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Effekte künstlicher Beschneiung auf den Strahlungshaushalt der Skiregion Saalbach-Hinterglemm

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Kurzfassung

Der Wintertourismus ist für den österreichischen Wirtschaftsstandort von großer Bedeutung und die Gewinne stehen in Abhängigkeit zu klimatologischen Parametern wie der Schneesicherheit in Skigebieten. Ein Ansatz, um diese Vulnerabilität zu vermindern ist die künstliche Beschneiung, welche neben dem Effekt von größerer Schneesicherheit, zu einer erhöhten Rückstrahlung des einfallenden Sonnenlichtes (Albedo) führt. Aus diesem Grund stellte das Joanneum Research in einer Studie die These auf, dass künstliche Beschneiung zu einer Abkühlung des Systems führt, da die positiven Effekte, welche durch die zusätzliche Rückstrahlung des Sonnenlichts, die negativen Effekte des Energieaufwandes zur künstlichen Beschneiung übertreffen. Das Ziel dieser Studie ist es nun, diese These für das Skigebiet Saalbach-Hinterglemm, mittels eines komplexen Strahlungsmodells, zu überprüfen und mit den Ergebnissen der Joanneum Research Studie zu vergleichen. Das 3-D Modell dieser Studie benutzt ein Digitial Elevation model (DEM) mit einer Auflösung von 10x10m für die Strahlungsmodellierung. Zusätzlich werden noch Landnutzungsdaten für die Abschätzung der Albedowerte der einzelnen Landnutzungsklassen verwendet, sowie Schneedaten aus dem SNOWGRID-Datensatz, welche mit Residuen-Kriging auf ein 10x10m Raster interpoliert wurden. Die Studie kommt zu dem Ergebnis, dass unter realen Schneebedingungen für den Monat April, das einfache Modell die Ergebnisse des komplexen Ansatzes um 600 % überschätzt. Zusätzlich kann noch gezeigt werden, dass die Berücksichtigung von Bäumen im Strahlungsmodell zu einem Rückgang des Strahlungsantriebs von 16%-46% führen. Mehrfachreflexion, Beschattung und die Einbindung des „Canyon-Effekts“ durch Bäume in das komplexe Strahlungsmodell haben einen signifikanten Einfluss auf das Ergebnis des Strahlungsbudgets, gegenüber eines vereinfachten Strahlungsmodells, wie es in der Joanneum-Studie verwendet wurde.

Abstract

Winter tourism is still of great importance for Austrian economy, but the profits are dependent on climatological parameters, as snow security. One approach, to reduce vulnerability of winter tourism due to climate, is artificial snow. Artificial snow can lead to a higher snow security in skiing areas, and additionally increase the reflection of the incoming solar radiation (albedo). In a study – conducted by the Joanneum Research – they concluded, that the positive effects, provoked by the additional reflectance of solar radiation, due to artificial snow, is excelling the negative effects of the energy consumption used for making artificial snow. This study aims to review this hypothesis, by the use of a more complex radiation model for the skiing area of Saalbach-Hinterglemm and to compare the final results with the study of Joanneum Research. The 3-D radiative transfer model of this study is using a Digital Elevation model (DEM), with a resolution of 10x10m. Additionally used data, are land-use files for estimating the albedo for each pixel in the study area and snow data from the SNOWGRID-model, which are interpolated to a 10x10m raster by residual-kriging. The study comes to the conclusion, that under real snow conditions for the month of April, the simplistic model is overestimating the complex approach of this study, by about 600%. Furthermore, consideration of trees (canyon effect) in the complex model lead to an additional reduction of the radiative forcing of 16%-48%. This means that multiple reflections, shading and the inclusion of the “canyon effect” in a complex 3-D model have major impact on the radiation budget and therefore, marginalizing the results yielded by the Joanneum-Research study.

C-1 Introduction

C-1.1 Problem overview

Tourism is an important factor in the Austrian economy, it contributes to 5.2% to the GDP (Gross domestic product), and if indirect effects are considered it increases to 7.4% for the year of 2012 (Moshammer et al. 2014). A significant proportion of this value is winter tourism, which is driven especially by winter sports like skiing. Furthermore, winter tourism in Austria is temporal dominated by the months of January and February, where the regional concentration lies in Salzburg and Tyrol (Fischer 2014; Moshammer et al. 2014). As most winter sports rely on snow safety of the region, climatological variability is an important factor considering the revenues of winter tourism. Hence, winter tourism is vulnerable to climate change. It was found that there is a significant but low correlation between overnight stays and snow depth (Steiger et al. 2019). It is assumed that overnight stays are a bad predictor, as some products are not dependent on snow conditions, high cancelation costs and most winter sport regions highly depend on day-trippers (Steiger et al. 2019; B. Abegg, Froesch, and Froesch 2002). Additionally, it was shown that the increasing artificial snow production lead to a reduction of the sensitivity of natural snow conditions (Toeglhofer, Mestel, and Prettenthaler 2012) for winter tourism and early investments in snow making have a higher impact for stable visits (Falk 2013). Furthermore, it can be shown, that higher altitude lead to a decrease in bankruptcy of skiing operators (Falk 2013; Töglhofer, Eigner, and Prettenthaler 2011), which will lead in Austria to a higher vulnerability of low elevation skiing areas, especially in the eastern part of the Alps (Bruno Abegg et al. 2007). Reduction of vulnerability is mainly yield by the technical improvement and investment in the production of artificial snow. Besides, that stable tourist visitors have major contributions to global greenhouse gas emissions (Moshammer et al. 2014) and adaption in the tourist sector would be most significant in changing mobility behavior or activities with low carbon emissions (Moshammer et al. 2014), a possible approach would be to use artificial snow for increasing the reflection of solar radiation and therefore reducing the energy staying in the earth system, which leads to a cooling effect. This adaption measurement is proposed by a study of Joanneum Research (JR, Schwaiger et al. 2017), in which they conclude that this will lead to a reduction in the carbon energy balance as the effect of increased albedo leads to a decrease of the overall carbon emission balance. This study assumes that the simplistic model of the JR tends to overestimate the effect of artificial snow for territorial albedo in a skiing area, as the JR-study does not consider multiple reflections, shading effects or a “canyon effect” by surrounding trees. Furthermore, there are studies regarding the complex terrain of mountainous area and the influence on short-wave radiation (e.g. Baumgartner et al. 2019; Chen, Hall, and Liou 2006; Hoch and Whiteman 2010; Matzinger et al. 2003), but this is the first study analyzing the effect of artificial snow for the albedo in complex mountainous areas. Hence, this study aims to analyze the effect of artificial snow on the radiation budget in Saalbach-Hinterglemm, an Austrian skiing area, by the use of an advance 3-D radiative transfer model.

In the following chapters the methodological approach of the JR-study and the approach of this study are introduced, followed by a results section and a discussion of the results. Next, the study objectives and research questions are shortly presented.

C-1.1.1 Study objectives

The main aims of this study are:

- Reproduction of the study of JR for the skiing region Saalbach Hinterglemm and the adjoining areas
- Realistic calculation of the short-wave radiation for the estimation of the albedo and the radiation balance for Saalbach-Hinterglemm for one winter season (one representative day for each month

- Quantification and comparison of the two model approaches for the “maximum effect” scenario and the cumulative effect over the whole season
- Sensitivity study regarding multiple reflection and shading effects also including the effect of surrounding trees in the radiation model

C-1.1.2 Research questions

This study is based on the main research hypothesis:

The increase of the Albedo by use of artificial snow in skiing areas and the assumed cooling effect, are reduced by the absorption and shading effects of nearby hillsides and by trees surrounding the skiing slopes.

Based on this hypothesis the study aims to answer three major science questions:

- Does multiple reflection and shading in a complex radiation model have an non-neglectable effect which is not taken into account in a simplistic approach?
- Is the radiation balance changing if trees are integrated in a radiation model?
- Is there a cooling effect in a skiing area caused by the use of artificial snow, due to a change in the radiation balance?

C-2 Methods

C-2.1 BOKU-Met approach

In this section the advanced 3D radiation modeling approach is described. The surface albedo can be defined as the ratio of reflected to incoming irradiance at the plane surface of the earth (Weihs et al. 2001). Surface albedo is not only dependent on the properties of the surface, but it is conditional to the wavelength of the incoming irradiance, elevation, the azimuth angle of the sun, physiogeographic properties of adjacent areas and additionally atmospheric conditions (Hoch and Whiteman 2010). Furthermore, it has be shown, that complex topographic structures and shadows lead to high variability of surface reflections (Chen, Hall, and Liou 2006) and to a lower average albedo in mountainous terrain compared to a flat topography (Weihs et al. 2000; Baumgartner et al. 2019). For example, neighboring trees can introduce shadowing effects and reduce the incoming radiation, or increased snow cover can lead to increased local radiative fluxes (Baumgartner et al. 2019). Mostly, such complex topographic structures were simplified for modelling approaches, but are insufficient for modelling smaller domains like one skiing area. In these cases, to introduce these terrain effects in the models, comprehensive photon tracing three-dimensional (3-D) radiative transfer (RT) models have been developed (Scheirer 2003; Weihs et al. 2012). The photons are traced by Monte Carlo techniques. The simulations in this study are performed by a GRIMALDI 3-D Monte Carl model at 11 wavelengths following the method used by Baumgartner et al.(2019). Incoming photons are randomly distributed by Monte Carlo methods (Macke et al, 1999). The GRIMALDI model is updated for the use in mountainous regions, and for digital elevation models (DEM). As input data a DEM file for the study region was used, additionally the aspect and the slope for every pixel were calculated. As this leads to discontinuity effects between the pixels the correction introduced by Weihs et al. (2012) was used to reduce these effects. The albedo of the diffuse (photons entering randomly the upper side of the box) and of direct radiation (photons entering the box with defined zenithal and azimuthal angles) at the upper limit of the 3D-box at 3000 m altitude are calculated separately. The albedo of global irradiance is calculated by weighting diffuse and direct albedo with climatological means of incident diffuse and direct radiation at 3000 m altitude for the respective time and date of the year. The effect of the albedo is then used for calculating the radiative forcing, which is defined by Lenton and Vaughan (2009) and Bright, Cherubini, and Strømman (2012) and was used by the JR study and ensures to compare results between the two approaches.

$$RF(y) = -ST_{\alpha}^{2}\Delta\alpha(y)$$

RF(y) is defined as the radiative forcing, S as the incoming solar radiation at the top of the atmosphere (TOA), T_α as the transmission factor, Δα as the difference of albedo per pixel and y is the day of the year. T_α is calculated by the ratio of the irradiance measured at the Sonnblick observatory and S, as this is suited at a higher elevation than the whole study area. The albedo in the study area is determined by the use of land-use classification which is based on the CORINE data set (‘CORINE Land Cover 2018 Österreich’ n.d.), but not all classes are used, and some are merged, if the land-use classes do not indicate different albedo values (results are shown in Figure 1). Additionally, a class of skiing areas is introduced, as artificial snow is assumed to be placed only on skiing slopes. The albedo value for artificial snow was determined with 0.85 as this was the highest value taken by the JR-study and to ensure to not underestimate the effect. Furthermore, the SNOWGRID snow data (M. Olefs et al. 2014) had to be interpolated from a 1x1km resolution to 10mx10m, as this is the resolution of the digital elevation file. In this context residual kriging is used. Kriging is a form of statistical interpolation in which neighboring points get different weights in relation to their distance to the target value and a semi-variance function. As a result of high uncertainty for low snow depth values, kriging was not performed on the snow depth, but on the empirical probability of snow for each pixel on a mean day of each month. This empirical probability was calculated by counting the days with snow depth over 5 cm for each month and dividing by all possible days. This results in the first step of residual kriging to find a detrending function for the spatial mean of the study area.

This function can either be deterministic or stochastic. In this study the relation between elevation and snow depth was used to calculate the spatial mean (Kyriakidis and Journel 1999). Simple linear regression model did overestimate the empirical snow probability, therefore a local regression approach was chosen. Gridded snow data was fitted to a LOESS (locally estimated scatterplot smoothing) model (Fahrmeir, Kneib, and Lang 2007) and residuals were calculated for kriging. Variograms were fitted by a Gaussian-model, which had the best overall performance, though overestimating the influence of far distant points.

C-2.2 JR approach

The approach of JR uses more simplistic methods for estimating the effect of the albedo than the BOKU-Met approach. First, the albedo difference (Δα) is not a result of modeling, it is the difference between the albedo of snow, which is varied between 0.65 and 0.85, and 0.2 and 0.3 for areas with no snow. In the reproduction of the JR-study, only the maximum and minimum difference was used for comparison, therefore Δα is either 0.35 or 0.65. The incoming solar radiation S is the mean for every month and is considered to be the same for both approaches, to reduce the differences to the effect of radiation modelling. The transmission T_α is differentiated in the JR-approach for south, west, north and east, whereby east and west have the same ratio. T_α is supposed to introduce the effect of different reflection, due to aspect and slope – but this is kept stable in the model by assuming a slope of 26.8% for all skiing areas. For the calculation of the aspect for the JR-approach, also the DEM file with a 10x10m resolution was used, due to this more accurate results than in the original study are expected. Furthermore, also the snow data that was used for the JR-approach was adopted by the SNOWGRID-data and not by the original study. Finally, the two approaches are compared by calculating Co2 equivalent emission reduction introduced by H. P. Schwaiger and Bird (2010):

$$\Delta CO_{2,eq}(y) \approx RF(y)\,\frac{A_\alpha}{A_E}\,\frac{CO_{2,ref}}{\beta}\left[\frac{m_{atm}M_{CO2}}{1x10^6 M_{air}}\right]\otimes InverseCo_2Decay(y),$$

where $\Delta CO_{2,eq}(y)$ are the emissions per year in CO_2 equivalence (Mg), $A_\alpha$is the area of the albedo change in (m^2), A_E is the area of the earth by 5.1 x 10^{14} m^2, β is the solar radiation constant of 5.35 W/m^2, $CO_{2,ref}$ the reference atmospheric CO_2 concentration of 400ppmv, m_{atm} is the mass of the atmosphere in Mg, M_{CO2} is the molecular mass of CO_2 and M_{air} the molecular mass of air. Furthermore, ⊗ is the convolution operator and $InverseCo_2Decay(y)$ is defined by a time series that is calculated as:

$$InverseCO_2Decay(y) \otimes Co_2Decay(y) = 1,$$

and

$$Co_2Decay(y) = A_0 + \sum_{i=1}^{3} A_i\, e^{\frac{-y}{T_i}},$$

as A_0 = 0.2173, A_1 = 0.2240, A_2 = 0.2824, A_3 = 0.2763, T_1 = 394.4 years, T_2 = 36.54 years, T_3 = 4.34 years (Joos et al. 2013).

C-2.3 Data

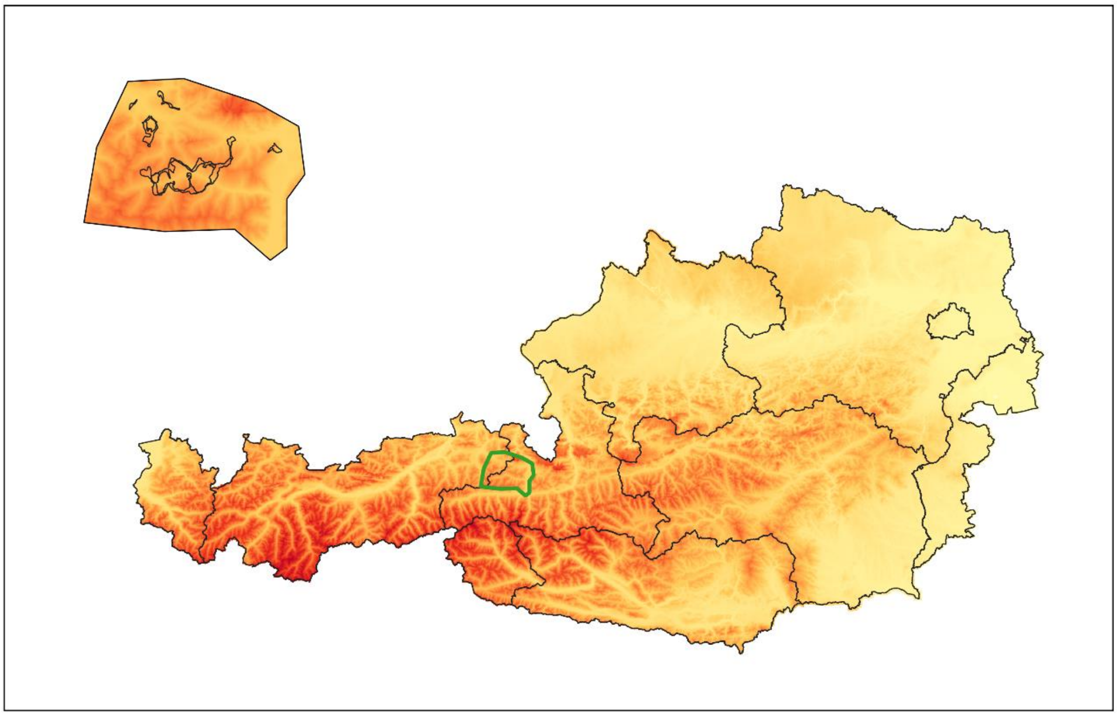

Figure 1: Location of study area in Austria and skiiing areas of Saalbach Hinterglemm

In the project proposal the aim was to use the skiing area of Schladming in Steiermark for our radiation model. After communication with the study authors of the JR, it was agreed to use the ski resort of Saalbach-Hinterglemm. The study area is located at the border of Salzburg and Tyrol in western Austria. The study region covers an area of 638.2 km², thereof 26 km² are skiing slopes, which is a proportion of 4.1 percent. The elevation in the study area ranges from 700 meter to 2631 meter, with mean elevation of 1344 meter. The BOKU-Met radiation model needs elevation, land use and snow height as input variables. In the study a 10mx10m elevation file was used (downloadable at data.gv.at). Slope and aspect were calculated from the elevation file by using the functions r.aspect and r.slope in QGIS. Basis for the land use classification was the CORINE Land cover data set (downloaded at umweltbundesamt.at). Land use classification of the CORINE data set was simplified for the purpose of this study. Land use cover was finally used to convert data into albedo values for model input of the radiation model.

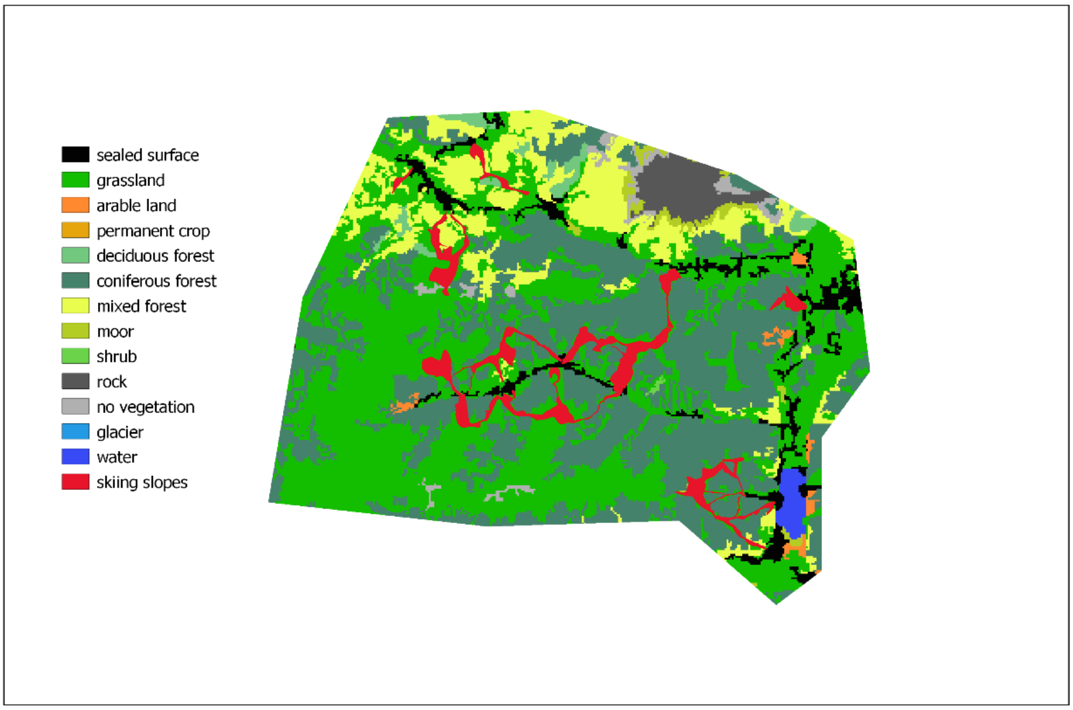

Figure 2 Land use classes of the study area

Snow data was provided by the ZAMG, by their SNOWGRID-snow data. SNOWGRID (M. Olefs et al. 2014) is a physically-based and spatially distributed snow model usually driven by gridded meteorological output from the integrated nowcasting model INCA (Haiden et al. 2011). The model output mainly consists of snow depth. Snow depth-data was available in a 1x1km resolution for Austria. Data for the replication of the JR study was partly available through the final report of their study and partly was provided by personal communication with the researchers at JR.

Statistical analysis and visualization in the study was performed in R (R Core Team 2019).

C-3 Results

C-3.1 Snow interpolation

This is a short description of the results for the snow interpolation. First step in this interpolation procedure was to calculate the empirical probability of snow occurring in each month. This was done by using a ten-day window for the middle day of the month and calculating the mean snow height for each pixel in the study area. If snow height was above 5 cm, the year was counted as snow event, if the height was below it was counted as no snow. Snow probability was then calculated for each pixel by dividing the amount of snow years by the length of the total time series. These probabilities were then used for interpolating to a 10x10m raster of the study area. Interpolation of absolute snow height was not performed, as this leaded to an overestimation of small snow height values, leading to a large bias in snow probabilities. Interpolation was performed by residual kriging, therefore a LOESS model was fitted to the data by using elevation as independent variable. The resulting residuals were then interpolated by kriging. Figure 3 shows the fit of the semivariogram for all winter months, by a gaussian model.

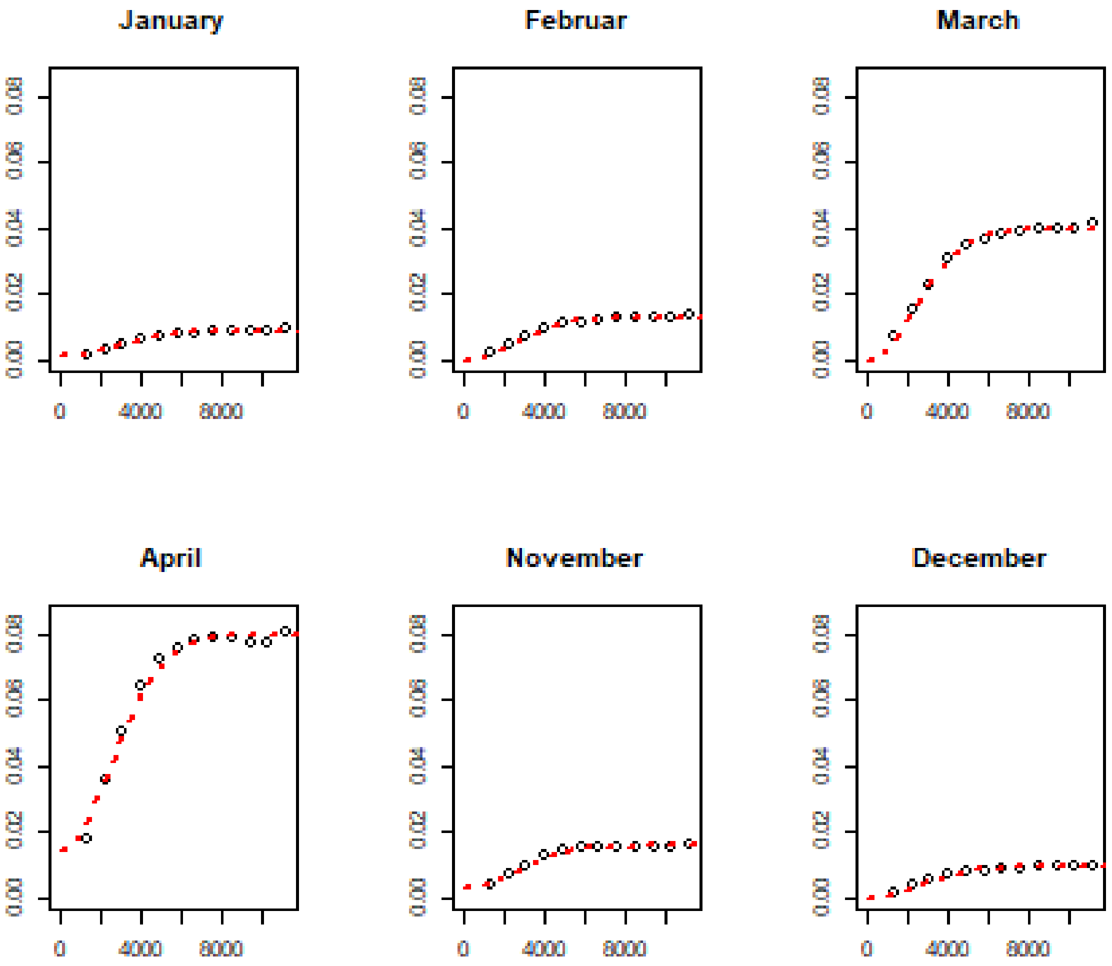

Figure 3 Semivariograms of all winter months

Histograms of the resulting snow probabilities for all months are shown in Figure 4, indicating that the months of December, January and February have a high area of snow cover in the study area.

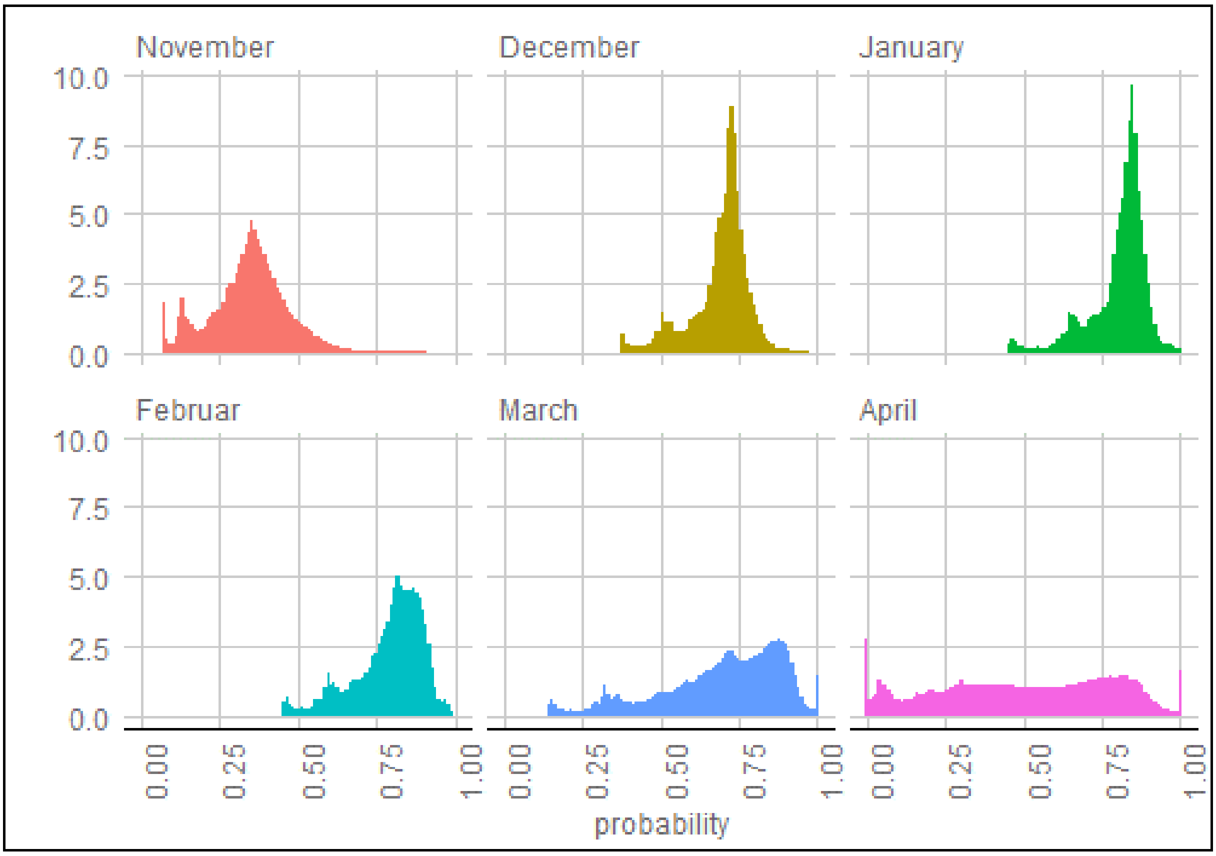

Figure 4 Histograms of snow probabilities

C-3.2 Radiation modelling

In this chapter, the results of the two modelling approaches are presented. Results are shown as positive radiative forcing ($RF(y) = S * T_{\alpha}^{2} * \Lambda_{\alpha}$), where a higher amount of radiative forcing would lead to an increased cooling in the overall radiation budget.

C-3.2.1 BOKU-Met approach

For all comparisons in this chapter an albedo of 0.85 for snow was assumed, so the results are best comparable to the maximum albedo approach of the JR-study. This part is divided into two subsections. First, the maximum effect model is introduced, which indicates that no snow is expected over the whole study area for all months. Additionally, a tree correction to account for the "canyon effect" was added. The second section describes the realistic scenario with added snow cover for the study area. Monthly and mean daily climatological values of diffuse and direct radiation were taken from station Sonnblick, since Sonnblick is situated at 3106 m altitude which is approximately the upper limit of the 3D system box. Therefore, the BOKU-Met approach uses mean climatological conditions by using diffuse and direct radiation from Sonnblick, for integrating cloudy conditions.

C-3.2.1.1 "Maximum effect" scenario with and without tree correction

In this chapter, the "maximum effect" scenario with and without tree correction is described. "Maximum effect" is defined by the conditions that no snow is persistent in the whole study area compared to artificial snow on the skiing slopes. The delta albedo of these to simulated values is then used as input for the calculation of the radiative forcing. One run was done without any tree correction. In a second run every land use class that was defined, increased the elevation by 10m. Figure 5 shows the average albedo of the ski slopes. No natural snow cover in the whole region is assumed. Simulations were performed with no snow at all, with artificial snow on all the ski slopes and finally with artificial snow on all the ski slopes but adding trees 10 m high. Trees were defined by the land use classes (see Figure 2**Fehler! Verweisquelle konnte nicht gefunden werden.**), summing up the classes mixed forest, deciduous forest and coniferous forest. These three classes are also the dominant land-use classes over the whole study area. The albedo of the ski slopes is much lower than the reflectance of the snow (snow reflectance = 0.85) because many pixels are shaded, the inclined planes reflect a large part of the incoming radiation towards the neighbouring pixels on the side which have a very low albedo. Trees reduce the albedo by 0.12 in December when the solar elevation is low, and by approximately 0.05 in April. Figure 5 shows also that maximum albedo difference between ski slope covered with artificial snow and "no snow at all" scenarios will reach maximum values of approximately 0.23 and of 0.28 when the effect of the surrounding trees is, respectively, taken into account or is neglected. Figure 6 shows the radiative forcing (RF) which is calculated based on the albedo calculations. The maximum effect scenario, using the BOKU-Met approach has its highest RF in April, followed by March and February, due to the zenith angle of the sun. If it is assumed that there is no snow in the whole study area, the effect is 33.05 W/m² for April, but 11.04 and 11.72 in January and December. Results also indicate that the effect is much higher in March and in April than in the winter months from December to February. In addition to the “simplest scenario” a tree correction of ten meters is added, the results change significantly. The tree correction is applied by adding 10 meters to all land classes that are classified as woods, to account for the canyon effect. RF is reduced by the canyon effect by 46% in December, 38% in January and 16% in April. This effect will be lower in summer months, but has large impact for winter months and results are overestimated if this condition is dismissed.

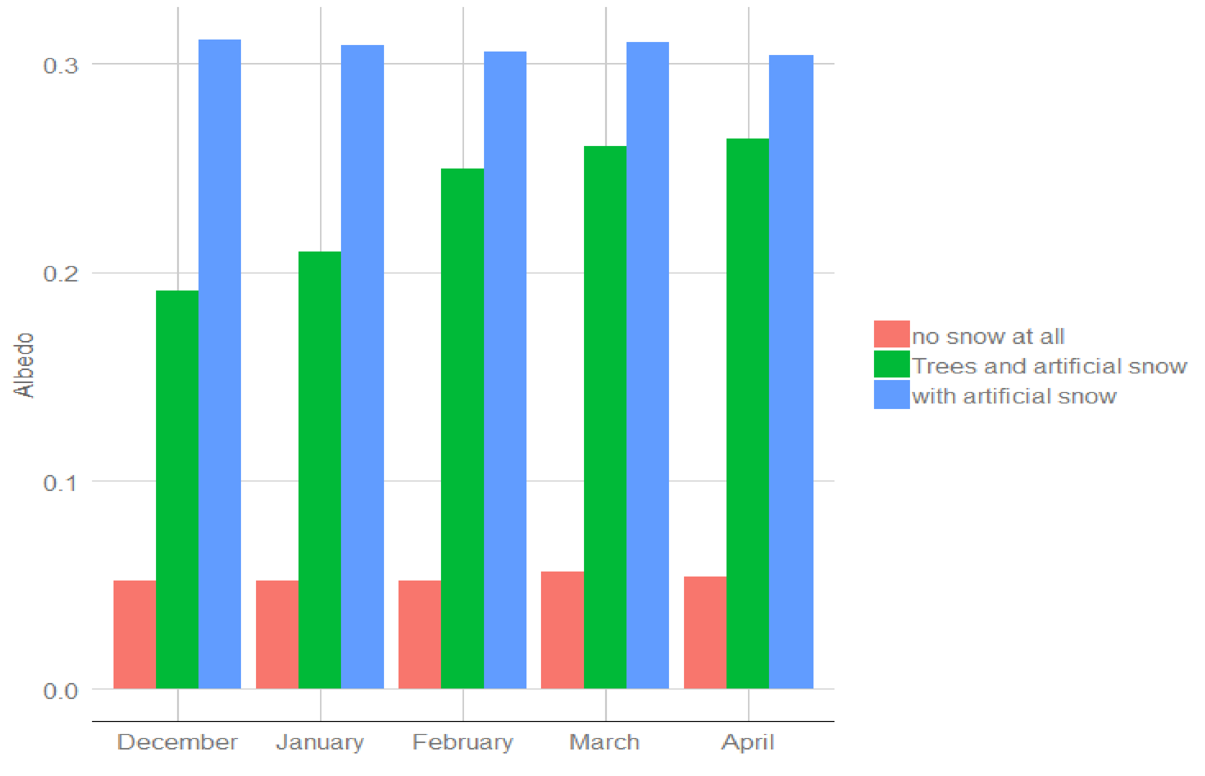

Figure 5 Average albedo

Average albedo of the ski slopes when no natural snow cover is existing and for 3 different scenarios: 1) artificial snow on the ski slopes, 2) no snow at all, 3) artificial snow on the ski slopes and effect of trees taken into account.

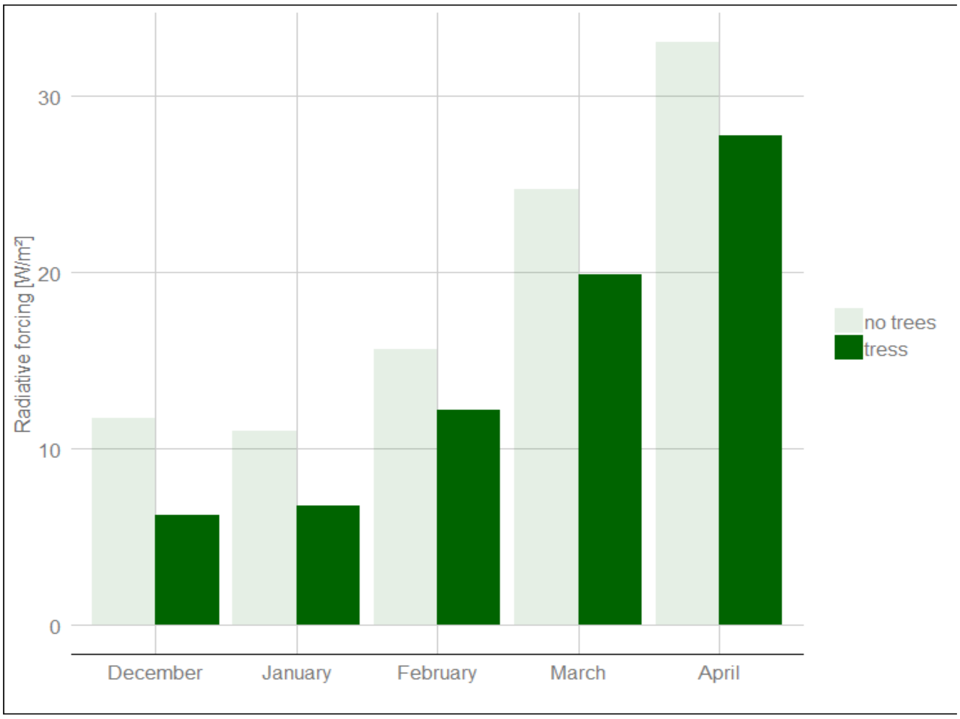

Figure 6 Comparison radiative forcing (RF)

Comparison of radiative forcing (RF) for the BOKU-Met approach and for a "maximum effect" scenario (no natural snow at all in the surroundings). The calculations of RF were performed using 1) the albedo difference between albedo of ski slopes covered with artificial snow and no snow at all and (no trees) 2) the albedo difference between albedo of ski slopes covered with artificial snow and influence of trees included and no snow at all (trees).

C-3.2.1.2 Simulations of radiative forcing for real conditions

This model approach is only shown for the maximum effect in April, as in the winter months the effect is marginal because of large snow cover. It is assumed that snow cover is reached by a snow depth of 5 cm, which is not the threshold for snow making. The following results were not only modeled for one time step, but the whole day to get information about the diurnal development. Figure 7, shows a diurnal cycle for April. The maximum effect for the whole day shows a cumulative effect of 447 kJ/m² and a mean effect of 2.32 W/m², which indicates that the effect of snow making has only a marginal effect in April under real conditions. The effect correlates with the sun zenith angle and is the highest around midday, which is expected, but this effect is driven by the diurnal cycle of the albedo and of the global radiation, the difference in the albedo values is indirect proportional to solar elevation. The albedo difference is lowest at one o’clock by 0.117 and highest in the morning and in the evening with 0.163.

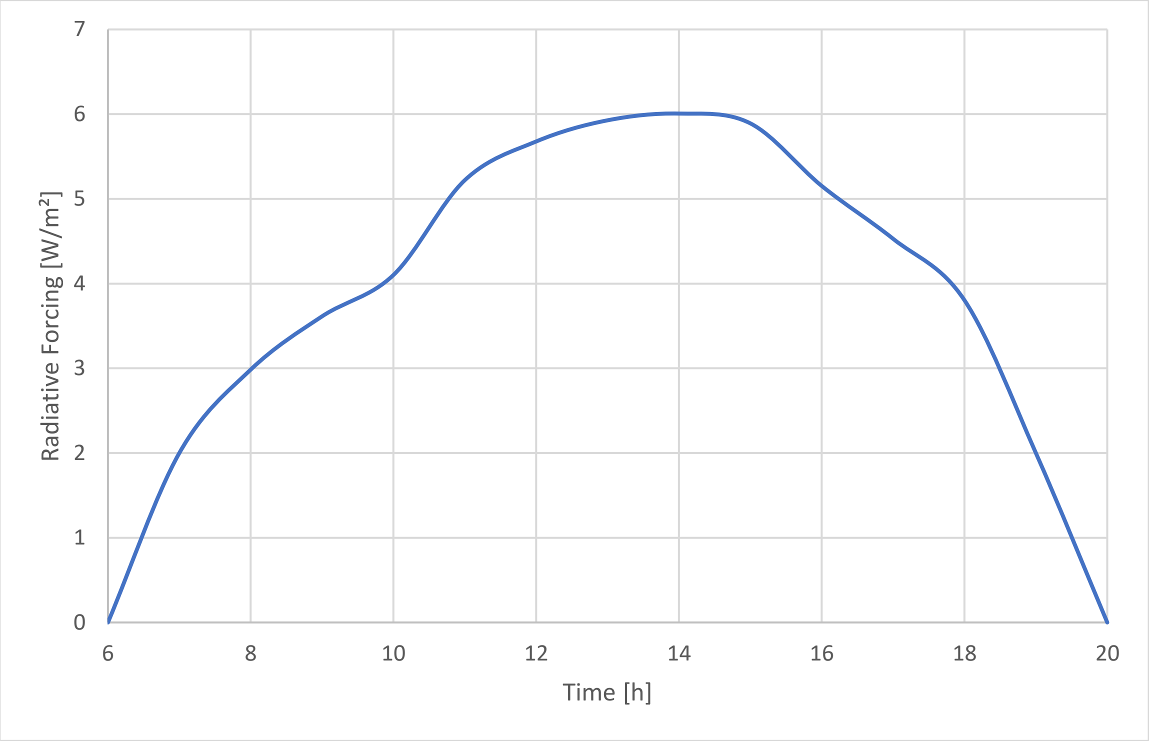

Figure 7 Diurnal cycle

Diurnal cycle of radiation forcing using the albedo difference between "real snow conditions" and "real snow conditions with artificial snow" in April.

C-3.2.2 Joanneum Research approach

As it was not possible to get exact estimates of the transmission factor for south and north orientation, the correction factor for north and south for each month was estimated by the average of several skiing areas of the original study, by dividing the global radiation to the incoming solar radiation for west, north, east and south slopes. The correction term differs between the four slope directions. East and west slopes have the highest transmission values in the winter months, the same as the slopes directed to the south, but here the difference between winter and summer months is higher. Northern slopes have the lowest transmission values in winter months. The transmission factor is lowest at northern slopes in October and November, which can be explained by the low angle of the sun.

The approach of the JR-study was applied for two scenarios. In the first, the radiation effect was quantified for the “maximum effect”. This means, that for the whole study area it was assumed that there is no snow and all skiing slopes would have to be covered in snow by artificial snow. The effect is the highest in the month April, followed by March and February. Lowest values are reached in November and December with 7.5 and 8.1 W/m² for an albedo difference of 0.35. The maximum albedo effect of 0.65 leads to a raise of 13.9 W/m² in December to 17.1 W/m² in January, where this albedo difference leads to an effect of 43.5 w/m² for April. As this is not a realistic scenario the right plot of Figure 8, gives a better approximation. In this scenario the estimated snow cover is considered for all months. There is no effect in the months of December, January and February, as the skiing slopes have a high probability to be snow covered by at least 5 cm, which would be enough for the natural snow albedo effect. In March, there is a marginal effect, where it is about 13.9 W/m² for November and a bit higher for April by 14.7 W/m² for an albedo difference of 0.65. It has to be stated, that if there is no albedo effect, because of skiing slopes being already snow covered, skiing slopes may still have to be additionally processed by artificial snow. Results additionally indicate, that the JR-study is highly dependent on the input variable of the albedo as the reduction from 0.65 to 0.35 of the albedo difference leads to reduction of 0.46% in radiative forcing.

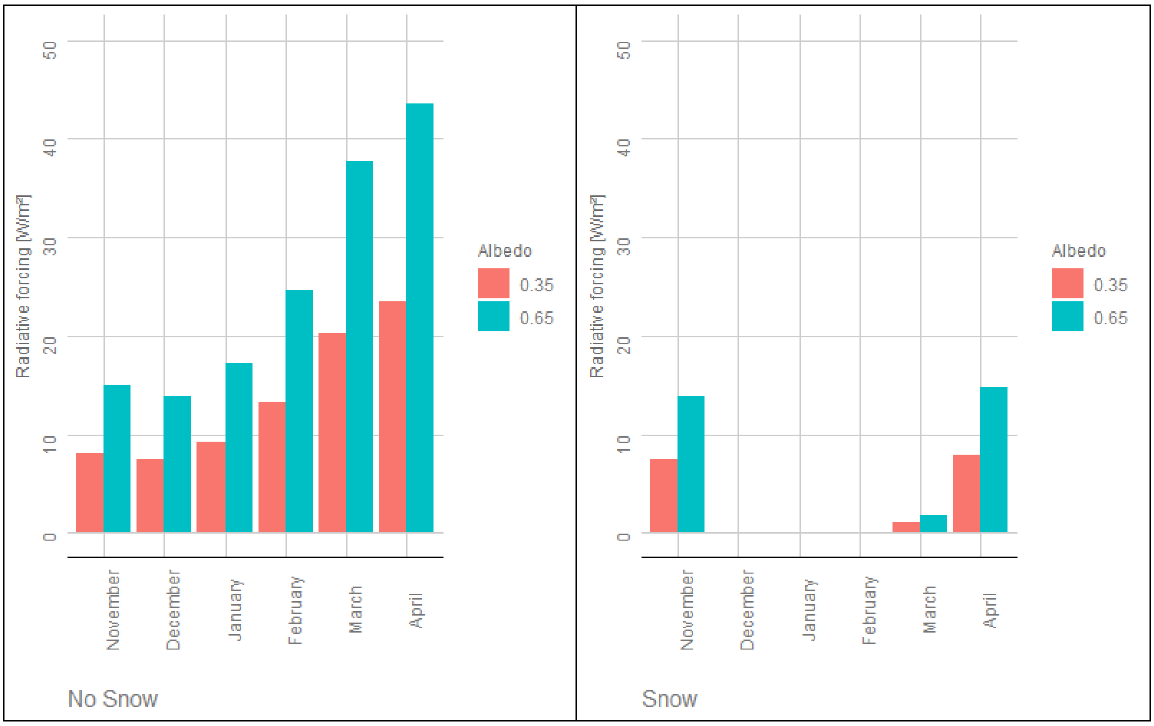

Figure 8 Comparison JR-study

Comparison of the results of the JR-study for Saalbach-Hinterglemm. The left plot shows the positive radiation forcing for the maximum effect, where it is assumed that there is no snow in the study area. The right plot shows the results, if snow is present, by using interpolated snow data.

C-4 Discussion and conclusions

In this study two different modeling approaches are compared for analyzing the effect of snow production for skiing areas on the radiation budget. In a first step the results were presented separately, where now they are compared and embedded in recent literature. Results are compared only for April as it is expected that the month with the lowest snow cover and highest radiation input shows the maximum effect for both models. Additionally, this analysis avoids comparison of different albedo values, therefore the replication of the model run of the JR-study, where an albedo difference of 0.35 is considered is dismissed, as for the BOKU-Met approach always an albedo of snow of 0.85 was assumed.

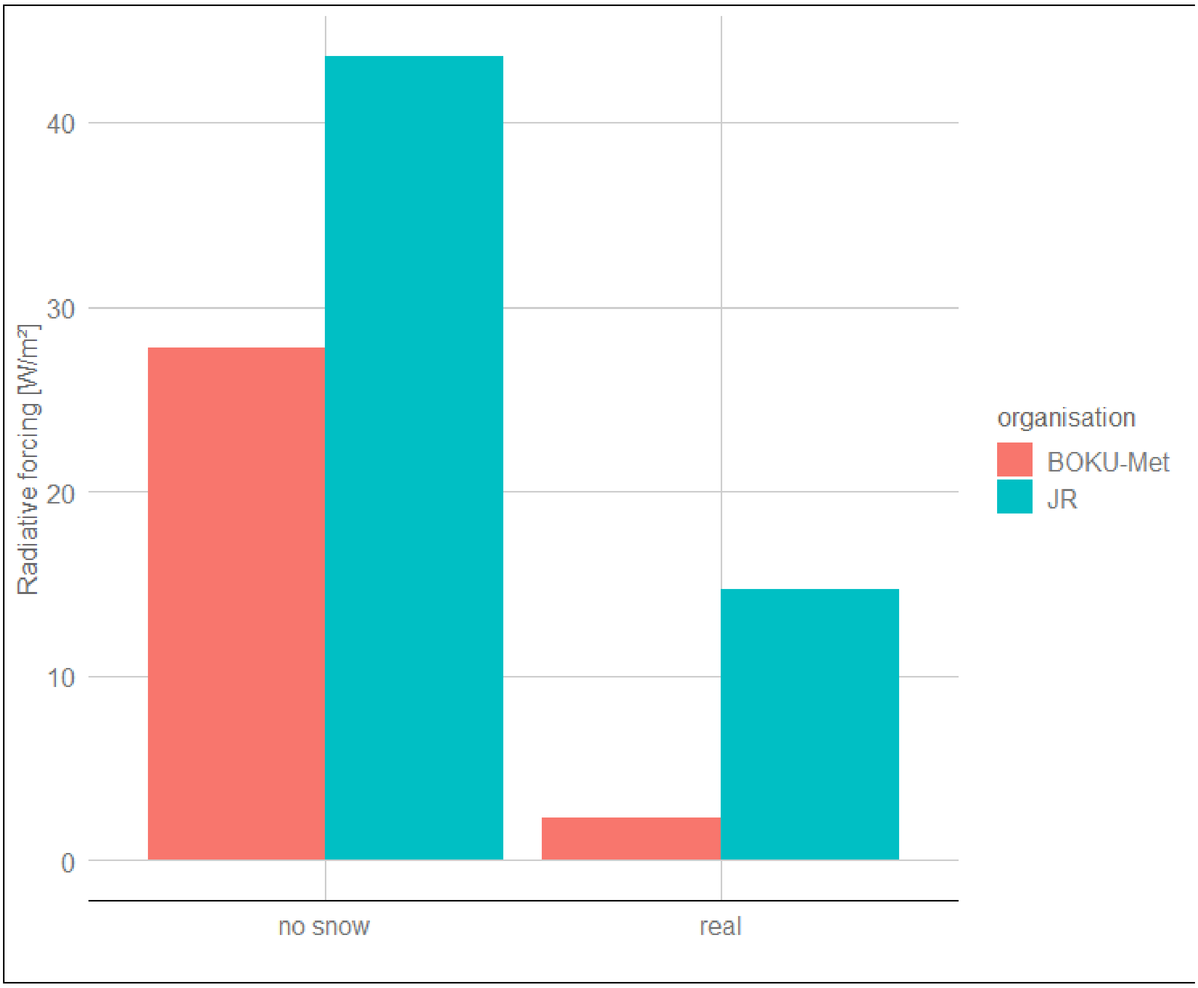

Figure 9 Comparison results BOKU-Met and JR-study

Comparison of the results of the BOKU-Met approach and the JR-study approach. Results are only compared for April as here the maximum effect is assumed.

Results indicate that, the JR-study is overestimating the effect in both cases, especially under real conditions. Where the BOKU-Met approach is finding a radiative forcing of 2.32 W/m² for real conditions, the JR-study estimates a radiative forcing of 14.7 W/m². The overestimation is lower if absolute no natural snow is assumed on the skiing slopes: BOKU_Met simulations amount to 33 W/m² whereas the JR-study simulations amount to 43.5 W/m². This discrepancy is a result of the simplified modelling approach of the JR-study. Considering the effect of this radiation forcing in CO2-equivanelt, this results in differences for the month April, calculated for one month and one year. For the BOKU-Met approach this would lead to a CO2 reduction of -6170 t CO2 and for the JR-study in a reduction of -39077 t CO2, illustrating the over estimation of the JR-study. An important point in the context of artificial snow making is, that artificial snow is even produced if there is snow cover, which would be sufficient for a natural albedo effect. Nevertheless, for skiing a snow depth a snow cover of at least 150 mm snow equivalent is needed, which is maintained in the months from December 15th to February 28th. Additionally snow making requirements can not be reduced to air temperature as in the JR-study, as conventional snow making requires meteorological conditions, like specific wind and humidity requirements.

For calculating the positive or negative effect of snow making, the CO2 equivalent has to be calculated for both approaches and an estimate of the needed energy for artificial snow has to be made. An important point in this context is, that artificial snow is produced even if there is snow cover, but for skiing a snow depth of at least 150 mm snow equivalent is needed, which is maintained in the months from December 15th to February 28th (Hanzer, Marke, and Strasser 2014). Additionally, not every day can be considered as snow-making day, but this will be not regarded in this study (Marc Olefs, Fischer, and Lang 2010).

It can be stated that the BOKU-Met approach could not confirm the high effect of artificial snow for the overall area albedo in a skiing area, in this study analyzed for Saalbach-Hinterglemm. A general negative radiative forcing can be assumed, but lies in the nature of the determination of the radiative forcing, as it can not be below 0 in this context. However, for real snow conditions in April, results indicate that using a complex 3-D radiative transfer model lead to a reduction of the “albedo effect” on RF by 75% compared to the “albedo effect” obtained within the scope of the JR-study. If multiple reflections and shading effects in a complex radiation model are considered by integrating complex terrain and detailed information about slope and aspect, the simplistic approach is overestimating results by a factor of 6. Additionally, the radiation balance is influenced by a “canyon effect” by surrounding trees, leading to a 16% reduction in the radiative forcing if considered in April. Reduction is higher in the months of December or January by up to 46%, because of the lower sun zenith angle. Furthermore, daily point estimates lead to an overestimation in the results of about 13%.

This study was a first approach to quantify the effect of artificial snow for the area albedo in the skiing area of Saalbach-Hinterglemm. It was found that a more complex model used in this study marginalize the effect of artificial snow as a cooling effect. It could be shown that complex terrain structures lead to more realistic results and a correction for the canyon effect of trees is leading to a reduction of the effect up to 46% in winter months. Simplistic radiation models should not be considered if analyzing the radiation budget in mountainous areas, as they are overestimating albedo effects by a factor of 6.

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Abbildungs- und Tabellenverzeichnis

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