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Modelling the King Island bushfire smoke

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The transport and dispersion of the smoke from the Winchelsea and King Island bushfires, 11 – 12 January 2001 has been simulated by the Australian Air Quality Forecasting System (AAQFS) and the HYSPLIT environmental emergency response system. Thick smoke from these fires led to the highest level of particulate recorded (at the time) in the Melbourne Airshed since Ash Wednesday and the Melbourne Dust Storm of 1983. Although there was some variation over the domain (the strength of the winds on the western side of the bay was underestimated whereas on the eastern side the winds were in agreement with the observations), in general the meteorological model predictions provided very good guidance.

The prediction of the AAQFS and HYSPLIT plumes generally show excellent agreement for the location of the major concentrations. Differences in detail in simulating the smoke plumes in the two models are discussed using comparisons with available satellite observations. The ability of AAQFS to capture events such as the transport of elevated smoke down to the surface by turbulent mixing is also demonstrated.

Introduction

On 11 January 2001 thick smoke was transported behind a cold front from the Lavinia Nature Reserve in the northeast corner of King Island, some 250 km to the northeast (see Fig. 1 for locations) to the Melbourne area. This event led to the highest level of particulate recorded (at the time) in Melbourne since the Ash Wednesday bushfires and the Melbourne Dust Storm of 1983. The smoke from the King Island fire arrived in the Melbourne suburbs during the evening. Earlier that afternoon smoke from a smaller fire at Winchelsea (100 km southwest of Melbourne) arrived with the cold front. The Australian Air Quality Forecasting System (AAQFS) and the Bureau of Meteorology's operational environmental emergency response system (HYSPLIT) at the time did not include irregular emission sources such as bushfire smoke. To demonstrate the ability of AAQFS and HYSPLIT to model such an event, the systems were re-run at a later date, HYSPLIT with particle tracer sources added at the fire locations and AAQFS utilising a simple emissions module. In this paper we will compare these 'hindcasts' with the available observations. As HYSPLIT was not initiated with an emis-

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Fig. 1 **Map showing the fire locations, Lavinia Nature Reserve and Winchelsea, in relation to Melbourne.**

sions model our discussion of the results will necessarily be qualitative. We will start with a brief overview of the two models, and then describe the fires and the meteorology of the event. This will be followed by an evaluation of the performance of the two transport models in simulating smoke transport during this event.

Description of transport models

The AAQFS model (Cope et al. 2004) is an Eulerian modelling system designed for forecasting the transport and physio-chemical transformation of gaseous and aerosol pollutants. The Chemical Transport Module (CTM) has been designed to run with multiple online one-way nesting for an arbitrary number of grid nests. Regional grids (98 x 98 east-west and north-south) with a grid spacing of 0.05° (~ 5 km) extend over large proportions of the States of Victoria and NSW. Nested within these regional grids are urban grids (Port Phillip - 130 x 96; Sydney basin - 98 x 56) with a spacing of 0.01° (~ 1 km). The CTM domains are configured with 17 non-uniform levels in the vertical extending to ~4 km, with the lowest level centred on 10 m. Eight aerodynamical size categories for aerosols and wet and dry deposition are included in the calculations. The AAQFS produces 24 h forecasts for Victoria and NSW twice daily. In the present study a simple emission model (Lee et al. 2002) was used to simulate the bushfire smoke although for comparison with HYSPLIT the results are described qualitatively. Only the Victorian regional grid was employed.

The HYSPLIT modelling system (Draxler and Hess 1997, 1998) is designed for computing trajectories, dispersion and deposition for environmental emergency response applications. Most of the applications so far have been for long-range or medium-range transport, but it has been successfully applied to smoke dispersion in Australia (Wain and Mills 2006). The model includes the option of computing the concentrations of gaseous or aerosol pollutants either as puffs, particles or as a combination of puffs in the horizontal direction and particles in the vertical direction. In the present study the last option has been chosen for increased accuracy. The transport includes wet and dry deposition. There are options for multiple aerodynamical size categories, radioactivity and chemical transformations, but these were not employed in this study.

Meteorological input data for both models is obtained from the Limited Area Prediction Scheme (LAPS) numerical weather prediction model (Puri et al. 1998) and its mesoscale derivatives. The AAQFS simulations were based on the meso-LAPS model run at 0.05° horizontal grid spacing for the Victorian domain; the HYSPLIT simulations were based on the meso-LAPS model run at 0.125° grid spacing, the resolution that allows emergency response for the whole of Australia.

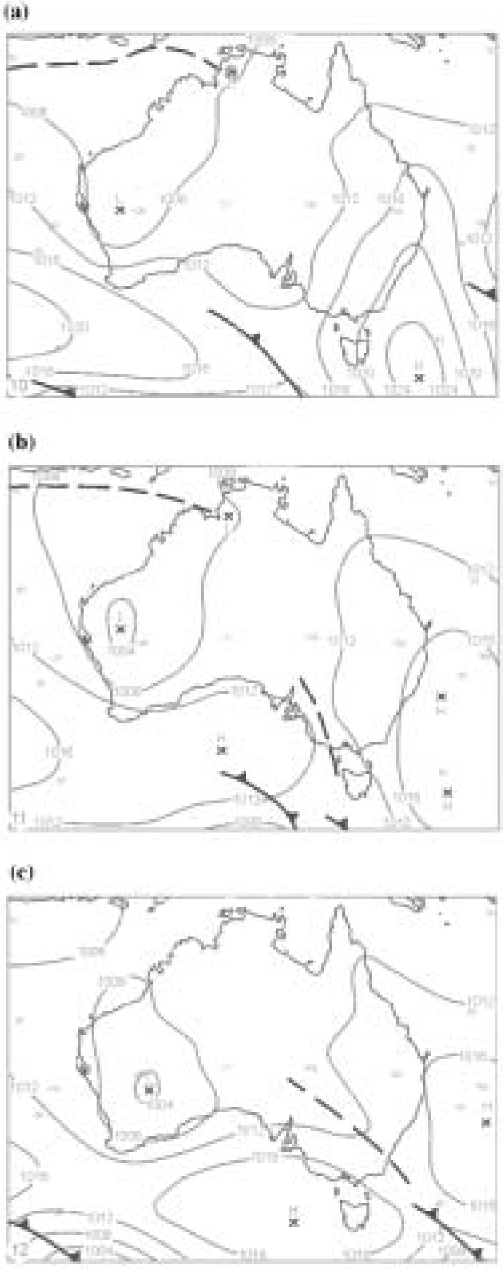
The King Island/Winchelsea fire events and synoptic meteorology

The King Island fire, started by a lightning strike on 1 January 2001, had been burning in the Lavinia Nature Reserve (see Fig. 1) for several days in a region of tea-tree and sage scrub overlying a peat swamp. Approximately 2000 – 3000 ha were burned. By 10 January the fire was thought to be under control, although it was still smouldering. The anemograph records at the King Island Airport indicate that a wind shift occurred at about 0900 Australian Eastern Daylight Time (AEDT) on 11 January 2001, associated with a cold front passage. The high winds associated with the front re-ignited the fire and an additional 5000 ha were burned.

The Winchelsea fire was smaller and started at 1555 AEDT on 11 January 2001. It was contained by 1800 hours, though smouldering continued for another two days. Approximately 320 ha of grassland was burned. Smoke from this fire was transported to Melbourne by the winds immediately behind the cold front and arrived at the same time as the wind change. The smoke from the Winchelsea fire was not visible in the satellite images, and the particle levels measured at the Brighton monitoring station were significantly less than from the King Island plume, which suggests the Winchelsea event was secondary to the King Island event. The remaining analysis will concentrate mostly on the latter event.

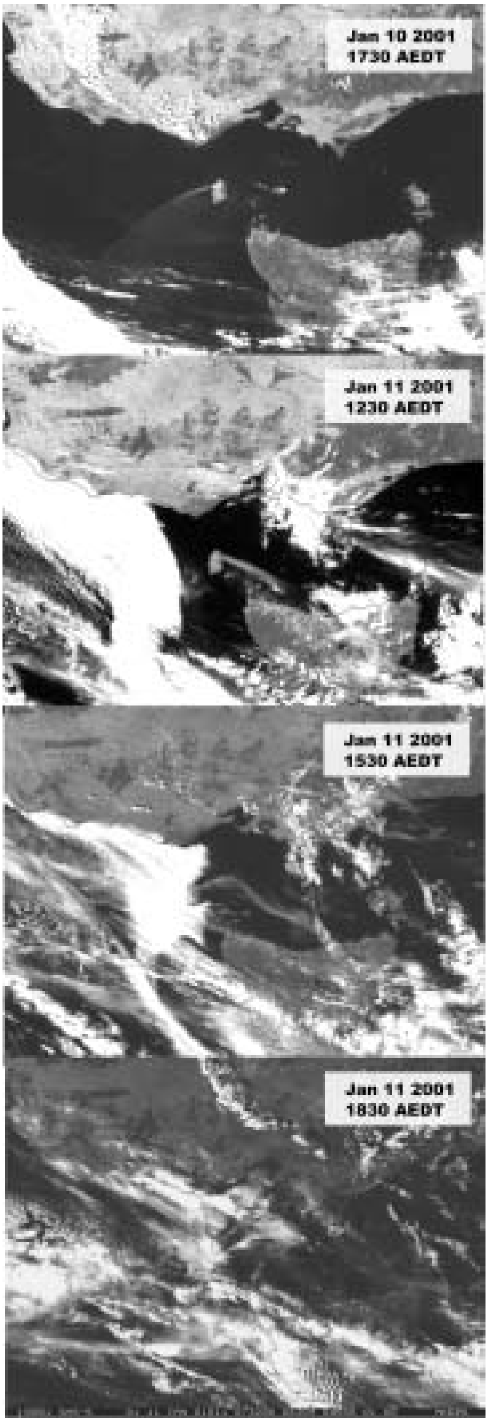
The synoptic conditions at 0000 UTC 10, 11 and 12 January are depicted in Figs 2(a) to (c) respectively. Figure 2(a) shows a high pressure system east of Tasmania directing a north-northeasterly gradient wind over most of Victoria and King Island. Figure 2(b) illustrates the pressure gradients were particularly weak in the southeastern Australian region, approximately six hours prior to the arrival of the cold front in Melbourne, with weak high pressure systems to the east and west. A trough is analysed (dashed line) running from the west of King Island through western Victoria and eastern South Australia. The trough propagated from west to east with time. Ahead of the trough the gradient wind was from the northwest and shifted to the southwest when the trough passed. The actual wind shift was particularly shallow which may explain why it was not analysed as a front. We show below that despite being shallow and dry the wind shift and associated temperature change was sufficiently large and abrupt to be considered frontal, and will be termed the ‘King Island front’ from here on. Figure 2(c) shows a broad weak high pressure system to the south of the mainland which directed southeasterly gradient winds over Melbourne. This wind flow was responsible for flushing the Melbourne area of smoke, ending the event over the urban area.

Fig. 2 **Synoptic pressure charts at 0000 UTC on (a) 10, (b) 11 and (c) 12 January 2001. Contour interval = 4 hPa. Cold fronts are depicted as full lines with triangles and the trough is depicted as a dashed line.**



The King Island smoke plume can be clearly identified from satellite images because it travelled over water, whereas the Winchelsea smoke plume, which mainly travelled over land, cannot. The sequence of GMS satellite images shown in Fig. 3 begins at 1730 AEDT on 10 January 2001. The plume can be seen extending to the southwest, indicating northeasterly winds prior to the passage of the cold front. By 1230 AEDT the next day the wind had changed direction from northeasterly to northwesterly (consistent with the gradient winds implied from Fig. 2). The smoke plume that extended to the southwest rotated with time to the southeast just prior to the arrival of the frontal wind change. At 1230 AEDT the image shows the visible smoke plume extends 150 km to the southeast. In subsequent images (not shown) over the period from 1330, 1430 and 1530 AEDT, the general direction the plume travels is to the southeast.

Fig. 3 **Sequence of GMS visible images 10-11 January 2001, showing the evolution of the King Island bushfire smoke plume and its transport towards the Melbourne Airshed.**



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 AEDT there is a distinct kink or dog-leg in the shape of the smoke plume, which becomes more pronounced in the final scenes taken at 1830 AEDT. The front continued to transport the smoke northward and westward to the Melbourne Airshed, but the presence of cloud cover associated with the front obscured the smoke plume in later satellite pictures.

Meteorological model performance

The model wind shift arrived 1–2 hours earlier than observed to the southwest and north of Melbourne, but southeast of Melbourne the timing was close to coincident. Compare Figs 4(a) and 4(b) (west and east of Melbourne respectively), which show time-series of observed and modelled wind, temperature, and dew-point temperature at Laverton and Moorabbin. The frontal arrival is marked by the drop in temperature, the rise in air moisture (represented by the rise in dew-point temperature) and the shift in wind direction. This is considered to be a good forecast since the cold front arrival is particularly sensitive to the balance between the weak synoptic northerlies and the development of sea and bay breezes. The latter winds can enhance the frontal structure, and accelerate or stall the larger scale wind change, which further complicates the frontal forecast. In this case the model sea/bay breeze influence differed on the two sides of the bay.

The vertical structure of the observed front is depicted in Fig. 5(a) which shows a time versus height profile of the temperature and wind structure from data collected by commercial aircraft as they take off from Melbourne Airport. The development of a well-mixed layer is evident in Fig. 5(a) (thick line) that extends to 850 hPa after 2100 UTC (0800 AEDT) with winds from the north-northwest. After 0500 UTC (1600 AEDT) the wind shifted to southerly and the temperature dropped significantly below 950 hPa, as the colder southerly flow arrived behind the front. Note the very stable layer that formed between the lower level cold air and the remaining warmer air above. This stable layer effectively put a lid on the smoke and helped maintain the high particle concentrations by inhibiting vertical dilution. An equivalent LAPS model chart (Fig. 5(b)) was constructed by interpolating the gridded model data to the flight paths. This shows the model vertical structure was well forecast. The timing of the change and depth of the cold air is in very good agreement with Fig. 5(a). The diagnosed planetary boundary layer (PBL) height (thick line) is over-predicted during

Fig. 4 Time series of surface temperature (*Ts*), dew-point temperature (*Td*), and wind speed (*Ws*) for the period from 1100 UTC (2200 AEDT) 10 January 2001 to 2300 UTC 11 January 2001 (1000 AEDT 12 January 2001), at (a) Laverton on the west side of Port Phillip bay and (b) Moorabbin on the east side (see Fig. 7 for locations). The dashed (solid) lines represent modelled (observed) values of *Td, Ts* and *Ws,* while the dark (light) arrows represent modelled (observed) wind direction. The arrival of the cold front is evident in the drop in temperature, rise in dew-point temperature and shift in wind direction between 0400 and 0600 UTC (1500 – 1700 AEDT) in (a) and near 0600 UTC (1700 AEDT) in (b).

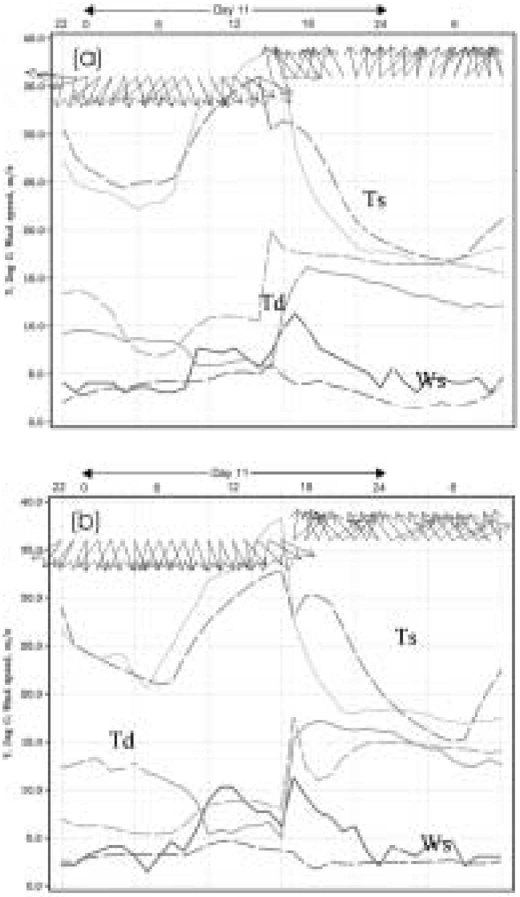
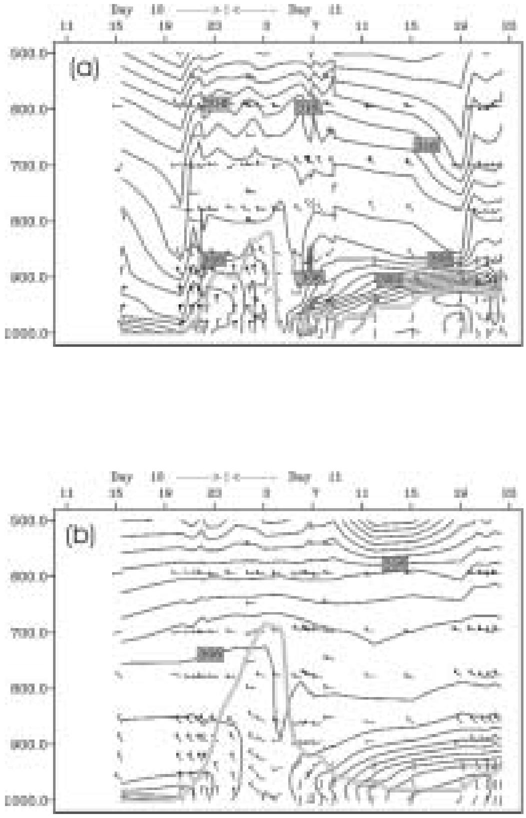


Fig. 5 Time-height profiles of potential temperature (contour interval 2 K) and winds (full barb = 10 knots), for the period from 1100 UTC (2200 AEDT) 10 January 2001 to 2300 UTC 11 January 2001 (1000 AEDT 12 January 2001). The thick line marks the approximate position of the top of the mixed layer, determined by the level at which the atmosphere is first 1 K warmer than the 10 m potential temperature. Image (a) was constructed from data collected by commercial aircraft as they take off from Melbourne Airport, and (b) from LAPS model data interpolated to the flight paths. The cold front arrival (determined from the wind barbs) occurred near 0600 and 0500 UTC (1700 and 1600 AEDT) in (a) and (b) respectively.



the day due to slightly cooler temperatures between 800 and 900 hPa. Other differences are largely due to limitations of the model grid resolution. This shows up in the less abrupt frontal leading edge and stable layer, and the more gradual wind shift from north to south.

The horizontal flow structure of the model front, as it crossed Port Phillip, is illustrated in Fig. 6 (1300 AEDT). Since the model front arrived about 1–2 hours early to the north and southwest of Melbourne, we have superimposed the observed winds from a time two hours later, to show the good agreement between the model and observed frontal structure.

Fig. 6 **Gridded 0.05° LAPS surface winds at 0200 UTC (1300 AEDT), 11 January 2001 with observed winds two hours later overlayed (circled). The letters 'L' and 'M' mark the locations of Laverton and Moorabbin referred to in the text, and 'B' marks the location of the Brighton EPA monitoring station. The cold front crossing the bay is defined by the line of converging wind barbs.**

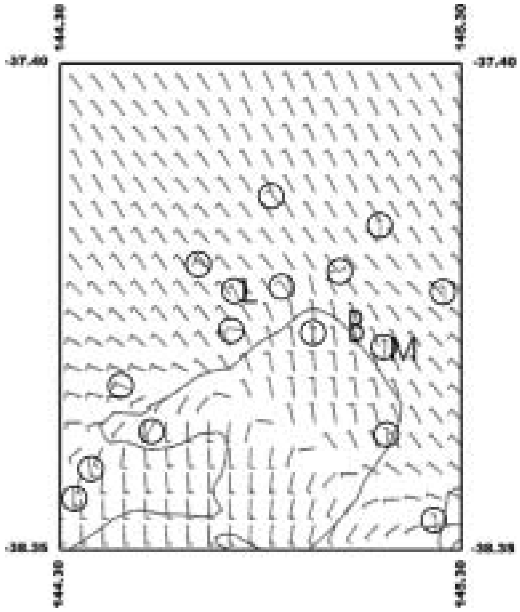
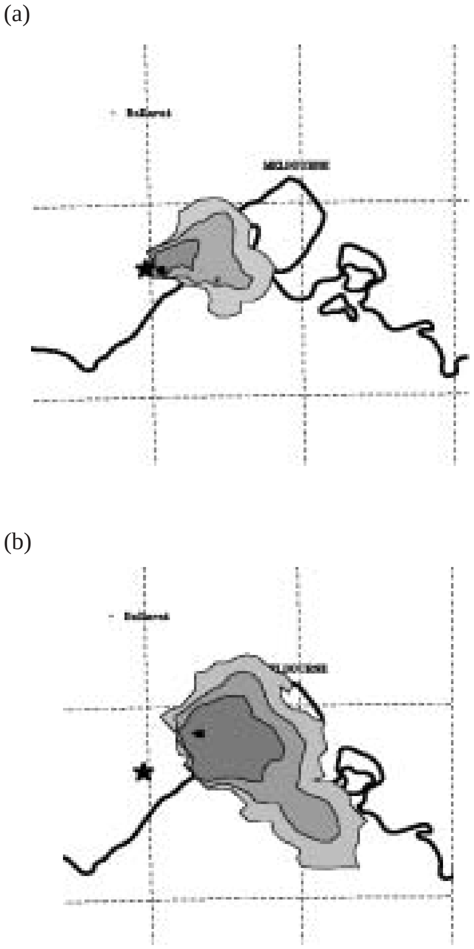


Fig. 7 **Predicted smoke plume for Winchelsea fire for the HYSPLIT model at (a) 1800 AEDT and (b) 1900 AEDT 11 January 2001. The star indicates the location of the fire at Winchelsea. Darker shading indicates higher relative concentration.**

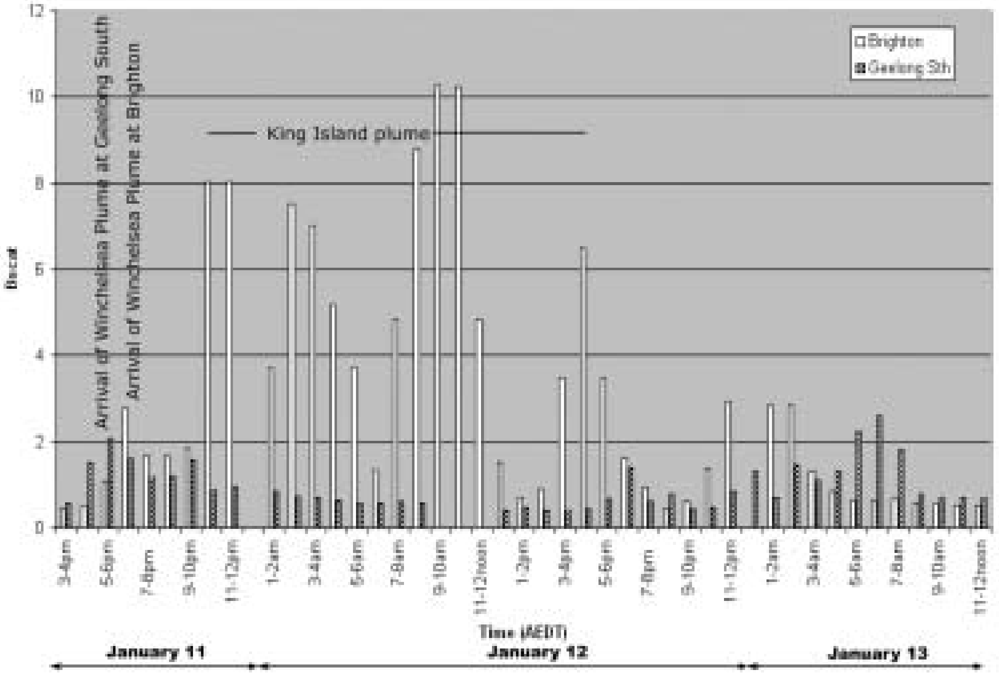


Comparison of model results

The models were initialised by parametrising the smoke from the fires as continuous line sources for the period of burning, extending to the height of a strong capping inversion at approximately 1000 m above the surface. The height of the inversion was determined from the LAPS meteorological model and, for the Winchelsea grass fire, confirmed by observations (Bob Barry, Country Fire Authority, Region 7, Geelong, personal communication, 2001).

We begin this section by examining the HYSPLIT simulation of the smoke plume from the Winchelsea grass fire (Fig. 7). The predicted smoke plume shows good agreement with the time series of nephelometer observations recorded at the Victorian Environmental Protection Authority's (EPA) Geelong South monitoring station (see Fig. 8). This station did not directly measure particulate concentrations at this time. Air quality was inferred from nephelometer measurements of light backscattering (Bscat). The observed peak in Geelong South's Bscat at 1800 AEDT is well predicted by the model smoke forecast. After that time the plume moved further eastward and the air over the Geelong region slowly cleared. A subsequent peak in Bscat at Melbourne metropolitan EPA stations was observed approximately one hour (Fig. 8) later. The HYSPLIT forecast plume had not quite reached the northeastern side of Port Phillip bay by 1900 (Fig. 7), eventually arriving at 2000. This indicates that the model

Fig. 8 **Time-series of back scattering (Bscat) recorded by Victorian EPA stations at Brighton and Geelong South, 11-13 January 2001 (Victorian EPA 2006). Times are in local summer time (AEDT).**



winds were lighter than the actual winds. This is confirmed by comparing the modelled and observed winds in the Geelong region shown in Fig. 6.

We now turn our attention to the King Island smoke plume. Figure 9 shows the plume, as observed by the NOAA-12 satellite at 0631 AEDT 11 January 2001, beginning to be obscured by cloud. Figure 10 shows the model plume for both AAQFS and HYSPLIT at a similar time to Fig. 9. Note there is good spatial agreement between the two modelled plumes and between the modelled results and observations. The HYSPLIT model shows greater lateral dispersion than the AAQFS model and the observations; far downstream both modelled plumes appear wider than the observed plume. However it must be noted that the comparison is qualitative, not quantitative. We do not know what the limiting concentration is for detection on the satellite image. The modelled dog-leg is less sharp due to the less abrupt modelled frontal change. It was difficult to distinguish smoke from cloud in all later images. From this time on we rely on the model hindcast and emission observations at metropolitan observing stations to understand the smoke transport.

Fig. 9 **NOAA-12 satellite image enhanced to highlight the King Island smoke plume 0731 UTC (1831 AEDT) 11 January 2001. At this time cloud is beginning to obscure the plume, which extends from King Island to near Phillip Island and then curves back to the southeast corner of the image.**

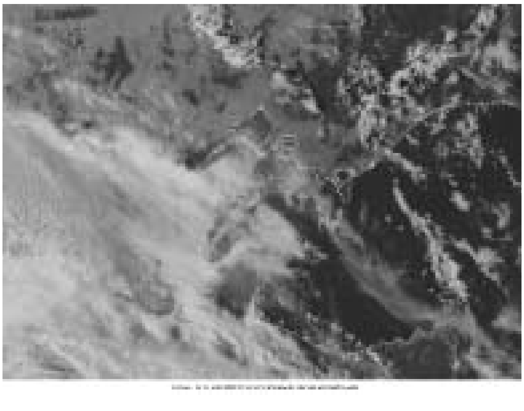
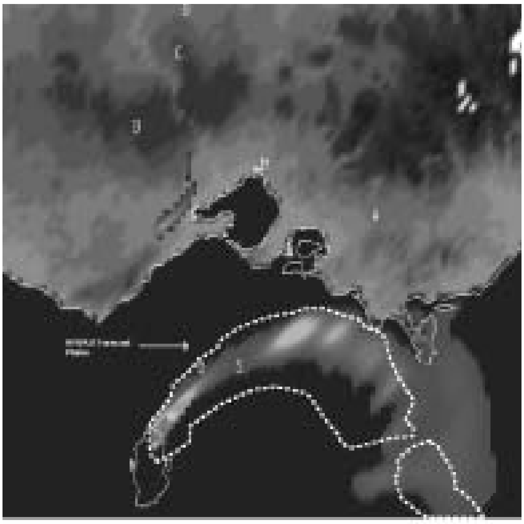


Fig. 10 **Comparison of the AAQFS and HYSPLIT (dashed line) predicted smoke plumes corresponding to the observed smoke plume shown in Fig. 9, at 1830 AEDT. Going from west to east the letters indicate the locations of the following: B = Ballarat, C = Castlemaine, B = Bendigo, M = Melbourne, W = Warragul, BS = Bass Strait.**



The model winds rotated from southwesterly to southerly during the night and consequently the King Island plume rotated counter-clockwise and swept over Melbourne from the southeast. This is evident in Fig. 11, which shows the surface plume at 1200 AEDT 11 January 2001, and 0000, 0600, 1200 AEDT 12 January 2001. Figure 11(a) shows the plume over Bass Strait prior to reaching the mainland. By midnight on 12 January the most concentrated part of the plume entered Port Phillip (Fig. 11(b)). The plume had swept across the bay by 0600 AEDT (Fig. 11(c)) and cleared the eastern metropolitan and bay regions by 0900 AEDT. However, three hours later these regions were once again covered by smoke (e.g. at Brighton, see Fig. 11(d)). This was due to fumigation as daytime turbulent mixing began to transport smoke down to the surface from above.

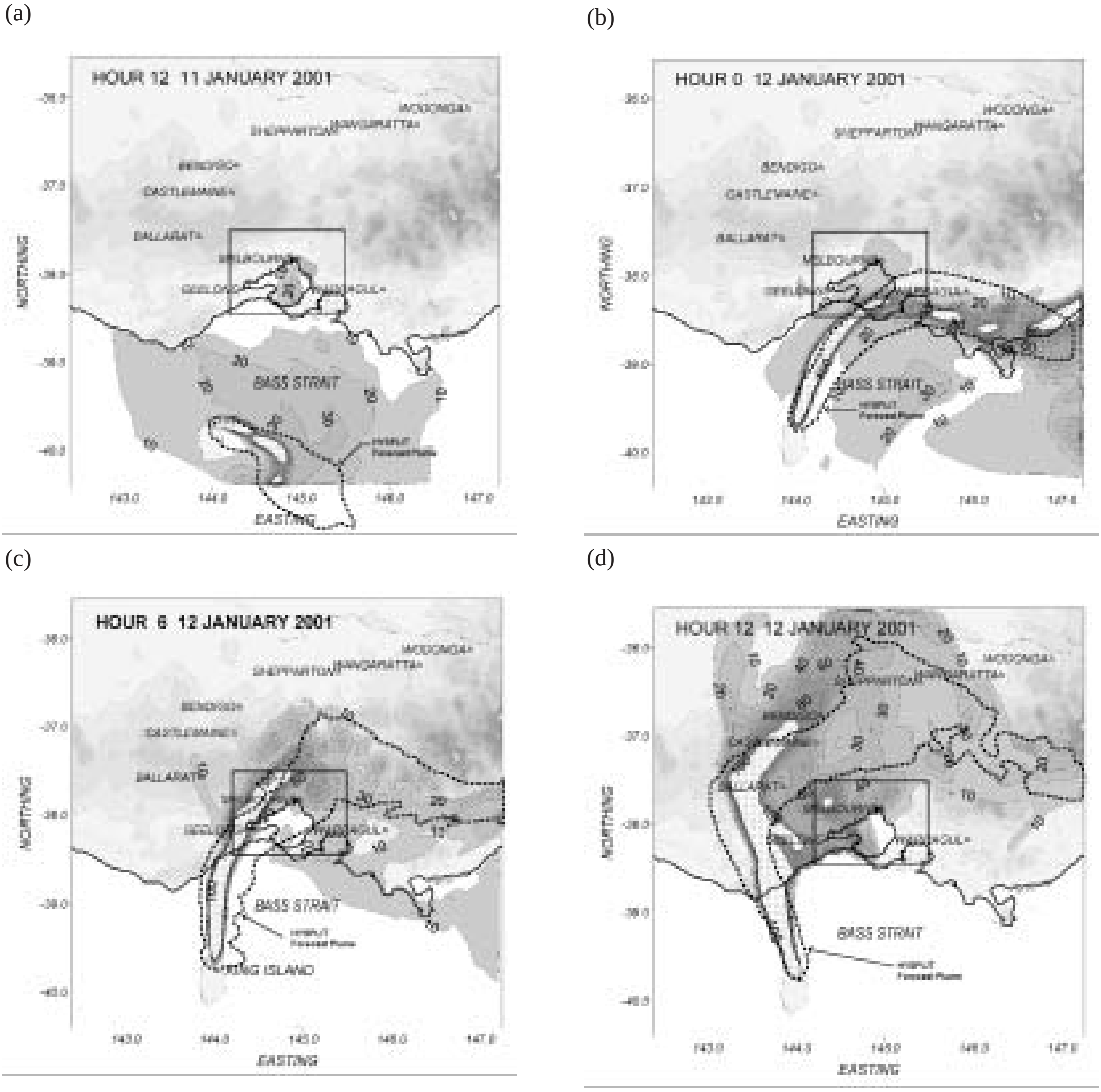
The vertical structure of the plume showed considerable variation with height due to the vertical variation of the frontal structure. The wind change arrived first at the surface (typical of cold fronts) that led to a lag in the plume rotation with height. The more gradual wind rotation from southwesterly to southerly that followed also lagged with height. The lag is evident when Figs 12(a) and 12(b) (same times as Figs 11(c) and (d) but at ~1000 m above the surface) are compared with Figs 11(c) and 11(d). This lag caused the plume to be sheared over more than one hundred km in the lowest 1000 m of the atmosphere by the time it arrived in Melbourne. As a result, after the smoke had cleared at the surface in the eastern suburbs of Melbourne, the plume remained not far above the surface. Later in the morning, after a few hours of solar heating, turbulent mixing began to transport the elevated smoke back down to the surface (fumigation) and eastern Melbourne and the bay were once again consumed by smoke (Fig. 11(d)).

Due to heavy cloud cover following the frontal passage, no satellite images with visible smoke were available after 1830 AEDT 11 January 2001. The only smoke verification in the Melbourne Airshed that is possible is based on comparisons with particle concentration measurements collected by the EPA monitoring stations. Data from the Brighton monitoring station are presented as a time series in Fig. 8. The data from the other city particle-monitoring stations (EPA 2006) show a similar pattern, but with a delay of one to two hours.

Model data from vertical north-south cross-sections through Brighton are presented in Fig. 13, at 1700 AEDT 11 January 2001, and 0100, 0900 and 1200 AEDT 12 January 2001. These vertical cross-sections show good consistency between the timing of the observed peaks and troughs and the model plume arrivals, plume clearing, and fumigation, especially on the eastern side of the bay. The initial peak in Fig. 8 (1700 – 2000 AEDT) is associated with the Winchelsea plume (see Figs 13(a) and 7(b)). As previously indicated, the strength of the winds on the western side of the bay was underestimated, and consequently the modelled Winchelsea plume arrived at Brighton about two hours later than observed (cf. Fig. 7(b)). The second peak in the time series, between midnight and 0600 AEDT, represents the King Island plume (see Fig. 13(b)), the trough near 0800 AEDT is the clearing that occurred before fumigation (Fig. 13(c)) and the 0900 AEDT to midday peak resulted from the fumigation (Fig. 13(d)). After this time the model smoke was cleared by easterly winds (implied in Fig. 2(c)). The final peak evident in Fig. 8 is believed to be due to sea-spray, and industrial and motor vehicle sources.

It is also noted that the AAQFS simulation was able to capture the fumigation event at midday on 12 January, but the HYSPLIT model did not. This is the result of slight differences in running the models in this preliminary comparison. The HYSPLIT model used updated forecast winds every 12 hours, whereas the AAQFS did not. When AAQFS was run with the later forecast wind fields (not shown) it also failed to produce fumigation.

Fig. 11 **A comparison of the AAQFS and HYSPLIT (dashed line) smoke plumes from the King Island fire, covering period from 1200 AEDT 11 January to 1200 AEDT 12 January 2001, when fumigation began.**



Conclusions

We have described the meteorological conditions associated with the Winchelsea and King Island bushfires events, which led to the highest concentrations of particles observed in the Melbourne Airshed since the Ash Wednesday bushfires and the Melbourne Dust Storm of 1983. Although there was some variation over the domain (the strength of the winds on the western side of the bay were underestimated whereas on the eastern side the winds were in agreement with the observations), in general the LAPS model provided very good guidance.

The AAQFS and HYSPLIT plumes show excellent agreement for the location of the major concentrations. There are some differences in detail in simulating the smoke plumes in the two models. The main AAQFS plume is narrower than the HYSPLIT plume, which in part is probably due to the absence of any explicit horizontal diffusion in AAQFS. The need to include explicit horizontal diffusion in AAQFS was noted by Tory et al. (2003) in studying CO transport to Cape Grim from Melbourne. However when satellite observations

Fig. 12 **AAQFS output where (a) and (b) are at the same times as Figs 11(c) and 11(d), respectively, except at ~1000 m above the surface. Comparisons with Figs 11(c) and 11(d) show the lag of the smoke plume with height.**

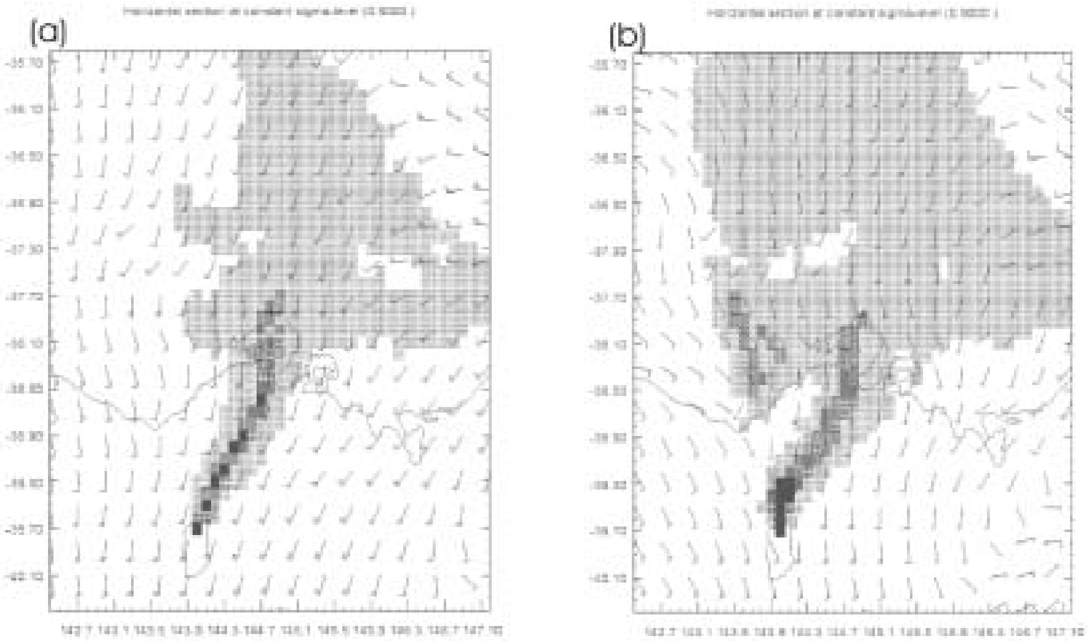


Fig. 13 **Vertical north-south section of the AAQFS model of the King Island smoke plume through Brighton (near 267 km on the horizontal axis, see Fig. 6 for the location). The horizontal winds are overlayed (full barb = 6 knots, flag = 30 knots). Downward (upward) pointing barbs represent wind flowing out of (into) the page. The Winchelsea plume arrived at Brighton near 1700 AEDT 11 January (a) accompanied by the cold front (see converging wind barbs). The King Island plume is located about 120 km behind. The King Island plume arrived at Brighton near 0100 AEDT 12 January (b). The two plumes had merged by 0900 AEDT (c). Note the clear air south of about 280 km and below 600 m in (c), with smoke above. Note also the return of smoke to the surface in (d) as far south as 250 km, due to fumigation, three hours later (midday).**

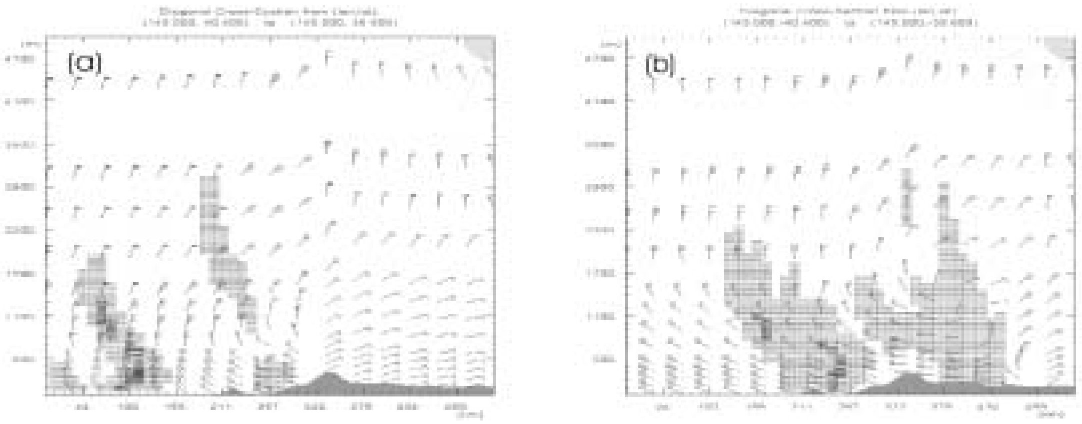
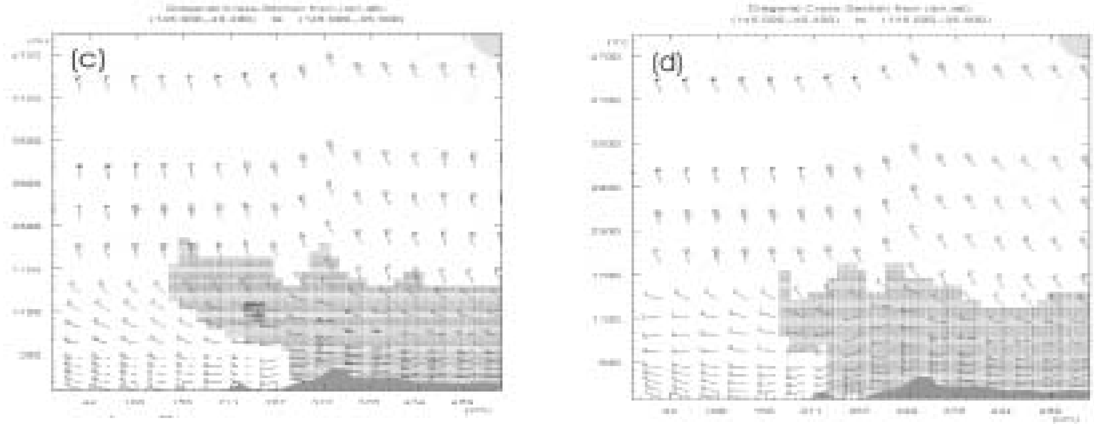


Fig. 13 Continued.



were available both modelled plumes appear to overestimate the width of the plume, especially far downwind. It is noted that these comparisons necessarily must remain qualitative, because the concentrations associated with the limits of detection of the satellite identification of the plume are not known. Nevertheless, the close agreement between the AAQFS and HYSPLIT results and between the predictions and observations is very encouraging, and further work comparing these two models and verifying their predictions against observations is continuing.

Acknowledgments

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