The impact of global warming on winter tourism and skiing: a regionalised model for Austrian snow conditions

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Abstract Possible climate change will modify snow-cover depth and change the characteristics of winter tourism and skiing districts. Our model describes seasonal snow-cover depth related to altitude in six Alpine climate regions as the best fit of all snow stations. Data cover 30 winter seasons (November to April values) from 1965 to 1995. We modified the data according to a scenario of temperature and precipitation change (2 °C warming, no precipitation change) and achieve a new simulated snow-cover depth. The indicators MARP (mean altitude of resident population) and MASPSL (mean altitude of starting point of ski lifts) serve as references for "critical altitudes" of Austrian districts. A warming implies a reduction of snow in all districts, but the loss is overproportional in lower altitudes. The direction of economic impacts is clear – income losses and adaptation costs – but magnitude and time frames remain uncertain.

Key words Regional climate modelling · Climate impact research · Winter tourism · Skiing · Snow · Rural and regional planning

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Introduction

The authors took part in a project to assess "climate sensitivity of Austrian districts with particular concern for winter tourism" (Breiling et al. 1997) ordered by the Austrian government to assess possible economic losses in connection with winter tourism and skiing. In this paper we focus on our snow model and the resulting implications of a reduced snow-cover depth on winter tourism and skiing. Snow is the most important resource for winter tourism and the physical base of skiing. In the case of Austria, a remarkable industry of winter tourism built up rapidly during the second half of this century. In Alpine rural areas the economic dependence on winter tourism increased steadily. However, there is concern nowadays about whether or not winter tourism can remain a sustainable economy if global warming and climate change continue. How much warming can be tolerated before the industry will come to an end? Additional investments in snow-making equipment and other supportive measures to adapt to warming seem to be necessary to help the skiing industry, but not all areas are suited to this adaptation, due to either financial or ecological reasons.

We have already discussed this problem (Breiling 1993; Breiling and Charamza 1994) and rooted our assumptions about the effects of warming on snow cover in an empirical model of Austria related to observations during 1851 to 1950 (Aulitzky 1985). This study gave a good overview of Austria on a national scale, but did not consider variations inside Austria. In addition, the reference period of this model seems to be outdated today. Therefore we wanted to elaborate the effects based on recent data. A co-operation agreement with the Austrian Central Institute for Meteorology and Geodynamics (ZAMG 1997) enabled us to go further and to construct an Austrian snow model by ourselves.

The problem of reduced snow cover for winter tourism was mentioned in the national climate report of Austria (Austrian Federal Government 1994). Statements like "Mountain economies may be undermined. A 1 °C rise in average temperatures combined with winter drought may reduce the duration of Alpine snow cover by 50% at 1500 m, with enormous consequences for the skiing industry" could not be quantified at the time the report was written, because a snow model covering all of Austria was not available at that time, and tests of various scenarios could not be made.

Abegg (1996) made a comparative overview of snow models designed for the same purpose to assess the likely losses of snow for winter tourism under warming, but for different areas of the world. The models cover Switzerland (e.g. Föhn 1991; Bultot et al. 1994), Canada (Crowe 1977; modified by McBoyle and Wall 1987, 1992; B. Abegg, personal communication) and Australia (Galloway 1988; modified by Haylock et al. 1994). These models are valid for a particular place or a smaller region. All models lead to the conclusion that a warming will be accompanied by snow losses for winter tourism, but the reduction of the winter tourism and skiing season is less severe in high altitudes. The selection of the warming scenario (in some cases combined with a precipitation change scenario) will determine the magnitude of snow loss. In some cases, the snow loss was evaluated as an economic loss later on.

In addition to the previously mentioned small-scale models, a regional model was developed in the case of southern Australia (Whetton et al. 1996). The size of territory is thereby comparable to Austria. This model uses monthly temperature and precipitation stations as well as the daily standard deviation relative to the monthly mean. It is particularly useful if there are no or few snow stations but plenty of temperature and precipitation stations available.

In the following paper, we first discuss the region and data we had at our disposal; second, we provide a description of the snow model; third, we show how we used the model and what results we obtained based on a scenario of 2 °C warming. Finally, we discuss these results.

Methods

Region description

All of Austria is the region of concern for this study. Regional climate information was collected from three sources: temperature, precipitation and snow-cover depth data. Socio-economic data originated from the population census 1991 (Austrian Central Statistical Office 1992), tourism statistics also from the Austrian Central Statistical Office (1992, 1996) and transport statistics from the Austrian Ministry of Transport (1993). We obtained monthly climate time series data from 1965 to 1995 related to the winter months November to April in accordance with the Austrian tourism statistics.

A classification of ten climate regions was prepared for us by Böhm (ZAMG 1997) under the condition of using the given administrative borders of 85 Austrian districts (Bezirke). In each of the climate regions, similar climate behaviour can be expected according to the altitude. This is particularly true for the temperature data; however, for the precipitation and snow-cover data, more detailed data should be given since these factors are more dependent on the local situation. In Table 1 we list the climate regions. In Fig. 1 we show their position within Austria, together with the position of the temperature stations. In Figs. 2 and 3 we show the division of each climate region into its

Table 1
Temperature stations according to climate regions and altitude

Temperature station	Climate region	Altitude (m)
Bürs	North Alpine West (NAW)	567
Langen/Arlberg	North Alpine West (NAW)	1218
Innsbruck-Universität	Inner Alpine West (IAW)	577
St. Anton/Arlberg	Inner Alpine West (IAW)	1280
Zeltweg	Inner Alpine East North (IAEN)	669
Stolzalpe	Inner Alpine East North (IAEN)	1305
Sonnblick	Inner Alpine East North (IAEN)	3106
Lienz	Inner Alpine East South (IAES)	668
Villacher Alpe	Inner Alpine East South (IAES)	2140
Schöckl	East Alpine Edge (EAE)	1436
Mondsee	North Alpine East (NAE)	491
Feuerkogel	North Alpine East (NAE)	1618
Krippenstein	North Alpine East (NAE)	2050

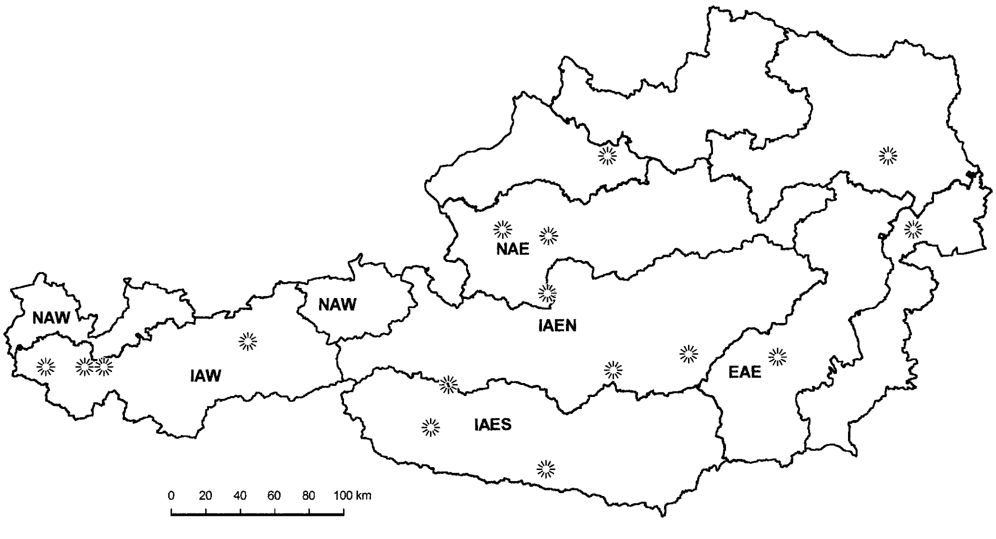

Fig. 1
Position of climate regions with 16 temperature stations

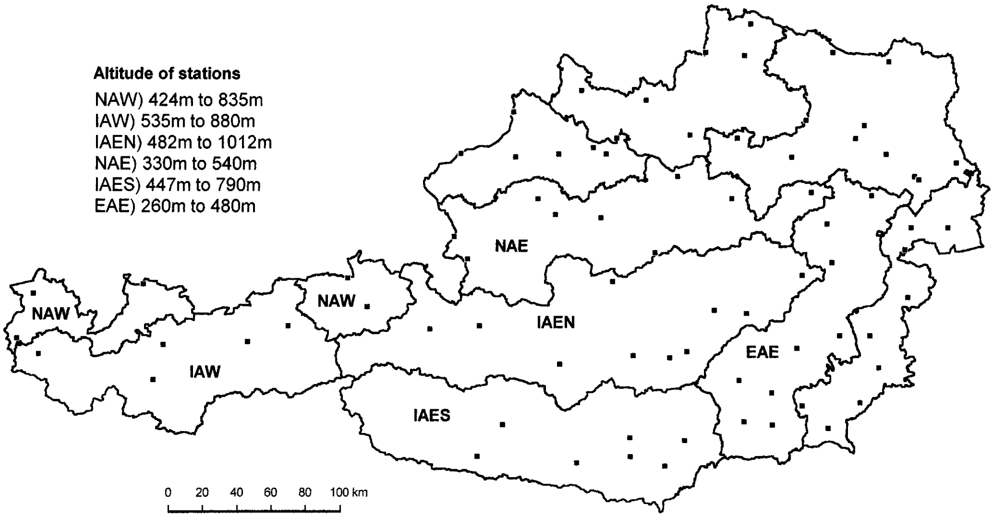

Fig. 2
Position of precipitation stations

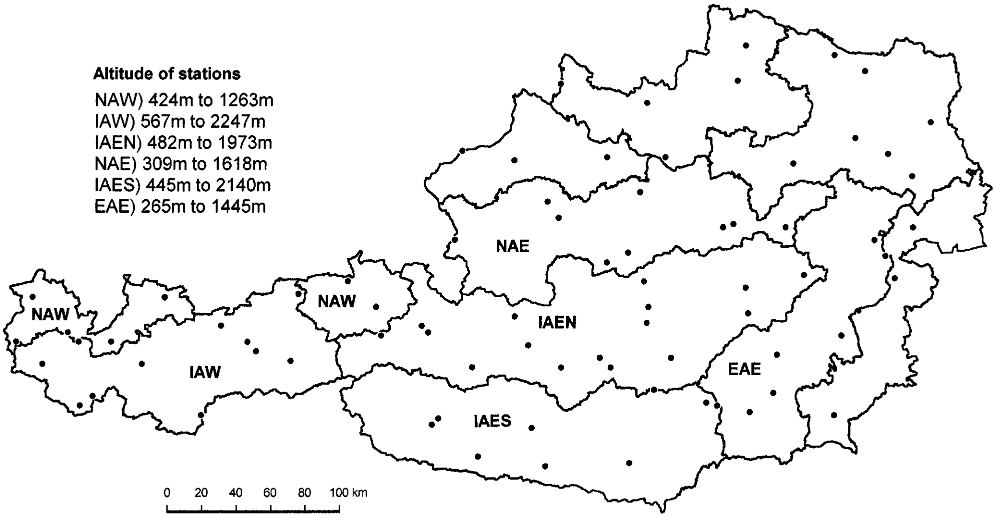

Fig. 3
Position of snow stations

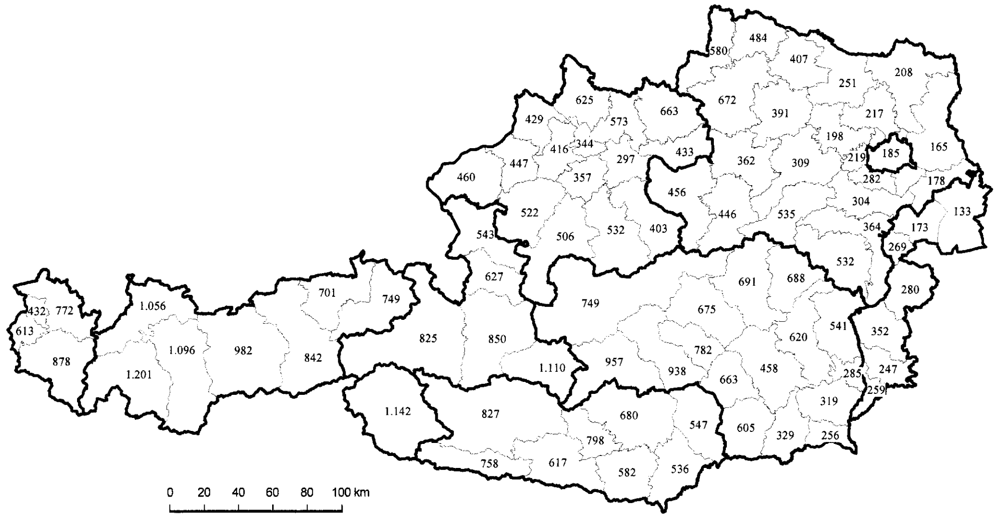

Fig. 4
MARP of Austrian districts (85 values)

districts, together with the position of the precipitation stations (Fig. 2) and the snow stations (Fig. 3). We show the administrative division into federal counties and 85 districts in Figs. 4 and 5. We considered only the six Alpine climate regions for our modelling approach. We excluded three climate regions because they cover low-

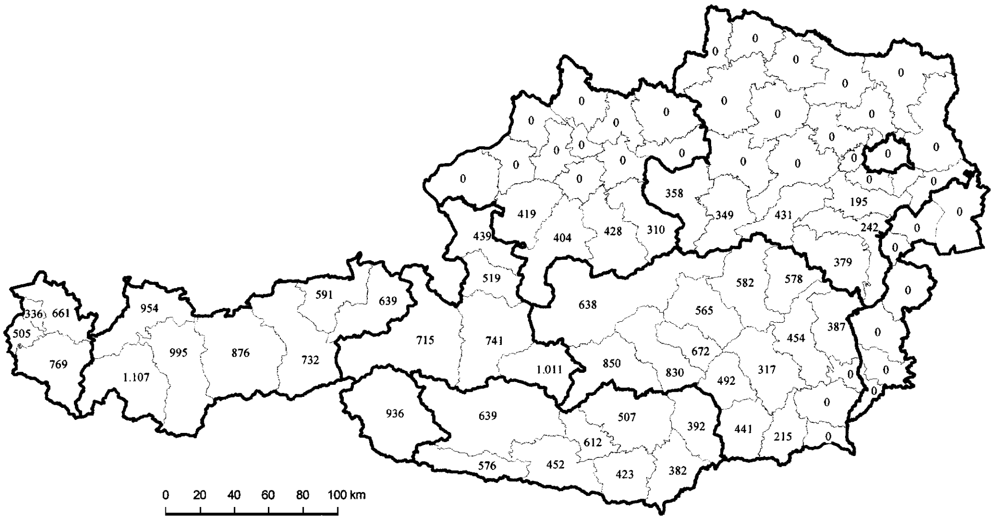

Fig. 5
MARP$_{(NEW)}$ at a warming of 2 °C (48 values)

lying territory as well as the most northern Austrian climate region – reaching a maximum altitude of 1400 m – because we have no temperature station data for this region.

Data description

Temperature

The average mean day-temperature data (in 0.1 °C) were available from 1965 to 1995 (November to April) and converted to monthly mean values for the stations described in Table 1.

Precipitation

Figure 2 shows an overview of the precipitation stations we used. For almost all Austrian districts (Bezirke), we obtained a representative precipitation station. The ratio of relative monthly precipitation to the seasonal precipitation (average of sum November to April) from 1965 to 1995 was provided in this case.

Snow

The snow stations we had at our disposal are depicted in Fig. 3. We obtained the amount of monthly snow-cover thickness (sum of all days with snow cover in centimetres and the number of days with snow cover) from the years 1965–1995 (all months). There is no information concerning snow quality such as water equivalent or snow density.

Snow model description

The snow model covers three steps. In the first step we model the relation of snow to temperature and precipitation at each snow station. In the second step we model the best fit of all stations to a regional dependence of snow cover and altitude. In the third step we use a scenario for temperature and precipitation change and compute a new snow-cover depth. Then we look at what altitude we find this snow-cover depth today.

Step 1: modelling the relation of snow to temperature and precipitation

Variables of the model are as follows:

1. $T_{(U,V,W)}$ – temperature (monthly mean in 0.1 °C) in the stations U, V, W.
2. $P_{(Z)}$ – relative precipitation (monthly value in percent of 30 years average of seasonal precipitation) at station Z.
3. $S_{(X)}$ – snow-cover depth (monthly sum of daily snow-cover depth in centimetres) at station X.

U is the name of the first temperature measurement station at altitude 1 (in all six climate regions); V is the name of the second temperature measurement station at altitude 2 (in five climate regions); W is the name of the third temperature measurement station at altitude 3 (in two climate regions); Z is the name of the representative district or closest precipitation measurement station; X is the name of the snow measurement station (between six and 17 stations per climate region).

Each of the snow stations was looked at in relation to the climate region and district. The snow-cover thickness at every station is related to the temperature of the relevant climate region and to the precipitation. The precipitation is measured at the precipitation station which is in the same district as the snow station. These relations can be understood from Figs. 1–3. For example: snow cover at the station RADSTADT is related to the district St. Johann im Pongau in the climate region IAEN (see Table 2). Hence, the temperature stations in IAEN – Zeltweg (669 m), Stolzalpe (1305 m) and Sonnblick (3106 m) – are considered, and the precipitation station in the district St. Johann im Pongau (station St. Johann im Pongau) is included in the model. By considering the linear approximation of the unknown functional relation, we can express the model in the following way:

$$S_{(X)} = t_1 * T_{(U)} + t_2 * T_{(V)} + t_3 * T_{(W)} + p * P_{(Z)} + \text{const} + \text{error}. \qquad (1)$$

The coefficients of the model were estimated by using the backward elimination in the multiple regression modelling approach: t_1 is a parameter of the influence of station U; t_2 is a parameter of the influence of station V; $t_3$is a parameter of the influence of station W; p is a parameter of the influence of station Z.

From the results of the individual models for each snow station (Tables 2–7) we can see that multiple correlation coefficient (*R*) is around 0.6; p only in some rare situations is it less than 0.5 and also rarely is it higher than 0.7. The approximate standard error of the models is 600 cm. This amount is for 1 month of cumulative snow cover, i.e. we can expect an error for 1 day of around 20 cm in our estimates.

The temperature coefficients are almost all negative. This is quite clear, since there is a negative correlation between snow cover and temperature. However, in some cases and especially at higher altitudes, positive coefficients can be observed. Take the example of Patscherkofel (Table 5). There is a coefficient of 54.22 for the lower temperature station which tells us that with 1 °C of warming there is 542 cm more snow cover. On

Table 2
IAEN region

Measurement station	Sonnblick t_1	Zeltweg t_2	Stolzalpe t_3	Precipitation p	Constant	*R*	Altitude (m) H
Admont	−6.5	−2.8		6.5	−405	0.68	660
Aflenz	−7.1	−2.3		4.9	−474	0.64	780
Badgastein	−3.6	−7.5		6.5	−297.2	0.61	1100
Bruck an der Mur	−2.2	−1.4			−117.2	0.3	482
Hohentauern	−28.5		7.8		−1822.2	0.46	1265
Judenburg	−2.9	−1.9		3.7	−188.2	0.62	730
Muerzzuschlag	−7.1	−1.9		4.7	−466.8	0.63	755
Noreia	−2.45	−1.8		4	−143.1	0.62	1060
Obertauern	−90.7		56.3		−5146.1	0.42	1740
Pass Thurn	−19.8	−7.3	11.4	9.9	−1520.13	0.48	1200
Radstadt	−18.9	−9	14.2	6.3	−1394.4	0.69	858
Schmittenhoehe	−83.5		57.7	20.1	−6003	0.65	1973
Schoeder	−6.6	−2.2			−296	0.58	900
St. Johann am Tauern	−12.1	−1.6			−720.3	0.7	1050
Stolzalpe	−6.7		−4.8		−145.6	0.61	1305
Tamsweg	−4.3	−3.3		7.34	−212.4	0.63	1012
Zell am See	−11.7	−7	9.2	6.8	−904.4	0.64	766

Table 3
NAE region

Measurement station	Krippenstein t_1	Mondsee t_2	Feuerkogel t_3	Precipitation p	Constant	*R*	Altitude (m) H
Feuerkogel	−55.6	32			−453.8	0.5	1618
Gmunden	−5.5	−2.8	5.2	1.8	5.66	0.68	426
Huttererboeden	−39.3	16.7			−44.1	0.5	1370
Lackenhof			−24.1		979.4	0.34	835
Lunz	−10.8	−3.7		7.2	79.9	0.69	615
Salzburg	−5.06	−2.4	4.6	2.1	−10.2	0.74	434
St.Aegyd am Neuwalde	−7.03	−4.3		8.7	112.3	0.74	490
Steyr	−2.5	−4.8	4.2		37.2	0.62	309
Windischgarsten	−5.8	−4.5		7.9	133.1	0.71	596

Table 4
NAW region

Measurement station	Buers t_1	Langen t_2	Precipitation p	Constant	*R*	Altitude (m) H
Bregenz		−3.37	2.54	70.7	0.65	424
Feldkirch	−0.58	−2.2	3.2	48.6	0.7	440
Holzgau	11.1	−32.6		956.6	0.64	1100
Kitzbuehel		−13.13	−6.9	676	0.63	763
Kufstein		−9.7		366	0.64	495
Reutte in Tirol	4.9	−19.8		549.6	0.66	870
Schoppernau	16.7	−40			0.6	835
Schroecken	47.82	−82.1		2130.4	0.6	1263

Table 5
IAW region

Measurement station	Innsbruck t_1	St. Anton t_2	Precipitation p	Constant	*R*	Altitude (m) H
Buers bei Bludenz		−6.58	5.23	128.13	0.63	567
Galtuer	57.5	−77	57.47	−963.43	0.59	1648
Innsbruck		−3.76	4.13	29.26	0.61	578
Landeck		−3.9		116.22	0.52	785
Lanersbach	15.05	−28.07	5.3	−47.23	0.69	1290
Obergurgel	46.66	−54.01		−314.54	0.45	1938
Obervermunt	100.3	−112.11	36.73	−1674.43	0.59	2040
Patscherkofel	54.22	−61.64	44.3	−914.74	0.48	2247
Seefeld in Tirol	39.02	−57.35	21.99	−1020.13	0.63	1200
Steinberg am Rofan	31.46	−47.71	16.4	−778.9	0.62	1000

Table 6
EAE region

Measurement station	Schoeckl t_1	Precipitation p	Constant	*R*	Altitude (m) H
Graz-Flughafen	−3.62	3.42	−0.75	0.64	340
Hartberg	−3.1	2.43	1.11	0.57	350
Hebalpe	−15.4	12.9	496.9	0.56	1440
Schoeckl	−14.9	15.5	296.8	0.58	1445
Stainz	−3.9	3.03	11.4	0.63	340
Wr. Neustadt	−1.55		25.55	0.59	265

Table 7
IAES region

Measurement station	Lienz t_1	Villacher Alpe t_2	Precipitation p	Constant	*R*	Altitude (m) H
Iselsberg	−2.16	−11.21		176.9	0.54	1200
Klagenfurt	−1.4	−4.87		−11.57	0.68	455
Lienz	−3.66	−7.09		171.56	0.57	659
Millstatt		−6.73		−102.13	0.54	575
Preitenegg		−12.63	4.45	−220.21	0.69	1055
Reisach im Giltal	−3.6	−13.07	6.84	2.92	0.65	646
Villacheralpe	14.89	−23	12.6	363.87	0.5	2140

the other hand, the coefficient −61.64 for the second temperature station tells us that with 1 °C of warming we will get 616 cm less monthly snow cover. On average, 1 °C of warming will cause 74 cm loss in snow cover per month. This effect can be explained by the fact that snow is affected not only by the temperature itself but also by the temperature difference between the upper and lower stations.

Step 2: modelling the relation between altitude and snow cover

In the next step we show how the altitude is dependent on the snow cover. When making a first picture of dependency we could see that with increasing snow-cover depth, the altitude also increases (but more steeply than a linear curve) and the variance of observations becomes larger. To avoid this unpleasant fact and to be more correct in our estimations we propose using a logarithmic transformation for both of the variables. Then we can use a linear regression model of the following form:

$$\log H_{(X)} = a * \log S_{seas(X)} + const + error. \qquad (2)$$

where $S_{seas(X)}$ is seasonal snow-cover depth (sum of daily snow-cover depth from 1 November to 30 April in centimetres); $H_{(X)}$ is altitude (in metres); X is the name of the snow measurement station (between 6 and 17 stations per climate region) and a is a parameter of the influence of snow-cover depth.

We used the average monthly snow cover over the last 30 years. We sum up these averages for all the months of the winter season (November to April) and get the seasonal snow-cover depth for every station. We take these numbers together with the altitudes of these stations and estimate the relation for all the climate regions. The results are given in Tables 8 and 9.

We observe similar behaviour in the regions NAE, IAEN, NAW, IAW and the second group created with EAE and IAES. In order to decrease the statistical error we combine the similar regions, taking the final estimates for two large climate regions from Table 9. The results of these equations are shown in Figs. 6 and 7.

Step 3: estimation of how the Alpine regions will shift altitude with a 2 C warming

Finally, we show the results of what will happen after 2 °C of warming (or another warming scenario) and no precipitation change (or another precipitation scenario) according to the following relations:

$$S_{\mathrm{Old}(X)} = t_1 * T_{(U)} + t_2 * T_{(V)} + t_3 * T_{(W)} + p * P_{(Z)} + \mathrm{const} + \mathrm{error} \tag{3}$$

Now we add 2 °C of warming (20 units as temperature is measured in 0.1 °C) and we obtain the following equation:

$$S_{\mathrm{New}(X)} = t_1 * (T_{(U)} + 20) + t_2 * (T_{(V)} + 20) + t_3 * (T_{(W)} + 20) + p * P_{(Z)} + \mathrm{const} + \mathrm{error} \tag{4}$$

From the above given relations we obtain:

$$S_{\mathrm{New}(X)} = S_{\mathrm{Old}(X)} + t_1 * 20 + t_2 * 20 + t_3 * 20 \tag{5}$$

where $T_{(U,V,W)}$ is temperature (monthly mean in 0.1 °C) at stations U, V, W; $P_{(Z)}$ is relative amount of precipitation (in percent of 30 years seasonal average) at station Z; $S_{\mathrm{Old}(X)}$ is old snow-cover depth (observed monthly aggregated sum of daily snow-cover thickness in centimetres) at station X; and $S_{\mathrm{New}(X)}$ is new snow-cover depth (simulated monthly aggregated sum of daily snow-cover thickness in centimetres) at station X.

Table 8

Results of linear regression models in six climate regions [*a* parameter of regional fit (inclination of linear regression)]

Region	*a*	Constant	*R*
NAE	0.28	1.9	0.8
IAEN	0.31	1.9	0.84
NAW	0.32	1.77	0.94
IAW	0.41	1.56	0.93
EAE	0.62	0.85	0.99
IAES	0.61	0.8	0.86

Table 9

Results of linear regression models in two larger regions [*a* parameter of regional fit (inclination of linear regression)]

Region	*a*	Constant	*R*
NAE, IAEN, NAW, IAW	0.35	1.75	0.84
EAE, IAES	0.58	0.95	0.94

In our estimates of the new snow-cover situation we did not assume precipitation change. However, if we consider a 10% precipitation increase it would change the value of $P_{(Z)}$ in Eq. (4) to ($P_{(Z)}$ + $P_{(Z)}/10$). This will give an estimate of the new snow cover in Eq. (5) depending also

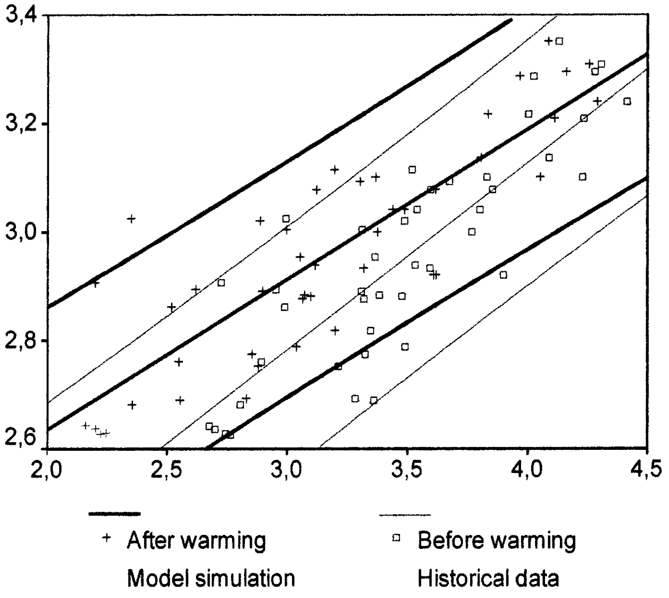

Fig. 6

Relation between log altitude and log snow cover in IAEN, IAW, NAW and NAE

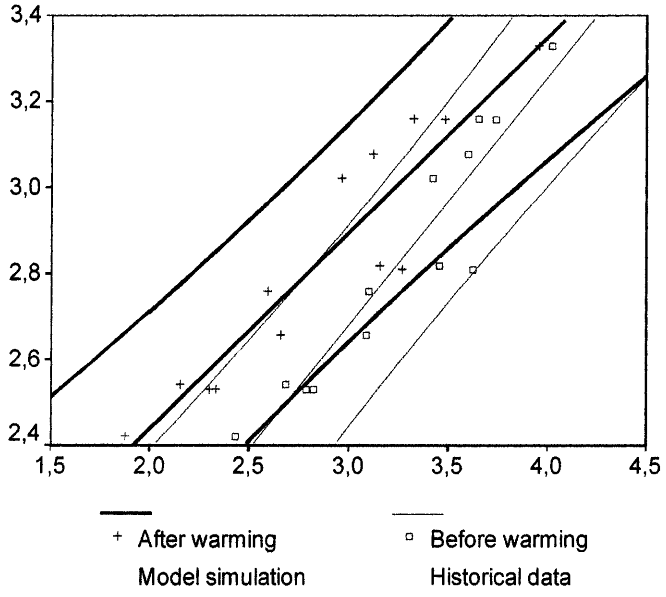

Fig. 7

Relation between log altitude and log snow cover in IAES and EAE on the change in amount of precipitation. However, we will not give results of the consequences of the precipitation in this paper mainly for the following two reasons: (1) it is not clear what will happen to precipitation after the global warming impact takes effect; and (2) the precipitation data were not available for this study in the same quality as the temperature data. hence the estimate of the snow cover could have a much larger error variation. However, generally from the Eqs. (3) and (4) and the estimates of parameters "p" in these equations (all are positive) it follows that the positive change in amount of precipitation will cause an increase in snow if the temperature is cold enough, and inversely a decrease in the amount of precipitation will cause a decrease in snow. A more detailed study concerning the interactions between snow, precipitation and temperature, mainly around the 0 °C temperature, could be carried out by using more detailed data. Due to the change in seasonal snow-cover depth, which is related to temperature or precipitation change, we will get new estimates of parameters in Eq. (2). Again, we look for the best fit of the dependence of the new altitude and snow-cover depth in each region and thereby we obtain the results for 2 °C warming (Table 10). As in step 2, we combine the climate regions and get the models for the two large-scale climate regions (Table 11).

Using this modelling approach we obtain estimates for the change in snow cover after different global warming scenarios. Taking a particular district, we can estimate its average snow-cover depth under the new situation at any given altitude of the district. According to the amount of snow, we can determine the present altitude of the district. We then determine the new altitude of the district in which it will appear after the warming outcome. We can anticipate that the current situation in the lower altitude will be the future situation in the higher altitude of the same district.

Table 10
Snow-cover model in the case of 2 °C warming for six climate regions [*a* parameter of regional fit (inclination of linear regression)]

Region	*a*	Constant	*R*
NAE	0.26	2.04	0.83
IAEN	0.24	2.22	0.76
NAW	0.28	2	0.93
IAW	0.37	1.79	0.94
EAE	0.52	1.29	0.99
IAES	0.48	1.37	0.83

Table 11
Snow-cover model in the case of 2 °C warming in two larger regions [*a* parameter of regional fit (inclination of linear regression)]

Region	*a*	Constant	*R*
NAE IAEN, NAW, IAW	0.3	1.97	0.84
EAE, IAES	0.49	1.35	0.94

The results of all the equations for large-scale regions are shown in Figs. 6 and 7. The square points show the situation before warming, i.e. the current situation of snow at the measurement stations. The middle weak line is the least squares fit of the data, explaining the relation between the snow cover and altitude. The upper and lower weak lines are the 95% confidence limits for this least squares fit. The bold lines have the same meaning for the situation after the 2 °C warming. Cross points refer to snow data predicted by the model.

If we take today's situation of 1000 m altitude, we see that the snow cover is 3728 cm (weak middle line). After 2 °C warming at 1000 m, we get 2712 cm seasonal snow depth (using the bold middle line). The corresponding altitude to this cumulative snow cover in the current situation is 895 m (using the weak middle line). So we get approximately a 105-m decrease of altitude at the level of 1000 m. We also observe an approximately 25% decrease in cumulative snow cover. This is true for the regions IAEN, IAW, NAW, NAE (Fig. 6). For the regions IAES and EAE (Fig. 7) we can follow the same method.

At 1000-m altitude, we see that the snow cover will shrink from 3424 cm (weak middle line) to 2330 cm (bold middle line) seasonal snow depth. Again, we can relate 2330 cm to the current altitude, getting 800 m of altitude using the weak middle line again.

Results

Use of the snow model: present and future relationship between winter tourism, skiing, altitude and snow

Current pattern of winter tourism and skiing at critical altitudes

There is no homogenous picture of Austrian winter tourism and skiing. In general, the resorts in the west are situated higher up, with more tourists – mainly from abroad – and a longer tourist season. The districts in the east are closer to large cities, with easier access for the majority of the Austrian population, but with a shorter winter season and many visitors coming for just 1 day.

All Austrian districts are situated between 113 and 3797 m altitude. The flat and populated districts in the north and east of Austria cannot offer snow-based winter tourism. We consider 400 m of altitude as a minimum for profitable winter tourism. The high Alpine zone with mountain peaks is excluded from winter tourism, either for safety reasons or due to unpleasant climate conditions. Snow conditions between 400 and 2800 m altitude are relevant to business success.

Each winter tourist district has a specific altitude range which we can divide into low, medium and high altitude. In the low altitudes of the range we find the majority of residential areas and most tourists stay overnight in this altitude. Here, one can practise cross-country skiing, sledge riding and enjoy the village atmosphere. Medium altitudes are those where ski centres start and high altitudes are where ski centres end. In particular, we are interested in the low and the medium altitudes of the range, because they are the most critical ones. If there is sufficient snow, even high altitudes will have enough snow. Cross-country skiing and sledge riding require some 10 cm of snow cover, alpine skiing and snowboarding demand some 30 cm of snow or even more above the timber line in rocky terrain.

Indicator mean altitude of residential population (MARP). We used the indicator "mean altitude of residential population" (MARP). This indicator covers every Austrian district (see Fig. 4). We aggregated height and area information of the 2355 Austrian communities (OESTAT 1993) together with 85 Austrian districts and calculated MARP of the district according to the altitudes of the communal main places weighted by the areas of the communities. In flat districts the altitudes of communal main places are close together, while in mountainous districts there can be large variations. The highest Austrian community is situated above 1700 m, while the highest district MARP value does not exceed 1150 m. We take the altitude of indicator MARP as a model input and compute the average seasonal snow-cover depth during 1965 to 1995 and at 2 °C warming. As the final result of our 2 °C warming scenario we get a new value of altitude $\mathrm{MARP}_{(\mathrm{NEW})}$ (see Fig. 5) for 48 districts.

The new snow cover is between 47 and 79% of the old snow cover. We excluded the lowest districts of Austria, where the reduction in snow should be considerably higher. The reduction in number of skiing days is proportionally higher than the reduction in snow-cover depth because of the initial minimum requirement of snow cover. The corresponding reduction in altitudes is from 305–1201 m to 195 m–1107 m in the future.

Indicator mean altitude of starting points of ski lifts (MASPSL). To determine the medium altitudes of the range we used the indicator "mean altitude of starting points of ski lifts" (MASPSL). In our calculations we considered all available Austrian ski lifts. In total, there are 3415 ski lifts registered in the statistical yearbook of the Austrian Ministry of Transport (1993). Altitude references are given for two kinds of lifts: small cable lifts (Kleinseilbahn) and main cable lifts (Hauptseilbahn). The most common kind of pull lifts (Schlepplift) are not registered according to altitude. As there are more districts with small cable lifts (36 districts and 490 MASPSL values) than with main cable lifts (26 districts and 250 MASPSL values), we chose the first kind of lift as our indicator. The MASPSL values are in the range 596 to 1889 m. Based on the number of small cable lifts in each district (from 1 to 55), we calculated MASPSL as the mean of all small cable lifts in the district. One should be careful with local interpretations if there is only one or a few lifts and should search for additional information. An example is the district Hermagor, which has only one lift in this category situated lower than the MARP value. For 34 districts we modelled the altitude of $\mathrm{MASPSL}_{(\mathrm{NEW})}$. The new snow cover will be 60–99% of the old snow cover. The range of altitude (689–1889 m) will decrease to 515–1879 m.

Implications of results for winter tourism and skiing

As we gain altitude, the snow is less vulnerable to warming. This is consistent with the results of other snow models we have mentioned in the "Introduction". At about 2000-m altitude a warming of 2 °C does not seem problematic concerning the amount of snow. We could even speculate about a possible increase in snow-cover depth and a "turning point" in a certain altitude above 2247 m, our highest snow station . In low altitudes the seasonal snow-cover depth will be reduced by a large percentage. Warming is further related to a stretching of the current altitude range. The stretching is larger at indicator MASPSL with 5.2% than at indicator MARP with 1.8%.

The 30 seasonal temperature means vary up to 3.7 °C. At 2 °C warming, almost half of the annual values will remain in the range of the 1965 to 1995 values. Thus, we will occasionally find good winter seasons, but we cannot count on a regular appearance like we could during 1965 and 1995. It is the frequency of good and bad seasons that will determine the future of resorts.

We obtained some hints concerning the magnitude of change by analysing the variability of decade means. The second decade (1975–1985) was the coldest one and the third decade (1985–1995) was the warmest one. On average, a season of the third decade was 0.8 °C warmer than a season of the second decade. The first decade (1965–1975) was 0.2 °C warmer than the second one and 0.6 °C colder than the third one.

The development of Austrian winter tourism and skiing infrastructure during the last 30 years was in accordance with the decade temperature variation. The period 1965–1985 was a relatively cold one. At that time an expansion of ski lifts occurred. The period 1985–1995 was considerably warmer. Most winter resorts had snow problems during this time, many of them serious ones. Artificial snow making became popular. Just 0.8 °C warming necessitated strong adaptation and the impact of 2 °C warming could leave only a few locations suitable for winter tourism and skiing restricted to high altitudes.

Discussion

Uncertainty concerning the economic impacts and time frames of warming

In a supporting analysis, ZAMG (1997) elaborated monthly trends of 162 Austrian temperature stations. Frequent temperature inversions during December and February make it difficult to distinguish between low, medium and high resorts and for this reason snow conditions can be similar in a range of several hundred metres. Each month shows a characteristic pattern that becomes indistinct in the seasonal picture. In terms of tourist revenues, February is the most important month with the highest monthly revenue. Particular weeks like Christmas and Easter are most important for business success, but are not highlighted in our current approach. A warming of 2 °C in combination with an offset of the inversion effect could lead to an overproportionally strong impact on skiing resorts in medium altitudes at economically most important times of the year.

It is further conceivable that warming rates at high, medium and low altitudes will be different, analogous to IPCC (Intergovernmental Panel on Climatic Change) assumptions that warming rates will be different at higher and lower latitudes. If warming at high altitudes turns out to be stronger than at low altitudes, the impact of warming might be worse than what we have anticipated in this paper, and even high-altitude resorts will have trouble long before expected here.

At present, we know the direction of economic impacts of warming if factors other than climate remain stable: low altitude ski resorts in the neighborhood of cities will disappear first; access to suitable resorts will become more difficult and expensive; the number of 1-day visitors will sharply decline. However, we cannot say what level of warming is necessary to ruin resorts economically. An adaptation with artificial snow making seems – at least partly – possible, but it might not be economically feasible. Attractiveness of the resort, disposable income of tourists and the availability of alternative destinations overseas – not based on winter tourism – are other points to be considered in a cost–benefit calculation and may limit the option to adapt to warming.

It is not possible to say when our assumed warming is likely to occur. The IPCC scenarios (IPCC 1996) based on annual means propose no particular date for 2 °C warming of the global mean temperature. With a doubling of CO_2 concentration in the atmosphere, which is anticipated in the second half of the coming century, the global mean temperature shall rise between 1 and 3.5 °C.

Our value is based on the average mean temperature of 6 months and on Austrian temperature stations (see Fig. 1). Therefore, it would only be congruent with the IPCC value if the warming of the summer half-year (May to October) was the same as the winter half-year (November to April) and if the warming in Austria was the same as the global warming. This is not the case. The IPCC (1996) considers that warming is higher in the northern hemisphere and during winter. Therefore our scenario of 2 °C warming should be reached much earlier than the scenario of 2 °C warming of the global mean temperature.

Outlook

We consider several possible improvements for regional snow modelling. We used relative values for precipitation. The real values would enable us to estimate snow cover more precisely. More temperature stations will give better results in a statistical model. We could further use the Australian snow model to discover the length of season (Whetton et al. 1996) and combine it with snow-cover depth data.

We would like to calculate a full range of scenarios and compare it with our reference scenario of 2 °C and 0% precipitation change which we have presented here. Having a set of scenarios, we would be able to determine the sensitivity of winter tourism and skiing or the “critical warming” in a district in relation to its altitude range. We would like to compare the observed problems in snow-cover depth during the decade 1985–1995 with the situation two decades before and build our snow model according to two periods: a warmer and a colder one. Based on this analysis, we expect to get a useful calibration for our indicator values MARP and MASPSL and to estimate climate impacts more precisely.

Furthermore, if we had access to daily data, we could calculate our snow model more accurately. Such a model perhaps not only would be useful to assess climate change situations in a long-term perspective, but also could be used to predict snow situations in the near future with increased practical relevance for ski operators and tourists.

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