CLIMATE CHANGE AND SNOW-COVER DURATION IN THE AUSTRALIAN ALPS

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Abstract. This study uses a model of snow-cover duration, an observed climate data set for the Australian alpine area, and a set of regional climate-change scenarios to assess quantitatively how changes in climate may affect snow cover in the Australian Alps. To begin, a regional interannual climate data set of high spatial resolution is prepared for input to the snow model and the resulting simulated interannual and spatial variations in snow-cover duration are assessed and compared with observations. The model provides a reasonable simulation of the sensitivities of snow-cover duration to changes in temperature and precipitation in the Australian Alps, although its performance is poorer at sites highly marginal for snow cover. (In a separate comparison, the model also performs well for sites in the European Alps.) The input climate data are then modified in line with scenarios of regional climate change based on the results of five global climate models run in enhanced greenhouse experiments. The scenarios are for the years 2030 and 2070 and allow for uncertainty associated with projecting future emissions of greenhouse gases and with estimating the sensitivity of the global climate system to enhanced greenhouse forcing. Attention focuses on the climate changes most favourable ('best-case scenario') and least favourable ('worst-case scenario') for snow cover amongst the range of climate changes in the scenarios. Under the best case scenario for 2030, simulated average snow-cover duration and the frequency of years of more than 60 days cover decline at all sites considered. However, at the higher sites (e.g., more than 1700 m) the effect is not very marked. For the worst case scenario, a much more dramatic decline in snow conditions is simulated. At higher sites, simulated average snow cover duration roughly halves by 2030 and approaches zero by 2070. At lower sites (around 1400 m), near zero average values are simulated by 2030 (compared to durations of around 60 days for current climate).

These simulated changes, ranging between the best and worst case, are likely to be indicative of how climate change will affect natural snow-cover duration in the Australian Alps. However, note that the model does not allow directly for changes in the frequency and intensity of snow-bearing circulation systems, nor do the climate-change scenarios allow possible changes in interannual variability (particularly that due to the El Niño-Southern Oscillation) and local topographical effects not resolved by global climate models. The simulated changes in snow cover are worthy of further consideration in terms of their implications for the ski industry and tourism, water resources and hydroelectric power, and land-use management and planning.

1. Introduction

In most years, the Australian Alps (latitude 35–38° S) experience a significant winter snow cover lasting from a few weeks at elevations of 1200–1400 m, and up to four months or more on the higher peaks (1800–2200 m). This natural winter snow cover supports major cross country and downhill skiing activities, forms part of the storage of water for use in hydroelectric power generation and irrigation, and contributes to the unique character of the natural environment of the Australian

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Alps. These functions could be significantly affected if snow cover is reduced in the future as a result of global warming expected due to enhancement of the greenhouse effect. Indeed, studies for mountain areas elsewhere in the world have demonstrated the potentially important economic implications of anthropogenic-induced climate change and reductions in snow cover (Cohen and Allsopp, 1988; Barry, 1992; Smith, 1993; Breiling and Charamza; 1994; Bultot *et al.*, 1994; Beniston, 1994).

Australian Alpine snow cover varies greatly in depth and duration from year to year (see Ruddell *et al.*, 1990). Variations can be directly related to changes in the occurrence of snow-bearing synoptic circulation systems (Colquhoun, 1978; Budin, 1985; Hewitt, 1991), but they can also be related to prevailing seasonal precipitation and temperature anomalies (which in part reflect the particular synoptic systems which occur). Indeed, Galloway (1988), Ruddell *et al.* (1990) and Duus (1992) have found that spatial and interannual variability in various measures of seasonal snow conditions in the Australian Alps can be very well simulated using models which use local monthly temperature and precipitation data as their only input.

This dependence on prevailing temperature conditions makes Australian alpine snow cover vulnerable to warming expected due to the enhancement of the greenhouse effect (Houghton *et al.*, 1990, 1992). Increasing temperature would be expected to have a detrimental effect on snow through increasing the likelihood of precipitation falling as rain rather than snow and through increasing the melting and evaporation of lying snow. However, it is possible that increases in precipitation could compensate for the effect of the warming, as long as a sufficient proportion of the precipitation still falls as snow.

Galloway (1988) estimated the effect on Australian alpine snow cover of changes in temperature and precipitation using a model of snow-cover duration which used monthly average climatic data as input. He found a strong sensitivity of simulated snow cover to increasing temperature at the limited range of sites he examined in the Australian Alps. Typically, snow-cover durations halved for a warming of 2 °C, and precipitation increases of up to 20% did little to compensate for the effect of the warming.

Other recent studies which use snow models to explore the sensitivity of snow conditions to scenarios of climate change include Martin *et al.* (1994) (French Alps) and Bultot *et al.* (1994) (single catchment in Switzerland). Both these studies showed very marked decreases in snow cover with increasing temperature, particularly at more marginal, low elevation, sites. The empirically based study of Koch and Rudel (1990) showed significant decreases in snow-cover duration throughout Austria under assumed enhanced greenhouse conditions. Hewitt (1994) used a very different approach when assessing the impact of climate change on snow conditions at Falls Creek in the Australian Alps. He devised a scheme in which daily snow variations are predicted from daily synoptic scale atmospheric circulation, temperature and humidity. He then applied the scheme to the daily output of the CSIRO global climate model under both current and $2 \times CO_2$ conditions. Largely due to the very marked warming under $2 \times CO_2$ conditions in the

Mark 1 model (4.8 °C globally averaged), Hewitt's scheme predicted snow cover to disappear almost entirely.

The current study assesses quantitatively how changes in climate may affect snow cover in the Australian Alps using a combination of the model of snow-cover duration of Galloway (1988), an observed interannual climate data set for the Australian alpine area interpolated to a grid of high spatial resolution (using an interpolation method which allows for effect of elevation on climate), and a set of regional climate-change scenarios based on the output of global climate models. The gridded observed climate data are used as input to the snow model which then produces gridded output of snow-cover duration. The climate-change scenarios are used to modify the input climate data so that model output can then show the impact on simulated snow-cover duration of changes in climate.

This study differs from that of Galloway (1988) in a number of important respects. Galloway (1988) looked at the effect of arbitrary climate changes on snow cover at a limited number of sites and used long-term mean climate as model input. Here, we calculate results on a detailed grid covering all of the Australian alpine area, consider the effect of GCM-derived climate-change scenarios for 2030 and 2070, and use interannually varing model input. In particular, by using interannual input data to the Galloway model, we are able to do the following:

- Compare observed and model simulated interannual changes in snow-cover duration, thus enabling the relative sensitivity of the model to changes in temperature and precipitation to be more thoroughly investigated
- Assess the impact of climate change on the frequency of high and low snow-cover years rather than just the changes in average conditions
- Assess when in the next century (if at all) the effect of climatic change might be expected to predominate over interannual variability.

Compared to the other recent studies cited above, the advantage of the approach used here is the simplicity of the input climate information required (montly means of temperature, precipitation and standard deviation of temperature). The model can be applied anywhere estimates of these data are available. More sophisticated models which require a large range of variables as input, such as that used by Bultot *et al.* (1994), may produce more accurate results, but cannot be applied so extensively. A unique feature of the current snow impact study is the nature of the climate-change scenarios employed. These have been constructed so as to increase the relevance of the results of the study to policymakers, and consider the likely best-case and worst-case scenarios for given dates in the future. The scenarios take into account uncertainty in estimating climate change for given times in the future due to our uncertain knowledge of future rates of emission of greenhouse gases, the sensitivity of the global climate system and the differing regional results of a range of global climate models.

Table I
Selected Australian alpine sites and their elevations. Note that the elevations are those resolved on the 2.5 km by 2.5 km topography grid used here and that actual summit elevations can differ slightly

Location	Elevation (m)
Mt. Donna Buang	1250
Lake Mountain	1400
Mt. Baw Baw	1564
Falls Creek	1643
Mt. Buffalo	1723
Mt. Buller	1805
Mt. Hotham	1883
Mt. Bogong	1986
Mt. Jagungal	2061
Mt. Kosciusko	2228

The study was undertaken under contract to the Victorian Government and more detailed results may be found in the report of Haylock *et al.* (1994). However, due to a minor modification in the model, the results presented here differ slightly from corresponding results in Haylock *et al.* (1994).

2. Study Domain and Data Sets

2.1. STUDY REGION

Figure 1 shows the topography of the study domain (145°30’ E to 149°30’ E and 38° S to 35° S). The Alpine area (roughly that area above 1250 m) includes mountainous areas in both the States of Victoria and New South Wales. The locations of nine mountain summits and one additional locality (Fall Creek) are shown in the figure and listed along with their elevation in Table I. These locations will be used here when presenting results for individual sites. They were selected so as to give a good geographical and altitudinal range, but also to include some important downhill and cross-country skiing centres (with greater emphasis to sites in Victoria because of the way the study was funded). There are two further sites that will also be mentioned in the text: Spencers Creek (near the Mt Kosciusko site) and Deep Creek (near the Mt Jagungal site).

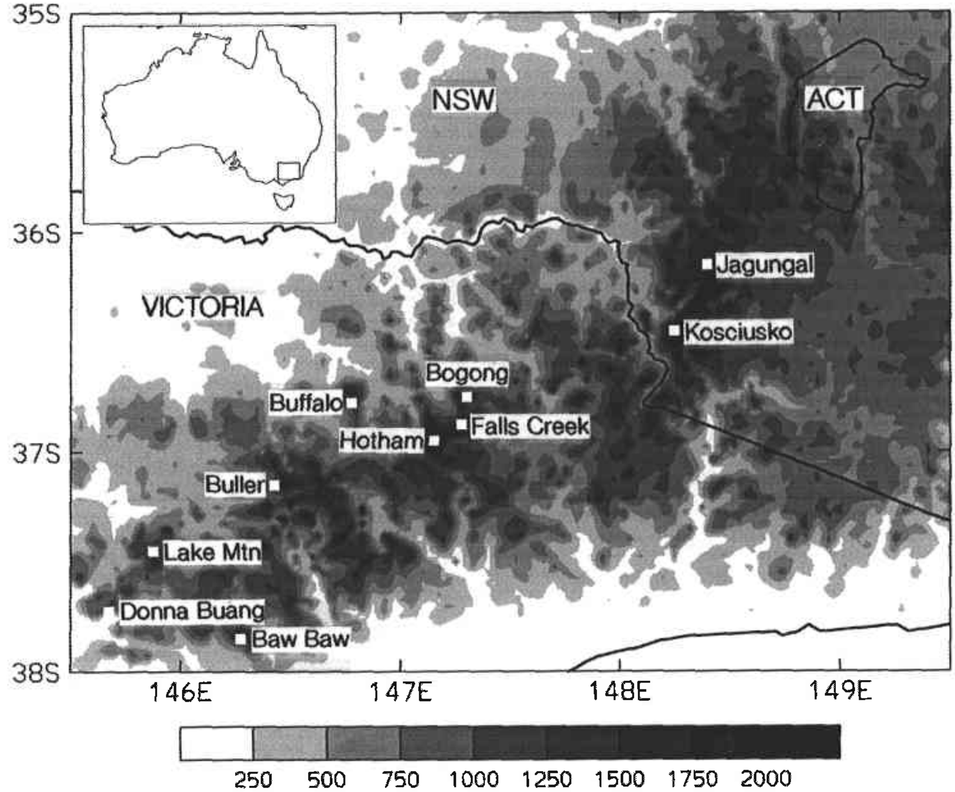

Figure 1. Alpine region of south-east Australia giving the elevation (m) of 2.5 km resolution topography grid used in study. Mountain sites referred to in this study are indicated.

2.2. CLIMATE DATA SET FOR THE AUSTRALIAN ALPS

The snow model used here requires an input monthly values of temperature, precipitation and standard deviation of daily temperature for each site at which calculations are to be undertaken. To obtain an appropriate data set, long-term monthly means, and monthly anomalies for a 20-year period were derived separately in the manner described below.

Long-term mean monthly precipitation, temperature and standard deviation of temperature were calculated for all the Australian Bureau of Meteorology stations in the study region which had at least 10 years of data. Station locations are shown in Figure 2. The stations numbered 49 for temperature and 395 to 403 (depending on the month of the year) for precipitation, and the averaging periods varied from 10 to 133 years. As we wish to simulate snow cover throughout the alpine area (including the significant regions without stations – see Fig. 2), interpolated climatic data needed to be derived. This was carried out using a Laplacian spline surface fitting routine (Hutchinson, 1989) which allowed for the elevation-dependence of

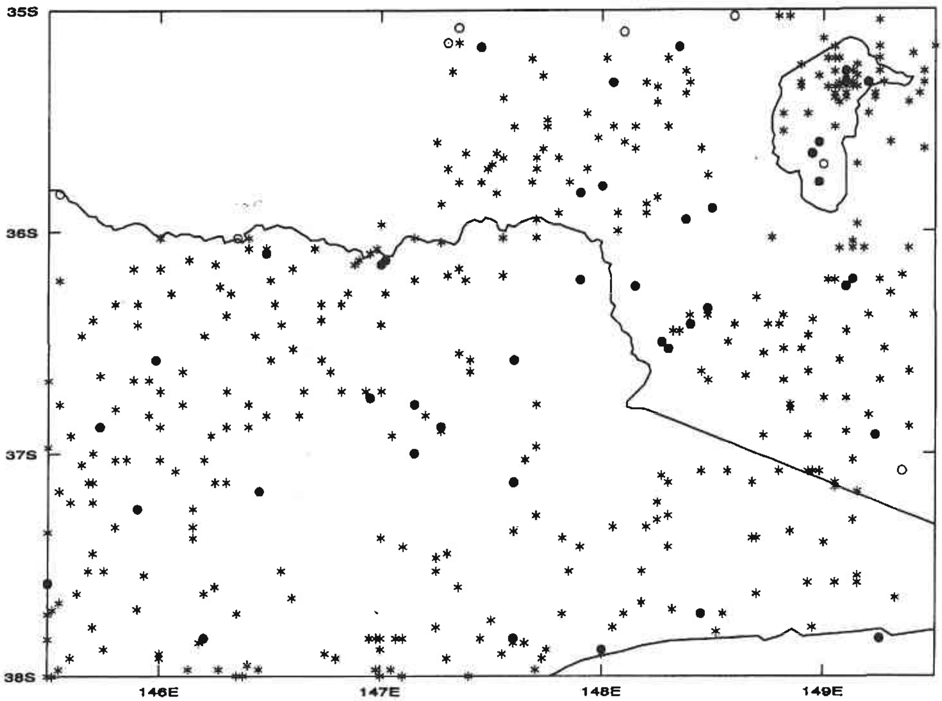

Figure 2. Stations giving precipitation only (∗), temperature and precipitation (•), and temperature only (∘) used for long-term average climatology.

the variables. This means that the dependence of precipitation and temperature on elevation is allowed for in estimating the climatic data for alpine sites. The topographical data base used had a resolution of 1/40th of a degree or around 2.5 km by 2.5 km (Hutchinson and Dowling, 1991) and was adequate for capturing most of the important topographical variations in the region. Note that it was not ideal to use station data from different data periods to construct these interpolated long-term mean data sets. However, given the region's sparse station network and marked topographical (and, therefore, climatic) variations, we considered the errors due to including stations with non-coincident data periods were likely to be less than those due to using a significantly poorer station network.

Next we returned to the original station data and selected those stations which had at least 80 months of non-missing data for May to October over a common 20-year of 1966-1985 (chosen to maximise available data). The distribution over the study domain of the resulting 336 precipitation and 30 temperature stations is not shown, but is similar to, but a little less dense than, that shown in Figure 2. For this period interpolated anomaly maps for precipitation (in percent) and temperature were constructed for each month of the 20-year period (and with the 20-year period used as the reference mean). In this case the interpolation to the 2.5 km grid used an elevation-independent Laplacian spline (Hutchinson, 1989) as anomalies would not be expected to show strong dependence on elevation. To calculate the absolute precipitation or temperature at each grid point for each month of 1966–1985, the anomalies were then added to the long-term average previously described rather than to the 20-year average. This was done because the long-term average was considered to better represent the alpine climate due to its larger number of contributing stations (even though some of these would be from non-overlapping data periods). The monthly standard deviation of temperature needed for model input was taken from the long-term climatology; interannual variations in this quantity were not considered.

2.3. OBSERVED SNOW DATA FOR THE AUSTRALIAN ALPS

Observed snow depths and durations are used to compare with simulated values. For Victoria, snow depth data were taken from a compilation by *Vicroads* for 1976 to 1985 for sites at Mt Hotham (2 locations), Mt Buller, Falls Creek and Mt Buffalo (see Ruddell *et al.*, 1990). These sites were not at the mountain summits. We also use snow-depth observations taken by the Snowy Mountains Hydro Electric Authority for 1955 to 1986 for both Deep Creek and Spencers Creek in NSW.

In all of these cases, the data sets give snow-depth variations through the course of each season, enabling total annual duration of snow cover to be estimated (total number of days when snow depth was non-zero). However, the data at the Victorian sites are, in many cases, limited only to the months June to September, and often only twice weekly within this period. The temporal resolution of any validation is therefore reduced, and when the snow cover extends beyond these months its duration cannot be accurately assessed. In particular, there appeared to be many occasions when there was a large depth of snow at the date of the last observation suggesting that the end of the snow cover was not observed. Data for these years at the sites concerned were not used in validating the model's simulation of interannual variability. Note also that in many cases, observations were taken at one observing location only, which, due to the effect of aspect and exposure, may not be representative.

We also use observed long-term average snow-cover duration for 19 locations in the NSW portion of the Alpine area given by Slatyer *et al.* (1985).

2.4. EUROPEAN CLIMATE AND SNOW DATA

To further validate the model performance, data from the European Alps are also used. Long-term means of temperature, precipitation, standard deviation of temperature (estimated from percentile values) and observed snow durations were assembled for the locations listed in Table II. The main sources used for these data were Schweizerischen Meteorologischen Anstalt (1959–79) and Österreich Hydrographisches Zentralbüro (1962, 1968, 1973).

Table II

Swiss (S) and Austrian (A) sites, and their elevations, used in snow model calculations for European data

Location	Elevation (m)		Elevation (m)
Basel (B)	317	Chateaux-d'Oex (S)	990
Altdorf IV (S)	449	Gaschurn (A)	1008
Weikertschlag (A)	450	Längenfeld (A)	1180
Sion (S)	549	Langen am Arlberg (A)	1270
Bern (S)	560	Leysin II (S)	1330
St Johann bei Herbergstein (A)	576	Davos (S)	1580
Hintersee (A)	685	Galtür (A)	1583
Alfenz Kururt (A)	780	Bever (S)	1712
Grobming (A)	780	Mooser Boden (A)	2036
Mariazell (A)	865	St Gotthard (S)	2090
La Chaux-de-Fonds III (S)	984	Säntis (S)	2500

3. The Snow Model

The snow model of Galloway (1988) uses monthly average temperature, precipitation and standard deviation of daily temperature as input. Empirically derived relationships are used to calculate monthly snowfall and potential ablation (potential to melt or evaporate snow). The model was developed with reference to detailed daily snow and meteorological observations at Spencers Creek (1768 m) in the Australian Alps.

3.1. SNOWFALL

The monthly average snowfall *S* is given by:

$$S = \alpha P \tag{1}$$

where *P* is the monthly average precipitation rate and α is the proportion of that precipitation falling as snow. *S* and *P* are in units of millimetres of water per day (mm/day). The factor α depends on the mean temperature of days with precipitation, which we will call the mean 'precipitation day temperature', T_d. This is estimated empirically (in °C) using the relationship:

$$T_d = (T - \sigma_t)/2 \tag{2}$$

where *T* is the monthly mean temperature, and σ_T is the monthly standard deviation of daily temperature. The relationship reflects a tendency observed in the Australian Alps, for days with precipitation to have a temperature below the monthly mean during warmer months or at lower sites, but to have a temperature above the

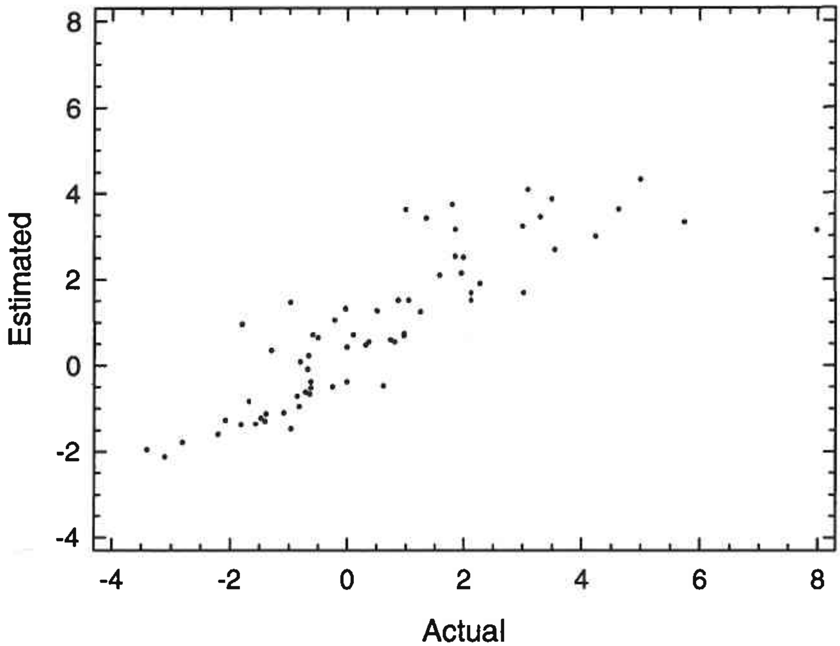

Figure 3. Comparison of estimated and actual monthly average 'precipitation day temperature' (°C). The estimated values (vertical axis) are obtained from the monthly mean and standard deviation of temperature. The actual values are obtained using daily temperature and precipitation data. The data used are for Mt. Hotham from 1977 to 1987.

monthly mean at the higher sites in mid-winter. Figure 3 shows a comparison between monthly mean T_d calculated from Eq. (2) and observed directly for Mt Hotham in the Australian Alps for data covering the period 1977–1987.

The relationship to α to monthly T_d was derived using the Spencers Creek snowcourse and daily temperature data. It is a smooth curve ranging from $\alpha = 1.0$ for $T_d < -3$ °C to $\alpha = 0.0$ for $T_d > 2$ °C. The extent to which this relationship is generally applicable will affect model performance at sites other than Spencers Creek. However, the exposure of Spencers Creek snow course to drifting snow is not unusual, and any peculiarities that could exist in the lapse rate of temperature at Spencers Creek are unlikely to be manifest on precipitation days.

3.2. POTENTIAL ABLATION

Monthly potential ablation rate A (in mm of water per day), is given by:

$$A = \beta \gamma D/n \quad (3)$$

where D is the degree days above zero for the month (in °C days), n is the number of days in the month, β is a constant known as the 'degree day factor' (in mm/°C day), and γ is the 'aborptivity factor' (which represents variations in the albedo of the snow). D is estimated from T and σ_T using the unpublished tables referred to by Braithwaite (1965). β was estimated as 2.9 mm/°C day using the Spencers Creek data, and agrees reasonably well with the median value of 3.2 mm/°C day for 13 field and laboratory determinations (Todd, 1970). γ varies with temperature and season and is based on a relationship noted by Martinec (1960). The factor is set to one for the winter season and temperatures less than -2.0 °C, but increases slightly in autumn and particularly in spring to simulate the snowpack's greater absorption of radiation at those times (due to higher zenith angle and, in spring, denser and dirtier snow). Note that variations in other factors relevant to ablation of snow (e.g., cloud and wind speed), were not included in the model. At the monthly time-scale changes in these factors are much less important than changes in temperature (but their importance would increase if daily variations in ablation were to be simulated).

3.3. CALCULATING SNOW-COVER DURATION

An interpolation method is used to construct smooth curves of snowfall and potential ablation throughout the year from the calculated monthly averages. These smooth curves are then used to calculate simulated snow cover. If, as one proceeds through the year, there comes a day where the interpolated daily rate of snowfall exceeds that of potential ablation then snow cover begins on that day. The depth of snow grows until (usually in the spring) ablation again exceeds snowfall. The snow depth then diminishes until the excess of ablation over snowfall has been sufficient to melt all snow. At that time the simulated snow-cover ends.

Figure 4 shows an example of a snow-cover duration calculation using long-term average monthly climate data for the summit region of Mt. Buller (see Fig. 1) from the interpolated long-term mean climate data set. The snow cover beings on day 160 when snowfall first exceeds potential ablation. The corresponding snow depth reaches a maximum when the rate of snowfall falls below the rate of ablation at day 244 and decreases until the end of snow cover at day 286, giving a total snow-cover duration of 127 days.

In this example the period of snow cover was continuous. In cases where there are breaks in the period of snow cover (which usually only occur when the model is run for individual years), snow-cover duration is defined as the total number of days of simulated snow cover, not the elapsed time between the dates of the first and last days of snow cover for the year.

The smooth annual trends in snowfall and potential ablation as seen in this example are a simplification of the real world which exhibits snowfall in a sequence of synoptic events rather than a continuous process. For example, cold fronts passing over the region every week or so can deposit large amounts of snow in the short period over which they occur, followed by warmer and drier periods when ablation occurs. Periods of heavy rain over the snowfields can also cause periods of rapid ablation. The relative frequencies of such events will of course be reflected

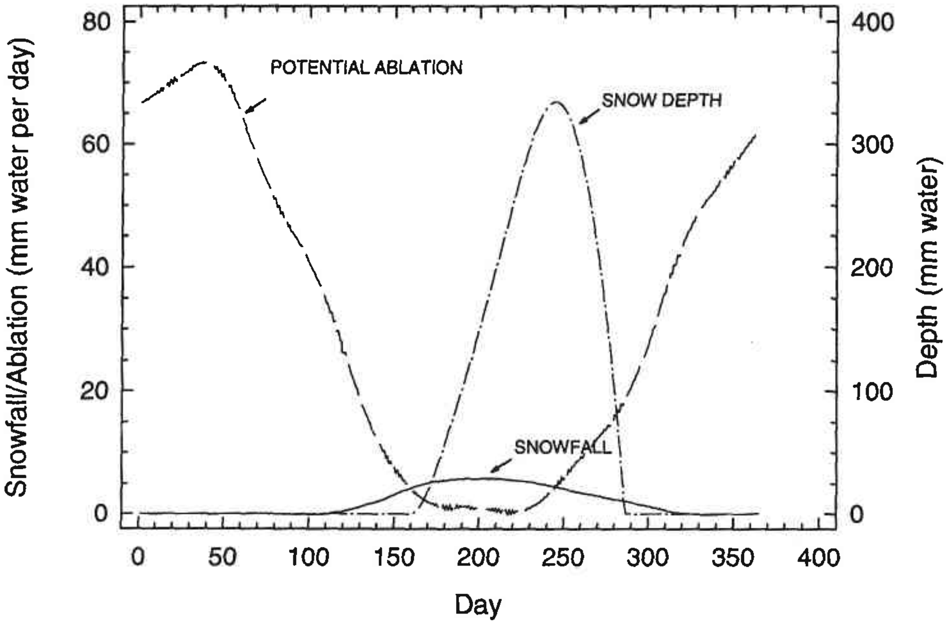

Figure 4. Example of simulated snow-cover duration calculation for Mt. Buller based on interpolated long-term average climate. Snowfall and potential ablation are plotted on the left vertical axis and snow depth is plotted on the right vertical axis. The horizontal axis refers to day number of year commencing on 1st January.

in the monthly average temperature and precipitation, but at more marginal sites, in particular sites of lower elevation which do not receive snowfall regularly, the simplification is less applicable. At these sites, snow deposition may still occur from individual synoptic events, although the monthly average conditions might be unsuitable for the accumulation of snow. Thus the model can be expected to significantly underestimate snow-cover duration at these sites. Also, as the model does not explicity allow for the diurnal cycle in temperature, the effect of snow falling at marginal sites only at night (when temperatures are usually below the diurnal mean) may not be represented.

Furthermore, snow cover is a highly spatially-dependent quantity, particularly at the end of a season. For example, snow accumulation is usually greater on the lee side of a hill, and ablation will be much higher on the side which receives the most direct sunlight. Therefore, simulated snow-cover durations, based on climate data representing conditions over a wide area (in this case, grid squares 2.5 km by 2.5 km), may poorly represent snow duration at some sites within that region.

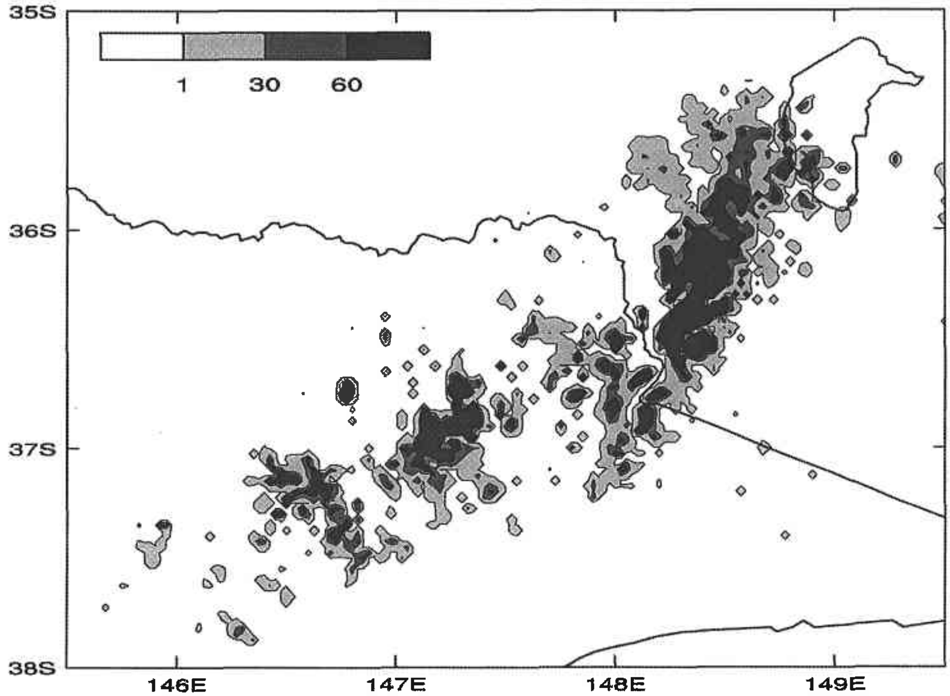

Figure 5. Simulated average snow-cover duration for 1966–1985 in days.

4. Simulated Snow-Cover Duration for Current Climate

4.1. SIMULATED AVERAGE SNOW-COVER DURATION

Figure 5 shows a map of the average snow-cover duration using the 1966–1985 interannual climate data as input to the model considered. Large areas are simulated to have average snow-cover duration in excess of 60 days. Tabulated results for the locations indicated in Figure 1 are given in Table III and range from just three days at the lowest site considered (Mt Donna Buang) to 187 at the highest site (Mt Kosciusko).

Because observed snow-cover durations exist only for a limited number of non-summit sites concentrated in the NSW portion of the region, corresponding observed data for Figure 5 and Table III cannot be easily presented. Instead, a more generalised comparison of observed and simulated durations is given (Fig. 6). The figure shows the average simulated snow-cover duration for all grid points with an average exceeding zero for 1966 to 1985, plotted against grid-point elevation. Also plotted, against their respective elevations, are the observed average durations for the 19 NSW sites of Slatyer *et al.* (1985) and for the five Victorian sites for which we had data. Simulated duration shows strong dependence on elevation and good correspondence with observations (errors are of the order of ±20 days for a given

Table III

Simulated average snow-cover duration for selected sites for current and changed climate conditions. The ranges given for the years 2030 and 2070 reflect the uncertainty in current CSIRO climate-change scenarios

Location	Duration (days)		
	Current	2030	2070
Mt. Donna Buang	3	0	0
Lake Mountain	29	0–16	0–7
Mt. Baw Baw	56	2–36	0–21
Falls Creek	113	36–101	0–88
Mt. Buffalo	116	41–106	0–94
Mt. Buller	127	52–116	0–103
Mt. Hotham	135	68–127	0–117
Mt. Bogong	159	103–151	1–142
Mt. Jagungal	163	110–156	5–149
Mt. Kosciusko	187	135–178	29–170

elevation). There is a slight tendency to underestimate duration at the very highest sites.

In Figure 6 there are insufficient observations at low elevation to adequately validate the model at marginal sites. However, common observation would suggest that the simulated values at lower sites (such as the tabulated values for Lake Mountain and Mt Donna Buang) significantly underestimate actual snow-cover duration. As discussed earlier, underestimates of days of snow cover at marginal sites is to be expected given that the input data are resolved only monthly. (Indeed, some experimentation we have undertaken with a version of the model which uses daily input data does simulate increased snow cover at marginal sites.)

To further illustrate the performance of the model we present a comparison of simulated and observed durations for the European sites listed in Table II. This is a particularly valuable test of the model as there is little overlap in the climates of the Australian and European sites (sites in the two regions of similar winter temperature have significantly higher precipitation in Australia, and sites of similar precipitation are warmer in Australia). Figure 7 is the corresponding figure to Figure 6 but using the European data and Figure 8 is a site-specific comparison of simulated and observed durations. The comparison of observed and simulated is very good except at the lowest sites where the durations are shortest. Note that, unlike the Australian calculations, the duration simulated in this case is that obtained when the long-term climate mean of the site is used as input. This would tend to increase the underestimation of observed average duration at marginal sites, which have frequent years of zero cover, but some years of extensive cover.

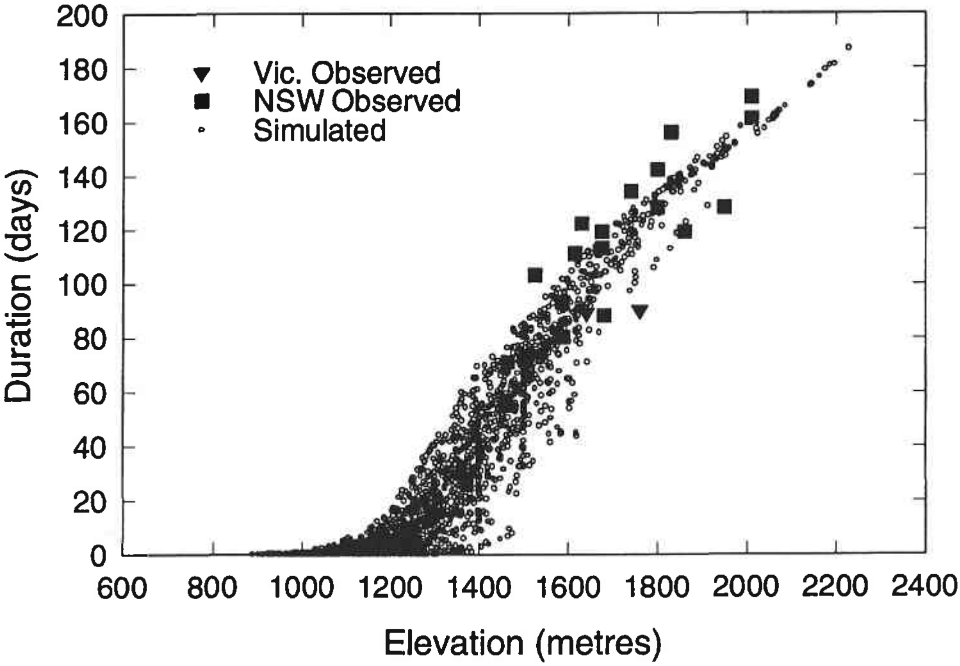

Figure 6. Average snow-cover duration versus elevation as observed for sites in Victoria (triangles) and NSW (squares) and as simulated by the model for points for the 1966–85 gridded climate data set (dots). Only gridpoints with a non-zero simulated duration are plotted. Note that the observed average durations at the Victorian sites are likely to be underestimates of the true values for these sites because years of long duration are sometimes truncated.

4.2. SIMULATED INTERANNUAL VARIABILITY IN SNOW-COVER DURATION

Validating the model performance over the large interannual variability in the current climate is a way of checking the sensitivity of the model to larger changes in temperature and precipitation. If the model performs well in simulating the snow-cover duration of quite different years in the past, more confidence can be given to results simulated under a future change in average climate conditions. However, it should be stressed that simulation of snow conditions for individual years is much more demanding than simulating average conditions. The use of monthly input meteorological data, rather than daily data, must limit significantly the ability to simulate accurately the varying snow conditions throughout an individual year.

Figure 9 shows the model duration plotted against the corresponding observed duration for six sites in Victoria and NSW with reliable observations within the period 1966–1985. When considering the difficulties (described above) that can be expected in simulating interannual variations with the current model and input data, the model performance in Figure 9 is quite good. Overall, and at the individual sites, the model simulates reasonably well interannual variations in snow cover. There is a root mean square error of 30 days. This error is partly contributed by a

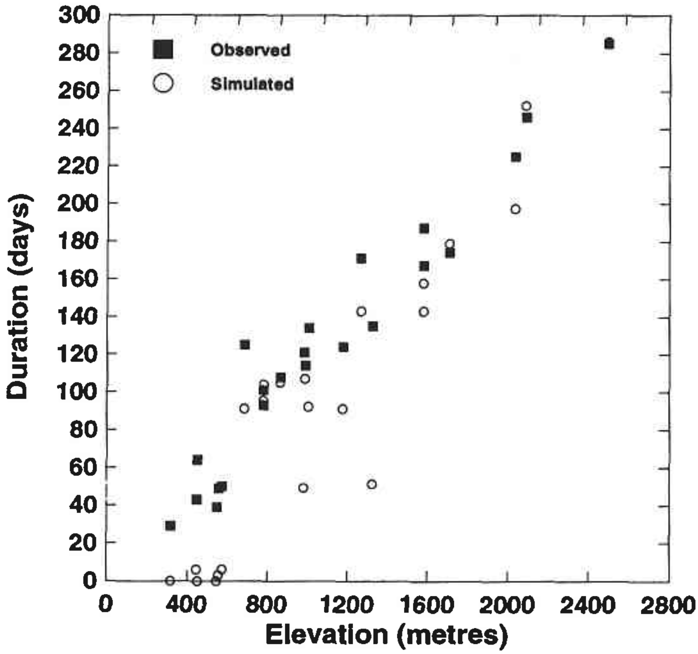

Figure 7. Snow-cover duration as observed and as simulated versus elevation for the European sites (Table II).

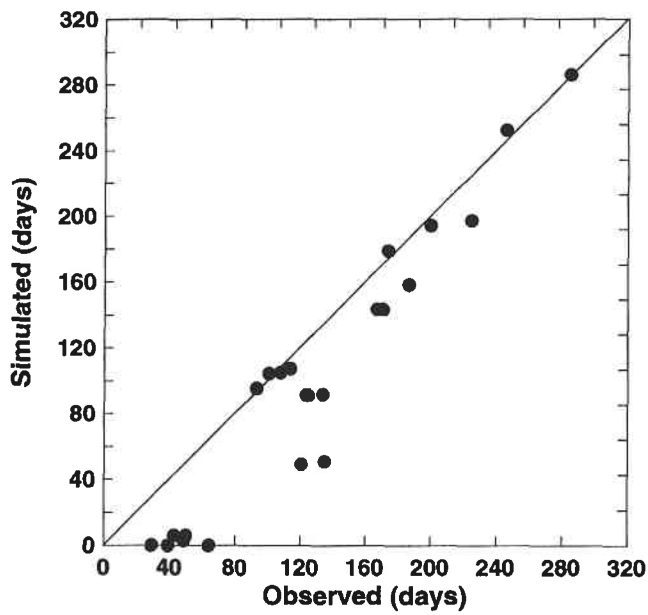

Figure 8. Observed versus simulated snow-cover duration for the European sites (Table II).

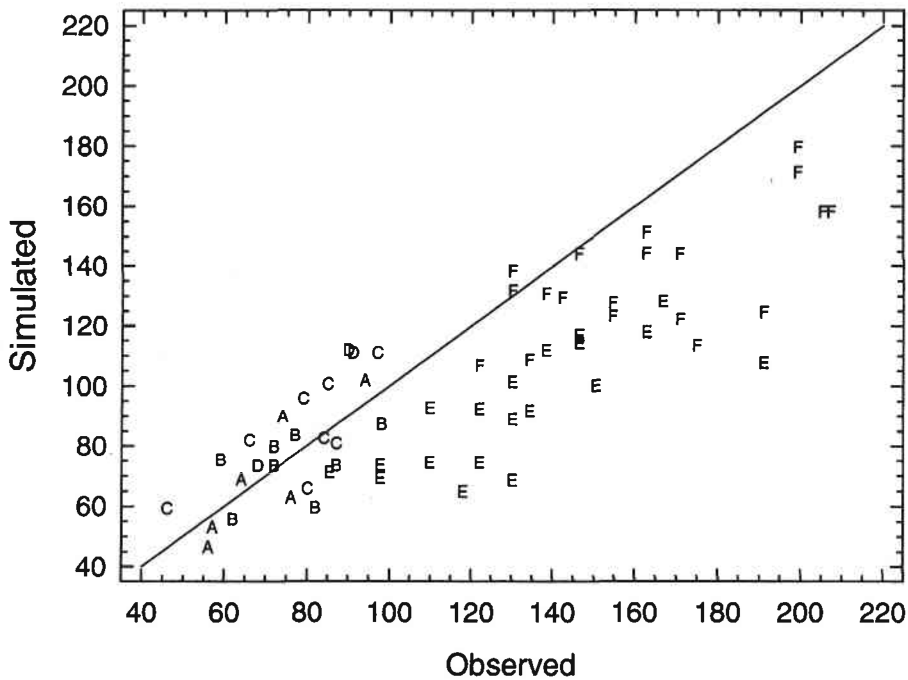

Figure 9. Modelled versus observed snow-cover duration for individual years. Days are numbered from the 1st January. The sites are Mt. Buffalo [A], Mt. Buller [B], Falls Creek [C], Mt. Hotham [D], Deep Creek (NSW) [E], and Spencers Creek (NSW) [F]. Note that for Mt Hotham, Mt Buller and Mt Buffalo, simulated results for grid points adjacent to summit points were used, so that the elevation of corresponding observed and model sites are similar.

general tendency to significantly underestimate season duration at the two higher sites (but note that a tendency this marked is not common to all high sites – see Fig. 6).

Figure 10 shows the time series of start and end days (the first and last days of the year with snow on the ground) as observed and as modelled for 1966 to 1985 for Spencers Creek (NSW), one of the few sites with an almost complete record over this period. Although there is a slight bias in the model data, the end days are much better simulated (correlation coefficient of 0.75) than the start days (correlation coefficient of 0.51). This tendency was also apparent at other sites. This is due to the fact that the beginning of snow cover in a particular year is more dependent on the particular sequence of synoptic circulation events (not used as direct model input) than is the season end which depends more on average seasonal weather conditions. Frequently, snow will fall in a brief event in the early months of a year then disappear completely before the next fall, whereas the model will not begin to accumulate snow until monthly average conditions are suitable. Early snow events of short duration will not have much effect on the overall total days of snow cover (except at the lowest, most marginal sites).

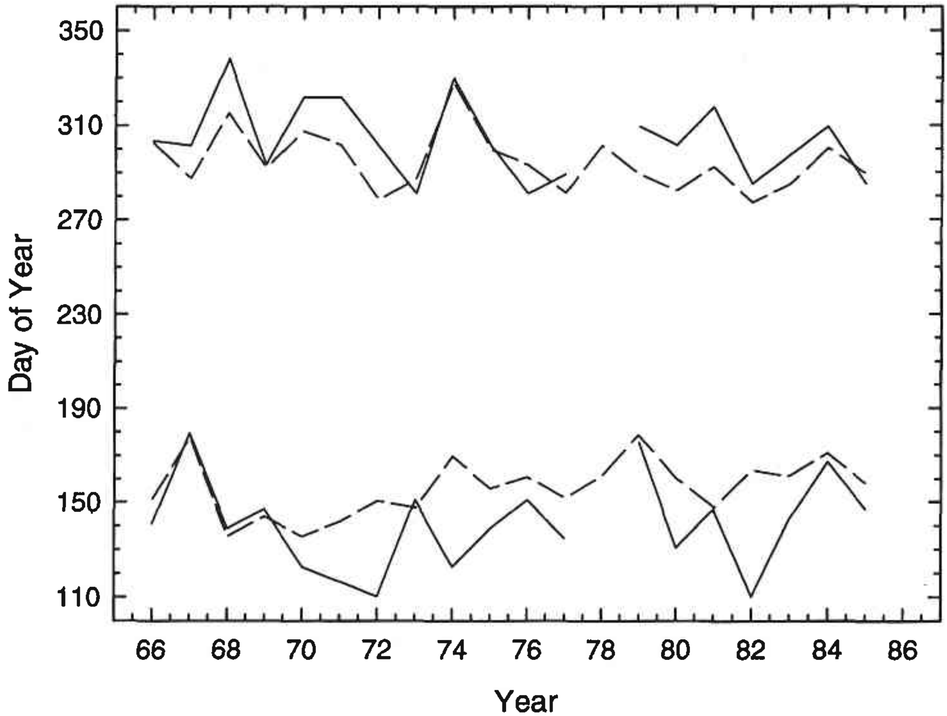

Figure 10. Observed (solid) and modelled (dashed) start and end days of snow cover for Spencers Creek from 1966 to 1985. Start days have lower day numbers (from the 1st of January) and appear at the bottom of the graph.

4.3. SUMMARY

For the Australian alpine area, the model was found to simulate reasonably well the observed altitudinal variation in average snow-cover duration (an effect dominated by changes in temperature), and to adequately simulate observed interannual variations in snow cover (where large changes in precipitation are important). There are errors in simulated durations (around ±30 days for simulating individual years), but the model does, in general, correctly simulate the interannual fluctuations of snow cover in response to fluctuations in temperature and precipitation. This suggests that absolute average durations simulated for particular sites can be significantly in error, but that the simulated response to climate change is fairly reliable. Errors in the aboslute average duration are most significant at lower, more marginal, sites, where the model appears to underestimate snow duration. At these sites observed snow cover can often be discontinuous through the year and would be better simulated if daily input data were used rather than the monthly data used here. This means that short simulated durations (less than about 30 days) should be viewed as 'marginal' and not interpreted literally.

Without any changes, the model also performed reasonably well at simulating snow duration under the substantially different climate of the European Alps. This increases confidence in the model being able to reliably simulate snow cover under changed climate conditions.

5. Simulated Snow-Cover Duration under Changed Climate

5.1. CLIMATE-CHANGE SCENARIOS

In this Section we examine the impact of changes in average precipitation and temperature on simulated snow-cover duration of the region. Sensitivity to these changes will be interpreted in the light of regional scenarios of climate change. These scenarios are described in some detail in CIG (1992), Whetton *et al.* (1993) and Whetton *et al.* (in press) although we summarise their main features here.

The basis of the regional climate-change scenarios are projections of global warming prepared by the Climate Research Unit, University of East Anglia, U.K. (M. Hulme, personal communication) and shown in Figure 11. The temperature curves are calculated using the simple upwelling-diffusion energy balance climate model of Wigley and Raper (1992) which was also used by the Intergovernmental Panel on Climate Change (IPCC – Houghton *et al.*, 1990). The broad range of future warming comes from making allowance for two important sources of uncertainty. The first is the range of greenhouse gas emission scenarios considered plausible by the IPCC (Houghton *et al.*, 1992). The highest and lowest CO_2 emission rates at 2030 differ by a factor of two. The second source of uncertainty relates to the sensitivity of global climate to increased greenhouse forcing, usually represented by the IPCC as the estimated global equilibrium warming range of 1.5–4.5 °C for a doubling of CO_2. This encompasses the range of results from many global climate models and reflects differences in how the models treat variable cloud cover and other potentially important interactions and feedbacks. The upper curve in Figure 11 represents the highest IPCC emission scenario combined with a climate sensitivity of 4.5 °C, and the lower curve is based on the lowest emission scenario and a climate sensitivity of 1.5 °C.

To prepare climate-change scenarios for Australia, the regional results of recent enhanced greenhouse experiments with five different global climate models were examined. These experiments were conducted with: the CSIRO model (CSIRO9) (McGregor *et al.*, 1993), the Bureau of Meteorology Research Centre Model (BMRC) (Colman *et al.*, 1994); and the three high resolution experiments used in Houghton *et al.* (1990) namely: the United Kingdom Meteorological Office high resolution model (UKMOH), the Geophysical Fluid Dynamics Laboratory high resolution model (GFDLH), and the Canadian Climate Centre model (CCC). This enabled estimates to be prepared for regional temperature change and percentage precipitation change per degree of global warming. The results of these five models suggested the following for regions within about 200 km of the south coast of

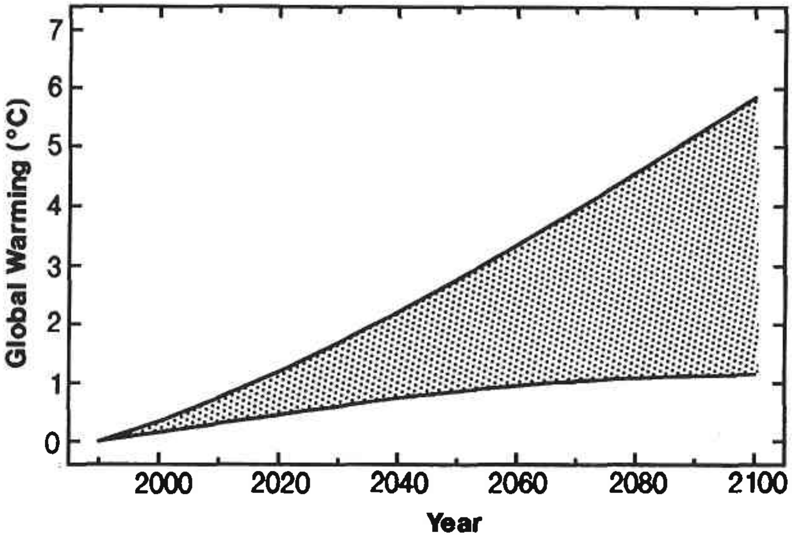

Figure 11. Global warming scenarios 1990–2100. See text for source.

Australia (which encompasses the Australian alpine area): warming of 0.8–1.2 °C per degree of global warming for all months and May to October precipitation changes of −5% to +5% per degree of global warming. Thus, these scenarios suggest that the alpine region will warm roughly in line with the global average, and could experience precipitation changes in either direction. If this information is combined with the global warming curves in Figure 11, it implies temperature increases of 0.5–2.0 °C and precipitation changes of −10% to +10% by 2030, and 1–5 °C and −20% to +20% by 2070. Scenarios for other dates can be constructed similarly. The climate-change scenario which can be considered the 'best-case scenario' for snow conditions is the least warming combined with the greatest precipitation increase. For 2030 this would be +0.5 °C and +10%, and for 2070 it would be +1 °C and +20%. The corresponding 'worst-case scenario' (greatest warming and greatest precipitation decrease) is +2.0 °C and −10% in 2030, and +5 °C and −20% in 2070. These best- and worst-case scenarios will be used in the following analysis.

These scenarios allow for three important and quantifiable sources of uncertainty in projecting future climate change, namely: the range of future greenhouse gas emissions, the range of estimates of the sensitivity of the global climate system, and the differing results of various global climate models at the regional scale. However, there are other factors potentially important in determining how global and regional climate may change, not well enough understood for their effect to be easily quantifiable. These include the climatic effects of increasing atmospheric sulfate aerosols (expected to be small in the southern hemisphere), the effect of CO_2 fertilisation of the biosphere on the growth rate of atmospheric CO_2, and possible changes in the El Niño-Southern Oscillation, ocean currents and natural variability. The scenarios are also only a broad scale assessment of regional climate change. No global climate model is at present able to represent the diverse topography of our study region, so topograhical effects which are important in determining precisely how future climate (particularly precipitation) will evolve over the Alps are not considered in the scenarios. This could be remedied at a later date by the use of finer resolution limited area models 'nested' in a global climate model (e.g., see McGregor and Walsh, 1994).

5.2. SIMULATED SNOW-COVER DURATION

For our selected sites, snow-cover response is calculated for all possible combinations of temperature change from −2 °C to +4 °C and precipitation change for −80 +80%. The changed climate results were obtained by applying average changes in temperature and precipitation to the input climate data for each year of the 20-year data set and averaging the results. Detailed results for six of the sites are presented in Figure 12. In each of these 'response surfaces', precipitation change is on the horizontal axis, temperature change on the vertical axis, and the contours represent simulated snow-cover duration for a given precipitation and temperature change. The point for zero on both axes gives the simulated duration for current climate. Boxes are drawn on the response surfaces to represent the range of climate changes for 2030 and 2070 given in the scenarios. The simulated range of average snow-cover duration for these climate-change scenarios is indicated by the range of duration values that fall within the boxes on the response surfaces. The top-left corner of the scenario box and the bottom-right of the scenario box represent, for impact on snow cover, the worst- and best-case scenarios respectively. (The response surface methodology has been used previously in impact studies by Fowler and de Freitas (1990) and Whetton *et al.* (1993).) A summary of the results for current climate and for the scenarios for 2030 and 2070 is given in Table III for all of the selected sites.

The obvious trend in the response surfaces of Figure 12, as would be expected, is for a decrease in snow for decreased precipitation and increased temperature. The sensitivity to increasing temperature is very high, particularly at lower elevation sites. For example, a 1 °C warming reduces simulated duration substantially at all sites, and reduces it greatly at sites of low elevation (e.g., Lake Mountain). For a 3 °C warming, the simulated duration at the Mt Bogong (a higher elevation site) is more than halved (from around 160 days to 70 days) and even at sites of moderate elevation with current simulated durations of over 100 days (e.g., Falls Creek) the duration is reduced to near zero. The response surfaces also show that large percentage increases in precipitation are needed in the model to compensate for relatively small increases in temperature. For example, at Mt Buller the model indicates that more than a 50% increase in precipitation is required to maintain current average snow-cover duration under a climate 0.5 °C warmer than present.

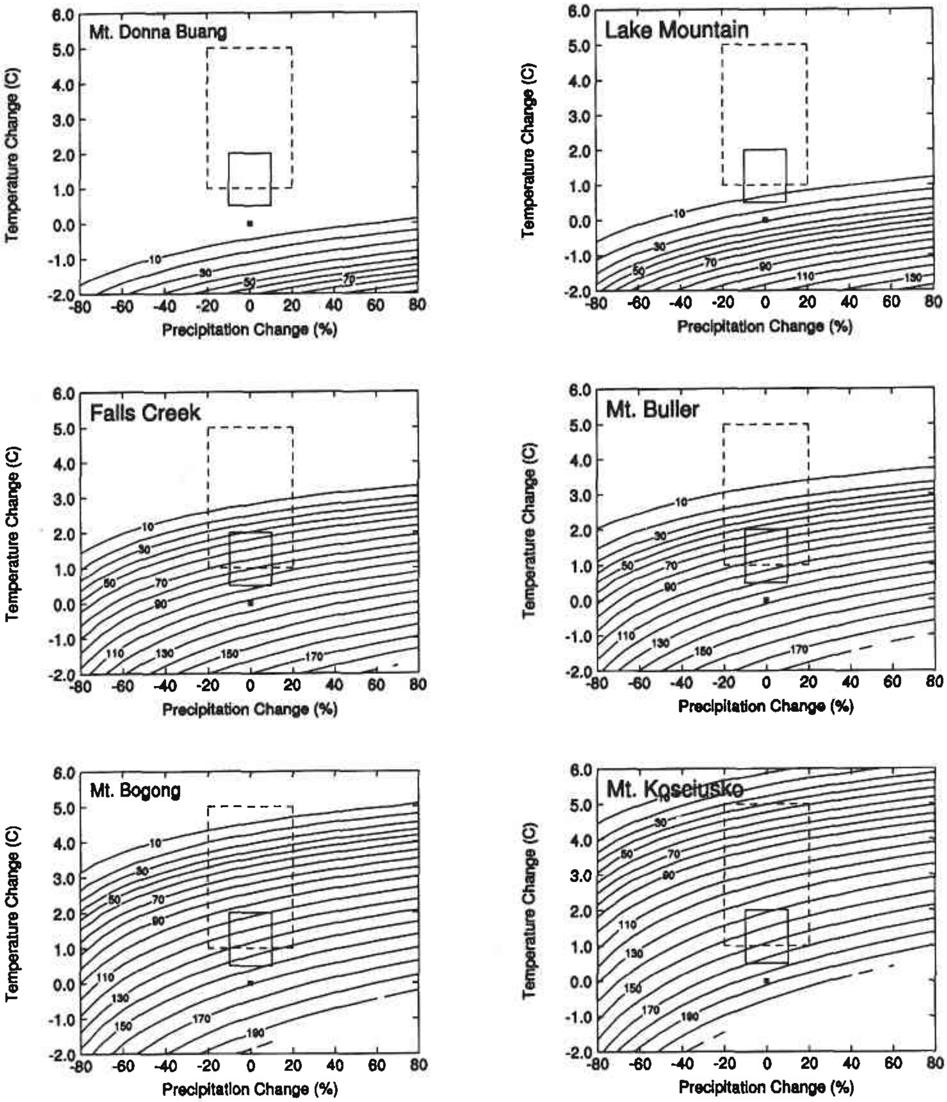

Figure 12. Response surfaces of snow-cover duration for changes in average temperature and precipitation for a selection of the sites given in Table I. Current climate simulation is indicated by a black dot, and scenario estimates for 2030 fall within the area enclosed by the solid line and those for 2070 fall within the area enclosed by the dashed line. (Note that when snow cover is simulated to still be present on 31 December, full duration is not calculated and these values are omitted from the graph.)

As discussed earlier, the very short durations calculated by the model for sites with climates (currently or as the result of climate change) marginal for supporting snow cover are likely to be significant underestimates. Therefore, a more instructive way to look at the results of Figure 12 may be to note, for example, that a 3 °C warming gives simulated snow cover at Falls Creek comparable to that for current climate at Mt Donna Buang.

In all cases, the snow-cover duration is reduced for the 2030 and 2070 climate-change scenarios (Fig. 12 and Table III). However, the range of simulated reductions for these dates is large. For example, the best-case scenario at 2030 has simulated snow-cover duration reduced at Mt Hotham by just 8 days (135 to 127 days). On the other hand, the worst-case scenario for Mt Hotham in 2030 is a halving of snow-cover duration (to 68 days). Under the best-case scenario for 2070 the simulated snow-cover duration reduces to 117 days, but to zero for the worst-case scenario. The impact is more marked at lower sites. For example, for 2030 at Mt Baw Baw the simulated duration reduces from the current 56 days to 36 days under the best-case scenario and to two days under the worst-case scenario. At 2070 the best-case result is 21 days and worst-case zero days. Indeed, under the worst-case scenario, all sites below around 2000 metres have zero simulated snow-cover duration by 2070, implying snow conditions no better (and generally much worse than) those of the most marginal of our selected sites under current climate (Mt Donna Buang). It should be noted that the snow-cover results for the 2030 and 2070 climate-change scenarios are largely a response to the warming contained in those scenarios. As can be seen in the response surface plots (Fig. 12), precipitation changes of the magnitude contained in the scenarios (no more than a 20% change by 2070) have only a small impact on simulated snow-cover duration.

Maps of simulated duration of snow cover for the best and worst cases for 2030 are given in Figure 13, and the corresponding results for 2070 are given in Figure 14. These maps should be compared with the map for the current climate given in Figure 5. The maps are useful for demonstrating changes in the areal extent of snow cover of various durations. For the best-case scenario, reductions in the area of some snow cover (duration greater than zero) are not very marked at 2030, although they are more noticeable by 2070. Much larger decreases in the area of some snow cover are simulated for the worst-case scenario, with the snow cover vanishing by 2070 in all but the very highest locations. The maps show a similar pattern of change for the area of snow cover of duration greater than 60 days.

Response surfaces and maps of the simulated frequency of years with snow-cover duration greater than a threshold of 60 days were also produced, but only a summary of these results is given here in Table IV. The table shows that simulated duration exceeds 60 days in all years at all but the three lowest sites under current climate conditions. Under the 'best-case' climate-change scenarios for 2030 and 2070, the frequency declines significantly at the lower sites (e.g., at Mt Baw Baw from 50% of years currently to 5% of years in 2070), but is maintained at the higher sites (e.g., Mt Hotham still has all years with duration greater than 60 days in 2070). Under the 'worst-case' climate-change scenarios, the frequency of such years is reduced significantly by 2030 and reaches zero by 2070, except at the highest site (Mt Kosciusko).

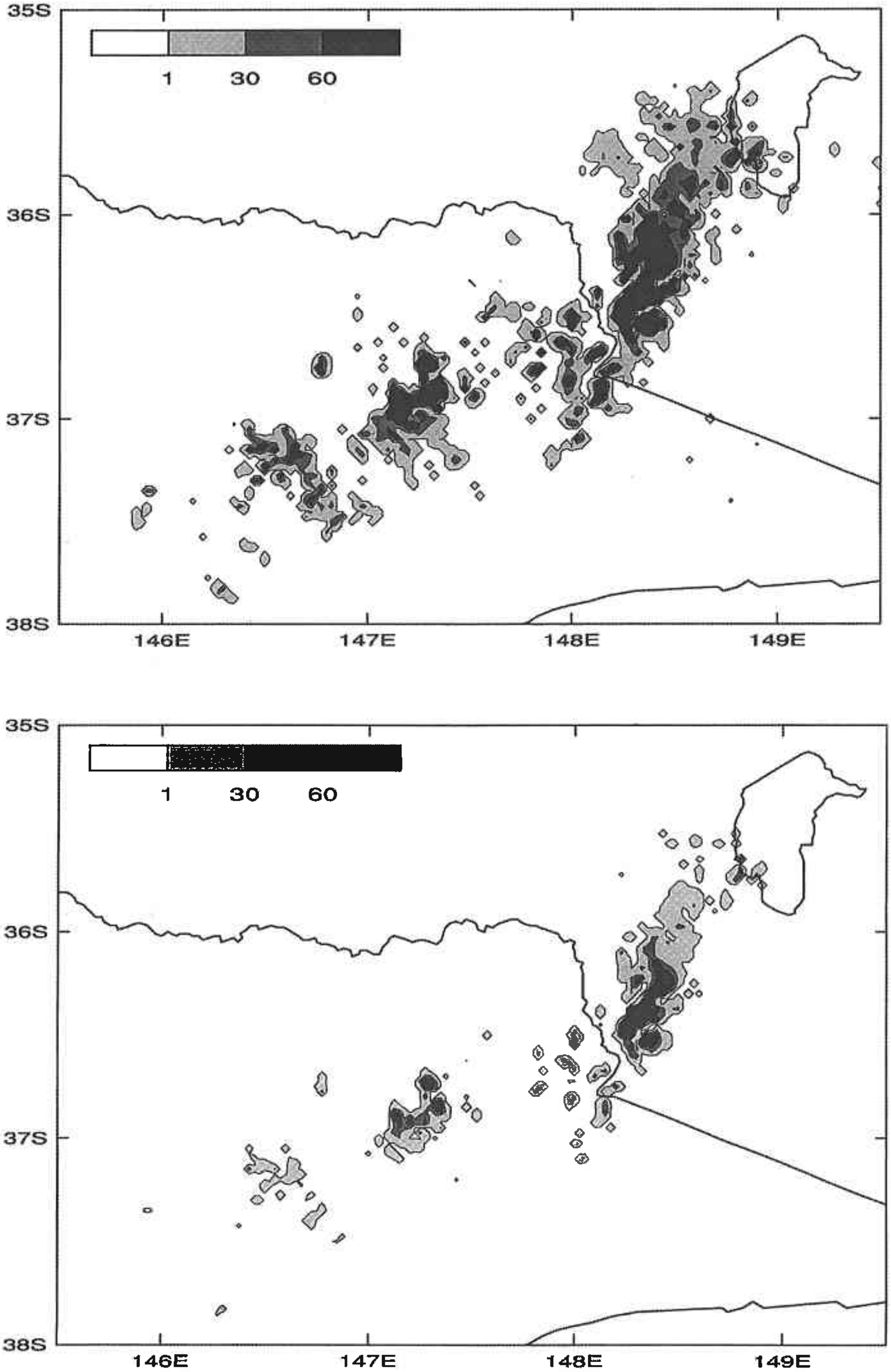

Figure 13. Simulated average snow cover duration (in days) for (a) the best-case scenario for 2030 and (b) the worst-case scenario for 2030. These maps should be compared to the current climate results given in Fig. 5.

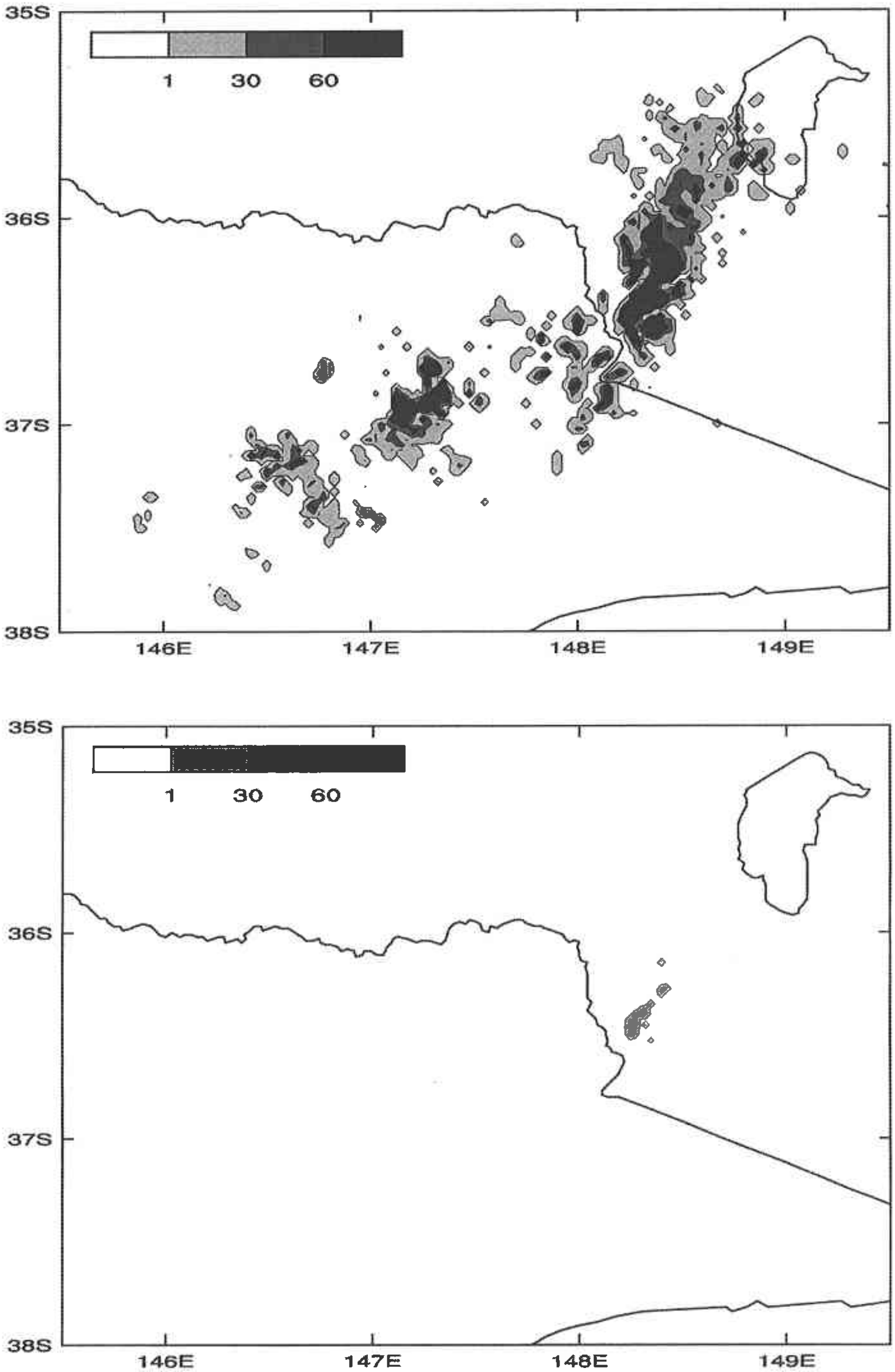

Figure 14. As for Fig. 13, but for 2070.

Table IV

Percentage of years with simulated snow-cover duration exceeding 60 days for the locations used in Table III and for current and future climate conditions. The ranges given for the years 2030 and 2070 reflect the uncertainty in current CSIRO climate-change scenoarios

Location	percent of years > 60 days		
	Current	2030	2070
Mt. Donna Buang	0	0	0
Lake Mountain	10	0	0
Mt. Baw Baw	50	0–15	0–5
Falls Creek	100	25–95	0–90
Mt. Buffalo	100	25–100	0–95
Mt. Buller	100	40–100	0–95
Mt. Hotham	100	55–100	0–100
Mt. Bogong	100	95–100	0–100
Mt. Jagungal	100	100	0–100
Mt. Kosciusko	100	100	20–100

We now use a different approach to further elucidate how a climate change may affect the relative frequency of years of high and low snow cover over time. Rather than using scenarios just for 2030 and 2070, we gradually alter the temperature and precipitation from their present day (1990) values through to 2100 for the best- and worst-case scenarios. These scenarios show a steady increase in temperature with corresponding changes in precipitation, like the global warming curves of Figure 11 (on which these scenarios are based). However, the future course of regional temperature and precipitation will not follow a smooth curve because of interannual variability. So we then impose the interannual variations in temperature and precipitation as observed during the 20-year period 1966–85. These are superimposed every 20 years beginning with 1990 and provide a time series which incorporates both a trend and observed interannual variability. This approach allows us to gain some insight into approximately when, for the best and worst cases, the effects of climate change on snow cover will clearly become apparent relative to normal interannual variability. This approach, of course, assumes that the interannual variability of the period 1966–85 (a fairly short period) can be taken to represent the variability of the next century.

This experiment was performed for Mt Baw Baw, Mt Buller and Mt Bogong. The resulting time series of snow-cover duration are given in Figure 15. For the best-case scenario, a declining trend in snow-cover duration is evident at the three sites, although it is not very large relative to the interannual variability. The changes are more marked when considering the change in frequency of years above a selected threshold. In all three cases, some 'good' years (better than average for 1966–85) occur through to the end of next century, but with declining frequency.

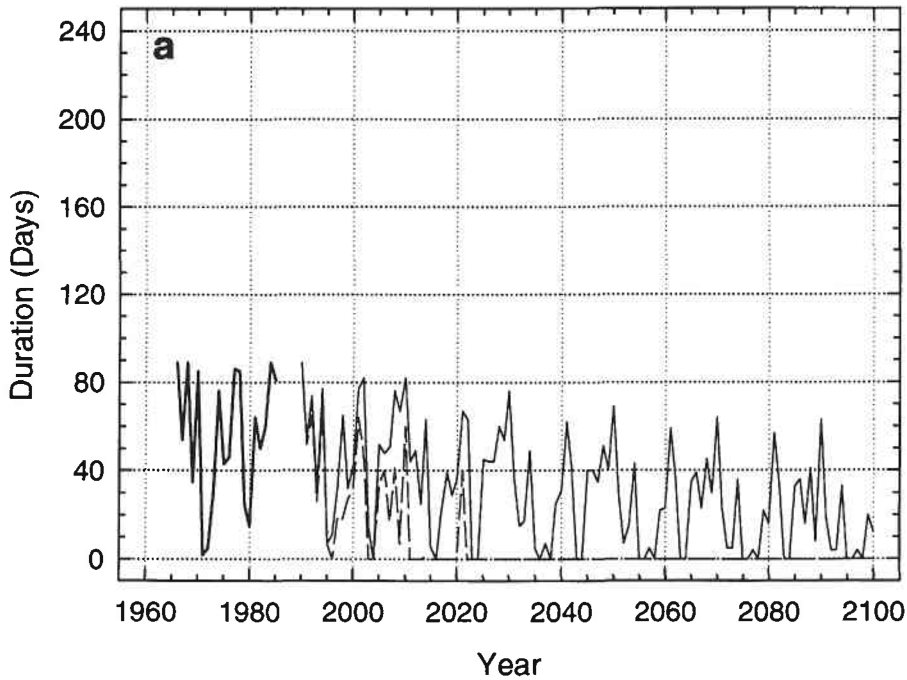

Figure 15a.

Figure 15. Simulated snow-cover duration at (a) Mt Baw Baw, (b) Mt Buller and (c) Mt Bogong using input climate data for 1966–85 (bold) and best-case (solid) and worst-case (dashed) time varying climate-change scenarios for 1990–2100. Interannual variability after 1990 is provided by superimposing, in 20-year cycles, the climate anomalies for 1966–85.

On the other hand, 'poor' years (worse than average for 1966–85) become more frequent. The worst-case scenario shows a rapid decrease in simulated snow-cover duration at all sites. As early as the third decade of the 21st Century, the best years are generally worse than the poorest years under current climate. In fact, all years are simulated to have a snow-cover duration of zero from around 2020 at Mt Baw Baw, 2050 at Mt Buller and 2070 at Mt Bogong.

Finally, some comment is warranted on the extent to which the results of the model are consistent with trends in observed snow conditions in recent decades. South-eastern Australia has experienced regional warming of 0.56 °C over the period 1930–1988 with nearly all of the increase occurring post-1950 (Jones *et al.*, 1990). Ruddell *et al.* (1990) identified decreasing trends in maximum snow depth at Victorian and NSW sites for the period 1957–89 (33 years), but found that these trends were not statistically significant. In essence, interannual variability has dominated over the effect of a trend (if any is present). We do not have the input data to simulate conditions for 1957–89, but the best-case scenario results for 1990–2030 in Figure 15 serve as a useful analogue for this recent period. The warming

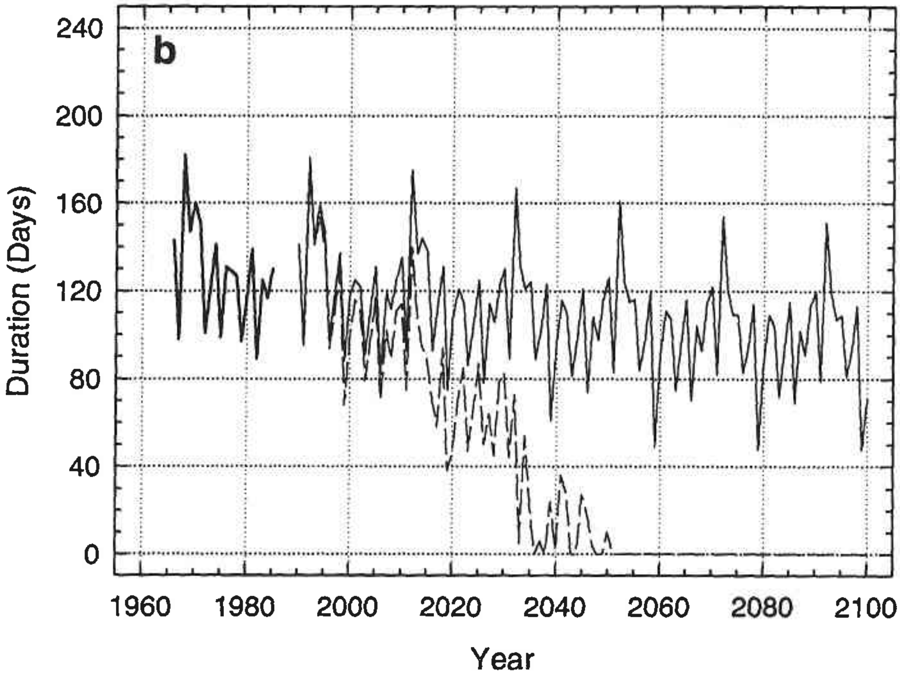

Figure 15b.

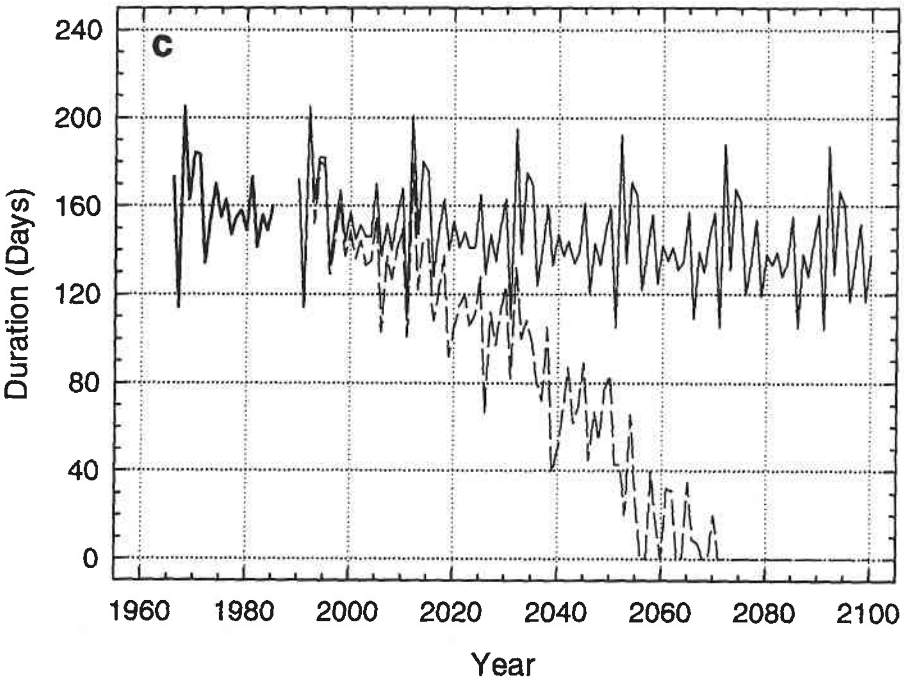

Figure 15c.

from 1990 to 2030 (41 years) was 0.5 °C under this scenario. The downward trends in snow-cover duration are not statistically significant (95% confidence level) at each site, indicating that interannual variability is again dominating over the trends (which we know are real in this case). This suggests that, despite the strong sensitivity of snow cover to temperature indicated by the model, we should not be too surprised that significant trends in snow conditions have yet to be detected.

6. Discussion

The results presented here are similar in qualitative terms to the results obtained using other methods in other locations. The recent European studies of Martin *et al.* (1994) and Bultot *et al.* (1994) both showed a marked sensitivity of simulated snow-cover duration to increasing temperature and that this sensitivity was strongest at low elevation sites with short snow seasons. The study of Martin *et al.* (1994) also examined the impact of variations in precipitation of 10%, and, in agreement with the current study, found snow-cover duration to be rather insensitive to such variations. However, they did find that maximum snow depth (which we do not examine here) is more responsive to changes in precipitation.

To be able to consider the practical implications of the results obtained in this study, we need to reconsider the caveats associated with this work. First, as discussed earlier, the climate-change scenarios encompass only those sources of uncertainty that are easily quantifiable. Allowance is not made for factors such as possible changes in interannual climate variability (such as that due to the El Niño-Southern Oscillation) and local topographical effects not resolved by global climate models which could affect the climate-change scenarios for the Alps. However, these uncertainties are more likely to affect estimates of regional precipitation change than they are those of temperature (in which confidence is higher). Indeed, the low sensitivity of the snow-cover model to precipitation change means that uncertainty in the climate-change scenarios (not already allowed for) is unlikely to greatly affect the calculated snow-cover impacts.

Second, no assessment has been made of possible changes in interannual variability in temperature and precipitation. Significant changes in these would not have much impact on trends in average snow-cover duration, but they could affect the changes in the frequency of high and low years. However, analysis of relevant global climate-model output (e.g., Cao *et al.*, 1992, Gordon and Hunt, 1994) suggest that large changes in interannual variability are unlikely. We should note, however, that our 20-year sample of interannual variability (1966–85) is short, particularly for precipitation, and may not adequately encompass the range of current interannual variability.

Third, there are caveats associated with the simulation of snow cover. There are errors in simulated durations (around ±30 days for simulating individual years), but the model does, in general, correctly simulate the interannual fluctuations of snow cover in response to fluctuations in temperature and precipitation. This suggests that absolute average durations simulated for particular sites can be significantly in error, but that the simulated response to climate change is fairly reliable. Errors in the absolute average duration are most significant at lower, more marginal, sites, where the model appears to underestimate snow duration. This means that short simulated durations (less than about 30 days) should be viewed as 'marginal' and not interpreted literally.

Finally, it should be noted that these results do not take changes in atmospheric circulation patterns directly into account, although they are considered indirectly through their influence on monthly precipitation and temperature anomalies. It is possible that significant changes in relative frequency or intensity of snow-bearing circulation systems (not adequately reflected in the average climate changes) may occur in the future as a result of global warming. However, it is likely that any such long-term change in circulation would be smaller in magnitude than current interannual fluctuations in atmospheric circulation. If so, this factor may be of some importance for snow cover when the regional warming is small (such as in the earlier decades of the best-case scenario) but is unlikely to be important as the warming becomes larger.

Taking these issues into consideration, we feel it can still be assumed that the results presented here for simulated snow-cover duration are indicative of how natural snow conditions in the Australian Alps may evolve in response to climate change. However, as discussed above, interpretation of the model results in quantitative terms should be done very carefully, and the uncertainties associated with estimating future climate change should be borne in mind.

The simulated changes in snow cover in the Australian alps are worthy of further consideration in terms of their implications for the ski industry and tourism, water resources and hydroelectric power, and land-use management and planning. Planning for development of the ski resorts may now include consideration of the range of possible future changes in natural snow cover given by the best- and worst-case scenario results. Some examples of studies of the impacts of reduced snow cover on tourism and regional economy in the European Alps include Abegg and Froesch (1994) and Breiling and Charamza (1994). As well as allowing for possible demand, changes due to climate change, water resource and hydroelectric planners may need to allow for decreases in the size of the winter snow pack, and consequent changes in the seasonality of discharge of rivers currently fed by winter snow. Such issues have been examined for the New Zealand region by Garr and Fitzharris (1994). Alpine ecosystems would also respond to early melting and absence of winter snow cover as well as the general increase in temperature (see Körner, 1994). Species adapted to the most extreme alpine winter conditions may find that their preferred environment will be reduced in area or disappear (Busby, 1988; Halpin, 1994). The earlier melting of snow and higher temperatures is also likely to reduce available moisture in summer, possibly leading to increased fire frequency among other effects.

A more thorough analysis of such impacts is beyond the scope of this study, but could be addressed through collaborative work with experts in these fields. For example, the model could be used to provide advice on the risks associated with new skiing developments due to climate change. This could include calculating the risk that certain threshold natural snow conditions will not occur frequently enough during the life of the development for it to be profitable. With some further development, the model, in conjunction with climate-change scenario information, could be used to assess the extent to which artificial snow making may be required at particular sites in the future, (and whether the prevailing climate would provide the opportunity for sufficient snow to be produced). Such work could consider simulated changes in snow depth, as well as duration, and use a range of climate-change scenarios, not just the extreme best and worst cases. Quantitative estimates of the climate-change impacts to water resources, and consequent impacts on irrigation and hydroelectric power generation, could be made through the area-integration of simulated snow accumulation combined with hydrological modelling (we are now collaborating with hydrologists at the Australian National University to achieve this end). Fine resolution models nested in global climate models could be used to improve the detail of the climate-change scenarios, to take account of the finer scale topographic effects on changes in precipitation.

7. Conclusions

This study has used the snow-cover duration model of Galloway (1988), combined with a high resolution interannual climate data set for the Australian alpine area, to assess how changes in climate may affect natural snow cover in the Australian Alps.

The model was found to simulate reasonably well the observed altitudinal variation in average snow-cover duration (an effect dominated by changes in temperature) and to adequately simulate observed interannual variations in snow cover (where large changes in precipitation are important). This suggests the relative sensitivities of the model to changes in temperature and precipitation are approximately correct. The model has a tendency to simulate durations that were too short at marginal, low elevations sites, where observed snow cover can often be discontinuous through the winter.

We considered the effect on simulated snow cover of a comprehensive set of climate-change scenarios for 2030 and 2070 which took into account major sources of uncertainty in projecting climate change. Under the best-case scenario, simulated average snow cover and the frequency of years with more than 60 days cover declines at all sites considered in the Australian Alps. However, at the higher sites (e.g., the summits of Mt Kosciusko and Mt Hotham) the effect is not very marked. Even by 2070 at such sites, most years are simulated to have more than 60 days of snow-cover duration (as they are also simulated to do for current climate).

The effect of the best-case scenario on lower sites is more marked. For example, at Mt Baw Baw, the frequency of years of more than 60 days (simulated as 50% under current climate) declines to 15% by 2030 and 5% by 2070. However, under this scenario it could be said that 'good' years are simulated to continue to occur at all sites throughout next century, although with declining frequency.

For the worst-case scenario, a much more dramatic decline in snow conditions is simulated. At higher sites, simulated average snow-cover duration roughly halves by 2030 and approaches zero by 2070. At lower sites (such as Mt Baw Baw and Lake Mountain), simulated average snow-cover duration approaches zero by 2030. At Mt Baw Baw, simulated durations of zero days for individual years begin to predominate as early as the decade 2010–2020. (Note that a simulated duration of zero days does not necessarily imply to snow cover at all; it means that, at best, conditions are highly marginal for the accumulation of snow.)

These simulated changes, ranging between the best and worst case, are likely to be indicative of how climate change will affect natural snow-cover duration in the Australian Alps. However, interpretation of the model results in quantitative terms should be done very carefully. In particular, it should be noted that the model does not allow directly for changes in the frequency and intensity of snow-bearing circulation systems, nor do the climate-change scenarios allow for factors such as possible changes in interannual variability (particularly that due to the El Niño-Southern Oscillation) and local topographical effects not resolved by global climate models. However, these uncertainties are more likely to affect estimates of regional change in precipitation (rather than those of temperature), to which the model is relatively insensitive.

The simulated changes in snow cover have important implications for the ski industry and tourism, water resources and hydroelectric power, and land-use management and planning. These could be explored in further studies.

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