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Source: Mountain Research and Development, 31(3) : 229-236

Published By: International Mountain Society

URL: <https://doi.org/10.1659/MRD-JOURNAL-D-10-00112.1>

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Winter Tourism and Climate Change in the Alps: An Assessment of Resource Consumption, Snow Reliability, and Future Snowmaking Potential

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The winter tourism industry is facing considerable challenges with climate change; it is increasingly responding with investments in snowmaking facilities. We present a study on 3 tourism destinations in the Swiss Alps that

addressed resource consumption of snowmaking, snow reliability, and future snowmaking potential in a warmer climate. The energy consumption of snowmaking in the ski resorts was in the lower range of what could be expected from literature values. It comprised ~0.5% of the respective municipality's energy consumption and was moderate compared with other tourism-related activities. Water consumption, however, was in the higher range with regard to what was expected from literature values and was also high compared with other water uses (eg 36% compared with drinking water consumption in one community). Natural snow cover was partly critical for winter sports at low elevations at ~1200 masl, but uncritical at higher elevations above 2000 masl. Snow cover will become even

more critical in a warmer climate but will probably still be sufficient above 2000 masl until 2050. Snowmaking may become critical at lower elevations in the early months of the season (November and December) due to warmer temperatures that can be expected in the coming decades. But, at higher elevations, the potential for snowmaking will probably remain sufficient. Our study provides straightforward and feasible approaches to assess resource consumption and snow cover. Careful consideration of resource consumption and snow cover can foster technical and economical advances as well as more sustainable development in mountains regions. Snow production can represent a valuable adaptation strategy at high-altitude destinations. However, given the increasing economic competition and the changing climate, it will be crucial to use specific regional strengths to provide high-quality winter and summer tourism activities.

Keywords: Artificial snow; technical snow; snowmaking; climate change; ski piste; Alpine ecosystems; sustainability; Switzerland.

Peer-reviewed: March 2011 **Accepted:** July 2011

Introduction

Reliable snow conditions represent a crucial economic prerequisite for the skiing industry (Elsasser and Messerli 2001; Scott et al 2003; Pröbstl 2006; Steiger and Mayer 2008). The lack of snow due to low precipitation or high temperatures is an immense challenge for winter sport destinations and especially mountain railway companies. Artificial snow production is the key adaptation strategy to rising temperatures, enhanced economic competition, and increasing requirements of winter tourists. The increase in snowmaking facilities in the Alps has been dramatic in recent years. In Switzerland, artificial snow production increased in cover from <10% of the total ski piste area in 2000 to 36% in 2010 (Seilbahnen Schweiz 2010). Austria has already reached 62%, whereas, in some areas in the Italian Alps, artificial snow can now be produced on 100% of the ski runs (Hahn 2004). The winter of 2010–2011 had below-average snow cover in

most parts of the Swiss Alps, however, the mountain railway companies look back on an economically successful season, possibly in part due to improvements in snowmaking technology (Seilbahnen Schweiz 2011).

Given the expected change in climate, the trend toward extensive snow production will continue and increase. Regional climate scenarios for Switzerland predict a rise in winter temperatures by +1°C until 2030 and +1.8°C until 2050 (OcCC-Consortium 2007). The snow cover at elevations below 1300 masl has already significantly decreased since 1980 (Latenser and Schneebeli 2003). In higher regions, a decrease in average snow depth was observed in early winter (November, December), which is a crucial period for winter sport.

The tourism industry is faced with numerous concerns given the future challenges of climate change. Therefore, it needs to estimate potential negative effects of a reduced natural snow cover and potential positive mitigating effects of snow production (Hoffmann et al 2009).

Frequently discussed ecological concerns are the consumption of water and energy for snow production (Hahn 2004) and the impacts of snowmaking on vegetation and soil (Rixen et al 2003; Rixen et al 2008; Roux-Fouillet et al 2011). Although several studies have addressed ecological aspects (for an overview see Pröbstl 2006), published results of energy and water issues are rare. Furthermore, technical concerns arise about the snowmaking potential in a warmer climate because higher temperatures will not only reduce the natural snow cover but also the ability to produce snow technically (Steiger and Mayer 2008; Steiger 2010).

Our study aimed at analyzing the following aspects of winter climate change and snowmaking: resource consumption (water, energy) and snow reliability linked to the ability of snowmaking in a future climate (see details in Teich et al 2007). We addressed the following research questions: (1) how much energy and water is required for the production of snow, and how does it relate to the regional and the resource consumption of other activities in tourism, and (2) how may snow reliability change, and will snowmaking be possible under the predicted temperature increase? The results of this study contribute to the discussion of pros and cons of artificial snow and its different impacts. The findings improve the knowledge base for decision-making in planning and implementing snowing facilities worldwide.

Methods

Study sites

Our investigations were carried out in the 3 Swiss tourism destinations of Davos (9°50'E, 46°48'N; Figure 1), Scuol (10°18'E, 46°48'N), and Braunwald (8°59'E, 46°56'N). These regions represent different types of destinations and different climates in the Alps, and, therefore, may be representative for other tourist destinations. Davos is one of the largest communities of Switzerland (284 km², ~12,500 inhabitants) and the highest town of Europe. The mean annual temperature is 2.8°C, and the mean annual precipitation is 1175 mm. Five ski resorts range between 1560 and 2844 masl, the largest being Parsenn-Gotschna and Jakobshorn. Davos also is renowned for its congress infrastructure. The municipality of Scuol covers 144 km² (2400 inhabitants), and its ski resort Motta Naluns ranges from 1250 to 2785 masl. Scuol is popular among tourists because of its relatively dry climate (750 mm annual precipitation, 6°C mean annual temperature) and a spa. Braunwald is a small municipality of 10 km² (~350 inhabitants). Its ski resort ranges from 1250 to 1904 masl, and the precipitation amounts to 2000 mm (mean annual temperature 5°C). The destination is popular among tourists because of its vicinity to the town of Zurich and because it is car-free and family friendly.

FIGURE 1 Ski piste with artificial snow in Davos where snow melts more than two weeks later than adjacent to the piste. (Photo by Christian Rixen)



Resource consumption in snowmaking

We compared the energy and water consumption in snowmaking based on what could be expected from the literature with what was actually used in the ski areas. According to reference values from the literature (SLF 2006; Steiger and Mayer 2008), the energy required for the production of 1 m³ of snow ranges between 1.5 and 9 kWh (or between 5000 and 27,000 kWh for 1 ha with 30 cm of artificial snow). The water consumption for the production of 1 m³ of snow ranges between 200 and 500 L (or between 600,000 and 1,500,000 L for 1 ha with 30 cm of artificial snow). These literature values were multiplied with the area with snow production per ski area to calculate the expected range of resource consumption.

Detailed information about the actual water and energy consumption for snowmaking in the investigated ski areas in the winter season 2006–2007 was gathered from local experts from mountain railway companies and environmental agencies of the communities. These data were then compared with other tourist activities in the

communities in 2006. In Davos, energy balances of the entire municipality were available from a detailed carbon footprint analysis (Walz et al 2008).

Snow cover, snowmaking, and climate change

Our calculations of snow days and snowmaking days in the current and a future climate were based on data from a total of 17 snow and climate stations run by MeteoSwiss and the SLF (Rhyner et al 2002) in or close to the respective communities. A snow day (SD) is characterized by a minimum snow depth of ≥ 30 cm required for alpine winter sports (Elsasser and Messerli 2001); a possible snowmaking day (D_{PB}) is defined by a dew point temperature of -4°C or lower (Schneider and Schönbein 2006). Daily mean values of air temperature (T), relative humidity (RH), and snow depth (HS) were used from 1 November to 15 April in the years 1982 through 2006 as the reference period. Scenarios of the future winter climate were taken from the latest reports for Switzerland (OcCC-Consortium 2007), which predict the following median temperature increases: $+1^{\circ}\text{C}$ by 2030 (95% probability: minimum $+0.4^{\circ}\text{C}$, maximum $+1.8^{\circ}\text{C}$); $+1.8^{\circ}\text{C}$ by 2050 (minimum, $+0.9$; maximum, $+3.4^{\circ}\text{C}$).

The number of snow days, SD, between 1 November and 15 April for different altitudes within the communities was calculated with

$$SD_i = \beta_{i1}h + \beta_{i2}, \quad (1)$$

where h is the elevation of a climate station in a municipality i , and β_{i1} and β_{i2} are regression coefficients. The respective regressions for the investigated ski areas were the following: Davos $SD = 0.050 h + 23.99$; Scuol: $SD = 0.092 h - 71.56$; Braunwald: $SD = 0.137 h - 71.26$.

The sensitivity of snow days, SD, to temperature changes was calculated with

$$SD_i = \beta_{i3}T_{season} + \beta_{i4}, \quad (2)$$

where T_{season} is the mean air temperature between 1 November and 15 April, and β_{i3} and β_{i4} are regression coefficients (regressions: Davos $SD = 8.44 T_{season} + 97.23$; Scuol $SD = 8.33 T_{season} + 36.58$; Braunwald NA because of gaps in snow depth data).

Based on Equations 1 and 2, we calculated the expected number of snow days, SD, in a warmer climate with

$$SD_i = \beta_{i1}h + \beta_{i2} - \beta_{i3} * \Delta T, \quad (3)$$

where ΔT is the expected change in temperature (regressions: Davos $SD = 0.050 h + 23.99 - 8.44 \Delta T$; Scuol $SD = 0.092 h - 71.56 - 8.33 \Delta T$).

The number of possible snowmaking days (D_{PB}) between 1 November and 15 April was counted for every

climate station and regressed for each municipality according to the equation

$$D_{PB} = \beta_{i5}h + \beta_{i6}. \quad (4)$$

The respective regressions for the ski areas were the following: Davos $D_{PB} = 0.053 h - 18.16$; Scuol $D_{PB} = 0.044 h + 12.25$; Braunwald $D_{PB} = 0.039 h + 1.88$.

For the scenarios for 2030 and 2050, the number of days with dew point temperatures at -4°C or lower was recalculated based on the predicted temperatures. D_{PB} was then calculated for a given elevation by using Equation 4.

The calculations above are based on past climate data from few climate stations and can only be seen as a first innovative approach to estimate future changes in snow cover and snowmaking conditions. The calculations are based on the underlying assumptions that (1) variation in snow depth is largely driven by temperature and can usually not be explained by precipitation alone (Scherrer et al 2004), (2) climate warming will be similar across different elevations, and (3) the relative humidity will remain unchanged in a warmer climate (Schneider and Schönbein 2006).

Results and Discussion

Resource consumption in snowmaking and other ecological aspects

The annual energy consumption for snowmaking in our study areas ranged between $\sim 14,000$ kWh in Braunwald (on 4.3 ha), ~ 1 million kWh in Scuol (on 144 ha), and 1.7 million kWh in Davos (on 150 ha in the Parsenn ski area; Table 1). These numbers demonstrate the large differences in energy consumption between a small ski area with only 25 km of ski pistes and snowmaking facilities for less than 5% of the pistes (Braunwald) and large ski areas with more than 80 km of pistes and snowmaking facilities for 20–30% of the pistes (Scuol and Davos). Also, the required energy/ m^2 of ski slope equipped with snowmaking (kWh) differed considerably between ski areas, with ~ 0.33 kWh/ m^2 in Braunwald and 1.13 kWh/ m^2 in Davos (Table 1). These differences could be explained either by climatic differences (more precipitation in Braunwald) or by generally higher snow production in the areas with a more developed and intense ski industry (Scuol and Davos).

The expected energy consumption for the ski areas showed a wide range because of the range in the literature values (SLF 2006; Steiger and Mayer 2008) that we used for the calculations (Table 1). Interestingly, the actual energy consumption was in the lower range of what might have been expected based on literature values: the actual energy consumption in Braunwald amounted to $< 26,000$ kWh compared with up to 116,000 kWh expected energy consumption and 1.7 million kWh versus up to 4

TABLE 1 Size of ski area and area with snowmaking facilities, expected (based on literature values), and current energy and water consumption in the 3 studied ski resorts.

Characteristics	Winter resort		
	Parsenn, Davos	Motta Naluns, Scuol	Braunwald
Total length of ski pistes (km)	125	80	25
Ski piste area with snow production (ha)	150	144	4.3
Share of ski slopes with snowmaking per ski area (%)	20	30	3
Expected energy consumption (kWh)	750,000–4,000,000	720,000–3,900,000	21,000–116,000
Actual energy consumption (kWh)	~1,700,000	1,000,000–1,250,000	14,000–26,000
Required energy per m ² of ski slope equipped with snowmaking (kWh)	1.13	0.69–0.87	0.33–0.60
Expected water consumption (m ³)	90,000–225,000	86,000–216,000	2600–6500
Current water consumption (m ³)	~300,000	~200,000	NA
Required water per m ² of ski slope equipped with snowmaking (m ³)	0.2	0.14	NA

NA, no data available.

million kWh in the Parsenn ski area in Davos. The lower than expected energy use may have been due to recent advances in more energy-efficient snowmaking technology (Fauve and Rhyner 2004). Nevertheless, we must consider that all of the investigated communities are located at relatively high elevation with good conditions for snowmaking. Other ski areas at lower elevation may consume much more energy for snow production because of higher temperatures or less natural precipitation.

The water consumption amounted to ~300,000 m³ water in Parsenn, Davos (~0.2 m³ required water per m² of ski slope equipped with snowmaking) and 200,000 m³ in Motta Naluns, Scuol (~0.14 m³ required water per m² of ski slope equipped with snowmaking; Table 1). The water consumption, other than the energy consumption, ranged rather higher than expected based on the literature: in Davos, a maximum water use of 225,000 m³ was expected, which was exceeded by the actual water use, and, in Scuol, a maximum of 216,000 m³ was expected, which was nearly reached by the actual water consumption (Table 1). The higher than expected water consumption through snowmaking may be explained with the relatively constant annual water consumption. Indeed, in late fall and early winter, the weather of the upcoming winter is not known, and, therefore, snow production in early winter is usually always high just to be safe (Hahn 2004). Hence, the snow production is not much less, even in years with high natural snowfall and cold temperatures.

In Davos, snowmaking (only considering electric power) represented ~0.6% of the municipality's entire energy consumption. By comparison, the entire energy consumption of the mountain railways (only electric power) comprised 2.4% that of the municipality. Housing

in the municipality of Davos (including oil and gas for heating and housing), however, required 32.5% of the entire energy budget (Walz et al 2008). The spa of Davos (heated with oil) consumed 0.7% of the municipality's energy. These comparisons show that measures such as improving insulation of buildings would probably be the most efficient way of saving energy in a high-elevation community with a relatively cold climate. However, calculations by Hahn (2004) showed that the entire annual energy consumption for snowmaking in the Alps may comprise up to 600 GWh, which is equivalent to the energy consumption of 130,000 households in Switzerland. Therefore, it is crucial to also improve the energy efficiency of snowmaking technology.

Water consumption for snowmaking in Davos comprised 21.5% of the entire drinking-water consumption of the municipality; in Scuol, it reached 36.2%. However, the water for snowmaking derived from independent sources (eg lakes), and, therefore, no conflict has originated so far from snow production competing with needs for drinking water (including agriculture). However, care must be taken that sufficient residual amounts of water remain in rivers because their water content in winter is already low (Hahn 2004). Water reservoirs in the ski area, which are filled during summer, can help mitigate such water shortages (Pröbstl 2006).

Another much-discussed ecological issue of skiing and snowmaking is the potential negative effect on vegetation and soil. It has been shown that skiing in general can exert disturbances to the vegetation because of the changed snow conditions (Wipf et al 2005) and that intact vegetation and plant biodiversity provide stable soils and reduce surface erosion (Pohl et al 2009; Martin et al 2010). The compaction of snow can induce hard soil frost, alter

soil processes, and mechanically damage plants (Keller et al 2004; Rixen et al 2004; Rixen et al 2008). The most dramatic disturbance on ski pistes especially at elevations around and above treeline, however, is machine grading in summer to create smooth surfaces (Wipf et al 2005; Burt and Rice 2009; Roux-Fouillet et al 2011). The production of artificial snow actually has the potential to change vegetation through an input of water and ions and through postponing the time of melt-out (Wipf et al 2005).

Snow cover, snowmaking, and climate change

To consider providing a reliable snow cover to make alpine winter sports economically viable for a ski resort, snow depth needs to exceed 30 cm at least on 100 days within the time period from 1 December through 15 April (Abegg 1996). Our analysis of the number of potential snow days showed that even today the snow cover is not reliable anymore at the lowest elevation (~1200 masl) of some ski resorts (Figure 2A): Scuol had only on average 43 potential snow days at 1250 masl and Davos-Klosters (valley station of the Parsenn ski region) had 83 snow days at 1179 masl in the present climate. Jakobshorn, Davos, and Braunwald were just above the limit with 101 potential snow days (Figure 2A). At mid and high elevation, however, all ski areas had sufficient snow in the present climate of at least 114 potential snow days (mid elevation Scuol) and up to 190 snow days at high elevation in Braunwald. The number of snow days was highest at all elevations in Braunwald for climatic reasons (less continental climate with more precipitation as snow despite warmer temperatures).

By 2030, the number of snow days was predicted to further decrease by 5 to 10 days, and in 2050 by 10 to 20 days. In all ski areas for which our calculations were carried out, the number of potential snow days dropped to below the critical number of 100 at low elevation by the year 2030. By 2050 the number of snow days at low elevation may drop to 86 days in Jakobshorn, Davos, 68 days in Parsenn/Gotschna, Davos, and 28 days in Scuol. At mid and high elevations, however, the number of snow days will largely remain at or above 100 even by the year 2050: Scuol may drop to 99 snow days at mid elevation but will probably have ~170 snow days at high elevation by 2050.

The number of snowmaking days at low elevations was considerably lower than at high elevations in all ski resorts (Figure 2B). The snowmaking potential was much lower in Braunwald than in the other areas, especially Scuol, because warmer temperatures limit the potential for snowmaking in Braunwald. According to our predictions for 2050, the number of snowmaking days may drop by 50% at low elevation in Parsenn (Davos).

The number of snowmaking days early in the season, when artificial snow is mostly needed, may decrease to a critical limit in the coming decades: snowmaking days at

low elevation in Scuol amount to ~6 days in November today but may drop to 4 by 2050. In December, the number may drop from ~16 to ~11. At the current state of technology, ~10 snowmaking days are required to provide a sufficient base layer of snow for the preparation of a ski run and skiing (Pröbstl 2006). Depending on the snowmaking technology of a given ski area, the required number of snowmaking days may be higher than 10 days (up to 40 days) or even lower (eg 5 days). With advancing technology, it is fair to assume that snowmaking will become more efficient in the future. Nevertheless, our results have shown that the number of snowmaking days may become critical early in the season in some areas at low elevation but not at high elevation.

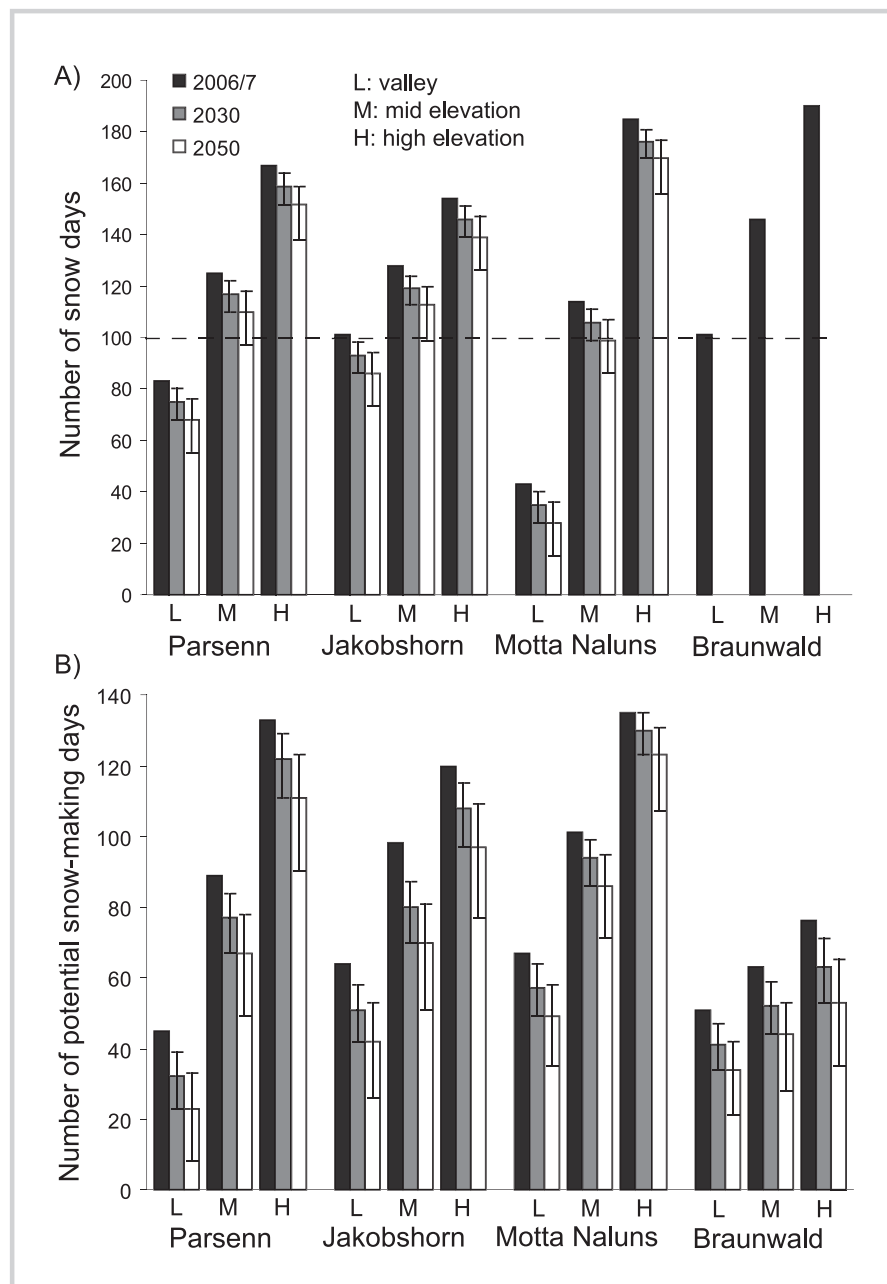
All of the investigated ski areas had sufficient and reliable snow cover for winter sports at mid and high elevations but not at low elevations (<100 snow days; Abegg 1996). In a warmer climate, almost none of the ski areas will have reliable snow conditions at low elevations, but high elevations would not be much affected. Other reports confirm that many ski areas may be threatened in a warmer climate. According to Agrawala (2007), countries with a large proportion of low elevation ski areas will be at the highest risk of losing reliable snow conditions: Germany, for example, could face a 60% decrease in naturally snow-reliable ski areas under a warming scenario of just 1°C. Switzerland, with a high proportion of high elevation ski resorts, would suffer the least of ski nations in the Alps, with a decrease of only ~10% snow-reliable ski areas under that scenario (Agrawala 2007).

Most studies have not included the snowmaking potential in their predictions of snow reliability (but see Steiger and Mayer 2008; Steiger 2010). Our calculations showed that temperatures in the investigated communities were sufficiently cold to provide enough base snow even at low elevations. In a warmer climate, snow production in general would still be possible, but the snowmaking potential would be considerably reduced at low elevations and only be possible under high operation costs (ie below 1500 m; Steiger and Mayer 2008). However, microclimatic conditions need to be carefully considered when snow days or snowmaking days are estimated. Elevation limits can only serve as guidelines for snow conditions, and snowmaking may be possible at lower elevations on shady slopes with a cold microclimate (Pröbstl 2006).

Conclusions and implications

Resource consumption and availability as well as snow cover and snowmaking potential are key issues when investing in snowmaking facilities. Our study showed that the energy consumption in ski resorts was in the lower range of what could be expected from literature values and that the energy consumption was also moderate

FIGURE 2 (A) Number of snow days, (B) number of potential snowmaking days today and according to the scenarios for 2030 and 2050 (median, minimum, and maximum values). Locations are the valley (L), mid (M), and high (H) elevations of the ski resorts of Parsenn and Jakobshorn in Davos, Motta Naluns in Scuol, and Braunwald. The dashed line at 100 snow days indicates the critical threshold according to the 100-day rule (Abegg 1996), above which winter sport tourism in ski resorts is considered economically viable. Snow day scenarios could not be calculated for Braunwald because of gaps in snow data.



compared with other tourism-related activities. Water consumption, however, was in the higher range in relation to what was expected from literature values and also was high compared with other water uses (eg 36% compared with drinking water consumption in 1 community). Natural snow cover was partly critical for winter sports at low elevations around 1200 masl, but uncritical at higher elevations, above ~2000 masl. Snow cover will become even more critical in a warmer climate but will probably still be sufficient above ~2000 masl until 2050.

Snowmaking may become critical at lower elevations in the early months in the season (November and December) due to warmer temperatures that can be expected in the coming decades.

Our study provides straightforward and feasible approaches to assess resource consumption and snow cover that could and should be applied in other winter sport destinations of the Alps and other mountain ranges in the world. Careful consideration of resource consumption and snow cover can foster technical and

economical advances as well as more sustainable development in mountains regions. We propose that, before constructions of new ski pistes and installations of snowmaking facilities, all stakeholders concerned (ie mountain railway companies, communities, tourism organizations, and nature conservation agencies) collaborate as early as possible in the planning process to optimize the sustainability of development and minimize technical failures and ecological impacts. Modern and efficient snowmaking technology should be applied to reduce energy and water consumption. Resource consumption and climatic conditions for snowmaking could be estimated easily by using the approach presented in this study. Potential ecological impacts should also be carefully considered.

Finally, but not least, each tourist destination should determine its regional strength. Based on the importance of ski tourism for the regional economy in Davos (Pütz et

al 2011), resource consumption of ski tourism was not higher than several other activities. The reliable snow cover thus was a regional strength in Davos (probably also in Scuol), and it is probably reasonable to support this regional strength by artificial snowmaking in the next decades. Braunwald clearly has other regional strengths, and it seems adequate to concentrate on these other strengths. Given increasing economic competition and the changing climate, it will be crucial to use specific regional strengths to provide high-quality winter and summer tourism activities.

Snow production at high-altitude destinations such as Davos and Scuol represents a valuable adaptation strategy to enhance winter tourism. Climatic conditions can differ considerably between regions, as our study demonstrates, and investment in snowmaking may not be the appropriate and timely measure in all tourism destinations.

ACKNOWLEDGMENTS

This study was funded by the MAVA foundation. We are grateful to Susanne Kytzia, Christoph Marty, Hansueli Rhyner, and Mathieu Fauve for scientific

collaboration. We also wish to thank all stakeholders from the investigated municipalities of Davos, Scuol, and Braunwald for their support.

REFERENCES

- Abegg B.** 1996. *Klimaänderung und Tourismus: Klimafolgenforschung am Beispiel des Wintertourismus in den Schweizer Alpen*. Zurich, Switzerland: Vdf Hochschulverlag.
- Agrawala S, editor.** 2007. *Climate Change in the European Alps—Adapting Winter Tourism and Natural Hazards Management*. London, United Kingdom: OECD (Organisation of Economic Co-operation and Development) Publishing.
- Burt JW, Rice KJ.** 2009. Not all ski slopes are created equal: Disturbance intensity affects ecosystem properties. *Ecological Applications* 19:2242–2253.
- Elsasser H, Messerli P.** 2001. The vulnerability of the snow industry in the Swiss Alps. *Mountain Research and Development* 21:335–339.
- Fauve M, Rhyner HU.** 2004. Physical description of the snowmaking process using the jet technique and properties of the produced snow. *Snow Engineering* V:215–218.
- Hahn F.** 2004. *Künstliche Beschneigung im Alpenraum: Ein Hintergrundbericht*. alpMedia / Dezember 2004. Schaan, Switzerland: CIPRA International (International Commission for the Protection of the Alps). www.cipra.org/pdfs/454_de/at_download/file; accessed on 21 July 2011.
- Hoffmann VH, Sprengel DC, Ziegler A, Kolb M, Abegg B.** 2009. Determinants of corporate adaptation to climate change in winter tourism: An econometric analysis. *Global Environmental Change-Human and Policy Dimensions* 19:256–264.
- Keller T, Pielmeier C, Rixen C, Gadiant F, Gustafsson D, Staehli M.** 2004. Impact of artificial snow and ski-slope grooming on snowpack properties and soil thermal regime in a sub-alpine ski area. *Annals of Glaciology* 38:314–318.
- Latenser M, Schneebeli M.** 2003. Long-term snow climate trends of the Swiss Alps (1931–99). *International Journal of Climatology* 23:733–750.
- Martin C, Pohl M, Alewell C, Körner C, Rixen C.** 2010. Interrill erosion at disturbed alpine sites: Effects of plant diversity and vegetation cover. *Basic and Applied Ecology* 11:619–626.
- OcCC-Consortium [Organe consultatif sur les changements climatiques].** 2007. *OcCC Report: Klimaänderung und die Schweiz 2050 (OcCC report: Climate change and Switzerland 2050)*. Bern, Switzerland: Organe consultatif sur les changements climatiques—Advisory Body on Climate Change.
- Pohl M, Aliğ D, Körner C, Rixen C.** 2009. Higher plant diversity enhances soil stability in disturbed alpine ecosystems. *Plant and Soil* 324:91–102.
- Pröbstl U.** 2006. *Kunstschnee und Umwelt - Entwicklung und Auswirkungen der technischen Beschneigung*. Bern, Switzerland: Haupt.
- Pütz M, Gallati D, Kytzia S, Elsasser H, Lardelli C, Teich M, Rixen C.** 2011. Winter tourism, climate change, and snow-making: tourists' attitudes and regional economic impacts. *Mountain Research and Development* 31(4), in press; <http://dx.doi.org/10.1659/MRD-JOURNAL-D-11-00039.1>.
- Rhyner J, Bründl M, Etter HJ, Steiniger M, Stöckli U, Stucki T, Zimmerli M, Ammann W.** 2002. Avalanche warning Switzerland and consequences of the avalanche winter 1999. In: Stevens JR, editor. *Proceedings of the International Snow Science Workshop, 30 September–3 October 2002, Penticton, British Columbia*. Victoria, British Columbia: British Columbia Ministry of Transportation. [no page numbers]
- Rixen C, Freppaz M, Stoeckli V, Huovinen C, Huovinen K, Wipf S.** 2008. Altered snow density and chemistry change soil nitrogen mineralization and plant growth. *Arctic Antarctic and Alpine Research* 40:568–575.
- Rixen C, Haeberli W, Stoeckli V.** 2004. Ground temperatures under ski pistes with artificial and natural snow. *Arctic Antarctic and Alpine Research* 36:419–427.
- Rixen C, Stoeckli V, Ammann W.** 2003. Does artificial snow production affect soil and vegetation of ski pistes? A review. *Perspectives in Plant Ecology Evolution and Systematics* 5:219–230.
- Roux-Fouillet P, Wipf S, Rixen C.** 2011. Long-term impacts of ski piste management on alpine vegetation and soils. *Journal of Applied Ecology* 48(4): 906–915.
- Scherrer SC, Appenzeller C, Latenser M.** 2004. Trends in Swiss Alpine snow days: The role of local- and large-scale climate variability. *Geophysical Research Letters* 31. L13215, doi:10.1029/2004GL020255.
- Schneider C, Schönbein J.** 2006. *Klimatologische Analyse der Schneesicherheit und Beschneibbarkeit von Wintersportgebieten in deutschen Mittelgebirgen*. Schriftenreihe Natursport und Ökologie 19. Cologne, Germany: Deutsche Sporthochschule.
- Scott D, McBoyle G, Mills B.** 2003. Climate change and the skiing industry in southern Ontario (Canada): Exploring the importance of snowmaking as a technical adaptation. *Climate Research* 23:171–181.
- Seilbahnen Schweiz.** 2010. *Fakten und Zahlen zur Schweizer Seilbahnbranche*. Ausgabe 2010. Bern, Switzerland: Seilbahnen Schweiz.
- Seilbahnen Schweiz.** 2011. *Saisonverlauf: Schweizweit kein Einbruch trotz schwierigen Rahmenbedingungen*. Bern, Switzerland: Seilbahnen Schweiz.
- SLF [Eidgenössisches Institut für Schnee- und Lawinenforschung].** 2006. *Bilanzierung und Reduktion der CO₂-Emissionen in der Landschaft Davos. Eine Machbarkeitsstudie zum Klimaschutz. Schlussbericht zum KTI-Projekt Nr. 7984.1*. Davos, Switzerland: Eidgenössisches Institut für Schnee- und Lawinenforschung SLF.
- Steiger R.** 2010. The impact of climate change on ski season length and snowmaking requirements in Tyrol, Austria. *Climate Research* 43:251–262.

Steiger R, Mayer M. 2008. Snowmaking and climate change: Future options for snow production in Tyrolean ski resorts. *Mountain Research and Development* 28:292–298.

Teich M, Lardelli C, Bebi P, Gallati D, Kytzia S, Pohl M, Pütz M, Rixen C. 2007. *Klimawandel und Wintertourismus: Ökonomische und ökologische Auswirkungen von technischer Beschneigung*. Birmensdorf, Switzerland: Eidgenössisches Forschungsanstalt für Wald, Schnee und Landschaft WSL.

Walz A, Calonder GP, Hagedorn F, Lardelli C, Lundstrom C, Stoeckli V. 2008. Regional CO₂ budget, countermeasures and reduction aims for the Alpine tourist region of Davos, Switzerland. *Energy Policy* 36:811–820.

Wipf S, Rixen C, Fischer M, Schmid B, Stoeckli V. 2005. Effects of ski piste preparation on alpine vegetation. *Journal of Applied Ecology* 42:306–316.