A Regional Snow Index – Analysing and Mapping Natural Snowfall Probabilities and Technical Snow Production Possibilities from Past to Future

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Abstract

The increase of the near surface air temperature within the last decades clearly indicates a climate change in the European Alps. Both the snow availability as well as the snow pattern changed causing the snow line to rise up to higher altitudes. This put stress on the popular skiing areas in the Alps, which were forced to produce large amounts of artificial snow in order to provide a thorough snow cover for tourists. However, the production of artificial snow is also limited in the changing climate, since higher temperatures also raise the energy costs required for the production of artificial snow. In this analysis we used the previously measured solid/liquid precipitation characteristics based on temperature datasets, obtained from 69 meteorological stations at different altitudes, in order to develop a probability relationship of precipitation and snowfall, based on the time series from 1981-2011. Additionally we used 25x25km resolution Danish Meteorological Institute climate datasets from 1991-2000 and 2021-2030 as a Network Common Data Form input variable to identify snow availability at different altitudes and days. We used ArcGIS to downscale these characteristics to LiDAR based digital elevation models in order to predict regional, past and future daily snow availability at certain altitudes. The forecasts predict a further receding snow line and thus fewer areas with natural snow cover. Under the present technical standards, the artificial snow production will be more and more limited in future, so that stakeholders, policy makers, and industry related planners can use these indications as a basis to define adaptation strategies against climate change impacts.

1 Introduction

Climate change is affecting the Alps and its freshwater resources more seriously than other parts of Europe (BENISTON 2005, SMIATEK et al. 2009). The impacts are caused by a trend of increasing temperatures and a changing precipitation pattern (AUER et al. 2005, AUER et al. 2007, MOBERG et al. 2006). The inter-annual climate variability of temperature is expected to increase in the near future, while the precipitation pattern is also becoming more complex and regionally extreme (SCHÄR et al. 2004, SENEVIRATNE et al. 2006). According to alpine wide climate time series trends (e.g. from the HISTALP project), precipitation events are expected to increase in winter and spring and decrease in summer and autumn (SCHMIDLI et al. 2007). AUER et al. 2007 confirm regionally changing precipitation patterns with annual increases of 9% in the north-western Alps and decreasing trends of 9% towards the south-eastern Alps. Climate modelling examples by CALANCA

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2007 prognoses an annual decrease in the frequency of wet days of about 20% by the end of this century. According to the EUROPEAN ENVIRONMENT AGENCY 2009, particularly the south-western Alps will face a significant decrease of 41% in summer precipitation, and longer periods of drier conditions are expected. Not only is the total amount of precipitation in general important, but the event based water deliveries are equally significant as the type of precipitation (FORMAYER et al. 2011).

In this manuscript we elaborate on the daily distinction between the possibilities of solid or liquid precipitation based on DMI (Danish Meteorological Institute) temperature time series from 1991-2000 and 2021-2030. We downscale these meteorological findings from 25x25km resolution to a local pattern using LiDAR datasets.

In recent years, many European countries are making an effort to derive high precision elevation datasets from LiDAR (Light Detection and Ranging). These datasets usually have a sub meter resolution and are available as Digital Terrain Model (DTM). In the framework of the Interreg IVa project “Prognosemodelle aus Geländemodelldaten” the German-Austrian cross-border case study area around the skiing destination “Steinplatte” has been used. The Federal States of Bavaria (Germany), Salzburg and Tyrol (Austria) joined efforts in the harmonised production of DTM datasets. In the framework of this project, the provincial governments Salzburg, Tyrol and Bavaria were looking for likely changes in the regional snow availability from the past to the future. They addressed the three main questions “Where can we expect natural snowfall at which time?”, “Where we are able to produce artificial snow in an economically efficient way?” and finally “How will the conditions of natural snowfall and technical snow production change until 2030?”.

2 Methods

2.1 Meteorological and elevation datasets used

In order to calculate the statistical relationship between solid and liquid precipitation we used 69 meteorological stations, with 68.000 single measurements in the time period from 1981-2011 from the ZAMG (Central Institute for Meteorology and Geodynamics, Austria) repository. Additionally, qualitative parameters from people observing the weather, deciding whether an event was snow or rainfall have been taken into account to validate the results.

Climate datasets from the Danish Meteorological Institute (DMI) for the time period 1991-2000 and 2021-2030 have been used at a 25 km raster cell size. Datasets are available free of charge at Ecochange website (Biodiversity and Ecosystem Changes in Europe; http://www.ecochange-project.eu/).

First and last pulse airborne laser scanning LiDAR datasets collected in the years 2008-2010 were used. The original point clouds of the Digital Elevation Model (DEM) have been pre-processed to one point per square meter in less dense areas, and up to four points per square meter in very dense areas. The files used are stored as *.xyz text files from which we began our GIS processing procedures.

2.2 Test Area

The cross border region "Steinplatte" comprising Tyrol, Salzburg and Bavaria was chosen as the case study area (Figure 1). For visualisation of results we choose the region Unken which has an extent 2,5 × 2,5km in size.

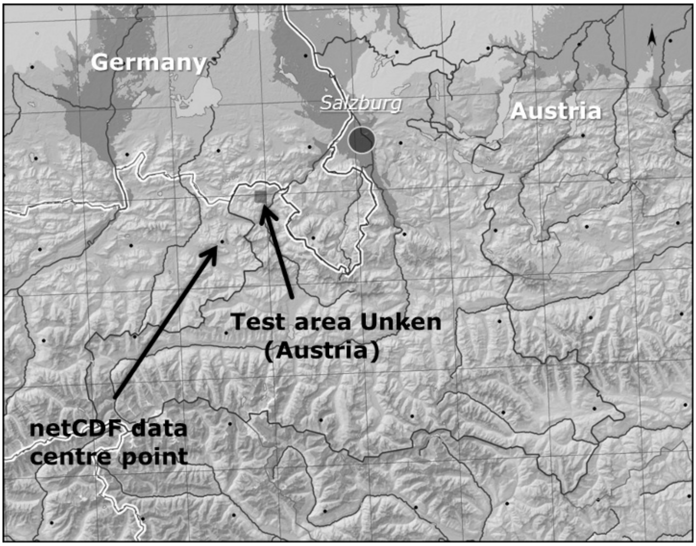


Fig. 1: The test area Unken in the Federal State of Salzburg

2.3 Calculating statistical meteorological relationships for predicting natural snowfall and artificial snow production

2.3.1 Description of the natural snowfall conditions

After selecting the desired daily average air temperatures and precipitation rates for the Province of Salzburg all initial datasets were combined to classes of 0.1°C and the percentage of snow was calculated. These combined values were integrated in the following Equation 1 where *y* is the probability of snowfall from 0-100%, *a* is a constant addressing the asymptotic delineation of the curve shown in Figure 3 and *x* is the air temperature for natural snowfall and the wet bulb temperature for artificial production probability (chapter 3.1), while b and c are calculation dependent variables:

Equation 1: $y = a * (1\text{-}\tanh((b * x) + (c)$

2.3.2 Description of the artificial snow production possibilities

In addition to the analysis of the climate induced changes of the natural snowfall probability, the skiing industry requires information about the possibility of the technical snow production in a certain region. To calculate the possibilities of artificial snow production we adopted the previous equation and exchanged air temperature for wet bulb temperature. The main challenge thereby, is that the wet bulb temperature is usually not measured; rather it needs to be calculated based on air temperature, humidity and air pressure in a transcendent equation.

The temperature steps of the resulting three-dimensional matrix (Table 1) were set to 0,1°C. In case of missing air temperatures we adjusted these with the international height equation based on the station height. The first column of the matrix shows the values of relative humidity (RH) in percent, the top row is showing the air temperature in °C while the resulting values of RH and air temperature are the wet bulb temperature values. For the calculation of the wet bulb temperature values we neglected the influence of air pressure out of simplicity reasons.

Table 1: Excerpt of the cross-matrix of humidity, air temperature and the resulting wet bulb temperature

RH*	**Air temperature in °C**										
	-7,0	-6,9	-6,8	-6,7	-6,6	-6,5	-6,4	-6,3	-6,2	-6,1	…
0	-11,5	-11,4	-11,3	-11,2	-11,2	-11,1	-11,0	-10,9	-10,9	-10,8	
1	-11,4	-11,3	-11,3	-11,2	-11,1	-11,0	-11,0	-10,9	-10,8	-10,7	
2	-11,4	-11,3	-11,2	-11,1	-11,1	-11,0	-10,9	-10,8	-10,8	-10,7	
3	-11,3	-11,2	-11,2	-11,1	-11,0	-10,9	-10,9	-10,8	-10,7	-10,6	
4	-11,3	-11,2	-11,1	-11,0	-11,0	-10,9	-10,8	-10,7	-10,7	-10,6	
5	-11,2	-11,1	-11,1	-11,0	-10,9	-10,8	-10,8	-10,7	-10,6	-10,5	
6	-11,2	-11,1	-11,0	-11,0	-10,9	-10,8	-10,7	-10,6	-10,6	-10,5	
7	-11,1	-11,1	-11,0	-10,9	-10,8	-10,8	-10,7	-10,6	-10,5	-10,5	
8	-11,1	-11,0	-10,9	-10,9	-10,8	-10,7	-10,6	-10,6	-10,5	-10,4	
9	-11,0	-11,0	-10,9	-10,8	-10,7	-10,7	-10,6	-10,5	-10,4	-10,4	
…											

* relative humidity in%

Considering the economically reasonable artificial snow production according to today's technical standards, Figure 2 shows the wet bulb temperature, related to humidity and air temperature, within which the production of technical snow is suitable, good, average, marginal and unsuitable.

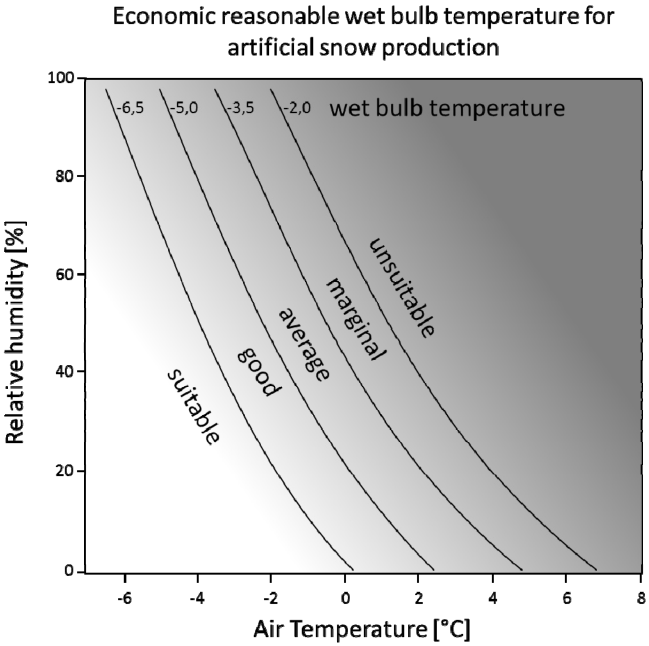


Fig. 2: Economically reasonable wet bulb temperature for artificial snow production reproduced after HOFSTÄTTER 2008 and FORMAYER et al. 2011

2.3.3 Integrating the netCDF climate datasets in ArcGIS

For the exploration of the netCDF datasets (Network Common Data Form) several tools are available (http://www.unidata.ucar.edu/software/netcdf/software.html). The toolsUI-4.2.jar for instance, allows investigation of the data structure and the data content. Since netCDF data cannot be used in ArcGIS from scratch, the "multidimension tools" have been used to derive from netCDF data single raster files. Since there are disparities between latitude and longitude values, a direct conversion is not possible. Thus, datasets are first stored as point files (multipoint feature layer) and these are subsequently converted to raster format.

2.4 Transferring the findings to the spatial domain

The *.xyz files from the DTM were integrated as raster files in ArcGIS. In order to apply the statistical meteorological relationships, a spatial layer with assigned temperatures is required. To transfer the temperature information from the 25 km netCDF datasets to the LiDAR datasets we calculated the mean height of the test area. We assigned the value from the netCDF datasets to the daily mean temperature and interpolated it with 0,65°C up (-) and down (+) per 100 meters using a linear function.

For the possibilities of artificial snow production we adopted the previously mentioned approach exchanging air temperature for wet bulb temperature calculated as outlined in chapter 2.3.2. We assigned the value of the wet bulb temperature to the LiDAR dataset and interpolated it with 0,61°C up (-) and down (+) per 100 meter using a linear function.

Finally we applied the general Equation 1 to both the air temperature dataset for natural snowfall probability, and the web bulb temperature dataset for the suitability for artificial snow production. We classified the spatially explicit results according to Figure 2 in order to analyse the changing spatial extent of suitable artificial snow production from 1991 to 2030.

3 Results

3.1 The statistical relationships of air temperature / wet bulb temperature and snowfall probability for natural snow and artificial snow production

Applying the function from chapter 2.3.1 we chose a = 50 to ensure that the curve adjusts asymptotically for the extreme values of 0% and 100% of solid precipitation. From the datasets used, we determined x as the air temperature [°C] with b = 0.48157 and c = -0.50245. Thus, the statistical relationship shows a 50% probability of snow/rain at a temperature of 2,3°C (Fig. 3). Considering the model, 50% of all snow/rain events range between 19% and 75% of solid precipitation.

The result of the wet bulb temperature analysis is also a tangents hyperbolicus (tanh) function. The parameters considering the wet bulb temperature could be defined as follows: a = 50, b = 0.46102, and c = -0.46702. Snow rain occurs in 50% of all events between 0°C (equals 72% of solid precipitation) and 2.9°C (15% solid precipitation) (Fig. 4).

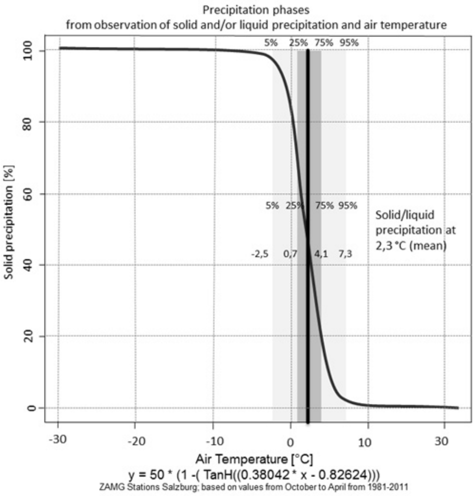


Fig. 3: The relationship between air temperature and snowfall probability for natural snow

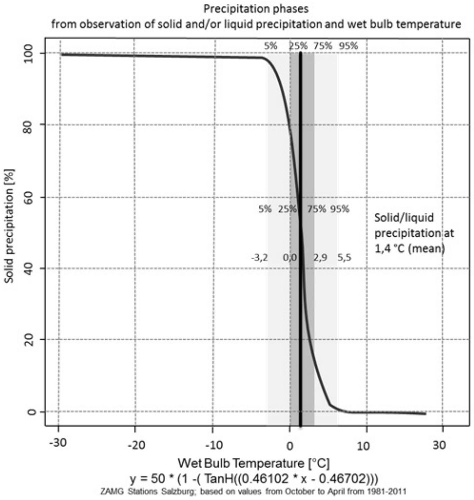


Fig. 4: The relationship between wet bulb temperature and snowfall probability for artificial snow production

3.2 The spatially explicit natural snowfall and artificial snow production probability

The black colours of the two dates visualised in Figure 5 indicate no snowfall, while the white areas at higher elevations indicate a strong probability of snowfall. The intermediate grey colours show the transition zone along the snow/rain path shown in Figure 3. The differential map (left) combines the conditions in 1991 with the forecast for 2030. Here, black colours show those areas that do not change between the two dates. White areas characterise areas subject to a change. The grey area in between again indicates the transition zone.

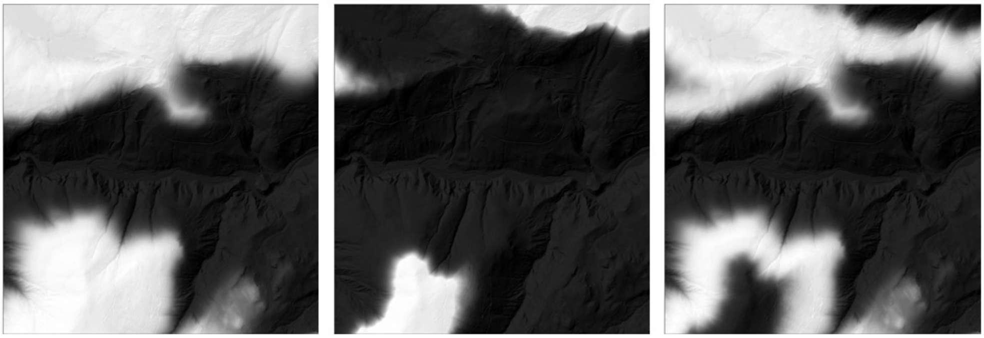


Fig. 5: Difference map of the natural, relief based snowfall probability for the dates 01.01.1991 und 01.01.2030

The black colours of the two dates in Figure 6 indicate a limited technical snow production possibility below 50% probability of snowfall, while the white areas in higher elevations indicate good opportunities for artificial snow production above 50% snowfall probability. Like in the previous example, the grey transition indicates the zone, where good to worse conditions for snow production are forecasted. The differential map (left) combines the maps from the first of January 1991 and 2030. Black colour again indicates no change between the two time steps, while white areas are subject to a change. The grey areas in between again shows the transition zone.

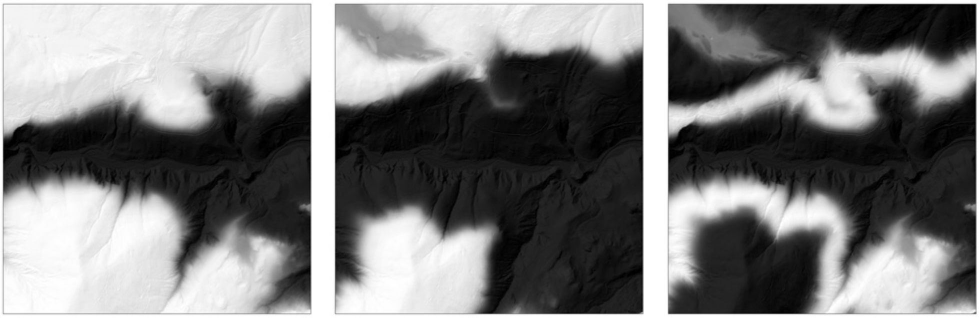
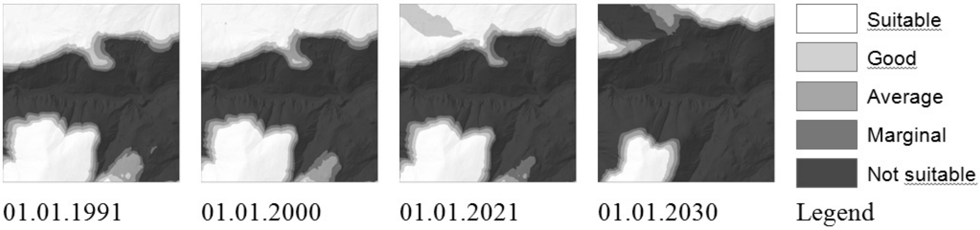


Fig. 6: Difference map of the artificial snow production probability for the dates 01.01.1991 und 01.01.2030

For the assessment of the spatially explicit representation of economically sensible areas for technical snow production according to the wet bulb temperatures (depending on air temperature and relative humidity; Figure 2) the four examples from the first of January in the years 1991, 2000, 2021 and 2030 are shown in Figure 7.



01.01.1991 01.01.2000 01.01.2021 01.01.2030

Fig. 7: Economically reasonable areas for technical snow production

4 Discussion and Conclusion

Considering the methodology used, there are many challenges which need to be taken into account when interpreting the final results. Without going into detail, climate change predictions resulting from global or even regional climate models already have many intrinsic uncertainties. Other factors are for instance the procedure of averaging the mean height of the test area which might also be seen as crucial, since the mean height is dependent on regional relief properties. Thus, when changing the area off interest slightly, changes will occur in the distribution of the snow/rain event probability as well. However, to our knowledge there is no information provided, on which reference elevation the 25x25km netCDF datasets provides information for e.g. temperature or precipitation.

Reflecting upon the research questions phrased in the introduction of this paper, we can confirm for the test area that the probability of snowfall at different days in the past and future are dissimilar. As the results illustrate, the area covered with natural snow will substantially decrease in future. This is not only valid for the first of January 1991, 2000, 2021 and 2030 which we used for our example, but also for other days throughout the winter period. The same applies to the conditions for technical snow production. The areas which are economically suitable for artificial snow production will further substantially decrease until 2030. Especially lower valley regions around 600-800 m, but also mid elevated regions from 1000-1200 m above sea level might be at risk of losing their winter tourism. Thus, either skiing will be abandoned in this area or the technical production of artificial snow needs to be enhanced wherever possible. However, with the expenses of several assumptions and the validity of climate forecasts from regional climate models in general, this exercise shows the likely regional distribution of snowfall, but neither can provide a validated prediction of future snow line developments, nor can we predict how much snow or rain will be available.

Applying this analysis to all of the days in the winter period from October to April, one could estimate on how many days the skiing industry will be able to produce artificial snow in an economically reasonable way. This probability is independent from the possibility of water abstraction, governmental restrictions concerning water uptake rights or any other rules reducing the artificial snow production time.

Acknowledgements

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