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A notable frost hollow at Coonabarabran, New South Wales

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Parallel observations taken for 28 months at two sites at Coonabarabran, New South Wales, show that topography has a dramatic influence on minimum temperatures at the two locations. Over the period of the study mean minimum temperatures at a valley site were 4.9°C lower than those at a plateau site 6.6 km away and 133 metres higher in elevation, with differences of up to 14.3°C occurring on individual nights. The results also indicate that the minimum temperature differences between the two sites are greater on clear nights than on cloudy nights, and are largely eliminated on nights where winds exceed 8 m s^{-1}. The observed minimum temperature differences imply a dramatic variation in frost risk, depending on local topography.

Introduction

Numerous studies have shown a substantial relationship between local topography and minimum temperatures, with a tendency towards warmer minima at hilltop sites and cooler minima at valley sites in the same area. The differences have generally been found to be greatest under clear, calm conditions, where extremes of stability are most likely to occur (Oke 1987), as air cools by long wave radiation at night and settles under gravity to the lowest part of a valley, and the consequent low-level inversions have the maximum opportunity to form without being broken down by winds mixing warmer air aloft down to the surface.

Local temperature differences can be very large, especially when snow cover is involved. The most famous example (Schmidt 1934) is the Gstettneralm hollow in the Austrian Alps. This is an enclosed depression with its base approximately 150 metres below the rim. On one occasion, with temperatures near -20°C in the upper parts of the hollow, -44.8°C was observed at the base. An almost equally extreme case was described by Hogan and Ferrick (1997), with ridge/valley differences of 16-18°C on one morning and inversions of up to 1.5°C/10 m elevation. Even in the absence of snow cover, numerous studies (e.g. Young 1920; Thompson 1973; Lindkvist et al. 2000) document ridge/valley differences of the order of 10°C on individual nights, and of 3-5°C in mean minimum temperatures over a period of time. Bootsma (1976) found that ridge/valley differences of up to 5°C could exist on clear nights in local relief as low as 20-30 metres.

Several studies (e.g. Bootsma 1976; Laughlin and Kalma 1987) have found that frost hollow magnitude (defined for these purposes as the temperature difference between the warmest and coldest site in a study area) is strongly influenced by cloud and wind, reducing with increased cloud amount and wind. Lindkvist et al. (2000) found that frost hollow magnitude in their study area approached zero once wind speeds reached a threshold of 8 m s^{-1}. Bootsma (1976) also evaluated the influence of a number of other variables (such as dew-point depression, cloud height and number of days since rain) on frost hollow magnitude and found that these had significantly less influence than cloud amount and wind.

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As a consequence of this dependence, there is typically considerable day-to-day variation in differences in minimum temperatures between ridge and valley sites, and hence the most extreme nights will show differences much greater than those found in long-term means. As an example, Laughlin and Kalma (1987) found differences in mean minimum temperature near 4°C in an area near Goulburn, New South Wales, with 150 m local relief, but differences of up to 14°C on individual nights.

Minimum temperatures tend to show their greatest dependence on topography on calm, clear nights. As the coldest nights are normally calm and clear (at least in most mid and high latitude climates), it follows that absolute minimum temperatures generally exhibit a greater dependence on local topography than mean minimum temperatures do. Catchpole (1963), in a (British) location where clear, calm nights are relatively rare, carried out a 20-year comparison between two neighbouring sites and found that, while mean minima were only 0.5°C lower at the valley site than the ridge site, absolute monthly minima over the 20-year period were up to 6°C colder at the valley site. The dependence of the variance of minimum temperature, as well as its mean, on topography was also demonstrated by Trewin and Trevitt (1996), who showed that ridge/valley differences at Inverell, New South Wales, were typically 3-4°C on the coldest 70 per cent of winter nights, but less than 1°C on the warmest five per cent.

Accurate information on minimum temperatures, particularly the risk of frost in specific locations, is of considerable economic importance. Late-season frosts caused substantial crop damage in southeastern Australia, with economic losses of millions of dollars, on several occasions in recent years (e.g. Bureau of Meteorology 1999). Accurate information on frost risk is therefore important for crop planning.

Most studies of the impact of topography on temperature have been based around dedicated field experiments taking place over a period of a few weeks or months, due to the difficulty (and expense) of maintaining a dense station network over an extended period of time. As the uncertainty in any estimates of mean daily temperature differences between sites (and of any other properties of their frequency distribution) decreases with an increasing number of observations, this limits the confidence that can be attached to the results of such studies. There have been few studies, particularly in Australia, which have involved comparisons of temperatures over periods longer than a year. This study is intended to partially address this gap, with the hope that a more extensive study can be carried out as the length of record available increases over time.

Sites and data availability

This study was carried out using two sites in the vicinity of Coonabarabran, New South Wales, both operated by the Australian Bureau of Meteorology. Temperature observations have taken place in the Coonabarabran area since 1879, with a second site being added in 2001. The two sites currently operating are:

- Namoi Street (31°16'S, 149°16'E, elevation 510 m, Bureau of Meteorology station number 64008). This site number has records since 1879, with observations at the present location commencing in 1994. It is located on vacant land near the edge of the town area, and in the base of a broad valley.
- Airport (31°20'S, 149°16'E, elevation 643 m, Bureau of Meteorology station number 64017). Observations commenced here in July 2001. The site is located on level ground near the top of a ridge, 6.6 km south of the Namoi Street site.

Both sites use a standard Stevenson screen, with manually read maximum and minimum thermometers at Namoi Street and an automated dry-bulb temperature sensor at the airport. Wind speed and direction and air temperature are continuously measured at the airport, whilst three-hourly observations (except at midnight) of cloud amount and current air temperature are made at Namoi Street. Observations are taken using local clock time. This is one hour ahead of standard time during the period of daylight saving time, which (during the years covered by this study) runs from late October to late March.

Maximum and minimum temperatures at the airport were only reported to whole degrees Celsius prior to July 2003 (when communications software was upgraded). Otherwise maximum and minimum temperatures were reported to the nearest 0.1°C. The effect of this is to introduce an additional, but unbiased, uncertainty of +/- 0.5°C into temperature differences between the sites prior to July 2003, due to the rounding practices employed.

Both sites are expected to continue operating for the foreseeable future (Parkinson, personal communication, 2002), although three-hourly observations, except at 0900 and 1500, ceased at Namoi Street in March 2005, after the end of the current study.

The data used in this study cover the period from July 2001 to October 2003. This period was somewhat drier than normal (rainfall for the 28-month period at Namoi Street was 84 per cent of the long-term average, and the calendar years of 2001, 2002 and 2003 all saw below-normal rainfall).

Days where the maximum or minimum temperature observations were missing at either site were not considered in the study. This affected 12 days (of a possible 851) for maximum temperature and nine days for minimum temperature.

Table 1. Mean and standard deviation of daily temperature differences between Namoi Street and airport site, July 2001-October 2003.

Season	*Temperature difference (°C) (Namoi St – airport)*					
	Maximum			*Minimum*		
	Mean	*SD*	*Number of obs*	*Mean*	*SD*	*Number of obs*
Autumn (Mar-May)	1.0	0.6	182	-5.0	3.1	184
Winter (Jun-Aug)	1.2	0.5	240	-6.0	3.7	239
Spring (Sep-Nov)	1.0	0.5	238	-5.2	3.9	239
Summer (Dec-Feb)	0.8	0.6	179	-3.0	3.1	179
All observations	1.0	0.6	839	-4.9	3.7	841

Temperature differences between the two sites

Table 1 shows differences in mean temperatures between the two sites. Over the year as a whole, mean maximum temperatures are 1.0°C cooler at the airport than at Namoi Street, whilst mean minimum temperatures are 4.9°C warmer. The differences in maximum temperatures show little seasonality, whilst the differences in minimum temperatures are greatest in winter, and least in summer.

As shown by the frequency distribution of temperature differences (Fig. 1), the differences in minimum temperatures between the sites also show much more day-to-day variability (standard deviation 3.7°C) than do those for maximum temperatures (standard deviation 0.6°C). The maximum temperature difference between Namoi Street and the airport lies between 0.0°C and 2.0°C on 95 per cent of all days, with the extreme values being +3.2°C and -1.3°C (a positive sign indicates Namoi Street is warmer). In marked contrast, Namoi Street has experienced minimum temperatures 10°C or more below those at the airport on nine per cent of all nights, but has been warmer than the airport on eleven per cent of nights (greatest difference 2.1°C). The greatest observed difference was 14.3°C on 10 November 2002, when the minimum temperature was 8.7°C at Namoi Street and 23.0°C at the airport.

Figure 2 shows mean three-hourly temperatures (except for midnight, when no data are available at Namoi Street) at the two sites for January and July. In January, Namoi Street is approximately 1.0°C warmer than the airport at each of the daytime observations, but is 1.2°C cooler by 2100 (which is about one hour after sunset), and is on average 3.5-4.0°C cooler at 0300 and 0600, immediately before sunrise. On July nights, large temperature differences develop quickly (1.8°C by 1800, 30-45 minutes after sunset, and 5.2°C by 2100), and are slower to dissipate, with Namoi Street still 3.0°C cooler at 0900. The lack of data at higher temporal resolutions make it impossible to compare the 0900 July observations with those at a similar length of time after sunrise in January (approximately 0800).

Fig. 1 Frequency distribution (1°C category widths) of differences between maximum and minimum temperatures at the two Coonabarabran sites.

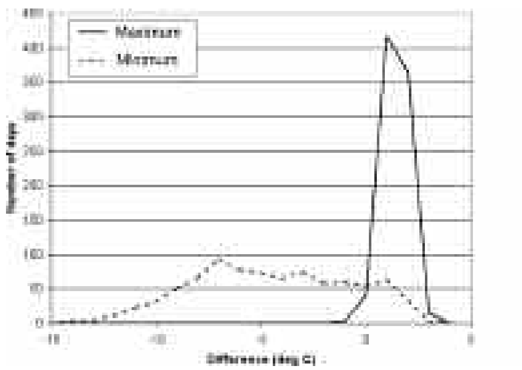


Fig. 2 Mean temperatures at three-hourly intervals at the two Coonabarabran sites for January and July.

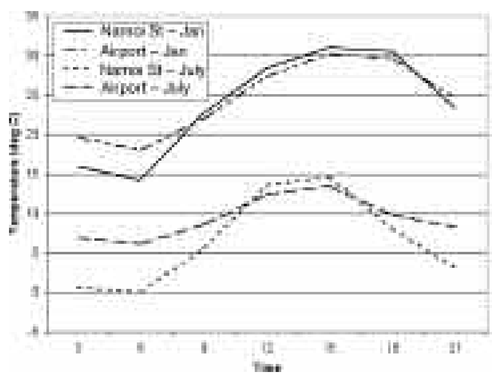
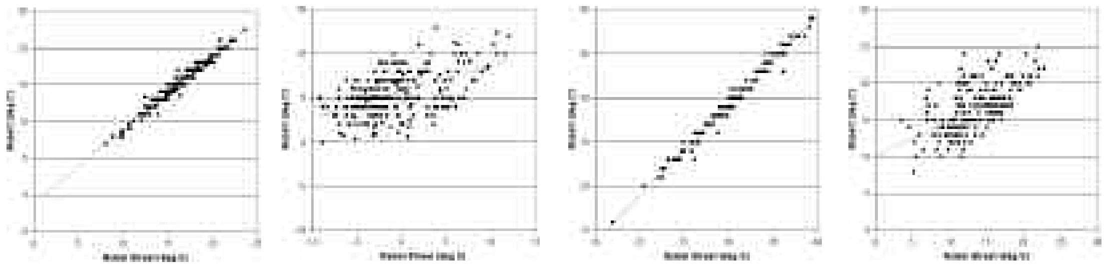


Figure 3 shows the relationship between temperatures recorded at the two sites. This shows that the difference in maximum temperature between the two

Fig. 3 Relationships between temperatures at the two Coonabarabran sites: (a) winter maxima; (b) winter minima; (c) summer maxima; (d) summer minima. The regression line of best fit is indicated by the dashed line.

(a) (b) (c) (d)



sites shows little dependence on temperature, with linear regressions between maximum temperatures at the two sites having slopes of 0.992 and 1.024 in winter and summer respectively. For minimum temperatures, however, the linear regression slopes are well below one, implying that the temperature difference between the sites is highly dependent on temperature, and in particular (by reference to the graphs) that minimum temperature differences between the sites are much greater on the colder nights. The relationship between daily minimum temperatures at the two sites is relatively weak for two sites so close to each other, with the regression on Namoi Street data explaining only 27 per cent of the variance of minima at the airport in winter, and 36 per cent in summer (compared with 96 and 98 per cent respectively for daily maxima).

This result is further reinforced in Table 2. In winter, the 10th percentile minimum temperatures differ by 7.6°C between the two sites, whilst the 90th percentile minima differ by only 3.0°C. The contrast is less dramatic, but still evident, in summer.

The large differences in minimum temperature between the two sites are reflected in large differences in the frequency of temperatures below specified thresholds. There were 196 days at Namoi Street during the period of the study with a minimum below 0°C and none at the airport, whilst for a threshold of 2°C the figures were 282 and 14 days respectively. It is particularly noteworthy that the airport did not record any minima below 0°C in the 28 months covered by this study, whilst Namoi Street reached -9.0°C on 12 July 2002, the lowest on record at any Coonabarabran site since 1957 (although it should be noted that the pre-1994 Coonabarabran site had somewhat warmer minima than Namoi Street). Given the extreme nature of the minima recorded in the 2002 winter, it seems reasonable to state that the airport site is virtually frost free, whereas Namoi Street has experienced an average of 65 nights per year with minima below 0°C in the 1994-2003 period, with median dates of the first and last nights with temperatures below 0°C being 11 May and 5 October respectively, and nights below 0°C recorded as early as 2 April (1995) and as late as 3 November (2003).

The data from the two sites also reinforce the result, found in studies such as Trewin and Trevitt (1996), that using mean temperature differences between paired sites may produce misleading results when data from one site are used to estimate the frequency of extremes at the other. In the case of Coonabarabran, using the observed differences in annual or seasonal means (as shown in Table 1), by adding the observed annual/seasonal (as appropriate) mean differences to each day's temperature at the airport, to estimate the frequency of minima below 0°C at Namoi Street significantly underestimates the actual frequency of such minima at Namoi Street (Table 3). This result is consistent with the results above which suggest that the largest temperature differences between the two sites occur on the coldest nights.

Influence of cloud and wind on minimum temperature differences

Observations made at 0300 and 0600 local time of cloud amount (in oktas, observed at Namoi Street) and wind speed (at the airport) were used to investigate the effect that cloud and wind have on the minimum temperature difference between the two Coonabarabran sites (Table 4). Where the sky at Namoi Street was obscured due to fog (which occurred only twice during the study period), the cloud amount was considered to be missing.

Table 2. Percentile points for minimum temperatures in winter (June-August) and summer (December-February) at the two Coonabarabran sites.

Percentile	*Winter (June-August) (°C)*			*Summer (December-February) (°C)*		
	Namoi St	*Airport*	*Difference*	*Namoi St*	*Airport*	*Difference*
10th	-5.4	2.2	-7.6	8.6	13.0	-4.4
50th	-0.9	5.0	-5.9	13.6	17.0	-3.4
90th	6.0	9.0	-3.0	18.5	21.0	-2.5

Table 3. Observed and estimated frequencies of minima below 0°C at Namoi Street, using daily data at the airport for July 2001-October 2003.

Actual number of days below 0°C	196
Estimated number of days below 0°C, using uniform 4.9°C adjustment to airport daily data	98
Estimated number of days below 0°C, using seasonal mean differences (Table 1) to adjust airport daily data	150

Table 4. Correlations between minimum temperature differences between the two sites and wind speed and cloud amounts.

Variable	*Correlation with daily minimum temperature difference*
0300 wind speed (airport)	0.19
0600 wind speed (airport)	0.21
0300 cloud amount (Namoi St)	0.41
0600 cloud amount (Namoi St)	0.39

These results suggest a significant (*t*-test, 99 per cent level) relationship between cloud amount and minimum temperature difference, and a less strong, but still significant (99 per cent level) relationship between wind speed and minimum temperature difference. An important caveat is that the wind observations, which are available only at the airport, may not be representative of conditions at a valley site such as Namoi Street and, in particular, that calm or near-calm conditions may prevail at Namoi Street even whilst there is some wind at the airport. Total cloud amount at Namoi Street, on the other hand, is likely also to be representative of the airport, except for the rare occasions when fog or very low cloud occurs in the valley. (There were only five days during the study period when fog was reported at Namoi Street at the 0300 or 0600 observation.)

The influence of cloud and wind on minimum temperature differences is further reinforced by the results shown in Table 5. Whilst the impact of wind speeds (at the airport) below 8 m s^{-1} on minimum temperature differences is modest, in the (limited) number of cases with winds exceeding 8 m s^{-1} there is generally little difference in minimum temperatures between the sites. This is consistent with the results of Lindkvist et al. (2000) who also found little topographic impact on minimum temperature when winds exceeded 8 m s^{-1} on exposed ground. Physically, this suggests that such a wind speed is sufficient to prevent the development of a diurnal temperature inversion, through dynamically driven mixing. The effect of cloud on minimum temperature differences is also evident, although large differences are not unknown even under overcast skies, with one instance (21 August 2002) of a difference of 9.9°C on a day with a mean 0300/0600 cloud amount of 7.5 oktas.

Conclusions and implications

The minimum temperature differences observed between the two Coonabarabran sites are the largest, both on an average and extreme basis, yet documented over an extended period in Australia for two sites associated within the same locality (apart from large metropolitan areas). It is likely that this reflects the lack of other examples of pairs of sites in close proximity to each other but showing a marked topographic contrast, rather than any specific characteristics of the Coonabarabran region. In particular, the topographic features of the Coonabarabran region are replicated in many areas in inland southeastern Australia, and short-term studies such as that at Goulburn (Laughlin and Kalma 1987), in an area with similar local relief to that which exists at Coonabarabran, suggest that the results of this study are potentially applicable throughout hilly parts of this region. Areas with much greater local relief (exceeding 1000 metres in places) exist near the mountains of southern New South Wales and northeastern Victoria, but no data are available to

Table 5. Effect of variations in cloud amount and wind speed on minimum temperature differences between the two sites.

Mean cloud amount ((0300+0600)/2) (oktas)	*Mean minimum temperature difference (Namoi St – airport) (°C)*	*Number of days*
0-0.5	-6.2	434
1.0-2.5	-5.0	122
3.0-5.0	-4.0	119
5.5-7.0	-2.5	63
7.5-8.0	-1.3	68

Mean wind speed ((0300+0600)/2) (m s^{-1})	*Mean minimum temperature difference (°C)*	*Number of days*
0-3.9	-5.6	505
4.0-7.9	-4.0	314
≥8.0	-0.5	16

investigate whether additional local relief creates minimum temperature differences significantly greater than those observed at Coonabarabran.

The results from this study, in conjunction with other cited work, suggest that the existing temperature station network, with typical mean station spacings of 50-80 kilometres in inland southeastern Australia, is generally not sufficient to resolve variations occurring on a scale of a few kilometres (or less). While such densities have previously been shown to be sufficient for describing Australia's large-scale climate variability and change (Jones and Trewin 2002), they are clearly insufficient for describing the micro-climate of topographically diverse regions. Historically, many observations have also taken place at (often poorly exposed) sites near the centre of country towns which are not necessarily representative of the surrounding area, although over the last ten years there has been a marked trend for observations to move to airports or other non-town centre locations.

The results of this study are also important in the context of maintaining homogeneous long-term observations of temperature through adjustments based on overlapping data at an old and new site. Guidelines for the GCOS Surface Network (GCOS 2002) indicate that the maximum acceptable bias for a 'homogeneous' series is 0.3°C, with a target of 0.1°C under ideal conditions. In the case of minimum temperatures at Coonabarabran, the standard deviation of the daily temperature differences (Table 1) ranges from 3.1°C to 3.7°C depending on season, suggesting that the number of observations required for the confidence interval of a mean temperature adjustment to be within +/- 0.3°C (Student's *t*-test) is between 420 and 680, and consequently that, for such a confidence interval to be achieved, two years of annual data are sufficient, but 4-8 years of seasonal data would be required. Whilst an evaluation of the uncertainties involved in the adjustment of daily data along the lines of the procedures used in Trewin (2001) is beyond the scope of this paper, it is likely that an even longer period of parallel data would be required in order to obtain an estimate of likely extreme daily values within a confidence interval of +/- 0.3°C. While Coonabarabran is clearly an extreme case, these results suggest that a period of parallel observations between an old and a new site may not be sufficient to produce a homogeneous dataset if the two sites contrast strongly in topography, or possibly in other ways.

The results of this study suggest that interpolation of minimum temperature and frost occurrence data at a point using observations taken elsewhere is a highly complex problem. A study is currently in progress (Hayman, personal communication), with the aim of assessing, using very dense observations over four experimental sites, how temperature variations at the farm level can be modelled using data from a single station as a reference point. The results obtained here suggest that information on wind and cloud, as well as temperature, will be important in the effective mapping of frost risk at the farm level.

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