). However the peak in the AQI observed at Brighton and Alphington an hour later is not quite as well forecast. The strength of the winds in this case appears to have been slightly under predicted by the meso-LAPS model, although the forecast still gives good qualitative guidance.

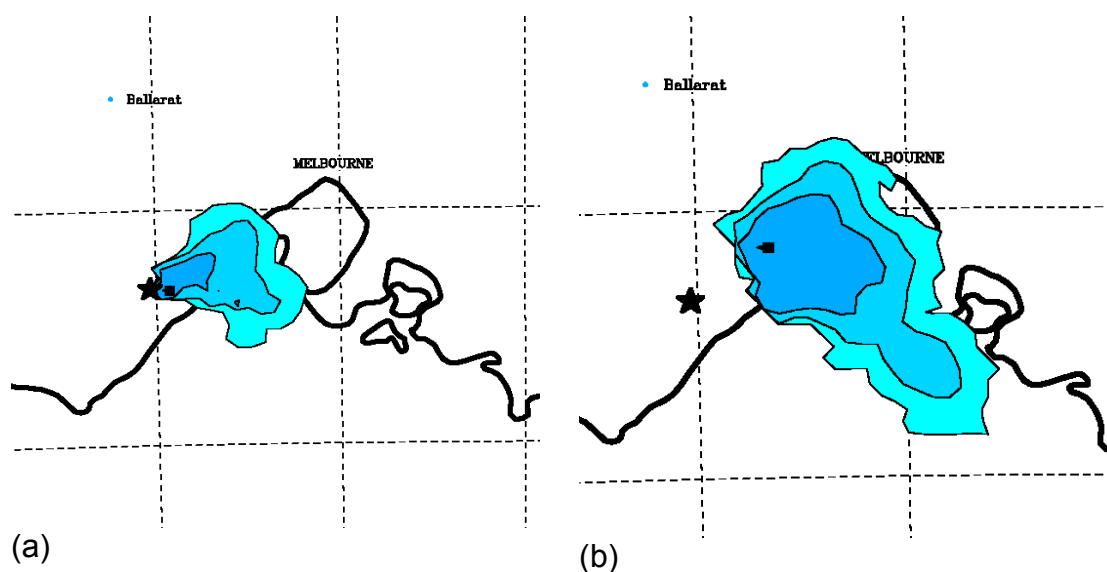


Fig. 28: Smoke dispersion forecast for the Winchelsea fire source. Forecasts are valid at (a) 1800 and (b) 1900 hours AEDST 11 January 2001.

The smoke plume emanating from the fire on King Island has been the subject of a much more extensive investigation. The plume is clearly visible on a series of GMS images from 3 January through to 18 January. This excellent visibility is largely a function of the fire's location on a relatively small island, the smoke plume being more easily detected over water than over land. This has enabled a good comparison

of the position of the observed plume and the forecast plume. The sequence of GMS satellite images in Fig. 29 begins at 0930 AEDT on 11 January. The wind has apparently just changed direction from NE to NW, the GMS image taken at 0930 showing a very short smoke plume, approximately 50 km in length, moving to the southeast. By 1230 AEDT the visible smoke plume extended 150 km to the southeast. Subsequent images show the plume over the period from 1330, 1430 and 1530 AEDT. The general direction the plume travelled during this time was to the southeast, however the increasing influence of a major wind change, this time from the WSW, is noticeable in the section of the plume nearest to the fire source. By 1530 there is a distinct kink in the smoke plume that becomes more pronounced in the final three hours of the sequence. The cool change, or shallow dry cold front, that brought this wind change is similar in structure to that described in detail by Mills (2002). Such cool changes are characterised by abrupt direction changes in coastal locations, and the post-frontal cool air is relatively shallow, consistent with the CFA reports of a strong inversion at ~ 1000 m near Winchelsea.

Over the course of this project several dispersion forecasts have been made for the King Island event using differing starting times, model parameters, and meso-LAPS model runs. Figure 30 shows dispersion forecasts commencing at 0000 UTC 11 January 2001 using the Lavinia Nature Reserve fire location as the source, with forecasts valid at 0700, 1300 and 1700 UTC 11 January (1600 and 2000 AEDT 11 January, and 0200 AEDT 12 January respectively). The differences between the two columns are the age of the meso-LAPS forecast – the forecasts on the left are based on the meso-LAPS run initialised at 1200 UTC 10 January, while the forecasts in the right-hand column are based on the meteorological forecasts initialised at 0000 UTC 11 January 2001. Both sets of forecasts show similar character, with the plume being advected to the northeast from King Island, and the backing of the winds with time following the cool change causing the plume to “rotate” anti-clockwise, moving towards Melbourne from the east with increasing time. The later forecast, though, shows a sharper wind change, a stronger southerly component to the post-frontal winds, and thus shows the plume crossing Melbourne a little earlier than the longer lead-time forecast, consistent with the peak in AQI in the early hours of 12 January shown in Fig. 26. Thus while both sets of forecasts were indicating the same general trend, the later set of forecasts was rather more accurate, as would generally be expected with a shorter lead time.

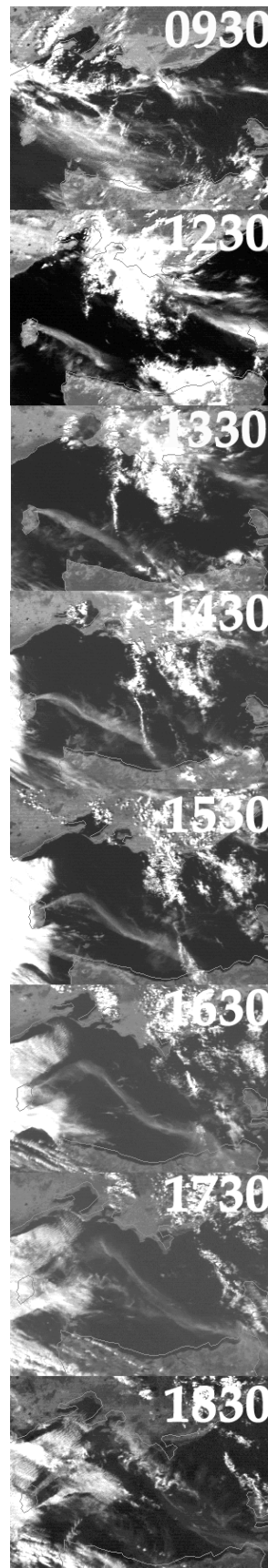


Fig. 29: Satellite picture sequence for King Island smoke event. Times are AEDST 11 January 2001.

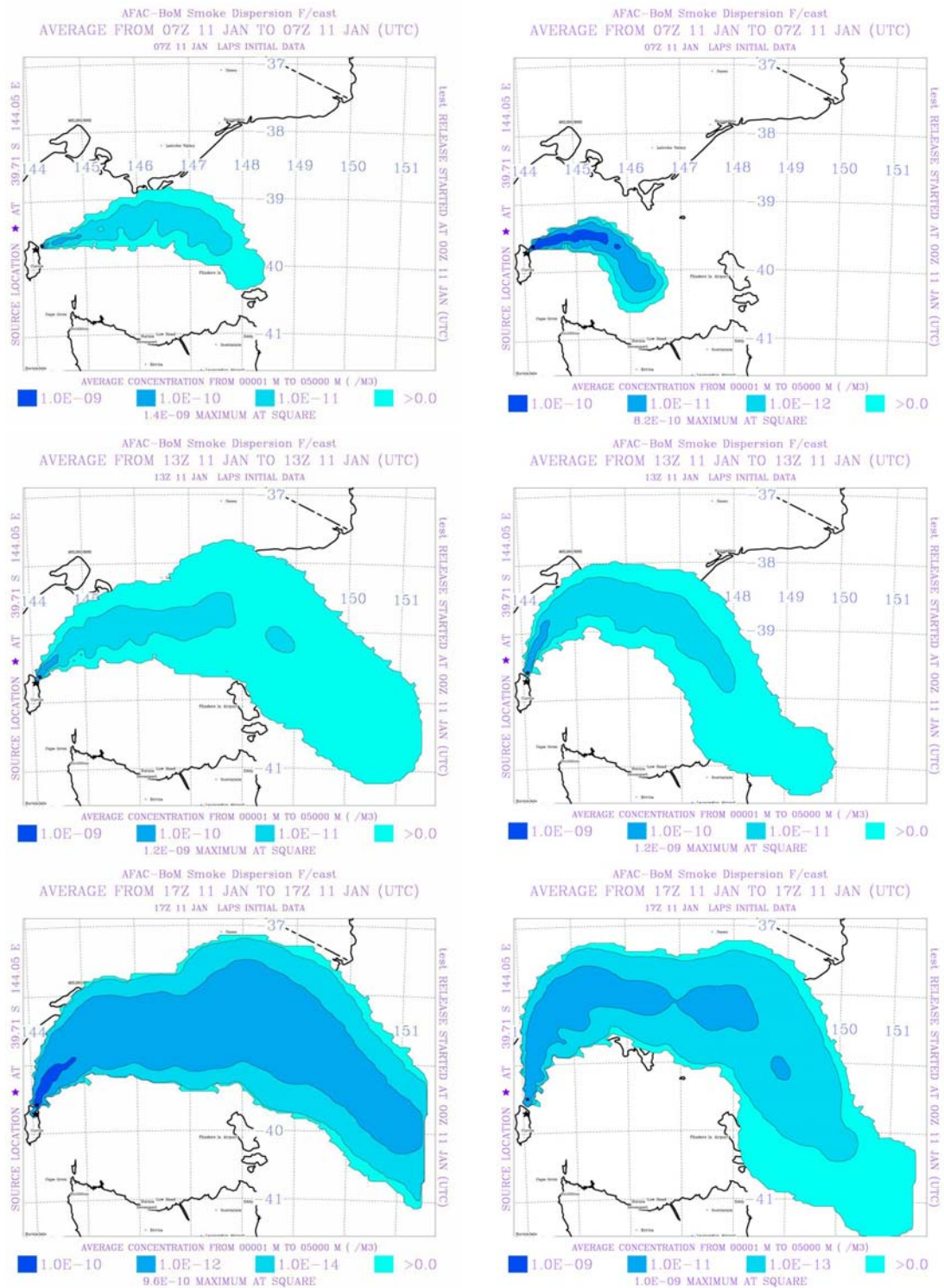


Fig. 30: King Island dispersion forecasts. Left column shows forecasts based on the 1200 UTC 10 January 2001 numerical model, the right panel uses 0000 UTC 11 January 2001 meso-LAPS data. Top row forecasts are valid at 0700 UTC, middle row at 1300 UTC, and lower row at 1700 UTC 11 January 2001.

This “King Island Smoke” event had large community impact, and not only did the smoke plume move across the waters of Bass Strait, allowing the plume to be

well-resolved in satellite imagery and thus provide excellent verification data, but also passed across the air quality monitoring network maintained by the EPA in the Melbourne metropolitan area. This made it an excellent case for study and a comprehensive comparison between the HYSPLIT forecasts and forecast from the AAQFS (Cope et al. 2004) forecasts is found in Hess et al (2005). The case has also been used as a validation of HYSPLIT upgrades before their being used to produce the operational smoke management forecasts.

Wildfire: Tulka (SA) – 2 February 2001

Around midday on 1 February 2001 a fire was reported burning near Tulka, on the Eyre Peninsula, north of Port Lincoln, South Australia (SA), and with strong northerly winds that afternoon the fire had burnt out 650 ha by 10 pm Central Daylight-saving Time (ACDT). On 2 February the fire area, fanned by strong northerly winds ahead of a cold frontal passage in the early afternoon, quickly grew from 900 ha at 9.30 am to over 5000 ha at 8 pm ACDT. The cool change passed through Pt. Lincoln at around 2 pm local time ACDT, and was followed by fresh southwesterly winds. The mean-sea-level pressure analysis at 0000 UTC 2 February 2001, some 2-3 hours before the change passed through Pt. Lincoln, is shown in Fig. 31. Smoke from the Tulka fire was initially transported to the south by the strong northerly winds, and could be identified on the satellite image at 2230 UTC 1 February (Fig. 32), prior to a cloud layer moving over the area. This large cloud mass eliminated the use of satellite imagery to verify the subsequent movement of the smoke. Observations of smoke were used to evaluate these dispersion forecasts.

Reports from observers in SA indicate the smoke plume from the fire passed over Kangaroo Island then later moved north over Adelaide. At Cape Borda, on the western tip of Kangaroo Island smoke was reported between mid-day on 2 February and 3am on 3 February (ACDT), and interestingly was observed both ahead of the cool change and in the southwesterly flow after the change. Observations recorded at Adelaide Airport report smoke at 6 am ACDT and 9 am ACDT 3 February, while at the Adelaide Regional Office at Kent Town (just east of the Adelaide central business district) smoke was observed from midnight to 6 am ACDT 3 February. Reports of smoke were also received from observing sites along the shores of Spencer Gulf. Dispersion forecasts valid 0800 UTC (6.30 pm ACDT) and 2000 UTC (6.30 am 3 Feb ACDT) 2 February and based on model data initialised at 0000 UTC 2 February are

shown in Fig. 33. The smoke moving southwards over Kangaroo island in the pre-frontal northerlies is seen in the earlier panel, while in the post-frontal southwesterly winds smoke was predicted to move northeastwards into St Vincents Gulf and northwards into Spencer Gulf. While comprehensive verifications are not available, these forecasts are consistent with the available observations.

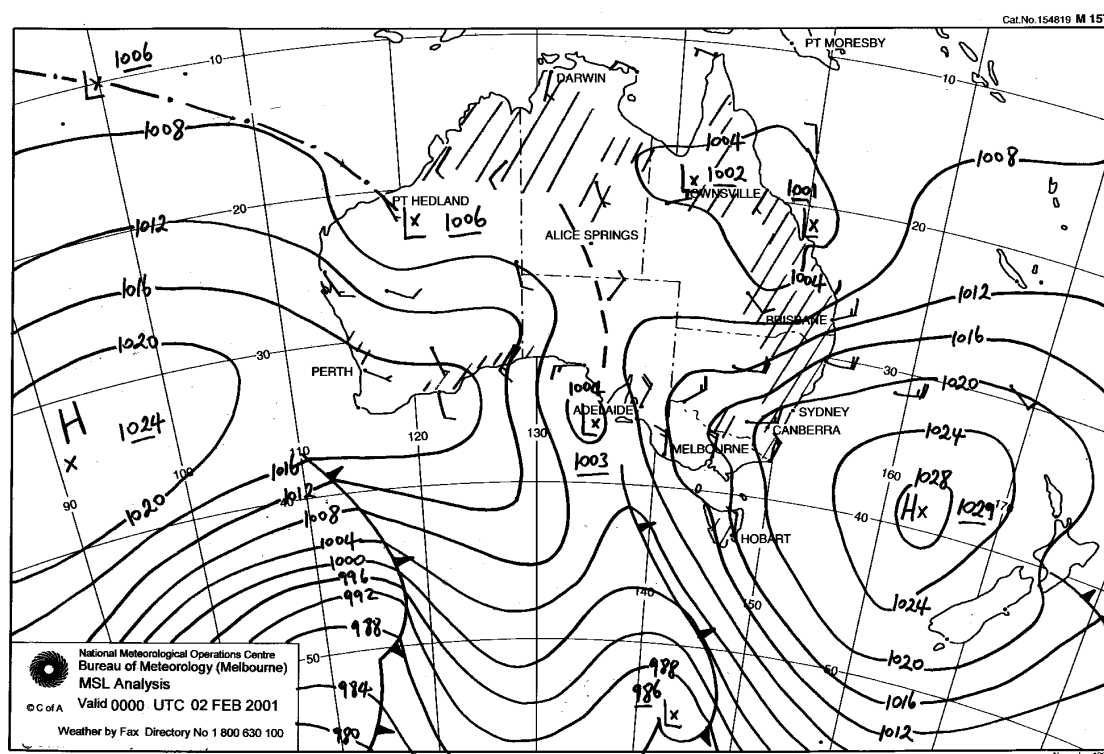


Fig. 31: MSLP analysis at 0000 UTC 2 February 2001 (Tulka case).

Wildfire (Long Duration): New South Wales – December 2001 to January 2002

While the smoke forecast guidance system was designed to provide tactical advice to assist the selection of prescribed burn sites, it can be applied to longer-duration wildfires. However, it is apparent from the case studies above that the HYSPLIT configuration used for the operational tactical guidance is not necessarily that which will provide optimal guidance for smoke emitted from long-duration wildfires. Major wildfires can persist for many days, and as a result large areas of high smoke concentrations may exist. It is thus desirable that these background concentrations are included in any new forecast, and thus there is a need to specify a background particulate concentration field to which is added “new” smoke from the existing fires. In addition, diurnal variations in atmospheric stability produce large variations in plume rise, and so a more dynamic specification of plume rise rather than a fixed

value is desirable. Further, as the lead-time of a forecast model increases, its accuracy generally decreases, and so it is desirable that the ability to restart a long-duration forecast with the latest meteorological forecasts be provided.

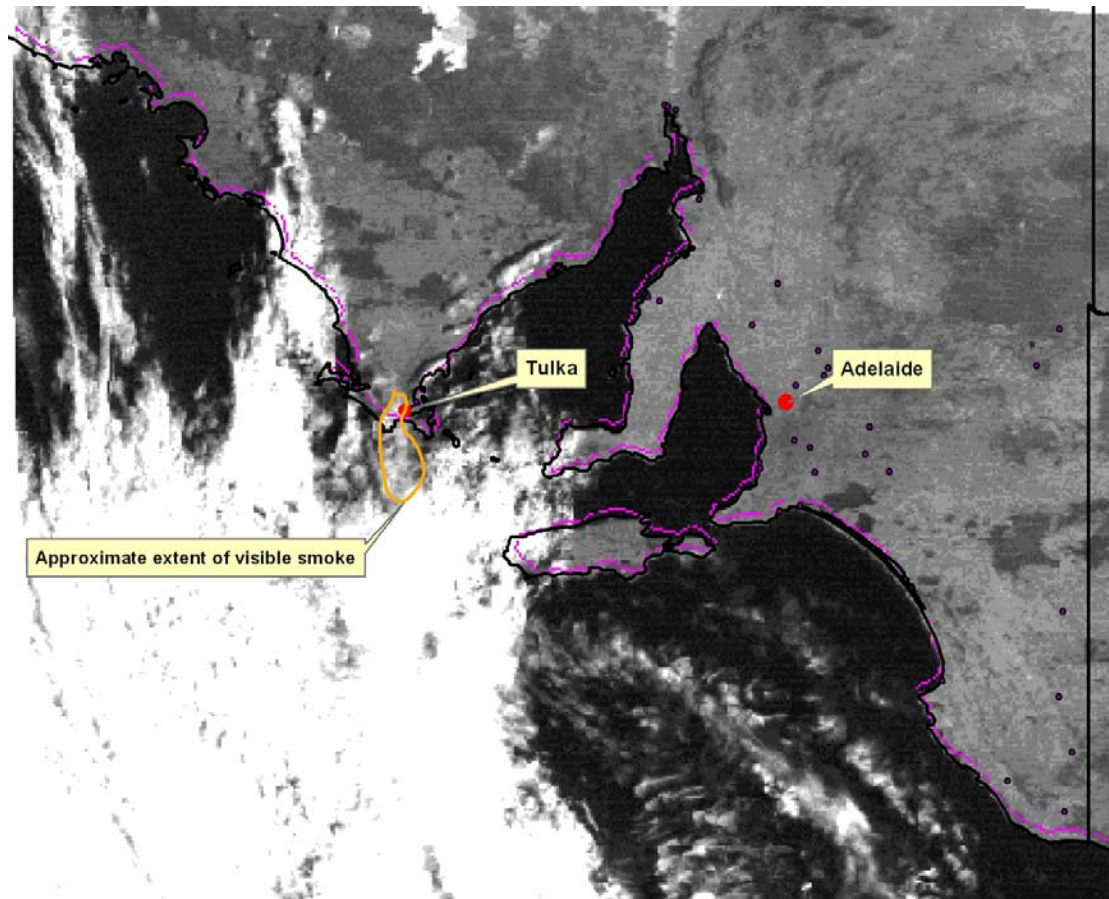


Fig. 32: Annotated GMS image at 2225 UTC 1 February 2001 (Tulka Fire).

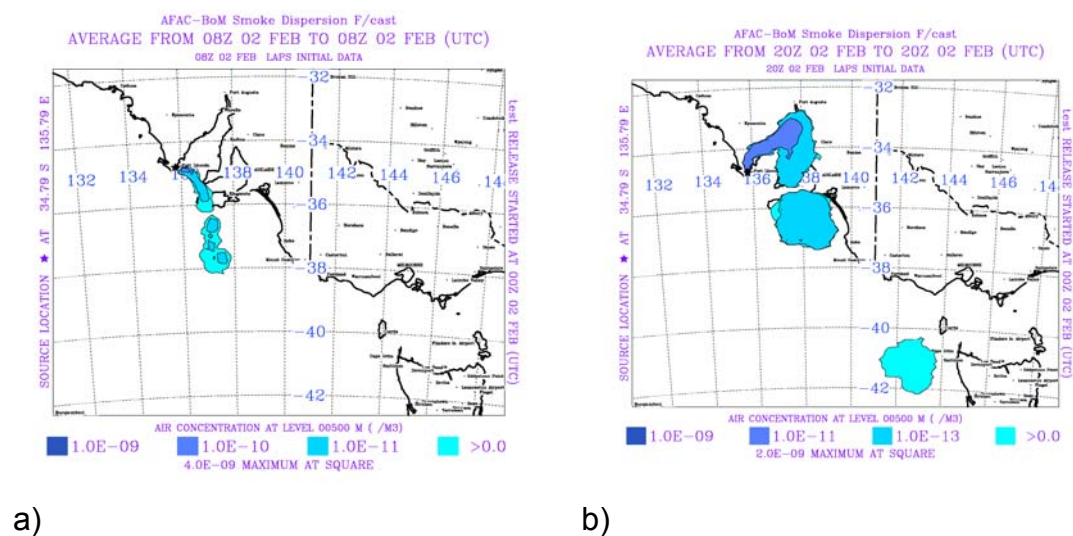


Fig. 33: Dispersion forecasts valid at (a) 0800 UTC and (b) 2000 UTC 2 February 2001 showing simulated smoke dispersion from the Tulka fire.

Such a configuration was developed and tested during the New South Wales (NSW) wildfires during the summer of 2001-2002, with smoke particles being retained in the dispersion forecast for 24 hours, sources added or deleted as new fires were declared or existing fires extinguished by NSW Rural Fire Service (RFS) (References obtained from RFS webpage), updated meteorological fields used after each new model run was completed (i.e. every 12-hours), and the height of the source being defined by the depth of the model's well-mixed boundary layer. This latter specification provided significant advantages, with mixed layer depths varying diurnally, and also synoptically, from just a few hundred metres to above 5 km. Figure 34 shows the HYSPLIT forecast for 1000-1100 UTC 26 December 2001, after some 83 hours of run-time, compared with a MODIS image for the same time, and the quality of the guidance is remarkably good.

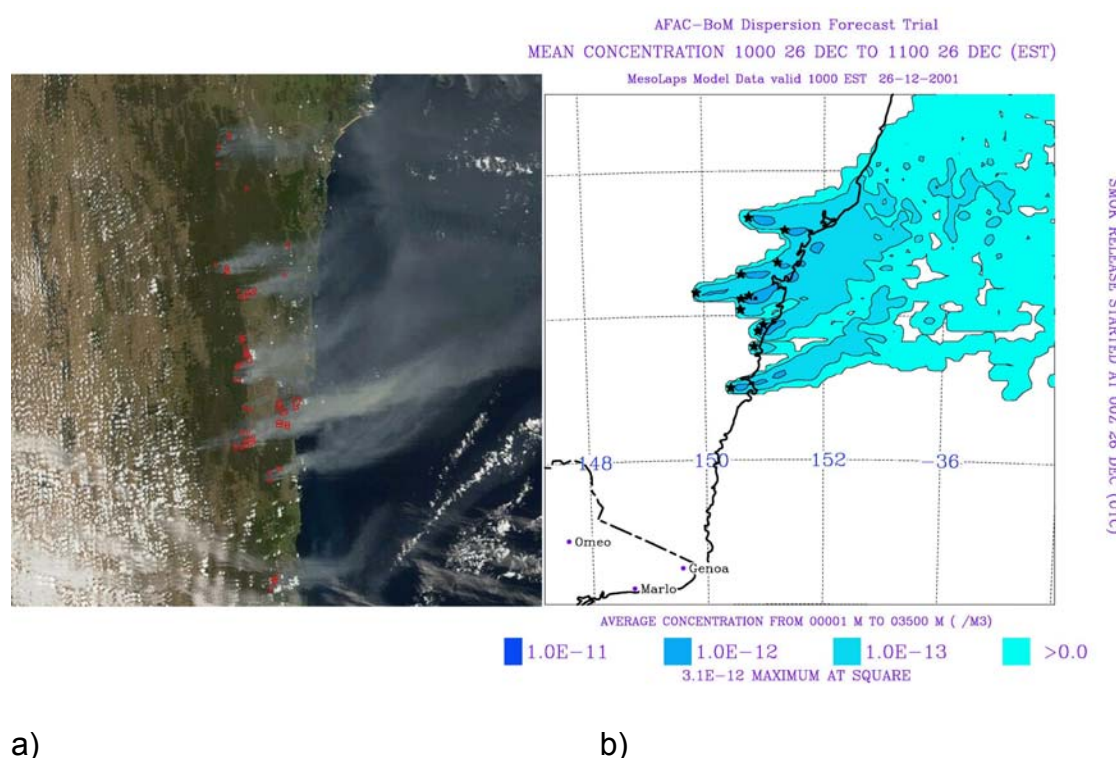


Fig. 34: Comparison of (a) a MODIS image and (b) HYSPLIT forecast valid at 1000 UTC 26 December 2002 using retained smoke, diurnally varying plume rise, and updated meteorological forecasts every 12 hours. At this time the HYSPLIT forecast had been running for 83 hours. The MODIS track is some way to the west of the fire location, resulting in an oblique view.

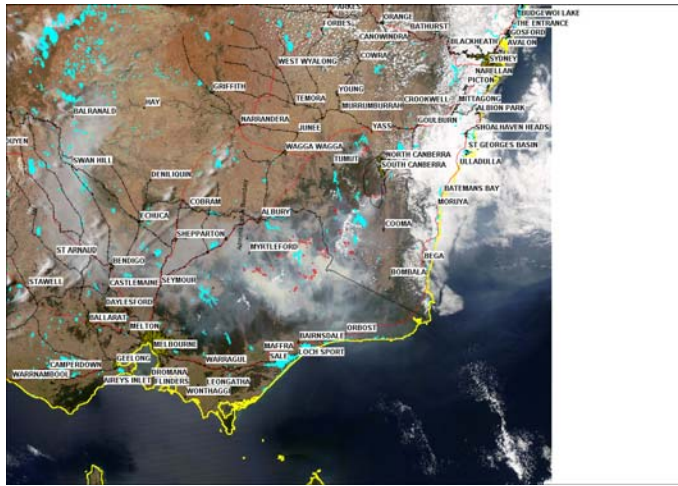
Wildfire (long duration): Eastern Australia – January 2003

The same configuration used in the NSW wildfires case was applied during the fires in the southeastern Australian high country in January-February 2003, when at times during that period smoke covered large parts of Victoria. The significant difference in this case was that fire locations were obtained from the MODIS "hot spot" data via the CSIRO Sentinel website. Figure 35 shows a significant improvement in the HYSPLIT forecast for 28 January 2003 when the smoke particles are retained. The "retained" forecast shows the dispersion of smoke into western Victoria while the forecast made without smoke retention shows smoke transport to the northeast only. This product, though not operational, was used to assist aircraft deployment during fire-fighting operations during these fires.

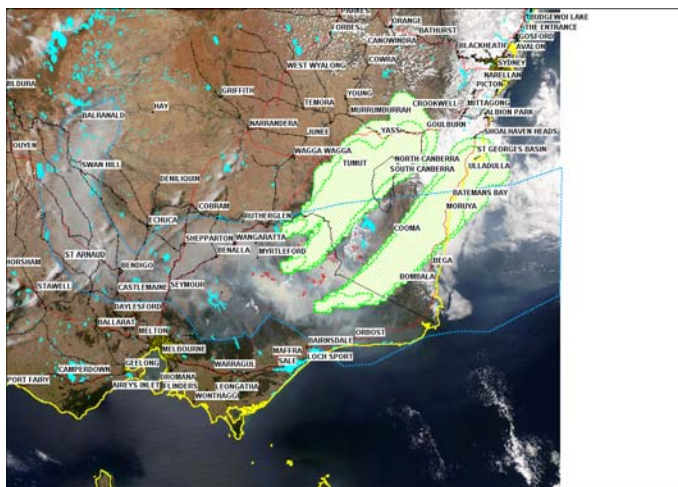
"Black rain" at Ceduna

On the 7 October 2000 the Bureau station at Ceduna observed sooty deposits on cars and other surfaces following light overnight rain. Similar observations of "black rain" were made at several sites on the Eyre Peninsula, the west coast of SA, and in the north of that state at Roxby Downs (Financial Review 13 October 2000). Media reports speculated about the possible origin of these deposits. An active trough system had passed through SA in the early morning hours of 7 October (Fig. 36) and a northwest-southeast oriented mid-level cloudband (Fig. 37) associated with this system produced the light rain observed at the SA stations. Given that the rain fell from mid-level cloud, it was hypothesised that the aerosols scavenged from the atmosphere had a non-local origin.

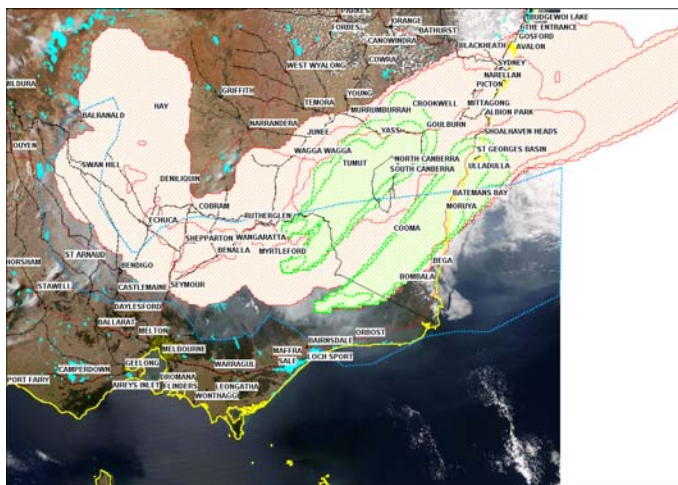
The TOMS images for 6-8 October (Fig. 38) show a large area of high aerosol concentration over northwestern Australia, but with an extended band of aerosol oriented northwest-southeast and moving eastwards, apparently transported by the winds associated with the same trough system that generated the northwest cloudband seen in Fig. 37. (This elevated aerosol event over northwestern Australia persisted from late September throughout most of October). Examination of AVHRR hotspot data revealed a number of hotspots (Fig. 39), and therefore presumably going fires, in the north of WA, and it is a reasonable assumption that these fires were the source of the elevated aerosol concentrations seen in Fig. 38.



a)



b)



c)

Fig. 35: a) shows the smoke from the eastern Australian fires at 0400 UTC January 28 2003 (source Aqua MODIS). b) shows the HYSPLIT forecast without retained smoke, while c) shows both the outlines from (b) and the smoke distribution with the retained particulate concentrations from the previous forecasts.

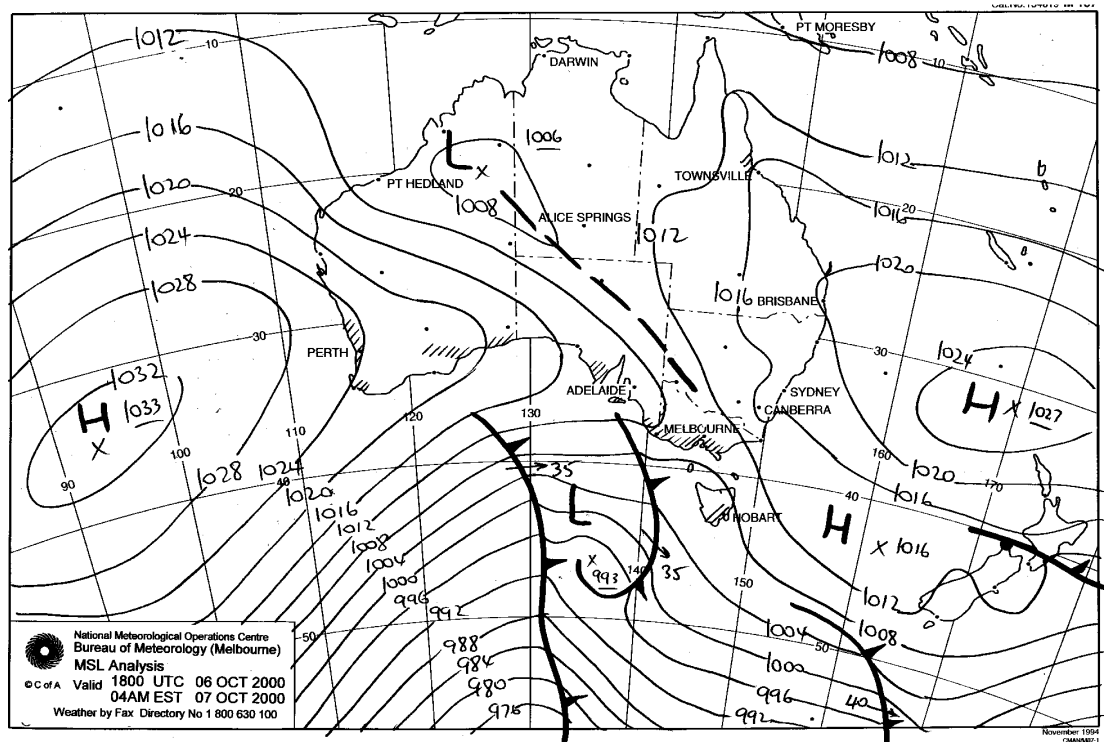


Fig. 36: MSLP analysis at 1800 UTC 6 October 2000 for the Ceduna “black rain” case.

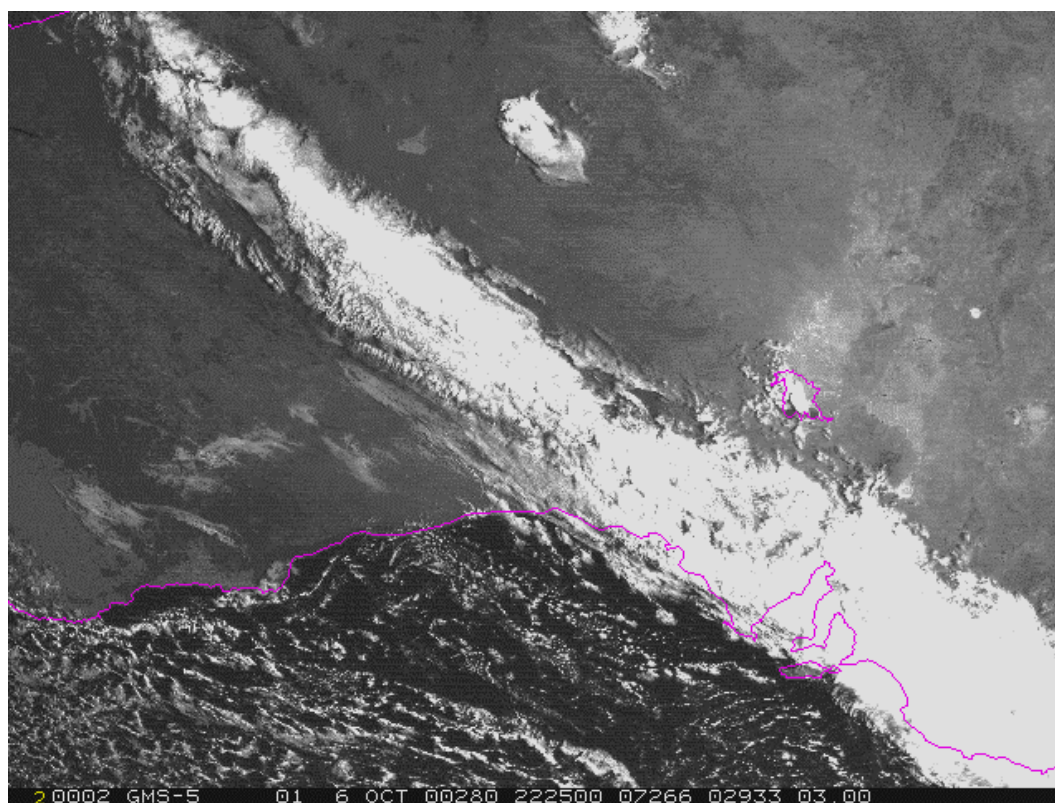


Fig. 37: GMS visible image at 2225 UTC 6 October 2000.

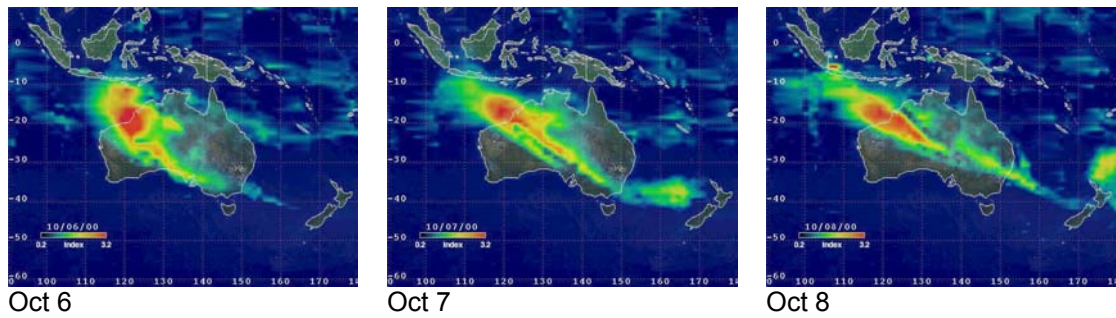


Fig. 38: TOMS images of aerosols over Australia, 6-8 October 2000. (Source NASA-GSFC)

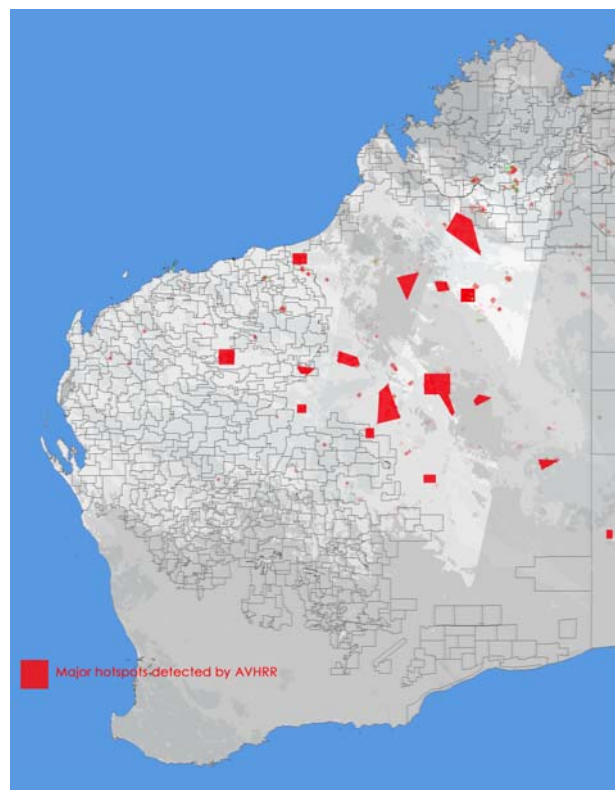


Fig. 39: Fire hotspots detected in Western Australia by the AVHRR instrument on the NOAA-12 satellite on October 5-6. Several of the more obvious areas of detected activity have been highlighted in red.

In order to test if the “black rain” could be related to some or all of these fires, 36-hour back trajectories were calculated from multiple levels above Ceduna. Several scenarios were tested over an 18-hour range beginning at 1200 UTC on 6 October 2000. Figure 40 shows that 4 of the 6 trajectories (those between 2500 and 4000 m) arriving at Ceduna at 0000 UTC on 7 October had been in the vicinity of the fire

hotspots, and particularly those fires near 24° S, two days earlier. Observations at Ceduna show that the surface trough passed through Ceduna at around 0800 UTC 6 October, and this is reflected in the back trajectories (Fig. 40) where the lowest trajectory arrives from the southwest while the others come from the WNW.

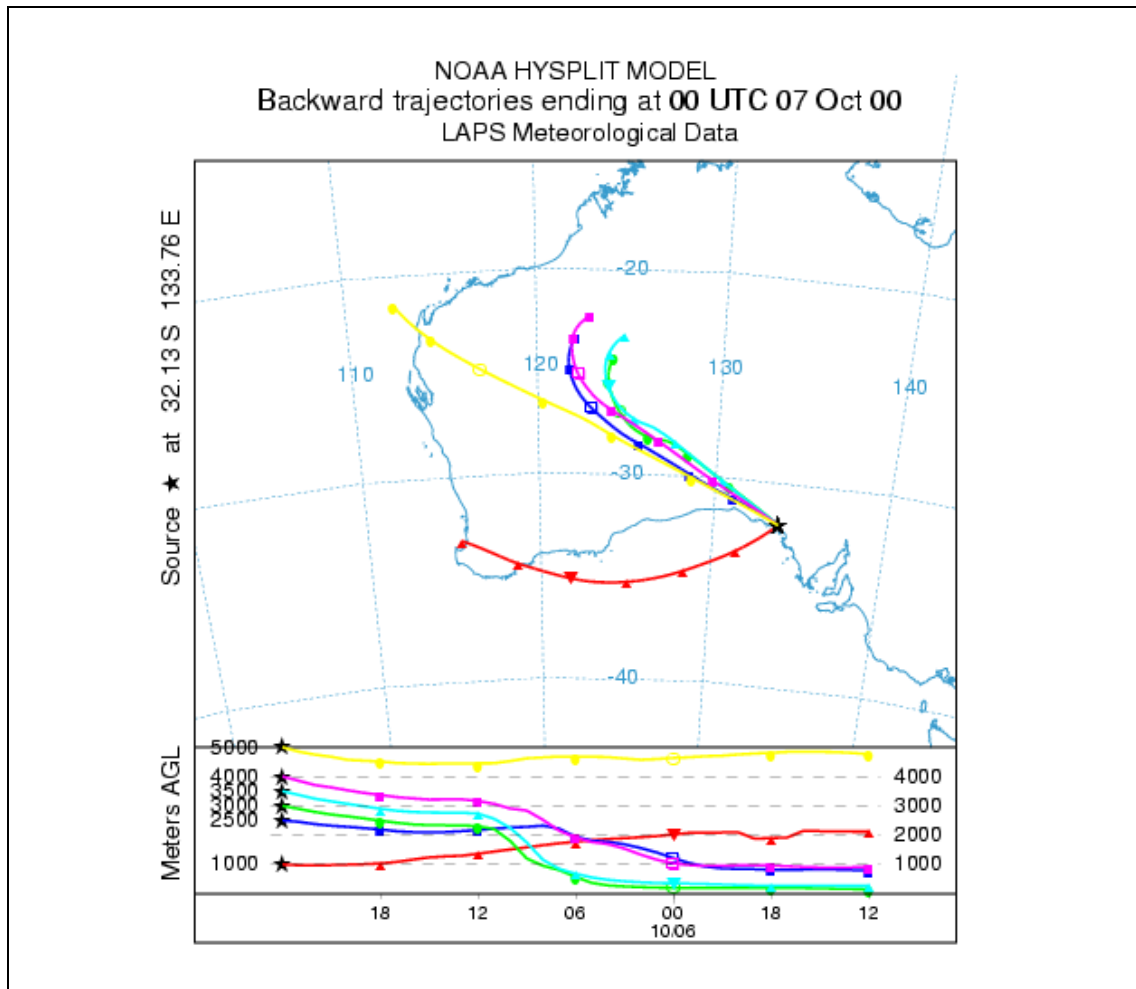


Fig. 40: Back trajectories from Ceduna at 0000 UTC 7 October 2000. Length of trajectories is 36 hours.

The three fire locations near 24S were then chosen as starting points for dispersion forecasts. The results (Fig. 41) show that the centrelines of the plumes from each location pass over Ceduna at approximately 4.30am CST on 7 October 2000. The shape of plume looks remarkably like the cloud visible in the GMS image (Fig. 37), and it appears that the smoke from these fires was entrained in the ascending conveyor-belt flow (Harrold, 1973) ahead of this trough that also generated the mid-level cloudband.

In this case given a set of rare circumstances;

- fires occurring in widespread locations
- the correct meteorological conditions to both transport aerosols and to rain lightly (enough precipitation to scavenge the aerosol, but not sufficient to wash it off the surfaces on which it was deposited)
- the availability of corroborative evidence from satellite instruments

then the use of accurate meteorological and transport models enable a plausible explanation for what otherwise may have been a “mystery event” to be provided.

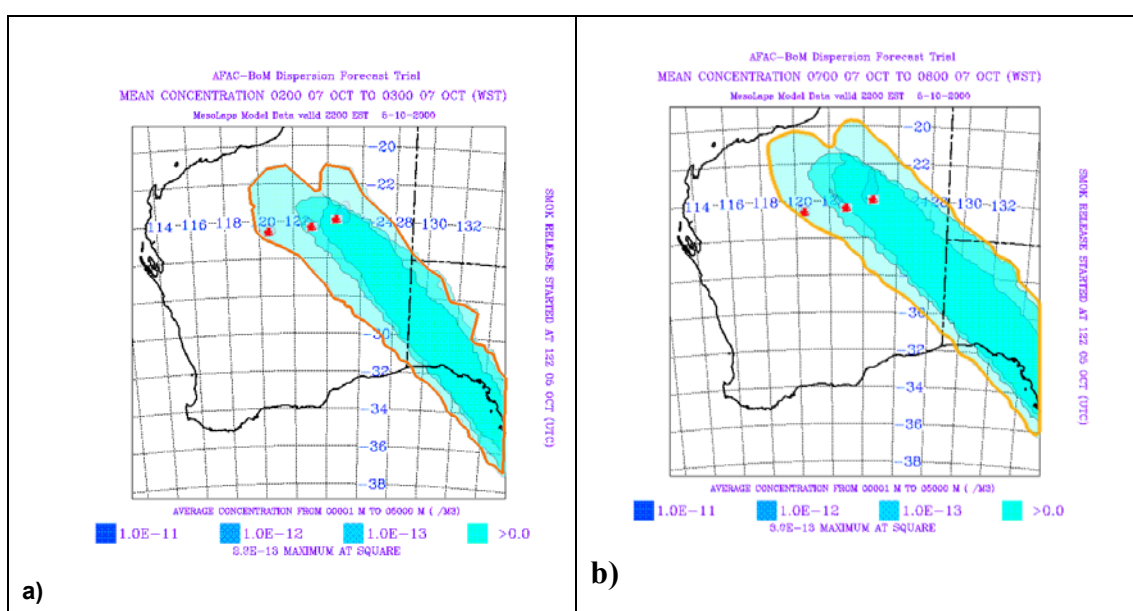


Fig. 41: Composite Images of smoke dispersion forecasts beginning at 1200 UTC 5 October 2000, valid at a) 0300 WST (0430 CST) and b) at 0800 WST (0930 CST) 7 October 2000.

Eastern Australian dust-storm – 23 October 2003

On 22-23 October 2002 a major dust storm occurred through SA, NSW, and Queensland as a very active cold front moved across those states. The dust was dramatically evident in geostationary (Fig. 42) and orbiting (Fig. 43) satellite imagery and dust was observed at many towns across the region, from Eyre Peninsula in SA through to cities on the eastern Australian seaboard.

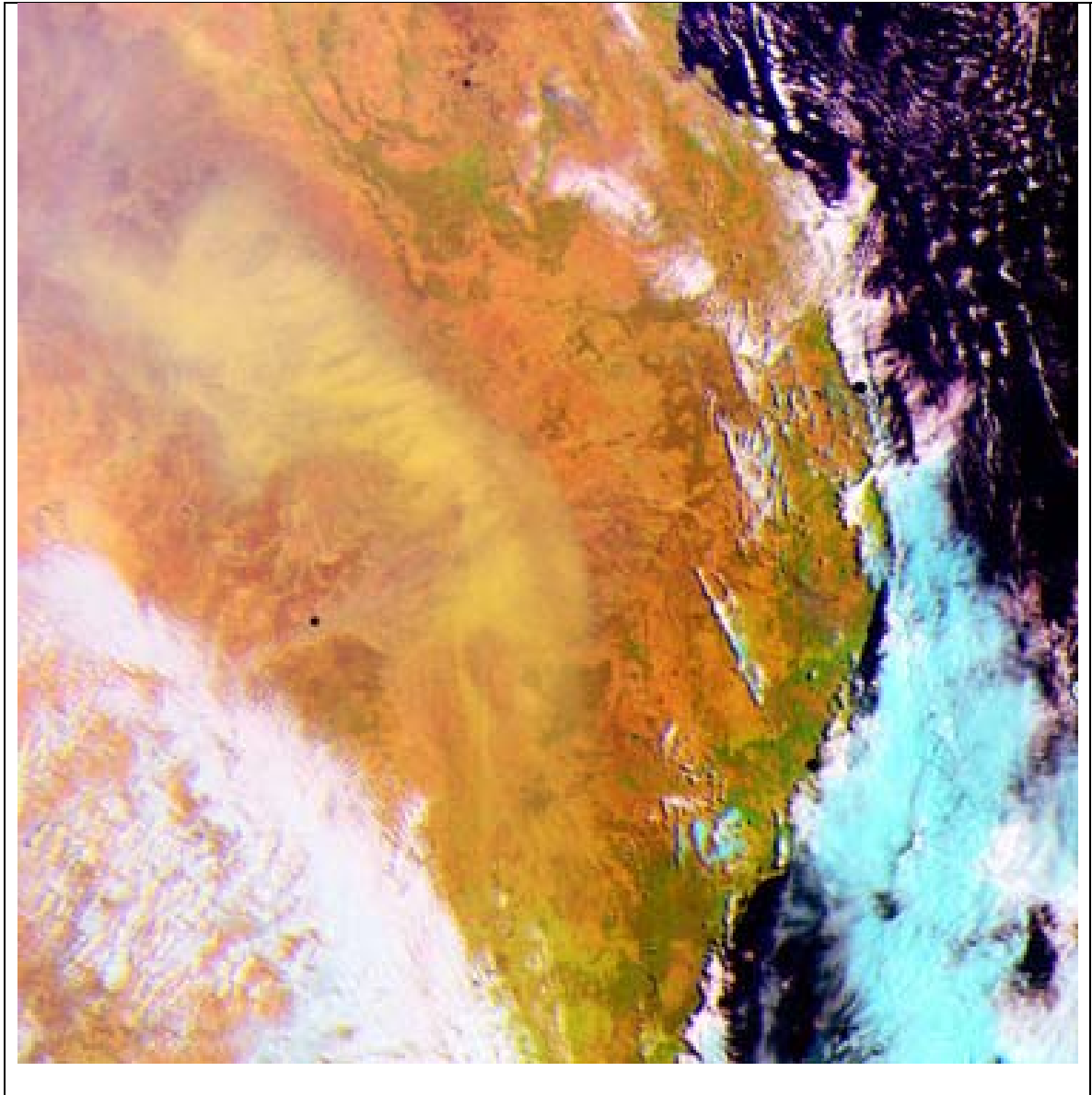


Fig. 42: FY1D imagery of dust storm – 23 October 2002

Dust emissions in HYSPLIT utilise the Draxler et al. (2001) PM₁₀ dust emission algorithm. When the wind speed exceeds a specified threshold velocity over a grid cell defined as desert the model emits dust, and transport begins from that location. The gravitational settling rate of the particles is determined using particle size, density, and shape. Using a land-use scheme based on the Lowe (1943) dust-storm frequency analysis and a threshold velocity necessary to initiate particle movement of 10 m s^{-1} , forecasts of dust transport were initiated at 0000 UTC 21 October 2002, with the meteorological fields updated every 12 hours. An example of the forecast is seen in Fig. 44, with the outline of the dust as observed from the satellite and surface observations for verification. The area of dust is well forecast in

terms of shape and size, although lags the observed dust area by a modest distance, and must be considered an excellent forecast given the simplicity of the land use distribution that was used. Further examples of forecasts for other times and comparisons of these forecasts with AAQFS forecasts are found in Wain et al (2005).

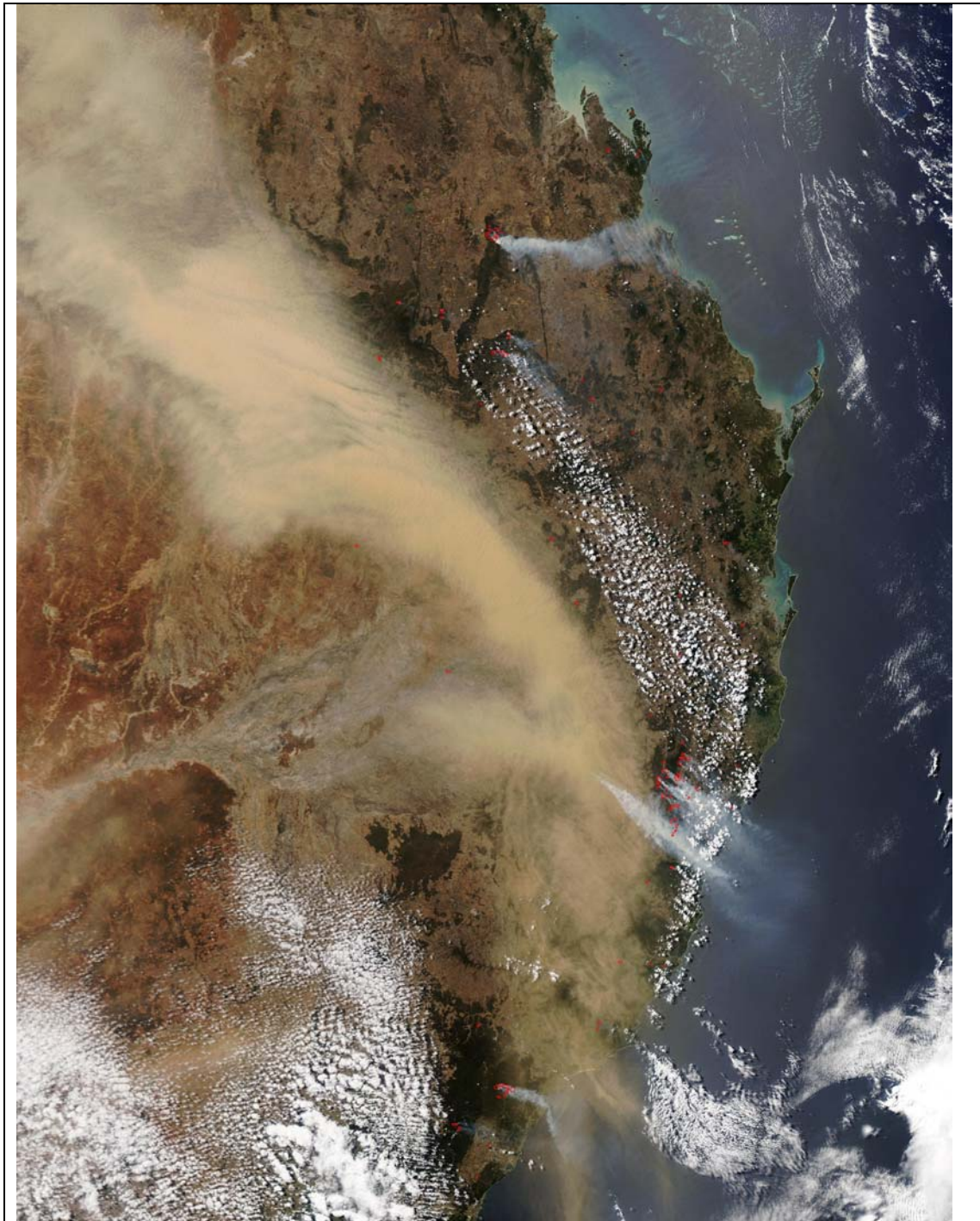


Fig. 43: MODIS imagery of dust storm at 0325 UTC 23 October 2002. Dust is brown, but several smoke plumes can be seen emanating from fires. The hot-spots identified by MODIS are shown in red.

While this situation is not one of smoke transport, it does provide an excellent opportunity to “stretch the limits” of the transport and dispersion system in a high impact and verifiable situation, and thus increase our confidence in and understanding of the performance characteristics of the system.

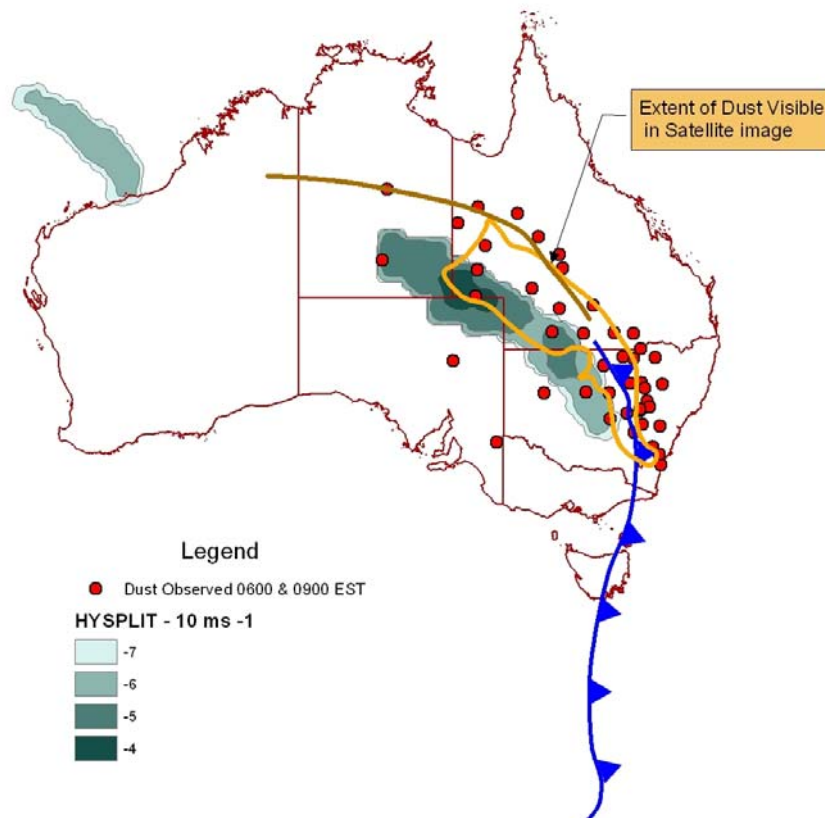


Fig. 44: HYSPLIT forecast and satellite outline of dust concentration at 0600 EST October 23. Blue line indicates position of surface front at the same time.

Discussion

The design and performance of the smoke management advice forecast system developed in the Bureau of Meteorology in collaboration with AFAC partners has been described. The range of case studies presented in this report show that the system has considerable skill at predicting smoke transport, and this is confirmed by feedback from those land management agencies that use the product on a regular basis. One of the strengths of the system is its delivery format, with a relatively simple set of output products designed to suit agency needs. The case studies do show, however, that this simplicity can at times lead to some ambiguity in interpreting the product, and the next phases of the project will attempt to alleviate some of these issues.

Perhaps the most limiting feature of the system is the specification of the initial plume rise. The initial selection of 1500 m was made somewhat pragmatically, with the expectation that a plume-rise model would be used in later versions of the system. However, the difficulty of estimating the rate of heat release from the source made this approach problematic, as the uncertainty in these fire/fuel parameters far outweighed the sensitivity of the plume rise to atmospheric parameters in our early plume rise calculations. Several case studies (Erica, Bribie Island, MJ019) presented here have demonstrated the importance of correctly specifying the initial plume rise. Given plume rise is a dynamic feature, changing as the fire intensity varies and also as the state of the atmosphere changes throughout the diurnal cycle, the use of a static plume rise value cannot be scientifically justified. Accordingly, the development of a dynamically-varying plume rise set to the height of the atmospheric surface mixed layer (as determined from the meteorological forecast used to drive the dispersion model) seems to be a good choice for use in the medium-term future.

Figure 45 shows the improvement obtained for the King Island case by calculating the plume height at 3 hourly intervals compared to the standard forecast method. Both forecasts begin at 1200 UTC 10 January. At 0330 UTC the standard forecast (outlined in white) shows the plume to be northward of the visible plume. The variable height plume (shown in red) displays a much better fit with the northern edge of the visible plume and extends south over northern Tasmania and this is supported by ground based observations at the time (T. Blanks pers.comm. 2005). However, it must be recognised that more intense prescribed burns may penetrate the top of this mixed layer and extend to much greater heights. Development of more deterministic plume rise specification remains a longer-term aim of this project.

There is obviously some error in the meteorological fields as well, and how to represent this uncertainty is less clear. Some of the case studies showed that in light-wind conditions (which are often those chosen for prescribed burning) the model wind fields can have large relative errors, even though the absolute errors may be small. This should be recognised in assessing the forecasts. There may also be some error in the model's representation of the depth of the mixed layer, and the effects of this may be exacerbated by the wind shear that usually exists across this layer. The provision of displays of the model's vertical wind and temperature structure at the source points, as has been experimentally provided to Tasmanian agencies, allows the user to make some interpretation of the model's accuracy in this matter, and also to interpret the

likely interaction between the specified plume rise and the model's vertical wind profile. Linking the model's mixed layer depth and the specified plume height will alleviate some of these concerns. One future approach may be to provide an ensemble of forecasts, with a range of meteorological forecast fields and a range of plume heights to provide a more probabilistic form of presentation. This would provide a wider range of potential outcomes, but would also require a greater degree of interpretation.

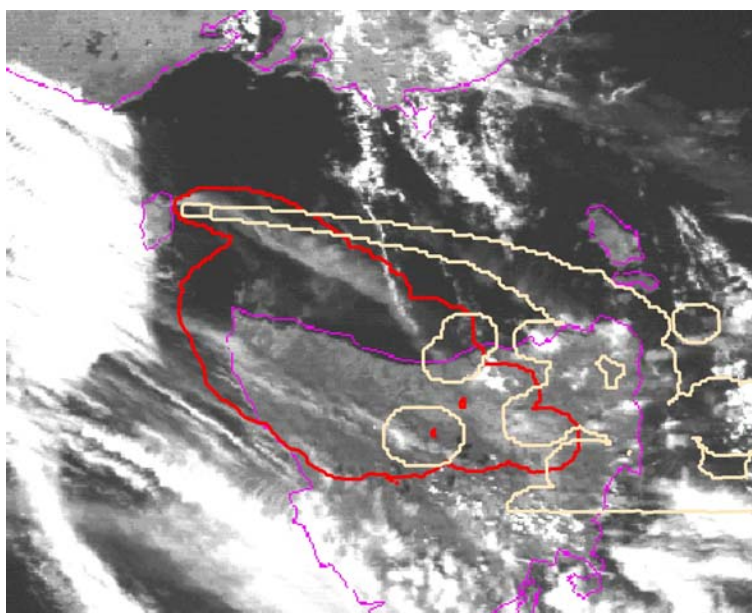


Fig. 45: Comparison of HYSPLIT forecasts for King Island Fire valid 0330 UTC 11 January 2001 with GMS visible satellite image. White outline shows forecast made with standard parameters. Red outline indicates forecast made with varying plume heights.

The first version of the system provided a mean smoke concentration, relative to the arbitrary source concentration, through the lowest 1500 m of the atmosphere. While this represents the smoke plume that is seen from aircraft, from the ground by an observer some distance from the plume, or from a satellite, it is perhaps the ground-level concentration that is most important from a human impact perspective. It is clearly desirable to provide the facility for concentration fields to be made available at different levels, although this again increases the complexity of the delivery system.

Since the initial implementation of the smoke management advice system, later versions of the HYSPLIT code allow the concentration fields to be output in GIS-compatible forms, and some examples of this form of the output have been shown in the case studies in this paper. This would allow the products to be integrated with other GIS-based management tools used by agencies, and this may be an

attractive option for product delivery. Tests of Scalable Vector Graphics (SVG) form of output have also been conducted in order to provide a web-based facility to pan and zoom by the user.

It must be constantly remembered that the concentrations shown in the forecasts are relative to an arbitrary unit source, and do not represent actual particle concentrations. It is clearly desirable that the system evolves towards quantitative prediction of particle concentrations, but before this can happen comprehensive emissions models for Australian fuels, and comprehensive fuel classification maps are required. Some of the projects in the Bushfire CRC are directed to assisting these needs.

Acknowledgments

Gary Morgan and Rick Sneeuwjagt sponsored this project to the Australian Fire Authorities Council, and were thus instrumental in its inception. During its first two years those gentlemen, and Mark Williams and Russell Stringer of the Bureau of Meteorology comprised the steering committee that provided oversight and guidance to the project. Since the inception of the Bushfire Cooperative Research Centre Mark Chladil has provided guidance as “user leader”. Many people in the participating agencies have assisted as users and in providing feedback and verification data, and these include Peter Billing, Terry Maher, Tony Blanks, Mark Chladil, Alen Slijepcevic and Paul De Mar. In the Bureau of Meteorology Russell Stringer and then Barry Southern have been strong supporters of the project, Paul Stewart has set up the systems by which the forecasts are run each day in the National Meteorology and Oceanographic Centre, and it has been a pleasure for us to collaborate with the staff in the Severe Weather Sections of each of the Regional Forecast Centres to deliver this product to the users.

Image Data Sources

GMS visible images and MSLP analyses were obtained from Bureau of Meteorology archives.

MODIS images were obtained from the MODIS Rapid Response System website

(<http://rapidfire.sci.gsfc.nasa.gov/>)

CALM provided the satellite imagery used in Figs. 5, 22, 23, 24, and 25c and the graphics in Fig. 10.

TOMS images for Fig. 38 were obtained from NASA's Goddard Space Flight Centre website (<http://jwocky.gsfc.nasa.gov/>).

Figure 39 was created from information obtained from the WA Dept. of Land Information Fire Hotspots website

(<http://www.dola.wa.gov.au/corporate.nsf/web/Fire+Hotspots>).

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