18th World IMACS / MODSIM Congress, Cairns, Australia 13-17 July 2009
http://mssanz.org.au/modsim09

Fire danger anomalies associated with foehn-like winds in southeastern Australia

Sharples, J.J. [1], **G.A. Mills** [2, 4], **R.H.D. McRae** [3, 4] **and R.O. Weber** [1, 4]

[1] *School of Physical Environmental and Mathematical Sciences University of New South Wales at the Australian Defence Force Academy, Australian Capital Territory*
[2] *Centre for Australian Weather and Climate Research, Melbourne, Victoria*
[3] *Emergency Services Agency, Curtin, Australian Capital Territory*
[4] *Bushfire Cooperative Research Centre, Melbourne, Victoria*
Email: j.sharples@adfa.edu.au

Abstract: In southeastern Australia the synoptic archetypical severe fire weather day is that of the dry "cool change", or coastally modified cold front. Less well known, however, are synoptic cases that occur in connection with the topography of the eastern Australian mainland and Tasmania, which can also lead to abrupt spatiotemporal changes in fire weather variables that ultimately result in locally elevated fire danger. Some of these cases are associated with cross-mountain flows, mountain wind waves and foehn-like occurrences, the latter of which are characterised by warm, dry winds on the lee side of mountain ranges.

In this paper we consider a number of foehn-like occurrences over parts of the southeast Australian mainland. In particular we focus on the Gippsland region, the south coast of New South Wales, central Victoria and the Canberra region. The events of interest are characterised by regional warming and drying at times when surface winds place the regions in the lee of significant topography. The warming, drying and strong and/or gusty winds lead to regional anomalies in fire danger levels. In previous studies conducted by the authors some foehn-like occurrences were shown to correspond to fire danger levels at or above the 95th percentile.

The events considered in the present paper occurred on 19 and 20 September 2008, 12 February 2009 and 18 January 2003. While these events may not have caused the extremes in fire danger that have been connected with other occurrences, they are worthy of examination due to the magnitude and rapidity of the changes in fire weather they caused or because of the fact that they occurred in the vicinity of large fires. On 20 September 2008, the rapid onset of foehn-like conditions resulted in a transition in fire danger rating from 'Low' to 'Very High' within 25 minutes. On 12 February 2009 localised warming and drying was observed in central Victoria within 50 km of active fire complexes (e.g. Yea-Murrundindi, Kinglake). In the early morning of 18 January 2003 nocturnal warming and drying was observed at Canberra; while the exact extent to which this event contributed to the extreme fire behaviour later in the day remains uncertain, it would have certainly caused lower fuel moisture contents than would otherwise have been expected. Given the clear potential for foehn-like conditions to impact detrimentally on fire management and safety, it is worth considering them as a driver of risk in formal risk management studies.

The foehn-like occurrences are analysed based on observational data. The 19 and 20 September 2008 case is also analysed based on the predictions of a numerical weather model. The numerical weather model suggests that foehn-like winds occur in connection with partial orographic blocking of relatively moist lower-level winds and large-scale mountain waves. The observational analyses provide an initial step in discerning regions that are prone to foehn-like conditions. Knowledge of the extent and frequency of foehn occurrences in southeastern Australia, in addition to knowledge of the physical mechanisms that cause them, will assist in the development of more complete bushfire risk management models.

Keywords: *Foehn winds, bushfire, fire weather, fire danger, risk modelling*

1. INTRODUCTION

The potential for the occurrence and development of bushfires is dependent upon the interaction of fuels with variables such as air temperature, atmospheric dryness and wind speed. By combining these variables with information on fuel type and drought effects, a number of fire danger rating systems have been devised around the world, each reflecting the different climates and fuel types in which they are employed (e.g. Rothermel, 1972; Noble et al., 1980; Forestry Canada Fire Danger Group, 1992). Typically these fire danger rating systems produce a numerical index that relates to the chance of a fire starting in a particular fuel, its spread and difficulty to control and the damage it is likely to cause (Chandler et al., 1983). Despite the differences in their design and implementation, all fire danger rating systems generally agree that warmer, drier and windier conditions result in higher fire danger levels. Understanding the synoptic processes through which changes in temperature, relative humidity and wind can occur is therefore an important problem and the development of synoptic models to assist in forecasting these changes is a key requirement in improving bushfire control and risk management practices.

In this paper we discuss synoptic cases that occur in connection with the topography of the eastern Australian mainland and Tasmania, which can result in locally elevated levels of fire danger. In particular we discuss cases associated with cross-mountain flows and foehn-like occurrences, the latter of which are characterised by warm, dry winds on the lee side of mountain ranges; the warmth and dryness of the air being due to adiabatic compression of the air descending the mountain slopes. While some knowledge about Australian foehn winds does exist, there appears to be very little formal knowledge about the extent to which the foehn effect applies over Australia's mountainous regions, the mechanisms behind it and how it might affect local fire danger levels.

In other parts of the world, the foehn effect occurs in the vicinity of many mountainous regions and has been linked with elevated wildfire risk. Particular examples include the autumn foehn (Santa Ana) in southern California, the north foehn in Switzerland and foehn winds in New Zealand and parts of Asia.

Foehn occurrence has been attributed to two main mechanisms: In the first, moist air forced to ascend a mountain barrier cools, ultimately resulting in condensation and precipitation. The precipitation removes much of the moisture from the air and the latent heat of condensation warms the air mass. The drier air is then warmed further by adiabatic compression as it descends the lee slope (Whiteman, 2000). In the second, moist low-level air is blocked by a mountain barrier with drier upper air flowing down to replace it in the lee. As the drier air from above descends the lee slopes it is warmed by adiabatic compression (Seibert, 1990; Ustrnul, 1992) The second mechanism typically occurs in association with a vertically propagating lee mountain wave (Drechsel and Mayr, 2008).

Commonly, three criteria are used to distinguish foehn conditions at stations in the lee of mountains: surface winds blowing from the direction of the mountains, an abrupt rise in air temperature in the lee of the mountains and an accompanying reduction in atmospheric moisture. Characteristic cloud formations also often accompany foehn occurrences, e.g foehn wall, foehn arch (Sharples, 2009).

We present a study of three foehn-like events that occurred over southeastern Australia on 19 and 20 September 2008, 12 February 2009 and 18 January 2003, the latter two of which occurred during major fires. The meteorology of the events is analysed using data from a number of automatic weather stations. In addition, the event on 19 and 20 September 2009 is analysed using output from a mesoscale numerical weather model. Based on the analyses we discuss the results and their implications for bushfire risk management in southeastern Australia.

2. CANDIDATE EVENTS, DATA & METHODS

On 19 September 2008 relatively warm and dry conditions were observed over the Gippsland region of Victoria and the south coast of NSW in connection with strong winds from the north-northwest and northwest, respectively. On 20 September 2008 winds remained strong but shifted to a general westerly flow. The region of the south coast of NSW in the lee of the mountains then experienced abrupt warming and drying with temperatures in excess of 25 ^{o}C and relative humidity falling below 10%. On both the 19 and 20 September 2008 regional fire danger anomalies were observed in connection with the local warming and drying.

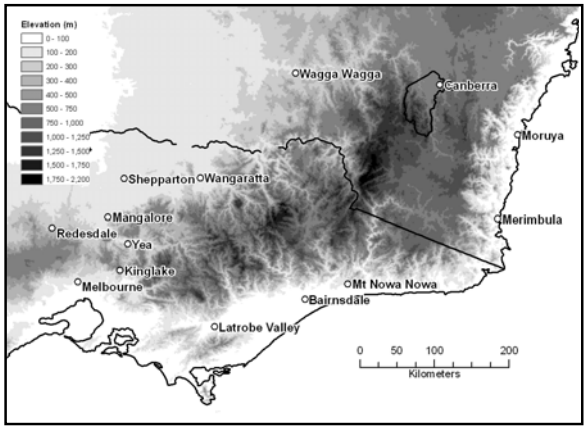

Figure 1. Map of southeastern Australia showing the locations of the automatic weather stations used in the study and the underlying topography.

During 12 February 2009, with a number of large fire complexes still burning nearby, a localised region of relatively warm and dry conditions were observed north of Melbourne and to the immediate northeast of the main range, near Mangalore and Redesdale (see figure 1). Winds were from a general easterly to southeasterly direction placing the region in the lee of the ranges.

In the early hours of 18 January 2003, the Canberra region experienced a drop in relative humidity. Webb et al. (2003) discuss the effect of this reduction in relative humidity on overall fuel moisture levels and note that it may have contributed to the extreme fire behaviour later in the day, when fires to Canberra's west merged and impacted the city.

To facilitate a more in-depth analysis of the events described briefly above, observational data from a number of automatic weather stations were obtained from the Bureau of Meteorology. The data included measurements of temperature, relative humidity, dew point and wind speed, direction and gust. The position of these stations in relation to the major topographic features of the southeast Australian mainland can be seen in figure 2. To supplement the observational study, analyses using the MesoLAPS mesoscale numerical weather model (Puri et al., 1998)) were also undertaken to investigate the atmospheric dynamics surrounding the occurrence of the foehn-like conditions on 19 and 20 September 2008.

3. RESULTS

In this section we provide a more detailed account of the meteorology of the two candidate events. In particular we focus on the evolution of temperature, relative humidity and wind observations at lee stations compared with those at windward stations during the candidate events. In addition we discuss the atmospheric dynamics associated with the event on 19 and 20 September 2008, as given by the meso-LAPS model.

3.1. 19 and 20 September 2008

Conditions along the Gippsland coast during the evening of 18 September 2008 were characterised by prevailing northwesterly to northeasterly winds. In northwesterly synoptic-scale flows the combination of the lee-trough and the land-sea temperature contrast acts to produce a markedly northeasterly flow along the Gippsland coast (Huang and Mills, 2006). Temperatures were observed to rise after sunset at Mt Nowa Nowa and Bairnsdale, with a complementary decrease in relative humidity. The time series of temperature and relative humidity at Mt Nowa Nowa and Bairnsdale along with that of the upwind station at Wangaratta can be seen in figure 2. The relatively warm and dry conditions persisted along the Gippsland coast for the remainder of the day with temperatures and relative humidity of around 16°C and 31%, respectively, in contrast to conditions encountered

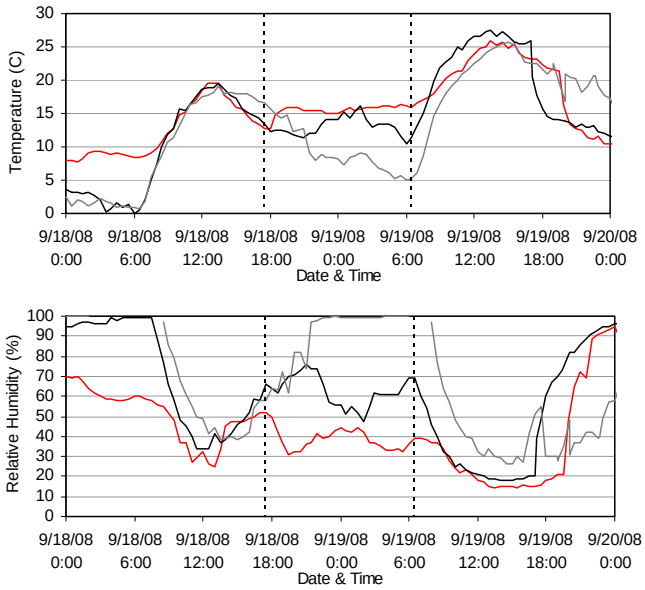

Figure 2. Time series of temperature and relative humidity at Mt Nowa Nowa (red), Bairnsdale (black) and Wangaratta (grey). The dashed vertical lines indicate the period when foehn-like conditions were most pronounced.

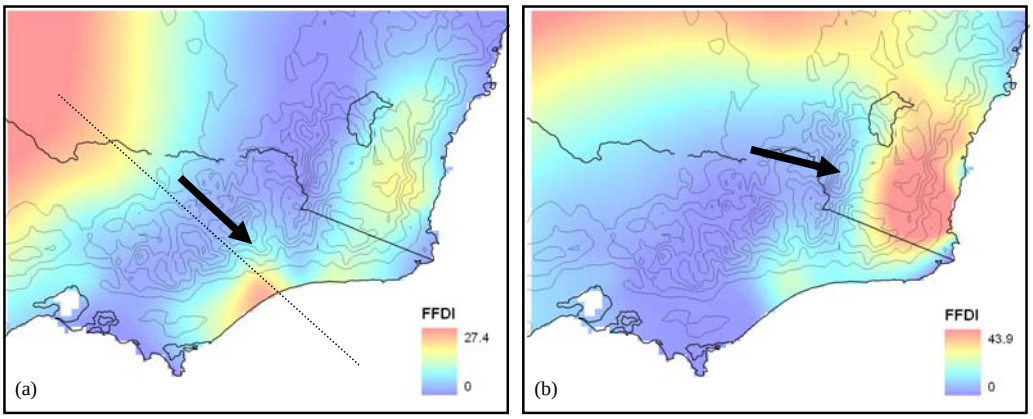

Figure 3. Interpolated surfaces of McArthur Mark 5 Forest Fire Danger Index (FFDI) for (a) 1400 hours, 19 September 2008, and (b) 1500 hours, 20 September 2008. The arrows indicate the synoptic wind direction and the dotted line in panel (a) approximately indicates the cross section used in figure 5.

upwind where temperatures and relative humidity were approximately 8°C and 82%. Figure 3a shows the resultant differences in the McArthur Mark 5 Forest Fire Danger Index (FFDI). A localised region of elevated FFDI can be seen along the Gippsland coast, immediately in the lee of the ranges. Observations of temperature and relative humidity at Moruya also exhibited anomalous maxima and minima on 19 September. These can be seen in figure 4a, while the associated changes in FFDI can be seen in figure 4b. These features coincide with brief instances of strong winds from between northwest and north.

On the following day (20 September 2008) at around midday the south coast of New South Wales experienced a change in wind direction from between northeast and east to between west and northwest, with an associated increase in wind speed gusting to over 60 km h^{-1}. Coincident with the wind change, temperatures exhibited an abrupt increase of approximately 8-12°C in less than an hour. By contrast, the temperatures on the upwind side of the mountains at Wagga Wagga only increased by about 2°C. Complementary decreases in dew point temperatures of the order of 15-21°C were also observed, with relative humidity falling from 79% at 12:00 to 8% at 14:22. Relative humidity at Wagga Wagga, while falling to around 20%, did not match the extreme lows recorded at lee stations along the coast; the rate of decline did not match the sharpness of the decline at the lee stations either. The effect of the localised warming and drying on FFDI can be seen in figure 3b, while the evolution of the abrupt warming and drying at Moruya can be seen in figure 4a. The sharpness of the changes at Moruya, for example, resulted in a significant and rapid increase in FFDI from around 1.3 (Low) to 24.5 (Very High) within an hour (figure 4b). In fact, the change in FFDI classification from 'Low' to 'Very High' took place in less than 25 minutes, between 12:35 and 13:00 hours.

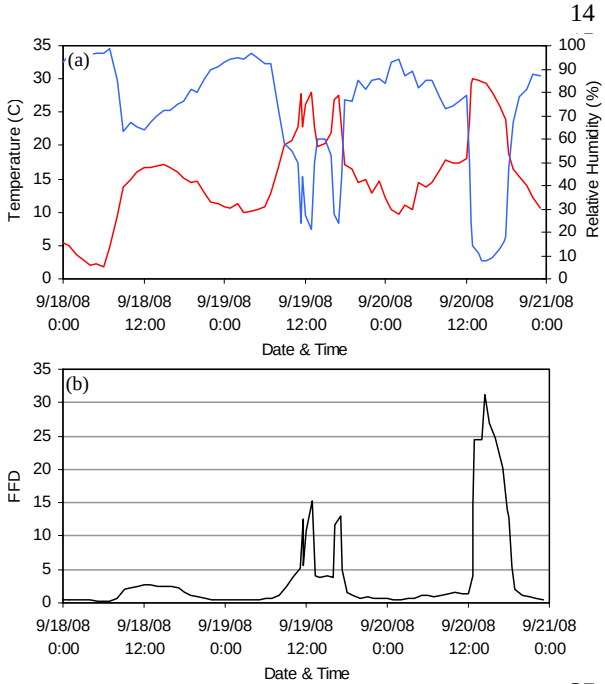

Figure 4. (a) Temperature (red) and relative humidity (blue) time series, and (b) FFDI time series for Moruya, 18-21 September 2008.

The Meso-LAPS output in figure 5 indicates the existence of a topographically-induced, vertically propagating gravity wave at a time when the foehn-like conditions were observed over the Gippsland coast. Vertical cross-sections of vertical velocity (figure 5a), and potential temperature and projected wind vector (figure 5b), exhibit definite buoyancy wave structure, while the streamlines (isentropes) in figure 5b suggest that the

foehn-like conditions were associated with partial blocking of relatively moist lower-level air on the windward side of the mountains, with drier upper air flowing downslope in the lee to replace it.

3.2. 12 February 2009

In early February 2009 the state of Victoria experienced a number of bushfires that resulted in an unprecedented loss of life and property. While the majority of damage occurred on 6 and 7 February, fires continued to burn in a number of complexes for most of the month. In particular, the Kinglake and Yea-Murrundindi complexes were both still being actively fought on 12 February and beyond.

Foehn-like conditions were observed near Mangalore and Redesdale on 12 February 2009. The conditions were notable because they were occurring near active fire complexes and because they were observed with a general southeast to easterly synoptic flow. This was in contrast to other foehn-like occurrences over southeast Australia considered by the authors, which all occurred with a synoptic flow from between north and west (Sharples et al., 2009).

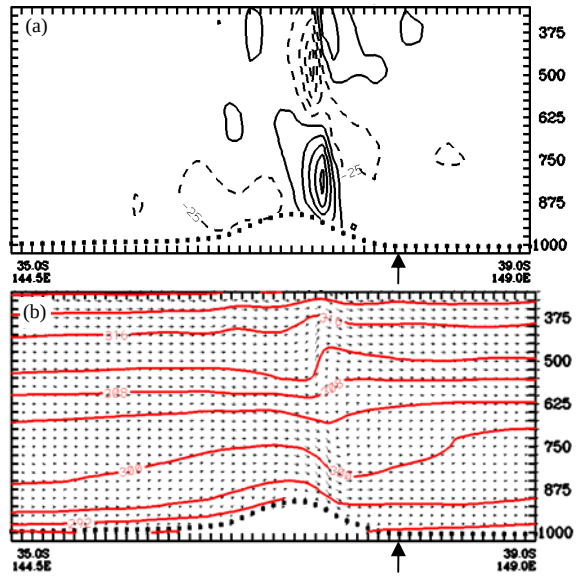

Figure 5. MesoLAPS output for 0700 19 September 2008. (a) Vertical cross-section of vertical velocity isopleths (hPa h^{-1}), (b) Vertical cross-section of potential temperature isentropes (K) and projected wind vector. (See figure 3a for cross section). The arrows indicate the approximate position of the coast.

Temperature and relative humidity at Mangalore and Redesdale were very similar to those recorded at Shepparton until winds at Mangalore shifted from a southerly to southeasterly direction, thereby placing Mangalore in the immediate lee of the ranges. The wind change occurred at 16:00 hours on 12 February, which is marked by the left-most vertical dashed lines in figure 6a and 6b. Figure 6a shows that after the wind change temperatures at Mangalore decreased at a slower rate than at Shepparton and remained around 3-4°C warmer than those experienced at Shepparton and on the upwind side of the range at Latrobe Valley. Similarly, the relative humidity at Mangalore remained around 30% lower than that at Shepparton and Latrobe Valley. The discrepancy persisted until the winds shifted back to a southwesterly direction (right-most vertical a dashed lines). Similar patterns in temperature and relative humidity were observed at Redesdale, though to a lesser extent.

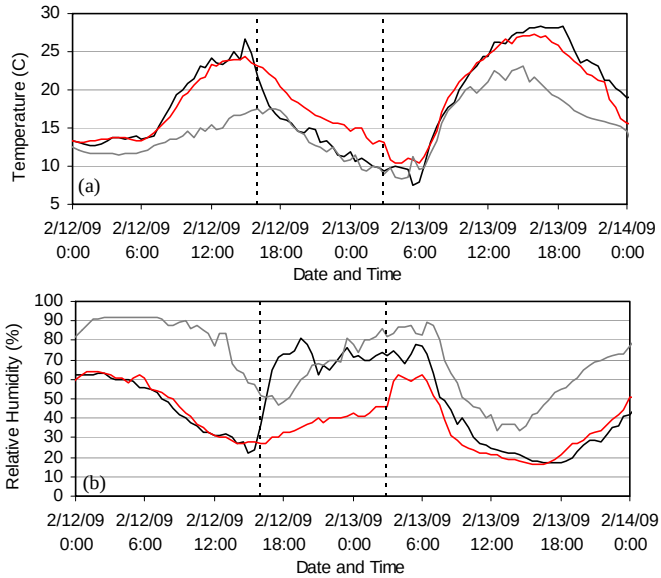

Figure 6. Time series of (a) temperature, and (b) relative humidity, for Mangalore (red), Shepparton (black) and Latrobe Valley (grey). Panel (c) shows the wind direction time series at Mangalore (blue) and Shepparton (black). The vertical dashed lines mark the period of interest.

During the period of interest, marked by the southeasterly winds at Mangalore, wind speeds were approximately 25-30 km h^{-1}, with gusts of over 50 km h^{-1}. In contrast, the winds at Shepparton initially changed to a northeasterly direction (figure 6c) and were of lower speed. It is of interest to note that the relative humidity at Shepparton decreased abruptly when the winds changed to a more easterly direction, at around 20:00 hours. Temperature at Shepparton also increased slightly at this time.

3.3. 18 January 2003

On 18 January 2003 fires that had started ten days earlier in the Brindabella Ranges to the west of Canberra, merged and impacted the city under extreme fire weather conditions. While the extreme conditions on the afternoon of 18 January are undoubtedly the main meteorological factor contributing to the extreme fire spread, it is of interest to consider some of the preceding meteorology. Webb et al. (2004) note that a reduction in relative humidity over the Canberra region in the early morning of 18 January would also have contributed to the extreme fire behaviour by hindering the overnight absorption of moisture by wildland fuels. Webb et al. (2004) do not mention what might have caused the reduction in relative humidity, nor do they mention a coincident increase in temperature.

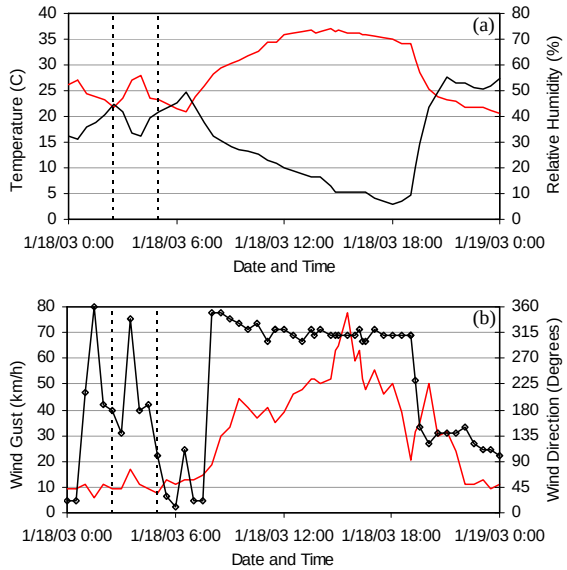

Figure 7. Time series of (a) Temperature (red) and relative humidity (%), and (b) Wind gust (red) and wind direction (black), for Canberra 18 January 2003. The vertical dashed lines mark the period 02:30 - 05:00 hours.

The increase in temperature and complementary reduction in relative humidity occurs at around 02:30 on 18 January, as can be seen in figure 7a. The temperature increases by 6°C in one and a half hours, while the relative humidity falls by about 12% over the same period of time. As can be seen in figure 7b the warming and drying occurs simultaneously with a change in wind direction from south to north-northwest, which would have placed Canberra in the lee of the ranges at some time during the change. Also as indicated by figure 7b, the warming and drying at Canberra coincided with a slight increase in wind gust. Average wind speed was observed to decrease at the same time, however, indicating erratic winds.

4. DISCUSSION AND CONCLUSIONS

The analyses presented above confirm the existence of anomalously warm, dry and windy conditions in the lee of the main mountain ranges of southeastern Australia consistent with foehn occurrence. Particular regions shown to be affected included the Gippsland region, the southern New South Wales coast and tablelands, and parts of central Victoria to the immediate northeast of the ranges.

Diagnoses of the 19 and 20 September 2008 event using NWP data indicated a connection between foehn-like conditions and partial orographic blocking of relatively moist low-level air on the upwind side of the mountains and subsidence of drier upper-level air in their lee. The NWP fields also indicated the presence of topographically-induced atmospheric waves in connection with foehn-like conditions occurrence. These waves originated with the descent of upper-level air above or slightly upstream of the ridge top and extended into the lee of the ranges as broad-scale, vertically propagating gravity waves. As such, the 19 and 20 September 2008 event appears to be a genuine and significant foehn occurrence. Enhanced mixing-down of drier upper air through wave breaking in the lee may also have been a contributing factor to this event, though it was not possible to identify such features with the hydrostatic model used.

The time series of temperature and relative humidity at Moruya (figure 4a) suggest that the existence of foehn conditions at the surface is dependent upon the interaction of the mountain wave features with other atmospheric structures such as inversions. On 19 September 2008 the foehn conditions intermittently experienced at Moruya did not manifest in the surface observations at Merimbula nearby. While Merimbula was also in the lee of the topography, it may have been protected from the downward-propagating dry air by a shallow marine inversion, with the onshore flow of cooler marine air being assisted by the lee trough in the surface pressure field. Hence, the absence of foehn conditions in the surface observations at a particular station does not mean that they cannot occur somewhere in the surrounding area, as the processes that develop surface inversions can vary widely over small geographic areas. The presence of wave structures in model fields and satellite imagery over regions in southeastern Australia should indicate the probability of foehn-like conditions occurring in some localities in that region.

The foehn-like conditions observed on the afternoon of 12 February 2009 and the morning of 18 January 2003 require further study. While the observations do fit the criteria for foehn occurrence, it is difficult to attribute them to a genuine foehn occurrence without the aid of numerical weather modelling. A low-level jet, for example, could produce similar changes in the surface observations (Sharples, 2008). Further investigation into these two events will be the subject of further work.

Foehn occurrence over southeastern Australia has significant implications for bushfire risk management. The elevated temperatures and depressed humidity levels associated with foehn-like conditions can result in the accelerated drying-out of wildland fuels, and more intense fire behaviour. The stronger winds associated with foehn occurrence can also increase the severity of fire behaviour characteristics such as rate of spread and spotting distance. As such, foehn occurrence can seriously compromise fire-fighter safety and suppression efforts. The abrupt transition of conditions that occur with the onset of foehn winds has significant implications for fire-fighting. Sudden changes in weather conditions have often been associated with loss of containment of bushfires and fire-fighter fatalities (e.g. Cheney et al., 2001). In this context, it is interesting to note that current Australian bushfire risk management frameworks do not formally account for foehn winds as drivers of bushfire risk, and the likely effects of foehn winds are not generally allowed for in alternate or 'worst case' scenarios.

Foehn occurrence also has bearing on prescribed burning and hazard reduction strategies. The event on 19 and 20 September 2008 occurred during a period typically set aside for hazard reduction burning. Thus, effective bushfire risk management, particularly concerning prescribed burning, in regions prone to foehn occurrence requires a proper appreciation of the precursor conditions for foehn winds and their likely (spatiotemporal) effect on fire danger levels. In particular, prescribed fires or wildfires that have not been sufficiently extinguished have significant potential to flare up and become problematic if impacted by foehn conditions.

ACKNOWLEDGMENTS

J.J. Sharples would like to thank Lesley Rowland from the National Climate Centre for the provision of automatic weather station data.

REFERENCES

Chandler, C., P. Cheney, P. Thomas, L. Trabaud, and D. Williams, (1983) *Fire in Forestry, Volume I: Forest Fire Behaviour and Effects*. John Wiley and Sons, 450pp.

Cheney, P., J. Gould, and L. McCaw, (2001) The dead-man zone: a neglected area of fire fighter safety. *Australian Forestry*, 64, 45-50.

Drechsel, S., and G.J. Mayr, (2008) Objective forecasting of foehn winds for a subgrid-scale alpine valley. *Weather and Forecasting*, 23, 205-218.

Forestry Canada Fire Danger Group, (1992) *Development and structure of the Canadian forest fire behaviour prediction system*. Forestry Canada, Science and Sustainable Development Directorate, ST-X-3, Ottawa, Canada.

Huang, X, and G.A. Mills, (2006) *Objective identification of wind change timing from single station observations*. BMRC Research Report No 120. 88pp

Puri, K., G.D. Dietachmayer, G.A. Mills, N.E. Davidson, R.A. Bowen, and L.W. Logan, (1998) The new BMRC Limited Area prediction System, LAPS. *Australian Meteorological Magazine*, 47, 203-223.

Rothermel, R.C., (1972) *A mathematical model for predicting fire spread in wildland fuels*. USDA Forest Service, Intermountain Research Station, INT-115, Ogden, Utah, USA.

Seibert, P., 1990: South foehn studies since the ALPEX experiment. *Meteorology and Atmospheric Physics*, 43, 91-103.

Sharples, J.J. (2009) Review of mountain meteorological effects relevant to fire behaviour and bushfire risk. *International Journal of Wildland Fire* (in press).

Sharples, J.J., G.A. Mills, R.H.D. McRae, and R.O. Weber (2009) Foehn-like winds and elevated fire danger conditions in southeastern Australia. *Journal of Applied Meteorology and Climatology*, (under review).

Ustrnul, Z., 1992: Influence of foehn winds on air temperature and humidity in the Polish Carpathians. *Theoretical and Applied Climatology*, 45, 43-47.

Webb, R., Davis, C. and Lleyett, S. (2004). Meteorological aspects of the ACT bushfires of January 2003. Proceedings of the Conference *Bushfire 2004: Earth, Wind and Fire - Fusing the Elements.* South Australian Department of Environment and Heritage, Adelaide, South Australia.

Whiteman, C.D., (2000) *Mountain meteorology fundamentals and applications*. Oxford University Press, New York.