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An overview of mountain meteorological effects relevant to fire behaviour and bushfire risk

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Abstract. Many of the processes that can occur in mountainous landscapes have the potential to significantly affect fire behaviour and bushfire risk in general. These processes can lead to otherwise unexpected fire behaviour and escalation in fire size and severity that could endanger firefighting crews and compromise suppression activities. Interaction of upper winds with rugged terrain can often result in highly variable and turbulent wind patterns and variations in temperature and humidity that can affect fire regimes in the long and short term. More generally, the effect of rugged terrain on atmospheric flows can give rise to complex dynamics and emergent properties that are discontinuous in nature. Hence, the 'fire weather continuum' that is often assumed in fire management practices is of reduced validity in mountainous or hilly landscapes. This paper presents an overview of the main elements of mountain meteorology relevant to fire weather and discusses the potential roles they may play in bushfire behaviour, development and risk. As such, the paper is intended to promote understanding, across the wide range of professions concerned with bushfire, of how mountain meteorological effects might contribute to fire potential and fire behaviour.

Introduction

The influence of meteorological factors on wildfire behaviour (or bushfire behaviour in Australia) has long been appreciated (Beall 1946; Byram 1954; McArthur 1966, 1967; Deeming and Lancaster 1971). Along with fuel and topography, weather variables such as temperature, humidity and wind strength and direction are considered the most important components determining fire behaviour and growth (Fosberg 1978; Noble *et al.* 1980; Chandler *et al.* 1983). These components interact with each other in a complex manner that directly influences fire spread, fire intensity and the flammability of fuels. At the climatological scale, variations in topographic characteristics such as elevation and topographic slope and aspect are linked to spatial variations in meteorological variables, which in turn play a major role in influencing the distribution of fuel types across a landscape (Barry 1992; Whiteman 2000). At shorter time scales, topography can also affect the spatial and temporal variability of weather, thereby affecting ignition potential and the manner in which a particular fuel type will burn (McCutchan and Fox 1986; Barry 1992; Gorski and Farnsworth 2000).

Fire behaviour and fire spread models are often employed to account for the characteristics of a fire spreading under a given set of environmental conditions. These models can be highly sensitive to weather variables and thus require meteorological inputs that match those at the fire site as closely as possible. In mountainous regions, however, the spatial and temporal variations in meteorological factors can be difficult to quantify accurately owing to the complex interaction between atmospheric flows and the rugged topography. Understanding the interaction between complex terrain and atmospheric flows is thus an important and challenging endeavour that is typically referred to as *mountain meteorological* research. Much of the literature on mountain meteorology, however, is outside the context of fire behaviour. A principal aim of the present manuscript is therefore to provide a review of some of the key elements of mountain meteorology that are relevant to fire behaviour.

In addition to the problem of predicting fire behaviour and growth, there is the broader problem of quantifying the risk of bushfires in fire-prone landscapes. Generally, risk is defined in terms of likelihood and consequence. The Australian Standard decrees that risk is the chance of something happening that will have an impact on objectives (Standards Australia 2004). Bushfire risk alludes to the risks inherent in fire-prone regions that arise owing to the interactions of the various facets of the environment, where by 'environment' I mean to include all the natural and man-made features of the region. The likelihood of a bushfire posing a risk in a particular region is usually separated into two components – the likelihood of ignition and the likelihood of growth, where the latter is meant to include all of the various facets of fire growth, such as fire-line intensity and rate and direction of spread. Assuming that these two components are independent of one another, the likelihood of a bushfire posing a risk is obtained by simple multiplication of the respective probabilities pertaining to ignition and growth. Ignition likelihood is generally broken down into the various sources of ignition, each of which is treated by the appropriate models. Ignitions are often simply classified as natural (lightning-induced) or otherwise. The likelihood of growth of a bushfire is typically derived

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using some form of fire spread model that combines information from fire behaviour models with knowledge of fuels, terrain and meteorological conditions to make a prediction of where the fire is likely to spread during its evolution and the characteristics (e.g. rate of spread and intensity) of the fire across its spatial extent.

Traditionally, fire-spread models have used synoptic-scale meteorological observations, in addition to information on vegetation type, fuel state and topography, as inputs to predict fire growth from rate of spread calculations. The Australian Fire Danger Rating system, based on the work of McArthur (1966, 1967), is a chief example of this. More detailed models allow for diurnal variations in meteorological variables. These diurnal variations are used to appropriately perturb the broader-scale observations so that finer-temporal-scale fire behaviour can be more adequately accounted for. When dealing with the problem of managing bushfire risk in mountainous landscapes, however, it is also important to understand the drivers of risk arising from the interaction of the atmosphere with the complex terrain encountered in these regions. Mountainous regions can have an influence on the wind and other weather variables owing to the strong stable stratification of the atmosphere, which inhibits vertical displacement. The effect of buoyancy will return vertically displaced air parcels to their equilibrium level even if this requires a broad horizontal excursion or the generation of strong winds (Smith 1979). Many of the meteorological processes encountered in high-country or mountainous landscapes can contribute significantly to the overall risk posed by a bushfire. In Europe and North America, the effect of mountain meteorological phenomena on fire behaviour and the risk posed by wildfires has long been recognised. This is reflected in research and education (Byram 1954; Ryan 1969, 1977, 1983; Furman 1978; Haines and Lyon 1990; Rothermel 1993; Butler *et al.* 1998; Conedera *et al.* 1998; Millán *et al.* 1998; Miller and Schlegel 2006*a*, 2006*b*) conducted over the last 50 years. In Australia, the extent to which mountain meteorological effects contribute to overall bushfire risk is, to a large degree, an open problem. Given the recent incidence of large fires in the Australian high country, e.g. 2003, 2006–7 (Nairn 2003; Wareing and Flinn 2003; Webb *et al.* 2004; McRae *et al.* 2006; Smith 2007) and the occurrence of severe fires in hilly terrain in the past, e.g. the Ash Wednesday fires (Billing 1983) and the severe 1967 fires in south-east Tasmania (Bond *et al.* 1967), the role that mountain meteorological effects play in the overall bushfire risk problem is worthy of further scrutiny.

Mountainous environments have a number of critical and complex management challenges, including biodiversity issues, cultural considerations and water-resource issues. In Australia, there are several endangered species that are endemic to the Alpine environment, sensitive soils that require protection through careful management and important geomorphologic sites. In the cultural sense, post-European settlement in the high country features significantly as part of the national identity and imagination. The Australian high country is also the setting for a number of stories and sites of great cultural importance to Australians of indigenous descent. A number of river systems, whose importance extends far beyond the immediate high-country region, also originate in the Australian Alps. These themes are echoed in many mountainous environments throughout the world. Wildfires have the potential to significantly impact on all of these aspects of mountainous environments. The question of how best to manage fire in mountainous environments is thus an important one that has bearing on a wider range of issues than just the immediate one of protecting life and property. The problem is complicated further by the effects of anthropogenic climate change, which are likely to cause critical shifts in biodiversity patterns, water availability and hence fire regimes in mountainous areas (Beniston 1994; Nogués-Bravo *et al.* 2007).

Elements of mountain meteorology thought to be important for bushfire risk in the Australian high country include mountain winds such as the foehn and mountain jets, dynamic channelling, atmospheric drying and interactions with the terrain that contribute to local atmospheric instability. To properly assess how mountain meteorological effects contribute to bushfire risk in the Australian high country, it is prudent to begin with a review of the available international literature dealing with the topic of wildland fire risk or fire propagation in mountainous areas. Given that the mountain meteorological effects discussed above have recently acquired a greater significance and importance to Australian fire managers, it is worthwhile to identify other fire-prone regions around the world that are likely to experience similar mountain effects. Examples of these regions include those parts of the United States that lie immediately east of the Rocky Mountains or west of the Sierras (California is a prime example) and certain mountainous regions in Europe where, for example, the dangers of foehn winds are well known. Moreover, it is useful to review what is known about how these mountain effects contribute to fire behaviour in these regions and how this might translate to the Australian case. Such a review will also aid in identifying gaps in knowledge about mountain effects and fire behaviour and is also likely to shed light on the placement of monitoring stations in order to capture these meteorological phenomena.

The paper is organised as follows. In the section entitled *Elements of mountain meteorology relevant to bushfire*, I provide a description of the causes and characteristics of a number of mountain meteorological phenomena that can significantly affect fire weather, as well as noting some of their implications for fire behaviour and bushfire or wildfire risk. Although the paper is written with the Australian context foremost in mind, the phenomena and their implications will apply to mountainous areas around the globe. I therefore use the terms 'bushfire' and 'wildfire' interchangeably. In the section entitled *Guidelines for fire operations in mountainous landscapes*, I discuss some of the operational issues faced by those tasked with using or suppressing wildfire in mountainous or high-country landscapes. In particular, a number of operational guidelines are provided.

Elements of mountain meteorology relevant to bushfire

In this section, I provide a brief description of some of the main mountain meteorological phenomena that have the potential to impact on fire behaviour and the risk posed by bushfires in mountainous areas. In doing this, I will concentrate on mountain effects that can significantly alter the key meteorological variables relevant to ignition likelihood and fire behaviour, i.e. temperature, humidity, wind speed and direction and atmospheric stability. It should be noted that, to a large degree, variations in temperature are driven by variations in insolation. In fact, the perceived importance of temperature to fire potential stems from its positive relationship with insolation, evaporation and fuel moisture content, which are the quantities that most directly influence the flammability of fuels.

It is important to note that complex terrain can also have a significant effect on the distribution of rainfall across a landscape. Rainfall can be highly variable over mountainous terrain, and as such can considerably complicate the estimation of spatial patterns of fuel moisture content and drought effects (Keetch and Byram 1968). Despite this, I will not make specific mention of rainfall in what follows. The interested reader is instead referred to the large body of literature on the relationship between topography and rainfall, e.g. see Smith (1979), Barry (1992), Barros and Lettenmaier (1993), Sharples *et al*. (2005) and the references cited in these works.

As mentioned above, the differential heating of the Earth's surface is one of the main factors driving the spatiotemporal variability of climate, weather and fuel moisture characteristics in mountainous regions. I therefore begin by discussing the effect this has on temperature and humidity.

Topographically induced variations in temperature and humidity

The amount of solar radiation reaching a point on the surface in mountainous terrain can vary significantly depending on the topographic slope and aspect and local relief. The insolation of a patch of land is a key factor in determining its microclimate. The interaction of solar radiation with topography is critically important in determining the spatial distribution of temperature, relative humidity, fuel moisture content and vegetation type. Geiger *et al*. (1995) demonstrated that under full sunshine in the mid-latitudes of the northern hemisphere, south-facing slopes are on average 3°C warmer than north-facing slopes. South-facing slopes also experienced lower relative humidity and lower soil and vegetation moisture content. It is reasonable to expect analogous results for north-facing slopes in the southern hemisphere, although shadowing of lower elevations by higher peaks and ridges can confound this effect. The passage of the sun during the day also leads to diurnal variations in the exposure of slopes and hence in the levels of temperature and relative humidity associated with them. It is important to note, however, that strong winds can negate any differences due to slope, elevation or aspect present at low wind speeds (McCutchan and Fox 1986). Diurnal variations in temperature also generate mountain winds (see the next section). The variability of elevation, slope and aspect across an area containing mountainous terrain can therefore lead to a large degree of spatial variability in temperature, relative humidity and precipitation across such landscapes (Cramer 1972; McCutchan 1976; McCutchan and Fox 1981, 1986). Over longer time scales, topographically driven variations in temperature and atmospheric moisture, along with other factors such as soil type, can be a major factor in determining vegetation type. This can result in significant differences in fire regimes on north- and south-facing slopes. Solar insolation in complex topography also plays a major part in the timing of snow-melt, which can be quite critical in mountainous areas where spring fire seasons dominate. Topographically induced variations in fuel moisture content or vegetation type can lead to changes in fire behaviour characteristics such as rate of spread and intensity, which can be utilised in fire management practices. For example, in the mountainous regions of south-east Queensland, rainforest gullies are often relied on as effective natural control lines in fire suppression and prescribed burning activities. More generally, spatial patterns of fuel moisture and vegetation, arising from the effect of topography on solar radiation, temperature and humidity, can shape the 'connectedness' of the landscape, with respect to its ability to carry a fire. Such information could be utilised in planning for fire suppression activities as well as providing additional information to help facilitate land management practices such as prescribed burning. Detailed information on the spatial variability of fuel moisture over complex terrain also provides a better understanding of ignition likelihood across mountainous regions, thereby improving the understanding of bushfire risk in those landscapes.

The elevation of a surface directly influences its temperature and relative humidity (McCutchan 1976). Typically, in the mixed layer, temperature decreases with height, whereas the mixing ratio changes little with height (Pielke and Mehring 1977; Hutchinson 1991; Whiteman 2000). Hence, with increasing height, there is a tendency for relative humidity to increase. This means that, under these conditions, surfaces at higher elevations have lower temperatures, higher relative humidity and higher moisture content in the soil and vegetation. This leads one to expect that higher elevations will generally experience lower fire danger. However, at night, temperature inversions and cold-air drainage can cause the relationship between temperature, humidity and elevation to reverse, leaving upper and mid-slopes with higher temperatures and lower humidity than the lower slopes and valley bottoms. The effects can be local (e.g. frost hollows) and larger in scale.

Under inversion conditions brought on by cold-air drainage, mountain tops and valleys can experience lower temperatures and higher fuel moisture content, while convex mid-slopes are warmer and drier. This phenomenon is known as the *thermal belt*. The existence of a thermal belt can lead to fire behaviour on mid-slopes that is more severe than what would be expected based on weather data recorded at lower sites, which incidentally are often the location for incident control centres. When the nocturnal inversion begins to break up owing to daytime heating, the induced mixing can cause temperatures to increase, relative humidity to decrease and wind may increase in strength and change direction suddenly.

Particular types of inversions known as *subsidence inversions*, which can occur whenever synoptic conditions are dominated by high pressure, are produced by subsiding air in anticyclones. As drier mid-tropospheric air sinks, it is warmed owing to adiabatic compression and eventually replaces the surface air, which is forced out as subsidence progresses. Mountaintops are particularly prone to the warming and drying effects of subsidence inversions and can thus be subject to fire danger conditions substantially higher than those simultaneously experienced at nearby low-land sites. Fig. 1 compares traces of the dew-point temperature at a low-land and elevated site, both in the Australian Capital Territory (ACT). The extreme event that occurs just after midnight on 30 November 2006 is due to a subsidence inversion. During this event, temperature and relative

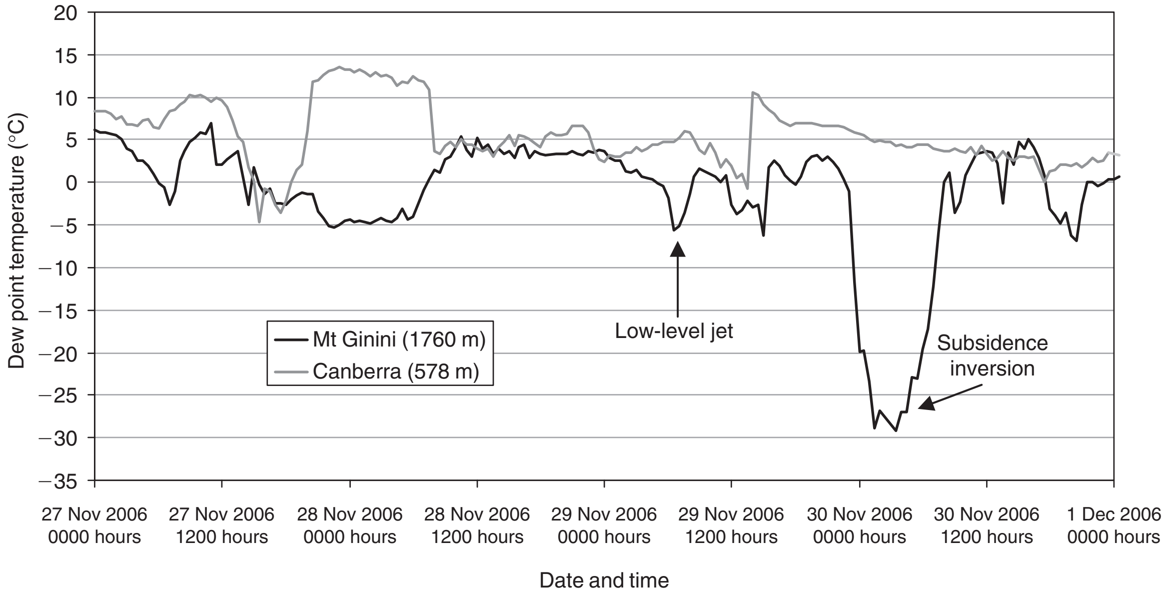

Fig. 1. Dew-point traces from Canberra Airport AWS (automatic weather station) 070014 (578 m ASL, above sea level) and Mt Ginini AWS 070349 (1760 m ASL). The effects of a low-level jet and a subsidence inversion are indicated.

humidity at the low-land site were relatively steady at 8–10°C and 75–80%, while at the elevated site temperature rose from 5 to 12°C and relative humidity dropped from 78 to 4%. This again means that fire danger in elevated regions can actually be greater than what can be expected based on calculations using weather data recorded at low-land sites. It is both interesting and alarming to note that the event on 30 November 2006 occurred only approximately a week before the outbreak of major bushfires in the Australian high country. Subsidence has also been cited as a major factor contributing to adverse fire weather conditions in other significant fires, e.g. the 1955 Medicine Bow fires in southern Wyoming (W. R. Krumm, unpubl. data, 1955).

Diurnal mountain winds

The thermal properties of any particular portion of the Earth's surface vary diurnally. In mountainous terrain, this diurnal variation causes a cycle of upslope and downslope winds. Technically, these winds are referred to as anabatic (upslope) and katabatic (downslope) winds. The thermally driven anabatic and katabatic winds arise as a consequence of thermally induced pressure gradients between the air near the elevated surface and air at a similar altitude over lower lands (McCutchan 1983; Sturman 1987). The various anabatic and katabatic winds form the *mountain wind system*, which follows a diurnal cycle. This system is composed of four separate wind systems: the along-slope, along-valley, cross-valley and mountain–plain wind systems. It is possible that these four wind systems could act in combination (Whiteman 2000):

- The along-slope wind system is driven by horizontal temperature differences between the air near the elevated slope surface and air at similar altitudes over lower lands. At night, when the surface cools, this results in a pressure excess that drives winds downslope. Such downslope winds can also be caused by cold surfaces such as ice or snow. During the daytime, the surface heats and the pressure gradient forces air to move upslope.
- The along-valley wind system is driven by horizontal temperature differences along the valley axis. During the daytime, winds tend to blow up the valley, while at night, the winds blow down the valley.
- In the cross-valley wind system, the winds flow perpendicular to the valley axis and are caused by temperature differences between the sidewalls of the valley. These temperature differences can be caused by differences in insolation of the two sides of the valley arising owing to the relation of the topographic aspect of the valley sidewalls and the position of the sun. These winds blow toward the valley sidewall experiencing the most heating.
- The mountain–plain wind system arises owing to temperature differences between the air over a mountain range and the air over a neighbouring plain. These winds are typically larger in scale. They tend to blow up the mountain slopes during the day and downslope during the night.

It is important to note that the characteristics of diurnal winds can be affected by the ambient meteorology and inherent circulations governed by the terrain (Gudiksen 1989; Gudiksen *et al.* 1992).

Diurnal mountain winds can alter fire behaviour significantly during times when the geostrophic or ambient winds are slight. The diurnal cycle of these winds is characterised by changes in wind speed and direction during the transition periods of dusk and dawn. During these times, crews working to suppress a fire must be aware that the fire's behaviour could change suddenly. These changes might include increases or decreases in the rate of spread and intensity of the fire, depending on which part of the fire perimeter is being considered. At worst, the rear or

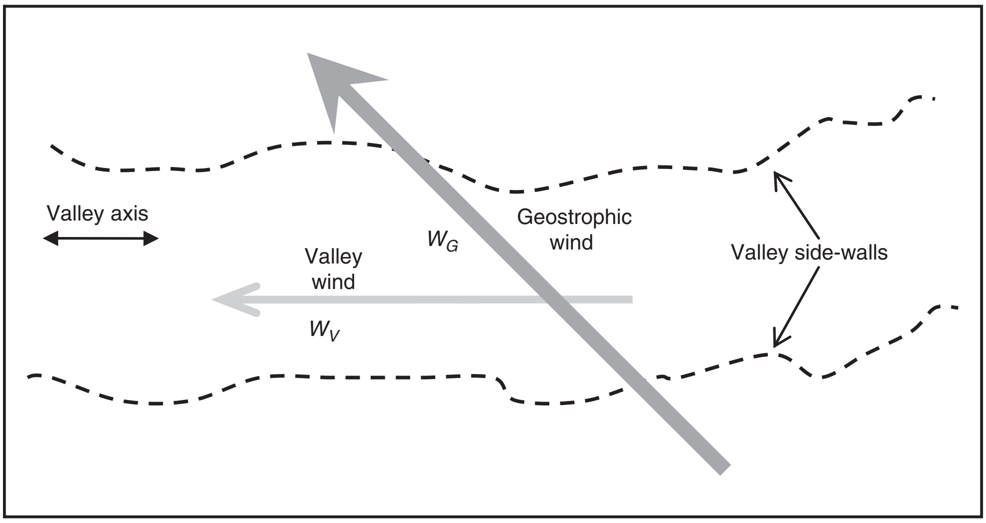

Fig. 2. Forced channelling along a valley. The geostrophic wind vector W_G, assumed at ridge height, blows across a valley at some angle. The surface wind vector within the valley W_V occurs owing to the deflection of the geostrophic winds by the valley sidewalls. The winds are forced along the valley.

flanks of a fire might become the head-fire as a consequence of the onset of upslope or downslope winds. When the ambient winds are strong, however, thermally driven winds are likely to be dominated by them and any channelling of these flows by the terrain.

Dynamic channelling

Channelling of airflows along valleys in mountainous regions can arise as a consequence of the interaction of upper winds with the complex topography encountered in such regions. These interactions have been extensively studied in connection with the problem of predicting the dispersion and impacts of pollutants released from the ground, or from elevated smokestacks, in and around populated mountain valleys (Doran and Whiteman 1992; Whiteman and Doran 1993; Weber and Kaufmann 1995, 1998; Kaufmann and Weber 1996). In this context, it is interesting to note that smoke from bushfires or from prescribed burning activities also are considered as pollutants. In addition to the thermally induced winds already mentioned, three separate mechanisms resulting in the formation of valley winds have been identified (Whiteman and Doran 1993):

- Downward momentum transport
- Forced channelling
- Pressure-driven channelling

Winds within a valley can arise as a consequence of the downward transport of horizontal momentum from above the valley. Downward transport can occur owing to vertical mixing caused by convective turbulence or by gravity waves that arise due to variations in buoyancy (Whiteman and Doran 1993). Conservation of momentum dictates that the direction of valley winds caused by downward momentum transport will be similar to the direction of the upper winds. Valley winds driven by the downward transport of momentum are most likely to occur over terrain of mild relief when atmospheric conditions are conducive to vertical mixing.

Forced channelling of the upper wind results when the sidewalls of the valley cause anisotropic friction, which is much less in the along-valley direction than it is in the across-valley direction. This difference in friction forces the wind to align preferentially along the valley axis, as is illustrated in Fig. 2. The direction and strength of the resulting channelled flow depend on the sign and magnitude of the component of the upper winds relative to the valley axis. Under very specific conditions, the induced valley winds can undergo an immediate change in direction of 180° as the upper-wind direction changes across a line perpendicular to the valley axis (Doran and Whiteman 1992; Whiteman and Doran 1993; Kossmann *et al.* 2001; Kossmann and Sturman 2002, 2003).

Pressure-driven channelling, a mechanism initially proposed by Fiedler (1983), and investigated by Eckman *et al*. (1992), Eckman (1998) and Kossmann *et al*. (2001), is driven by the component of the geostrophic pressure gradient along the valley axis. This is illustrated in Fig. 3. Consequently, valley winds arising from pressure-driven channelling will switch direction by 180° whenever the pressure gradient vector crosses a line perpendicular to the valley axis. Thus, in contrast to forced channelling, valley winds resulting from pressure-driven channelling will switch direction by 180° whenever the upper wind direction crosses a line parallel to the valley axis. Pressure-driven channelling can therefore result in counter-currents (Wippermann and Gross 1981; Wippermann 1984; Gross and Wippermann 1987), which flow in opposition to the main component of the upper winds. An example of the pressure–terrain configuration required for development of a counter-current valley wind is given in panel (*b*) of Fig. 3.

Kossmann *et al*. (2001) note that only a few observations are available to support the concepts of forced and pressure-driven channelling, and so for most topographic configurations, it is still unclear which concept best describes the dynamically channelled

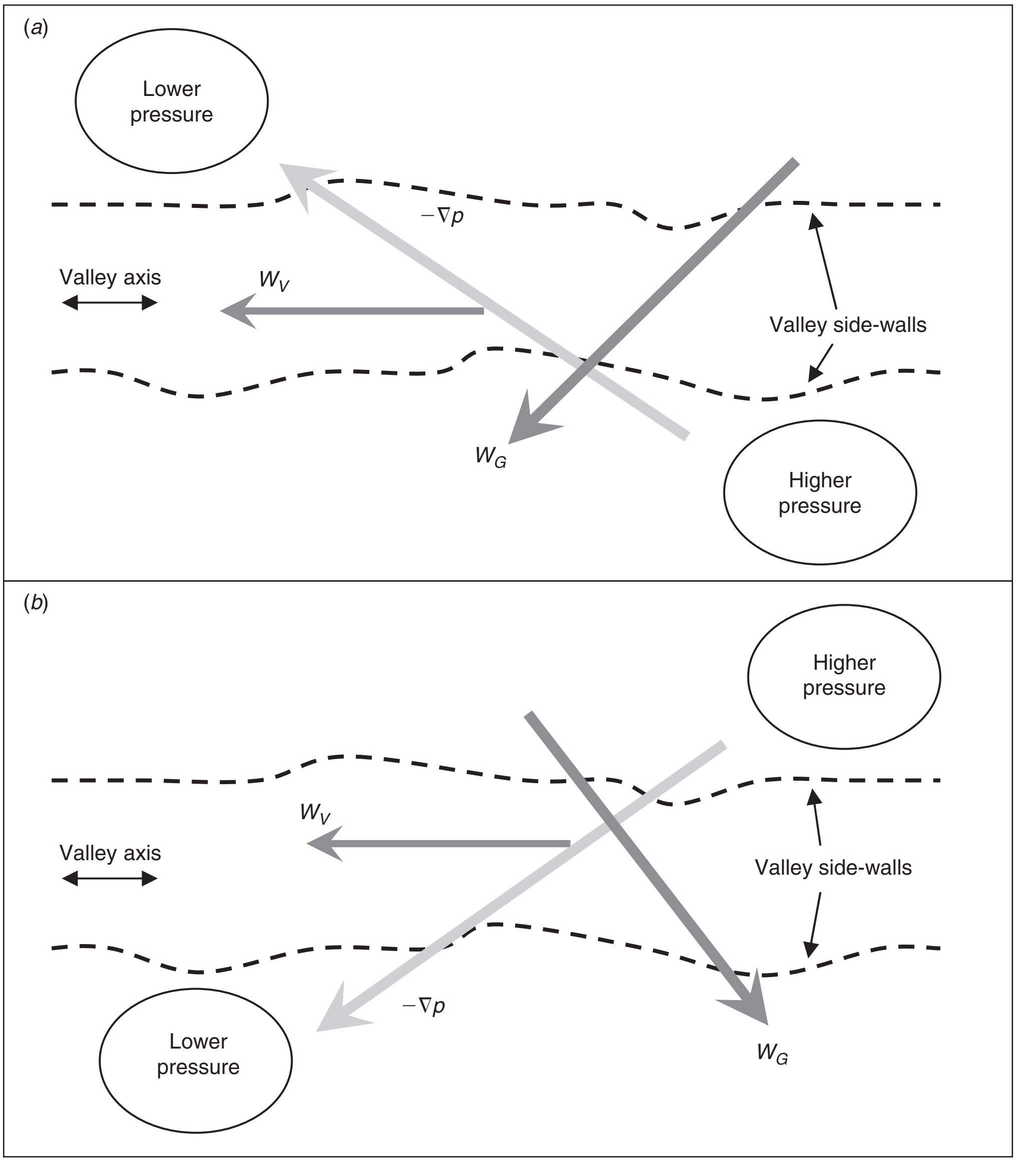

Fig. 3. Pressure-driven channelling for a valley in the southern hemisphere (after Kossmann *et al*. (2001), fig. 1). The geostrophic wind vector is denoted by W_G and is assumed to be at ridge-level height. The surface wind vector within the valley is denoted by W_V. The light grey lines represent the (reverse) pressure gradient $-\nabla p$. In panel (*a*), the valley wind direction produced by pressure-driven channelling coincides with that produced by forced channelling, whereas in panel (*b*), pressure-driven channelling produces a counter-current within the valley. In each case, the valley wind follows the local pressure gradient.

airflows correctly. This is particularly true in the southern hemisphere. Observational studies in the northern hemisphere suggest that pressure-driven channelling is mainly responsible for the modification of large-scale winds in broad and long valleys (Wippermann and Gross 1981; Whiteman and Doran 1993), whereas forced channelling seems to mainly occur in small valleys, mountain passes or saddles (Weber and Kaufmann 1998). A study by Smedman *et al*. (1996), who considered airflows in an intermediate valley, suggests that forced and pressure-driven channelling can even occur in combination, enhancing or counteracting each other depending on the direction of the upper winds. Moreover, Croxford (1997) notes that the presence of thermally induced valley winds further complicates the task of diagnosing which type of channelling process is at play. Further work by Kossmann and Sturman (2002, 2003) has extended the study of channelling effects to curved valleys, which are commonly present in real landscapes.

In the case of strong geostrophic winds, particularly those with strong vertical shear, airflows resembling dynamic channelling can also occur along lee slopes in mountainous terrain, even without the presence of a definite valley. In these instances, the winds are forced up and over ridge-lines, often resulting in

Fig. 4. Spot fires in complex terrain reveal the high variability in the surface wind pattern. In the right of the photograph, smoke is being blown up a slope against the wind in an eddy-like structure. In the middle and left of the photograph, smoke is moving to the left along a small gully. (Photograph courtesy of Stephen Wilkes.)

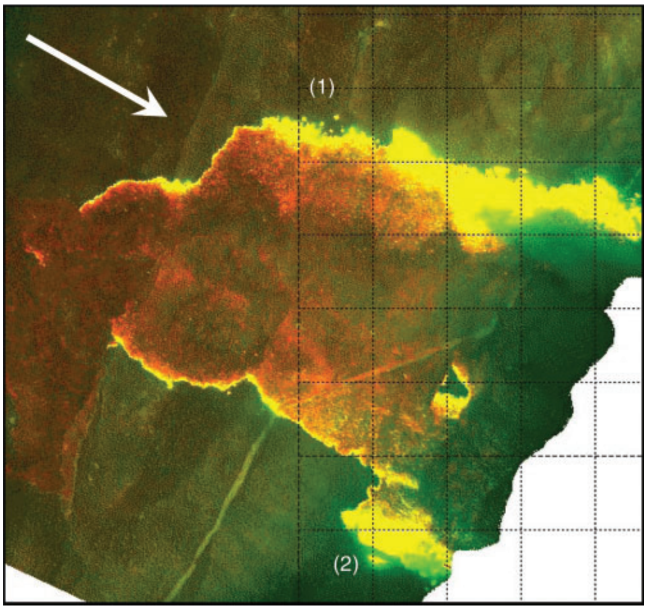

Fig. 5. Multispectral linescan imagery of the Broken Cart fire, south-west of Canberra, 18 January 2003. The arrow indicates the WNW direction of the bulk winds. Spot fires can be seen forming laterally to the north of the northern flank (1) and to the south of the southern flank (2) in association with rapid expansion of the flanks. Both of these regions are in the lee of steep ridges.

flow separations or separation eddies in the lee of the ridge where the flow overturns on itself. These horizontal-axis eddies can extend along the entire length of the ridge (Whiteman 2000). Such features are a consequence of the partial decoupling of the geostrophic winds and the near-surface winds in the lee of the ridge-line (Lee *et al.* 1981; Byron-Scott 1990; Papadopoulos *et al.* 1992). The partial decoupling of the near-surface and upper winds in the lee of ridge-lines also permits air to flow horizontally in a direction dictated by local pressure gradients or thermal influences, essentially independent of the geostrophic wind direction. The net effect is for the air to follow a spiral or corkscrew pattern about a horizontal axis aligned approximately parallel to the ridge-line. Such a process is typically referred to as a lee-slope rotor or lee-slope eddy (Byron-Scott 1990), but given the possibility of lateral flow within these structures, the process could be termed lee-slope channelling (McRae 2004). Fig. 4 gives an example of highly variable wind directions over complex terrain; a lee-slope eddy is evident in the right of the figure.

The various forms of dynamic channelling all have the potential to significantly increase the risk posed by a bushfire in mountainous terrain. The onset of a channelling event, combined with low fuel moisture contents, can lead to a rapid escalation in the overall size of a fire and can seriously compromise the safety of crews working to suppress a fire. For example, if the flank of a fire enters a region prone to dynamic channelling, given the necessary environment and stability for it to occur, this flank may become a fast-moving head-fire spreading along a valley in a direction that is transverse to the main head-fire direction of spread. Any crews working to suppress the flank in such a location would find themselves in serious trouble. Moreover, when fuel moisture contents are low, the turbulent nature of channelled flows can result in the mass generation of embers. This can be particularly troublesome when strong ambient winds produce intense separation eddies (Byron-Scott 1990). The eddy motion can loft burning embers into the air where they can be 'peeled off' by the upper winds and deposited large distances downwind. The net result is rapid fire spread in two dimensions: rapid flank expansion and lateral spotting along channelling-prone valleys and lee slopes as well as rapid downwind expansion due to spot-fire ignitions (McRae 2004). This appears to be what is taking place in the multispectral line scan image seen in Fig. 5. The resulting deep flaming zones can then contribute to violent pyro-convection and the formation of pyro-cumulonimbus, which can lead to extremely dangerous and unpredictable fire behaviour and growth and can affect the upper atmosphere on hemispheric scales (Fromm *et al.* 2006). To further complicate matters, the effects of the fire itself on the channelling mechanisms are not well understood. This being the case, the behaviour of a fire in a region prone to dynamic channelling is likely to be highly unpredictable. The ensuing uncertainty associated with such situations complicates the treatment of bushfire risk considerably. Dynamic channelling of airflows by topography contributed to unexpected and extreme fire behaviour during the 1994 South Canyon fire on Storm King Mountain in western Colorado (Butler *et al.* 1998, 2003) and the 2003 Canberra firestorm that originated to the west of the Australian Capital Territory (Webb *et al.* 2004; McRae *et al.* 2006). Both of these fires resulted in considerable loss of life and property.

The projected effects of climate change are likely to result in extended periods of drought and warmer temperatures that will act to move low-land fire regimes up into mountainous landscapes. Under such a scenario, the effects of dynamic channelling on fire are likely to become more frequent and increasingly apparent. Indeed, since 2002 in Australia, there has been an apparent increase in the incidence of stratospheric injection of particulates, induced by violent pyro-convection, though research is continuing to discern whether this is due to climate change or simply better detection (McRae *et al.* 2008).

Foehn winds

Foehn winds (also written föhn) are a common meteorological feature found in the lee of many mountainous regions (Barry 1992; Rasilla 1998). When synoptic conditions are favourable, the effects of complex topography can alter the mechanical and thermodynamic properties of airflows, resulting in these distinctive flows down the lee slopes of mountain ranges. In general terms, according to Brinkmann (1971), a foehn wind is a strong, warm, dry wind descending in the lee of mountain ranges. The generic term originates in Europe in connection with the warm, dry winds experienced on the northern slopes of the Alps, though it is interesting to note that the word 'foehn' derives from the Greek word for fire (Miller and Schlegel 2006*a*). Foehn winds are also known by various local names throughout the world. Examples include the Chinook winds of the north-west United States, the Santa Ana winds of southern California, the diablo winds of northern California, the north foehn and south foehn of the Alps (Drobinski *et al.* 2007), the oroshi of Japan, the Canterbury north-wester in New Zealand and the Suradas in northern Spain (Brinkmann 1971; Rasilla 1998).

Brinkmann (1974) reports that Chinook windstorms at Boulder, Colorado, have been accompanied by temperature rises of up to 15–20°C, while Ryan (1991) recounts a Santa Ana occurrence in 1859 where temperatures on the Californian coast rose from 29°C in the late morning to a record setting 56°C by 1400 hours! Weather instruments during that period were unreliable, however, and the actual temperature is believed to have been closer to 43°C. Wind speeds associated with foehn occurrences can exceed 100 km h^{-1} and have even been recorded as high as 160 km h^{-1} (Brinkmann 1974; Miller and Schlegel 2006*a*). It is not uncommon for relative humidity to suddenly drop to single digits during foehn conditions.

The classical mechanism attributed to foehn winds involves the forced ascent of moist air due to a mountain range. As the air is forced to rise on the windward slopes, moisture is condensed and removed from the air through precipitation. The latent heat release accompanying the condensation warms the ascending air. On the lee slopes, the drier, descending air warms further owing to adiabatic compression. As the saturated adiabatic lapse rate (~5–6°C km^{-1}) is lower than the dry adiabatic lapse rate (~10°C km^{-1}), the process results in higher potential temperatures on the lee side of mountain ranges (Hann 1866, 1867; Barry 1992). This mechanism is often referred to as the thermodynamic foehn process. Alternatively, as noted by Hann (1885), foehn winds may occur without accompanying precipitation. This can occur, for example, when a strong pressure gradient causes dry air from an elevated mountain plateau to flow into lower lands where the air is warmer owing to adiabatic heating during its descent. The Santa Ana winds provide an example of this type of foehn mechanism. Foehn winds without associated rainfall can also occur when lower-level air is blocked by a mountain barrier, allowing the drier air above the blocked layer to replace it in the lee of the mountains. This effect, coupled with adiabatic compression of the descending air, will result in relatively warmer temperatures and lower atmospheric moisture on the lee side of the mountains. Such a process could be described as a 'blocking foehn'. Instances of blocking foehns have been studied in the United States by Cook and Topil (1952) and Brinkmann (1973, 1974), in the British Isles by Lockwood (1962) and in Europe by Seibert (1990) and Ustrnul (1992). Blocking of airflows can persist until changes in the large-scale pressure gradient forces the air from one side of the mountain to move over the crest and down the other side (Smith 1979).

Specifically defining a foehn wind is a problem of some importance because it has bearing on the calculated frequency of foehn conditions within a particular region. Throughout the literature, a number of criteria have been used to distinguish 'foehn conditions' (Ives 1950; Schuetz and Steinhauser 1955; Lockwood 1962; Longley 1967; Brinkmann 1971; Yoshino 1975; Barry 1992). Commonly though, three criteria are used at stations in the lee of mountains, all of which must be satisfied for foehn occurrence (Osmond 1941; Frey 1957):

- surface winds blowing from the direction of the mountains;
- an abrupt temperature rise; and
- a simultaneous drop in relative humidity.

However, as a temperature rise is often accompanied by a drop in relative humidity, the last two criteria are hard to separate. It is therefore perhaps better to alter the last condition above to be 'a simultaneous drop in dew-point temperature' or 'specific humidity'.

Synoptic criteria have also been used to distinguish foehn conditions. In a number of instances, foehn conditions develop only when a steep pressure gradient exists across a mountain range, which arises owing to a high-pressure ridge on the windward side and a low-pressure trough in the lee (Beer 1974; Hoinka 1985; McGowan and Sturman 1996). For example, conditions leading to the Santa Ana are typified by the presence of a high-pressure system over the Great Basin, which reverses the normal pressure gradient that causes winds to blow off the ocean (Whiteman 2000). Such conditions are distinctive, easily forecast and often display a strong seasonality; for example, the Santa Ana occurs mostly in autumn. Brinkmann (1970), studying the Chinook, required that the upper air flow should be approximately perpendicular to the main orientation of the mountains and that the surface pressure field should display a ridging over the mountains (the 'foehn nose'). It should be pointed out, however, that the use of synoptic criteria can be confounded by the influence of other meteorological phenomena that can occur in a particular region (Brinkmann 1971).

The theory of lee mountain waves affords another criterion for the occurrence of foehn conditions. Scorer and Klieforth (1959) assert that the upstream blocking of airflows by mountain barriers is dependent on a stability factor known as Scorer's parameter (Scorer 1949) defined as (Beer 1974; Barry 1992):

$$l^2(z) = \frac{N^2}{U^2} - \frac{1}{U}\frac{\partial^2 U}{\partial z^2}$$

where $N = N(z)$ is the frequency at which an air parcel will oscillate when displaced vertically within a statically stable environment (Brunt–Väisälä frequency), and $U = U(z)$ is the vertical profile of the horizontal wind speed. Studies by Lockwood (1962) and Beran (1967) both indicated that Scorer's parameter was moderately useful for predicting foehn occurrence.

Of greater significance to the question of whether a flow will be blocked by a mountain barrier is the Froude number (Smolarkiewicz and Rotunno 1989):

$$Fr = \frac{V}{NL}$$

where V is the wind speed component across the mountain, L is the height (or sometimes width) of the mountain and N is the Brunt–Väisälä frequency of the upstream environment. For Froude numbers much less than unity, the flow will be blocked, whereas for Froude numbers much greater than unity, air will flow over the mountains.

Foehn conditions are often accompanied by distinctive cloud formations. While these cloud formations often bear their own local names (e.g. the 'Chinook arch'), I will refer to them in generic terms as the foehn wall and foehn arch. The foehn wall is an orographic cloud band that forms along the ridge-tops of mountain ranges, while the foehn arch is an extensive layer of altostratus cloud that forms downwind of the mountains in the rising portion of a standing lee mountain wave. A region of clear air called the foehn gap is often observed between the wall and arch clouds.

The characterising features of foehn winds all act to exacerbate fire danger. The high wind speeds, low atmospheric moisture and elevated temperatures associated with foehn conditions can significantly increase the rate of spread and intensity of a fire through their direct effect as well as enhancing ignition potential owing to the drying effect they have on fuels. When foehn winds occur after extended periods of drought, fire behaviour can be extreme (Gorski and Farnsworth 2000). This was the case, for example, in Southern California where antecedent climate and moderate Santa Ana foehn conditions, coupled with long-term accumulation of fuels, led to extreme wildfires that burned over 300 000 ha in October 2003 (Westerling *et al.* 2004). Further analysis revealed that the majority of large fires during autumn and winter occurred during Santa Ana events (Westerling *et al.* 2004). According to Miller and Schlegel (2006*a*, 2006*b*), foehn-like winds in California have contributed to significant loss of life and property, particularly in regions where development has encroached on wilderness interfaces. Examples cited include the Oakland fire of 1991, which reignited and spread by the Diablo foehn, while in 2003, the Cedar fire, the biggest in Californian history, increased in size by a factor of 60 in just 4 h under the influence of Santa Ana winds. More generally, Keeley (2004) found that the autumn foehn (Santa Ana) in southern California was a key driver in determining area burned, overriding most other climate signals.

The potential for increased fire danger during foehn conditions is also appreciated in European countries that are subject to foehn conditions (Conedera *et al.* 1998; Gómez-Tejedor *et al.* 1999). Carrega (1991) discusses occurrences of catastrophic fires near the French–Italian border driven by westerly foehn winds, while Conedera *et al*. (1996) report that in southern Switzerland, the main time for forest fires is during north foehn occurrences. Conedera *et al.* (1998) report that all fires that burned more than 50 ha per day occurred in conjunction with the north foehn and that during north foehn conditions, there is normally more than one forest fire per day reported. Foehn winds are also routinely mentioned in New Zealand fire weather assessments owing to the effect that they have on humidity levels in the lee of the main mountain ranges (Salinger *et al.* 2000; Salinger and Porteous 2002; Gosai and Salinger 2003, 2004, 2005), and have been connected with elevated forest fire risk in Japan (Kondo and Kuwagata 1992; Ninomiya *et al.* 1985) and certain parts of Korea (Lim 2002), despite the milder topography encountered there.

The effect of foehn conditions on bushfire risk in south-eastern Australia does not seem to have received the same attention as it has in other fire-prone parts of the world. The only references specific to foehn winds in Australia appear to be very brief mentions (e.g. the odd sentence in three or four of the Bureau of Meteorology's internal forecasting notes) that are based on experience rather than detailed scientific studies. These note the possibility of higher temperatures, or reduced fog occurrence, in the lee of ranges in some instances (P. Riley, pers. comm., 2006). An exception is the study by Marsh (1987) that notes the possibility of a large-scale 'foehn-type' downslope flow contributing to the extreme fire weather on 6 November 1982 in south-east Tasmania. Discussions that the author has had with several fire managers revealed that conditions that can be described as 'foehn-like' do indeed occur in south-eastern Australia. Fig. 6 depicts one such occurrence during 2006. The foehn wall can be seen over the mountains in the left of the image while the arch can be seen on the right. The fact that these types of events tend to occur from autumn to spring, when landowners traditionally perform hazard-reduction burns, has important ramifications for bushfire risk management in the lee of the major mountain ranges in south-eastern Australia. In fact, the image in Fig. 6 contains an active fire perimeter within the foehn gap.

Climate change is also likely to have an impact on the interaction between foehn winds and wildfire. Miller and Schlegel (2006*a*) indicate that the occurrence of the Santa Ana in autumn is likely to increase under some climate-change scenarios. Coupled with warmer temperatures and increased frequency and severity of drought, such findings have serious consequences for the wildfire risk problem in California. Similarly in Australia, Hennessy *et al*. (2005) indicate that climate change will increase the fire-weather risk in spring, summer and autumn and will increasingly shift periods suitable for prescribed burning toward winter, thereby coinciding with the times of year when foehn-like occurrences are most commonly observed.

Research into foehn phenomena is still an active area of mountain meteorological research. This is particularly the case in Europe, where the Mesoscale Alpine Program (MAP) has been under way since the 1990s. MAP includes a subproject that focusses on the foehn in the Rhine valley (Tschannett and Furger 2006). Drobinski *et al*. (2007) provide an interesting history of studies concerning the Alpine foehn in Europe and a review of some of the findings of the Mesoscale Alpine Program (MAP). In addition, Drechsel and Mayr (2008) and Mayr and Armi (2008) discuss some of the more recent findings on Alpine foehn dynamics and diagnostics.

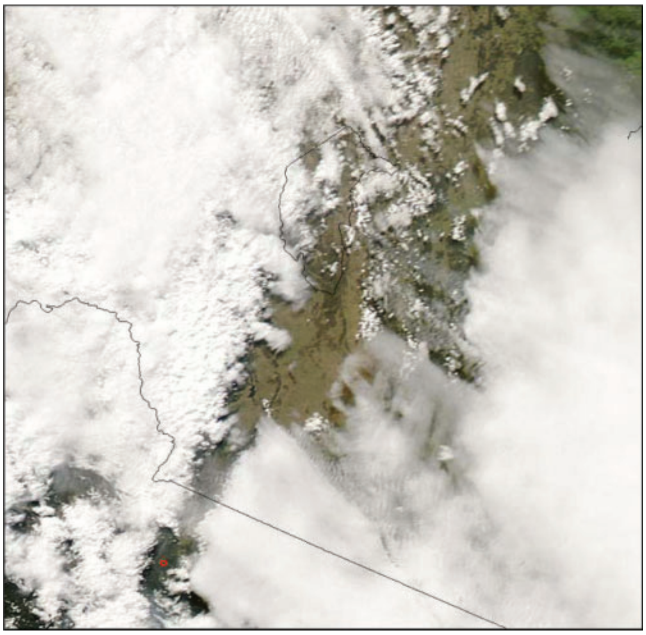

Fig. 6. MODIS (Moderate Resolution Imaging Spectroradiometer) image from August 2006 capturing a foehn event over south-eastern Australia. The foehn wall cloud can be seen in the left of the image, obscuring the mountains underneath, while the arch cloud is seen in the right of the image. There is a clearly visible foehn gap between the two cloud masses. The red area in the bottom left of the image is an active fire.

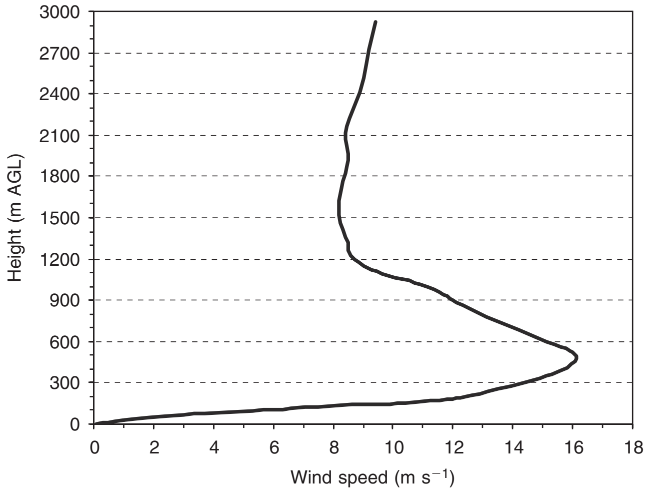

Fig. 7. A typical jet wind speed profile. In this case, the jet would qualify as a low-level jet. AGL, above ground level.

Low-level jets

A jet is defined as a narrow current of fast-moving air. A jet is distinguished by a *jet wind-speed profile*, which is a vertical wind-speed profile characterised by a relatively narrow current of high winds with slower-moving air above and below. A large wind shear occurs above and below the jet axis. Fig. 7 is a typical example of a jet-wind speed profile. Jets exist at different levels of the troposphere and vary in strength, width and length. Familiar examples include the subtropical jet stream, which is found at some longitudes, between 20 and 30° latitude, and the polar frontal jet (Davies 2000). Jet phenomena are also observed much lower in the atmosphere, sometimes as low as 100 m above the ground (Banta *et al.* 2002). These types of jet phenomena are referred to as low-level jets.

The prevalence of low-level jets is now widely accepted (Wexler 1961; Browning and Pardoe 1973; Sládkovič and Kanter 1977; Brook 1985). A southerly or south-westerly low-level jet frequently occurs during night-time and early morning over the Great Plains of the United States (Bonner 1968; Whiteman 2000), while a jet at a height of a few hundred metres, which reaches its strongest intensity between 0300 and 0500 hours, is a frequent feature of the low-level wind profile at Daly Waters in the Northern Territory of Australia (Allen 1980, 1981; Brook 1985; Garratt 1985). Such night-time jets occur throughout the world (Gerhardt 1962; Thorpe and Guymer 1977; Hsu 1979; Dickison and Neumann 1982; Drake 1985) and are termed nocturnal low-level jets. The most commonly cited mechanism for the formation of a nocturnal low-level jet involves a decoupling of the flow just above the surface, as a result of cooling near the ground after sunset. This decoupling from the frictional forces near the ground produces a vertically narrow layer of fast-moving air that often exhibits a maximum in the vertical wind-speed profile within a few hundred metres of the ground (Blackadar 1957; Thorpe and Guymer 1977; Singh *et al.* 1993; Banta *et al.* 2002). Studies suggest that the low-level jet formed through this mechanism would produce a wind-speed maximum ~8 h after the effects of turbulent mixing cease in the early evening (Hoxit 1975; Stensrud 1996).

Nocturnal low-level jets can also form through other mechanisms. For example, they can result from synoptic pressure gradients or baroclinicity produced in inclined boundary layers over sloping terrain. In regions where there is a significant change in surface characteristics, the horizontal differences in sensible and latent heat fluxes produce strong baroclinicity with the planetary boundary layer. This can produce low-level jets through strong geostrophic forcing, where the low-level jets are oriented parallel to the low-level horizontal temperature gradient (Bonner and Paegle 1970; Stensrud 1996). Bleeker and Andre (1951) proposed a similar mechanism based on horizontal differences caused by variations in elevation. This mechanism is the same as that described in the along-valley wind system section above and can produce jet-like vertical wind profiles during the night time. Terrain can also produce jet-like winds when airflow is accelerated through narrow passes (Pamperin and Stilke 1985; Macklin *et al.* 1990; Stensrud 1996). Paegle *et al*. (1984) show that nocturnal low-level barrier jets can also be produced through the effects of terrain blocking owing to stable stratification at night.

While jet-like phenomena lead to increased wind speeds regardless of when they occur, nocturnal low-level jets can also affect fire weather through distinctive fluctuations in temperature and atmospheric moisture (Izumi and Barad 1963; Izumi 1964; Kaimal and Izumi 1965; Izumi and Brown 1966). Izumi (1964) demonstrates that upper-level temperature increases in the hours before sunrise are commonly associated with low-level jet occurrence. These upper-level temperature increases, which tend to occur at the same time as intermediate levels are undergoing cooling, are probably due to subsidence associated with the low-level jet or with intermittent mixing due to generation of Kelvin–Helmholtz shear waves. Izumi and Brown (1966) report significant changes in temperature and atmospheric moisture at upper levels during nocturnal low-level jet occurrence. The onset of the nocturnal low-level jet is accompanied by a period of abrupt warming and drying of the atmosphere at upper levels, followed by a long period of elevated temperature and wind speed, and decreased atmospheric moisture. Nocturnal low-level jets also play an important role in the transport of atmospheric quantities during night-time. Banta *et al*. (1998) showed that nocturnal low-level jets significantly affect the movement of pollutants through the atmosphere. The wind shear generated by nocturnal low-level jets is also likely to play a part in controlling fluxes between the surface and upper atmosphere (Banta *et al.* 2002).

It is important to note that although in many cases low-level jet phenomena are not, strictly speaking, mountain meteorological phenomena, elevated terrain downwind of the region of jet formation is more susceptible to their effects. Indeed, jet phenomena occurring in the lower parts of the troposphere are more likely to intersect elevated ground in mountainous terrain than low-lying areas. The predawn event on 29 November 2006, seen in Fig. 1, is due to a low-level jet intersecting elevated terrain.

The characteristically high wind speeds of low-level jets act to increase the intensity of a fire that is already burning. The abrupt atmospheric warming and drying associated with nocturnal low-level jets compounds this effect in addition to increasing ignition likelihood. Indeed, Byram (1954) pointed out the link between intensification of wildfires and low-level wind maxima. The contribution of low-level wind jets to the development of large fires is also discussed in Brotak and Reifsnyder (1977) and is briefly mentioned in Potter (1996). The effect of a low-level jet on fire behaviour is illustrated by the 1988 Canyon Creek fire in the northern Rocky Mountains. The Canyon Creek fire began on 25 June as a small fire that showed little activity. Things changed, however, on 6 September when a low-level jet drove the Canyon Creek fire into the largest single-day fire growth ever recorded in the United States (Mann 2005). Mills (2005) also notes a prefrontal low-level jet associated with extreme fire weather during the 2003 Alpine fires in south-eastern Australia. The fact that the most severe changes in wind speed, temperature and atmospheric moisture occur at upper levels means that low-level jet-like phenomena can lead to significant differences in the weather variables recorded at elevated and low-land sites. This can be particularly troublesome at night when fire weather conditions are usually expected to be milder. The author is aware of several anecdotal reports of night-time containment burns in high-country settings that have suddenly become uncontrollable, much to the surprise of the fire crews that were present.

It should also be pointed out that a number of alternative mechanisms that account for jet-like profiles have been proposed. For example, synoptic cold fronts, sea-breeze fronts, post- and pre-cold-frontal jets and gust fronts associated with thunderstorms can exhibit a low-level jet wind speed profile.

Mountain waves and other meteorological phenomena

Deflection or perturbation of airflows by mountainous terrain can result in a number of different phenomena. These include mountain wind waves, induced instability and thunderstorms. In a stable atmosphere, air flowing over a mountain barrier can produce mountain wind waves. These are a form of gravity, or buoyancy, wave that results from the effects of gravity on variations in air density. As a parcel of air rises over a mountain, it cools adiabatically. If the atmosphere is stably stratified, the parcel will become denser than the surrounding air, and thus begin to sink in the lee of the mountains. This descending parcel can often overshoot into regions where it is less dense than the surrounding air, which causes it to ascend again. The net result is an oscillation of the airflow about some equilibrium level. Two categories of mountain waves are often cited: *vertically propagating* or *trapped lee* waves. Vertically propagating mountain waves can have horizontal wavelengths of many tens of kilometres and extend into the upper atmosphere (Gill 1982; Whiteman 2000). In fact, foehn conditions are often accompanied by a vertically propagating mountain wave. Trapped lee waves typically have horizontal wavelengths of the order of 5–35 km and occur within a stable layer of air with moderate wind speeds.

In general, the characteristics of lee waves will depend on a number of factors, including the vertical profile of the wind, the geometry of the mountain barrier and the stability of the atmosphere (Barry 1992; Whiteman 2000). Of particular importance in describing these factors are the Froude number and the Scorer parameter. I have already mentioned how the Froude number helps to determine if the atmospheric flow will be blocked by a mountain barrier, and hence if mountain waves will be generated. The Scorer parameter provides information on whether the wave will be vertically propagating or trapped, and what wavelengths will be trapped. When the Scorer parameter is near constant with height, conditions are conducive for the formation of vertically propagating mountain waves. However, if the vertical profile of the Scorer parameter displays a strong decrease with height, trapped lee waves are expected. When sufficient moisture is present, lee waves can produce distinctive cloud patterns. An example of the distinctive cloud formation associated with trapped lee waves can be seen in Fig. 8. Other types of wave clouds include cap clouds, lenticularis and rotor clouds.

In particular, rotor clouds develop when severe downslope winds decelerate rapidly in the lee of a mountain range (typically downwind of a steep slope) and reverse in direction back towards the mountains (Doyle and Durran 2004). Rotors are notorious for producing strong, highly localised and transient surface wind fields.

Changes in the latitude of the passage of low-pressure cells (e.g. across the Great Australian Bight) due to the effects of climate change are likely to affect the frequency and intensity of mountain wind waves and associated phenomena like the foehn effect.

Under certain stability, flow and topographic conditions, large-scale instability can cause the mountain wave to undergo an abrupt change into what is termed a hydraulic flow. Hydraulic flow is characterised by a region of wave-breaking aloft, a sudden jump in the streamline patterns, high wind speeds on the leeward slopes, a cavity at the bottom of the slope and severe turbulence immediately beyond the cavity (Lilly 1978; Whiteman 2000). Klemp and Lilly (1975) discuss another mechanism for downslope windstorms that involves the partial reflection or breaking of vertically propagating mountain waves due to the presence of an inversion just above the mountain top. In

Fig. 8. MODIS (Moderate Resolution Imaging Spectroradiometer) image from 1 September 2006 showing trapped lee mountain waves over the Australian Capital Territory. In this case, the waves are being generated by a high ridge that runs north–south just to the left of the middle of the image.

this mechanism, the vertical propagation of energy is restricted, allowing the flow near the surface of the mountain to accelerate downslope. Regions where lee waves are breaking would tend to more neutrally stable conditions and could provide a mechanism for the transport of dry upper air to lower altitudes. The processes that lead to the exchange of this air with the surface require further investigation.

Mountain wind waves, and in particular lee waves, pose some interesting questions for fire management in complex terrain. Lee waves form under stable conditions, which are usually considered benign in the context of fire behaviour and bushfire risk. However, conditions will be unstable in the lee trough and elevated terrain in the lee of a main ridge-line can experience strong downburst winds if it happens to be in a region that coincides with the descending part of the lee wave. Moreover, if a hydraulic flow transition occurs, winds can dramatically increase in strength, and stability can significantly decrease in the upper atmosphere. Furthermore, if a fire is present, the lower density of the air above the fire can increase the chances of lee-wave breaking, resulting in less stable conditions in the vicinity of the convection column of the fire. Reduced stability can exacerbate fire behaviour through a number of processes. When the atmosphere is unstable, the lower resistance to vertical motion allows convection columns to achieve greater heights, thereby producing stronger indrafts, convective updrafts and downbursts. This in turn can increase the downward transfer of momentum from upper winds, thus producing stronger, gustier winds on the surface that can directly influence a fire. When combined with low atmospheric moisture, atmospheric instability can produce very dangerous fire activity (Haines 1988; Werth and Ochoa 1993; Werth and Werth 1998; McCaw *et al.* 2007). Unstable conditions are also more likely to result in the exchange of dry upper air with the surface. The blow-up fires of 18 January 2003 in Canberra and 11 January 2005 in the Eyre Peninsula both coincided with the passage of dry upper air over the particular regions, as detected in water vapour imagery (Mills 2005, 2006).

In an unstable atmosphere, terrain-driven mechanisms can also lead to the development of convective cells and thunderstorms. Thunderstorms and convection are common features over many mountain ranges throughout the world. Mountainous terrain can cause orographic lifting of airflows either by vertically deflecting horizontal flows or by anabatic flows induced by daytime heating, which result in updrafts in the vicinity of mountain peaks. These can result in the formation of convective cells and thunderstorms. Channelling of airflow by ascending valleys and lee-side convergence of horizontally displaced airflows can also generate thunderstorms and induce further instability.

The development of convective cells and thunderstorms (particularly dry thunderstorms) over mountainous regions has important implications for bushfire risk management. Increased convective activity over mountainous terrain can assist in the vertical development of convection columns arising from fires burning in such regions, thereby increasing the likelihood of plume-dominated fire behaviour. Lightning produced by thunderstorms over mountainous terrain can start multiple fires in a short space of time in inaccessible areas, making initial attack difficult and expensive. Fires ignited like this have greater potential to develop and merge into large conflagrations. For example, the large fires that impacted Canberra on 18 January 2003 originated as a number of smaller fires ignited by a dry lightning storm on 8 January (Nairn 2003; McRae 2004; McRae *et al.* 2006).

Guidelines for fire operations in mountainous landscapes

In this section, I consider aspects of fire operations that can be affected by the various processes discussed in the preceding section. Particular focus will be placed on situations that could possibly compromise the safety of fire crews and suppression tactics during major fire events. A number of operational guidelines designed to avoid or reduce the negative impacts of specific processes will be outlined.

Topographically induced variations in fire weather

The variation of insolation across mountainous landscapes can result in fire weather patterns than display significant spatiotemporal variability. Currently in Australia, solar radiation is calculated at a national scale, based on irradiance data collected by satellite and supplemented by a coarse network of (less than 100) pyranometers. Results are typically depicted on a 6-km grid, which is far too coarse to discern any local effects produced by the topography. To improve understanding of finer-scale insolation patterns, studies using portable weather stations capable of measuring solar radiation would be required. Such studies could be supplemented by fuel moisture surveys in mountainous terrain. Maps derived from these studies could then be used to assist in planning fire operations.

The interaction of atmospheric inversions with complex terrain also has an effect on fire weather patterns. For example, the existence of a thermal belt is an important consideration when planning and conducting overnight operations in mountainous valleys. Relying solely on observations taken on ridge-tops or in valleys can lead to underestimation of likely fire behaviour. When assessing the timing for implementation of assigned tactics, it is important to also obtain weather data from convex mid-slopes, particularly on clear nights with slight winds. However, doing so may be difficult and dangerous in itself, depending on the status of the fire. Observers should have clear escape routes and be able to leave rapidly and safely. If a thermal belt is known to exist, then fuel moisture, likely fire behaviour and spotting potential should be estimated at both extremes. Cold-air pooling, associated with a thermal belt, also has the potential to impact on air operations through increased occurrence of fog in low-lying areas.

Dew-point anomalies

High-country sites are prone to a number of processes that can result in anomalously low dew-point temperatures, e.g. low-level jets, foehn winds, subsidence inversions. Consequently, when a fire is burning in or around Alpine areas, it is important to maintain a proper dialogue between fire weather forecasters, fire behaviour analysts and incident controllers. Although there is an expectation that fire weather forecasters will be monitoring water vapour imagery for dry-air regions of various forms, there is an obligation on incident controllers to seek such information, or at least notify forecasters of on-going fire activity, even if they are not of sufficient intensity to require special fire weather forecasts. Sustained depression of dew-point temperatures can also dry out fuels, thereby increasing the likelihood of fire ignition.

Good forecasting and observation of dew-point temperatures is essential in high-country landscapes, particularly at night-time. Many night-time events do not intensify until after midnight. An early start to a prescribed burn that may take several hours, or indeed other longer-term operations, should therefore be carefully planned and discussed with fire weather forecasters. It is important to assess the likelihood of occurrence of events that can cause depressed dew-point temperatures.

Dynamic channelling

The effects of dynamic channelling can cause a fire to propagate with such a speed and intensity that it would be difficult to react in time to achieve crew safety or protect life and property. Crew safety in these circumstances requires prior identification of channelling-prone landforms and clear instructions on how to watch for and react to rapid changes in fire behaviour to crews operating in remote rugged areas. Steep lee slopes and incised valleys aligned almost perpendicularly with the geostrophic winds should be viewed with particular caution. The deep flaming that can be caused by a channelling-driven fire event can also trigger the development of pyro-cumulonimbus, provided the stability properties of the atmosphere are conducive to their formation.

It should be noted that operational models that employ fluid mechanics and other methods to estimate terrain-forced winds (Ryan 1969, 1977, 1983; Forthofer *et al.* 2003; Forthofer 2007) have the potential to identify forced channelling but would not generally be able to identify pressure-driven channelling. Operational models based on mass consistency (Forthofer 2007) would also not be able to identify lee-slope eddies.

Foehn winds

Under foehn conditions, weather can vary greatly over short distances and short periods of time. For example, the Lone Pine fire in the southern ACT was crowning at midnight in May with rain reported 10 km to the west (R. McRae, pers. comm.). The seasonal character of foehn winds in Australia means that they often coincide with the prescribed burning season. As such, foehn winds can result in the loss of control of prescribed burns and have significant potential to reignite fires that have not been sufficiently extinguished. The Santa Ana also displays a strong seasonality, occurring in autumn, often after periods of extended drought over summer.

Strong cross-mountain flows should be treated with caution, particularly when windward conditions are conducive to blocking of low-level air flows. In autumn and winter in Australia, cross-mountain flows are typically associated with the passage of low-pressure cells across the Australian Bight. The presence of foehn clouds in visual satellite or water vapour imagery can also indicate the occurrence of foehn conditions. In Australia, the presence of a foehn arch is particularly telling. Discussions with fire weather forecasters should address foehn events. The longer a fire takes to extinguish, the greater the chance of encountering an event.

Low-level jets

Low-level jets can be difficult to detect but are potentially forecastable. Further research will improve the situation and will also provide more climatological information about these events. Good field observations are an important part of identifying potential problems. Low-level jets can significantly increase the probability of fire escalation. It is therefore important for incident controllers to discuss the likelihood of low-level jet occurrence with fire weather forecasters when planning the next shift at a campaign fire on high ground. If occurrence is likely, then their effects should be accounted for in incident tactics. Apart from the direct effect of increased wind speeds on fire danger levels, the effects of turbulence and the possibility of depressed dew-point temperatures should also be considered.

Mountain wind waves

Mountain wind waves can lead to erratic conditions on some parts of the landscape. Field observers should watch for parallel lines of cumulus that are stationary over the ground. At higher levels, the appearance of altocumulus standing lenticularis clouds indicates strong waves reaching high levels. Pressure charts should always be checked to see if the geostrophic winds are aligned with local escarpments.

Summary

Many of the processes that can occur in high-country or mountainous landscapes have the potential to significantly affect fire behaviour and bushfire risk in general. These processes can lead to otherwise unexpected fire behaviour that could endanger firefighting crews and compromise suppression activities.

In particular, many of the processes discussed above can have a considerable effect on surface wind patterns and atmospheric moisture. It should be stressed that while changes in wind dynamics will generally affect the behaviour and growth of fires that are already burning, they will not necessarily affect the potential for ignition. Although the wind does play a small part in determining the microclimate surrounding fine fuels, its biggest role is in transporting warmer and drier air masses over the fuels, rather than directly influencing fuel moisture content.

Mountain meteorological effects can also contribute to escalations in the size and severity of fires burning in regions that are prone to them. Wind–terrain interactions such as dynamic channelling and lee-slope eddies lead to highly variable wind patterns in rugged terrain. Turbulence induced through these effects may also cause fire whirls and increased ember generation. Terrain–atmosphere interactions may lead to highly variable spatiotemporal patterns in temperature and atmospheric moisture across hilly terrain, which can affect the distribution and type of fuels in the long term and directly influence fire behaviour in the short term. The foehn effect can elevate local fire danger levels through an influx of warm, dry, accelerated air while regional fire danger may be much lower. Nocturnal low-level jets can lead to more severe fire behaviour during the early morning when fire crews would otherwise expect fire behaviour to be mild. Elevated terrain is particularly prone to being impacted by these wind maxima in the lower atmosphere. Mountainous terrain can also affect atmospheric stability through orographic lifting and lee-wave breaking. These effects often occur in combination, thereby complicating the study of the individual phenomena.

The fact that low-land and mountainous environments can experience weather patterns that are quite different forces one to conclude that mountainous areas should not in general be considered as part of the low-land fire environment. The effect of rugged terrain on atmospheric flows can give rise to complex dynamics and emergent properties that are discontinuous in nature. Thus, applying information extrapolated from knowledge of fire weather conditions in lower areas to the high country can lead to inaccurate assessment of ignition and fire behaviour potential. In particular, side slopes, deep valleys, peaks and ridge-tops can have weather patterns that cannot be well predicted from observations taken elsewhere. Moreover, these terrain features are often neglected when it comes to placement of weather monitoring stations. Indeed, there are relatively few data sources in mountainous landscapes, and their placement is biased towards the most easily accessible parts. Although the cost of installation and maintenance of permanent weather monitoring stations in complex topography may be prohibitive, short-term studies using dense networks of portable weather stations could prove valuable in characterising the nature of fire weather in difficult terrain. Data obtained from such studies could be used to assist in the development of synoptic and mesoscale weather models and models designed to emulate airflow over complex terrain. Combining these types of models with other data sources, such as satellite imagery, could provide an improved and more detailed understanding of fire weather in complex terrain. This is the philosophy behind projects such as the MAP, albeit with a non-fire weather focus. Incorporating information on mountain effects into fire weather training materials, policy and planning would also result in improved safety on the fire-ground in mountainous terrain.

The biodiversity and hydrology of mountainous environments are particularly susceptible to the effects of climate change. Thus, given the likely impacts of climate change on mountainous landscapes and fire danger in general, it would seem prudent to better understand, or at least better appreciate, the role that mountain meteorological effects have on bushfire behaviour and risk. As such, the present paper is intended to provide a first step in increasing understanding, across the wide range of professions (meteorologists to fire managers) concerned with bushfires, of how mountain meteorology might contribute to local fire danger and fire behaviour. The topics covered and the examples presented in the paper provide a good basis for a number of case studies that could be undertaken. For example, the extent to which the foehn effect contributes to elevated fire danger conditions in Australia is an open problem, as is the role that nocturnal low-level jets, mountain waves or subsidence inversions play in the overall bushfire risk problem. Undertaking case studies and conducting further research on these topics will improve understanding of the particular processes that are important in the Australian context and how knowledge of these processes could be incorporated into risk management frameworks and operational fire weather reports. Indeed, research that addresses both of these aspects is required to improve the efficiency and safety of fire management practices in mountainous terrain.

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