

The potential impact of climate change on seasonal snow in New Zealand: part II—industry vulnerability and future snowmaking potential

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Received: 21 November 2011 / Accepted: 8 February 2012 / Published online: 13 July 2012
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Abstract Seasonal snow in New Zealand is likely to be subject to substantial change due to the impacts of climate change. These changes will have wide ranging impacts on the New Zealand's economy through the energy, agricultural and tourism sectors. In this paper, we assess the impact of climate change, at a micro-scale for a selection of ski area locations in New Zealand. Where available, we have used current observations of snow depth to calibrate the snow model output for the current climate. We consider the change in the number of days with snow depths exceeding 0.30 m, 'snow-days', at each of these locations for the 2030–2049 (mid-point reference 2040) and 2080–2099 (mid-point reference 2090) time periods, for the three different emission scenarios (B1, A1B and A1FI). These future scenarios are compared to simulations of current, 1980–1999 (mid-point reference 1990), number of snow-days at these locations. We consider both an average year in each 20-year period, as well as a 'worst-case' year. At each ski area, we consider an upper and lower elevation site. Depending on the elevation and location of the specific site, our analysis shows that there will be a reduction in the number of snow-days in nearly all of the future scenarios and time periods. When we consider a worst-case or minimum snow year in the 1990s, the number of snow-days at each site ranges from 0 to 229, while by the 2040s, it ranges from 0 to 187 (B1), 0 to 183 (A1B) and 0 to 176 (A1FI). By the 2090s the number of snow-days ranges from 0 to 155 (B1), 0 to 90 (A1B) and 0 to 74 (A1FI). We also simulate

the hourly future climate for the 2040s and 2090s, for the A1FI scenario, to enable calculations of the potential available time for snowmaking in these two future time periods. We use simulated temperatures and humidity to calculate the total potential snowmaking hours in the future climates. For the snowmaking analysis, only a worst-case year in each time period, rather than an average year, was used to assess the snowmaking potential. This was done to ensure consistency with snowmaking design practices. At all sites, for the A1FI emissions scenario and for both future time periods, a reduction in potential snowmaking hours is observed. By the 2040s, there is only 82 to 53 %, and by the 2090s, there is only 59 to 17 % of the snowmaking time as compared to the 1990s in a worst-case year. Despite this reduction in snowmaking opportunity, snowmaking was still possible at all sites examined. Furthermore, the amount of snow which could be made was sufficient to reinstate the number of snow-days to the lesser of either that observed in the 1990s for each site or to exceed 100 days. While our snowmaking analysis has some limitations, such as neglecting calculation of melt in the man-made snow component, this study highlights the importance of considering adaptation options such as snowmaking for a more complete impact assessment.

1 Introduction

Climate change will impact the extent, amount and duration of seasonal snow in New Zealand. This has been quantified at a nationwide scale for New Zealand by Hendrikx et al. (2012). However, this nationwide assessment is not sufficient in itself to assess the potential impact at a smaller scale, e.g. at the scale of a single ski area. If we specifically consider the ski industry, the Ski Areas Association of New Zealand (SAANZ) estimate that about 300,000 New Zealanders ski or snow board regularly, and in 2009, the

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industry announced a record of 1.5 million skier days in New Zealand. A 2005 study conducted in the Southern Lakes region near Queenstown showed that ski areas were a vital component of the local economy, with an estimated NZ\$92.8 million contributed by international and domestic visitors (New Zealand Tourism Research Institute 2005). Furthermore, an individual operator of a ski area is less concerned about the national average than the specific changes at their respective site. Results at this fine scale could also influence decisions on investment priorities at individual ski areas. For example, if revenue is to be spent on building another chair lift, at what elevation should/can it be located? Or will there need to be more snowmaking?

The impact of climate change on the ski industry has been assessed in several countries, examples include: Australia (Hennessey et al. 2003; Bicknell and McManus 2006; Hennessey et al. 2008); Austria (Abegg et al. 2007; Steiger 2010; Steiger 2011); Canada (Scott et al. 2003; Scott et al. 2007); France (Abegg et al. 2007); Germany (Abegg et al. 2007); Italy (Abegg et al. 2007); Japan (Fukushima et al. 2003); Sweden (Moen and Fredman 2007); Switzerland (Elsasser and Messerli 2001; Scherrer et al. 2004; Rixen et al. 2011); and USA (Hayhoe et al. 2004; Scott et al. 2008). The work by Hennessey et al. (2003) is of particular relevance, as this is the nearest region where a similar study was undertaken, and there is a strong and mobile Australian ski tourism market that is able to ski in either region. Hennessey et al. (2003) considered both a 'low impact' and a 'high impact' scenario for the 2020s and 2050s and examined both changes in natural snow and snowmaking opportunities.

The results of these studies, and many more, are unanimous and show a general decline in snow with projected warming. However, the change is not uniform across all regions and some areas see relatively more or less change depending on the various local and regional factors. Scott et al. (2007) identified that only a sub-set of the current literature has examined these potential impacts and considered the adaptive capacity of the ski industries through snowmaking. Therefore, many previous studies are likely to have overestimated the resulting impact of climate change in these regions (Scott et al. 2007).

In this paper, we present the results of both the site-specific snow modelling for a number of key ski areas in New Zealand and also assess the snowmaking potential in the future climates. We examine each area with respect to both the current and future number of days with snow depths exceeding a minimum operational threshold of 0.30 m; 'snow-days'. Abegg et al. (2007) note that the '100-day rule' (i.e. snow cover sufficient for skiing for at least 100 days) has been widely used as a tool to assess the susceptibility of ski areas to climate variability and change. This threshold is commonly set at 0.30 m. Our analysis considers cases both with and without snowmaking.

We have used the snow model described by Clark et al. (2009), and as used by Hendriks et al. (2012), but have recalibrated it for each individual ski area location. Where available, we have used observations of snow depth to calibrate the snow model output for the current climate. Where reliable observations of snow depth were not available, a default parameter set for the snow model (as used by Hendriks et al. 2012) has been used. This local calibration is desirable as it improves the confidence in our modelling, as it essentially accounts for the processes that the model cannot resolve at this fine scale (e.g. local scale redistribution of snow, etc.). This calibration was necessary to ensure that the model could simulate the current snow conditions as accurately as possible at each of the selected sites. This is a critical step before one should attempt to simulate a future climate. Having generated modelled snow for the current climate, we then proceed to model natural snow for the 2030–2049 (mid-point reference 2040) and 2080–2099 (mid-point reference 2090) time periods, for the three emission scenarios, B1, A1B and A1FI (IPCC 2007). In each case, we benchmark these snow depth results to the number of days (snow-days) above the 0.3-m threshold and examine the change from the current climate.

Additionally, we use simulated hourly temperatures and humidity to calculate the total potential snowmaking hours in the future climates. For this snowmaking analysis, only the A1FI scenario 'worst-case' year in each time period, rather than an average year, was used to assess the snowmaking potential. This was done to ensure consistency with snowmaking design practices. Using manufacture-supplied information on snow machine flow rates at given wet bulb temperatures, we then calculate the potential snow volume, and thereby depth, that one snow gun can produce for a 10,000-m² area (assuming unlimited water supply). This combined analysis allows for an assessment to be made about both the change in natural snow cover and also the ability of each specific location to adapt to the potential impacts of climate change through potential snowmaking.

2 Study area

The ski areas considered in this study are all located in New Zealand, with two in the North Island and the other eight in the South Island (Fig. 1 and Table 1). The location of New Zealand, in the Pacific Ocean and away from continental influences and constant exposure to the westerly winds, gives the climate a distinct maritime character. A more complete description of the climate can be found in Sturman and Tapper (1996), Sturman and Wanner (2001) or Hendriks et al. (2012). The most northern location for this study is at approximately 39.2° S, while the most southern location is at approximately 45.1° S. At each ski area, an upper and lower

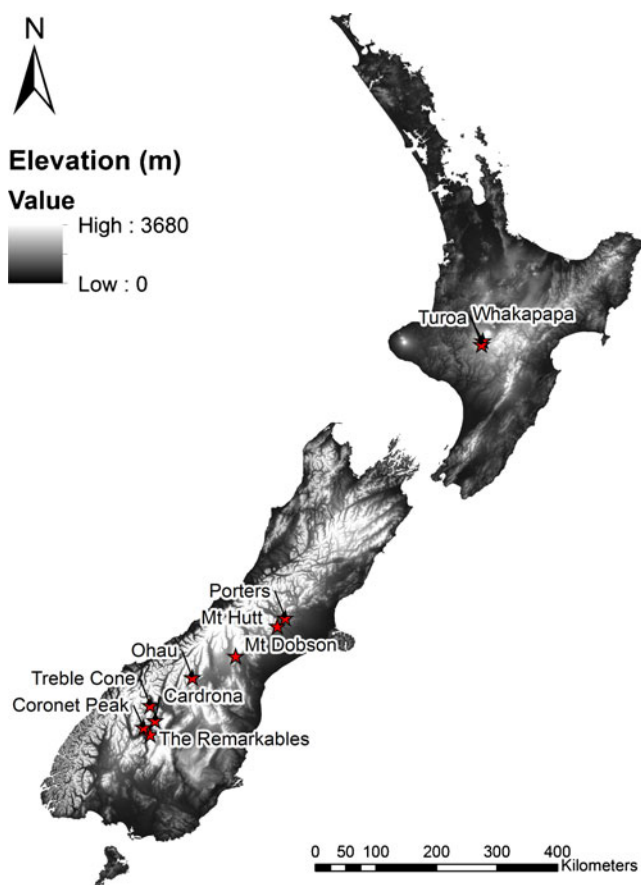


Fig. 1 Map of New Zealand showing the location of the ten ski areas considered in this study. At each site, both an upper and lower elevation location was considered. A 30-m digital elevation model has been used as the background

elevation site was considered. These sites were typically representative of the upper and lower regions on the respective ski area. Elevations for the lower sites ranged from 1,200 to 1,640 m, while upper elevation sites ranged from 1,650 to 2,050 m (Table 1). In most instances, the lower site was at or near the base elevation of the ski area. Therefore, results from these lower sites can be viewed as a worst-case for each ski area.

3 Methods

3.1 Climate data

To simulate the snowpack and snowmaking potential at each location, climate information is required for the current climate, and for two future scenarios, referred to in this work as the 2040s and 2090s time periods. Tait et al. (2006) described a statistical method to interpolate station observations to a 0.05° grid (approx. 5 by 5 km) and generate a set of high-resolution daily climate maps for

New Zealand. Each daily precipitation map is created by using thin-plate splines to interpolate 24-h precipitation observations at each station. This set of data is named the virtual climate network (VCN) data.

For each ski area location (Table 1 and Fig. 1), the nearest grid point from the VCN was selected. Given that the VCN is a regular grid of precipitation and temperature, with approximately 5×5 km spacing across New Zealand, the nearest grid point was never more than a few kilometres away. Each VCN grid point has an elevation attributed to it; this is the mean elevation for the area within this grid point. To ensure that the nearest VCN grid point reflected the climate of the selected location as closely as possible, the VCN temperature was lapsed either up or down using a $5^\circ\text{C}/\text{km}$ lapse rate. For example, if our selected VCN grid point had an elevation 200 m lower than our selected site, then the temperatures in the VCN record (at this selected grid point) were decreased by 1°C . This ensured that the selected VCN grid point was not only the closest in terms of horizontal direction, but also reflected the elevation of the site accurately. Precipitation was unmodified at this stage, but was used as one of the key calibration parameters.

The VCN maximum and minimum temperature, precipitation and relative humidity data for the grid points closest to the selected sites, from 1 January 1980 to 31 December 1999, were extracted for this study (as shown in Table 2). These were used as the data for the current (1990s) climate.

3.2 Snow model calibration for current climate

Clark et al. (2009) and Hendrikx et al. (2012) have described and used a snow model for New Zealand-wide snow modelling applications and have shown that this model provides reasonable estimates of snow behaviour. For this work, we have used the same snow model, but used only point input data from the nearest VCN grid point as described above.

The snow model presented by Clark et al. (2009) was developed primarily for hydrological applications and as such calculates snow in terms of the snow water equivalence (SWE). However, for the purpose of this paper, we have used these model results and expressed the number of days above the 0.30-m snow depth threshold. Where snow depth is presented, SWE has been converted to snow depth using a varying snow density to snow depth relationship. This relationship captures our general understanding of snow processes, in that the early season snowpack has a low density, which gradually increases over time as the snowpack ‘ripens’ and becomes isothermal. While it is acknowledged that snow on the piste will ‘ripen’ much more quickly due to regular grooming, and compaction by skiers, this study considers snow on the entire mountain, rather than just an individual piste, so still consider this slow seasonal densification an

Table 1 Site names, IDs, longitudes, latitudes, and elevations

Site name	ID	Longitude	Latitude	Elevation (m)
Whakapapa Carpark	20	175.556	-39.236	1,600
Whakapapa Upper	19	175.563	-39.254	2,000
Turoa Upper	17	175.546	-39.300	2,050
Turoa Carpark	18	175.527	-39.307	1,620
Porters Carpark	16	171.643	-43.276	1,320
Porters Upper	15	171.623	-43.274	1,960
Mt Hutt Carpark	14	171.539	-43.497	1,590
Mt Hutt Upper	13	171.531	-43.487	2,050
Mt Dobson Carpark	12	170.662	-43.944	1,700
Mt Dobson Upper	11	170.671	-43.940	2,000
Ohau Carpark	10	169.779	-44.225	1,480
Ohau Upper	9	169.771	-44.220	1,900
Treble Cone Carpark	8	168.896	-44.635	1,250
Treble Cone Upper	7	168.883	-44.631	1,760
Cardrona Carpark	6	168.949	-44.874	1,640
Cardrona Upper	5	168.945	-44.861	1,800
Coronet Peak Carpark	4	168.737	-44.928	1,200
Coronet Peak Upper	3	168.739	-44.918	1,650
The Remarkables Carpark	2	168.815	-45.055	1,640
The Remarkables Upper	1	168.828	-45.054	1,900

important consideration. Our simple snow density to snow depth function starts on 1 April with 200 mm of SWE representing 1 m of snow depth, increasing at a linear rate to 400 mm of SWE representing 1 m of snow depth by 1 December of that year. This time period (April–December) covers all available snow depth observations that were available for comparative use.

Due to the scale of this analysis, we recalibrated the snow model for each selected ski area. Where available, we have used observations of snow depth to calibrate the snow model output for the current climate. We obtained suitable snow depth data from six of the ten ski areas. These data ranged in duration from 6 to over 20 years of record. In our calibration, we have only permitted ourselves to alter two parameters, namely the temperature threshold and the gauge under catch parameters. We consider that these two parameters can be justifiably modified, based on our understanding of processes for snow accumulation and the gridded input data that we are using. The temperature threshold parameter in the model distinguishes between rain and

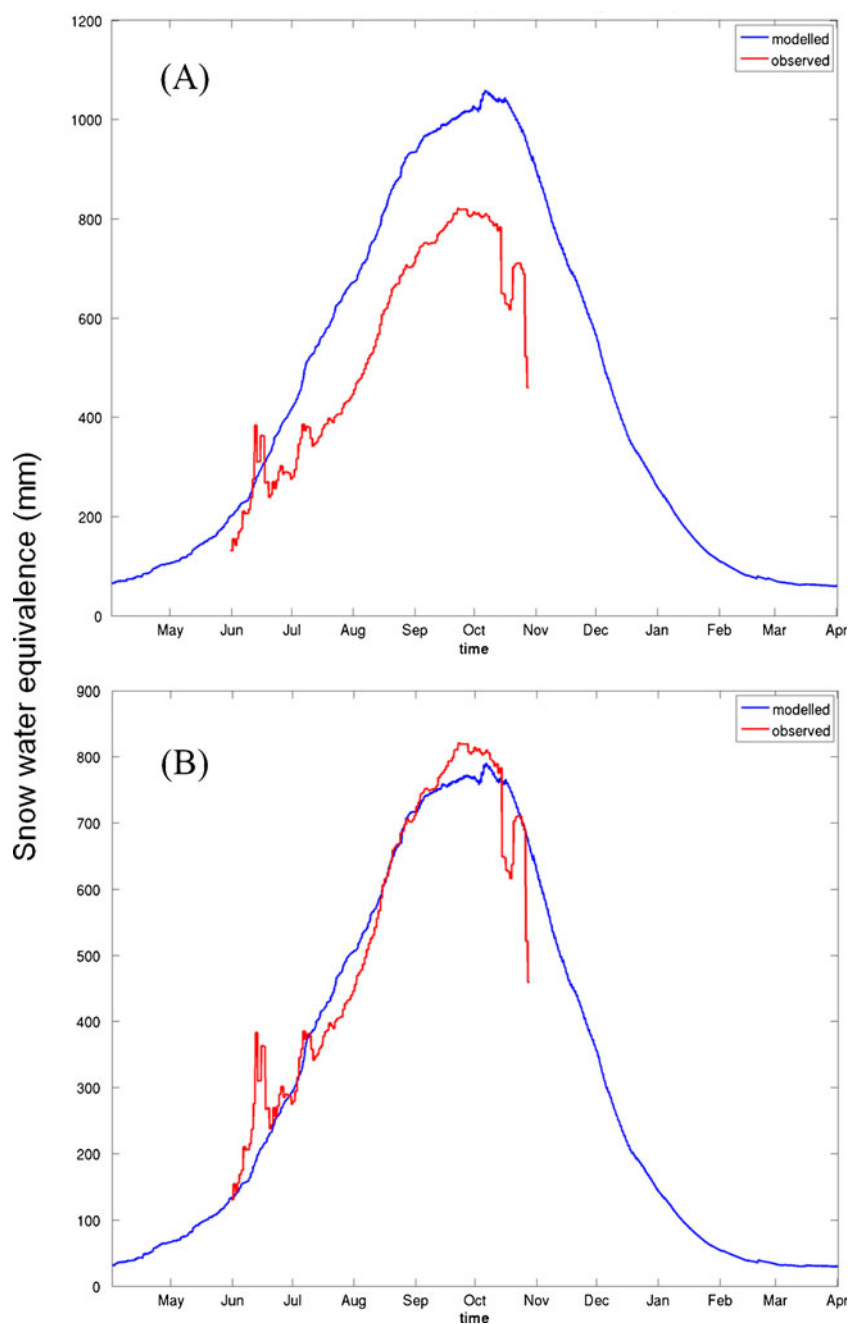
snow. While this is unlikely to change substantially from one site to another, we are using point data from an interpolated temperature surface for the snow model, so adjusting this parameter is akin to updating the temperature field where we may not have sufficient reliable observations to constrain the spline. It is also worth noting that we use a fixed lapse rate (5 °C/km), so calibration of the temperature threshold in the snow model accounts for this variability and uncertainty as well. The gauge under catch is the parameter which allows us to enhance or reduce the precipitation experienced at a location. Woods et al. (2006) have documented that the VCN precipitation grid is deficient in the mountains, so adjustment of this parameter is justifiable in our calibration as it allows us to fit the precipitation data to the available observations.

Where reliable observations of snow depth were not available, our default parameter set for the snow model (as used for the nationwide modelling by Clark et al. 2009, and climate change assessment by Hendrikx et al. 2012) has been used. Figure 2 shows the difference between the default parameter

Table 2 Meteorological parameters extracted from closest VCN point

Symbol	Description	Units
Rain	24-h rainfall total from 9:00 a.m. local day	mm
T_{\max}	Maximum temperature over 24 h from 9:00 a.m. local day	°C
T_{\min}	Minimum temperature over 24 h from 9:00 a.m. local day	°C
RH	Relative humidity over 24 h from 9:00 a.m. local day	%

Fig. 2 Modelled (*blue*) and observed (*red*) snow water equivalence with the default parameter set **a**, *above*, and the calibrated parameter set **(b)**, *below*



set and the calibrated parameter set at one ski area. In Fig. 2a, we can see that the snow model with default parameters captures the gross features of the observed snow at this location (Whakapapa Knoll, ID #19). However, in this case, the snow model overestimates the total snow when the default parameters (274 K/+1 °C temperature threshold/1.0 gauge under catch) are used. Figure 2b shows the calibrated snow model for this site which instead uses a parameter set with a lower temperature threshold (of 273 K) and the same gauge under catch value. This new parameter set provides a much better fit to the available observations and is still within a sensible and thus allowable range for these two parameters.

This local calibration is desirable to improve the confidence in our modelling, as it essentially accounts for the processes that model cannot resolve at this fine scale (e.g. local scale redistribution of snow) and for potential errors in our input data. This calibration was necessary to ensure that the model could simulate the current snow conditions as accurately as possible at each of the selected sites.

3.3 Climate change data and application to the snow model

Hendrikx et al. (2012) provide an overview of the climate change data available, which have also been used for this

study. In brief, statistically downscaled GCM delta-change projections were developed for 12 different models for each VCN grid point. The directly downscaled changes were for monthly mean values of temperature and precipitation. The change referred to is the average difference between the period 2030–2049 (2040s) and 2080–2099 (2090s), when compared with the base period 1980–1999 (1990s or current). Hendrikx et al. (2012) for New Zealand-wide snow modelling have highlighted the importance of using each of the 12 different models, rather than an average of the 12 for impact analysis. However, in contrast, for the purpose of this study, the impact of the various emission scenarios was of primary interest, so for this reason, the 12 model average has been used. From the downscaled precipitation and temperature changes, change projections for the 2040s and 2090s periods were developed for use as input for the snow model. In all cases, the hourly future climate was developed by applying the downscaled changes to the current climate VCN data. The A1B emission scenario was used as the base and then rescaled for the other two emission scenarios considered (B1 and A1FI). The scaling factors vary between about 0.6 for the B1 scenario to about 1.0 for A1B and 1.4 for A1FI (but are model-dependent, and we have used the 12 model average) (Ministry for the Environment 2008). While this is not an ideal or a common approach, this was necessitated due to the absence of a full suite of high-resolution regional climate model results for both time slices, across all three scenarios. Thus, the downscaled changes that were used for the other scenarios (B1 and A1FI) have exactly the same spatial pattern as A1B, but with a different amplitude.

In our analysis, we have also empirically adjusted daily precipitation so that there is more precipitation in the future climate on days with high precipitation and an increased number of days without rainfall. The magnitudes of these changes are proportional to the temperature change and so the change is least for the B1 scenario (least warming) and the largest for the A1FI scenario (most warming). Using this approach, for every degree of warming, the most extreme events are increased by approximately 8 %. This captures the concept and current understanding of a future climate with larger extreme precipitation events, especially in areas with an increase in the mean precipitation. The methodology used in this study has been described fully by the Ministry for the Environment (2010).

To simulate snow at our selected sites for the two time periods (2040s and 2090s), for each of the future climate change scenarios (B1, A1B and A1FI), we repeated the described snow simulation for the current climate (Hendrikx et al. 2012) at a point, altering only the temperature and precipitation input data as described above, in line with the three emission scenarios for the two time periods. The snow model and model parameter set were unchanged from the

calibrated parameter set when used for the future snow simulations. Future estimates of snow depth and thereby snow-days over 0.30 m were then compared to the current baseline, so we compare modelled snow-days with modelled future snow-days. For each site, we modelled both the 20-year average snow-days and the 20-year minimum snow-days, for the current, 2040s and 2090s for all three future scenarios.

3.4 Snowmaking

For each location, we also simulated the hourly climate for the two future time periods, for these three future scenarios, to enable calculations of the available time for potential snowmaking. Using a delta-change approach, we used the VCN hourly temperatures and humidity to estimate the future hourly wet bulb temperatures and thereby calculate the total potential snowmaking hours in the future climates. For the snowmaking analysis, we only present a worst-case (1 in 20) year in the A1FI scenario for the 2040s and 2090s, rather than an average year, as this is more consistent with snowmaking design practices.

To calculate the snowmaking potential for a particular location, a threshold wet bulb temperature of $-3\text{ }^{\circ}\text{C}$ is typically used in an operational setting when designing snowmaking requirements (Quane 2010). Using current technology, snow can be produced at wet bulb temperatures warmer than this, but the volumes are very small. We were provided with manufacturer-specified snowmaking rates in litres of water per minute, at different wet bulb temperatures from -1.7 to $-13.5\text{ }^{\circ}\text{C}$ (SMI 2010). To simplify the analysis, we choose to use just one type of snow gun with a fixed pressure of 300 psi. In our analysis, we included any hourly period with a wet bulb temperature at or less than $-1.7\text{ }^{\circ}\text{C}$, as this was the highest temperature that snowmaking could occur using current technology. We used this higher temperature threshold of $-1.7\text{ }^{\circ}\text{C}$ as discussion with the industry indicated that in warm years this was how the machines were operated, despite the cost and small amounts of snow that can be made at these warmer temperatures. We summed the total number of snowmaking hours for the current climate as well as for the worst-case year in the 2040s and 2090s under an A1FI scenario. We then compared the number of snowmaking hours at each location for the current climate worst year to that of the future climate scenario.

We then used the information on flow rates at given wet bulb temperatures to calculate the potential snow volume that could be created by one snow gun in this potential future time period. To do this, we converted litres of water to snow volume by dividing by 0.6, i.e. 600 L of water equates to 1 m^3 of snow. The snow volume was then converted to a snow depth over an area of $10,000\text{ m}^2$ (assuming unlimited water supply). It should be noted that an area of

10,000 m² is much larger than that which is typically recommended for optimal piste preparation by one snow gun (Quane 2010). However, we choose to use this larger area for two reasons: first that it provides a convenient value for estimation of what would be needed, at a very minimum, for an entire ski area (not just the piste), and second, we are only considering the question of whether there is sufficient time in the prescribed future climate for adequate snowmaking to provide minimum levels of coverage with the minimum number of snow guns.

Furthermore, as noted above, the results presented are only for the worst year in the 2040s and 2090s under the A1FI scenario. The reason we have taken this ‘pessimistic’ approach is that a snowmaking system is not typically designed around an ‘average’ year, but rather an extreme year when there is very little (or no) natural snow early in the season, which has an expect return period of 1 in 20 years (Quane 2010). In our analysis, a year is defined as a worst year in the 20-year time series if it has the least total amount of snow (i.e. the area under the snow depth curve) in the period before 1 August of that year.

We then calculated the cumulative snow depth that one snow gun could generate everyday (from 15 May to 31 August); in this future climate, it was then added to any natural snow (if present). This combined snow depth was then compared to the minimum threshold snow depth of 0.3 m and if it was equal or greater than the threshold it was considered a snow day. Snowmaking was not continued after 31 August, as the industry had informed us that the early to mid-season is the most critical. We have maintained this cut-off date for snowmaking in both the future time periods.

It is important to note that while the snow model which calculates the natural snow allows for snowmelt, the snow volume as calculated from the snowmaking does not. No losses for any reason (e.g. wind, sublimation and rain-on-snow) are directly accounted for in the snowmaking snow depth calculations, but the high snow density value we have used does indirectly allow for at least some of this. Due to these limitations and the associated uncertainties in the snowmaking analysis, we also present the average relative percentage for the amount of snow that can be theoretically made by one snow gun for the whole period at each site (relative to the 1990s worst year).

Finally, we must also stress that we do not assess the ability of a particular location to create ‘optimal’ piste preparation or comment on target times to achieve required depths. However, if the minimum desired coverage can theoretically be generated by one snow gun, neglecting melt, as shown in this analysis, then increasing the number of snow guns would obviously increase the likelihood of more snow volume and attainment of optimal piste preparation.

For the snowmaking analysis, we only present the 2040s and the 2090s A1FI scenario for a worst-case year. We have

chosen to do this, as this represents a worst-case scenario and if sufficient snow can be made in this future climate then we can be sure that at least this amount, and likely more, can be made under the other emission scenarios with less warming (e.g. A1B and B1). Furthermore, if the current trend on observed global greenhouse gas emissions exceeding the IPCC scenario range continues (e.g. Raupach et al. 2007) then the A1FI scenario would seem prudent for long-term planning applications.

3.5 Limitations and uncertainties

All of the site-specific snow modelling and snowmaking potential is calculated from the nearest grid cell in the interpolated VCN. The daily temperature and rainfall VCN data for the current climate come with the caveats noted in the associated publications (Tait et al. 2006; Tait 2008). The temperature downscaling is based on T_{mean} only, and the same offset is assumed to apply to both T_{max} and T_{min} . Particularly relevant to the snow simulations are the well-known challenges in estimating precipitation and temperature in alpine regions from a sparse station network (Clark and Slater 2006; Slater and Clark 2006). To some extent, the limitations in the VCN are reduced in their impact as the snow model has been calibrated to each individual site (where observations were made available); however, these observations in themselves also add uncertainties to the modelled results. Some of the snow depth observations were considered to be of dubious quality, showing physically implausible processes, such as a complete absence of settlement in the days following a storm event. The limitations in the VCN are even more relevant to those locations with no snow depth observations and these will increase the overall uncertainty associated with the snow model output for these locations without suitable snow data.

The snow volumes and thereby depths, that have been calculated as made from the snowmaking, are likely to be a maximum potential volume. This is for a number of reasons: firstly because at any time when the wet bulb temperatures dropped below -1.7 °C, immediate snowmaking was assumed to be possible. While this is realistic in a fully automated snowmaking system, for most systems, this is not. Furthermore, snow guns were permitted to make snow at any time, for up to 24 h per day, from 1 May of each year, if possible (i.e. below the wet bulb threshold). Again, most operations would not run their snow guns in this fashion. Calculated snow volumes were also as per manufacturers' specifications as based on water flow rates, and the resultant snow depths were calculated for much larger areas than operationally recommended. Finally, there was also no account made for any potential losses in snow as made by the snow guns. Factors such as losses due to wind, sublimation, snowmelt and rain-on-snow events were all ignored. Essentially, all

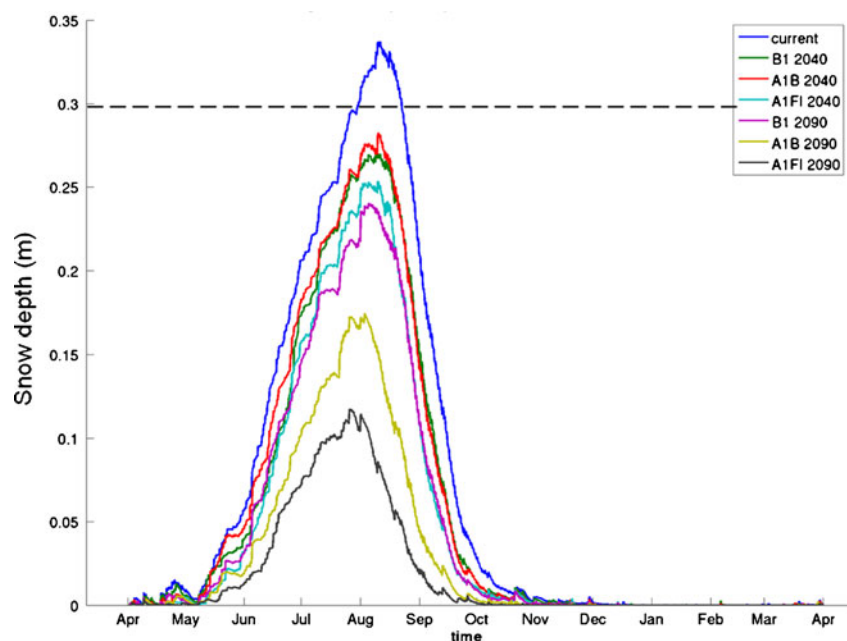
of the cumulative potential water flow rate from the snow gun was assumed to become snow at these sites. An assessment of the hydrological or financial ability to make this snow was considered outside the scope of this paper, but would need to be considered in future studies.

4 Results

We examined ten ski areas throughout New Zealand, considering both a low elevation (e.g. car park/base building) site and an upper elevation (e.g. top of the ski area) site, resulting in 20 detailed modelling locations. Figure 3 provides an example of the calibrated 20-year averaged modelled snow depths for a lower elevation site (ID #4), for the current, the 2040s and 2090s for each of the future emission scenarios. From this summary plot, we were then able to calculate the number of snow-days, (i.e. the days that had snow depths exceeding 0.3 m). In this case, only the current (1990s) had days with snow depths exceeding 0.30 m. In the other two time periods, and three scenarios, there were 0 days with snow depth above this threshold.

We repeated the analysis and also generated plots for the lowest snow depth year in each 20-year period for each site, a worst-case year. For the lowest snow depth year in the case of the A1FI scenario, we also included the number of days with snow depths above the 0.3-m threshold when all possible snowmaking (neglecting any melt) is combined with any natural snow. For brevity, we have not presented all of the results in graphical format (i.e. all 40 plots for the 20 locations). Instead, we have summarised these results for the two time periods, for the three scenarios for an average year (in Table 3) and for a minimum year (Table 4 and Fig. 4).

Fig. 3 Twenty-year averaged modelled snow depths for a lower elevation site, for the current, the 2040s and 2090s for each of the future emission scenarios. The *dashed line* indicates the 0.3-m snow depth threshold to be considered a snow-day



Tables 3 and 4 and Fig. 4 show that depending on the elevation and location of the specific site in question, there will be a reduction in the number of snow-days in nearly all of the future scenarios and time periods. If we consider Table 4, then we can see that for a minimum year in the 1990s, the number of snow-days ranges from 0 to 229, while by the 2040s, it ranges from 0 to 187 (B1), 0 to 183 (A1B) and 0 to 176 (A1FI). When we account for potential additional snow from snowmaking in the A1FI scenario, the number of snow-days is increased, with a range from 100 to 182. By the 2090s, the number of snow-days ranges from 0 to 155 (B1), 0 to 90 (A1B) and 0 to 74 (A1FI) and with snowmaking considered from 84 to 131. When we consider the sites that have less than 100 snow-days in the current climate, the addition of snowmaking in the A1FI scenario for both the 2040s and 2090s results in a greater number of snow-days than in the current climate, clearly showing the ability for snowmaking in these climates. When we consider the sites with more than 100 snow-days in the current climate, then adding the snow from snowmaking results in a similar number of snow-days, rather than a dramatic increase.

Due to the aforementioned limitations and uncertainties contained within the snowmaking analysis (e.g. our neglect of snowmelt), we also present the relative percentage of time in which snowmaking can be theoretically undertaken under this worst case 2040 and 2090 A1FI scenario (relative to the 1990s worst year) (Fig. 5). Figure 5 shows that depending on the elevation and location of the specific site in question, by the 2040s, there is only 82 to 53 % and by the 2090s only 59 % to 17 % of the snowmaking time as compared to the 1990s in a worst-case year. It is worth noting that elevation alone is not the only factor in determining this reduction in

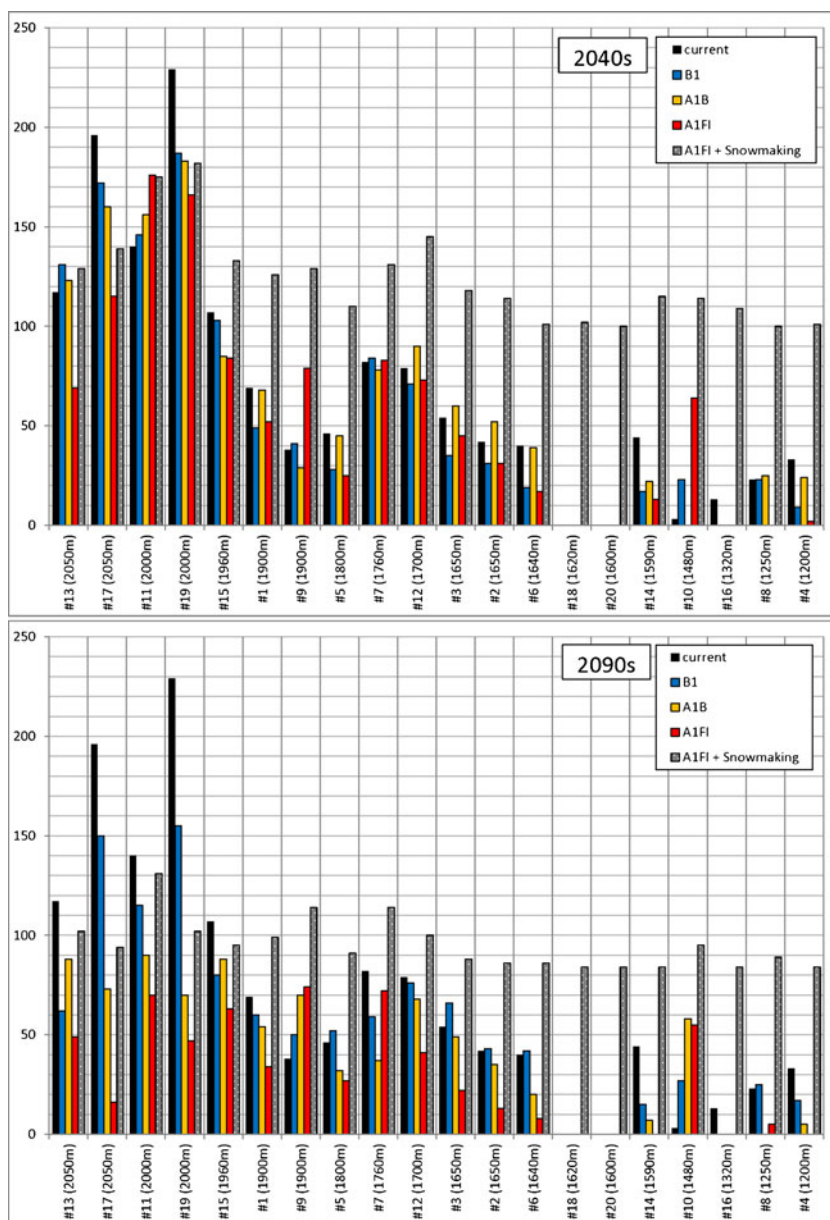
Table 3 Number of days with snow depths exceeding 0.30 m, for each site, for an average year within each time period (1990s, 2040s and 2090s), under each of the three emission scenarios (B1, A1B and A1FI)

ID	Elevation (m)	Current (1990s)	2040s			2090s		
			B1	A1B	A1FI	B1	A1B	A1FI
1	1,900	105	87	87	85	83	75	58
2	1,640	72	60	58	55	52	37	0
3	1,650	88	79	76	68	68	51	31
4	1,200	23	0	0	0	0	0	0
5	1,800	70	60	52	49	49	37	11
6	1,640	45	40	35	34	27	0	0
7	1,760	137	117	116	111	113	98	82
8	1,250	73	54	45	36	31	0	0
9	1,900	137	119	119	113	113	104	96
10	1,480	92	79	78	77	72	54	32
11	2,000	192	168	166	146	154	128	108
12	1,700	137	114	116	105	109	87	66
13	2,050	171	143	144	118	114	98	75
14	1,590	86	69	71	55	50	2	0
15	1,960	139	112	114	99	97	76	55
16	1,320	50	2	0	0	0	0	0
17	2,050	263	231	212	197	205	154	120
18	1,620	120	93	91	72	75	27	0
19	2,000	293	252	227	212	216	170	130
20	1,600	113	85	83	68	71	12	0

Table 4 Number of days with snow depths exceeding 0.30 m, for each site, for a minimum year within each time period (1990s, 2040s and 2090s), under each of the three emission scenarios (B1, A1B and A1FI), including the added snow-days from including snowmaking

ID	Elevation (m)	Current (1990s)	2040s				2090s			
			B1	A1B	A1FI	A1FI + snowmaking	B1	A1B	A1FI	A1FI + snowmaking
1	1,900	69	49	68	52	126	60	54	34	99
2	1,640	42	31	52	31	114	43	35	13	86
3	1,650	54	35	60	45	118	66	49	22	88
4	1,200	33	9	24	2	101	17	5	0	84
13	2,050	117	131	123	69	129	62	88	49	102
14	1,590	44	17	22	13	115	15	7	0	84
5	1,800	46	28	45	25	110	52	32	27	91
6	1,640	40	19	39	17	101	42	20	8	86
7	1,760	82	84	78	83	131	59	37	72	114
8	1,250	23	23	25	0	100	25	0	5	89
9	1,900	38	41	29	79	129	50	70	74	114
10	1,480	3	23	0	64	114	27	58	55	95
11	2,000	140	146	156	176	176	115	90	70	131
12	1,700	79	71	90	73	145	76	68	41	100
15	1,960	107	103	85	84	133	80	88	63	95
16	1,320	13	0	0	0	109	0	0	0	84
17	2,050	196	172	160	115	139	150	73	16	94
18	1,620	0	0	0	0	102	0	0	0	84
19	2,000	229	187	183	166	182	155	70	47	102
20	1,600	0	0	0	0	100	0	0	0	84

Fig. 4 Number of snow-days (with snow depths exceeding 0.30 m), for each site, for a minimum year within each time period, 2040s (*top*) and 2090s (*bottom*), under each of the three emission scenarios (B1, A1B and A1FI), including the added snow-days from including snowmaking in the A1FI scenario. Sites are ordered approximately from highest to lowest elevation



snowmaking hours. Furthermore, the percentage reduction is within a relatively tight range at elevations above approximately 1,650 m and then decreases more rapidly below this.

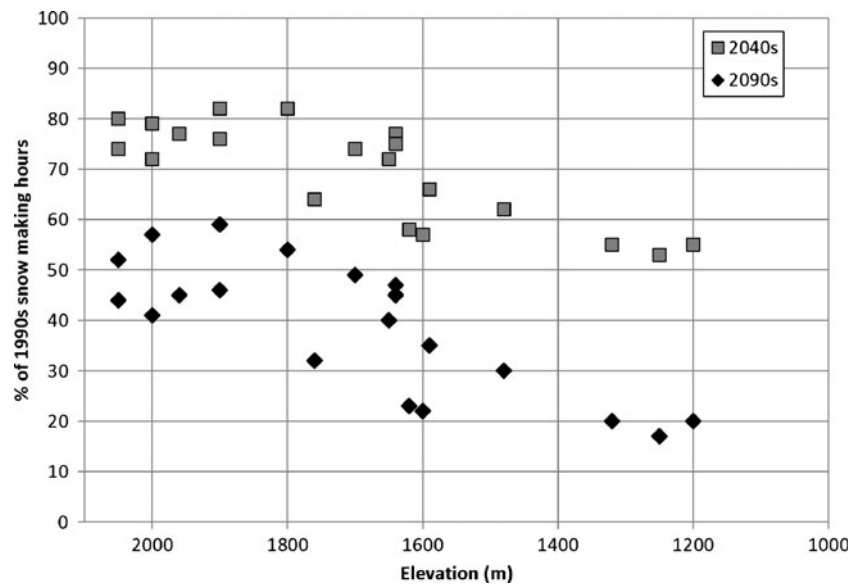
5 Discussion and conclusions

Our results show that climate change will reduce the natural snow which is available at all the sites considered. These are the first quantitative assessments of the potential effects of climate change on seasonal snow in New Zealand at a ski area scale. The results are somewhat expected and are generally consistent with our understanding of snow processes. The magnitude of the reduction in the number of snow-days (i.e. days above the 0.30-m threshold) is generally

negatively correlated to the elevation of the site, with lower elevation sites generally showing the greatest change and higher elevation sites the least. Sites with elevations below 1,650 m generally show the greatest decline in the number of snow-days. While elevation is clearly an important factor in determining the potential impact of climate change on seasonal snow, other factors such as the local climatology of each site also play an important role.

It is worth noting that the number of snow-days in the current climate is less than 100 days at almost all of the sites considered. Only five sites have natural snow cover that exceeds this 100-day threshold, which as noted by Abegg (2007) is considered a measure of a ski areas' viability, while ten sites have less than 50 days above this threshold. Not surprisingly, all of these ten sites with less than 50 snow-

Fig. 5 Percentage of 1990s snowmaking hours in the 2090s (diamonds) and 2040s (squares) for all sites, for a worst-case year under an A1FI scenario, plotted against elevation



days in the current climate already have substantial snowmaking infrastructure in place. This group includes one ski area with more than 200 snow guns which is able to open the entire ski area following 5 days of snowmaking, even in absence of any natural snow (Quane 2010).

The snowmaking analysis, despite its limitations, shows that snow can be made at all sites, even in a worst-case year by the 2090s under an A1FI scenario. It also indicates that snowmaking could make up the deficit in the natural snow, sharply increasing and reinstating the number of snow-days back to the 1990s level at all sites considered. We must however remember that this threshold of 0.3 m for a snow-day is a bare minimum for operational variability and while the snowmaking analysis shows that the number of days in the 2090s A1FI scenario is close to or could even exceed the number of natural only snow-days in the current climate, the overall quantity of snow is much less and therefore the overall skiing experience would likely be reduced more than what this metric may suggest. In relative terms, the potential future snowmaking hours are also reduced at all sites, but it is still possible to make snow at all sites examined. The reduction in snowmaking hours, like the decline in natural snow-days, is generally negatively correlated with elevation.

Similar to the work by Scott et al. (2007), we have highlighted the importance of accounting for the snowmaking component when considering climate change impacts on ski areas. While we have not undertaken an assessment of the economic constraints of our snowmaking analysis, discussion with the ski industry suggested that our reduced snowmaking potential (and thereby inferred increase in snow guns) would not be prohibitive cost-wise, especially given the 2090s time frame. In many cases, the snow machine infrastructure is considered to be under-utilised in the current climate as it is

only used in the first few weeks of the season. While our snowmaking analysis has some limitations, this study illustrates the importance of considering adaptation options such as snowmaking for a more complete impact assessment.

In contrast, a recent study in Switzerland by Rixen et al. (2011) showed that the snowmaking component may become the critical link for the ski areas with the lowest elevations (i.e. below 1200 m), as they will simply be too warm for economical snowmaking to be possible by the 2050s. Furthermore, a study by Pickering (2010) examining snowmaking requirements in Australia also indicated that at the lowest elevations, the required snowmaking would be too costly there, even just to meet the 2020s projected demand. This difference can likely be attributed to the relatively modest increase in temperature (and increased, opposed to decreased precipitation) in the New Zealand sites considered here.

While the results we present are consistent with our understanding of snow processes, we must still urge some caution in their use. Foremost is that the snowmaking analysis may be overly optimistic given that we have not calculated losses incurred from melt in the snow made from snowmaking. The change scenario methodology employed is a relatively simple delta-change approach; in particular that it does not make any allowance for changes in extremes. These extreme events are of great importance, particularly for operations such as ski areas as often one large and well-timed storm can be more beneficial for a ski area than the same amount of snow arriving in small amounts over the space of a few weeks. Furthermore, we have not made an assessment of the economic or hydrological reality of making snow in these future climates at each location. Future work should investigate these and other related issues through the coupling of a regional climate model with the

snow model and snowmaking model, to better simulate future climates and their potential impacts in this industry.

Acknowledgments We would like to thank New Zealand's Foundation for Research Science and Technology for supporting a part of this work under contract C01X0804 'Regional Modelling of Future New Zealand Climate'. We also acknowledge the support from the SAANZ for coordinating and obtaining funding from the following industry partners to complete the majority of this research: Ruapehu Alpine Lifts, NZSki, Porters, Mt Dobson, Ohau, Treble Cone, Cardrona, Doppelmayr Lifts Ltd. and Ski Industries Ltd. Finally, we would also like to thank the two anonymous reviewers that provided a thorough review of this paper and significantly improved the final result.

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