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Climate variability, climate change and the Australian snow season

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Maximum winter snow depth at Spencers Creek in the Snowy Mountains of southeastern Australia has decreased somewhat since 1962, but the snow depth in spring has declined strongly (by about 40 per cent). The stronger decrease in spring snow depth is largely attributable to warming during July-September. The slight decline in precipitation that has been observed during this season is too weak to account for the decline in snow depth. Interannual variations in regional surface air pressure are closely related to snow depth, but there is only a weak trend in pressure and this trend is insufficient to account for the decline in spring snow depth. Thus the warming that is the proximate cause of the decline in spring snow depth is not simply reflecting a change in the synoptic patterns. In the light of recent studies implicating the enhanced greenhouse effect in the warming trend over Australia, the results of this study suggest that the Australian alpine region may already be experiencing significant effects of greenhouse climate change.

Introduction

'Alpine systems are generally considered to be among the most vulnerable to future climate change' (Hughes 2003), and changes in snow depth and cover in the Australian mountains would likely affect many animals. For instance, the Pygmy Possum depends on snow cover for stable, low temperatures during hibernation (Walter and Broome 1998). In years of shallow snow cover populations of Dusky Antechinus and Broad-toothed Rats decline, presumably because of increased predation by foxes when snow is reduced (Green and Osborne 1981). Hughes (2003) and Green (2002) summarise evidence of shifts in vertebrate ranges to higher elevations and toward earlier arrival of migratory bird species in the Australian alpine zone in the last few decades. As well, the Australian ski industry could be affected by changes in snow cover, and changes in snow cover may also affect the seasonality of runoff (Beniston 2003). It seems important, therefore, to determine whether the snow cover has been changing and, if so, to determine the causes of this change.

Diaz et al. (2003) reported a decline in snow cover in many areas where temperature has been increasing over the past 50 years, but did not examine the relatively small alpine areas of Australia. Many researchers have investigated snow cover records in the Australian Snowy Mountains. Budin (1985) examined snow-depth data at several locations in southeast Australia, and demonstrated that high snow depth occurred in years with stronger than normal westerly winds over the southeast. Slatyer et al. (1985) developed an empirical model of the length of the snow season incorporating

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effects of both temperature and precipitation. (According to Galloway (1988) this model indicated that a temperature rise of 2°C coupled with a 20 per cent fall in precipitation would reduce snow season length to values expected at elevations 267 metres lower.) Ruddell et al. (1990) determined statistical relationships between snow cover and winter precipitation and temperature, but found no evidence of a statistically significant trend in long-term variations of snow cover. Duus (1992) developed an empirical model to estimate the annual snow cover at Spencers Creek in the Snowy Mountains, based on precipitation and temperature observations. He reported a relationship predicting the snow depth at Spencers Creek at the end of August, based on the observed June-August average temperature and total rainfall. Duus used this relationship to estimate a measure of a season's snow cover from 1910 to 1968, based on observed climate data. He examined the trends from these estimates and observed cover from 1954 to 1991 but did not find evidence of a statistically significant linear trend. Haylock et al. (1994) and Whetton et al. (1996, 1998) used the model of Galloway (1988) to estimate snow depth and cover at southeast Australian sites, and to estimate the influence of climate change on snow season duration. They found that a warming of 3°C would reduce the snow season to close to zero days at many locations. In a Macquarie University study, Slater (1995) reported a decreasing trend in snow depth at Spencers Creek from 1954 to 1993, but was unable to find clear relationships with other variables (e.g. temperature, atmospheric pressure) that would explain this trend. Osborne et al. (1998) found no statistically significant trend in the duration of snow cover, or the start and end dates of the snow season at Spencers Creek from 1954 to 1996. They did report a gradual decline in snow cover (calculated by multiplying mean snow depth for each year by the number of days of continuous snow cover) from the early 1960s to the late 1980s, followed by a weak increase. Green and Pickering (2002) extended the snow depth cover index of Osborne et al. (1998) up to 1999 and demonstrated that the downward trend in this index had resumed from the mid-1990s. Hennessy et al. (2003) found a weak decline in maximum snow depth in three out of four sites examined from the mid-1950s to 2002, including Spencers Creek, and a moderate decline in snow depth in August and September. They speculated that this difference in the strength of the decline, between maximum snow depth and late season snow depth may reflect a tendency for mid-late season snow depth to be driven by ablation, while early season snow depth may be more driven by precipitation.

In summary, research on Australian snow cover trends, thus far, has reported observed trends in some, but not all, measures of snow cover, and no convincing explanation for these trends, nor for why some indices do not exhibit such trends, has been advanced. In this study data from Spencers Creek from 1962 to 2002, temperature and precipitation data from Cabramurra, and sea-level pressure data (from Melbourne and from NCEP/NCAR reanalyses) are used to document the causes of declines in spring snow depth in the Snowy Mountains.

Data and methodology

Snow-depth data from Spencers Creek (elevation 1830 m grid reference 8525 Kosciusko 205677) were provided by the Snowy Mountains Hydro-Electric Authority. These data are observed every few days through the snow season. Budin (1985) and Ruddell et al. (1990) discuss the nature and quality of the snow-depth data. Two indices of snow depth were derived from these data. The first index was the maximum snow depth recorded in each year; the second index was the snow depth recorded in the first observation in October each year. The second index provided a simple measure of mid-spring snow depth and would provide an indicator of whether the snow season would end early or late. Trends in these two indices were examined. Spencers Creek data were used because they provide a series with few breaks (Slater 1995).

The relationships between the two snow-depth indices and mean maximum temperatures and precipitation at the nearby climate station, Cabramurra (148°23'E, 35°56'S, elevation 1482 m), were calculated. The intention of this part of the study was to determine whether temperature or precipitation (or both variables) contributed to any trends in the snow-depth indices. Cabramurra temperature data are only available from 1962 (although precipitation data were available from 1955), so only snow data from 1962 onwards were examined in this study. The manually operated climate station ceased operation in 1999, but an automatic weather station (AWS) was opened in 1996. In this study the AWS data from 1997 are used with the earlier (1962-1996) data from the manually operated station, without correcting for changes between the two stations. The analyses described below, however, were repeated after adjusting the earlier data by the difference in mean temperatures and precipitation between the manual station and the AWS in the overlapping years of 1997 and 1998. None of the conclusions reached in this paper would be altered if these adjusted data were used instead of the unadjusted data. Temperature data are not available for June 1986, so this year was generally omitted from the analyses that required June temperatures. The correlations reported below use 40 years of data.

The snow-depth data were also correlated with sea-level pressure data from Melbourne Regional Office (144°58’E, 37°49’S) and with sea-level pressure from the NCEP/NCAR Reanalysis (Kistler et al. 2001). The correlations with the reanalysis data were calculated on the Climate Explorer website (http://climexp.knmi.nl) maintained by Geert Jan van Oldenborgh. The purpose of these correlations was to explore the larger scale synoptic causes of the trends in snow depth, i.e. to determine whether they were associated with changes in synoptic activity.

Locations of all stations referred to are indicated in Fig. 1.

Results

Trends in snow depth at Spencers Creek

Yearly values of the two snow-depth indices from 1962 to 2002, along with linear trend lines, are shown in Fig. 2. The two variables are closely related (r = 0.85), but the snow depth at the first October observation shows a stronger downward trend (correlation with year, r = -0.26) than does the maximum snow depth (correlation with year, r = -0.09). The decline in the depth of the first observation in October is substantial, from around 175 cm in the early 1960s to about 100 cm by 2002 (although there is substantial interannual variability around these means), i.e. a decline of about 40 per cent over 40 years. The decline in the maximum snow depth was from about 210 cm to about 190 cm, i.e. only about 10 per cent.

Fig. 1 **Locations of Spencers Creek, Cabramurra, and Melbourne.**

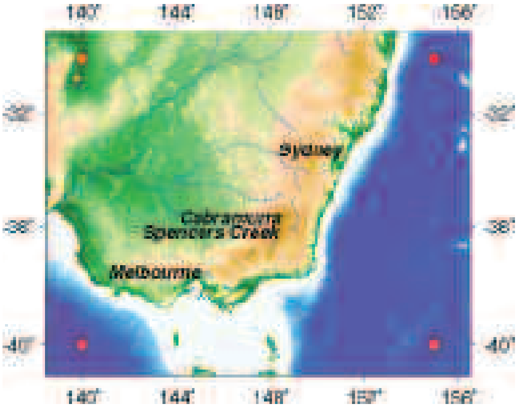
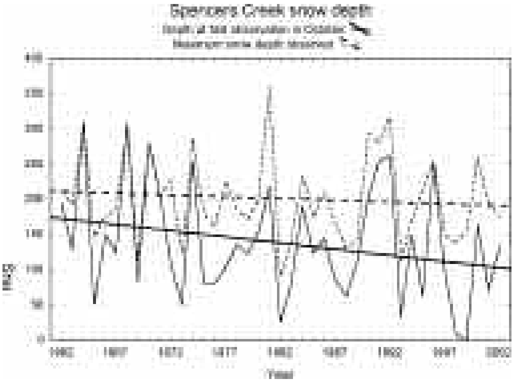


Fig. 2 **Time series of maximum snow depth (broken line) and snow depth at first observation in October (solid line) at Spencers Creek. Linear trends indicated with thick lines.**



Relationships between snow depth, temperature and precipitation

The maximum snow depth is strongly correlated with Cabramurra winter (June to August) total precipitation (r = 0.67) and mean maximum temperature (r = -0.64). Time series of these three variables are shown in Figs 3 and 4, illustrating the close relationship between the snow depth and the two climate variables. The interannual variations of snow depth and temperature are very closely related, especially in the first two decades of the record (Fig. 4), but the temperature exhibits a strong warming trend whereas the trend in snow depth is weak. This difference in trends explains why the correlation of snow depth with precipitation (Fig. 3) is stronger than that with temperature. The strong temperature trend, because it is not matched by a strong trend in the snow depth, degrades the correlation evident in the year-to-year variations. The trend in precipitation at Cabramurra is also weak as is the case with the snow-depth trend, so the correlation arising from the interannual variations is not degraded by one variable exhibiting a strong trend. Detrending the three time series, by calculating differences from year to year, and then calculating the linear correlation between these differenced variables confirms that the trend in the temperature is degrading the correlation between temperature and snow depth. The correlation between these two variables increases in magnitude to – 0.72 on the differenced variables, whereas the correlation between the year-to-year differences of maximum snow depth and winter precipitation only increases to 0.70. That is, the correlation of the differenced snow-depth data (i.e. the interannual variations) with temperature is stronger than with rainfall.

Fig. 3 Maximum snow depth at Spencers Creek (broken line) and total winter precipitation at Cabramurra (solid line). Linear trends indicated with thick lines.

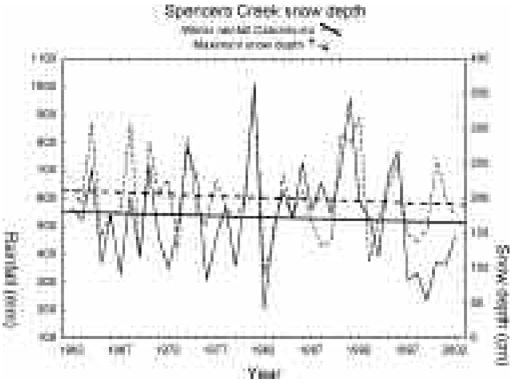


Fig. 4 Maximum snow depth at Spencers Creek (broken line) and mean winter maximum temperature at Cabramurra (solid line). Linear trends indicated with thick lines. Note inverted scale for temperature.

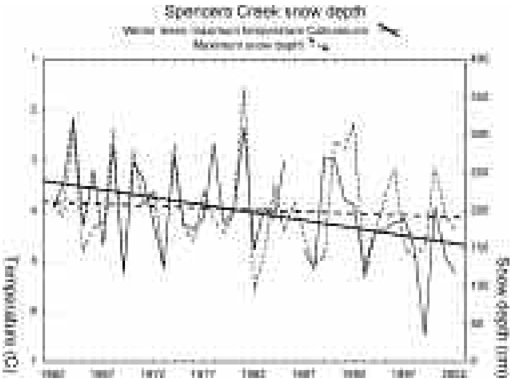
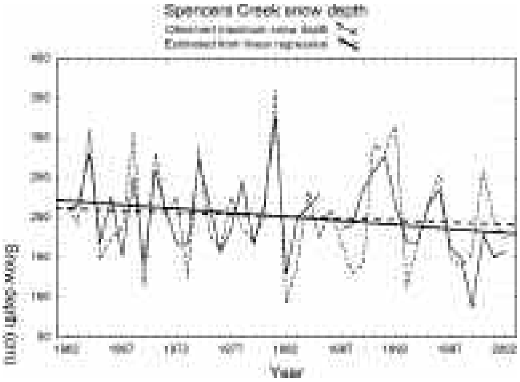


Fig. 5 Maximum snow depth observed at Spencers Creek (broken line) and estimated from linear regression with Cabramurra winter mean maximum temperature and winter total precipitation as predictors (solid line). Linear trends shown with thick lines.



Multiple linear regression was used to develop an equation to estimate Spencers Creek maximum snow depth from Cabramurra winter mean maximum temperature and winter total precipitation. The regression equation is:

$$\text{Maximum snow depth} = 226.8 - 27.52\,\text{MaxT} + 0.16\,\text{Precipitation}$$

where 'MaxT' is winter mean maximum temperature at Cabramurra. The multiple correlation was 0.74, and the partial correlations of maximum snow depth with mean maximum temperature and precipitation were -0.44 and 0.49 respectively. Thus the two independent variables contribute similar amounts to explaining the variance of maximum snow depth. Figure 5 shows the observed maximum snow depth and the snow depth estimated from the above equation. The equation reproduces most of the variability, but the estimates for the last four years are consistently underestimated. Possible causes of this bias are discussed later.

Simple linear regressions were also calculated, using (separately) the June-August mean maximum temperature and the total July-September precipitation, to estimate the maximum snow depth. These are shown in Fig. 6, along with the observed snow depth. Comparison of the trends in the observed and estimated snow depth can provide a guide to how much of the decline in snow depth can be attributed to each of the two variables. The snow depth estimated from the precipitation observations exhibits a downward trend, although this is somewhat weaker than the observed trend. The trend in snow depth estimated from the temperature alone is considerably stronger than that observed. This indicates that the decline in precipitation is not sufficient to completely explain the decline in maximum snow depth. On the other hand, the warming is too strong to account for the rather small decline in maximum snow depth. Some combination of the weak decline in precipitation, coupled with the stronger warming, seems to be a better fit to the observed decline (Fig. 5).

Fig. 6 **Maximum snow depth observed at Spencers Creek (solid line) and estimated from linear regressions with Cabramurra June-August mean maximum temperature and total precipitation (separately) as predictors (broken lines). Linear trends shown with thick lines.**

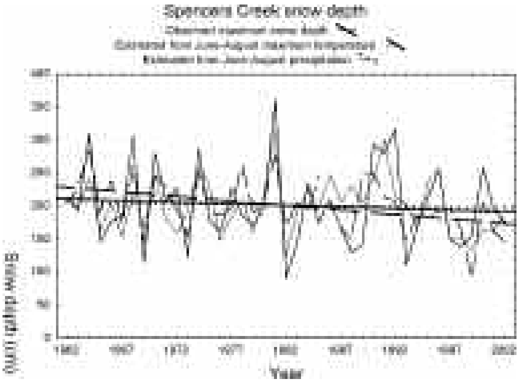


Fig. 7 **Snow depth at Spencers Creek at first observation in October (broken line) and total July-September precipitation at Cabramurra (solid line). Linear trends indicated with thick lines.**

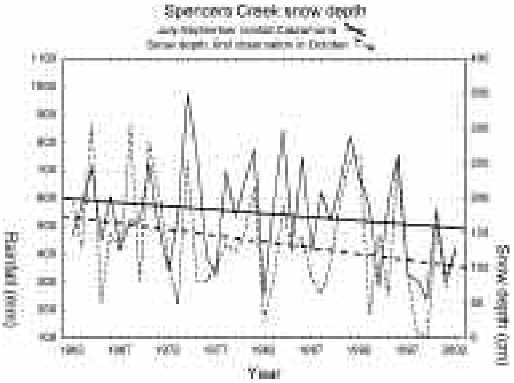
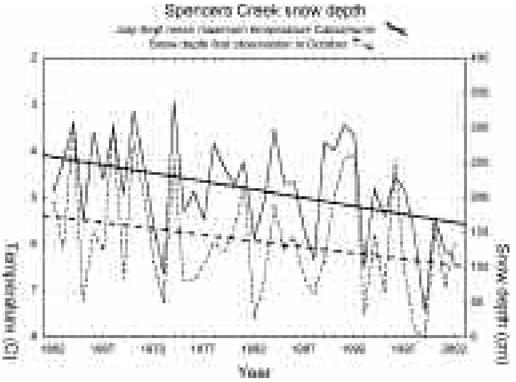


Fig. 8 **Snow depth at Spencers Creek at first observation in October (broken line) and mean July-September maximum temperature at Cabramurra (solid line). Linear trends indicated with thick lines. Note inverted scale for temperature.**



The above analysis was repeated using snow depth in the first observation in October, in place of the maximum snow depth, and using July-September values of the climate variables instead of winter (June-August), although no substantial difference in the results occurs if winter values were used here. The snow depth in the first observation in October is strongly correlated with Cabramurra July-September total precipitation (r = 0.62) and mean maximum temperature (r = -0.81). Time series of these three variables are shown in Figs 7 and 8, illustrating the close relationship between the snow depth and the two climate variables. All three variables exhibit trends, although the precipitation trend is weaker than the others (correlations of the variables with year are -0.26 (early October snow), 0.40 (temperature), and -0.19 (precipitation)).

Multiple linear regression was again used to develop an equation to estimate Spencers Creek snow depth in the first observation in October, this time using Cabramurra July-September mean maximum temperature and total precipitation. The regression equation is:

$$\text{October snow depth} = 357.71 – 54.21\ \text{MaxT} + 0.08\ \text{Precipitation}$$

where 'MaxT' is July-September mean maximum temperature at Cabramurra. The multiple correlation was 0.82, and the partial correlations of maximum snow depth with mean maximum temperature and precipitation were -0.69 and 0.22 respectively. Thus the mean maximum temperature contributes substantially more than does precipitation to explaining the variance of October snow depth. Figure 9 shows the observed October snow depth and the snow depth estimated from the above equation. The equation reproduces most of the variability, including a very good estimate of the downward trend, in October snow depth, but the estimates for the last four years are somewhat underestimated. Again, the possible causes of this bias will be discussed later.

Fig. 9 **Snow depth observed at Spencers Creek in first observation in October (broken line) and estimated from linear regression with Cabramurra July-September mean maximum temperature and total precipitation as predictors (solid line). Linear trends shown with think lines.**

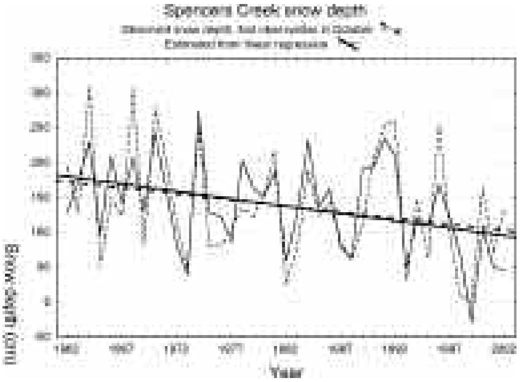
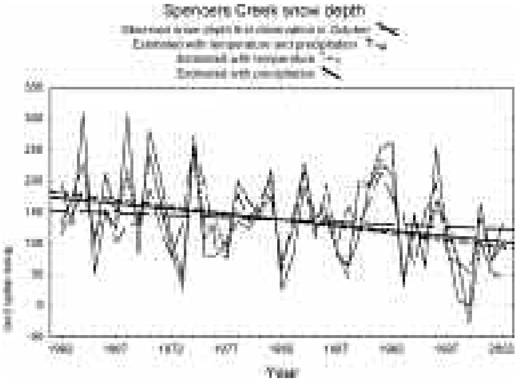


Fig. 10 **Snow depth observed at Spencers Creek in first observation in October (solid line) and estimated from linear regressions with Cabramurra July-September mean maximum temperature and total precipitation together as predictors, and separately (broken lines). Linear trends shown with thick lines.**



Simple linear regressions were also calculated, using (separately) the July-September mean maximum temperature and the total July-September precipitation, to estimate the snow depth at the first observation in October. These are shown in Fig. 10, along with the observed snow depth and that estimated from the multiple linear regression using temperature and precipitation (together) as predictors. Comparison of the trends in the observed and estimated snow depth can provide a guide to how much of the decline in snow depth can be attributed to each of the two variables. The snow depth estimated from the precipitation observations exhibits a downward trend, but this is substantially weaker than the observed trend. The trend in snow depth estimated from the temperature alone is slightly stronger than that observed, and is almost identical to that using both temperature and precipitation as predictors. This indicates that the decline in precipitation is not sufficient to explain the decline in snow depth in October. On the other hand, the warming is sufficient to account for the decline in snow depth. Estimating the snow-depth trend using both temperature and precipitation does not substantially improve the fit to the observed snow depth, or to the trend in snow depth (compared with the fit from just using temperature).

Relationships between snow depth and large-scale atmospheric fields

The above discussion demonstrates that local warming is the factor leading to the observed decline in snow depth in spring but that warming is not leading to a strong decline in maximum snow depth. Here the question of whether this relationship between trends in snow depth and temperature related to synoptic changes in the Australian region is addressed. We do this by first correlating variations in snow depth with surface atmospheric pressure from the NCEP/NCAR Reanalyses (Kistler et al. 2001).

Figure 11 shows the correlation between the snow depth at Spencers Creek in the first observation in October and atmospheric pressure averaged over July-September. Strong negative correlations exist with pressure southeast of the Snowy Mountains, reaching a maximum magnitude exceeding 0.8 between Tasmania and New Zealand. In years when pressures are low in this region there would be anomalous southwesterly flow across the Snowy Mountains and this would be accompanied by increased precipitation and cooler temperatures. This would increase snowfall and delay melting.

The extent to which trends in atmospheric pressure could explain the trend in snow depth at Spencers Creek was assessed by calculating the linear regression between snow depth and Melbourne Regional Office 9 am mean sea-level pressure for July-September. This regression was then used, with observed pressure, to estimate the snow depth. Figure 12 shows the time series of this estimated snow depth, along with the observed snow depth at the first observation in October. As expected from the very strong correlations shown in Fig. 11 (the correlation between snow depth and Melbourne pressure was -0.75) the interannual variations are very similar. However, the

Fig. 11 **Correlation between Spencers Creek snow depth in first observation in October, and sea-level pressure from NCEP/NCAR reanalyses.**

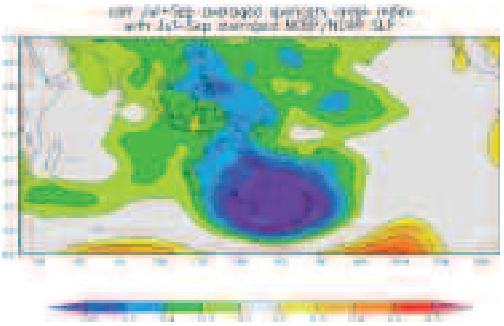
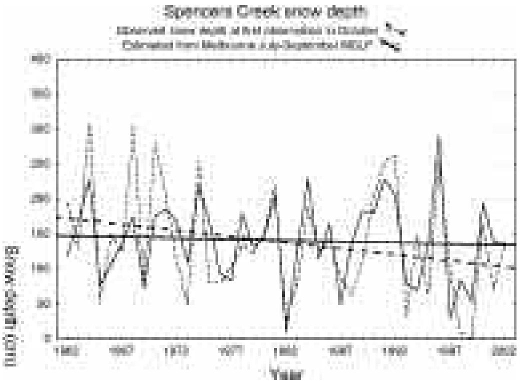


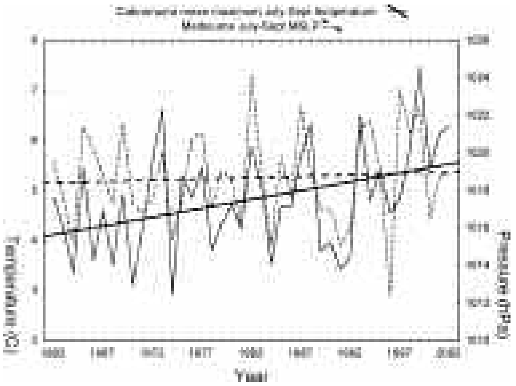
Fig. 12 **Snow depth observed at Spencers Creek in first observation in October (broken line) and estimated from linear regression with Melbourne Regional Office 9 am mean sea-level pressure July-September as predictor (solid line). Linear trends shown with thick lines.**



snow-depth time series estimated from Melbourne pressure exhibits only a very weak downward trend, compared with the strong observed trend. That is, despite the regional-scale pressure pattern being a major controller of snow depth, changes in pressure and thus synoptic patterns are NOT a major factor causing the trend in snow depth.

The warming trend at Cabramurra is also not primarily related to a trend in atmospheric pressure. Figure 13 shows time series of the Cabramurra July-September mean maximum temperature and of Melbourne Regional Office 9 am mean sea-level pressure. The interannual variations in the two variables are, clearly, very strongly related. However, the trend in temperature is much stronger than that in pressure (correlation with year of 0.40 and 0.08, respectively). So, despite the close relationship between the two variables, on interannual time-scales, the warming trend observed at Cabramurra (which in turn accounts for the decline in October snow depth) does not have, as a primary cause, changes in synoptic behaviour observable as trends in surface pressure.

Fig. 13 **Cabramurra mean maximum temperature July-September (solid lines) and Melbourne Regional Office 9 am mean sea-level pressure (solid lines). Linear trends shown with thick lines.**



Discussion and conclusions

This study of snow depth at Spencers Creek in the Snowy Mountains of southeastern Australia has shown that:

(a) Maximum snow depth has decreased somewhat since 1962, but the snow depth in spring, as measured by the first observation in October, has declined strongly (by about 40 per cent).

(b) Variations from year to year of snow depth (both maximum and spring snow depths) are strongly correlated with winter or July-September mean maximum temperature and precipitation at Cabramurra.

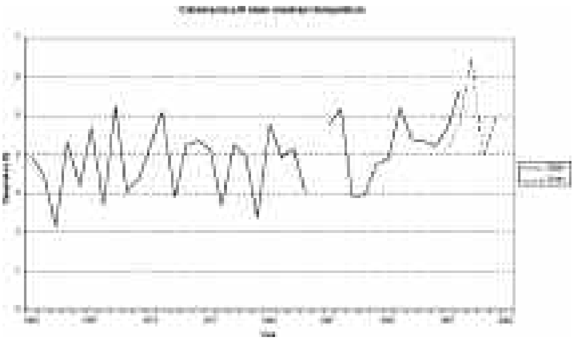
(c) The decline in maximum snow depth seems to be attributable to a combination of a weak decline in winter precipitation coupled with a strong warming trend. The warming is too strong to account for, by itself, the rather weak decline in maximum snow depth. The precipitation decrease is somewhat too weak to account, by itself, for the decline in maximum snow depth.

(d) The stronger decrease in spring snow depth is largely attributable to warming during July-September. The weak decline in precipitation substantially underestimates the trend in snow depth (if used alone to estimate the trend), while the strong warming somewhat overestimates the snow-depth trend (but is much closer to the observed trend).

(e) Interannual variations in regional surface air pressure are closely related to snow depth, but there is only a weak trend in pressure (at, for instance, Melbourne). This trend is insufficient to account for the decline in spring snow depth. Thus the warming that is the proximate cause of the decline in spring snow depth is not simply reflecting a change in the synoptic patterns. Rather, the warming is taking place despite the absence of substantial synoptic changes in the region (or at least of those synoptic changes that would be reflected by trends in pressure).

One reason the temperature trends overestimate the magnitude of the decline in snow depth (both maximum snow depth and October snow depth) relates to the temperatures observed in the last four years examined here (1999-2002). Snow depth estimated using multiple linear regression with both precipitation and temperature as predictors substantially and consistently underestimates snow depth in these last four years (Figs 5 and 9). This appears to be mainly because temperatures were warmer than would be expected to accompany the observed snow depth of these years. As noted earlier, the manual station at Cabramurra was replaced with an automatic weather station in 1999. The AWS records were used in this study from 1997, without adjustment to match the records from the manual station. Did the change in station, perhaps because of a change in elevation or exposure, lead to consistently warmer temperatures from the AWS which would have introduced a bias to lower estimated values of snow depth? Figure 14 shows time series of winter (June-August) mean maximum temperatures from the two stations. The overlapping two years (1997 and 1998) indicate that the new AWS station, in fact, records lower temperatures than did the manual station. This suggests that the change of station did not lead to the overestimates of the last four years, unless there was a change in the AWS after the manual station was decommissioned in 1999. If the 1997 and 1998 overlapping records had been used to adjust the earlier, manual records to match the current AWS records, then the underestimates of snow depth in the last four years would have been even more severe. This does not suggest that instrumental changes or exposure changes have led to the apparent underestimates seen throughout this study. However, no alternative possible explanation has been uncovered at this time. Despite this problem, the conclusions noted above are not affected by the change in station.

Fig. 14 **Mean maximum winter (June-August) temperatures at Cabramurra. Data from manual station 72091 (solid line) and automatic weather station 72161 (broken line).**



The strong observed decline in spring snow depth is not principally caused by changes in precipitation or synoptic activity but reflects warming rather separate from any changes in synoptic activity. The ability of the warming to explain the decline in snow depth provides confirmation of the reality of the warming trend in late winter and early spring. The fact that the warming trend is not the result of a trend in synoptic activity, as measured by the sea-level pressure, suggests that some other mechanism is causing the warming and the decline in spring snow depth.

It is clear that variations in synoptic activity (specifically the depth and frequency of systems bringing strong southwesterly flow across the southeast of the continent) from year to year lead to year-to-year variations in total winter precipitation and mean temperature in the mountains, which in turn cause interannual variations in the maximum snow depth. The fact that the decline in maximum snow depth is much weaker than would be expected if this decline is being controlled by temperature, suggests that maximum snow depth is strongly affect by the occasional large ‘dumps’ of snow. On the other hand, the larger decline in spring snow depth which is clearly related to the strong warming, suggests that the main factor leading to this decline is the melting of the snow once it has fallen, rather than the amount of snow falling during the season. The warming observed at Cabramurra in winter and early spring reflects the regional and continental-scale warming of the past 50 years or so (Nicholls 2003, 2004), and is most likely, at least partly due to the enhanced greenhouse effect. The results of this study, in turn, suggest that the impacts of the enhanced greenhouse effect are already being observed in the Australian alpine region. It seems likely, therefore, that as predicted by various authors (e.g. Hennessy et al. 2003), the duration of snow cover will decrease as the warming effect of the enhanced greenhouse effect accelerates.

Acknowledgments

Jason Venables from the Snowy Hydro Limited provided the snow-depth data. David Jones, Kevin Hennessy, Rob Allan and Janette Lindesay commented on earlier versions of this paper. The calculations involving the NCEP/NCAR Reanalyses were performed on the Climate Explorer website developed and maintained by Geert Jan van Oldenborgh. The map of locations was generated by MapIt software (http://stellwagen.er.usgs.gov/mapit/).

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