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Snow Cover Modelling as a Tool for Climate Change Assessment in a Swiss Alpine Catchment

D. Gellens*, K. Barbieux*, B. Schädler, E. Roulin*, H. Aschwanden**, and F. Gellens-Meulenberghs***

*Royal Met. Institute of Belgium, B-1180, Brussels, Belgium
**Swiss National Hydrological and Geological Survey, CH-3003, Berne, Switzerland

The daily step conceptual hydrological model IRMB (Integrated Runoff Model – Bultot) is further developed by the addition of a module designed to calculate the energy balance in high spatial resolution in a basin with very distinct relief and to simulate the surface related processes in a distributed way. The basin considered, the Landquart basin (area at the outlet Felsenbach : 616 km^2, mean altitude 1,800 m a.s.l.), situated in the eastern part of the Swiss Alps, has been subdivided with GIS-methodology into 2,704 homogeneous units (altitude and aspect). Among all other water balance elements snow water equivalent is simulated for a period of 15 years. Climate scenarios for the 21st century from three climate change experiments are used in order to estimate the change in the distribution of the snow water equivalent in the basin. Finally, impacts on the potentiality of Alpine skiing activities in this region are discussed. It shows that the areas where profitability minimum requirements is reached from the point of view of snow amounts, are decreasing, because this limit would go up by about 250 m from 1,500 to 1,750 m a.s.l. for the 2020 scenario. Statistical tests indicate, however, that this change is still within the natural variability observed in the reference period 1981-1995.

Introduction

In Alpine environment snow accumulation and melting have decisive influence on the hydrological regime and in consequence on low water and flood generation. Water management of small and large basins depends on changes in the hydrological regimes due to climatic variations: in small scale for the management of alpine

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reservoirs for hydropower production, in large scale for the water resources management of large rivers that are fed by melting water during the dry season in summer and autumn. In addition snow cover development is economically very important for winter tourism in Switzerland (Abegg 1996).

In the framework of an international research program dealing with the river Rhine basin (Grabs 1997), snow cover development in the Alpine region has been modeled in detail in four hydrological basins for the same climate change scenarios. Two different model approaches have been used: in the three basins Murg, Ergolz and Broye, situated in the Swiss Pre-Alps with a moderate relief and medium range altitudes between 400 and 1,500 m a.s.l., the daily step semi-distributed conceptual IRMB model (Bultot *et al.* 1994; Gellens and Schädler 1996; Grabs 1997) has been used.

For the Landquart basin, a real Alpine basin with very distinct relief, steep slopes and altitudes up to 3,250 m a.s.l., an additional module to the IRMB model has been developed. This new module is designed to calculate the energy balance in high spatial resolution, based on the radiative net flux (Grabs 1997). First results have been presented at the Second International Conference on Climate and Water (Schädler *et al.* 1998) and have been reviewed to improve the IR balance assessment procedure in the energy budget.

In recent years other studies referring to climate change and its impact on snow and glaciers and on their consequence for winter tourism economy have been published. Ehrler (1998) uses the SRM (Snowmelt Runoff Model, Martinec 1975) for the simulation of runoff in the neighboring upper Rhine basin. Compared to the SRM, which simulates snow water equivalent only indirectly and in a very lumped approach for elevation belts of 500 m, IRMB simulates snow cover taking into account the entire energy balance including the complex radiation processes in slopes for about 2,700 units. Also, due to this fact the impact on the suitability of the different regions within the Landquart basin for winter ski tourism depending on climate change could be determined in much more details compared to Abegg (1996). As glaciers cover less than 0.05 per cent in the Landquart basin, the IRMB model version used here was not improved for glacier modelling. Hence, recent length variation and mass balance observations are published in Herren *et al.* (1999), simulations for possible changes in glaciation are discussed in Maisch *et al.* (1999).

The description of the regionalization procedure of the Landquart basin is tackled in the first chapter of this paper, followed by the outline of the data and the procedure developed for estimating the energy balance of the units issued from the regionalization. Then a chapter summarizes the model used to simulate the snow accumulation-melting process and its validation by means of observed water equivalent of the snow cover, and also by verifying glacier locations and runoff at the outlet. After a brief description of the climate change scenarios adopted, the study of the impacts on the snow cover is presented for the Landquart. The consequences for the profitability of the snow activities are then examined. Conclusions are finally drawn.

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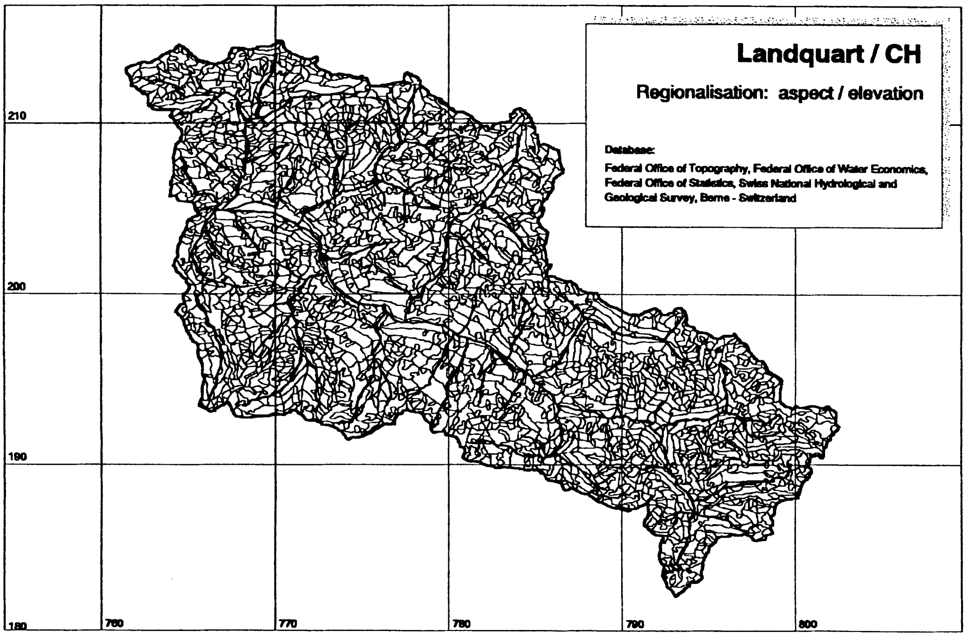

Fig. 1. Map of the Landquart basin with upward north orientation. Regionalization applied to the Landquart basin defining surfaces with given aspect at different elevation levels (background : river network and coordinate grid 10×10 km^2).

Regionalization of the Basin in Homogeneous Units

In order to subdivide the Landquart basin in homogeneous units, the Swiss National Hydrological and Geological Survey used the GIS ArcInfo software. For this purpose a high resolution 25m-DTM (DHM25 1993) and the Swiss landuse classification on a 100 m basis (OFS 1993) were available.

From the DTM the slope and the aspect (classified into 8 categories) have been derived. To avoid too many spatial units and to get smoothed boundaries the classified grid of the aspect was generalized and iteratively processed in a way that the portions of each category were approximately maintained. Because of their scarcity in an alpine region and due to the absence of an orientation, surfaces with a slope less than 5 degrees were specially handled. In a second step the regionalization of the aspect was overlaid with the elevation zones, which were defined as 250 m layers. As a result of this combination, 2,704 homogeneous units were built. These surfaces constitute the adopted partition of the catchment area in parcels. Fig. 1 represents the result of the regionalization applied to the Landquart basin.

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For each parcel the centroid coordinates, area, mean elevation, slope, aspect and landuse have been assessed. Moreover a horizon shading study was carried out : the horizon and all the visible parcels were determined for each parcel using its centroid as the observer position.

Interpolation of the Meteorological Data

Meteorological data (air temperature and humidity, wind speed at 2 m above the ground level) observed by the Swiss Meteorological Institute at Chur (9°31'54" E, 46°52'18" N, 555 m), at Davos (9°50'54" E, 46°48'49" N, 1,590 m) and at Weissfluhjoch (9°48'37" E, 46°49'51" N, 2,540 m) are at first used to assess their daily altitude gradients. These slopes are used to assess at a reference level the "reduced" meteorological data values. For the centroid location of each parcel the data are then interpolated at this reference level and then projected back to the true centroid altitude, following their altitude gradients. Temperature values are in addition corrected in order to take the aspect of the parcel into account (in approximately the same way as Schulla (1997)). For relative sunshine duration no gradient has been adopted.

The daily precipitation amounts observed at 12 climatological stations were corrected according to site particulars. These coefficients were suggested by Sevruk (1989 and personal communication). Using monthly climatological rain/altitude gradients, the daily observed precipitation amounts are reduced to a reference level, interpolated and projected back to the centroid level.

Assessment of the Energy Budget on Homogeneous Parcels

The daily surface net radiation of the snow cover Q_d is assessed as the balance of the short and the longwave surface components, $Q_d = K\downarrow (1 - a) + L\downarrow - L\uparrow$, where $K\downarrow$ is the shortwave radiation flux, a is the albedo determining the part of $K\downarrow$ reflected by the surface, $L\downarrow$ is the downward longwave radiation flux, $L\uparrow$ is the upward longwave radiation flux. Q_d is computed for each parcel considering its slope, aspect and environment. The surrounding horizon and the influence of the other parcels located in the vicinity are taken into account. The topography related effects are not negligible and in the case of some parcels, the visible part of the sky drops to only 30% of the hemisphere. The landuse determines radiative parameters like the emissivity and the albedo. Therefore, Q_d needs to be assessed for each surface type inside the parcel, possibly covered by snow. Interpolated meteorological data are also required by some parameterizations (*e.g.* the emissivity). Energy budget is assimilated to the net radiation by neglecting the heat conduction flux into the ground.

The incident shortwave radiation $K\downarrow$ is expressed as the sum of three contributions, $K\downarrow = K_s + K_d + K_e$, where K_s is the direct solar radiation, K_d the diffuse solar

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radiation and K_e the radiation flux reflected by the surrounding surfaces. K_s and K_d are computed following Dogniaux (1984) taking into account the slope and aspect of the parcels and the cloudiness. The effect of the horizon has been introduced to fix the sunrise and sunset moments and to determine the portion of the sky used in the energy budget assessment. K_d is slightly adapted from the initial method of Dogniaux (1984) and is computed by clear or cloudy sky as the sum of the contributions of homogeneous entities ($10^\circ \times 10^\circ$ cells in polar coordinates) of the sky over the horizon. K_e is iteratively calculated to use the updated values of $K\downarrow$ assessed on the other parcels. To save time when assessing K_e, only the most contributing surrounding parcels are selected and parcels outside the catchment have been omitted. Isotropic reflection on vegetated units determined by monthly values of their albedo has been adopted. Snow albedo a varies in addition with the age of the snow cover.

The downward infrared radiation $L\downarrow$ is expressed by the sum $L\downarrow = L_a + L_e$. L_a is the infrared radiation emitted by the atmosphere. This is at first calculated on an horizontal surface by means of a bulk formula (Bolz 1949; Brutsaert 1975) using the interpolated values of the air temperature, the vapour pressure and the sunshine duration. The horizon as well as the slope and the aspect of the parcel are then considered taking the anisotropy into account with the Unsworth and Monteith formula (1975). L_e represents the terrestrial radiation emitted from the surrounding surfaces that reaches the parcel. It is calculated with the same contributing parcels as for the reflected visible radiation. The upward infrared radiation $L\uparrow$ is the infrared radiation emitted by the surface itself. It is estimated for all cloud conditions by means of the empirical relationship of Dogniaux and Lemoine (1985). An "equivalent surface temperature", the interpolated air temperature and the net shortwave radiation are used. Constant emissivity values are introduced for each land cover.

Snow Modelling

The main characteristics of the snow accumulation-melting model have been described in detail in Bultot *et al.* (1994). Let us nevertheless keep in mind that the precipitation amounts are considered as snow when the interpolated parcel temperature is lower than 0.5 °C. The water equivalent WSN_d of the snow cover on day d is governed by the mass equation $WSN_d = WSN_{d-1} + SN_d - SNM_d$, where SN_d is the snow precipitation and SNM_d the quantity of water proceeding from the partial or total melting of the snow cover in the course of day d.

The maximum amount of water that could be released by the melting process is obtained by dividing the energy budget of the snow cover on day d by the latent heat of the ice melting λ_f. The energy budget for each parcel is approximated by the sum of the radiation budget Q_d and the fluxes of sensible heat H_d and of latent heat of condensation E_d. Hence,

$$SNM_d = (Q_d + H_d + E_d) / \lambda_f,$$

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where

Q_d is assessed by the method described in the former chapter,
$H_d = \lambda\,\gamma\,(0.205 + 0.028\, u_d)\, T_d$,
$E_d = (\lambda + \lambda_f)\,(0.205 + 0.028\, u_d)\,(e_d - 6.1)$

where λ is the latent heat of vaporization, γ the psychrometric coefficient, u the wind speed (kmh^{-1}), T the temperature (°C) and e the air water vapour pressure (hPa). According to Bultot *et al.* (1994), the accumulation of liquid water in the snow pack has been introduced by means of a simplified algorithm driving the snow density.

Compared to other snow models based on the degree-day (*e.g.* Braun 1985 or Martinec 1989) or to more complex estimations of the energy balance of the snow layer (Rohrer and Braun 1994), the present approach has been oriented to simulate the energy balance on the basin sides, *i.e.* with shading effect, aspect and slope, Hence it allows to reproduce the valley side effects. The mean annual water equivalent of the snow cover for the different altitude slices (10 classes) and aspects (8 classes) are represented in Fig. 2. Each 250 m altitude step corresponds to almost 50 mm water equivalent. The mean values are reaching 400 mm for the parcels situated between 2,500 and 2,750 m (slice 9). While being dominated by the altitude, the snow cover is affected by aspect effects mainly at the upstream part of the catchment. It is only for the highest slices that northern and southern units reveal different mean water equivalents.

The highest altitude slice (2,750-3,000 m) has not been taken into consideration in Fig. 2. It presents water equivalent greater than 400 mm and even reaching almost

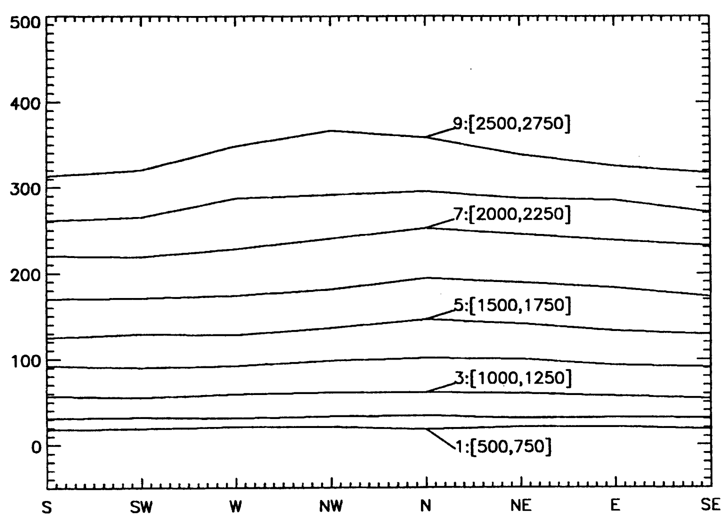

Fig. 2. Mean annual water equivalent of the snow cover (mm) as a function of the slope orientation and the altitude. Period 1981-1995.

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1,000 mm for parcels with northern and northern-western orientation. These parcels situated in the highest eastern part of the catchment are snow-covered 365 days a year (with at least 100 mm) during the whole simulation period 1981-1995. These high values maybe due to some simplifications in the model. Hence there is no redistribution of the snow from one unit to another due to the wind or the slope of the terrain, there is neither avalanche like phenomenon nor iceflow which are all typical high mountain processes that have been skipped in the present approach. These parcels have nevertheless been processed and associated with glaciers in the validation step.

Validation

The validity of the simulated water equivalent of the snow cover can be appraised by comparing snow observations made[1] at two stations inside the Landquart catchment, *i.e.* St Antoenien (9°50'7" E, 46°58'30" N, 1,480 m) and Klosters (9°53'48" E, 46°51'43" N, 1,200 m), with the snow cover of the corresponding parcels. Three additional stations exist close to the catchment border at Davos, Bueschalp (9°48'42" E, 46°48'38" N, 1,960 m) and Weissfluhjoch. In these cases, the closest catchment parcels having almost the same altitude and a quasi-horizontal slope have been selected. All the data of the 1981-1995 period are taken in this validation exercise as no parameters of the snow model have been fitted by means of observation. The location of these stations is given in Fig. 4.

Table 1 gives some comparison indexes for the simulations at the 5 locations. The good agreement of the model simulations with the observed snow amounts is clear

Table 1 – Comparison of the observed and simulated daily water equivalents (mm) of the snow cover at some locations. Number of observed data, observed and simulated means, bias, relative bias, relative residual mean square error (rmse), correlation coefficient (r) and NTD Nash coefficient (Aitken 1973).

station	period	n	observed mean	simulated mean	bias	relative bias (%)	relative rmse (%)	r	NTD
St Antoenien	1981-1991	68	241	260	19	8	35	0.85	0.71
Klosters	1981-1995	141	208	202	-6	-3	32	0.90	0.78
Davos	1981-1995	130	172	275	103	59	82	0.84	-0.40
Bueschalp	1981-1985 1991-1995	94	331	445	114	34	43	0.93	0.34
Weissfluhjoch	1981-1995	219	523	488	-35	-7	19	0.94	0.86

[1] By the Swiss Federal Institute for Snow and Avalanche Research, Davos, and the Geography Department of the Federal Institute of Technology, Zurich, Rohrer *et al.* (1994a).

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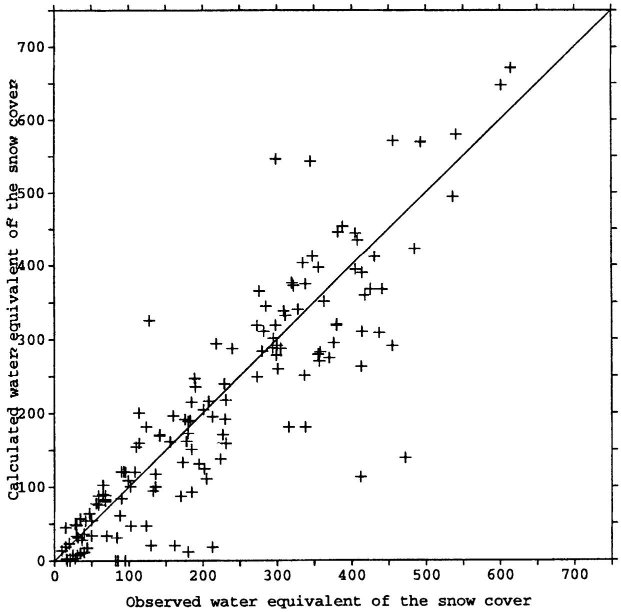

Fig. 3. Scatter plot of the observed and simulated water equivalent of the snow cover (mm) at Klosters period 1981-1995.

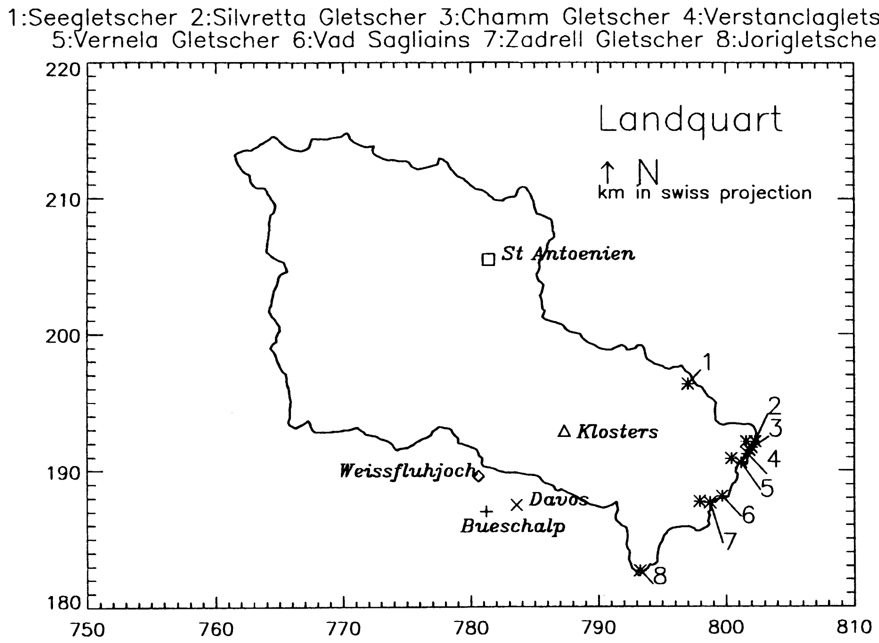

Fig. 4. Location of the glaciers and of the stations used for snow validation.

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for St Antoenien, Klosters and Weissfluhjoch with a relative bias smaller than 10% and a NTD coefficient greater than 0.7. Fig. 3 presents the scatter plot of the observed and simulated values for the Klosters station confirming the quality of the snow model. In comparison with first simulations presented in Schädler *et al.* (1998), the strong improvement for Klosters was obtained after changing the IR radiation modelling in very complex terrain configuration. For the Davos and Bueschalp stations, the correlation remains high but the bias is rather large (more than 100 mm). This is probably due to an inappropriate choice of the parcels to compare with these 2 stations. Indeed the general southern orientation and the most probably smaller amount of precipitation of these two stations may explain the observed bias.

The ability of the snow model can also be checked by analyzing the location of the parcels presenting a permanent snow pack and that can be associated with glaciers. Fig. 4 shows the 12 parcels covered 365 days a year with at least 100 mm during all the 1981-1995 period. Consulting topographical maps they can be identified with some small glaciers located in the eastern part of the catchment (Jörigletscher, Seegletscher, Vernela Gletscher, Chamm Gletscher, Verstanclagletscher, Silvretta Gletscher, Zadrell Gletscher and Vàd Sagliains).

In addition, the runoff measured at the outlet of the catchment (Felsenbach, 9°36'48" E, 46°58'33" N, 571 m) can also be considered as a good test to evaluate the quality of the snow model. In this high altitude, the runoff regime is mainly driven by snow melting and accumulation, the NTD (Aitken 1973) reaches 0.90 and 0.91 respectively for the 1982-1986 calibration and 1987-1995 verification periods while the correlation reaches 0.96 for the two periods. The observed daily runoff reaches respectively 3.35 and 3.28 mm while the simulated corresponds to 2.96 and 3.06 mm. These small biases can be due to some slight underestimation of the precipitation amounts. These high scores nevertheless require necessarily a good simulation of the snow processes.

Climate Change Scenarios

Climate change scenarios built by the Climate Research Unit (CRU) of the University of East Anglia (UK) (Hulme *et al.* 1994) are used. The outputs of three GCM experiments were processed: the stationary experiments using the Hadley Centre model (ukhi) and the Canadian Climate Centre model (ccc), and the transient experiment running the Hadley Centre model (uktr). These scenarios have been built in the framework of an EC project and in particular have been used in a sensitivity study of the Rhine river basin (Grabs 1997; Middelkoop *et al.* 2000). The available monthly scenarios are combining information related not only to temperature and precipitation amounts as it is the case for the IPCC scenarios (Cubash *et al.* 1994), but also to water vapour pressure, wind speed and sunshine duration. These scenar-

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Table 2 – Monthly mean precipitation (in mm) and temperature (in °C) of the Landquart basin in present-day conditions (period 1981-1995). Monthly precipitation (in percent) and temperature (in °C) scenarios yielded by the stationary ukhi and ccc experiments and the transient uktr experiment.

Precipitation	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	year
observed	75.4	96.3	136.4	132.4	103.1	117.2	97.3	119.6	163.5	167.3	169.5	137.4	1515.4
ccc2020	-0.1	4.8	5.9	5.9	4.5	5.1	3.8	0.6	-1.3	-4.5	-2.1	-2.8	1.2
uktr3140	7.6	18.0	13.0	2.2	28.9	-6.4	-3.8	3.1	-12.2	-5.5	-2.0	-33.0	-0.7
ukhi2020	0.9	1.8	5.1	6.8	5.4	3.4	1.6	0.2	-1.5	-3.1	-3.8	-5.6	0.6
ukhi2050	1.9	4.0	11.4	15.0	12.0	7.6	3.6	0.4	-3.3	-6.9	-8.4	-12.6	1.2
ukhi2100	3.7	7.7	22.0	29.0	23.1	14.6	6.9	0.8	-6.4	-13.3	-16.2	-24.2	2.3
Temperature													
observed	4.1	-1.3	-4.0	-5.4	-5.5	-2.8	0.0	4.7	7.4	11.0	10.4	7.4	2.2
ccc2020	0.6	0.6	0.6	0.6	0.7	0.6	0.4	0.4	0.5	0.6	0.6	0.6	0.6
uktr3140	1.9	2.3	-0.4	1.4	5.8	0.8	1.2	0.5	1.6	0.9	2.4	2.0	1.7
ukhi2020	1.0	0.7	1.0	1.2	1.4	1.2	1.0	0.7	0.7	0.7	1.0	1.1	1.0
ukhi2050	2.2	1.5	2.2	2.8	3.2	2.8	2.2	1.7	1.7	1.5	2.3	2.5	2.2
ukhi2100	4.3	2.9	4.3	5.3	6.1	5.3	4.3	3.2	3.2	2.9	4.5	4.8	4.3

ios are neither aspect dependent nor altitude dependent. Available information allows only building lumped scenarios.

For practical reasons the attention has been focussed here on two sets of scenarios. The three scenarios corresponding to the year 2020, *i.e.* the stationary experiments ukhi2020 and ccc2020 and the transient simulation uktr3140. The second set of scenarios corresponds to the stationary experiments ukhi in the years 2020, 2050 and 2100. The first set will allow a comparison of the impacts of climate change on snow in some 20 years ahead and the second will produce a long-term picture of the evolution of the snow cover. Temperature and precipitation scenarios are presented in Table 2. The important common features of the scenarios are the increases of temperature throughout the year and the winter increase and a summer decrease of the precipitation amounts.

Impacts on the Snow Cover

The impact on the snow cover of the climate change scenarios has been assessed by perturbing the input observed data (reference period 1981-1995) with the increments described in the previous chapter. Due to the temperature increase, the snow cover is undergoing a reduction. As shown in Table 3 for the year 2020 the response of the integrated water equivalent of the snow cover is fairly small. The smallest decrease is simulated in the ccc scenario with less than 10 mm (mean temperature rise close to half a degree) and the strongest is yielded by the uktr scenario with about 30 mm.

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Table 3 – Monthly mean water equivalents of the snow cover (mm) in the stationary ukhi and ccc experiments and the transient uktr experiment. Period 1981-1995. Parcels associated with glaciers have been omitted.

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	year
present	19.0	58.0	154.0	271.0	374.0	454.0	490.0	343.0	150.0	27.0	4.0	8.0	196.0
ccc2020	17.0	56.0	155.0	274.0	380.0	456.0	484.0	314.0	117.0	17.0	3.0	7.0	190.0
uktr3140	10.0	43.0	143.0	267.0	344.0	392.0	419.0	277.0	97.0	11.0	1.0	2.0	167.0
ukhi2020	14.0	51.0	146.0	261.0	362.0	430.0	444.0	279.0	101.0	16.0	3.0	5.0	176.0
ukhi2050	8.0	38.0	125.0	228.0	316.0	361.0	352.0	198.0	58.0	6.0	1.0	2.0	141.0
ukhi2100	3.0	22.0	88.0	159.0	203.0	206.0	174.0	78.0	16.0	1.0	0.0	0.0	79.0

This scenario gives in February a 5°C temperature increase which must be taken with caution compared to the almost 1°C increase during the other months. The long-term perspective simulated by means of the ukhi scenarios shows a rather strong depletion of the snow in 2050 and especially in 2100. In 2050 the snow amount represents only 72% of its present day value and in 2100 it drops dramatically to 40%. This implies that below 1,500 m the mean water equivalent does not reach 20 mm. Obviously the lowest relative impact on the snow cover is concentrated during the cold winter months with a reduction smaller than 50%. For November and April a reduction exceeding 60% is simulated in 2100. The simulations show thus that on the average the snow cover is rather insensitive to a temperature rise of only half a degree (ccc2020) and starts to respond to a one degree warming (ukhi2020 and uktr3140). This is in agreement with the results yielded for the Broye catchment in the case of an older set of climate change scenarios (Bultot *et al.* 1994).

Impacts on the Profitability of the Ski Resorts

In mountainous regions, winter tourism activities depend strongly on snow cover thickness and duration. The skiing activities period usually starts in Mid December and ends in Mid April. After this date most of the ski resorts are closed. The profitability of the Alpine ski resorts requires a minimum of 100 days during this period of some 120 days with a snow cover that has a water equivalent larger than 100 mm (Abegg 1996).

The number of days for Alpine ski has thus been studied for each parcel and a representation of its value is given at Fig. 5 with a gray scale. White colour represents the area where ski resorts are economically possible today. Only small aspect-related effects are visible in the main E-W valley. The 100 days are reached above some 1,500 m. The Fig. 6 presents this information as a function of the aspect and of the altitude range. It confirms that on an average the profitability region starts between 1,250 and 1,500 m (altitude slice 4) in the northern orientation and that for more exposed surfaces 1,500 m are required (altitude slice 5:[1,500 m-1,750 m]).

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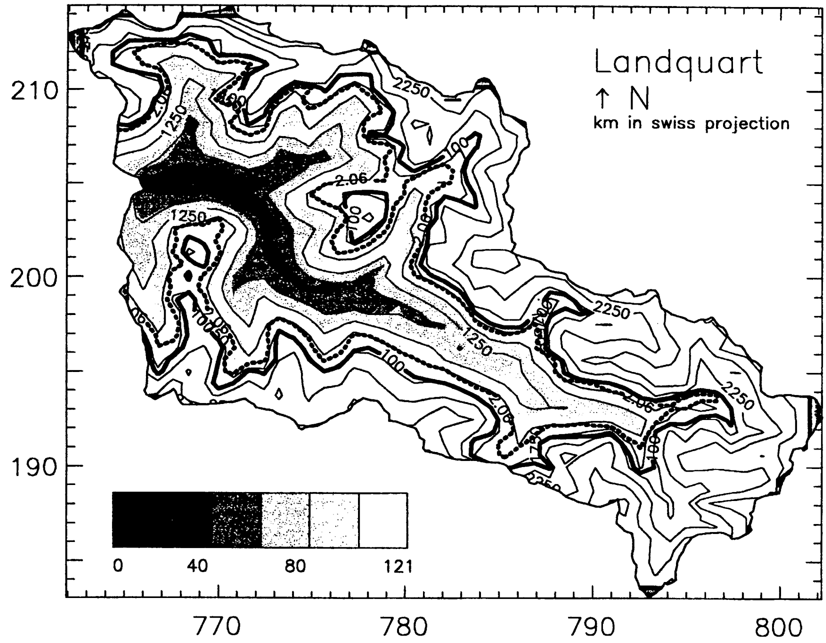

Fig. 5. Mean number of days with a water equivalent of the snow cover greater than 100 mm during the ski season in present climate condition (gray scale). Period 1981-1995. Limit of the profitability area (100 days) in the ukhi2050 scenario (bold line) and with significant change of ski conditions (bold dashed line, see text).

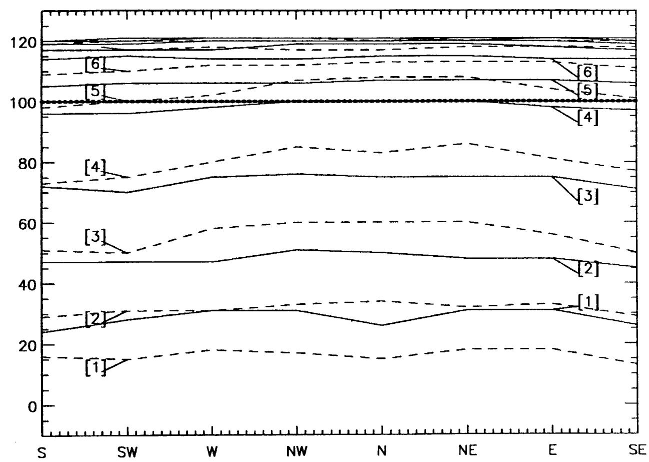

Fig. 6. Mean number of days with a water equivalent of the snow cover greater than 100 mm during the ski season in the present climate conditions (continuous line) and in the uktr3140 scenario (dashed line). Limit of the profitability area (100 days) in doted line. Period 1981-1995. Same altitude belts as in Fig. 2.

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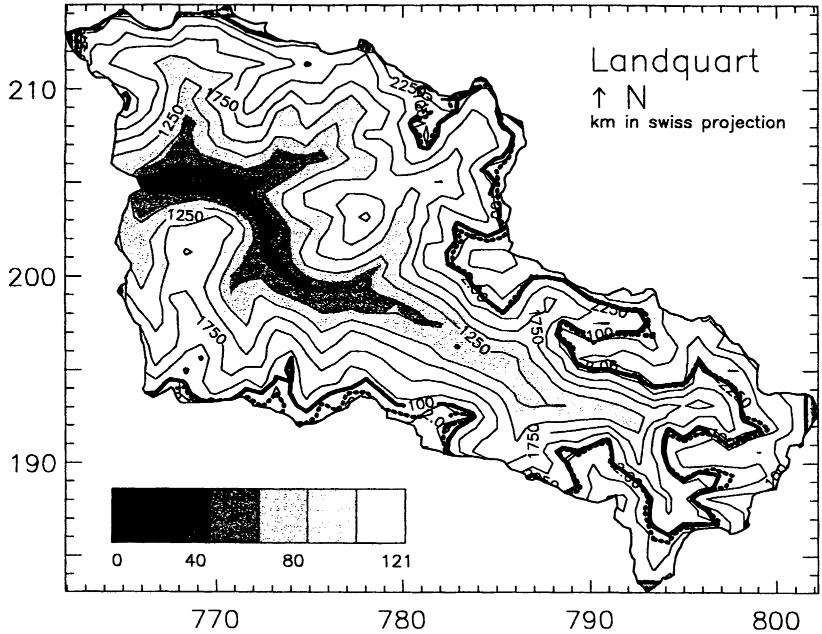

Fig. 7. Mean number of days with a water equivalent of the snow cover greater than 100 mm during the ski season in present climate condition (gray scale). Period 1981-1995. Limit of the profitability area (100 days) in the ukhi2100 scenario (bold line) and with significant change of ski conditions (bold dashed line, see text).

The impact of the uktr3140 scenario on the profitability index has been examined in function of the aspect and elevation. Fig. 6 gives in dashed lines the corresponding values in this climate change projection. A shift of one altitude slice, *i.e.* 250 m has been simulated. This means that an altitude of at least 1,500 m through 1,750 m must be reached to have more than 100 days with sufficient snow. The scenario ukhi2020 produces more or less the same response, while the ccc2020 induces only small changes. In scenario ukhi2050 which corresponds to a temperature rise of almost 2°C, a shift of 500 m has been simulated. The ukhi2100 scenario gives a dramatic jump of some 1,000 m. Only the highest and steepest parts of the catchment would remain favorable to this kind of activities.

In order to identify under climate change scenarios the significant changes in the number of Alpine ski days, a statistical comparison (using a Student test to compare two populations with unknown means and standard deviations) has been applied on the snow simulation of each parcel and added in Fig. 5 and Fig. 7 for the scenarios ukhi2050 and ukhi2100 respectively. The bold line represents the lower limit of the profitability region in the scenarios and the dashed bold line indicates the upper limit of the area where changes in Alpine ski conditions would be significantly per-

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turbed (probability level 0.95). It shows that in the stationary scenario ukhi for the year 2050, only the regions which are above the profitability level in the present climate conditions but below in the scenario conditions, are undergoing a change greater than the natural variability observed nowadays. Fig. 7 shows that in 2100 the limit of the area of significant changes will be very close to the 100 days line for the scenario ukhi for the southern valley side and will overlay this line for the northern side. In 2020, the changes are not significant for the stationary scenarios and significant for only some parcels in the strongest scenario (uktr3140). Statistically the climate change would thus remain hidden by the natural variability of the snow cover.

Conclusions

The improved model IRMB successfully simulates the detailed temporal and spatial distribution of the snow water equivalent in the Alpine basin of the Landquart River with its very distinct relief. The comparison with the snow water equivalent measured twice per month at 5 locations proved the good quality of the simulation. The quality of the streamflow simulation at the catchment outlet and the location of glaciated areas confirm this statement. The influence of the orientation on the amount of snow water equivalent is increasing with altitude: in lower altitudes, where the snow cover disappears several times during the winter season, the influence is low. In higher regions, above about 2,750 m, northwest oriented slopes more snow than south oriented slopes.

Climate change scenarios showed that in 2020 the mean overall snow water equivalent reduction is fairly small – depending on the climate model – and is estimated to 3 to 14 per cent. The today's snow distribution is shifted upward by about 250 m in altitude. This mean figure increases for the years 2050 and 2100. The mean reduction of the snow reaches 28 and 60 per cent respectively and the corresponding upward shift increases to some 500 and 1,000 m in altitude respectively.

In consequence the profitability for Alpine ski resorts is diminishing. The areas where the profitability minimum requirements is reached from the point of view of snow amount, are decreasing, because this limit would also go up by about 250 m from 1,500 to 1,750 m a.s.l. for the 2020 scenario. Statistical tests show nevertheless that this change is still within the natural variability observed since 1981, a period which was quite poor in snow, but was not absolutely exceptional compared to long-term observations (Rohrer *et al.* 1994b). For the 2050 and 2100 scenarios, the profitability limit would rise very significantly by 500 and 1,000 m, respectively. The rise of the level corresponding to the 100 days threshold means an important reduction of skiing areas due to the unfavorable hypsometric distribution and due to the steep and rocky areas in high altitudes that are not suitable and much too dangerous for skiing activities.

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Address:
Daniel Gellens,
Royal Meteorological Institute of Belgium,
Avenue Circulaire 3,
B-1180 Brussels,
Belgium.
Email: D.Gellens@oma.be

K. Barbieux, E. Roulin and F. Gellens-Meulenberghs
Same address.

B. Schädler and H. Aschwanden,
Swiss National Hydrological
and Geological Survey,
CH-3003 Berne,
Switzerland.

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