Modelling the Thermal Belt in an Australian Bushfire Context

R.H.D. McRae[a] **and J.J. Sharples**[b]

[a]*ACT Emergency Services Agency, PO Box 158, Canberra, ACT 2605, Australia*
Email: rick.mcrae@act.gov.au
[b]*Applied and Industrial Mathematics Research Group, School of Physical, Environmental and Mathematical Sciences, University of New South Wales at the Australian Defence Force Academy, Canberra, ACT 2600, Australia*

Abstract: On many occasions fire crews tasked to suppress fires at night in rugged landscapes have been surprised by fire intensity on mid slopes. While it has long been stated that this is due to a thermal belt, no studies have been done into how this occurs or the magnitude of its impact on fire behaviour.

Radiative heat loss at night leads to cooling of surface air and subsequent density-driven drainage and pooling. This can produce a nocturnal inversion below the mid-slopes of a valley, and has been the subject of numerous studies of its effects on agriculture. The resultant pattern in weather can also be significant for fire managers. Mid slopes can be significantly warmer and drier than valley floors or ridgetops, and are termed the thermal belt. The formation of a thermal belt requires a continental air mass and light or no winds.

A terrain model has been developed to show the formation pattern and intensity of the thermal belt. It uses adiabatic lapse rates, slope position and drainage patterns to model distinct dynamic elements of the system. When combined these provide a useful indication of the extent of the belt.

Initially the model looks at a sunset temperature reading and uses the dry adiabatic lapse rate to estimate temperature across a local catchment. An ambient cooling rate of about 1°C per hour applies to the entire system. Then the effects of radiative heat loss from the ground are considered. The portion of this that is transferred to air in contact with the ground makes that air denser. This air then flows along fall lines until it reaches a drainage line. Air flowing along the drainage becomes density stratified due to unequal sideslope drainage times. The time taken to reach the exit-point of the catchment can be readily estimated in the field.

An additional consideration is pooling of cold air in the low points of the landscape. Some straightforward geometric techniques can be used to estimate the pooling depth at any point with time, as drainage flows from an increasing fraction of the area arrive.

While the current model is empirical, there is a need for further work towards a physical model. The model successfully indicates the formation of a thermal belt with time after sunset. As the thermal belt develops, and using assumptions about variations in dew point temperature, it possible to use the model to estimate changes in fire behavior over time, across the catchment. More work is underway to link this model into bushfire management requirements.

Keywords: *Intensity of Thermal Belt, Radiative Cooling, Rugged Terrain, Bushfire Management*

1. INTRODUCTION

Accurate prediction of fire weather conditions in mountainous regions can be complicated by a number of complex phenomena that are endemic to high-elevation and/or rugged terrain (Sharples, 2009). In particular, the presence of atmospheric inversions in rugged terrain can produce effects that invalidate standard methods for elevation-based adjustment of air temperature and relative humidity. For example, if an inversion is present, the assumption of an adiabatic lapse rate (ALR) over the entire vertical extent of a rugged terrain surface can result in incorrect estimation of temperature at elevated sites.

Application of ALR to estimate fire weather conditions can also be invalidated due to process such as differences in the rates of radiative cooling and nocturnal drainage in rugged terrain. For example, these processes can interact to produce something called the ‘thermal belt’ or ‘thermal zone’. The thermal belt refers to a band of elevation along a terrain slope where night-time surface temperatures remain relatively warm compared with temperatures at higher and lower elevations.

In simple terms, a thermal belt forms when drainage winds carry the coldest air down the slopes to the bottom of valleys resulting in a belt of warmer air, which lies above the pool of cold air. Above the thermal belt temperatures exhibit their normal decline with elevation, augmented by increased radiation loss from lower air density and lower moisture content at high altitudes (Glickman 2000). Historically, the earliest settlements in countries such as Germany took advantage of the existence of a thermal belt (Geiger *et al.*, 1995), while its effects on the length of growing season and crop availability have long been recognised. Yoshino (1984) provides a more detailed account of the history of research into thermal belts and a more detailed discussion of its underlying mechanisms.

The effects of the thermal belt have also been recognised in the context of fire management in mountainous regions of North America and Europe, but have received only fleeting attention in the context of bushfires in Australia. This is despite the obvious effects that a thermal belt can have on fire danger levels and fuel moisture content on mid-slopes. Indeed, in certain circumstances the formation of a thermal belt can result in localized fire danger maxima occurring overnight. This can impact on the effectiveness and safety of overnight suppression strategies and tactics. It must be remembered that for reasons of access and logistics, the majority of weather instrumentation is situated on ridge-tops or in lower lying areas, away from where the effects of a thermal belt would be obvious. The same can be said of Fire Control Centres, which are typically situated in lower-lying, easy to access locations. Thermal belt observations made by the authors (unpublished) indicated that temperatures on the mid-slopes could be 6-8°C higher than those on the valley bottom, while relative humidity could be 25-30% lower.

The present paper presents the results of an effort aimed at providing a more comprehensive understanding of the thermal belt in an Australian bushfire context. In particular it reports the development of a process model for predicting the existence, evolution and intensity of thermal belts in a specific catchment located to the west of Canberra (Figure 1). The catchment, which is located approximately at 148° 49’ E, 35° 20’ S and has an elevation range of 800 – 1400 m ASL, was severely affected during extreme bushfires in 2003 and so is a relevant location to consider in the context of fire management. For bushfire management purposes, the key goals of the modelling are knowing where a belt may form and its intensity. There is thus a need for a model of how temperature differentials may form across a rugged landscape due to nocturnal radiative heat loss.

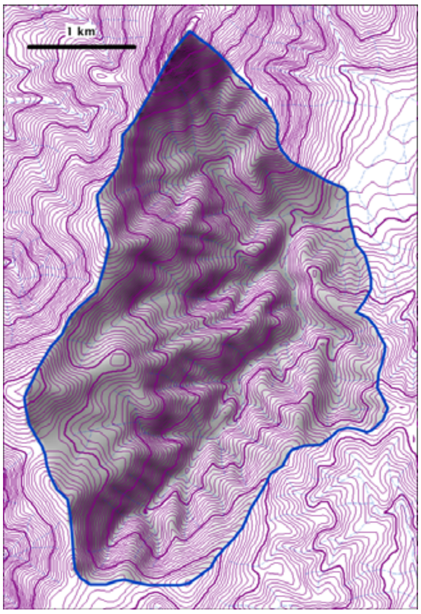

Figure 1. A sample catchment, used to explain the concepts.

2. MODELLING METHODOLOGY

It is assumed that for fire purposes the air is not saturated. Thus, at sunset, the dry adiabatic lapse rate applies. In the study area this implies about 10°C cooling for every additional kilometre of height. Thus if a reference temperature, T_{REF}, is available at sunset, the sunset temperature at another site, T_S, can be estimated – see Figure 2.

During the formation of a thermal belt in a rugged valley, the landscape can be divided into three types of site.

- In the first the weather reflects sunset conditions with a dry adiabatic lapse rate (DALR) and localised solar radiation patterns dominating spatial variability.

- In the second, cooled air flows downslope along fall-lines and concentrates into drainage lines.
- In the third, cold air pools in valley floors or where topography impedes drainage.

All sites radiate heat from the ground into the atmosphere throughout the night. This cools the ground, but not the air. However, air in contact with the cooled ground will exchange heat conductively. Thus a parcel of air in contact with the ground will continuously cool through the night.

As the air cools, it will flow downslope. As long as it remains cooler than its surroundings it will remain a parcel of air in contact with the ground.

The radiative heat loss from a given area of ground will result in a temperature anomaly, which will disperse into its surroundings as equilibrium is sought. Some of this will stay in the ground, some will cool the air adjacent to it, and some will act to cool the entire surroundings through cooling the vegetation and through turbulent mixing. Where two drainage lines meet, the air leaving the longer tributary is likely to have been in ground contact for longer, and should undercut the other, breaking its cooling sequence. As both are cooler than the surrounding air, they will continue to undercut it, but as a stratified group.

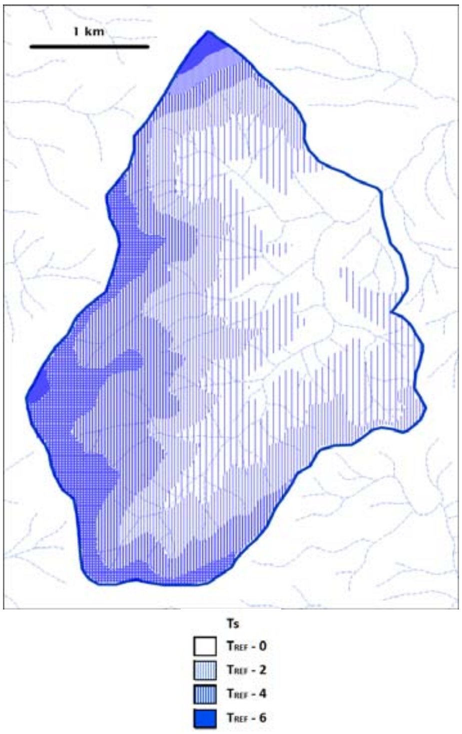

Figure 2. Effect of DALR in the catchment.

Over time this will lead to a change in the vertical temperature profile in the valley. As cooling progresses, and as stratification develops, the lowest level will be cold and there will be an increase in temperature with height through the stratification. Above the air affected by the ground, temperature will reduce with height. At sunrise, or with replacement of the continental air mass, the pattern will break down.

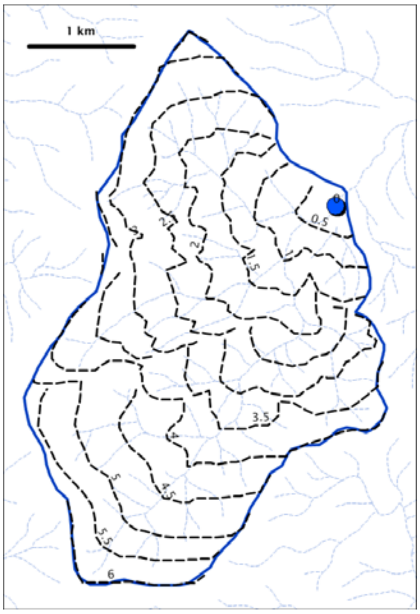

Figure 3. Estimated arrival times at the catchment outflow, in hours after sunset. Each hour corresponds to c.0.7°C cooling.

After sunset it is assumed that through radiative heat loss to the atmosphere the catchment will be continually cooling. This cooling will be by means of heat loss from the ground surface. This thermal radiation will be at wavelengths to which the unsaturated atmosphere is transparent. Thus the air can only cool by conduction after contact with the ground. This cooled air may be mixed upwards by turbulent processes, or may remain in contact with the ground.

Turbulent mixing and other processes will produce a steady cooling of all surface temperatures across the catchment. Field measurements, in summer on ridgetops in rugged eucalypt-covered landscapes and under a continental air mass, suggest a cooling rate of about 1.0°C per hour, the ambient cooling rate (*ACR*).

Air that gets additional cooling through direct ground contact will come under the influence of density differentials. The denser, cooled, air will tend to flow downslope. Its net horizontal velocity will reflect the balance of friction, due to rocks and vegetation, and the drainage gradient.

The quasi-exponential hydraulic profile of a stream in rugged landscapes will be effectively a combination of steep headwater segments and flat valley segments. As will be seen later the valley segments are quickly isolated from the side-slope cooling processes due to pooling, and can be considered separately. Thus the hydraulic gradient can be typified as steep for this analysis. In the range of 10° to 30° the horizontal velocity will be a balance between factors such as gravitational acceleration and friction.

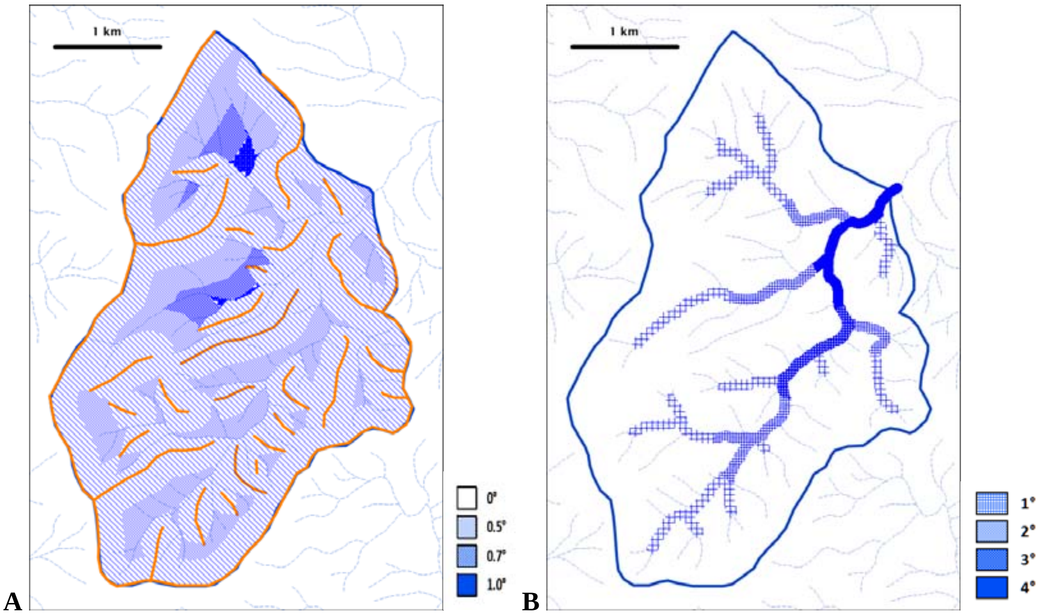

Figure 4. A) Cooling due to flow path along sideslopes. Orange lines are ridgetops and spurlines. B) Cooling along main drainage lines.

It can then be assumed that the drainage length over which a parcel of air has flowed due to density gradients is linearly proportional to the time since sunset. Field measurements indicate that this value in rugged eucalypt forested landscapes in summer is about 1 km hr^{-1}. Additional field measurements indicate that for every kilometre travelled, the conductive cooling is about 0.7°C per hour, the drainage cooling rate (*DCR*).

The cooling influence at a site in a catchment at time *t* will reflect only that subset of the catchment that could flow over that site in time *t*. For some part of the night, a proportion of the catchment will have no influence on that site. At any time *t*, some sub-catchments will have exerted their full influence on the site, and thus can cause no further drainage cooling. Other sub-catchments may at that time be exerting only part of their potential cooling influence at that site (see Figure 3). A site near the watershed will be fully influenced early in the night, while a site near the end of the valley may experience growing influence throughout the night. At that time *t* there will be both a cooling due to sideslope drainage residence time (*SDT*) and a cooling due to drainage line residence time (*DTL*) (Figure 4 A and B respectively).

Further, cooling due to valley floor pooling (*VFP*) will bring cooled air higher up the slopes than would otherwise occur. The pooling of cooled air on the lowest parts of the valley is shown in Figure 5. This is modelled from the digital elevation model. For each point from a grid of points and with an elevation *z* (metres), the lowest elevation value (z_{min}) within a 1500m radius is extracted. Pooling occurs from there upwards, with the depth increasing through the night until the entire catchment is affecting the outflow site. The pooling depth would be a function of the contributing area raised to the two thirds power (based on geometric principles). Based on field data, pooling was limited to the lower third of the site's elevation range after full drainage development through the night, and this was assigned an equivalent cooling of 12°C in its lowest strata, allowing a purely empirical model to be produced.

$$VFP = \min\left(0{,}36\,((z - z_{\min}) - 0.083\,t^{2/3})\right) \qquad (1)$$

These elements may be brought together, allowing a model of the temperature at time *t* (hours since sunset), T_t, of:

$$T_t = T_S - t\,ACR - \left(\min(SDT, t) + \min(DLT, t)\right)DCR - VFP \qquad (2)$$

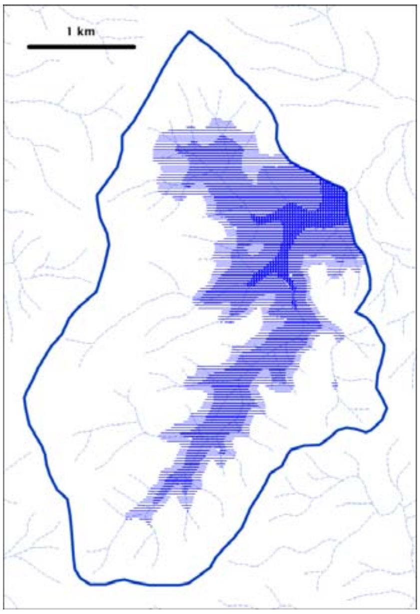

Figure 5. Drainage pooling model for midnight with a fully developed drainage pool.

	% of local relief	% of area
🟦	Up to 14%	6%
▤	14% to 28%	14%
▢	Over 28%	10%

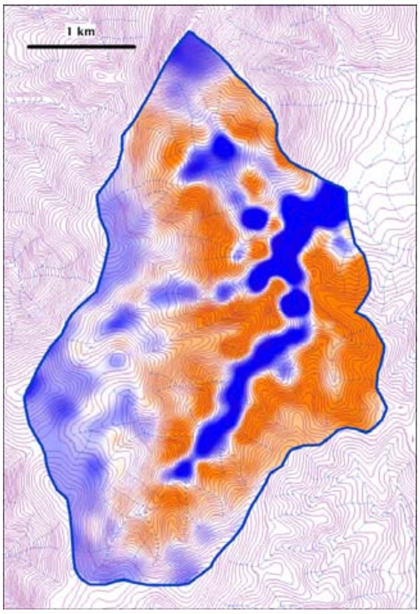

Figure 6. Combined model output, showing the thermal belt in orange.

🟧	21.0°
⬜	18.5°
🟦	16.5°

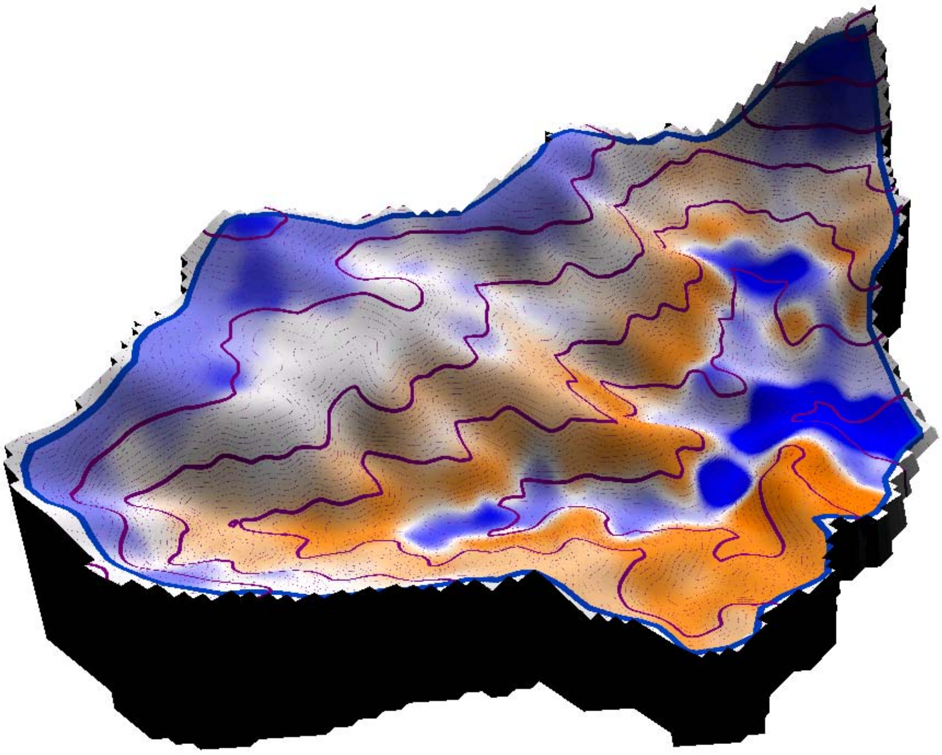

Figure 7. Visualisation of the catchment showing the model output.

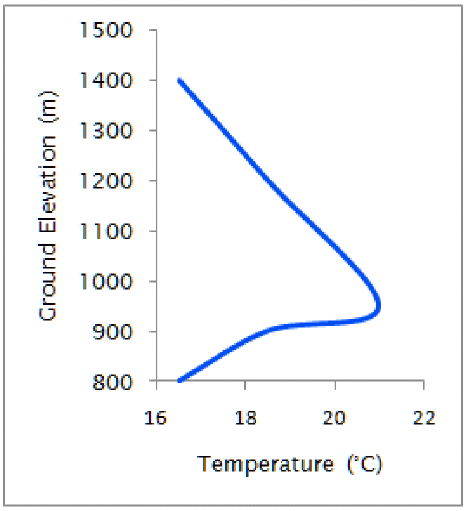

Figure 8. Temperature profile late in the night.

Air will generally not cool below its Dew Point Temperature (DP) – instead it becomes saturated and forms fog which stops further radiative heat loss. Where mechanical processes due to drainage force cooling to continue, T may fall below the DP. It is possible for frost to form under fog through this process. The stratification may be estimated by combining the data in Figure 3 with that in Figure 6. Higher altitude DP depression events (Sharples 2009) may permit low DP air to flow down from some distant sub-catchments, producing marked differences in the state of the pooled air, sometimes visible as clear air under fog.

3. RESULTS

Figure 6 and Figure 7 show a model run for midnight with T_{REF} = 28° C. A clear thermal belt has resulted. The temperature at the lowest points of the landscape is equal to that at the highest points. The temperature profile across the centre of the catchment is shown in Figure 8. Figure 9 shows model output for conditions two hours after sunset.

4. DISCUSSION AND CONCLUSIONS

As with many micro-meteorological processes, a comprehensive model of the thermal belt would involve a range of physical processes. This could include all elements of heat transfer, air flow and friction effects. However this study is oriented towards developing a model which can be run in the field in a computationally limited environment.

A simplified process model produces a thermal belt. Work is underway into further calibrating this model using field data and remote sensing. The range of about 5° C in the midnight simulation is in accord with field observations. A comparison of Figure 6 and Figure 9 gives insight into the manner of formation of the thermal belt. It starts out as a simple terrain-based zone. As time passes it is eroded by both deepening of the pooling zone in the valley floor and by strengthening of the drainage down sideslopes and into headwater gullies. As the belt decays into a series of remnant patches on prominent terrain it would become more of a challenge, in the field, to estimate its extent using surface observations. This demonstrates the value of modeling processes such as this.

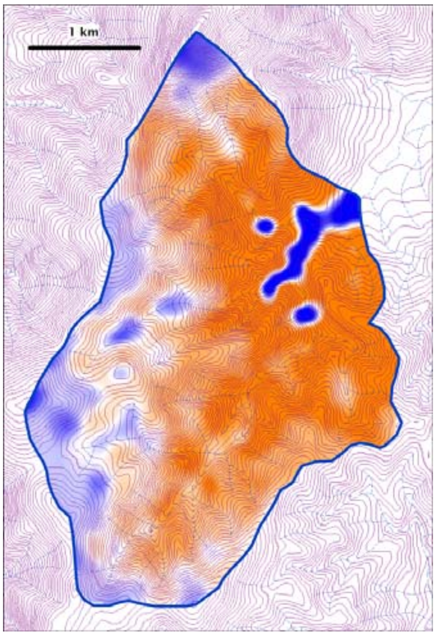

Figure 9. Model output for early in the night.

Work is needed to explore how generally applicable the calibration of the model used is to other localities, with different vegetation, hydraulic gradients and local relief.

A range of real-world processes may upset the clear pattern produced by the model. Turbulent mixing combined with thermal winds may redistribute the thermal anomalies. Studies, such as that of Nitze (1936), have shown the subsequent complexities that are elements of the atmospheric cross-section of a catchment.

Localised solar radiation patterns prior to sunset can alter the initial temperature conditions, making subsequent patterns less predictable.

Different vegetation types may have differing abilities to transfer temperature anomalies from the soil into the free air. The water regime of the soil is also likely to modify heat fluxes through latent heat effects. Many studies into vegetation effects are reported in Geiger *et al.* (1995). Further research should aim to explore the effect of vegetation type as a priority, and should address the correlations between vegetation and landscape position.

If the DP is assumed to be constant in a catchment, the modeled temperature regimes indicate the potential for wide ranges in fire weather to occur during the night. This indicates the value of ongoing, more detailed analysis from a fire management perspective.

REFERENCES

Geiger, R, Aron, R.H. & Todhunter, P. (1995, 5th Edn). *The Climate Near the Ground.* Vieweg.

Glickman, T. (2000) Glossary of Meteorology. 2nd Ed. American Meteorological Society, Boston MA.

Nitze, F.W. (1936). Untersuchung der nachtlichen Zirkulationsstromung am Berghang durch stereophotogrammetrisch vermessene Ballonbahnen. *Biokl. B.* **3**, 125-127.

Sharples, J.J. (2009). An overview of mountain meteorological effects relevant to fire behaviour and bushfire risk. *International Journal of Wildland Fire* **18**: 737-754.

Whiteman, C.D. (2000). *Mountain Meteorology: Fundamentals and Applications*. Oxford.

Yoshino, M.M. (1984) Thermal belt and cold air drainage on the mountain slope and cold air lake in the basin at quiet, clear night. *GeoJournal* **8.3**: 235-250.