Incorporating Vertical Winds into PHOENIX RapidFire's Ember Dispersal Model

Technical Report

A report prepared by:

Derek Chong (University of Melbourne/Bushfire CRC)
Kevin Tolhurst (University of Melbourne)
Thomas Duff (Bushfire CRC)

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Cover photo: Smoke plume of the Glenpatrick Fire, Victoria, 12 March 2001. (DSE Victoria)

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Summary

PHOENIX RapidFire is a fire simulation model developed in Australia as part of the Bushfire CRC. One unique aspect of the modelling process is the way spotfires are modelled and incorporated into fire spread. Part of the spotting process requires modelling of ember release, transport and spotfire ignition. In the first iteration of spotfire modelling, surface wind (10 m in the open) was used to estimate the distance and spread of embers falling ahead of a fire. However, it is acknowledged that upper-winds usually differ in speed and direction from surface winds. It was therefore thought that that fire modelling could be improved by using the wind speed and direction data produced by the numerical weather prediction models.

PHOENIX was modified to incorporate multi-level wind data, however, the forecast data had an uncorrected bias that results in incorrect ember transport modelling results. The lack of systematic, high resolution and comprehensive upper-wind observations makes bias correction and fire model testing impossible at the current time. It was therefore not possible to develop an improved ember transport model for PHOENIX.

This report describes the process and results obtained from this research. In the end, a version of PHOENIX that can use a single layer of upper-wind data as input was developed. This will allow some theoretical testing of PHOENIX, but cannot be used for operational fire predictions with the currently available data.

Introduction

The spotting phenomenon is an important mechanism for fire spread in Australian bushfires. The aerodynamic and combustion properties of eucalypt bark types allow for extended flight times of up to 20 minutes which can ignite fires up to 30 km downwind of large bushfires (Luke & McArthur 1978 p.102). To achieve these distances embers and flaming bark are lofted high into the atmosphere where they are exposed to transport winds which can be radically different to those of the surface.

The PHOENIX fire characterisation model (3.9/4.0) utilises input winds measured or modelled at 10 m above surface. In the case of forested areas, this is assumed to be at 10 m above the canopy. This reflects the underlying empirical spread functions which have been calibrated for 10 m input winds. This approach is consistent with the majority of operational fire spread models available today however a 10 m wind does not adequately capture the variability of the vertical wind field when it comes to embers which can be lofted thousands of meters into the atmosphere.

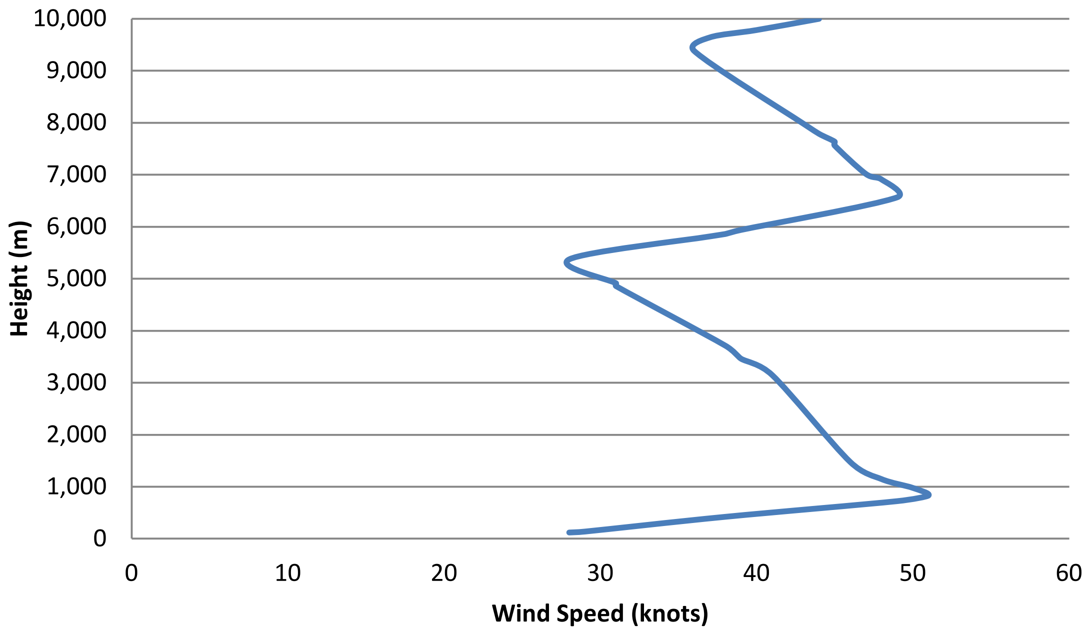

Figure 1. Graph showing variation in wind speed with elevation from Melbourne Airport sounding data on Black Saturday at 1100hrs EST, 7th February 2009.

PHOENIX models fire in the landscape by the mechanism of surface-level spread captured by a continuous expanding flaming perimeter and spotting. Under the right conditions, a modelled fire can generate embers which result in new fires that can grow and coalesce with each other and the source fire to rapidly expand the burning area.

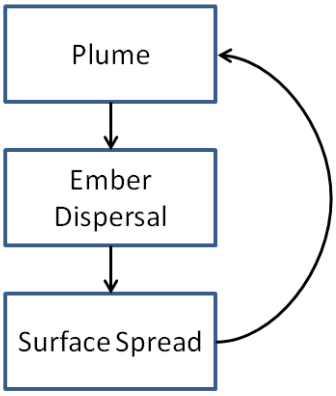

Figure 2 - Conceptual flow chart showing coupling between surface fire spread, the plume and ember dispersal

The surface spread mechanisms for bushfires are fairly well captured in the current suite of operational models however the spotting phenomenon which can account for up to 50% of a fires spread rate (McArthur 1967, Macaulay & Tolhurst 2001) is less so.

The key concepts required for a model to adequately capture the spotting phenomenon are:

- Spatially expression of the quantity and type of potential ember material,
- Ember lofting potential of a fire and the areas affected,
- Ember trajectories and probability of ignition

This document discusses the current ember transport mechanisms within PHOENIX, their limitations and looks at the viability of using available vertical wind data to improve the ember transport model.

With the increasing availability Numerical Weather Prediction (NWP) data, a more detailed picture of the expected vertical atmosphere is now available. Sounding data (observations) from weather balloons is also becoming more accessible allowing validation of the vertical components of NWP outputs.

Existing methods of incorporating vertical winds into ember dispersal

Research activity into the spotting phenomenon and its affect of fire spread has been increasing in recent years. A review of the literature describing ways of incorporating vertical atmospheric conditions, especially wind into ember dispersal indicates these studies:

- have been largely theoretical
- focus on relatively short distance spotting < 2km
- consider only relatively mild or 'intermediate fire severity'
- assume a simple constant, logarithmic or exponentially increasing wind field
- centre on either North American spotting fuel types or theoretical ember shapes which have very different flight characteristics to those of Australia's eucalypt spotting material
- provide very little in the way of viable mechanisms for capturing the often highly variable upper levels winds present in high fire danger weather conditions in Australia

In summary, there have been no studies that describe a suitable way of incorporating NWP vertical atmospheric data into the PHOENIX model for ember transport. No studies were found to address the potential impact of the convective plume on transport winds due to atmospheric coupling.

A two part approach to determining ember trajectories is commonly used. A lofting phase where embers are only affected by conditions within the plume, followed by a descent phase where a horizontal transport wind is applied as the embers fall to the ground.

It is widely recognised that the winds aloft can be vastly different to those experienced at the surface (Tarifa, Notario et al. 1965; Bañuelos-Ruedas, Angeles-Camacho et al. 2010). The importance of this to the accurate calculation of ember trajectories is highlighted in one study (Anthenien, Tse et al. 2006) which concludes that wind speed has a "near linear effect' on propagation distances of viable embers.

A constant wind field was found to be the most commonly for ember transport with several studies using the wind speed at 6 m above the canopy as the transport wind (Perryman, Dugaw et al. 2012), 'above-canopy wind' represented by 10 m open wind speeds (Gould, McCaw et al. 2007) , whilst other theoretical studies simply assume an arbitrary constant transport wind (Tarifa, Notario et al. 1965; Woycheese, Pagni et al. 1999).

The one-seventh power law is sometimes used to express an increasing wind speed with altitude (Sardoy, Consalvi et al. 2008), however it is known to vary from the daytime $\frac{1}{7}$ value to $\frac{1}{2}$ during the night and is only suitable for heights up to 150 m (Bañuelos-Ruedas, Angeles-Camacho et al. 2010)

A recent model developed for crown fire spotting (Albini, Alexander et al. 2012) utilises a logarithmic wind speed profile, however the study points outs that the model is not suitable for Australia's eucalypt bark which can spot up to 30 km or more ahead of the fire compared to the < 2 km maximum distances observed in North America. It also concludes that the model is still at a 'theoretical' stage. Albini's earlier work on spotting also assumes a logarithmic wind speed relationship with height (Albini and Forest 1979).

A study using a coupled atmospheric fire spread model (Koo, Linn et al. 2012) to describe the complex and often significant interaction between fire, plume, embers and atmosphere provides an incredible insight into ember trajectories and distribution. The processing required to model the phenomenon however limited the study domain to 640 m x 320 m and a height of 615 m which is a orders of magnitude smaller than the recent large bushfires experienced in South Eastern Australia (Cruz, Sullivan et al. 2012) which exhibited plume heights well over 10,000 m.

PHOENIX ember transport

The current ember transport mechanism employed in PHOENIX (3.9/4.0) is based on surface 10 m, non-terrain adjusted wind. The model is based on an empirical relationship between a fires' convective strength and surface level winds manually fitted to the Victorian fires of 7 February 2009.

The convective strength of a fire is calculated by taking the hottest 25% of all fire perimeter segments, aggregating them if they are deemed close enough to interact and then calculating the heat output and extent of the aggregated values. This combined heat output is called the convective strength. This is shown pictorially in Figure 3.

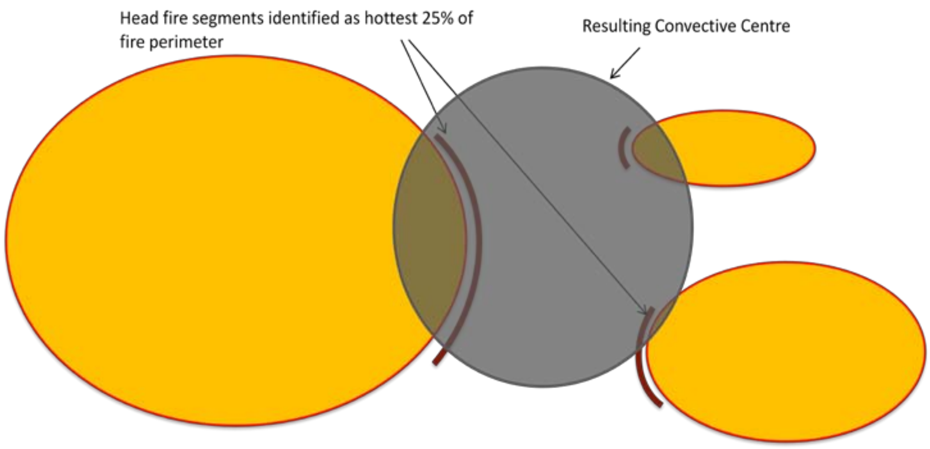

Figure 3. Diagrammatic representation of the method used to calculate convective strength in PHOENIX. Yellow areas represent fire areas, brown lines represent the hottest 25% of perimeter segments and the grey area represents the main convective area.

The translation of surface level winds to the ember impact extent is achieved by the means of a convective strength derived 'Hang Time' parameter. This value is intended to represent the maximum time a viable ember can remain aloft, however in its current implementation it is used as a scaling mechanism that encapsulates an increased wind speed with altitude as experienced in the vicinity of the major fires of the 7th February 2009 (see Figure 1) to a height of approximately 5000 m.

$$Hang\ Time = 0.6\ \times Convective\ Strength \div 10000$$

Hang time values increase linearly with convective strength with maximum values achieved in the Kilmore and Murrindindi fires 28 and 36 minutes respectively.

Without knowing the 'actual' lofting heights, descent rates or vertical wind profile (which is assumed to be different from the sounding location and change during the day), it is not possible to capture the 'real' transport winds experienced by the spotting material. Instead, an empirically fitted 'resultant' spatial ember density distribution is calculated for each cell in the PHOENIX landscape as it is impacted. A Weibull/bimodal distribution provided the best fit to observed spotting patterns (Sardoy, Consalvi et al. 2008). The bimodal distribution captured the medium to long distance spotting phenomenon better than a traditional exponential decay model which only addresses short distance spotting.

The model does not explicitly model the trajectories of each individual piece of spotting material; this would be computationally unfeasible given the amount of spotting material discharged into the atmosphere during a large bushfire. A transport wind is not explicitly incorporated into the PHOENIX ember transport mechanism.

Decoupling the current model requires an explicit relationship between convective strength and the maximum height a viable ember can reach. It also requires a mechanism to integrate wind at different levels during an embers descent. To date, no models or studies relevant to Australian bushfires exist in the published literature.

PHOENIX has been under ‘operational’ evaluation for the last 3 fire seasons by the Victorian Department of Sustainability and Environment in their online fire prediction PHOENIX FireMap and landscape risk modelling framework. The current ember transport mechanism has been found to be realistic and representative of behaviour observed in the field. An independent evaluation of the PHOENIX model commissioned by the New South Wales Rural Fire Service (Cook 2009) concluded that the PHOENIX model matched well with actual fires and that the “spotting and ember ignition model is highly valuable” and that the input data inaccuracy accounts for most of the prediction error.

Analysis of NWP vertical wind data

For the FireDST project, data generated using the ACCESS NWP model for 3 test case fires was provided by the Bureau of Meteorology (BOM). The model was run at 400, 1200, and 3600 m resolutions to produce surface level (10 m) weather variables. Upper level wind field data was produced for the 3600 m runs.

It was anticipated that this data would closely reflect the conditions of the day, and as such would provide a suitable basis for a refinement of the current ember transport model and allow a more accurate reconstruction of the test case fires than previously possible using observations recorded at automatic weather stations (AWS). AWS locations are rarely in close proximity to going fires and even then, fires can move quickly and end up at some distance from the stationary AWS, making their observations less relevant to the conditions at the head of a fire.

The dynamic nature of fires means they can respond quickly to changes in atmospheric conditions. Large fast moving fires are particularly sensitive to wind speed and direction. Analysis of the surface level data from the NWP model showed considerable biases in wind speed and/or direction when compared to AWS data.

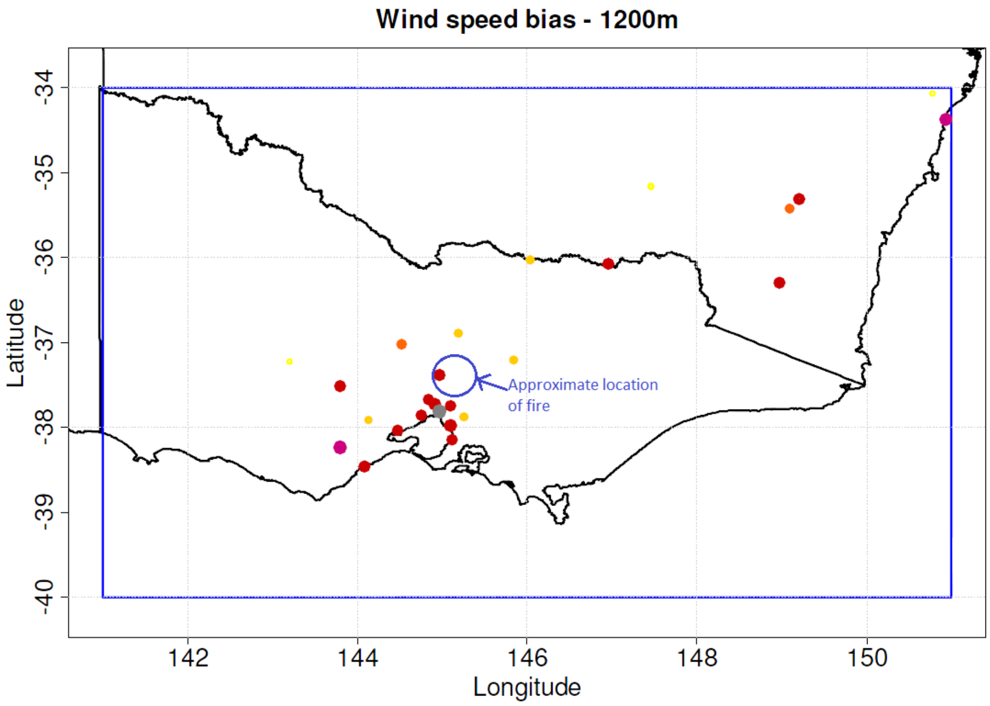

Figure 4: Wind speed bias plot – 1200-metre model run. The ratio of the average wind speed for the windiest hour in the model to the average wind speed of the windiest hour in the observations is calculated. Wind speed ratios are calculated to two decimal places. Ratios less than one imply the model is underestimating the wind speed. Ratios are coloured as ● = 1.0, ● = 0.90 to 0.99, ● = 0.80 to 0.89, ● = 0.70 to 0.79, ● = 0.60 to 0.69, ● = 0.50 to 0.59, ● = larger than 1. Larger circles denote larger departures from the ratio of 1.

Figure 4 Diagram showing the extent of 10 m wind speed underestimation from the 1200 m model run with the approximate location of the case study 1 Kilmore fire from Black Saturday shown. (Source: Robert Fawcett, BOM)

The 10 m wind speed bias is also present in the 400 m and 3600 m data and appears most prominent when wind speeds exceed 40 km/h. This is important to note as observed wind speeds exceeded this value for a large part of the day in the area of the Kilmore fire.

A bias correction was performed on the 10 m data by Geoscience Australia to improve the fit to observed AWS data however this was not done for upper level winds. With sounding data for Victoria limited to only two locations twice daily it is doubtful that this could be done in a meaningful way.

A comparison of the sounding data from Melbourne Airport on the morning of the fire (Fig. 5) indicates that the bias identified at the surface in the region of the fire extends some way up into the upper atmosphere. This puts into question the applicability of this dataset for use with, or in the development of an ember transport model.

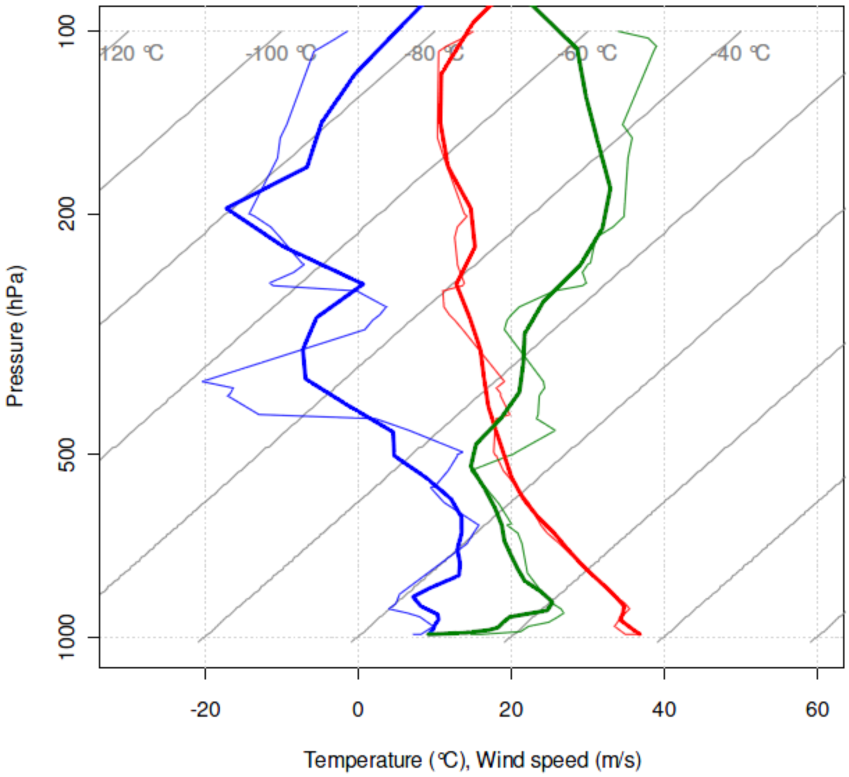

Figure 5. Comparison between 3600 m vertical wind profile and sounding data on the morning of Black Saturday. Thick green line is modelled wind speed; thin green line is observed data. (Source: Robert Fawcett, BOM)

The 2009 Kilmore fire on Black Saturday is the best documented large fires currently available and has been the source of intense scrutiny from the research community and has formed the basis for several of the models developed in PHOENIX. To maintain credibility in the scientific community and amongst end users it is important that any models developed for use with PHOENIX are defensible and at a minimum maintain the models current accuracy when used against these fires. The NWP data provided by the BOM provides some interesting insights into the atmospheric dynamics of the day; however its use in model development and validation is limited due to the timing of the change and wind speed biases both at the ground level and vertically.

NWP data provided for the second and third case study also exhibits problematic biases (e.g. Fig.6), both at the surface and vertically. These are covered in more detail in BOM reports for the study areas.

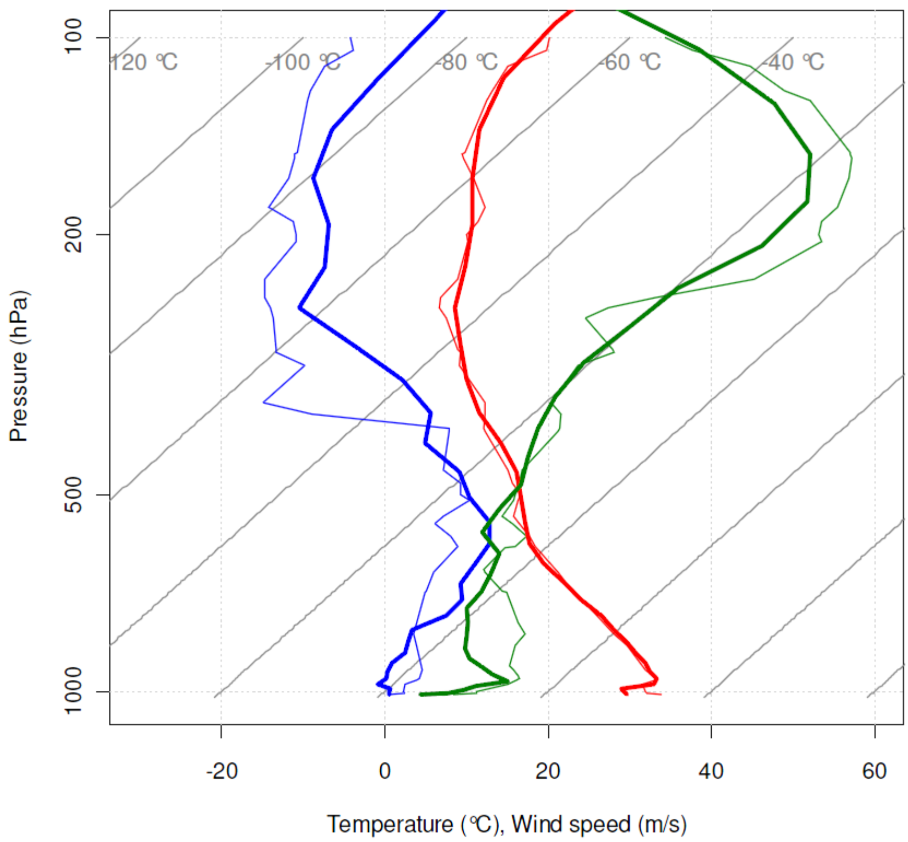

Figure 6. A comparison between 3600 m vertical wind profile and sounding data on the morning of the Wangary fire from Adelaide Airport. Thick green line is modelled wind speed; thin green line is observed data. Wind speed bias plots are not available at this time. (Source: Robert Fawcett, BOM)

Analysis of sounding data

With the problems encountered using the NWP modelled data, an alternative study was conducted looking at possible relationships between surface and elevated wind speeds using weather balloon data collected at Melbourne Airport.

Sounding data for Melbourne Airport was sourced from 1999 – 2009 and AWS data for the corresponding period was analysed. Sounding data where the Fire Danger Index (FDI) had exceeded 35 at the time of the morning sounding (1100h) were selected. A FDI of 35 falls into the 'Very High' fire danger rating category.

This yielded a sample of 115 days, with the predominant wind direction being from the north (105 days) and temperatures over 28^{o}C (92 days) at 11:00.

Plume driven lofting winds are a chaotic mix of up and down draughts and vortices, both vertically and horizontally oriented (Potter 2012), and little is known about the affect these phenomenon have on ember flight trajectories. Even less is known about the interaction of large plumes with the atmosphere, especially the wind field which is responsible for ember transport. As a result, determining heights achieved by spotting material in large Australian bushfires is not possible at this stage. There is also evidence than spotting distances increase with fire size and intensity. This may indicate ember launch heights are related to the scale of fires, determining this relationship is not a trivial task and at this point in time very little is known in this area.

For this analysis 4000 m was assumed to be the maximum possible height a viable piece of spotting material could achieve. The for comparative purposes, the relationship between surface 10 m winds and sounding data was investigated at 1000, 2000 and 4000 m.

Daily sounding data was plotted as a percentage of 10 m AWS wind speed for all 115 days to highlight any possible relationships.

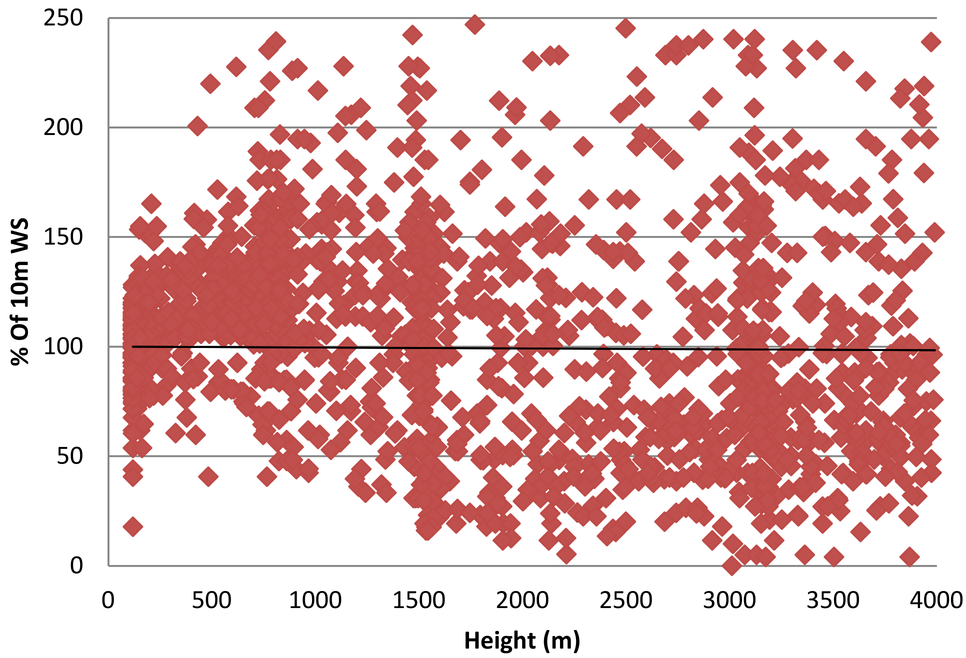

Figure 7. Data up to 4000 m shows a wide scatter with no obvious trends with a spread between 0% and 250% of 10 m wind at various heights.

No obvious pattern presented when looking at data to 4000 m (Fig. 7), however closer inspection of the sounding data revealed a significant amount of noise at 120 m when compared to the 10 m AWS observations. Discussions with meteorologists indicated that the launch phase of a weather balloon is extremely challenging in strong winds. This can affect the initial readings due to rocking or swinging of the sounding equipment below the balloon.

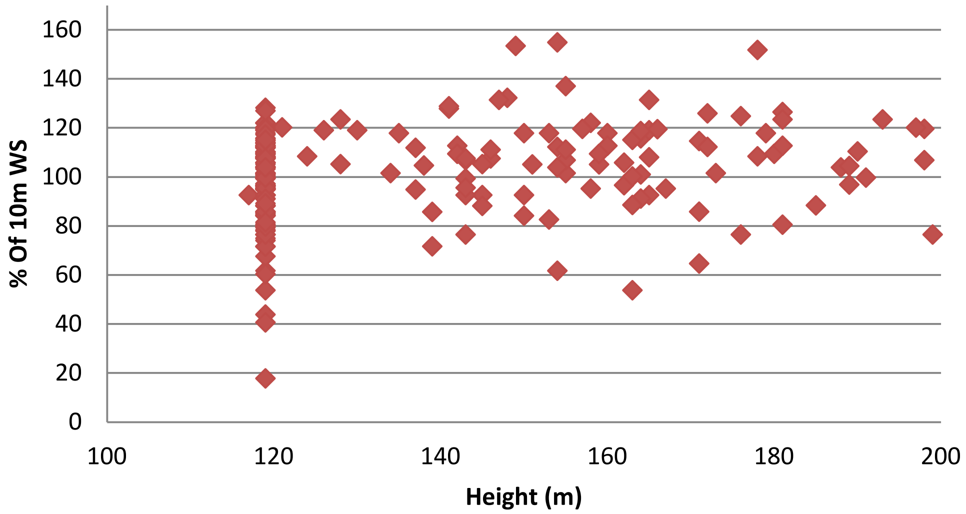

Figure 8. Scatter chart showing the comparative wind speed between 120 and 200 m and 10 m wind speed.

For the 1000 and 2000m comparisons all sounding data below 125m was excluded to reduce the noise.

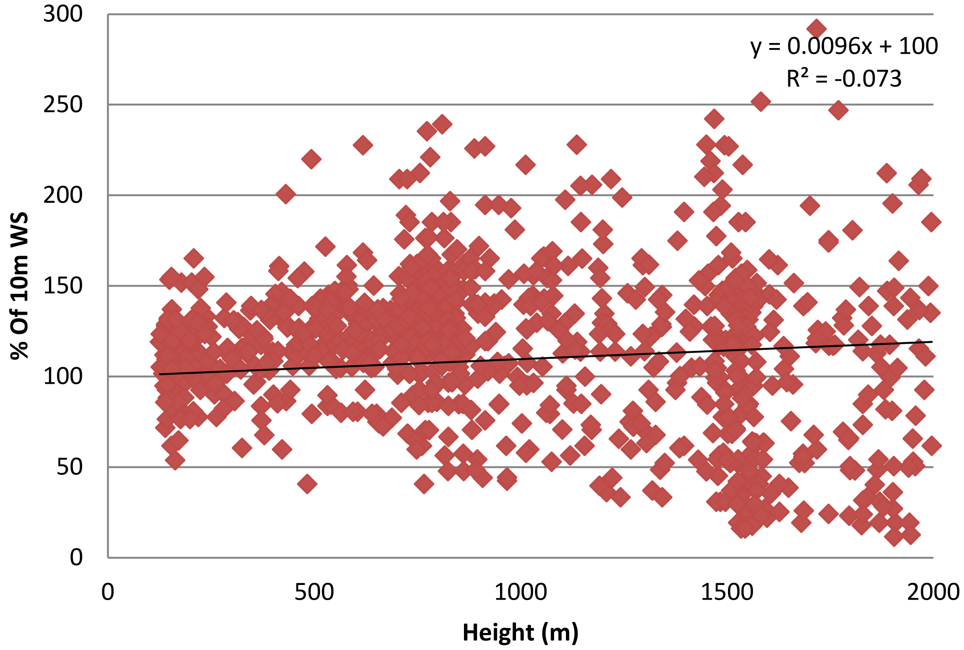

Figure 9. Scatter chart showing data to below 2000 m still showing little in the way of a relationship between surface (10 m) and elevated winds.

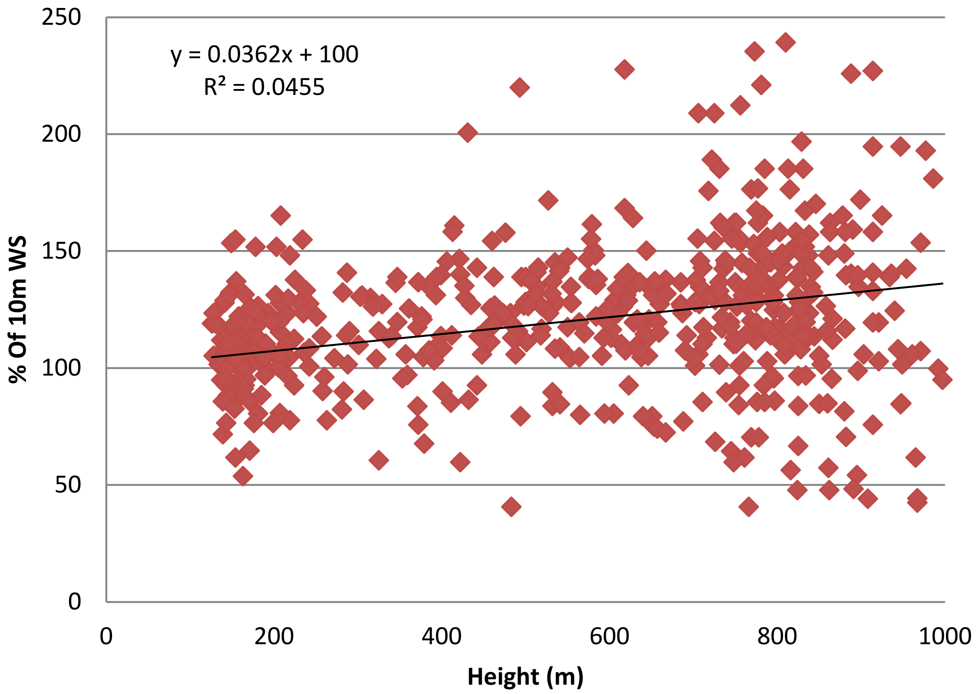

Figure 10. Restricting data to below 1000 m begins to show a possible increasing trend but the low height, 50%-250% spread and poor R^2 limit its applicability.

It was hoped that a simple relationship between surface and elevated winds for conditions that would result in significant fires would be present. This study however demonstrates that for these conditions there is no significant relationship between the winds experienced at ground level and those up to 4000 m.

For meteorological purposes, upper winds are verified using data from satellites, radiosondes and aircraft. An example of the results of such an analysis is shown in Figure 11. This analysis shows that for winds at 850 hPa (about 1500 m), the mean error in the predicted wind speeds is less than ±0.5 m/s, however, this is over periods of 24 hours or more. This level of accuracy is excellent for general forecasts, but to effectively model fire behaviour, the predictions need to be this accurate on an hourly or sub-hourly basis. If a fire is spreading at a rate of 12 km/h, an error in timing of 15 minutes may have a very significant impact on identifying areas at risk.

In the absence of forecasts accurate to an hour or less, one operational option would be to perform a number of fire simulations incorporating the range of uncertainty in the weather input variables. This ensemble approach has been used successfully in other fields and whilst it has computational time costs, that is not a major impediment. However, without hourly observations of winds at multiple levels in the atmosphere, it is not feasible to develop an empirically based spotting model for bushfires. This becomes a block to using the ensemble approach when there might be significant bias or errors in the fire model as well as uncertainty in the forecast weather.

TABLE 7.7 AUSTRALIA/N.ZEALAND VERIFICATION AGAINST RADIOSONDES

850 hPa WIND FEBRUARY 2013

FORECAST PERIOD (HOURS)	MEAN SPEED ERROR (m/s) 00 GMT	MEAN SPEED ERROR (m/s) 12 GMT	RMSEV (m/s) 00 GMT	RMSEV (m/s) 12 GMT
24	-0.1	0.2	4.0	4.0
48	-0.2	0.2	4.4	4.4
72	-0.3	0.1	4.8	4.7
96	-0.3	0.0	5.4	5.3
120	-0.4	-0.1	6.0	6.0
144	-0.4	-0.2	6.9	6.6
168	-0.5	-0.2	7.5	7.1

NUMBER OF OBSERVATIONS USED 00 GMT = 35 12 GMT = 24

Figure 11. Data showing the performance of forecast upper winds against observations in February 2013. (Source: Bureau of Meteorology, Operations Centre, Quarterly Report)

Conclusions

A detailed review of the available literature into the use of vertical winds in ember transport yielded an increasing interest in the spotting phenomenon however methods employed to capture vertical wind variability were limited to a simplistic constant, or logarithmic/exponential increasing wind field, neither of which capture the variability of upper level winds prevalent on days of high fire danger in Australia. No studies to date had utilised vertical wind data generated from NWP models, or described the possible affect the plume may have on the wind field affecting spotting material.

Vertical wind data provided by the BOM at 3600 m exhibits similar biases to those present at 10 m. Comparisons to sounding data at Melbourne Airport indicate surface level biases extend some way up into the atmosphere limiting its use as a dataset for developing an ember transport model. With very limited sounding data available for validation, it is doubtful any meaningful bias correction can be performed on the vertical wind data.

A study into a possible relationship between surface and elevated winds comparing ground based ASW observations to sounding data at Melbourne Airport was conducted as an alternative method of capturing vertical wind variability. Results clearly demonstrate that there is little evidence of any clear relationship between the conditions on the surface to those aloft.

Without suitable data and further research into this area it is not possible at this time to implement a meaningful ember transport model based on vertical winds provided by the BOM. Manufacturing an arbitrary ember transport mechanism based on the NWP data would create an unrealistic expectation from both research partners and end users that it will somehow ‘improve’ the PHOENIX model’s predictive ability.

To address Geoscience Australia's requirement to incorporate an 'alternative' ember transport winds to capture input data sensitivity, a secondary set of gridded wind data inputs will be accommodated as gridded weather inputs in the implementation of the PHOENIX model for the FireDST project.

The additional wind speed and direction grids matching both the temporal resolution and range, and spatial resolution and extent of the surface wind (10m) grids will be used to override the current surface values used in the current ember transport model. Data for these grids will be provided by Geoscience Australia.

References

Albini, F. A., M. E. Alexander, et al. (2012). "A mathematical model for predicting the maximum potential spotting distance from a crown fire." International Journal of Wildland Fire **21**(5): 609-627.

Albini, F. A. and I. Forest (1979). Spot fire distance from burning trees: A predictive model, Intermountain Forest and Range Experiment Station, Forest Service, US Department of Agriculture.

Anthenien, R. A., S. D. Tse, et al. (2006). "On the trajectories of embers initially elevated or lofted by small scale ground fire plumes in high winds." Fire Safety Journal **41**(5): 349-363.

Bañuelos-Ruedas, F., C. Angeles-Camacho, et al. (2010). "Analysis and validation of the methodology used in the extrapolation of wind speed data at different heights." Renewable and Sustainable Energy Reviews **14**(8): 2383-2391.

Cook, B. (2009). Review of Potential Applications for Bushfire Behaviour Models for Bushfire Management in NSW.

Cruz, M., A. Sullivan, et al. (2012). "Anatomy of a catastrophic wildfire: The Black Saturday Kilmore East fire in Victoria, Australia." Forest Ecology and Management.

Gould, J., W. McCaw, et al. (2007). "Project Vesta." Fire in dry eucalypt forest: fuel structure, fuel dynamics and fire behaviour. Ensis-CSIRO, Canberra ACT, and Department of Environment and Conservation, Perth, WA.:: Google Scholar.

Koo, E., R. R. Linn, et al. (2012). "Modelling firebrand transport in wildfires using HIGRAD/FIRETEC." International Journal of Wildland Fire **21**(4): 396-417.

Luke, R.H. and McArthur, A.G. (1978). "Bushfires in Australia" Australian Government Publishing Service, Canberra.

McArthur, A.G. (1967). Fire Behaviour in Eucalypt Forests. For. & Timb. Bur. Leaflet 107

MacAulay, A.S. and Tolhurst, K.G. (2001) Using computer simulation to determine the effects of short distance spotting on head fire rate of spread. Australian Bushfire Conference, 3-6 July 2001, Christchurch N.Z.. Pp. 334-338.

Perryman, H. A., C. J. Dugaw, et al. (2012). "A cellular automata model to link surface fires to firebrand lift-off and dispersal." International Journal of Wildland Fire: -.

Potter, B. E. (2012). "Atmospheric interactions with wildland fire behaviour – II. Plume and vortex dynamics." International Journal of Wildland Fire **21**(7): 802-817.

Sardoy, N., J. L. Consalvi, et al. (2008). "Numerical study of ground-level distribution of firebrands generated by line fires." Combustion and Flame **154**(3): 478-488.

Tarifa, C. S., P. P. d. Notario, et al. (1965). "On the flight paths and lifetimes of burning particles of wood." Symposium (International) on Combustion **10**(1): 1021-1037.

Woycheese, J. P., P. J. Pagni, et al. (1999). "Brand propagation from large-scale fires." Journal of Fire Protection Engineering **10**(2): 32-44.