

**Final Report to the Grape & Wine Research & Development Corporation**

# Assessment of the Frequency and Impacts of severe Advective Frosts in the Canberra Viticulture Region


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*Cover image: from Kamberra Wines website*

# Table of Contents


1 Introduction 1

2 Background 2

*2.1 Australian climate and weather systems* *2*

*2.2 South-east Australian climate: the Canberra region* *4*

3 Frost climatology 6

*3.1 Types of frost* *6*

*3.2 The role of topography* *7*

*3.3 Cold air outbreaks* *8*

4 Synoptic analysis of advective frost events 9

*4.1 Identifying events* *9*

*4.2 The 27-28 October 1998 cold air outbreak* *11*

*4.3 Summary of synoptic characteristics* *15*

5 Vineyard temperature comparison & prediction 16

6 Management options 20

7 The role of changing climate 21

*7.1 Temperature trends* *21*

*7.2 Trends in frost occurrence* *23*

*7.3 Future temperature: implications for frost* *25*

8 Summary & Conclusions 27

Acknowledgements 28

References 30

# 1 Introduction

Australia has an inherently variable climatic regime, characterized by marked fluctuations in both space and time (*e.g.* Hobbs, 1998; Lindesay, 2004). This high degree of variability is due largely to Australia's geographic location and the associated oceanic influences and weather systems to which the continent is exposed. The majority of the Australian landmass lies in the subtropics (between ca 20ºS and 45ºS); the southern areas are relatively temperate in summer, and are exposed to midlatitude weather systems and low minimum temperatures in autumn, winter and spring and to the relatively regular occurrence of frost in the colder seasons.

Frost is a phenomenon that is potentially damaging to plants, as it involves the freezing of moisture either on the surface of the plant, or within the plant tissue. It therefore represents a management issue for agriculture in the frost-prone areas of the world, not least Australia. Although several agricultural sectors are frost sensitive (*e.g.* grains and pome fruits), viticulture is particularly exposed to potential frost damage; the success of grape growing relies in part on a well-defined cold season, which limits the practice of viticulture to the southern half of Australia where frost is most common. Other climatic determinants of suitability for viticulture, including sunshine hours, temperature stress and adequate rainfall, further limit the areas where the industry is likely to be most successful (Jackson and Schuster, 1994; Spellman, 1999). The oldest vine-growing regions in Australia are located in the south-east, in South Australia, Victoria, New South Wales and Tasmania; and in the south-west, in Western Australia (Figure 1) (Dry and Smart, 1988).




**Figure 1.** Location of the main viticultural regions in south-eastern Australia, with the location of Canberra highlighted in red.

One of the more recently established viticultural regions is the Canberra region in south-eastern Australia, where a number of cool-climate vineyards and wineries have been developed in the last 20-30 years. In October 1998 a late (spring) frost occurred across much of south-eastern Australia and caused large-scale damage to the region's agriculture, including viticulture. The event was an advective frost, associated with a cold air outbreak from the midlatitudes; these are potentially the most damaging frosts to agriculture, as they are linked to severe plant tissue damage. In the Canberra region this frost destroyed the majority of the grape crop for that season, resulting in an economic loss to the regional wine and viticulture industry estimated at $50 million (Cashman, 2000). The magnitude of this loss, the general lack of specific climatological knowledge of advective frost events in the region, and the perceived need for targeted forecasting of future events, highlighted the need for this study. The research focussed on the Canberra region, and aimed to

- establish a general climatology of frost in the region, including consideration of the potential impacts of climate change on frost
- develop a synoptic climatology of advective frosts, to enhance understanding of the particular weather system characteristics associated with such frosts in the region
- investigate temperature aspects of the microclimatology of vineyards in the region, so that local-scale effects such as topography could be considered in relation to frost, and
- establish the relationship between temperature (and frost) in the viticulture region and that at the official Bureau of Meteorology weather station for Canberra, to contribute to targeted forecasting for the viticulture region.

Growers in the Canberra region were surveyed as part of the research in order to investigate their experience and knowledge of late frost in the region, their preferred methods to ameliorate the effects of late advective frosts, and the perceived utility of targeted frost forecasts. The response rate was 53%, with 34 questionnaires returned and analysed. The results are summarised in Cashman (2000) and Koh (2000).

# 2 Background

## 2.1 Australian Climate & Weather Systems

The climate of the Australian continent is determined by the geography of the land mass, which extends from the tropics in the north, through the subtropics to the fringes of the midlatitudes in the south. Each of these broad latitude zones is characterized by different dominant weather systems. In the tropics (0º-20ºS), easterly airflow and tropical disturbances (including tropical cyclones), and in some areas the wind reversals and distinct dry and wet seasons associated with the monsoon, dominate the rainfall regime. In the subtropics (± 20º-40ºS) anticyclones with slowly descending air masses and clear skies are prevalent, disrupted by heat lows and tropical disturbances in summer and by midlatitude cold fronts in winter. In the midlatitudes (south of 40ºS), a succession of frontal low pressure systems moves across the fringes of the continent in the prevailing westerly airflow, each front bringing a sequence of weather conditions including warmer, dry airmasses ahead of the front and cooler, moist air with the potential for rainfall and possible thunderstorms with the passage of the front. Following the front high-pressure anticyclonic conditions are generally re-established, with attendant clear skies, dry air and relatively low temperatures (Hobbs, 1998; Sturman and Tapper, 1996). These climatic zones play a fundamental role in shaping the distribution of frost in Australia.

In addition to the broad zonation of weather systems, the large west-east extent of the continent leads to generally dry conditions and extremes of temperature in the interior, which is remote from the moderating thermal effects of the oceans and from the sources of moisture-bearing winds, particularly easterlies, crossing the coasts. The result is annual average rainfall and temperature patterns with a general gradient from the warm to hot monsoonal tropics to the cool midlatitudes, and wetter conditions around the northern, eastern and southern coastal fringes (Figure 2a and 2b). The interior is generally hot and dry, particularly in summer (Hobbs, 1998; Sturman and Tapper, 1996), and shows the largest seasonal temperature range (Figure 3, where Alice Springs mean temperatures are on average 15ºC higher in summer than in winter). Lowest annual average temperatures (Figure 2b) are found

in the southernmost parts of Australia (Tasmania) and in the relatively high-elevation south-eastern areas (the Australian Alps, Victoria and New South Wales).

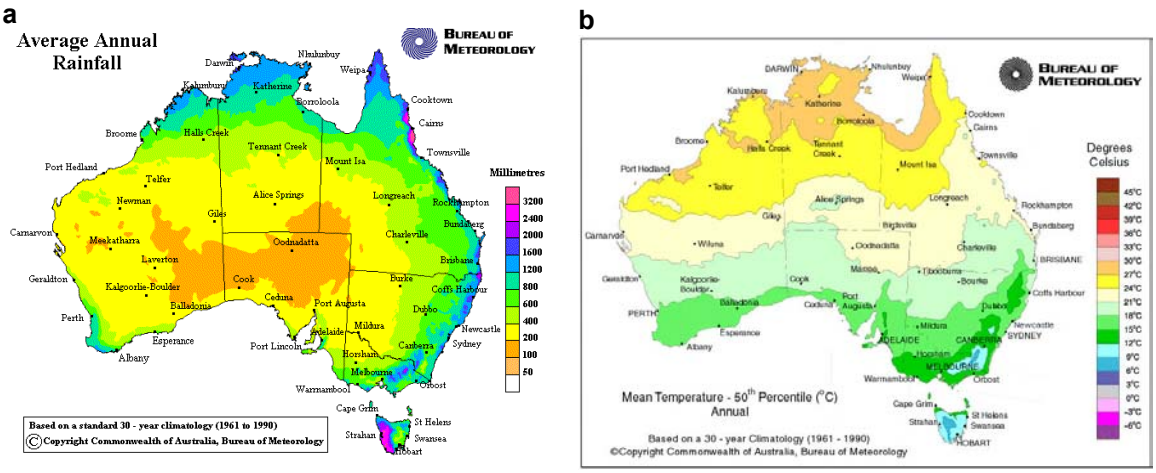



**Figure 2.** (a) Average annual rainfall totals, and (b) most commonly occurring (50$^{th}$ percentile) mean annual temperatures (source: Australian Bureau of Meteorology, www.bom.gov.au)

Seasonal variations in weather occur as a result of the northward migration of the overhead sun in winter, and consequent expansion of the cold Antarctic airmasses and northward movement of midlatitude low pressure systems over southern Australia; and the expansion of warm, humid tropical airmasses southward in summer, bringing tropical disturbances and moisture sources further south over the continent (Hobbs, 1998; Sturman and Tapper, 1996). These general seasonal climatic conditions are reflected in the most frequently occurring annual average temperatures in summer and winter (Figure 3a and b). These are average conditions, however, and as is characteristic of the global subtropics much of Australia is subject to a high degree of interannual climatic variability. Both tropics and midlatitudes may be affected by large-scale circulation fluctuations from year to year that can affect the location, frequency and intensity of particular types of air masses and weather systems. Any changes in these two zones will impact on the subtropics, which are thus particularly prone to interannual variability as expressed in extremes of rainfall and temperature. Temperature extremes, shown as the highest 10% of maximum temperatures in summer and the lowest 10% of minimum temperatures in winter (Figure 3c and d), are clearly greatest across subtropical central Australia.

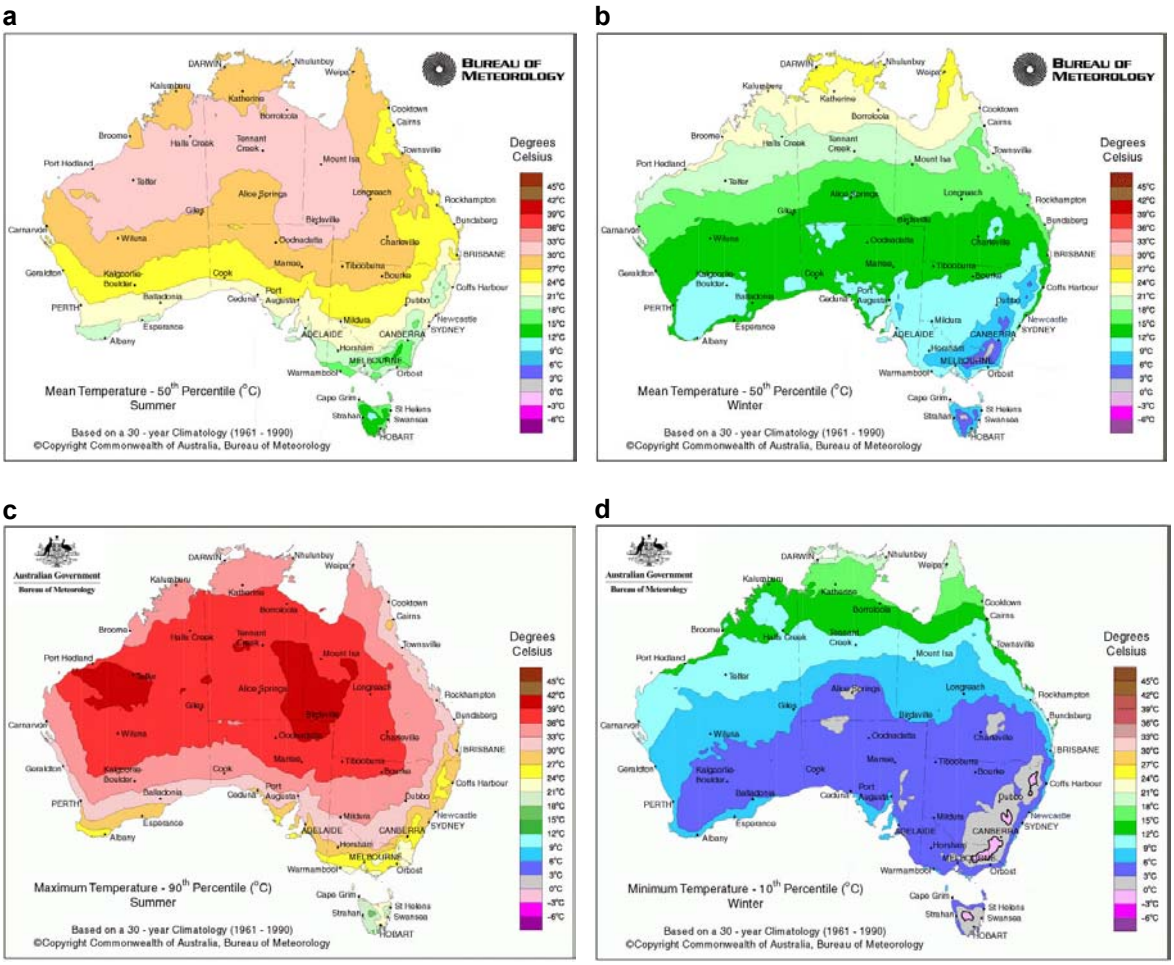



**Figure 3.** Seasonal variation in the most common (50th percentile) mean temperatures across Australia, in (a) summer, and (b) winter (source: Australian Bureau of Meteorology, www.bom.gov.au)

## 2.2 South-east Australian climate: the Canberra region

Canberra is located in south-eastern Australia, on the subtropical-midlatitude fringe, and is exposed geographically to a number of different weather systems and influences. This is reflected in the range of seasonal rainfall regimes across the wider region, from predominantly winter rainfall in the south-west (Victoria), through approximately uniform summer and winter rainfall in southern NSW and the ACT, to a summer rainfall regime in the north. Both tropical and midlatitude airmasses and weather systems can bring rainfall to the area, and anticyclonic ridging along the south-east coast can also be an important source of onshore moist airflow for cloud formation and precipitation. Interannual rainfall variability in the area is high (*e.g.* Lindesay, 2004). The seasonal variation of daytime maximum and nighttime minimum temperatures across the region (Figure 4) reflects the influence of the seasonal cycle in solar radiation, and of warm to hot subtropical airmasses in summer and cool to cold midlatitude airmasses in winter. The general effects of the complex topography of the region are also clear, with both summer and winter

temperatures on average 6-9ºC degrees colder in the alpine region than at lower elevations nearby.

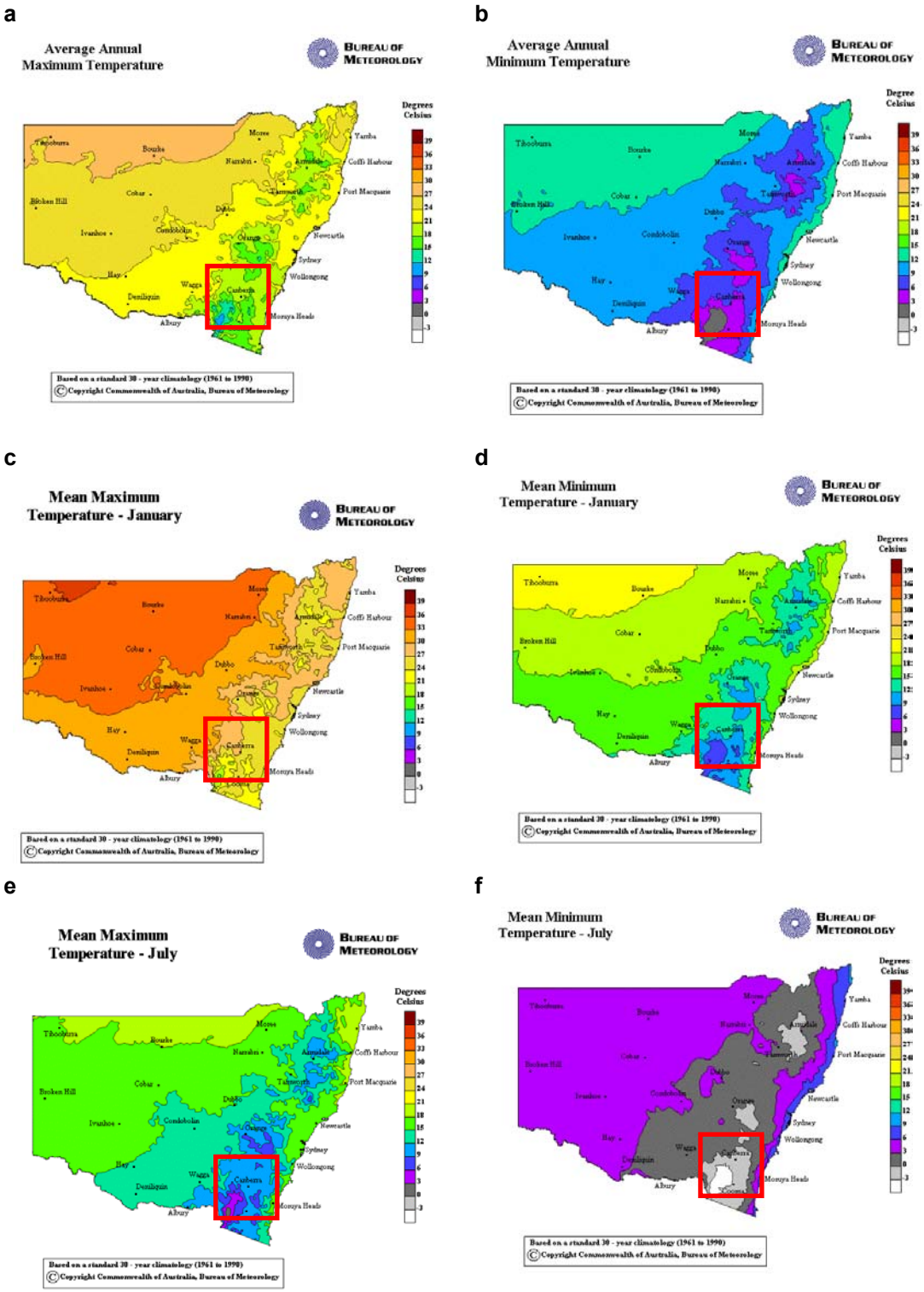



**Figure 4.** The seasonal cycle of maximum and minimum temperatures in NSW and the ACT: (a) and (b) annual average maximum and minimum temperatures; (c) and (d) summer (January) temperatures; and (e) and (f) winter (July) temperatures. The area around Canberra is indicated by the red square (source: Australian Bureau of Meteorology)

Monthly average temperatures at Canberra (Figure 5) are typical of its location on the fringe of the subtropics, exhibiting a clearly defined seasonal cycle. The warmest month is January (mean temperature 20.3°C; average maximum temperature 27.7°C; average minimum temperature 13.3°C), and the coldest July (mean temperature 5.4°C; average maximum temperature 11.2°C; average minimum temperature –0.4°C). Mean and maximum temperatures are more variable in the warmer months of spring and summer, and least variable in autumn. Although maximum temperature is influenced by the presence of cloud and the degree of surface heating, it is also affected by the source of the air mass on a particular day; for example, summer northerly to northwesterly airflows from the continental interior bring high maximum temperatures to the Canberra region. Minimum temperatures are most variable in winter, due to their sensitivity to nocturnal cloud cover. On clear nights in winter the unimpeded loss of longwave radiation from the surface leads to low near-surface air temperatures; on cloudy nights some of the outgoing longwave radiation is absorbed and re-radiated to warm the near-surface air, keeping temperatures higher. Frost is most likely to occur in late autumn, winter or early spring, under the clear-sky conditions outlined previously.

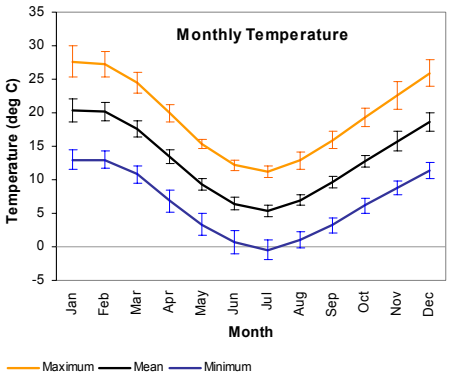



**Figure 5.** The annual temperature cycle at Canberra Airport, for the standard period 1961-1990. Mean temperature is calculated as the average of daily maximum and minimum temperatures (data: Australian Bureau of Meteorology)

# 3 Frost climatology

## 3.1 Types of Frost

Frost is defined as a "Deposit of soft white ice crystals or frozen dew drops on objects near the ground; formed when surface temperature falls below freezing point" (Australian Bureau of Meteorology, www.bom.gov.au). The formation of ice crystals on a surface can occur by sublimation (the direct freezing of water vapour, without going through the liquid phase) when the temperature of the surface and the air close to it drops below freezing (0°C). However, it is more common for the air close to the surface to cool to the dewpoint (the temperature at which the air

becomes saturated and water vapour condenses to liquid), so that dew forms on exposed surfaces; this will freeze to form frost if the temperature of the surface falls below the freezing point (Linacre and Geerts, 1997). If the air is particularly dry when freezing point is reached there may be little or no surface frost formation, but the water within plant tissues may freeze. In freeze-sensitive plants this can cause cells to rupture, killing the affected parts of the plant. In freeze-tolerant plants such as grape vines, frost damage occurs by dehydration (Sakai and Larcher, 1987). This process, called plasmolysis, occurs when ice forms between the plant cells; water from inside the cells diffuses to freeze on the ice mass, leaving a contracted cell. On thawing the unequal pressures across the cell membrane destroy its semi-permeability and also the functionality of the cell (Sakai and Larcher, 1987; Rogiers, 1999).

*Radiative frost* is the most common form of the phenomenon. Nocturnal longwave (heat) radiation loss from the surface leads to the progressive reduction of surface temperature (and that of the adjacent air) between sunset and sunrise (Oke, 1987; Linacre and Geerts, 1997). In winter, when days are shorter and the solar zenith angle at noon is further from the vertical than in summer, solar radiation receipt at the surface is minimised during the day; this reduces daytime surface heating. At the same time, longer nights provide the maximum period for longwave radiation loss. This combination results in the lowest surface air temperatures in the annual cycle (see Figure 5); at Canberra the average minimum air temperature in the coldest month, July, is –0.4°C; the average July maximum temperature is 11.2°C.

*Advective frost* occurs under meteorological conditions that typically include the passage across a region of a large mass of very cold, dry air followed by clear and calm conditions, usually under the influence of an anticyclone (Scholefield, 1994; Davidson, 1997). In Australia these conditions are most likely to occur following the passage of a midlatitude depression (or cold front) across southern parts of the continent in winter or early spring. Thus the conditions for radiative frost occur in an airmass that is colder and drier than average for the time of year, and with a deep cold air layer that extends across a broad region. Advective frosts are therefore particularly severe in terms of low temperature and low humidity; and particularly widespread in their impacts.

## 3.2 The role of topography

In addition to the general climatological and meteorological conditions associated with frost occurrence, local topography plays an important role. Both radiative and advective frosts can occur in a range of topographic settings, but the presence of hillslopes and local low points enhance the likelihood of low temperatures and frost occurrence. As radiative cooling progresses through a clear night, air close to the ground cools more rapidly than the air at some distance above the surface. The near-surface air becomes relatively dense and moves downslope in the phenomenon known as katabatic flow (Oke, 1987; Linacre and Geerts, 1997). Thus low-lying areas and the lower parts of hillslopes are likely to experience colder conditions and a greater likelihood of frost than points higher up the slope. As cold air pools close to the surface and in low points in the topography such as valley floors, while air above the surface remains warmer, temperature increases with height above the surface and a temperature inversion is formed ("inversion" refers to the reversal of the normal decrease of temperature with height through the lower atmosphere). Inversion conditions are stable and restrict vertical mixing of air, promoting the persistence of radiative cooling and katabatic flow (Oke, 1987).

The role of topography in determining the thermal environment is well recognised in viticulture, and hillslopes are often used to enhance cold air drainage and thereby reduce potential frost damage. Slope aspect can also be important, with east-facing slopes receiving the first insolation following sunrise so that frost can dissipate there first; west-facing slopes remaining warmer after sunset; and south-facing slopes generally avoided in the southern hemisphere because they receive less overall sunshine and are colder.

Other environmental considerations relating to viticulture in the Australian context and more generally, such as soils and land management, proximity to water bodies and the effects of windbreaks, are discussed comprehensively by Gladstones (1992).

## 3.3 Cold air outbreaks

The meteorological phenomenon associated with advective frosts in southern Australia is the cold air outbreak. These have been well documented in North America (*e.g.* Malihot, 1992; Liu *et al*., 1992; Konrad, 1996), but relatively few published studies exist for Australia (Pook, 1992; Perrin and Simmonds, 1995; Simmonds and Richter, 1999). Cold air outbreaks generally involve a high latitude source of polar or sub-polar air that is forced equatorward in conjunction with the development of a cyclone-anticyclone couplet (*i.e.* a midlatitude depression or cold front, followed by a well developed anticyclone). In this case the southerly winds behind the front are enhanced by the presence of the anticyclone, ensuring that the cold air advection equatorward continues as the systems move eastward. Advection of the polar airmass across an expanse of ocean, as occurs for any such airmass approaching Australia, will generally result in increases in temperature and moisture that grow as the ocean transit time increases. Rapid movement of the airmass northward across southern Australia is therefore necessary to retain the low temperature and humidity characteristic of these events.

Although cold air outbreaks affect only the southern regions of Australia (Hannay, 1960), they are important because of their possible effects on infrastructure (particularly if they are associated with heavy snowfalls) and agriculture (if they result in advective frosts). In a study of cold air outbreaks over Melbourne, Perrin and Simmonds (1995) found that the airmasses involved did not usually originate as far south as Antarctica; and in comparing these events in Melbourne and Perth, Simmonds and Richter (1999) identified pressure anomalies in key regions preceding the outbreaks. It is therefore likely that hemispheric-scale circulation features play a significant role in the occurrence of cold air outbreaks (Perrin and Simmonds, 1995; Konrad, 1996).

Despite the recognition that advective frosts associated with cold air outbreaks are potentially particularly severe, there is no differentiation in official meteorological records of frost between advective and radiative frosts. Identification of advective frost events from the historical record requires detailed examination of meteorological conditions, and knowledge of the geographic distribution of particularly low temperatures. One of the aims in this project was to present a climatology of advective frost events affecting the Canberra region, so that future events can be identified with reasonable certainty as part of the weather forecasting process for the region.

# 4 Synoptic analysis of advective frost events

## 4.1 Identifying events

Advective frosts are large-scale phenomena associated with synoptic-scale weather systems rather than specific local conditions, although local conditions affect the intensity of the resulting frosts. The synoptic meteorological data used in this analysis therefore includes records from weather stations across south-eastern Australia, from Adelaide to Sydney. The synoptic climatology was constructed using the following data

- 3-hourly dry-bulb temperatures at the Canberra Airport Bureau of Meteorology weather station, 1939 to 2003
- 3-hourly wet-bulb temperatures at Canberra Airport, 1951-2003
- twice-daily mean sea level (MSL), 700 hPa and 500 hPa analysis charts for selected days (from Bureau of Meteorology)
- MSL analysis (synoptic) charts from the Monthly Weather Review published by the Bureau of Meteorology
- twice-daily radiosonde and wind data for weather stations at Adelaide, Mt Gambier, Mildura, Laverton, East Sale, Wagga Wagga, Canberra and Sydney, for selected days (from Bureau of Meteorology)

A severe advective frost event with the potential to cause damage to plant tissue was defined as having the following characteristics

- occurrence following the onset of spring plant growth (September-October), and
- sub-zero temperature reached by or before 0100, or
- sub-zero temperatures reached after 0100 and persisting for at least another three hours, with a further fall in temperature of at least 1°C within that time

These criteria were used to identify possible advective frost events in the Canberra region in the spring months September and October (Table 1). It is clear from this identification that

- spring advective frost events are relatively rare in south-eastern Australia, as identified from the Canberra record – there have been only 20 in the 64-year period 1940-2003, giving an occurrence rate of 0.5%.
- the frequency of these events is variable, and shows no clear pattern. In the 1950s there were eight events meeting the criteria, in the 1970s six nights (but only four discreet events), and in the 1980s only one event.
- the event with the lowest minimum temperature was that on 10 September 1982 (below zero at midnight, -4.5°C at 0300, and -6.4°C at 0600).
- the event on 28 October 1998 had a minimum temperature at 0600 of -1.9°C, following sub-zero temperature at 0300; it was relatively moderate in comparison with the other events identified here.

It is important to remember that the potential advective frost events listed in Table 1 have been identified on the basis of temperature criteria only, and require a complete synoptic analysis to clarify their status as advective frost events associated with outbreaks of cold air across the region.

**Table 1.** Potential advective frost events in the Canberra region, identified using temperature criteria applied to 3-hourly temperatures at Canberra Airport, 1939-2003 (data from Australian Bureau of Meteorology). The minimum temperature on each day is highlighted in bold italics. The wet-bulb depression is the difference between the air temperature and the wet-bulb temperature; the greater the difference, the drier the airmass. Days on which synoptic analysis indicates cold air outbreak conditions have the date in bold type.

| Events per decade | Date | Temperature (°C) | | | Wet-bulb depression (°C) |
|---|---|---|---|---|---|
| | | 0000 | 0300 | 0600 | 0600 |
| 1940s : 2 | 1 Sep 1944 | | ***-2.7*** | -2.4 | |
| | 6 Sep 1945 | | -1.7 | ***-2.8*** | |
| 1950s : 8 | 4 Sep 1950 | 0.5 | -1.9 | ***-2.2*** | |
| | 5 Sep 1951 | 3.9 | -1.1 | ***-2.3*** | 0.4 |
| | 7 Sep 1951 | 1.3 | -1.1 | ***-2.2*** | 0.6 |
| | 12 Sep 1953 | 1.6 | -1.5 | ***-3.2*** | 0.1 |
| | 4 Sep 1957 | 1.2 | -1.2 | ***-2.8*** | 0.3 |
| | **4 Oct 1957** | 1.2 | -2.0 | ***-3.1*** | 0.5 |
| | 1 Sep 1958 | 2.2 | -1.1 | ***-2.6*** | 0.2 |
| | 2 Sep 1959 | | -1.7 | ***-2.9*** | 0.4 |
| 1960s : 2 | **7 Sep 1966** | 1.1 | -1.2 | ***-2.3*** | 0.4 |
| | **26 Sep 1968** | 2.7 | -1.6 | ***-2.8*** | 0.1 |
| 1970s : 6 | **2 Sep 1971** | 0.1 | -1.2 | ***-2.7*** | 0.4 |
| | 3 Sep 1971 | 1.4 | -1.6 | ***-3.1*** | 0.2 |
| | **12 Sep 1971** | 2.8 | -1.1 | ***-2.2*** | 0.5 |
| | **6 Sep 1975** | -2.0 | -3.0 | ***-4.9*** | 0.3 |
| | **1 Sep 1979** | ***-1.0*** | ***-1.0*** | ***-1.0*** | 1.3 |
| | **2 Sep 1979** | 0 | -2.0 | ***-3.0*** | 0.3 |
| 1980s : 1 | **10 Sep 1982** | -0.5 | -4.5 | ***-6.4*** | 0.7 |
| 1990s : 2 | **14 Sep 1992** | 1.8 | -1.4 | ***-2.5*** | 0.2 |
| | **28 Oct 1998** | | -0.6 | ***-1.9*** | 0.4 |
| 2000s : ? | 11 Sep 2002 | -0.6 | -3.0 | ***-3.8*** | |

The synoptic characteristics of each of the events in the period 1960-2000 has been studied in detail (Koh, 2000). A case study of the event of 27-28 October 1998 is presented here to illustrate the principal features of advective frost events associated with cold air outbreaks across south-eastern Australia.

## 4.2 The 27-28 October 1998 cold air outbreak

### *4.2.1 Surface weather patterns & upper-air circulation*

An advective frost event associated with a cold air outbreak is characterised by low temperatures during the day preceding the event, and sustained sub-zero temperatures during the night of the frost. The temperature record at Canberra Airport for the period pre, during and post the event of 28 October 1998 (Figure 6) clearly illustrates these characteristics. Falling temperatures accompanied the passage of a midlatitude depression and associated cold front on the night of 26-27 October, followed by a daytime maximum of only 11°C on 27 October in the cold airmass behind the front. Already preconditioned for low temperatures, conditions on the night of 27-28 October saw temperatures fall below zero between midnight and 0300, and reach a minimum of –1.9°C at 0600. These low temperatures, and the rapid warming following sunrise on 28 October (to a maximum of 15°C that day), indicate the clear-sky conditions accompanying the anticyclone that had moved over the region that night.

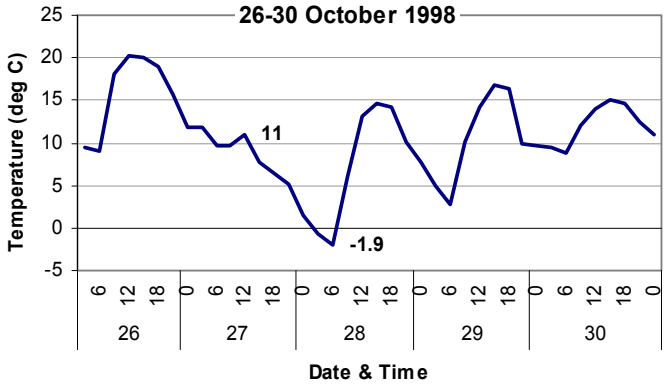



**Figure 6.** Canberra Airport 3-hourly temperatures, 26-30 October 1998 (data: Australian Bureau of Meteorology). The maximum temperature (11°C) the day prior to the frost, and the minimum temperature (-1.9°C) on the night of the frost are indicated.

This synoptic sequence is illustrated in the surface synoptic charts in Figure 7, which shows the cyclone-anticyclone couplet characteristic of a cold air outbreak. As is typical of such events, the isobars immediately behind the midlatitude depression (cyclone) are orientated south-north across south-eastern Australia, indicating the advection of cold air from the south over the region.

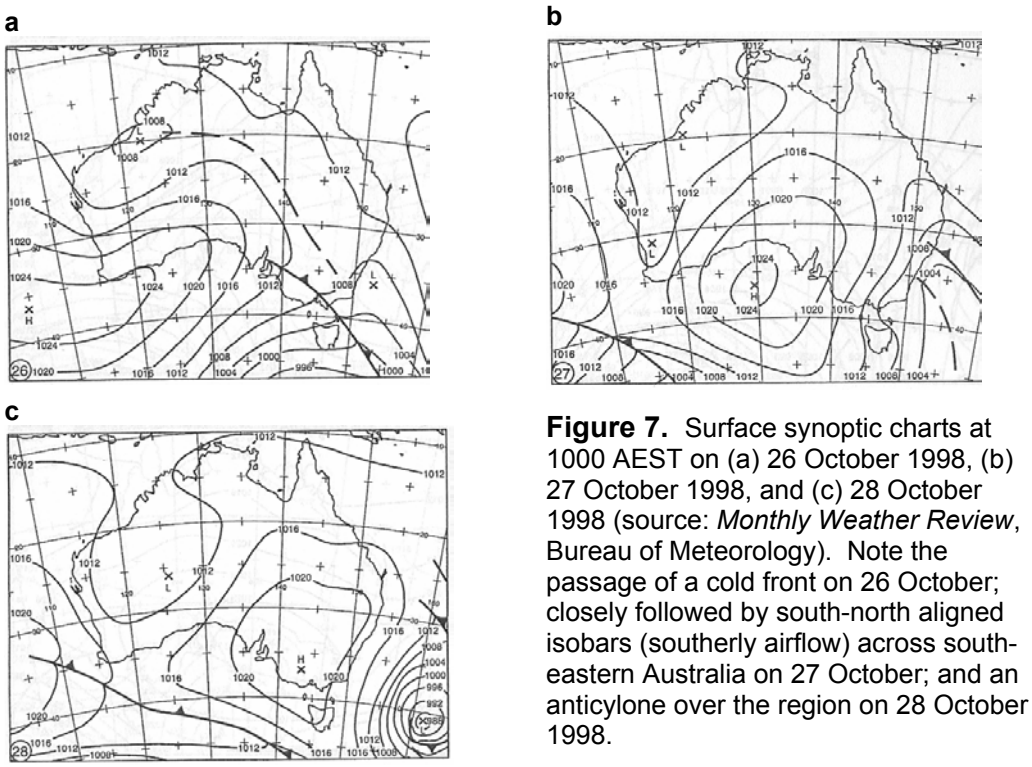



**Figure 7.** Surface synoptic charts at 1000 AEST on (a) 26 October 1998, (b) 27 October 1998, and (c) 28 October 1998 (source: *Monthly Weather Review*, Bureau of Meteorology). Note the passage of a cold front on 26 October; closely followed by south-north aligned isobars (southerly airflow) across south-eastern Australia on 27 October; and an anticylone over the region on 28 October 1998.

The airflow associated with this synoptic sequence and responsible for the cold air advection is shown at the 850 hPa level (ca 2,000 m above the surface) in Figure 8. The northward trajectory of the airmass was well established at 1000 on 27 October, with relatively strong winds rapidly advecting the cold air across south-eastern Australia. The wind vectors clearly show the clockwise rotation around the midlatitude depression (which has low windspeeds at its centre, and higher windspeeds to the north and west), and the conjunction of this system with the anti-clockwise circulation around the following anticyclone. The close proximity of these two systems produced the strong southerly airflow across south-eastern Australia. By contrast, at 0400 on 28 October (close to the time of minimum temperature and frost occurrence) the weather system had moved eastward, and winds across south-eastern Australia were light as is typical of a strong anticyclone.

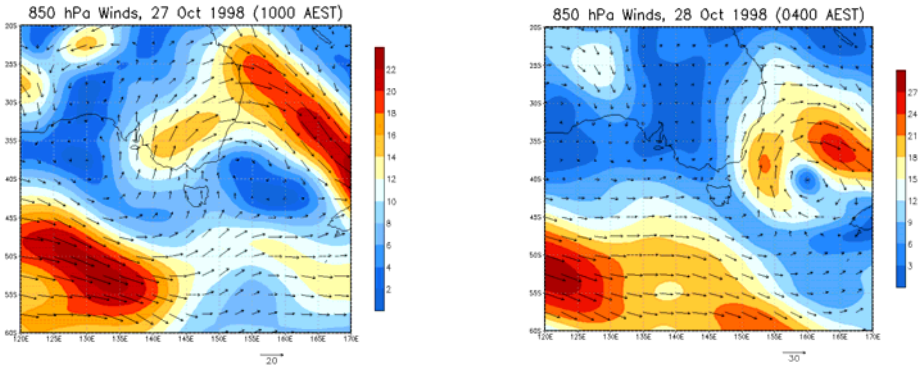



**Figure 8.** Airflow in the lower atmosphere, 27 and 28 October 1998 (derived from NCEP-NCAR Reanalysis). Arrows show wind direction; wind speed proportional to length. Wind velocity (knots) indicated by shading.

### 4.2.2 Airmass temperature

The extent of the cold airmass that constituted the cold air outbreak is indicated in the 850 and 500 hPa temperature maps in Figure 9. Temperatures were below zero across southern NSW and the ACT in the lower troposphere (850 hPa); and in the middle troposphere (500 hPa, ca 5,000 m above the surface) the air across the Canberra region was at between –17 and –20°C.

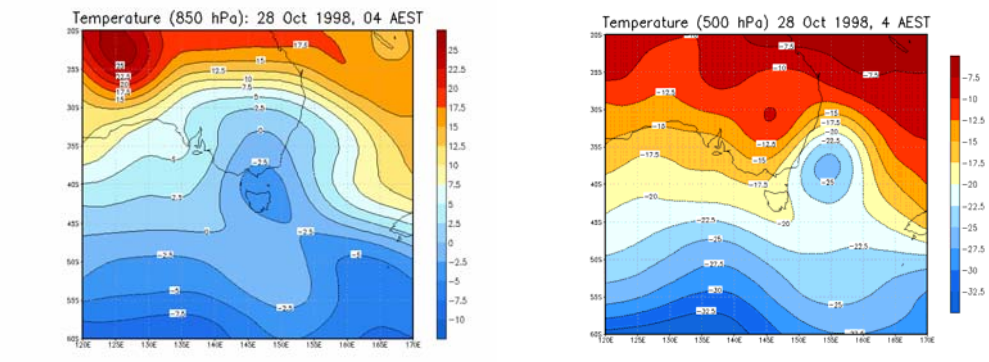



**Figure 9.** Temperature at 850 hPa (lower troposphere) and 500 hPa (middle troposphere) at 0400 on 28 October 1998 (derived from NCEP-NCAR Reanalysis).

### 4.2.3 Airmass humidity

The airmass across the region on the night of 27-28 October 1998 was not only cold, but relatively dry (Figure 10). This is borne out by the vertical temperature profile at Wagga Wagga on 27 October 1998 (Figure 11). On this diagram the two lines on the chart show the air temperature (or dry-bulb temperature) as the right-most curve, and the dewpoint temperature as the left-most curve. The further apart these two lines are, the drier the air at that height above the surface. At 1000 on 27 October the airmass at Wagga Wagga was cold (surface temperature ca 10°C) and relatively dry, with dryness increasing to 500 hPa. This is consistent with the passage of the frontal system across the region in the hours prior to the sounding. The airmass at Wagga Wagga at 1000 on 28 October, the morning after the frost event, was clearly drier still. The sounding also indicates a temperature inversion at ca 700 hPa which is probably associated with strong subsidence of air in the anticyclone across the region.

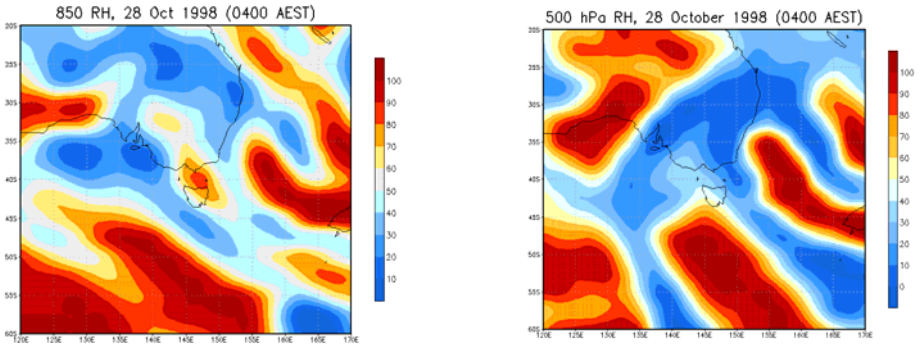



**Figure 10.** Relative humidity at 850 hPa (lower troposphere) and 500 hPa (middle troposphere) at 0400 on 28 October 1998 (derived from NCEP-NCAR Reanalysis). Near-surface humidity values increase at night as temperature falls, and decline during the day; humidity higher in the atmosphere is not affected by the diurnal heating cycle of the surface.

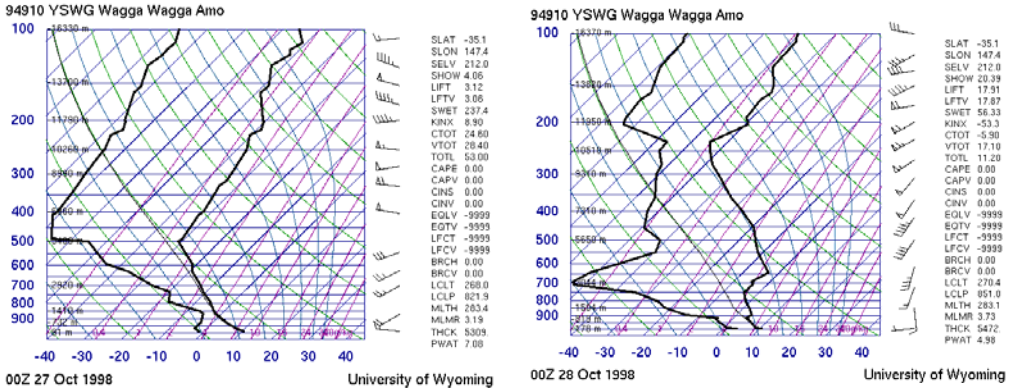



**Figure 11.** Atmospheric soundings of temperature (right-most curve on each graph) and dewpoint temperature (left-most curve) at Wagga Wagga – to the west of Canberra – at 1000 on 27 and 28 October 1998 (source: University of Wyoming). Routine soundings are made once a day at this station, which is the nearest upper-air sounding station to Canberra.

It is important to remember that although soundings at Wagga Wagga may represent general airmass characteristics applicable across south-eastern Australia, local conditions including modification of the near-surface windfield and other characteristics by topography can make these soundings less appropriate to the Canberra region.

### *4.2.4 Hemispheric-scale circulation*

It has been suggested (Perrin and Simmonds, 1995) that hemispheric-scale circulation characteristics are important in driving the occurrence of cold air outbreaks. The mid-troposphere (500 hPa) map of geopotential height (Figure 12) shows the overall pattern of airflow around the southern hemisphere at 0400 on 28 October 1998. This map, like those for all the other advective frost events studied for this project, shows a relatively high hemispheric wave number of 5 (the usual number is 3 or 4). The number of

waves is indicated by the wave-like distortions of the lines on the chart away from a roughly circular pattern around Antarctica. A high wave number equates to a low zonal index ( the degree to which airflow is west-east, as opposed to north-south in orientation). This pattern sets up conditions suitable for weather systems to follow trajectories with a more south-north component than is possible when the flow is strongly zonal, allowing advection of cold airmasses northward from higher latitudes. Another distinctive feature of all the cold air outbreak cases studied is the presence of a well developed anticyclone across the Bight, to the south-west of the Canberra region.

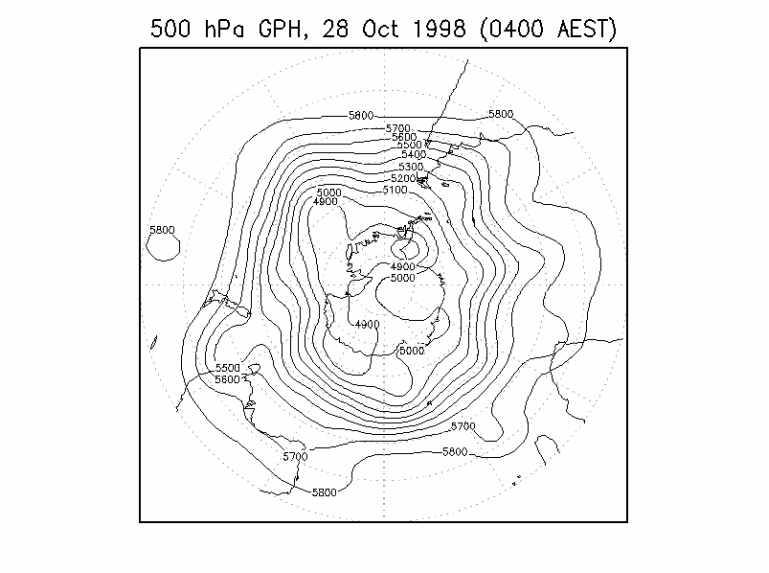



**Figure 12.** Southern hemisphere circulation pattern at 500 hPa (ca 5,000 m above the surface), 28 October 1998 at 0400 AEST (NCAR-NCEP Reanalysis).

## 4.3 Summary of synoptic characteristics

In all the cases of cold air outbreaks studied, and as exemplified in the case study of the 28 October 1998 event, there are several key distinguishing features of the synoptic circulation associated with these events. These are:

1. The conjunction of a midlatitude depression (cyclone) and frontal system with a following anticyclone, usually observed as a well-developed anticyclone over the Bight

2. A south-to-north or north-east orientation of the isobars and airflow across south-eastern Australia in the area of interaction between the two systems

3. Relatively strong winds and rapid advection of the cold airmass across the region, so that low temperatures and humidity are maintained

4. Low temperatures during the day prior to the frost, due to the low temperature of the airmass

5. Establishment of an anticyclone (with high pressure, clear skies and light winds) in the afternoon or evening following the passage of the depression, so that radiative heat loss is maximised overnight

6. Low moisture content in the airmass both at and above the surface, to promote heat loss (water vapour absorbs outgoing longwave radiation, as do clouds)

7. On a hemispheric scale, a relatively high wave number (4 or above), and low zonal index, to promote meridional (north-south) transfer of airmasses

Knowledge of these synoptic characteristics of cold air outbreaks and advective frost events, coupled with sophisticated numerical weather forecast modelling by the Bureau of Meteorology, means that these events can now be forecast with some accuracy in terms of the general likelihood of occurrence, between one and four days in advance. Given the spatial scale of synoptic analysis, however, this aspect of the research does not allow targeted local forecasting. Such forecasting relies on specific knowledge of the modifications of general temperature conditions by local influences, primarily topography, and requires local monitoring of temperature in particular.

# 5 Vineyard temperature comparison & prediction

Temperature and other meteorological data were recorded in two vineyards near Murrumbateman, which is located approximately 40 km from Canberra, during 2001 and 2002. Automatic weather stations were set up in exposed positions at "Quandialla" and "Stringybark Hill" (Figure 13), providing almost continuous three-hourly records of temperature and humidity from December 2001 to December 2002. The data for Stringybark Hill show a persistent bias, and are not used further in this analysis; the remainder of this section is based on the three-hourly temperature data collected at Quandialla.

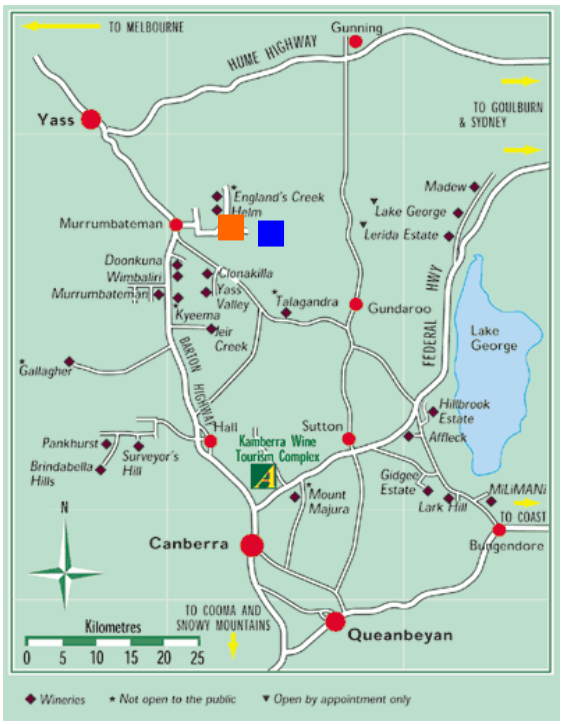
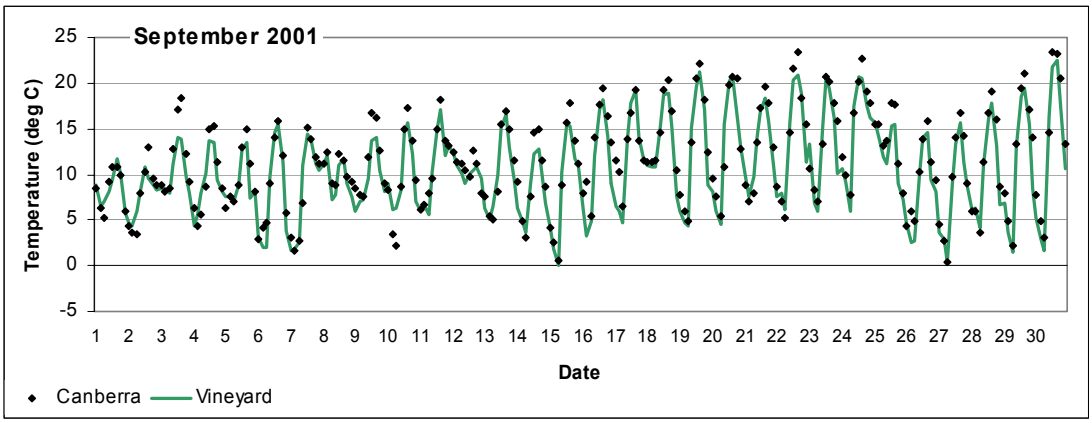



**Figure 13.** The Canberra Viticulture Region (source: www.helmwines.com.au). The approximate location of "Stringybark Hill" is marked with an orange square, and of "Quandialla" with a blue square.

The spring months of interest in terms of late advective frost events, *i.e.* September and October, show the key characteristics of the relationship between temperatures in the vineyards and those recorded at Canberra Airport throughout the year. The two locations clearly have closely similar temperature regimes, as illustrated by the time series of three-hourly temperatures in September 2001 and 2002 (Figure 14a and b). The overall correlations (r=0.95 in 2001; r=0.94 in 2002) suggest that temperature conditions are almost indistinguishable at the two places (Figure 15a and b), particularly in 2001. However, there are some important differences.

**a**




**b**

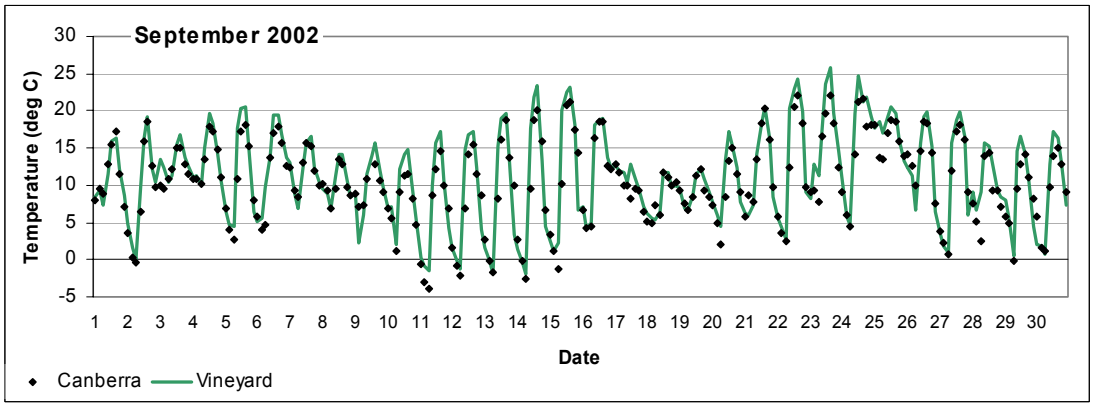



**Figure 14.** Three-hourly temperatures for September 2001 and 2002, at Canberra Airport and at the vineyard "Quandialla" near Murrumbateman in the Canberra Viticulture Region.

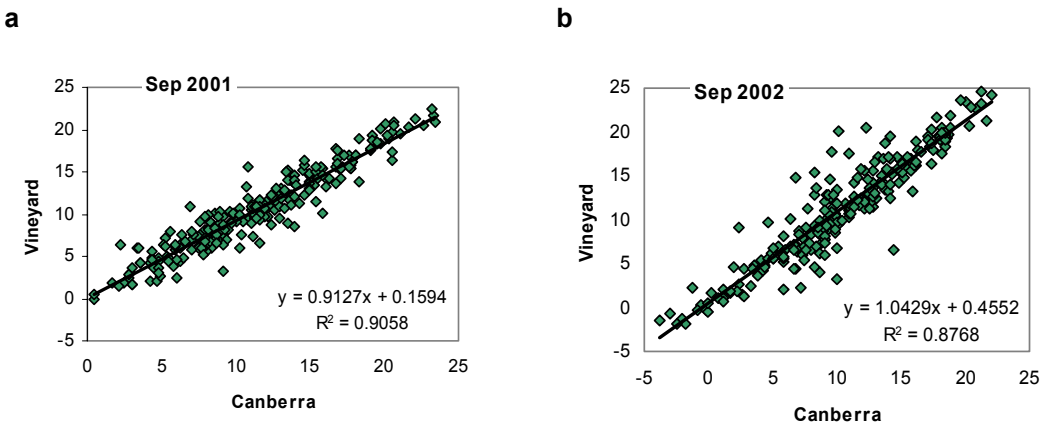


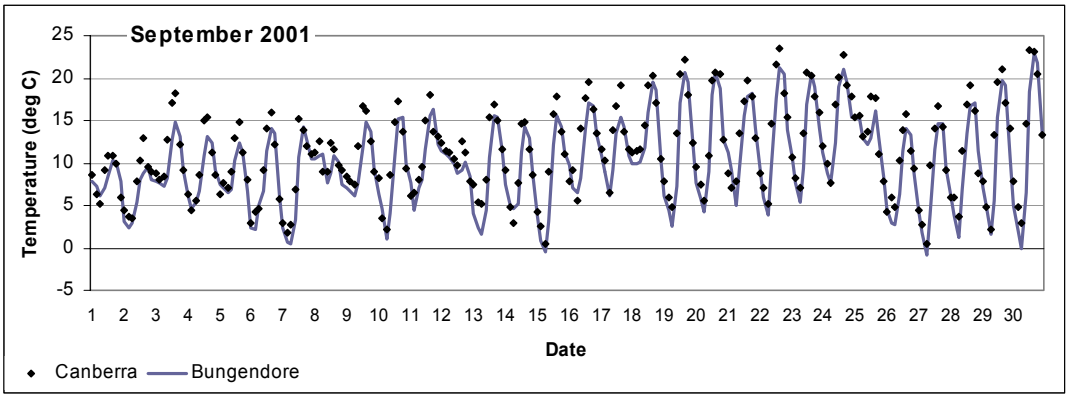

**Figure 15.** The relationship between three-hourly temperature at Canberra Airport and at "Quandialla" near Murrumbateman (Canberra data from Australian Bureau of Meteorology).

In 2001 maximum temperatures were lower in the vineyard than at Canberra by between 1 and 2°C on average (Figure 14a), but although minimum temperatures were also lower in the vineyard on more than 60% of nights in the month, the average difference was only 0.2°C (ranging from 2.6°C lower to 4.6°C higher). In 2002 the reverse occurred (Figure 14b); maximum temperatures were higher in the vineyard than at Canberra (by as much as 3.9°C), as were minimum temperatures which were higher on more than 60% of nights (average 0.8°C; ranging from 3.3°C lower to 6.6°C higher). There are no known site-specific variations that could account for this change between the two years. This result therefore suggests that large-scale circulation factors affect the nature of the temperature difference between Canberra and the vineyard, probably associated with different weather systems and air mass trajectories across the region. This suggestion is supported by the particular dissociation between the two series on days when the diurnal temperature cycle is disrupted, probably by the passage of a midlatitude depression and associated frontal disturbance (*e.g.* 3-5 and 8-10 September 2001, Figure 14a). The cloud cover accompanying these weather systems reduces the diurnal temperature range and raises nighttime minimum temperatures. By contrast, settled anticyclonic conditions between 19 and 24 September 2001, and between 11 and 15 September 2002, allow maximum daytime heating of the near-surface air as well as maximum radiative heat loss and cooling at night, producing a well defined diurnal cycle and large temperature range.

Settling this question would require detailed analysis of wind data and synoptic circulation patterns that is beyond the scope of the present analysis. What is clear, however, is that it is not possible to generalise the relationship between temperature in the vineyard and at Canberra, beyond stating that the two are closely associated; one is not always colder (or warmer) than the other, nor is the daily temperature range noticeably different.

The absence of a generalisable relationship between vineyard temperatures and those at Canberra does not mean that no such relationships exist. A similar analysis has been undertaken for Bungendore, to the south-east of Canberra and approximately 60 m higher in elevation (Figure 16a and b). Temperatures at the Bungendore site, both maximum and minimum, are clearly lower than at Canberra on almost all days in September and October 2001 and 2002. At least part of this difference may be due to the difference in elevation.

a




b

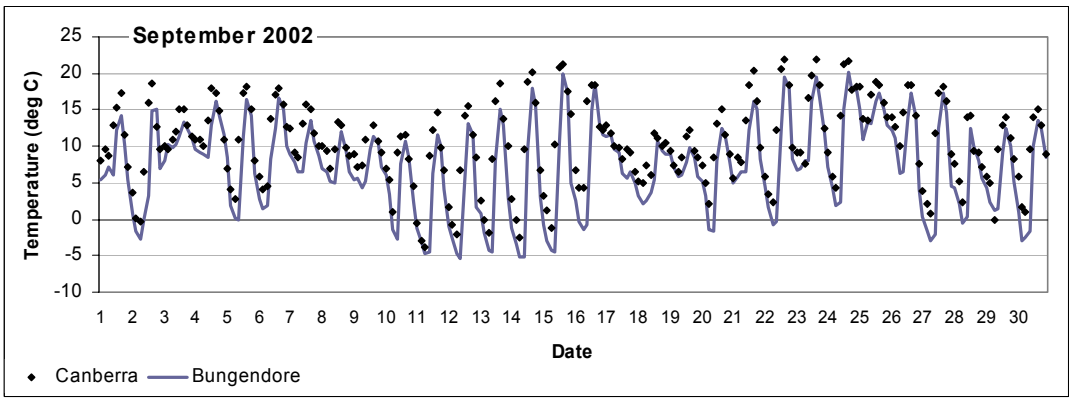



**Figure 16.** Three-hourly temperatures for September 2001 and 2002, at Canberra Airport and at Bungendore to the east of Canberra (Canberra data from the Australian Bureau of Meteorology; Bungendore data from M. Ball, pers. comm.).

Despite the lack of a broadly generalisable relationship between Canberra temperatures and those in the vineyard, it is possible to develop a simple statistical function to predict vineyard temperature from the temperature observed at Canberra Airport. For Quandialla the linear regression equation used to predict temperatures at the automatic weather station from temperatures at Canberra Airport is

$$y = -0.486+1.015x$$

where y = temperature at Quandialla, and x = temperature at Canberra Airport. The accuracy of the predictions is illustrated in Figure 17. There is no particular bias in the predictions, and the $R^2$ values of 0.91 in September 2001 and 0.93 in October 2001 show an excellent fit (which is replicated in the other spring months for which vineyard data are available for comparison).

A test application of the model to predict frost occurrence (sub-zero temperatures for at least two consecutive three-hour observations) modelled these events with 90% accuracy in September and October 2002.

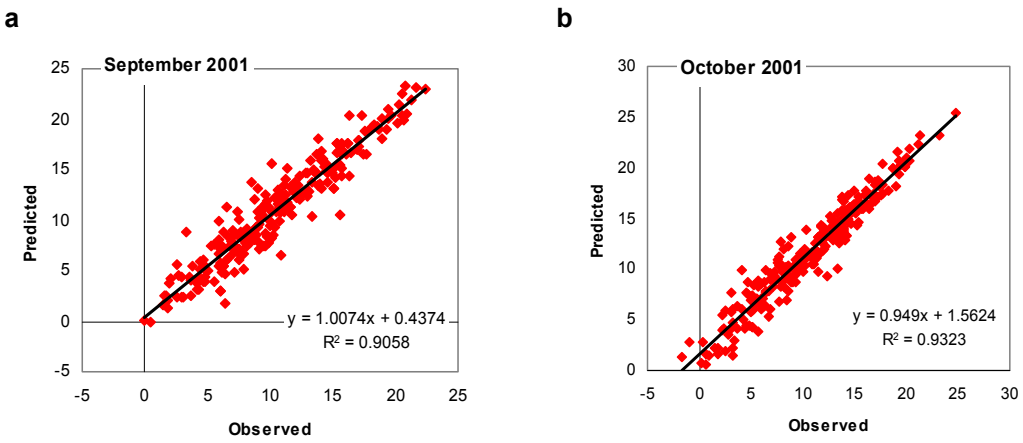



**Figure 17.** The relationship between observed and predicted three-hourly temperature at "Quandialla" near Murrumbateman. Predictions are based on observed temperatures at Canberra Airport (Canberra data from Bureau of Meteorology).

This simple approach shows that a useful predictive relationship can be established for temperatures at vineyards in the Murrumbateman area, based on temperatures observed at Canberra. When combined with the insight gained into the synoptic meteorological characteristics of cold air outbreaks affecting the Canberra region, such relationships could be used to provide targeted forecasts for the CVR. However, the statistical function may not apply to other sites in the area; its wider applicability would need to be tested using detailed temperature observations from other vineyard locations.

The local effects of topography must also be considered when applying such an approach; the prediction can be considered to apply only to the location of the weather station, unless its more widespread relevance can be shown. Topographic effects on temperature at one vineyard near Murrumbateman have been illustrated for this project by Koh (2000), who used data over a small number of nights to show that under calm, clear conditions the temperature profile closely mirrored the topography. Over a difference in elevation of only 25 m, temperatures were up to 5°C lower at the foot of the slope than at the crest in the pre-dawn period due to radiative cooling and katabatic drainage of cold air down-slope. Spatial modelling of temperature using topography as a conditioning variable would be a useful approach to addressing the problem of extrapolating the results presented here.

# 6 Management options

A range of options is available to growers seeking to manage frost risk, although some frost mitigation measures used overseas (such as wind machines and smoke pots) are less common in Australia. In advective frost events, when the cold air layer is particularly deep and nocturnal radiative cooling is not the sole mechanism producing sub-zero temperatures, neither of these approaches will work. If it is not possible to reduce radiative cooling, or to access a source of warmer air aloft to mix down to the surface, the available management options then focus on adding heat or moisture to the air around the vines, or applying cultural practices that offer either some degree of protection from frost, or of at least partial recovery from a killing frost (*e.g.* long-cane pruning)

Most growers surveyed in the Canberra region (65%) reported suffering some frost damage on average every two years. Although this is more likely to be due to radiative rather than the relatively rare advective frost events, it provides the impetus for 60% of growers to have implemented, or be considering, active measures for mitigation including

- Sprinkler systems: spraying the vines provides water that releases latent heat when it freezes, thereby warming the plant surface. However, in an advective frost event the sub-zero temperatures may persist for up to six hours, and substantial amounts of water would be needed. Supplies of water for this purpose may be severely limited by rainfall variability and drought. The system is also expensive to install.
- Polymer sprays: these chemical sprays reduce thermal conductivity and retain heat stored in the plant and soil. One Canberra-region grower reported 50% protection from damage in the October 1998 advective frost event in rows sprayed with polymer, compared with complete loss in the rows not sprayed in the same vineyard. This approach is costly to install and to use, however.

The majority of growers surveyed were aware of the passive measures available to attempt to avoided frost damage: 85% were using cultural practices such as trellising or maintaining short grass between the rows; 82% had planted their vines on slopes to aid cold air drainage; and 58% avoided topographic low points for planting. Slightly more than half of the experienced growers surveyed believed that passive measures were more effective than active ones. Those who were not intending to implement active measures cited cost rather than perceived effectiveness as a deterrent. Given the high costs of active mitigation strategies, there was considerable support from growers for accurate, targeted forecasting of advective frost events; fewer than 15% were able to anticipate the October 1998 event, and 77% considered that advance warning of such an event would be useful for their management decision making.

# 7 The role of changing climate

## 7.1 Temperature trends

Near-surface air temperature records from around the world show that annual average temperatures are increasing almost everywhere, with the most rapid increase in global average temperature observed since about 1980. South-eastern Australia conforms with observations elsewhere in this respect, as illustrated here using the Canberra temperature record (Figure 18). There is considerable interannual variability in temperature, but the underlying trend is clear. Average temperature has increased by almost 1°C since the 1950s, with a particularly strong trend in maximum temperature of ca 1.5°C. Minimum temperatures have warmed by ca 0.5°C, annually averaged.

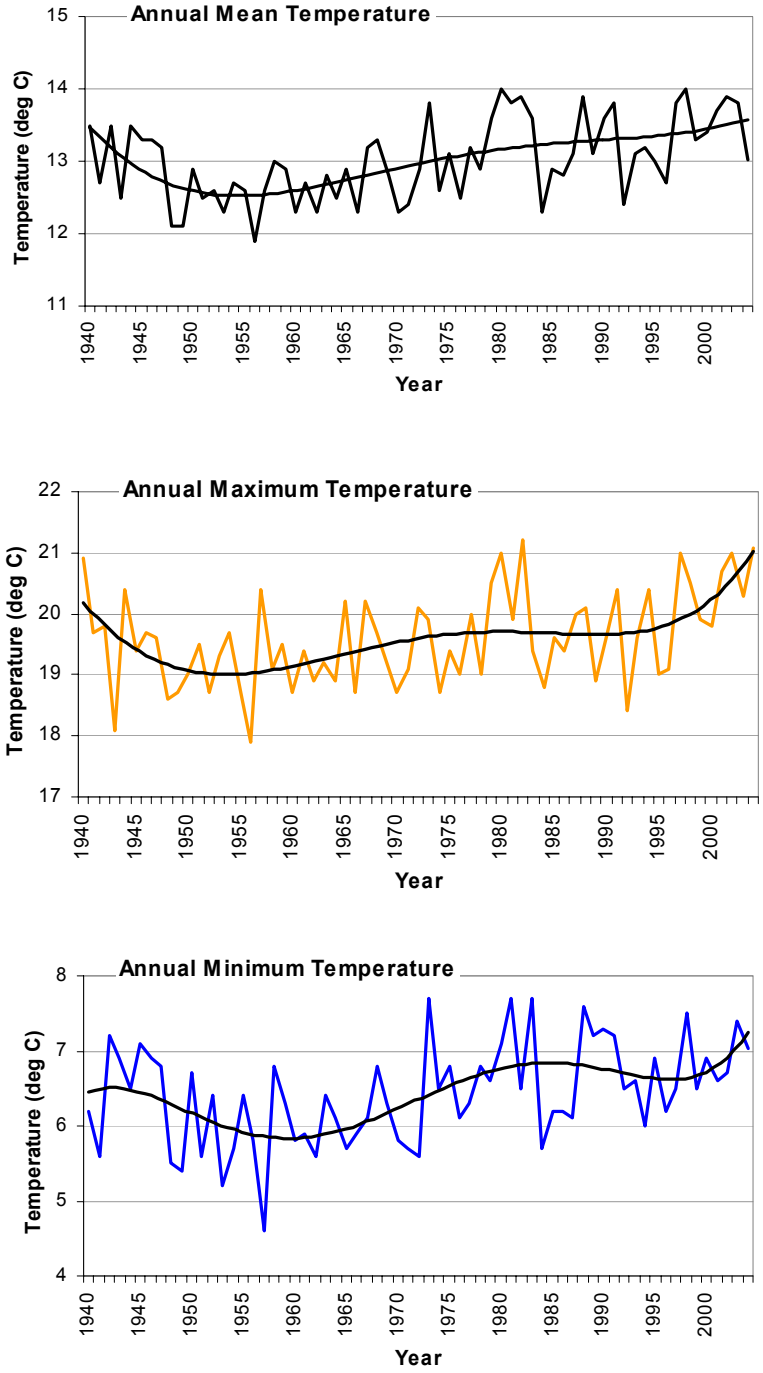



**Figure 18.** Temporal variation in annual averages of mean, maximum and minimum temperature at Canberra Airport, 1940-2004. Mean temperature is calculated as the average of daily maximum and minimum temperatures. Trend line is a fourth-order polynomial: $R^2$=0.35 (data: Bureau of Meteorology)

However, there is considerable intra-annual variation in the temperature increases. Comparing monthly minimum temperatures in the periods 1940-1959 with those in the 1980-1999 period (Figure 19a) shows warming in every month, but most significantly, relative to the average monthly temperature, in May, July, August and September (Figure 19b). (Note that mean annual minimum temperature in July is –

0.4°C.) In relation to spring frosts, Septembers were 42% warmer at night in the more recent period, and Octobers averaged 13% warmer. The increases in minimum temperature have occurred steadily through the period of record (Figure 19c), as illustrated for late winter and spring. Although none of these months shows a statistically significant temperature increase, the consistent trend is clear. Rising minimum temperatures are often associated with increasing cloud cover reducing radiative heat loss (e.g. Karl *et al.*, 1993). They could also reflect a change in the source/s of airmasses over a region; for example, an increase in frequency of winds with a northerly, rather than southerly, component across south-eastern Australia in spring would result in higher daytime and nighttime temperatures. Whatever the causes of the observed temperature increases, it is reasonable to suggest that the trend towards warmer nights should also be reflected in a decline in the occurrence of frost.

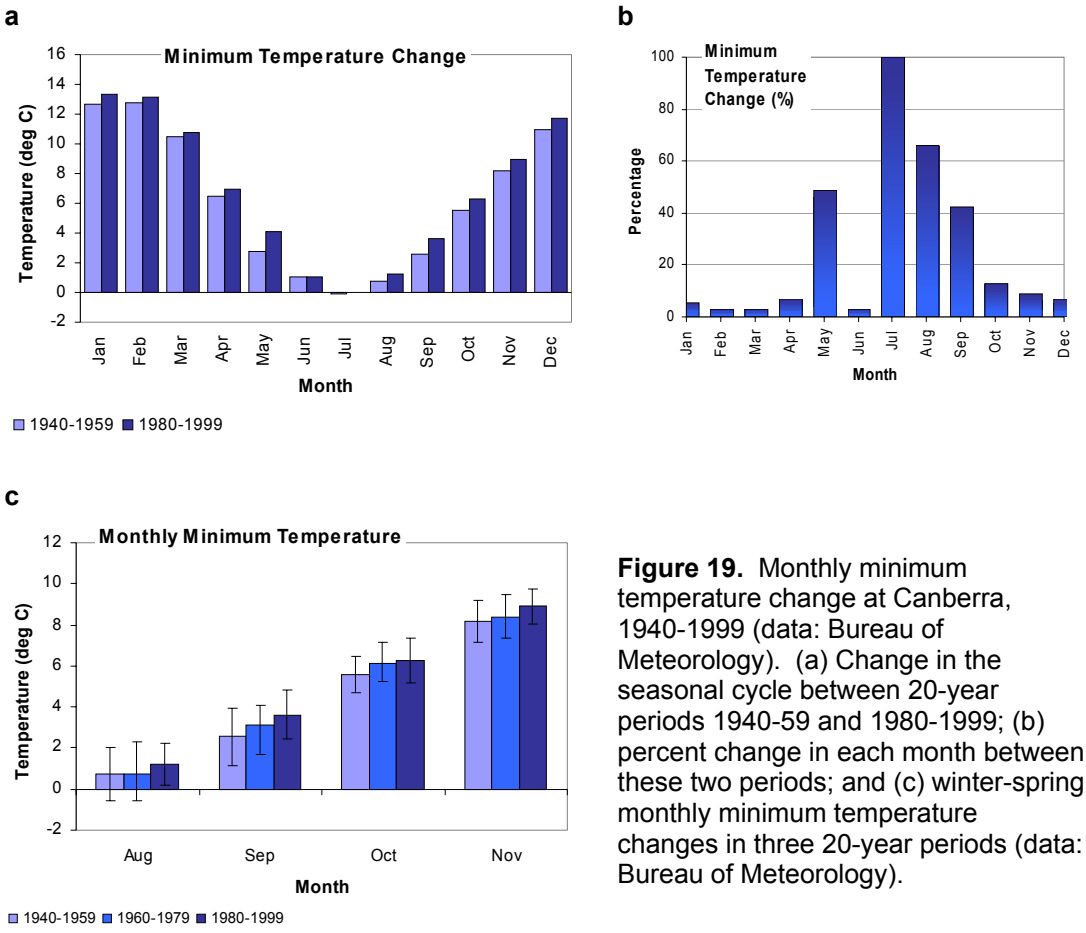



**Figure 19.** Monthly minimum temperature change at Canberra, 1940-1999 (data: Bureau of Meteorology). (a) Change in the seasonal cycle between 20-year periods 1940-59 and 1980-1999; (b) percent change in each month between these two periods; and (c) winter-spring monthly minimum temperature changes in three 20-year periods (data: Bureau of Meteorology).

## 7.2 Trends in frost occurrence

Frost occurrence has been reported at the Canberra Airport weather station since the beginning of the record in 1939; no distinction is made between radiative or advective frost, however. As expected, the trend in the annual number of days with frost (Figure 20) is inversely related to the trend in minimum temperature: there are generally more frosts when temperatures are lower. This is most apparent in the 1950s (1959 had the most frost days on record in Canberra, with 139) and 1960s. Frost occurrence then declines to a low of only 61 days in 1998. This is followed by

an increase to 127 days with frost in 2002 (which was also a warm year, particularly from April to December when large parts of Australia were in severe drought and record high temperatures were reached in many places). This suggests that the relationship between frost and temperature is not necessarily simple. It is possible, for example, that in particularly dry periods the clear skies and low humidity contribute to enhanced direct solar radiation during the day, contributing to higher daytime temperatures, and also to greater nocturnal radiative heat loss, resulting in more frosts. These relationships require further exploration.

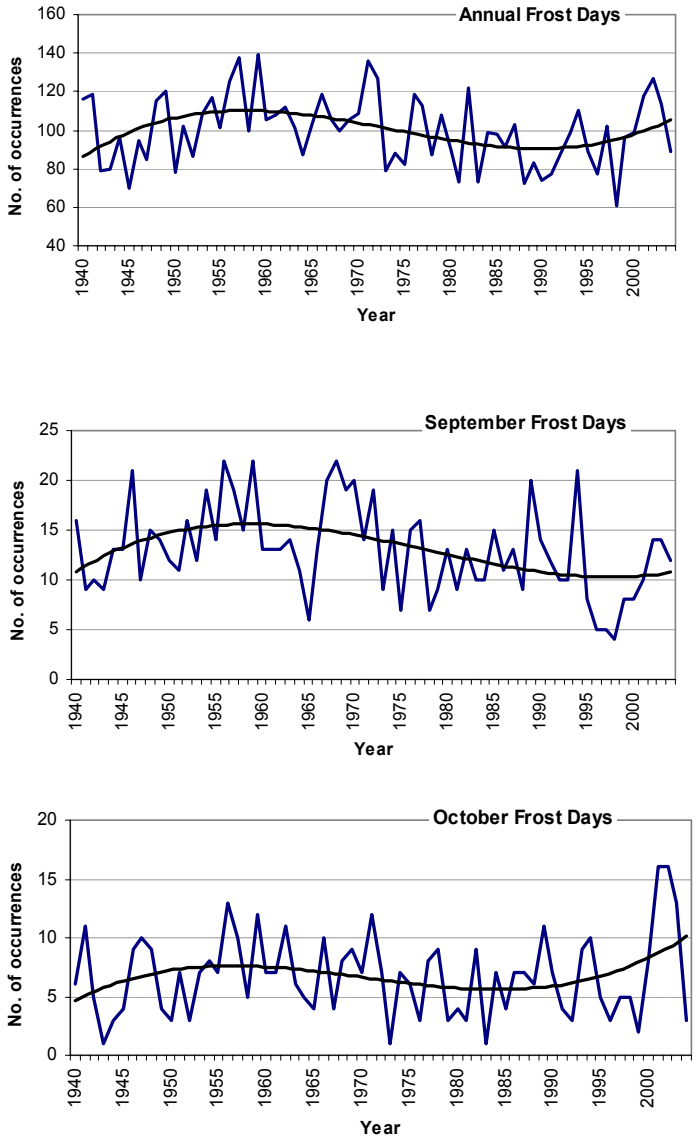



**Figure 20.** Temporal variation in annual averages of mean, maximum and minimum temperature at Canberra Airport, 1940-2004. Mean temperature is calculated as the average of daily maximum and minimum temperatures. Trend line is a fourth-order polynomial: $R^2$=0.35 (data: Bureau of Meteorology)

It is also apparent that there can be quite different trends in frost occurrence in different months: in September and October (Figure 20), for example, the general

trend towards fewer frosts since about 1960 is offset by peaks in frost occurrence in 1989 and 1994 (September), and in 2001 and 2002 (October). It is possible that frost occurrence, like rainfall, is showing evidence of seasonally-specific increases in interannual variability. Such changes in variability are a likely response to climate change (IPCC, 2001).

Both the general decline in frost occurrence over the period of the Canberra record (from 104 days per year in 1943-1975, to 95 days per year in 1976-2004), and the range of monthly frost occurrences possible in individual years, are illustrated in Figure 21. The reduction in frost occurrence is not statistically significant; it will be important to continue these observations into the future to confirm the trend. In 1959, the year with the most frosts on record for Canberra, frosts exceeded the long-term average in every month from March to October (Figure 21b). There was a particular peak in May, when nearly every day that month recorded frost. In 1998, by contrast, there were fewer frosts than average in every month from March to October, and particularly in September (Figure 21c). Clearly the degree of interannual variability in frost occurrence is large, and may be increasing in response to climate change.

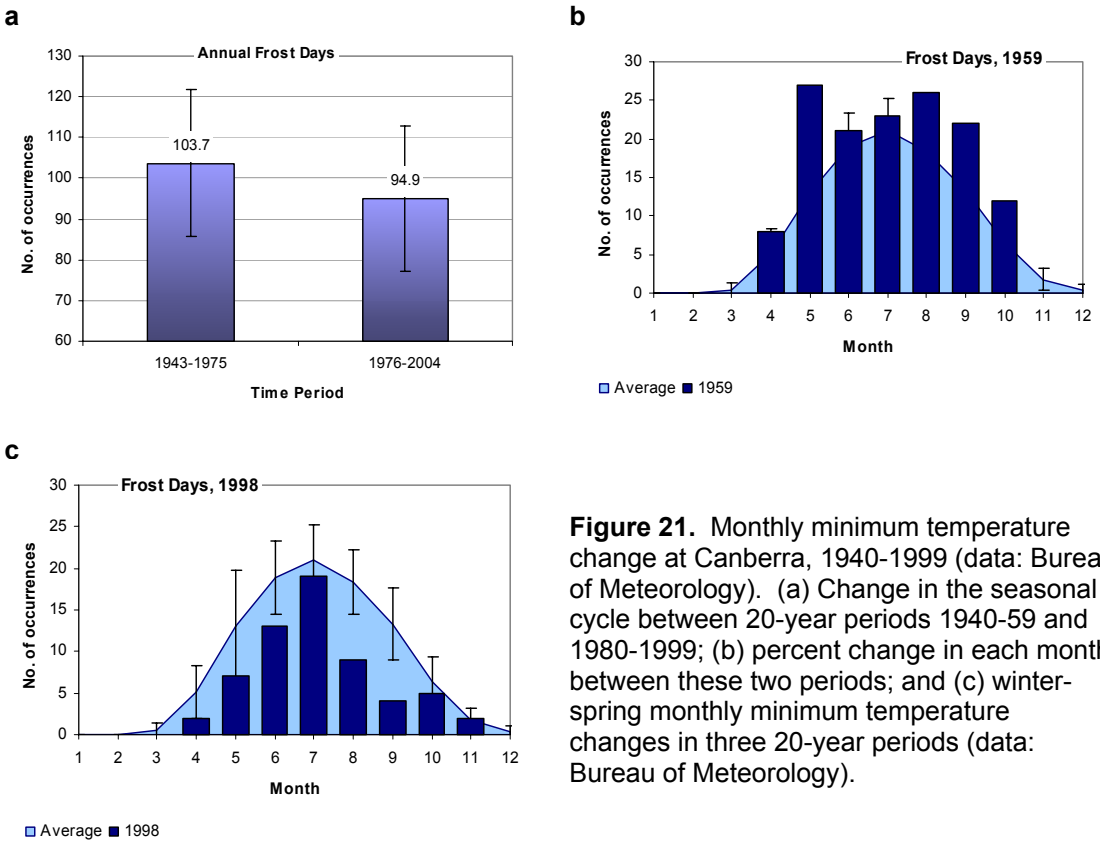



**Figure 21.** Monthly minimum temperature change at Canberra, 1940-1999 (data: Bureau of Meteorology). (a) Change in the seasonal cycle between 20-year periods 1940-59 and 1980-1999; (b) percent change in each month between these two periods; and (c) winter-spring monthly minimum temperature changes in three 20-year periods (data: Bureau of Meteorology).

## 7.3 Future temperature: implications for frost

The parameter about which there is the greatest scientific confidence in the climate change areas is temperature. All the principal global climate models produce scenarios of higher temperatures everywhere as the concentrations of greenhouse gases in the atmosphere increase (Houghton *et al.*, 2001). The projected temperature increases tend to be larger at high than low latitudes, and over the continents relative to the oceans. Scaling these broad projections to the regional

scale that is relevant for most decision making in natural resource management requires limited-area rather than global models. For Australia, CSIRO (CSIRO, 2001) has produced a synthesis of annual and seasonal climate change scenarios for the years 2030 and 2070 (by which time atmospheric carbon dioxide concentrations will have doubled relative to pre-industrial levels). The scenarios for winter and spring average temperatures are shown in Figure 22. Winter is the season with the smallest temperature increases in this analysis, whereas spring has one of the largest increases. Across south-eastern Australia it is likely that temperatures will be between 0.5 and 1.8°C higher by 2030, and between 1 and 6°C by 2070. Although an increase in average temperature of 1-2C may not seem significant, it is important to remember that this could also mean a larger change in either maximum or minimum temperature (as seen in the observational record to date); and that interannual variability of at least the magnitude experienced over the last 20-30 years is superimposed on the mean. If variability is increasing, it is likely that particularly high-temperature events will increase in frequency. It is also likely that frost frequency will continue to decline. This does not mean, however, that late advective frosts will no longer occur, as indicated by the case of October 1998 and the particularly high frost frequencies in spring of 2001 and 2002; the latter was a particularly warm year overall.

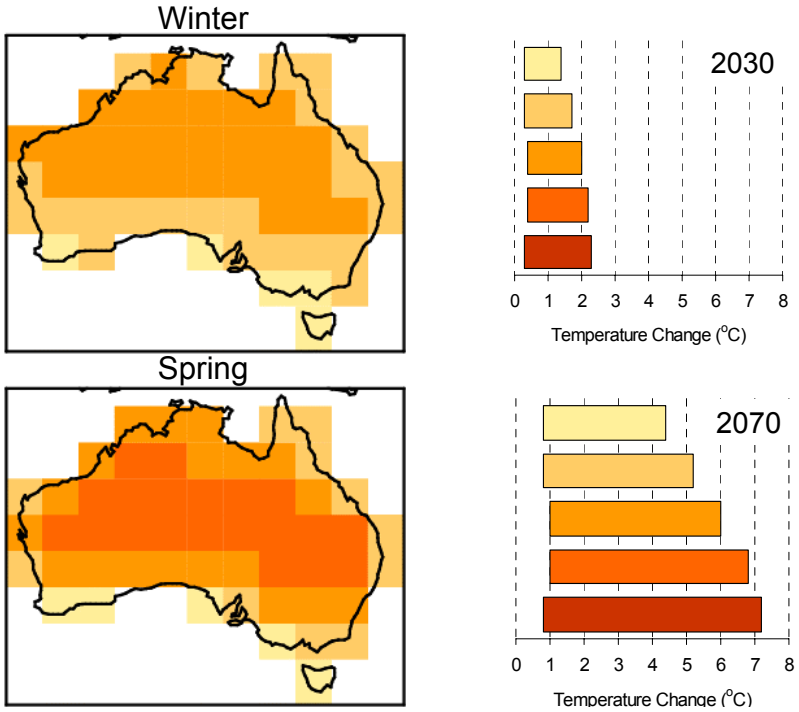



**Figure 22.** Scenarios for seasonal average temperature change in winter and spring, for 2030 and 2070. The range of possible future temperatures is indicated, based on a range of climate model projections (source: CSIRO Marine & Atmospheric Research)

There are a range of other considerations when thinking about the effects of climate change on any sector of agriculture. In addition to temperature change, alterations in the seasonality and amounts of rainfall and changes in humidity and in soil moisture could also be significant. The carbon dioxide fertilisation effect needs to be considered; in some plant types the additional growth promoted by rising carbon dioxide concentrations changes the water use efficiency of the plants, and may also

render some species more susceptible to frost damage at particular growth stages (Houghton *et al.*, 2001). Phenological studies, particularly in the northern hemisphere, show that bud-break is occurring progressively earlier in some plant types, and faunal breeding patterns are changing as warming proceeds. If this were to occur in vines, they would be susceptible to frost damage earlier than at present – perhaps in August rather than September or October.

# 8 Summary & conclusions

Frost damage to plants is a management issue for agriculture in the frost-prone areas of the world, not least Australia. Although several agricultural sectors are frost sensitive (*e.g.* grains and pome fruits), viticulture is particularly exposed to potential frost damage; the success of grape growing relies in part on a well-defined cold season, which limits the practice of viticulture to the southern half of Australia where frost is most common. The research reported here aimed to

- establish a general climatology of frost in the region, including consideration of the potential impacts of climate change on frost
- develop a synoptic climatology of advective frosts, to enhance understanding of the particular weather system characteristics associated with such frosts in the region
- investigate temperature aspects of the microclimatology of vineyards in the region, so that local-scale effects such as topography could be considered in relation to frost, and
- establish the relationship between temperature (and frost) in the viticulture region and that at the official Bureau of Meteorology weather station for Canberra, to contribute to targeted forecasting for the viticulture region.

A grower survey investigated the experience and knowledge of spring frosts in the region, as well as preferred methods to ameliorate the effects of late advective frosts, and the perceived utility of targeted frost forecasts.

The principal synoptic characteristics of spring cold air outbreaks (or late advective frosts) over south-eastern Australia have been determined from an analysis of a subset of 20 potential events, identified on the basis of temperature criteria. These characteristics include

1. The conjunction of a midlatitude depression (cyclone) and frontal system with a following anticyclone, usually observed as a well-developed anticyclone over the Bight
2. A south-to-north or north-east orientation of the isobars and airflow across south-eastern Australia in the area of interaction between the two systems
3. Relatively strong winds and rapid advection of the cold airmass across the region, so that low temperatures and humidity are maintained
4. Low temperatures during the day prior to the frost, due to the low temperature of the airmass
5. Establishment of an anticyclone (with high pressure, clear skies and light winds) in the afternoon or evening following the passage of the depression, so that radiative heat loss is maximised overnight

6. Low moisture content in the airmass both at and above the surface, to promote heat loss (water vapour absorbs outgoing longwave radiation, as do clouds)
7. On a hemispheric scale, a relatively high wave number (4 or above), and low zonal index, to promote meridional (north-south) transfer of airmasses

Knowledge of these synoptic characteristics of cold air outbreaks and advective frost events, coupled with sophisticated numerical weather forecast modelling by the Bureau of Meteorology, means that these events can now be forecast with some accuracy in terms of the general likelihood of occurrence, between one and three days in advance. The possibility of targeted local forecasting, which relies on specific knowledge of the modifications of general temperature conditions by local influences, primarily topography, has been increased substantially by the findings of the work relating temperatures observed in the vineyards to those at the official Bureau of Meteorology weather station at Canberra Airport, 40 km away. A simple predictive relationship has been established for temperatures at some vineyard locations in the Murrumbateman area, based on temperatures observed at Canberra Airport. Spatial modelling of temperature using topography as a conditioning variable would be a useful approach to addressing the problem of extrapolating these results.

The results of this work have been considered in the context of the general temperature climatology of the region, and of observed temperature and frost occurrence trends. In keeping with results reported elsewhere, both nationally and internationally, temperatures in the Canberra region have been increasing over the last two to three decades. The trends in minimum temperature are less marked than those in maximum temperature, but nights are generally becoming warmer. Frost occurrence in the region has declined over time, as is expected given the warming trend. In the spring months of September and October, however, the interannual variability of minimum temperature and of frost occurrence has been large in recent decades. Despite the general warming trend, it is clear that cold air outbreaks and associated late advective frosts have continued to occur; the relationship between higher annual mean temperatures and nocturnal minimum temperatures is not necessarily simple.

These results, together with the scenarios for future temperature (and rainfall, humidity and soil moisture) changes, suggest that while the climate continues to warm, spring advective frosts are likely to continue to occur, at least in the short to medium term. Growers should also be aware of other factors that could potentially affect vines in south-eastern Australia and elsewhere. These include impacts on plants from rising atmospheric carbon dioxide concentrations, possible changes to frost tolerance, and phenological changes as a result of changing temperature seasonality that could make vines susceptible to cold air outbreaks and frost in August, rather than October.

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