Australian Meteorological and Oceanographic Journal 63 (2013) 303–313

Towards the development of long-term winter records for the Snowy Mountains

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(Manuscript received April 2012; revised December 2012)

Alpine regions are highly sensitive to climate change and its resultant impacts on ecosystems and human activity. Small changes in temperature and precipitation in these regions can have large effects on ecosystems while changes in snow cover could affect the viability of the ski industry in some regions. Long-term datasets of temperature, precipitation and snow depth in these regions are therefore important in identifying whether any climate change signal is in fact evident.

This paper investigates a method for developing long-term winter records of temperature, precipitation and seasonal snow depth from available climate data in the Kosciuzsko National Park region using linear regression techniques and draws inferences from these records with respect to historical trends.

The imputed winter snow depth dataset indicates that although extreme heavy snow events may not have changed over the record, the average snow depths around the turn of the 20th century appear to have been between five per cent and 14 per cent higher than the 1961–1990 average while in the last decade they have dropped by around 15 per cent. This reduction in snow depths supports the expected impacts of global warming on the Australian alpine region and highlights the impacts on the ecosystems and human activity that may be occurring in this sensitive climatic region.

This analysis also indicates that the signal from global warming has become a significant factor in both the temperature and snow records after around 1985 as well as identifying issues with regard to the use of the automatic weather stations (AWS) rainfall data from Cabramurra post-1997 in climate analysis.

Introduction

Long-term climate records are important in establishing whether climate change is occurring and the speed of any such change. Such records are extremely important in alpine regions as these regions are considered to be highly sensitive to climate change not only with respect to human activity, but also with respect to impacts on plants and animals (Marchant 1998, Good 1998, Wardlaw 1998, Green 1998, Green and Osborne 1998, Walter and Broome 1998). Small changes in location in these areas can also have considerable impacts on both observed temperature and precipitation (Osborne et al. 1998). Beniston (2003) has suggested that mountain regions represent unique areas for the detection and assessment of climate change due to these sharp transitions that occur in these ecosystems and climate zones. He provided a summary of the possible impacts that climate change may have on mountain regions and of the difficulties in the assessment of such change.

The Snowy Mountains is the major mainland alpine region of Australia and identification of climate change in this region is difficult because of the lack of station specific long-term climate records. It is also a marginal alpine region due to its latitudinal position with respect to snow producing mechanisms and relatively low mountain heights and is subject to high natural and inter-annual climate variability induced by complex topographic features.

There have been several studies of the climate of this region, and of snow depths in particular, dating back nearly 30 years. Budin (1985) investigated the inter-annual variations of snow depth in the Snowy Mountains in relation to the changes in broadscale drivers of the snow producing weather systems over Australia. Slatyer et al (1985) provided the first study of the commencement and cessation of the snow seasons through the analysis of snow depths in Australia and compared them to Switzerland. Duus (1992) investigated the long-term history of snow depth for the

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period 1910–1992 and developed a method for calculating an integrated value for snow coverage over the region on an annual basis. Slater (1995) also investigated changes in snow depth, but concluded that while there had been a decline in snow depth at Spencers Creek between 1954 and 1993, he could not establish any specific reason due to the lack of suitable data. Davis (1998) investigated the meteorology of snow in the Australian alpine region in terms of snow climatology, snow producing systems as identified by Colqhoun (1978), snow forecasting techniques and possible changes to snow depths in the region over time. He also concluded that there was no clear relationship between snow depths and the effects of global warming up to 1998. However, using more recent data, Nicholls (2005, 2009) found that the snow season was now ending earlier and suggested that this may in fact be a result of greenhouse climate change.

Whetton et al. (1995) and Whetton (1998) investigated possible changes to snow depths and extent of snow coverage in the Australian region under climate change scenarios using computer modelling. Hennessy et al. (2008) analysed trends in snow cover and provided estimates from computer models of the expected decline during the 21st century. These results support other research in finding that the most significant factor on the effect on snow depth is in the change of temperature.

All these studies highlight the need to develop a long-term climate record for this region that can be used to identify climate change.

This paper investigates the application of linear regression techniques to the available long-term temperature and precipitation records from Kiandra, Cabramurra and Tumbarumba located in the Kosciuszko National Park to impute average daily maximum winter temperatures and winter precipitation for Cabramurra for each year back to 1866. These datasets, in conjunction with the available Snowy Hydro weekly snow depth data from Spencers Creek, are then used to impute a long-term seasonal maximum snow depth record for Spencers Creek. Inferences from these datasets are then examined.

Table 1 provides a list of the sites, their elevations, length of record and data accessed while Fig. 1 indicates the topography and locations of the sites used in this analysis.

Figure 1 indicates that all these sites are located on the northern and western side of the ranges so are subject to the same precipitation producing weather systems, particularly during the winter months where these systems move in from the west and northwest.

As temperature is a major factor in determining snow development both the June–August southern hemisphere temperature anomaly (SH JJA anomaly) and the southeast Australia winter maximum temperature anomaly (SEA JJA anomaly) as calculated against the 1961–1990 mean were used to investigate the impact that global warming may be having on the Cabramurra long-term maximum temperature records.

While precipitation data were available from 1866 for the region the only viable temperature data available prior to 1910, when Stevenson screens became standard in Australia, are the SH JJA anomaly values.

Methods

The available winter (June, July and August) precipitation and temperature data from Kiandra, Cabramurra and Tumbarumba were accessed via the Bureau of Meteorology website (http://www.bom.gov.au/climate/data) as were the SH and SEA JJA temperature anomaly data (http://www.bom.gov.au/climate/change). Snowy Hydro weekly snow depth data for Spencers Creek available at http://www.snowyhydro.com.au/water/snow-depths-calculator/ were used to determine the maximum seasonal snow depth for each year. Linear regression techniques were then applied to these datasets to develop long-term winter precipitation and maximum temperature records for Cabramurra and maximum seasonal snow depths for Spencers Creek over the period of record.

Precipitation data

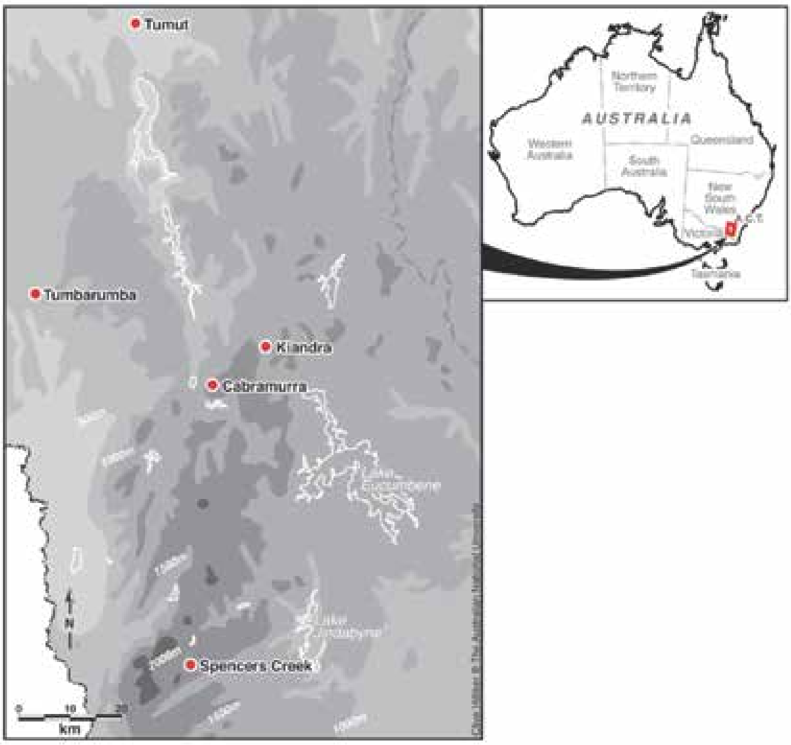
Given the high correlations in the winter precipitation between Tumbarumba and Cabramurra manual site (132 months, $R^2 = 0.77$), Tumbarumba and Kiandra (257 months, $R^2 = 0.71$) and Cabramurra and Kiandra (50 months, $R^2 =$

Table 1. List of sites, their elevations and length of record.

Site (station number)	*Lat/Long*	*Elevation*	*Length of record*	*Data used (as available)*
Kiandra Chalet (071010)	35.88S 148.50E	1395 m	1866–1974	Monthly winter precipitation and maximum temperature
Cabramurra (manual) (072091)	35.94S 148.38E	1475 m	1955–1998	Daily and monthly precipitation and winter maximum temperature
Cabramurra (AWS) (072161)	35.94S 148.38E	1482 m	1996–present	Daily and monthly precipitation and daily winter maximum temperature
Tumbarumba (072043)	35.78S 148.01E	645 m	1886–present	Monthly precipitation
Spencers Creek	36.43S 148.35E	1830 m	1954–present	Maximum seasonal and winter snow depths
East Sale (085072)	38.12S 147.13E		1957–2008	Monthly 9.00 am pressure (winter)

The Kiandra site is located around 12 km from Cabramurra manual site while the distance between the Cabramurra AWS and manual sites is around 500 m.

Fig. 1. The sites and their underlying topography.



0.79) the imputation approach as described by Orchard and Woodbury (1972) was applied to the winter precipitation data from these sites to impute a long-term winter precipitation record for Cabramurra where only Tumbarumba and/or Kiandra precipitation was available.

Although there was an overlap in precipitation data between the Cabramurra manual and AWS sites between Dec 1996 and April 1999 analysis of this data raises issues as to the accuracy of the AWS record. While the new site is in a slightly more exposed location (B. Trewin, pers. comm.) and therefore differences in winter precipitation may be expected, these differences in daily precipitation between the two sites are quite considerable. Rasmussen et al (2012) assesses some of the difficulties in measurement of snowfall associated with automatic precipitation measurements and considers that local wind variations have considerable impacts. However, there also appears to have been recording and communication problems associated with the AWS over this period which has also impacted on the accuracy of the AWS record. The correlation data between these sites are listed in Table 2. This table indicates that while the correlations between the AWS and Tumbarumba have improved after 2001, they are still below those obtained when compared to the manual site.

The percentage difference of the average decadal winter precipitation from the 1961–1990 means between the sites is shown in Table 3. This table suggests that there may still be anomalies in the precipitation reported from the AWS given the large drop in precipitation from the AWS site for the 2001–2010 period compared to the previous decadal periods

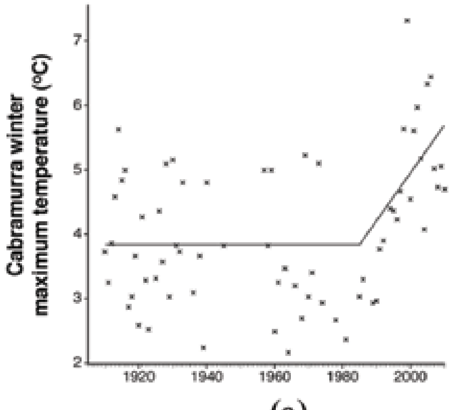
Table 2. Comparison of available monthly precipitation records for Tumbarumba, Cabramurra Manual and Cabramurra AWS.

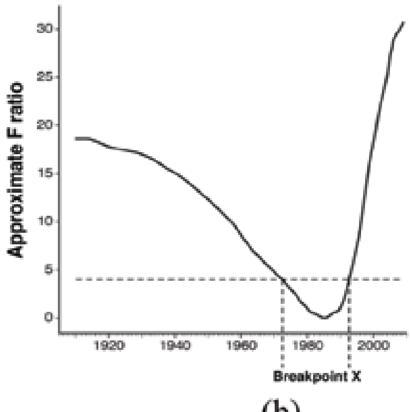
Comparison sites	*Overlap dates*	*R^2 value*
Tumbarumba/manual	Winter 1955–1998	0.77
Tumbarumba/manual	Dec 1996–Apr 1999	0.74
Tumbarumba/AWS	Dec 1996–Apr 1999	0.37
AWS/manual	Dec 1996–Apr 1999	0.55
Tumbarumba/AWS	Jan 1997–Dec 2001	0.53
Tumbarumba/AWS	Winter 2002–2010	0.59

Table 3. Percentage differences in decadal winter precipitation for Cabramurra manual, Cabramurra AWS and Tumbarumba as calculated against the 1961–1990 means.

Decade	*Tumbarumba (%)*	*Cabramurra (%)*
1959–1968	–10	–5 (manual)
1969–1978	–7	–5 (manual)
1979–1988	12	6 (manual)
1989–1998	10	11 (manual)
2001–10	5	–29 (AWS)

Fig. 2. Analysis of optimal break point for temperature change: (a) broken stick analysis and (b) optimum break point analysis.





especially as Tumbarumba rainfall has increased over this decade. As a result only the actual winter precipitation data from the manual site (1954–1998) were used in calculating the correlations from the linear regressions.

Duus (1992) raised some doubts about the veracity of Kiandra precipitation observations prior to 1910 and indicated that precipitation data from Tumbarumba had not been checked. Comparisons of winter precipitation over timescales of around 20 year periods between Cabramurra and Tumut, another long-term precipitation record in the region covering a similar time period, shows a high consistency with R^2 values varying between 0.74 and 0.87. These results indicate that the winter precipitation data from Tumbarumba can be considered to be reliable over the whole time period.

Temperature data

A linear regression was applied to the monthly average daily maximum temperatures for the available winter months between the Cabramurra manual and Kiandra sites for the period of overlap (1962–1974) to develop an adjusted temperature record for Cabramurra. This regression equation was

$$MaxT\,(\text{Cabramurra}) = 0.95 \times MaxT\,(\text{Kiandra}) - 1.0$$

The correlation between these sites was extremely high ($R^2 = 0.94$). This equation was then applied to the available Kiandra winter monthly temperatures to develop an adjusted winter temperature for Cabramurra for the period 1910–1961.

The AWS daily maximum temperatures were recorded in whole numbers during this period. A comparative record for daily maximum temperatures from the manual site was developed by applying the Bureau of Meteorology standard practice of rounding to the odd number to this record. Comparison of the two records indicated that the AWS site was around 0.6 °C cooler than the manual site ($R^2 = 0.96$). This difference is consistent with the adjustment calculated in the developing the Bureau of Meteorology ACORN-SAT record and would be explained by the change in exposure between the two sites. The post 1998 AWS data were then corrected by this factor to reflect the manual temperatures. As the differences between the adjusted and manual daily maximum temperatures were generally less than 0.2 °C, these two datasets were combined into a single record.

There were three months with five or more missing observations in the post 1998 record and these months were excluded from the analysis. Another nine months, including June 1986, had three or less missing observations. In these cases the monthly average of the remaining days was used as the monthly value. Several techniques were examined to adjust for the missing data, but as all resulted in very minimal changes it was considered unnecessary to try to fill these gaps.

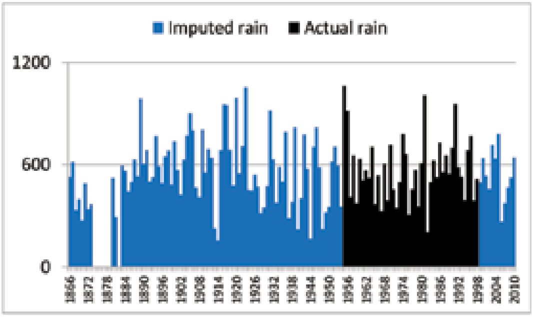
A broken stick analysis was applied to the adjusted Cabramurra temperature dataset to determine whether any signal from climate change could be detected in the record. These results are shown in Fig. 2. The residual sum of squares was calculated for a range of possible values for the breakpoint in the broken stick model. The residual sum of squares at the estimated value were then subtracted and this value divided by the residual mean square. The result is plotted in Fig. 2(b). The horizontal line is the 95 per cent point of an F-distribution with degrees of freedom one and the number of degrees of freedom of the residual mean square. The region for which the statistic is below this line is an approximate 95 per cent confidence region for the breakpoint as described by Toms and Lesperance (2003).

The result of this analysis indicates that the break point year was 1985 with a 95 per cent confidence level that the break point occurred between 1973 and 1993. While any climate change signal will tend to occur over a period of time, for the purposes of this paper the datasets were split into the periods 1866–1985 and 1986–2010 for the temperature analysis.

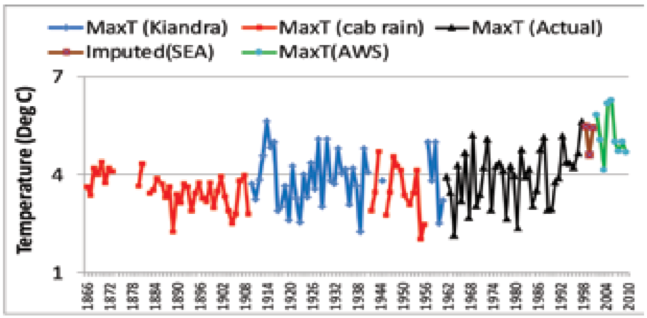
A bivariate regression analyses of the adjusted Cabramurra maximum temperature dataset with the Cabramurra winter precipitation and the SH JJA temperature anomalies showed that the influence from precipitation ($R^2 = 0.37$) on the

Fig. 3. Final combined imputed and actual data sets 1866–2010: (a) Cabramurra winter precipitation, (b) Cabramurra winter maximum temperature and (c) Spencers Creek maximum seasonal snow depth.

(a)



(b)



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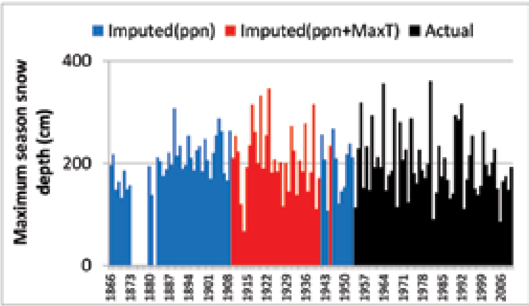


temperatures for the period 1910–1985 was far greater than from the SH JJA temperature anomaly ($R^2 = 0.005$). However, for the 1986–2010 period, the influence from the SH JJA anomaly increased significantly ($R^2 = 0.41$) while the influence from precipitation more than halved ($R^2 = 0.15$). This change is indicating that the winter maximum temperatures in the region after 1985 appear to be responding to broadscale hemispheric temperature changes.

Substituting the SEA JJA anomalies for the SH JJA anomalies in the 1986–2010 regressions resulted in significantly higher correlations ($R^2 = 0.62$). These results were found to be highly significant at the one per cent level. The regressions selected for imputing Cabramurra winter maximum temperatures were as follows:

- Cabramurra Winter MaxT = 5.21 – 0.00245 × (Cabramurra winter rain) (1910–1985)
- Cabramurra Winter MaxT = 4.27 + 1.18 × (SEA JJA anomalies) (1986–2010)

The reconstructed maximum temperature record for Cabramurra in this paper consists of:

a. adjusted and actual temperatures from Kiandra, Cabramurra and Cabramurra AWS for the available years 1910–2010;
b. imputed temperatures based on winter precipitation from Cabramurra for the period 1866–1985 as required; and
c. imputed temperatures based on the SEA JJA anomalies for the gaps after 1985.

The veracity of this approach was checked by substituting the actual Tumbarumba precipitation for the imputed Cabramurra precipitation (1910–1985) in the regression equations.

Snow depth data

Over the period 1954–2010, there were 23 occasions when the seasonal maximum snow depth occurred in September. However, as there were only minimal differences in the correlations using either the maximum winter snow depth or the seasonal snow depth, the seasonal maximum snow depth was selected for this analysis.

While snow depth data are available for the period 1954–2010, measured precipitation and temperature data from Cabramurra were restricted to the periods 1955–1998 and 1962–2010 (excluding 1999–2001) respectively. The regression equations developed from comparing the maximum season snow depth with maximum temperatures and precipitation at Cabramurra were as follows:

- Spencer Creek max season snow depth = 0.245 × (Cabramurra winter rain) + 66 (1955–1998 as available)
- Spencer Creek max season snow depth = 391.5 – 46.6 × (Cabramurra winter MaxT) (1962–2010 as available)
- Spencer Creek max season snow depth = 252.5 – 37.9 × (Cabramurra winter MaxT) + 0.18 × (Cab winter rain) (1962–1998 as available)

The individual regression correlations between snow depth and precipitation ($R^2 = 0.46$) and maximum temperature ($R^2 = 0.48$) are very similar. This is not unexpected as the two main ingredients for snow development are both moisture content and overall temperatures of the atmosphere. As the correlation from the bivariate regression combining both winter precipitation and maximum temperatures was higher than the individual values ($R^2 = 0.64$), this equation was used to impute snow depth where both adjusted temperature record and precipitation were available. Snow depths were imputed from the precipitation regression where no measured temperatures were available given that the temperature record was also imputed from precipitation.

Nicholls (2005) also developed regression equations to determine the maximum season snow depth for Spencers Creek using the winter maximum temperatures and precipitation by combining the manual site (1962–1996) and the unadjusted temperature and precipitation values from the AWS (1997–2002). The regression equations from his analysis are:

- Spencer Creek max season snow depth = 0.25 × (Cabramurra winter MaxT) + 71.9
- Spencer Creek max season snow depth = 226.8 – 27.52 × (Cabramurra winter MaxT) + 0.16 × (Cabramurra winter rain)

The use of Cabramurra precipitation in calculating snow depths enables a direct comparison with the imputed values from Nicholls to be undertaken. The average snow depths using the Nicholls' equations were around 8.5 cm higher for the precipitation regression and 4.3 cm for the bivariate regression. This difference is most likely a result of the more detailed treatment of the AWS temperature and precipitation datasets as carried out in this paper.

The veracity of these imputed snow depths was checked by comparison with snow depths calculated by substituting both the measured Tumbarumba precipitation and the 9.00 am MSL pressures from East Sale for the Cabramurra precipitation.

The pressure data from East Sale aerodrome, located on the Victorian coast directly south of the region, reflect the inter-annual winter broadscale weather patterns across the region and consequently the temperature and precipitation experienced in the alpine region. A linear regression relating the 9.00 am winter MSL pressures from East Sale with the maximum snow depth for the period 1957–1985 (R^2 = 0.74) indicates that the imputed snow depth values are very close to those calculated from Cabramurra precipitation alone. However, as pressures across the region are not readily available prior to 1957 the regression equation with Cabramurra precipitation was used to impute the Spencers Creek maximum season snow depth.

Results

Final datasets

Figure 3 provides the combined time series of the imputed and actual datasets for the precipitation and maximum temperatures for Cabramurra and maximum seasonal snow depths for Spencers Creek for the period 1866 to 2010 as determined by this analysis. Figure 3(a) shows the combined winter precipitation time series from the actual measurements for Cabramurra and the derived rainfall data for Cabramurra.

Figure 3(b) shows the combined winter maximum temperature time series as derived from all sources. Cabramurra AWS and Kiandra are the adjusted values after applying the correlations as calculated while the MaxT(rain) is derived from the Cabramurra rain record and the MaxT (SEA) is derived from the SEA JJA temperature anomalies.

Figure 3(c) shows the maximum seasonal snow depth time series as derived from all sources. The imputed (ppn) values have been calculated using the Cabramurra derived rainfall while the imputed (ppn+MaxT) values have been calculated using the rainfall and temperature data where both were available.

Temperature correlation comparisons

Figure 4 provides comparisons of both imputed winter maximum temperatures and the combined time series for winter maximum temperatures for Cabramurra using all sources. These graphs indicate that while the imputed values for maximum temperatures pre-1986 reflect the overall trends of the measured dataset, they tend to reduce the inter-annual variability, as expected for any regression analysis. In comparison, the post 1985 imputed record follows this variability more closely.

Figures 4(a) and (b) indicate how close the imputed temperatures are irrespective of whether Cabramurra or Tumbarumba precipitation are used while Fig. 4(a) indicates the temperature values calculated from the Cabramurra precipitation tend to reflect the inter-annual variations slightly better than those using the Tumbarumba precipitation. The main differences are in the earlier part of the record where the temperature values imputed from Tumbarumba precipitation are slightly higher. It must be noted that there is a lack of any long-term climate data across this region which could be used for comparison.

Snow depth correlation comparisons

Figure 5 provides a comparison between the imputed snow depths using Cabramurra precipitation and East Sale pressures with the actual season maximum snow depths.

These graphs indicate that while the imputed datasets reflect the overall trend of the actual measurements and therefore should reasonably reflect the past snow depth trends, they also produce a reduced inter-annual variability when compared to the actual values for the period 1955–1985. The fact that the imputed snow depths from both pressure and precipitation are close supports the use of the imputed values from precipitation to provide an estimate of past maximum seasonal snow depth trends.

The comparison of the snow depths calculated from the use of the imputed Cabramurra precipitation and measured Tumbarumba precipitation prior to 1955 is shown in Fig. 6. These graphs indicate that the imputed snow depths are very similar between the two with a very high correlation (R^2 = 0.93). Again the main differences are in the early record, where snow depths calculated from Cabramurra precipitation are slightly higher with more inter-annual variability.

Regression statistics summary

Table 4 provides a summary of the statistics for the regression equations used to impute the maximum temperatures and snow depths in this paper.

Long-term trends

While the imputed winter temperature, precipitation and maximum snow depths may not fully reflect the inter-annual variability of the measured datasets, the fact that they do reflect the underlying trends suggests that they can provide indicators of trends over longer timescales, such as

Fig. 4. Comparisons of actual and imputed mean daily winter maximum temperature data sets for Cabramurra from all sources: (a) Time series of imputed temperatures 1885–1985, (b) Comparison of imputed temperatures 1886–1985, (c) Time series of measured and imputed temperatures 1910–1961, (d) Comparison of the measured and imputed temperatures 1910–196, (e) Time series of measured and imputed temperatures 1962–1985, (f) Comparison of the measured and imputed temperatures 1962–1985, (g) Time series of measured and imputed temperatures 1986–2010, and (h) Comparison of the measured and imputed temperatures 1986–2010.

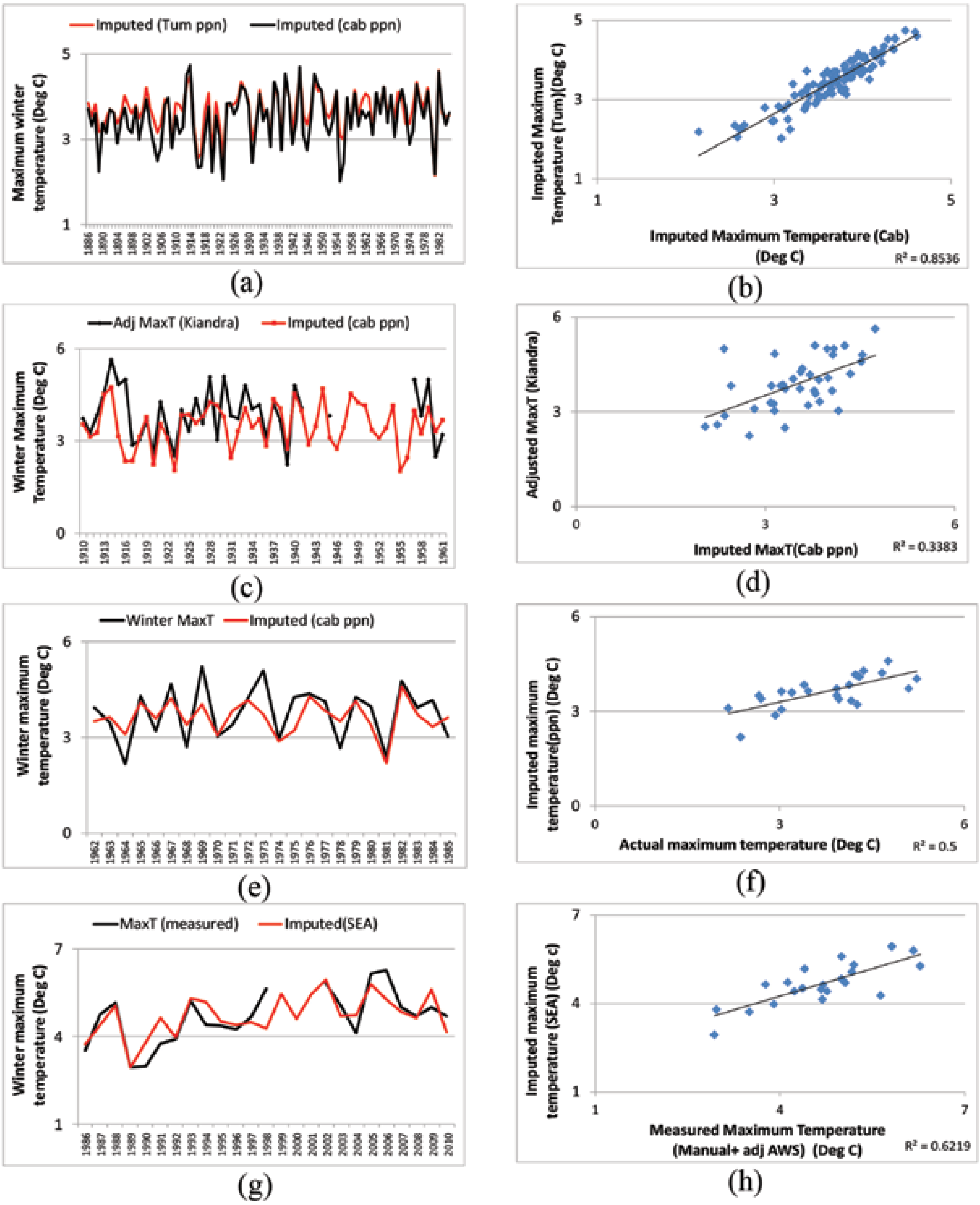
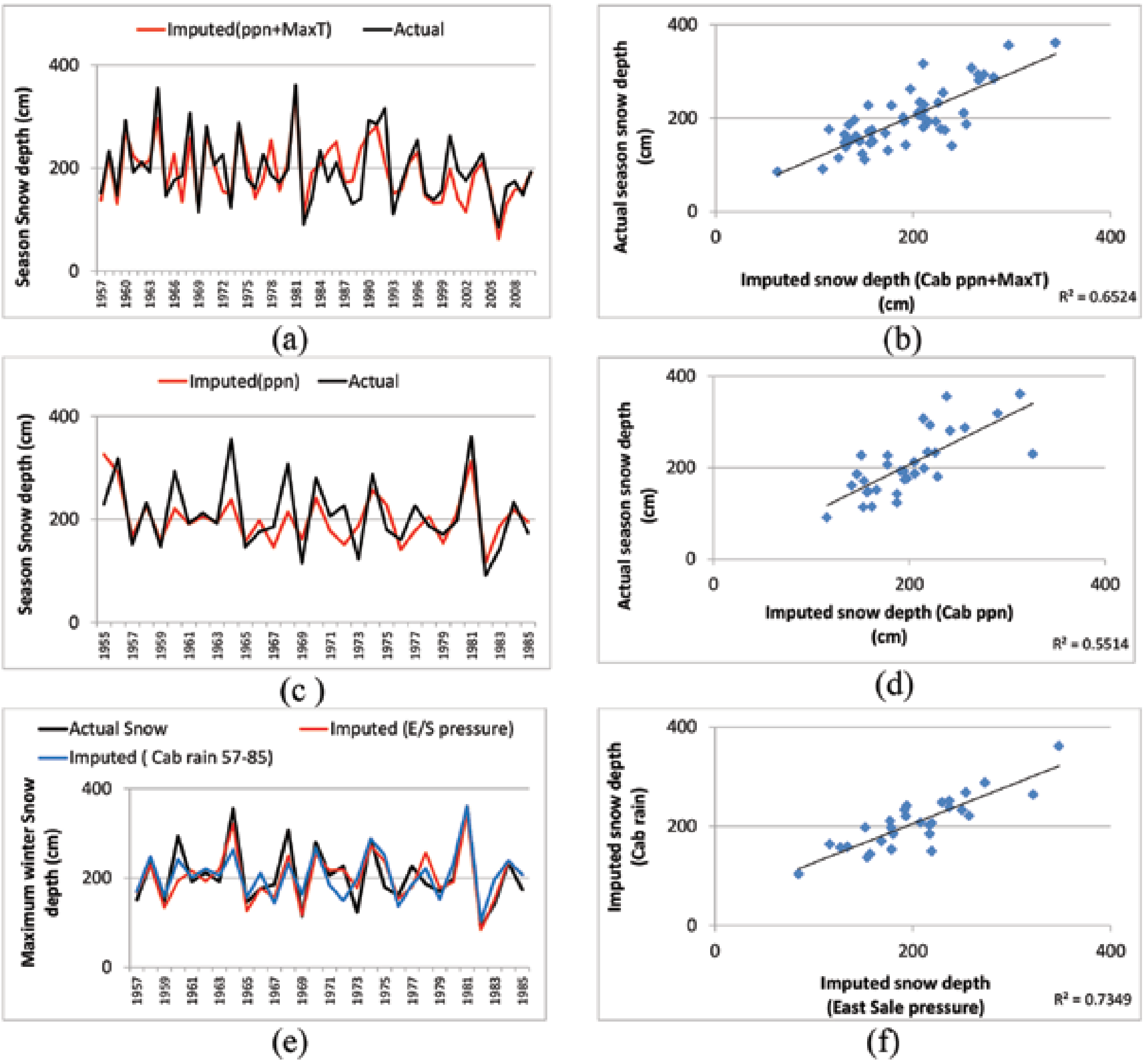


Fig. 5. Comparisons of imputed seasonal snow depths with actual snow depths: (a) Time series of measured and imputed snow depths 1957–2010, (b) Comparison of the measured and imputed snow depth datasets 1957–2010, (c) Time series of measured and imputed snow depths 1955–1985, (d) Comparison of the measured and imputed snow depth datasets 1955–1985, (e) Time series of measured and imputed snow depths 1957–1985, and (f) Comparison of the imputed snow depth datasets 1957–1985.



on a decadal basis, where the effects of this variability are reduced. Figure 7 shows the percent differences from the 1961–90 mean by decade from 1881–1890 to 2001–2010 for the Cabramurra winter precipitation and temperature and Spencers Creek maximum snow depth.

Figure 7(a) indicates that there has been no significant change in winter precipitation at Cabramurra. Figure 7(b) indicates that there has been a considerable increase in average daily winter maximum temperatures at Cabramurra over the last two decades.

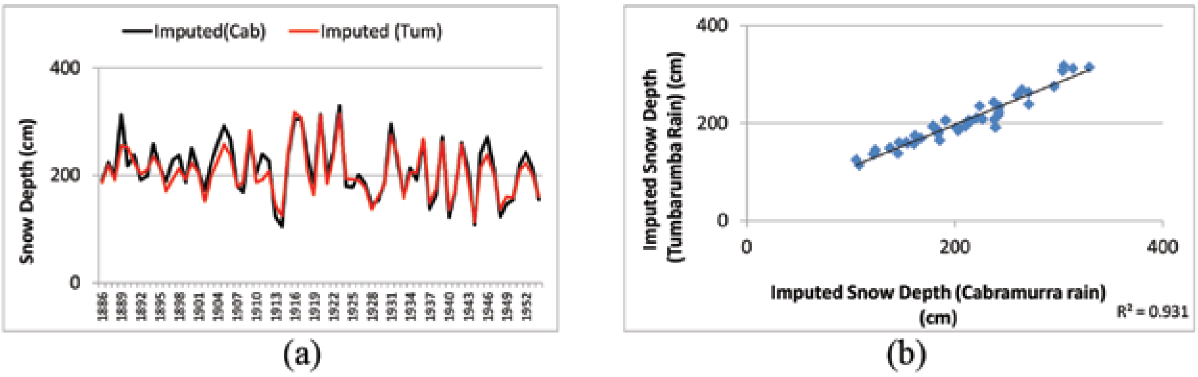
Figure 7(c) shows the ranges of imputed snow depths compared to the actual values on a decadal basis. Overall while Nicholls' values are slightly higher for most decades and Tumbarumba are slightly lower, the trends across the decades are similar for all three imputed values of snow depth. The main differences being in the 1981–1990 decade, where all the imputed snow depths are higher than the actual values, and in the 1991–2000 decade, where the imputed values were less than the actual values. One possible reason for these differences may be in the type of precipitation experienced during winter in these decades and requires further investigation. On the other hand all imputed values reflect the large drop in the measured snow depths over the last decade with Tumbarumba producing the largest drop. As overall precipitation has not dropped this suggests that rising temperatures are directly affecting the amount of snow being produced.

The imputed snow depths indicate that the snow depths around the turn of the 20th century may have been five per cent to 14 per cent above the 1961–1990 mean. These results would support the anecdotal evidence regarding snow conditions in these early periods. Cooler winters with deeper snow depth

Table 4. Summary of statistics from regression equations used in this analysis.

Regression factors	*R2 value*	*Co-efficient (Standard Error)*	*P values*
Cabramurra MaxT (1962-74) vs Kiandra Max	0.94	0.95 (0.05)	1.33E-17
Cabramurra MaxT(1910-85) vs SH JJA anomaly	0.005	0.32 (0.57)	0.57
Cabramurr MaxT (1910-85) vs Cabramurra Rain	0.37	-0.0025 (0.00042)	1.68E-07
Cabramurra MaxT (1986-2010) vs SH JJA anomaly	0.41	4.63 (1.25)	0.00014
Cabramurra MaxT (1986-2010) vs SEA MaxT anomaly	0.62	1.18 (0.21)	1.3E-05
SC Snow depth (NN) vs Cabramurra rain	0.44	0.25 (0.05)	3E-06
SC Snow Depth (55-98) vs Cabramurra rain	0.46	0.245 (0.04)	4.35E-07
SC Snow depth (NN) vs Cabramurra rain+maxT	0.45	NA	NA
SC Snow depth (62-98) vs Cabramurra rain+MaxT	0.64	Rain=0.18 (0.05) MaxT=-37.9 (9.33)	Rain=0.0005 MaxT=0.0003
SC snow depth vs Cabramurra MaxT (62-98)	0.49	-55.3 (9.6)	1.54E-06
Tumbarumba rain vs Cabramurra rain (monthly 55-98)	0.77	1.51 (0.07)	3.5E-43
Kiandra rain vs Cabramurra rain (monthly 55-74)	0.79	1.02 (0.08)	5.71E-18

Fig. 6. Comparisons of imputed maximum season snow depths from Cabramurra and Tumbarumba precipitation 1886–1954: (a) Time series and (b) Comparison of datasets.



would imply that snow would extend further down the slopes while in the last decade with warmer temperatures and less snow the seasons have tended to be both more variable with less overall depth, less vertical extent and an earlier finish to the season as found by Nicholls (2009). Conditions during the 1951–1970 periods, when there were cooler temperatures, higher precipitation and greater snow depth coincided with the building of the Snowy Mountains scheme and may have been more representative of those conditions experienced in the early part of the 20th century. These conditions were most likely a result of natural variability and possibly related to longer term cycles such as the IPO and its impact on the development of ENSO conditions in the Pacific Ocean. This period was a period where several strong La Niña episodes occurred and very few El Niño episodes.

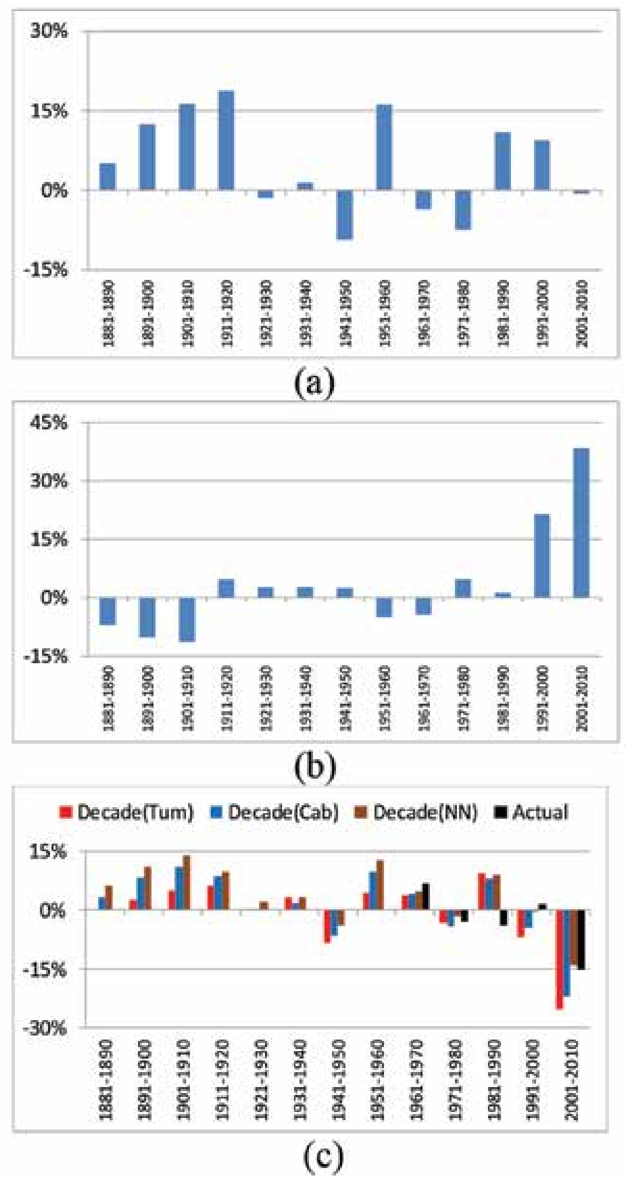
Conclusion

Although there are discontinuous precipitation and temperature datasets across the Snowy Mountains region of New South Wales, enough overlap exists in these records to construct long-term databases for winter precipitation and average daily maximum temperatures for a single site at Cabramurra through the use of linear regression techniques. These datasets have then been used to impute maximum winter snow depths for Spencers Creek extending back until 1866 as available data allows. While these datasets are not perfect, as any regression-based estimates will tend to have reduced inter-annual variability, the decadal averaged datasets can be useful in providing estimates of possible climate trends and the impacts on the ecosystems of the region.

The imputed snow depth values suggest that while there is no apparent change in the magnitude of the extreme snow events, the seasons around the turn of the 20th Century may have had maximum seasonal snow depths between five per cent and 14 per cent higher than the 1961–1990 average compared to the last decade where snow depths have been more variable and around 15 per cent lower. This is consistent with expected changes associated with projected climate change.

The signal from global warming appears to have had a significant impact on the increase in winter temperatures at

Fig. 7. Decadal anomalies in winter precipitation, maximum temperature and seasonal snow depths measured against the 1961–1990 mean: (a) Winter precipitation at Cabramurra, (b) Winter maximum temperature at Cabramurra, and (c) Seasonal maximum snow depth at Spencers Creek.



Cabramurra after 1985, and particularly over the last decade, with a consequent decrease in the maximum seasonal snow depths at Spencers Creek while there has been no apparent impact on precipitation.

This study also identified a discrepancy between the Cabramurra manual and AWS rainfall which raises questions as to the use of the AWS rainfall in climate analysis.

Although beyond the scope of this paper, two areas for follow up would be to examine these imputed records in relation to the major seasonal climate drivers for Australia such as ENSO, IOD and SAM and also to further investigate the impact that changes in broadscale pressure patterns may be having on the region.

Acknowledgments

The author would particularly like to thank Dr Emlyn Williams of the Australian National University (ANU) Statistical Consulting Unit and Dr Jeff Wood at the Fenner School for Environment and Society at the ANU for their advice and assistance in the imputation of data used in this paper with respect to precipitation and in determining the break point in the temperature record.

The author would also like to thank Professors Michael Hutchinson (ANU) and Neville Nicholls (Monash University) for their time and effort in providing input and feedback into this paper.

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