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Australian Snowpack Disappearing under the Influence of Global Warming and Solar Activity

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Abstract

Average depth of snow in the mountains of southeastern Australia is decreasing at a rate of 0.48 cm a^{-1}, while the duration of the snowpack has been shortened by 18.5 days since 1954 (−3 days per decade). The major factors responsible for these declines are an increasing temperature trend of 0.36 °C per decade, and a reduction in winter precipitation at the rate of 10.1 mm a^{-1}. While the depth of the snowpack is dependent upon precipitation trends and minimum temperatures (multiple $r^2 = 0.43$), the shortening in the length of the snow period is best predicted by increasing temperatures and reduced humidity. The major forcing of the warming trend involves greenhouse gasses, in particular atmospheric carbon dioxide and water vapor. However, the decline in winter precipitation seems to be unrelated to the forcing of greenhouse gasses, and is instead statistically associated with the Southern Oscillation Index ($r = 0.38$). Inverse correlations were found between depth of snow and solar irradiance, which in turn is inversely correlated with the number of sunspots per cycle. The latter findings suggest that the declining precipitation and snow trends could additionally be associated with a reduction in solar activity during the past five decades.

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Introduction

Snow constitutes a useful climatic index, since it integrates the main weather variables, i.e. precipitation and temperature, over a large part of the northern hemisphere, the poles, and mountain ranges throughout the world. Thus, snow measurements can act as a surrogate providing information on inter-annual climatic fluctuations as well as long-term trends in climate variations (Cayan, 1996). Monitoring of snow cover using remote sensing technology is also being used to study soil moisture and water flow budgets in the northern hemisphere (Robinson, 1991; Barry et al., 1995; Armstrong and Brodzik, 2003), where up to 50% of the land surface can be covered by snow during the winter season, and at least 30% of that land experiences regular seasonal snow cover (Edwards et al., 2007). In relation to the latter areas, the snowpack duration has important implications for ecosystems: it determines the extent of microbiological activity in the soil, the length of the vegetative period and growth of plants, and the rates of leaching and movement of nutrients in the geochemical processes that take place between soil and atmosphere (Edwards et al., 2007).

For the above reasons, most studies on snow cover refer mainly to the northern regions of the planet, from the Arctic (Brown et al., 2007) and North American mountainous regions (Cayan, 1996; Moore et al., 2001) to the British Isles (Qian and Saunders, 2003), continental Europe, and Asia (Hurrell, 1995; Ye, 2001; Armstrong and Brodzik, 2003). Snow records for mountains in both North and South America have been analyzed by Diaz et al. (2003). Since a major review on the importance of snow in Australia (Green, 1998), there have been a number of studies examining the impacts of reduced snow cover or earlier snowmelt. However, although the earlier snowmelt can be explained by a trend of warmer springs (Nicholls, 2005), the causes of the decline in the amount of snow have not been fully explored. There are suggestions that this is unrelated to precipitation levels, as the slight increase postulated by Hennessy et al. (2003), or the small decrease for July–September would be insufficient to account for changes in snowpack (Nicholls, 2005). By contrast, suppression of precipitation in the Snowy Mountains due to insufficient droplet size as a consequence of industrial pollution has been suggested (Rosenfeld, 2000; Rosenfeld et al., 2006).

Understanding the decline of snow cover in the Snowy Mountains region is important because it is affecting various facets of the Australian economy. These mountains, located at 36°27′S, 148°16′E in the southeastern corner of the Australian continent (Fig. 1), are the source of the Murray and Murrumbidgee Rivers, which together provide 30% of the water draining into the Murray-Darling basin. Because of its size and importance, the Snowy Mountains Hydro-electric Scheme, the most complex hydroelectric engineering work in the world, was completed there in 1974. With a net of 16 major dams and seven major power stations connected through 145 km of trans-mountain tunnels and 80 km of aqueducts, it diverts water that would normally flow to the Pacific Ocean westward to provide extra water for irrigated agriculture further inland. The scheme generates 3800 MW of hydroelectric power, which is about 50% of the renewable energy produced in eastern Australia (Snowy Hydro, 2010). The long-term viability of both power generation and irrigated agriculture in the Murray-Darling basin depend on precipitation in the Snowy Mountains, of which snow constitutes about 60% in the subalpine zone. This makes the study of snow cover in the region most relevant for managing the water resources in the catchment.

This paper examines several climatic and solar factors that could be affecting the decline in snowpack in the Snowy Mountains of Australia. The results of linear correlations and multiple regressions between the snow data and those factors are discussed.

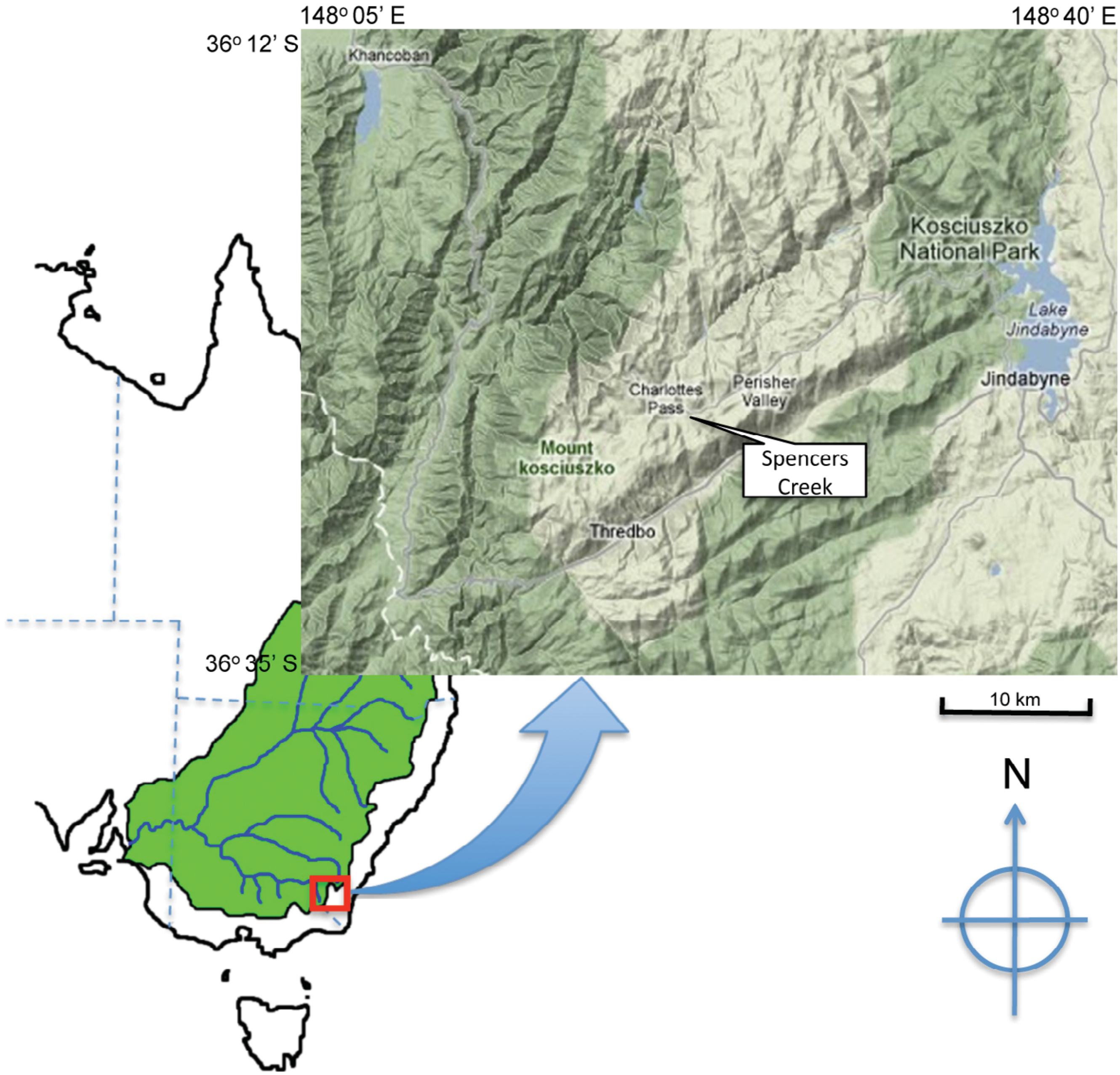

FIGURE 1. Location of the Snowy Mountains (insert) and the Murray-Darling basin (in green) in southeastern Australia. Spencers Creek and the other meteorological stations used in this study are indicated (see Methods).

Methods

DATA SOURCES

Records of snow data, including depth and date of recording, are from Spencers Creek (1841 m a.s.l.) and were taken weekly between June 1954 and November 2011. Daily weather data (precipitation, temperature, and relative humidity) are from 4 locations in the Snowy Mountains: Thredbo (1957 m), Charlotte Pass (1755 m), Spencers Creek (1768 m), and Perisher (1735 m), and were provided by the Australian Bureau of Meteorology. Data at some stations are fragmented, so interpolation by spatial kriging was used whenever missing data were found. In the case of absolute humidity, missing values between 1968 and 1985 were estimated from the relative humidity recorded at the nearby Khancoban station (337 m), after adjusting for the difference in altitude. Absolute humidity (g H_2O m^{-3}) was calculated from the daily average temperature and relative humidity at each location, using the equation

$$AH = RH \times 0.0412\ e^{(0.065t)}, \quad (1)$$

where RH is the relative humidity (%) and t the air temperature in degrees Celsius. Solar irradiance at the surface is from 2 of these stations (Charlotte Pass and Perisher) plus 2 more located in the western and eastern valleys of the Snowy Mountains (Khancoban, 337 m, and Jindabyne, 930 m, respectively).

All the above records are ground measurements, but solar irradiance data at the surface were calculated by the Bureau of Meteorology using the hourly MTSAT-1R (Geostationary Meteorological Satellite) visible data, as well as hourly cloud albedos.

Good quality data are available from 1990 onwards, since previous records are deemed unreliable. The Bureau of Meteorology compares the data obtained from the satellite grid (resolution 6 km) with ground measurements to check the accuracy of the model. The hourly irradiances are then integrated to give daily insolation totals in megajoules per square meter, which were converted here to watts per square meter (1 MJ $=$ 277.8 W h^{-1}). Further information on the quality of these data can be found on the Bureau of Meteorology's website (http://www.bom.gov.au/sat/solradinfo.shtml).

Monthly data on the Southern Oscillation Index (SOI) were obtained from the public website of the Bureau of Meteorology (http://www.bom.gov.au/climate/current/soihtm1.shtml). Concentrations of atmospheric carbon dioxide were obtained from the Keeling Curve at Mauna Loa in Hawaii (http://scrippsco2.ucsd.edu/data/atmospheric_co2.html), covering monthly readings from 1958 to the present, which cover almost the entire period of snow records. Astronomical data on sunspots were obtained from the National Geophysical Data Center at Boulder, Colorado (http://www.ngdc.noaa.gov/stp/SOLAR/solintro.html), a service of the National Oceanic and Atmospheric Administration (NOAA) in the U.S.A.

DATA ANALYSIS

Trends in snow cover from Spencers Creek and weather data from the 4 mountain weather stations were analyzed by linear regression, since all the variables exhibited a random pattern of distribution over the entire period of recording (58 years). However, in order to detect periodic patterns in precipitation, snow trends, and SOI (136 years data), autocorrelation and spectral analysis were used. Sunspot data were also analyzed this way for a period spanning 263 years, i.e. since records began in 1749. For all analyses of the time series, annual values of all the variables were used.

In a first approach to find out what factors are determining the snow trends, correlations between the snow parameters (average and maximum depth, length of snow cover period) and weather variables (precipitation, temperature, absolute and relative humidity, and SOI) were performed using the annual values from the above locations. These data were also split into summer and winter seasons, with the latter season encompassing only the months of snow cover. This allows a more specific analysis of the snow trends. Further correlations between the snow and weather variables with two external factors, namely solar surface irradiance at the 4 stations and atmospheric carbon dioxide concentrations, were also carried out. Sunspot data were used as a proxy of solar activity, and were correlated to snow data using either annual mean numbers or half-cycle averages. In the latter procedure, the solar cycle is divided into 2 parts, the maxima (peaks) and minima (troughs) years, and averages of sunspot numbers are calculated for the respective half-cycle periods. The same applies to the snow variables for those periods, so that both sets of data can be analyzed using correlation or regression analysis. This allows detection of periodic fluctuations among random data that are not apparent when using annual data. Whenever significant correlations were found between pairs of variables, the data were plotted and a best regression curve fitted. Although correlation does not imply causation, a lack of correlation ($p > 0.05$) was taken to indicate no cause-effect relationship between the variables, thus helping discard factors that are unrelated.

Finally, annual and winter data were subjected to multiple linear regression analysis, using a stepwise backward procedure in order to discard variables that are intercorrelated. Since solar irradiance data were available only from 1990 onwards, two sets of multiple regressions were obtained in each case: (i) the entire data record from 1954, which excludes solar irradiance, and (ii) a subset from 1990 including the solar irradiance data. S-PLUS® 2000, version 3 (Insightful, Seattle, Washington, U.S.A.) was used to perform all statistical analyses.

Results

CHANGES IN SNOW COVER AND WEATHER VARIABLES

The snow cover trends and climatic fluctuations in the Snowy Mountains were analyzed based on the climatic records for the 4 weather stations above 1700 m. After 58 years of continuously recording the snow depth at Spencers Creek (1841 m; Fig. 1), two clear downward trends emerge: (i) the average depth of snow accumulated during the winter season has decreased by 27.2 cm, or 24% since 1954 (Table 1), while the maximum depth of the snowpack has decreased by 44.8 cm during the same period; (ii) at the same time, the snowpack duration has shortened by some 18.5 days (Fig. 2, part a). Although the annual rates of change for both variables (-0.48 cm average snow depth and -0.32 days snowpack duration) are not statistically significant, the two combined have resulted in a significant downward trend in the integrated snow profile (depth multiplied by duration) with the 5-year running mean ($F_{1,50} = 26.467$, $r^2 = 0.35$, $p < 0.0001$), highlighting the 30% reduction in 5 decades (Green and Pickering, 2009; Green, 2010).

The downward trend in annual precipitation (-8.5 mm a^{-1}, $p = 0.031$) follows closely the decreasing trend in snow depth (Fig. 2, parts a and b), with good correlations between annual precipitation and snow depth variables: $r = 0.40$, $p = 0.003$; and $r = 0.46$, $p = 0.001$ for average and maximum depth, respectively (Table 2). Indeed, precipitation in the Snowy Mountains has decreased 459 mm since 1957, an average decline of 22% since the building of the Snowy Mountains Hydro-electric Scheme. This trend towards a drier mountain climate has occurred in spite of the inter-annual fluctuations and the wet conditions of the past two years: 2373 mm in 2011 and 2095 mm in 2010 compared to a running average of 1770 mm in 58 years. A seasonal analysis reveals that such reduction in annual precipitation is due to a decreasing trend only during the winter snow season (-10.1 mm a^{-1}, $p = 0.004$), whereas summer rainfall has remained unchanged over 55 years and slightly increased in the past 2 years (Table 1). These data indicate a remarkable 44% drop in precipitation during the snow season, which is significantly correlated with decreasing trends in the average snow depth ($p \leq 0.001$, $r = 0.46$), the maximum snow depth ($r = 0.54$), and the length of the snow period ($r = 0.48$) (Table 2).

Even more significant ($p < 0.001$) is the change in air temperatures, which has increased by an average 1.79 °C since the records began in the area (Fig. 2, part c; Table 1). Such an increase is mainly due to a rise in maximum temperatures, which are rising at 0.4 °C per decade, while the minimum temperature has remained

TABLE 1

Trends for snow, some common weather variables, and other factors. SOI = Southern Oscillation Index.

Variable	Period	n (years)	Initial*	Final*	Net change	Yearly rate	r^2	P value
Average snow depth (cm)	1954–2011	58	113.0	85.7	−27.2	−0.48	0.05	0.099
Max snow depth (cm)	1954–2011	58	220.5	175.7	−44.8	−0.79	0.04	0.122
Snow duration (days)	1954–2011	58	162.2	143.8	−18.5	−0.32	0.05	0.091
Precipitation (mm)	1957–2011	55	2015	1556	−459	−8.50	0.08	0.031
Winter (snow season)			1233	687	−547	−10.12	0.16	0.004
Summer			770	812	42	0.78	0.00	0.783
Temperature (°C) average	1962–2011	50	4.36	6.14	1.79	0.04	0.34	<0.001
Average winter			0.80	1.70	0.90	0.02	0.14	0.007
Maximum (year)	1962–2011	50	8.21	10.24	2.02	0.04	0.34	<0.001
Maximum winter			4.09	5.08	0.99	0.02	0.12	0.013
Minimum (year)	1962–2011	50	0.48	0.31	−0.17	−0.003	0.01	0.519
Minimum winter			−2.64	−2.91	−0.27	−0.005	0.02	0.378
Absolute humidity (g m^{-3})	1962–2011	50	3.9	4.6	0.8	0.02	0.74	<0.001
Solar irradiance (W m^{-2})	1990–2011	22	174.6	194.9	19.9	0.95	0.27	0.013
Winter (snow season)			140.1	125.8	−14.3	−0.68	0.06	0.274
Summer			218.3	249.1	30.7	14.6	0.15	0.071
Atmospheric CO_2 (ppm)	1958–2011	54	315.3*	391.5*	76.3	1.46	0.99	<0.001
Sunspots (number)	1954–2011	58	92.4	46.4	−46.0	−0.81	0.07	0.052
SOI index	1954–2011	58	1.2	−1.1	−2.2	−0.04	0.01	0.488

*Initial and final values determined by the respective regression lines, except for CO_2 which are the actual measured values

practically unchanged—a slight, non-significant decrease by 0.17 °C in 50 years. The average winter temperatures have doubled from 0.8 to 1.7 °C, causing the inevitable thawing of the snow (Table 1). The overall rate of temperature increase in the Snowy Mountains (0.36 °C per decade) is slightly lower than the 0.6–1.2 °C change recorded in the Nepal Himalayas in the period 1971–1994 (Shrestha et al., 1999). Average temperature correlates well with the decrease in maximum snowpack depth ($r = -0.34$, $p = 0.015$) and the overall shortening of the snow cover period ($r = -0.31$, $p = 0.026$), but less so with the average amount of snow present at any time ($r = -0.29$, $p = 0.038$) (Table 2).

In parallel with temperature, since hotter air holds more water vapor, the absolute humidity has significantly increased by 20% during the same period (Fig. 2, part d). Water vapor is a greenhouse gas that contributes to global warming through a positive feedback mechanism (Philipona et al., 2005; Bony et al., 2006). Therefore, it is not surprising that a significant correlation was found between annual mean temperatures and absolute humidity ($r = 0.70$, $p < 0.001$) in the Snowy Mountains. By contrast, monthly temperatures in the area show strong inverse correlations with relative air humidity (r range -0.76 to -0.81), but this relationship only indicates that hot weather is associated with dryness of the air at these high altitudes. However, neither absolute nor relative humidity appears to be significantly correlated with the declining snow trends in these mountains (Table 2).

A multiple regression analysis on the annual data set indicates that average and maximum depth of the snowpack in the Snowy Mountains depends significantly on precipitation and minimum temperatures (multiple $r^2 = 0.43$, $p < 0.001$), and to a lesser extent on humidity and the SOI index (Table 3). However, the length of the snow period can be explained by the trends in air humidity and average temperatures only (multiple $r^2 = 0.25$, $p = 0.004$), both of which are strongly correlated with atmospheric CO_2 ($p < 0.001$, $r = 0.84$ for absolute humidity and $r = 0.56$ for average temperature). The inclusion of solar irradiance in the subset for 1990–2011 only changed the outcome of the length of the snow period, which can be mostly explained by the SOI index (multiple $r^2 = 0.18$, $p = 0.046$). It should be noted that the SOI index is significantly correlated ($p = 0.014$) with precipitation ($r = 0.34$) and average temperatures ($r = -0.35$).

Similar results were obtained with the multiple regression analysis performed on the winter data set (Table 3). Once again, precipitation is the main factor that explains the average and maximum depth of the snow pack ($p < 0.001$), with temperatures and humidity playing a secondary role (p range 0.016 to >0.05). In the winter data set, the length of the snow period is explained by precipitation and the SOI index only. Multiple regression coefficients are in the same range as the annual data set, i.e. $r^2 = 0.25$–0.50. Inclusion of solar irradiance data in the subset for 1990–2011 produced different regression equations for the snowpack depth because some climatic variables were excluded due to multicollinearity. Thus, whilst the average depth of the snowpack is explained only by the precipitation trend, the maximum depth is better explained by precipitation and CO_2 combined ($r^2 = 0.41$, $p = 0.007$). Finally, the snow period can be successfully described by a combination of most factors (multiple $r^2 = 0.50$, $p = 0.035$), including solar irradiance instead of CO_2.

Spectral analyses of the annual precipitation and snowpack depth indicate that neither of these variables showed any periodic pattern. Annual values for the SOI did not have periodicity either, with all variations of the autocorrelation factor falling within the 95% confidence intervals (−0.17, 0.17). As it is known, sunspots

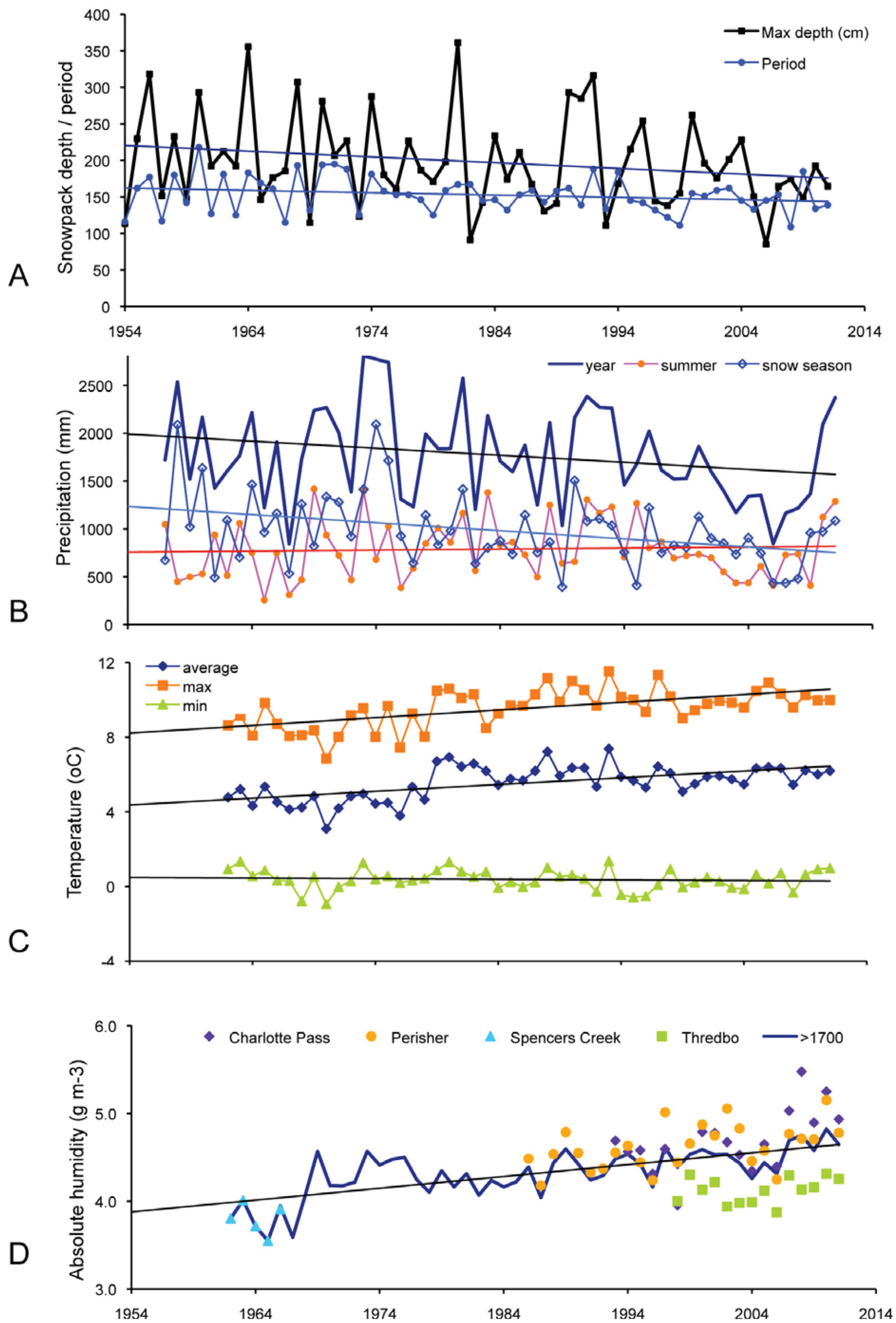

FIGURE 2. Temporal changes in snow cover and weather variables in the Snowy Mountains since 1954. Black straight lines are the trends as determined by linear regression on the annual data (see also Table 1). For each parameter, the mean values of 4 weather stations above 1700 m are shown. (A) Maximum depth of snowpack at Spencers Creek and length of the annual snow-covered period. (B) Total annual and seasonal precipitation. (C) Annual maxima, minima, and average air temperatures. (D) Annual absolute humidity in the air.

follow a sinusoidal pattern of 10.8 years per cycle (Cole, 1973), but the spectral analysis of 263 years showed also a second cycle every 83 years.

POSSIBLE CAUSES OF THE SNOW TRENDS

Apart from the two weather variables (precipitation and temperature) responsible for these changes, the snow data gathered so far correlates well (Table 2) with three other factors: (1) There is a significant inverse correlation ($r = -0.32$, $p = 0.019$) between the atmospheric CO_2 concentrations over the past 54 years and the duration of the snow period at Spencers Creek. (2) Maximum and average depth of snow are also inversely correlated ($r = -0.45$, $p = 0.035$ for maximum, and $r = -0.42$, $p = 0.049$ for average snow depth) to the surface solar irradiance in the region (average of 4 stations; see Methods) during the past 22 years (January 1990 to December 2011), as shown in Figure 3. (3) Snow depth fluctuations, which spectral analysis reveals do not follow any periodic pattern, appear to have a significant correlation with the average number of sunspots per half a cycle ($r = 0.72$, $p = 0.008$ for maximum, and $r = 0.71$, $p = 0.010$ for average snow depth), as shown in Figure 4. Data for the periods of solar maxima and minima are presented in Table 4.

The amount of precipitation, and consequently, snow during the winter season, depends on the alternating cycle of El Niño (warm and dry) and La Niña (cool and wet) events, which can

TABLE 2

Correlation coefficients between snow variables and weather, atmospheric, and astronomical factors.

	Average snow depth (cm)	Max snow depth (cm)	Snow period (days)
Annual precipitation	**0.40** (p = 0.003, n = 51)*	**0.46** (p = 0.001, n = 51)	0.14 (p = 0.345, n = 51)
Winter precipitation	**0.46** (p = 0.001, n = 51)	**0.54** (p < 0.001, n = 51)	**0.48** (p < 0.001, n = 51)
Average temperature	**−0.29** (p = 0.038, n = 50)	**−0.34** (p = 0.015, n = 50)	**−0.31** (p = 0.026, n = 50)
Max temperature	**−0.34** (p = 0.016, n = 50)	**−0.33** (p = 0.020, n = 50)	**−0.29** (p = 0.039, n = 50)
Min temperature	−0.25 (p = 0.075, n = 50)	**−0.34** (p = 0.015, n = 50)	**−0.29** (p = 0.041, n = 50)
Absolute humidity	−0.33 (p = 0.071, n = 31)	−0.30 (p = 0.098, n = 31)	−0.32 (p = 0.080, n = 31)
Relative humidity	−0.05 (p = 0.808, n = 31)	0.03 (p = 0.853, n = 31)	−0.22 (p = 0.224, n = 31)
Atmospheric CO_2	−0.23 (p = 0.096, n = 54)	−0.24 (p = 0.086, n = 54)	**−0.32** (p = 0.019, n = 54)
Solar irradiance	**−0.42** (p = 0.049, n = 22)	**−0.45** (p = 0.035, n = 22)	0.09 (p = 0.703, n = 22)
Sunspots (annual mean)	0.21 (p = 0.118, n = 58)	0.21 (p = 0.112, n = 58)	0.11 (p = 0.409, n = 58)
Sunspots (half-cycle average)	**0.71** (p = 0.010, n = 12)	**0.72** (p = 0.008, n = 12)	0.52 (p = 0.086, n = 12)
SOI index	0.23 (p = 0.081, n = 58)	0.21 (p = 0.119, n = 58)	−0.02 (p = 0.905, n = 58)

*Significant correlations (p < 0.05) are indicated in bold.

TABLE 3

Parameters of the multiple linear regression between snow variables and climatic factors.

			Average snow depth		Maximum snow depth		Snow period	
Data	Period*		Coefficient	P	Coefficient	P	Coefficient	P
Annual	1954–2011	Multiple r^2	0.38	<0.001	0.43	<0.001	0.25	0.004
		Intercept	362.08	<0.001	402.60	<0.001	72.95	0.359
		Precipitation	0.03	<0.001	0.07	<0.001	—	—
		Average temperature	—	—	—	—	10.58	0.139
		Minimum temperature	−33.69	<0.001	52.92	<0.001	—	—
		Absolute humidity	—	—	70.67	0.008	−90.22	0.004
		Relative humidity	−4.30	0.001	—	—	5.65	0.009
		SOI index	1.27	0.056	—	—	—	—
	1990–2011	Multiple r^2	0.32	0.024	0.70	<0.001	0.18	0.046
		Intercept	46.49	0.028	−42.08	0.871	145.61	<0.001
		Precipitation	0.03	0.014	0.07	0.001	—	—
		Minimum temperature	−19.21	0.060	—	—	—	—
		Absolute humidity	—	—	−262.60	<0.001	—	—
		Relative humidity	—	—	17.72	<0.001	—	—
		SOI index	—	—	—	—	1.23	0.046
Winter	1954–2011	Multiple r^2	0.41	<0.001	0.42	<0.001	0.26	<0.001
		Intercept	329.42	<0.001	450.73	0.008	117.40	<0.001
		Precipitation	0.06	<0.001	0.13	<0.001	0.04	<0.001
		Average temperature	54.74	0.033	83.60	0.072	—	—
		Maximum temperature	−40.78	0.029	−56.15	0.096	—	—
		Minimum temperature	−31.19	0.016	−50.77	0.305	—	—
		Relative humidity	−3.28	0.005	−4.64	0.027	—	—
		SOI index	—	—	—	—	−0.79	0.034
	1990–2011	Multiple r^2	0.25	0.017	0.41	0.007	0.50	0.035
		Intercept	52.24	0.006	619.88	0.109	−97.50	0.426
		Precipitation	0.05	0.017	0.11	0.020	0.04	0.031
		Maximum temperature	—	—	—	—	−22.02	0.018
		Absolute humidity	—	—	—	—	69.38	0.052
		CO_2	—	—	−1.40	0.159	—	—
		Solar irradiance	—	—	—	—	0.50	0.079
		SOI index	—	—	—	—	−1.30	0.015

*Solar irradiance included only from 1990 to 2011.

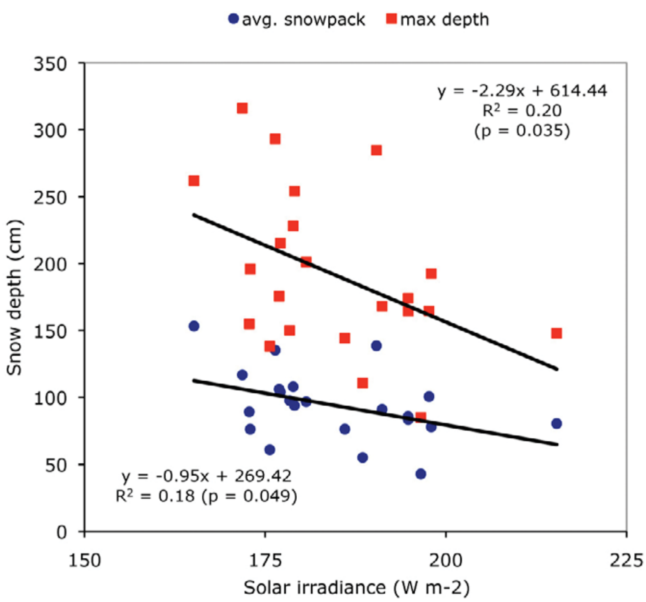

FIGURE 3. Decline of the snowpack in relation to surface solar irradiance at the Snowy Mountains since 1990.

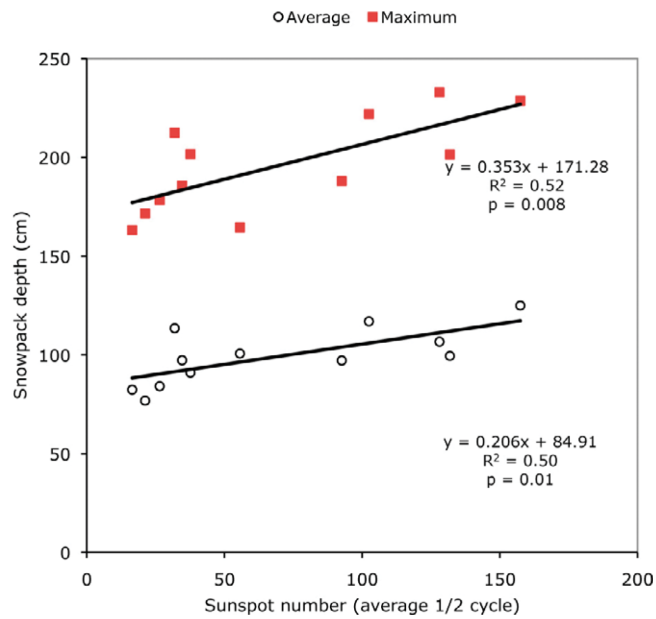

FIGURE 4. Relationship between snow cover in the Snowy Mountains of Australia and sunspot numbers for half a cycle (5–6 years).

partly be described by the SOI ($r = 0.34$; Fig. 5), while its declining trend is correlated with the increase in CO_2 concentrations in the atmosphere ($r = 0.29$, $p = 0.035$). On the other hand, the duration of the annual snow period seems to be directly related to the air temperature (Tables 2 and 3), which is mainly caused by the concentration of atmospheric CO_2 ($r = 0.56$, $p < 0.001$), although the SOI cycle may influence the trends (Fig. 6, part b).

The trend in temperatures appears to be significantly correlated ($r = 0.43$, $p = 0.046$) with solar irradiance at the surface (Fig. 6, part c), at least for the last 22 years of available data. Such positive relationship may result from the lack of cloud cover during periods of dry weather, since the correlation of solar irradiance with precipitation (as a surrogate of cloud cover) is negative, although non-significant ($r = -0.13$, $p = 0.553$). In support of this explanation is the fact that solar irradiance appears to have increased, particularly during summer (14.6 W m^{-2} a^{-1}), whereas during the winter season it has remained almost constant during the past two decades; the apparent decline is not statistically significant ($p = 0.274$; Table 1; Fig. 7, part a). The fact that solar irradiance data are well correlated not only with temperature but also with the atmospheric CO_2 concentrations ($r = 0.55$, $p = 0.009$) and the absolute humidity ($r = 0.45$, $p = 0.036$) seems to indicate that these associations are the product of auto-correlation, as all these variables show parallel trends over the past two decades. Therefore, as with CO_2, solar irradiance is often discarded in the stepwise multiple regression analyses (Table 3).

Finally, surface solar irradiance from the Snowy Mountains for the past 22 years is significantly correlated with the annual mean number of sunspots ($r = -0.57$, $p = 0.006$), which can be taken as a proxy of solar activity. It is a well-established fact that solar activity increases with the number of sunspots (Lean, 2000), following a sinusoidal pattern of 10.8 years per cycle. Contrary to this expectation, in the Snowy Mountains of Australia surface solar irradiance appears to decrease with increasing solar activity (Fig.

TABLE 4

Average number of sunspots, depth of snow and duration of snow season for the periods of solar maxima and minima.

Solar cycle	Period	Sunspots	Snow depth (cm)	Max snow depth (cm)	Snow duration (days)
18 (min)	1954–1955	21.2	76.8	171.6	139.0
19 (max)	1956–1960	157.4	125.0	228.6	166.8
19 (min)	1961–1966	31.9	113.5	212.5	157.7
20 (max)	1967–1970	102.5	116.9	222.0	158.5
20 (min)	1971–1977	37.6	91.0	201.6	164.7
21 (max)	1978–1982	131.9	99.5	201.5	152.8
21 (min)	1983–1987	34.6	97.3	185.7	147.0
22 (max)	1988–1992	128.1	106.7	233.0	158.0
22 (min)	1993–1997	26.5	84.1	178.5	147.4
23 (max)	1998–2003	92.6	97.2	188.0	143.3
23 (min)	2004–2010	16.5	82.4	163.2	143.4
24 (max)	2011–	55.6	100.7	164.6	139.0

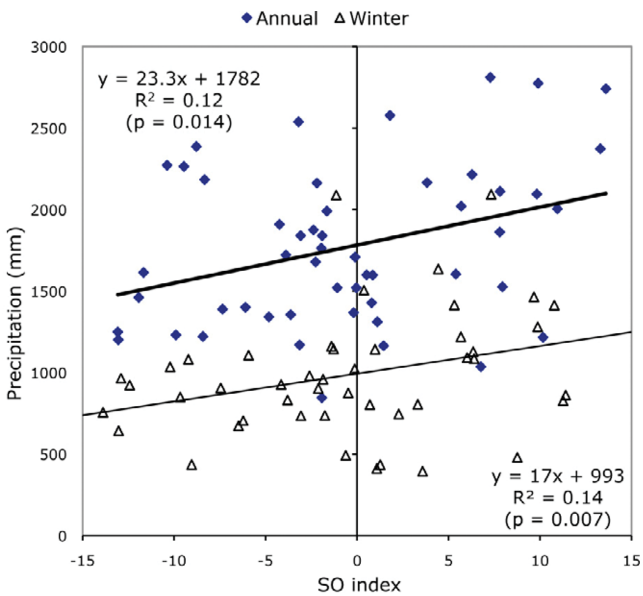

FIGURE 5. Precipitation at the Snowy Mountains in relation to the Southern Oscillation Index (SOI).

7, part b). This relationship, however paradoxical, is consistent with the increasing depth in the snowpack observed during years of more solar activity (Fig. 4).

Discussion

Depth of the snowpack can be explained by two factors alone: amount of precipitation in the form of snow, which falls mainly between autumn and spring, and air temperatures. Both correlation and multiple regression analyses support this finding. Abundant precipitation during winter is the necessary condition—albeit not the only one—for a thick snowpack throughout the snow season in any one year, and such snowfalls tend to be more frequent during the wet years of La Niña weather events (Fig. 5). Our data show that a decline in winter precipitation over 58 consecutive years is the primary factor responsible for the decline in snowpack thickness and duration (Table 2). The underlying causes of a reduced precipitation in the last decades are presently speculative, even if atmospheric CO_2 is associated with the declining trend; however, this association is not causative but may result from indirect effects of this greenhouse gas on the global weather. The trend of the SOI towards drier weather is clearly non-significant (Table 1), particularly since the past 2 years have turned around the previous El Niño event that lasted almost 3 decades (Lee and McPhaden, 2010). Another possibility is aerosol pollution, which may affect negatively the precipitation patterns in the Snowy Mountains (Rosenfeld et al., 2006).

In addition to less precipitation in the form of snow, it is also evident that large volumes of snow can quickly thaw under warm conditions. Ensuring that the snowpack remains frozen for a long time requires, therefore, that heavy snow precipitations are followed by lengthy cold periods. Indeed, low minimum temperatures and relative air humidity are explanatory variables of the thickness of the snowpack in the multiple regression analysis (Table 3). In this regard, Nicholls (2005) has shown that a trend of warmer

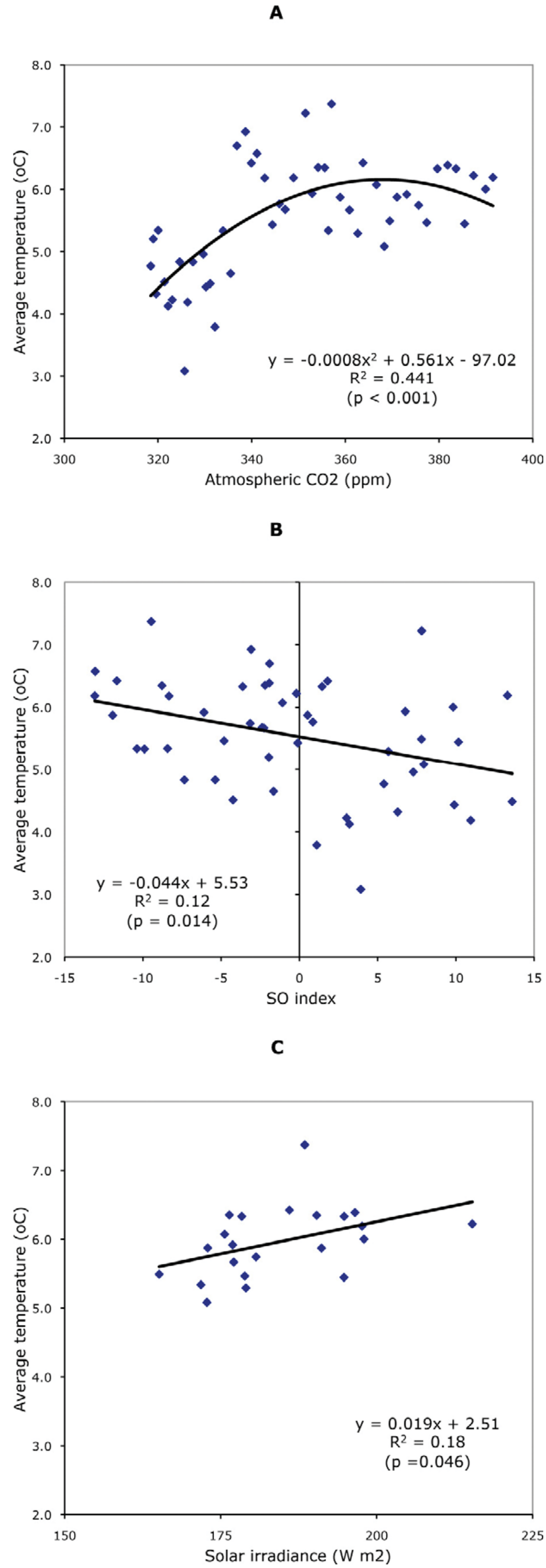

FIGURE 6. Annual average air temperature in the Snowy Mountains in relation to (A) atmospheric CO_2 concentrations; (B) the Southern Oscillation Index (SOI); and (C) surface solar irradiance.

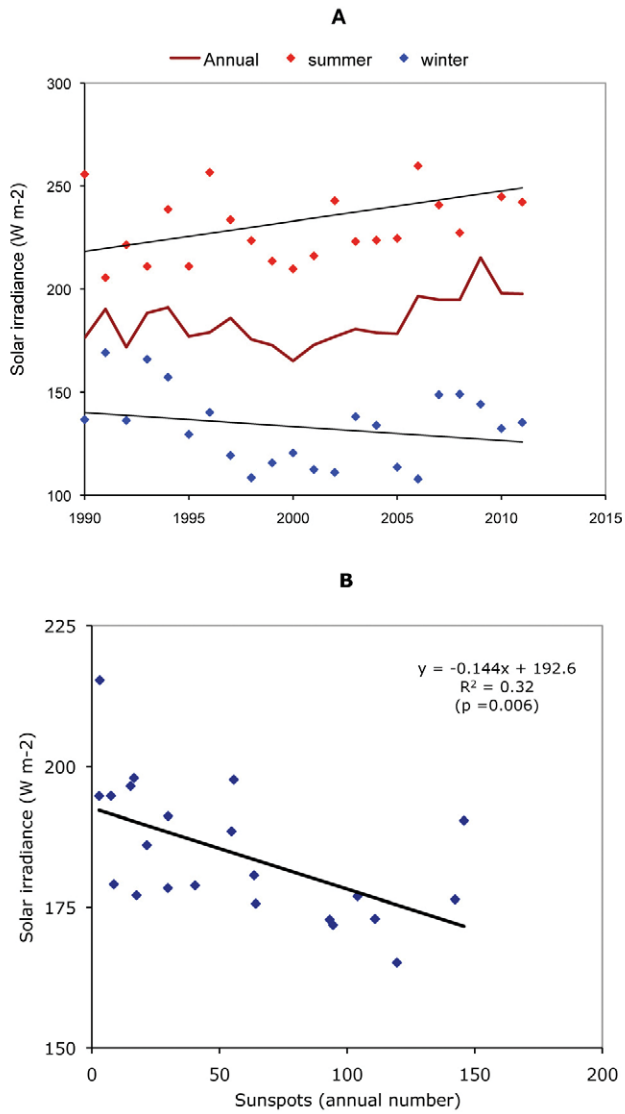

FIGURE 7. (A) Trends in surface solar irradiance in the Snowy Mountains above the treeline (>1700 m). (B) Relationship of the annual solar irradiance with the average number of sunspots per year.

springs results in an early thawing, thus reducing the overall length of the snow period. Correlations and multiple regression analyses indicate that temperature is the main factor responsible for the shortening of the snow period, and a secondary factor affecting the depth of the snowpack (Tables 2 and 3). The effect of increasing temperature in the Snowy Mountains in the past half a century only exacerbates the declining snow cover in the region, since the trends of both precipitation and temperature run counter to each other (Fig. 2; Table 1). As a consequence of the opposite relationships of these weather variables with the SOI index (Figs. 5 and 6, part b), snow seasons are expected to become more extreme in the future. Thus, during the dry El Niño events the snowfalls may decrease more and the snowpack may last for shorter periods, whereas during the wet La Niña we can expect more precipitation, but given the increasingly warmer conditions much of it would be as rainfall and a reduced proportion may fall as snow.

Atmospheric carbon dioxide can be considered the major forcing responsible for the increase in temperature in these mountains, given the very significant correlation between these variables ($r = 0.56$, $p < 0.001$). Although CO_2 appears correlated to the duration of snow cover in the univariate analysis (Table 2), this is discarded in the multiple regressions (Table 3) where a combination of other factors, some correlated to CO_2, are significant. By contrast, correlations between absolute humidity and snow data were found to be non-significant at the 95% probability level in the univariate analysis, whereas both absolute and relative humidity are explanatory variables in the multiple regression analyses (Table 3). Some authors have shown that a drastic drop in atmospheric moisture at the end of the 19th century and the ensuing drier climatic conditions are implicated in the glacier retreat on Kilimanjaro (Kaser et al., 2004). However, increasing air humidity is also contributing to atmospheric warming, but the concentration of water vapor in the air follows the temperature increase, so it is regarded as a secondary factor enhancing the global warming rather than being its main cause (Diaz and Graham, 1996). In any case, average and maximum temperatures in the mountain tops have not kept pace with the increasing carbon dioxide concentrations (Fig. 6, part a). This indicates that other factors are probably involved in regulating the air temperature in the mountains. Also, average minimum temperatures in the Snowy Mountains have remained constant throughout the past 50 years. It is possible that increasingly cloudless skies may have played a role in reducing night temperatures in recent decades as it appears to have occurred in the Swiss Alps (Philipona and Dürr, 2004), thus allowing greater energy losses of long-wave radiation at night. Similar trends in temperature have been reported for the mountains of central Japan, where a shift in the treeline at Mt. Fuji provides evidence of decreasing mean minima temperatures (Gansert, 2004). The absence of data on cloud cover for the Snowy Mountains prevents us from giving a definite answer to an issue that requires further attention.

The second forcing involved in the reduction in snow cover could be solar irradiance at the surface (Table 2). Changes in solar radiation have been suggested to be important in snow sublimation and ablation processes, particularly under dry air conditions (Kaser et al., 2004). However, because of its high albedo, new snow reflects most short-wave radiation coming from the sun, and therefore small variations in solar inputs hardly affect the melting process (Molotch and Bales, 2006). Instead, solar forcing can operate indirectly through the hydrological cycle in the mountains (e.g. evapotranspiration) or in the region, the latter involving surface water evaporation from the oceans, cloudiness, changes in air pressure, and wind strength. Our analysis indicates that a high annual solar irradiance is significantly associated with decreasing depth of the snowpack (Fig. 3), but this is mainly due to increases during the summer months since winter irradiance has remained almost constant. However, solar irradiance does not have a significant weight in the multiple regression analysis of the winter data (Table 3), perhaps because of its collinearity with temperature (Fig. 6, part c) and SOI variables. While the declining snow trend is as much the result of melting due to increasing temperatures as it is due to insufficient precipitation in the mountains, the latter is probably associated with changes in the cyclic weather patterns of the southern oceans. The SOI index appears in all the multiple regressions of Table 3 as one of the explanatory variables of the snow trends.

For instance, a change to less precipitation during the winter months would affect the average depth of the snowpack through the year (Green and Pickering, 2009). Such change could originate from warm El Niño events in the South Pacific, which result in dry weather and cloud-free skies in eastern Australia, thus increasing the solar irradiance at the surface. Certainly, solar irradiance can be regarded as the second major forcing involved in climate change (Philipona et al., 2009), its indirect effect on precipitation running parallel to the effect of carbon dioxide on temperature. With both CO_2 and solar irradiance at present on the rise, their additive forcing is having a greater impact on the climate than would be expected from greenhouse forcings alone, as some authors have already pointed out (Rahmstorf et al., 2006).

Current measurements worldwide indicate that solar irradiance is increasing at an annual global rate of 0.66 W m^{-2} (Wild et al., 2005; Ohmura, 2006). In the Snowy Mountains the average solar irradiance trend at 4 meteorological stations is also increasing at an annual rate of 0.95 W m^{-2} (5.2% per decade; Table 1; Fig. 7, part a), which is higher than the global average. This difference likely reflects the fact that at higher altitudes the air is thinner and allows better transmission of radiation. Explanations for the increasing solar inputs have been tested in central Europe, where it seems that atmospheric conditions represent a forcing of +1 W m^{-2} per decade, of which 16% is due to reduced cloudiness and 84% to lowered air pollution; the latter as a consequence of the major efforts employed to minimize dust particles and aerosols in recent years (Ruckstuhl et al., 2008). Such figures explain only 10% of the increase in radiation in the Snowy Mountains and 15% of the global brightening, so that most of that change remains unaccounted for. Reduced cloudiness is the most plausible explanation for the increasing solar irradiance in the mountains of the Australian region, as this would be consistent with the declining precipitation pattern and also the trend in minimum temperatures (Allan, 2006) (Table 1). Thus, increases in solar irradiance at the surface would result from cloudless skies, effectively meaning decreasing precipitation. Less likely is the move towards cleaner air by reduced pollution, particularly since frequent bushfires and the constant incidence of plumes of dust from coal power stations in the southwestward La Trobe valley affect negatively the precipitation patterns in the Snowy Mountains (Rosenfeld et al., 2006). However, should precipitation in the eastern part of Australia have decreased as a result of air pollution alone, the same aerosols and dust particles would have reduced the solar radiation in the region (Ramanathan et al., 2001; Philipona et al., 2005), thus contradicting the solar irradiance data shown here.

Until recently solar forcing has either been ignored in studies of climate change or dismissed as a small contributor to climatic changes (Foukal et al., 2006), although some models involving complex mechanisms have been proposed (Haigh, 2003). However, its importance has been highlighted recently in relation to climate variability in the northern hemisphere (Lockwood et al., 2010; Ineson et al., 2011). Total solar irradiance at the surface of the earth has been changing at least since measurements began in the early 1960s. During the period 1960–1990 a 'global dimming' was observed (Liepert and Tegen, 2002), and evidence to date suggests this loss of radiation resulted from scattering by air dust and aerosol pollution as a consequence of burning fossil fuels (Stanhill and Cohen, 2001; Ohmura, 2006). However, from about 1990 a reverse, increasing trend or 'brightening' has been recorded in most parts of the world (Wild et al., 2005), except in countries such as India, China, and some African states, where air pollution is still a major problem (Menon et al., 2002; Ohmura, 2006). Because of these observations, such brightening is rather thought to be a 'recovery' back to the levels of radiation experienced before the period 1960–1990 (Wild et al., 2007).

It should not be forgotten that the levels of solar radiation reaching the surface depend ultimately on the solar activity. Whereas the total solar irradiance changes by about 0.1% over the course of the solar cycle, the irradiance in the UV part of the solar spectrum varies up to 10% in the 150–300 nm range and by more than 50% at shorter wavelengths (Krivova et al., 2009). These variations affect the earth's climate system, as UV radiation plays an active part in the chemistry of the stratosphere and mesosphere (Ineson and Scaife, 2009). Solar cycles, therefore, are remotely implicated in the periodic fluctuations of weather, while solar activity, and the total irradiance received by the earth, is largely determined by the sunspots (Foukal et al., 2006). It should be noticed that annual solar irradiance in the Snowy Mountains is inversely correlated with sunspot numbers ($r = -0.57$, $p = 0.006$; Fig. 7, part b). In connection to this, we observed that the majority of maximum snow depths recorded (1956–1960, 1968, 1981, 1990–1993, and 2000) tends to coincide around years with the highest number of sunspots (Table 4), following a quasi-decadal repetitive pattern. Similar decadal cycles in snow deposition have been observed in the northern hemisphere (Ye, 2001), although the authors appear to miss the link with the solar pattern. The annual number of sunspots, however, is not correlated with the snow depth nor its duration in the Snowy Mountains, but the average number of sunspots during the years of solar maxima and minima are significantly correlated to the average depth of the snowpack in these mountains (Table 2; Fig. 4). Considering sunspots as a proxy of the long-term radiation (Lean, 2000), the trends shown in Figure 4 predict that the years with highest snow falls should occur around the solar maxima periods.

A final consideration: sunspot numbers have also decreased in recent times (Table 3), following the same trend as the declining pattern of precipitation and snow cover. The oncoming sunspot maximum in cycle 24, predicted for 2013–2014 (Cole, 1973), will shed more light on this matter. If the next solar maximum is lower than that in the previous cycles, we will be bracing for another decade of low precipitation and El Niño weather patterns in the Snowy Mountains, thus exacerbating the already negative effects of global warming in this part of the world. However, should the current solar cycle reach the levels of activity seen during the 1950s and 1960s, one could expect a reverse of the current trends, leading to increasing precipitation and reducing the surface solar irradiance by cloudiness, all of which would result in increasing amounts of snow in the mountains. We hope these findings prompt other researchers to look into the physical mechanisms that may explain the relationship between cyclic solar activity and the regional weather patterns directly involved in snow precipitation in Australia or elsewhere.

Conclusions

The reduction in depth of snow in the Snowy Mountains during the past 6 decades is primarily due to lower precipitation in the mountains during the winter season. Increasing warming of the air, the main forcing of which are carbon dioxide emissions and secondarily water vapor, seems to be concurrently influencing the decreasing trends in snowpack depth and its duration. Declining precipitation appears to be related to the known cyclic weather patterns of El Niño–La Niña, and both climatic variables are correlated with an increasing trend in surface solar irradiance, possibly as a result of less cloud cover. In turn, the latter trend could be due in part to anthropogenic forcing, but it is also well correlated to changes in the sun's internal activity as indicated by the decreasing sunspot trend. While additional evidence from the current solar trend will take some years for this relationship to be elucidated, we encourage the scientific community to look into this issue further.

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