Environmental Science and Policy 126 (2021) 65–78

Contents lists available at ScienceDirect

Environmental Science and Policy

journal homepage: www.elsevier.com/locate/envsci

Using Decision Making under Deep Uncertainty (DMDU) approaches to support climate change adaptation of Swiss Ski Resorts

Saeid Ashraf Vaghefi [a,b,*], Veruska Muccione [a], Kees C.H. van Ginkel [c,d], Marjolijn Haasnoot [c,e]

[a] Department of Geography, University of Zurich, Zurich, Switzerland
[b] Eawag: Swiss Federal Institute of Aquatic Science and Technology, Dübendorf, Switzerland
[c] Deltares, Delft, The Netherlands
[d] Institute for Environmental Studies, VU University, Amsterdam, The Netherlands
[e] Utrecht University, Utrecht, The Netherlands

ARTICLE INFO

Keywords:
Decision making under deep uncertainty (DMDU)
Winter tourism
Climate change
Tipping points
Scenario discovery
Dynamic adaptive policy pathways (DAPP)

ABSTRACT

Climate change threatens winter tourism in the Alps severely, and ski resorts are struggling to cope under uncertain climate change. We aim to identify under what conditions physical and economic tipping points for ski resorts may occur under changing climate in six Swiss ski resorts representing low, medium, and high elevation in the Alps. We use exploratory modeling (EMA) to assess climate change impacts on ski resorts under a range of futures adaptation options: (1) snowmaking and (2) diversifying the ski resorts' activities throughout the year. High-resolution climate projections (CH2018) were used to represent climate uncertainty. To improve the coverage of the uncertainty space and account for the climate models' intra-annual variability, we produced new climate realizations using resampling techniques. We demonstrate the importance of five factors, namely climate scenarios (RCPs), intra-annual climate variability, snow processes model, and two adaptation options, in ski resorts survival under a wide range of future scenarios. In six ski resorts, strong but highly variable decreases in the future number of days with good snow conditions for skiing (GSD) are projected. However, despite the different characteristics of the resorts, responses are similar and a shrunk of up to 31, 50, and 62 days in skiing season (Dec-April) is projected for the near-future (2020–2050), mid-future (2050–2080), and far-future (2070–2100), respectively. Similarly, in all cases, the number of days with good conditions for snowmaking (GDSM) will reduce up to 30, 50, and 74 days in the skiing season in the near-, mid-, and far-future horizons, respectively. We indicate that all ski resorts will face a reduction of up to 13%, 33%, and 51% of their reference period (1981–2010) revenue from winter skiing activities in the near-, mid-, and far-future horizons. Based on the outcomes of the EMA, we identify Dynamic Adaptive Policy Pathways (DAPP) and determine the adaptation options that ski resorts could implement to avoid tipping points in the future. We highlight the advantages of adaptive planning in a first of its kind application of DMDU techniques to winter tourism. We specify the possible adaptation options ranging from "low revenue diversification and moderate snowmaking" to "high revenue diversification and large snowmaking" and demonstrate when an adaptation action fails and a change to a new plan is needed. By the end of the century, we show that only ski resorts with ski lines above 1800–2000 m elevation will survive regardless of the climate scenarios. Our approach to decision-making is highly flexible and can easily be extended to other ski resorts and account for additional adaptation options.

1. Introduction

The collapse of winter sport tourism due to climate change has been recently identified as a socio-economic tipping point, alongside farmland abandonment and sea-level rise induced migration (van Ginkel et al., 2020). In this context, the term "tipping point" refers to a critical threshold which a system abruptly switches to a fundamentally different state (Ashwin et al., 2012; Lenton et al., 2008). It is well established that climate change threatens the survival of ski resorts and the well-being of many mountain communities, depending on income from snow sports (Debarbieux et al., 2014). Therefore, it is common practice for governments to provide subsidies to alleviate the economic loss in winter

* Corresponding author at: Department of Geography, University of Zurich, Zurich, Switzerland.
E-mail address: saeid.vaghefi@geo.uzh.ch (S. Ashraf Vaghefi).

https://doi.org/10.1016/j.envsci.2021.09.005
Received 29 December 2020; Received in revised form 6 September 2021; Accepted 11 September 2021
Available online 6 October 2021

tourism due to climate change (Steiger et al., 2020).

Winter tourism relies on favorable atmospheric conditions such as temperature, precipitation, and snow cover and is therefore sensitive to changes in the climate (Hartl et al., 2018). The impact of climate change on the viability of ski resorts has been widely addressed in the literature (e.g., Abegg et al., 2007; Collins et al., 2013; Marty et al., 2017; Spandre et al., 2019a, 2019b; Steiger et al., 2019). Warmer winters, melting glaciers, changing precipitation patterns, reduced snowfall, and shorter snow seasons are some of the clearest features of climate change (e.g., Beniston et al., 2018; Hock et al., 2019a, 2019b). Ski resorts are already suffering from a lack of natural snow coverage (Hendrikx and Hreinsson, 2012; Hoogendoorn et al., 2020; Lievens et al., 2019; Matiu et al., 2020; Pütz et al., 2011; Rixen et al., 2011; Schöner et al., 2019; Spandre et al., 2016, 2019a; Wobus et al., 2017). For the Northern Hemisphere, Collins et al. (2013) projected a snow cover decrease of 7% and 25% under RCP2.6 and RCP8.5, respectively, for the 2080 s compared with the reference period of 1986–2005. European Alps ski resorts are at the frontlines of the challenges brought by climate change. From 1960–2017, the Alpine snow season has shortened by 38 days, starting an average of 12 days later and ending 26 days earlier (Kluger, 2020). Ski resorts in the Alpine region could lose as much as 70% of their snow cover by 2100 as temperature rises (Marty et al., 2017). By analyzing snow reliability of 175 ski resorts in France (Alps and Pyrenees), Spain, and Andorra under past and future conditions using the snowpack model (Spandre et al., 2016) and climate projections from the EURO-CORDEX dataset (Verfaillie et al., 2018, 2017), Spandre et al. (2019a, 2019b) projected no snow-reliable ski resorts would exist in the French Alps and the Pyrenees at the end of the century (2080–2100).

Economically, winter tourism has become crucial for Alpine tourism by contributing at least two-thirds of annual revenue in many regions in Austria and Switzerland (AlpNet, 2016). European Alps comprise 35% of the world's ski resorts and serve an estimated 120 million tourists each year across eight countries (Vanat Laurent et al., 2020). Ski resorts in the Alps are already struggling. In December 2019, for the first time, a ski resort in the French Alpine town of Montclair failed to amass enough snow through natural means or artificial snow machines to cover its pistes (Euronews, 2020). Instead, it had to use a helicopter, at a high cost, to bring down snow from higher elevations. Similarly, in February 2020, the French resort Luchon-Superbagnères used a helicopter to shift 50 tons of snow from its upper regions to cover bared slopes due to a mild winter (Ruitenberg, 2020). Repeated mild winters and poor snow coverage conditions might simply push resorts and mountain communities in the Alps to reach tipping points that winter tourism is not viable anymore.

To secure their survival, operators of ski resorts and winter tourism destinations would need to make decisions in the short term about how to adapt over a long time. van Ginkel et al. (2020) argue that the tipping point for ski resorts is mainly related to their financial viability and the ability to make a successful profit in several consecutive years. If there is a reduced number of good snow years, this reduces the profitability of the resorts, and in the longer term, a decision might be made to cease operation or partially shut down. Decision-makers need to consider appropriate adaptation measures to keep resorts functioning and to avoid reaching tipping points, situations that are not reversible and could lead to a complete shutdown of ski resorts.

While most global climate models (GCMs) have robust agreement on temperature increase, there is less agreement on how precipitation quantitatively will change in the future, especially in high-elevation areas (Beniston et al., 2018). Furthermore, deep uncertainties exist on the effectiveness of response options over time (Walker et al., 2013). Dealing with uncertainty has become unavoidable in many planning problems and even more so because of climate change (Dessai et al., 2009; Lempert, 2003) and is often referred to as decision-making under deep uncertainty (DMDU) (Marchau et al., 2019). The essence of a DMDU is using a bottom-up, decision-oriented approach in problems that decision-makers are confronting with many possible sources of uncertainty. A core concept is robust decision making (RDM) which involves that models and data should be used in an exploratory rather than a projective way (Groves and Lempert, 2007; Lempert et al., 2006). Exploratory modeling is a well-established computational research method, which uses numerous experiments to analyze uncertain and complex system behaviors. The objective of exploratory modeling is to execute many instances of the model to seek the consequences of uncertainties for decision making by evaluating which parameter-scenario sets lead to unfavorable outcomes (Bankes et al., 2013; Kwakkel and Pruyt, 2013). Across the DMDU landscape, adaptive planning and dynamic adaptive policy pathways (DAPP) have emerged to guide robust decisions through plans that are adapted over time in response to how the future unfolds in the real world. DAPP devise policies that are not optimal to the best-estimated future but relatively robust across a range of plausible future outcomes (Hamarat et al., 2013; Kwakkel et al., 2010; Walker et al., 2001). DAPP has been conceptualized as made of several short and long-term actions where new and/or additional actions may replace actions that have failed (i.e., reached a tipping point) (Haasnoot et al., 2013; Kwakkel et al., 2010, 2015; Wilby and Dessai, 2010).

This study uses an exploratory modeling approach to (i) to project the impacts of climate change on good days for skiing, good days for snowmaking, and financial status of ski resorts in the Swiss Alps (ii) identify tipping points of ski resorts in the Swiss Alps, to (iii) uncover the combinations of socio-economic and biophysical conditions leading to tipping point occurrence, and to (iv) design adaptation policies enabling the survival of ski resorts. By exploring many possible futures, rather than a prior selection of one scenario, we implement a bottom-up approach to investigate the survival of the ski resort under different climatic and socio-economic conditions. To our knowledge, this is the first DMDU-application to the tourism sector. This paper is structured as follows. Section 2 introduces the case studies: six representative ski resorts in the Swiss Alps; the DMDU-framework; the model; and the input data. Section 3.1 examines the impacts of climate change on the number of good days for snowmaking and skiing and the financial status of ski resorts. Sections 3.2 and 3.3 present the results of feature scoring and scenario discovery techniques of exploratory modeling. Section 3.4 illustrates the adaptive policy pathways to prevent tipping points. Section 4 discusses the decision-relevance of the study and its limitation, followed by conclusions in Section 5.

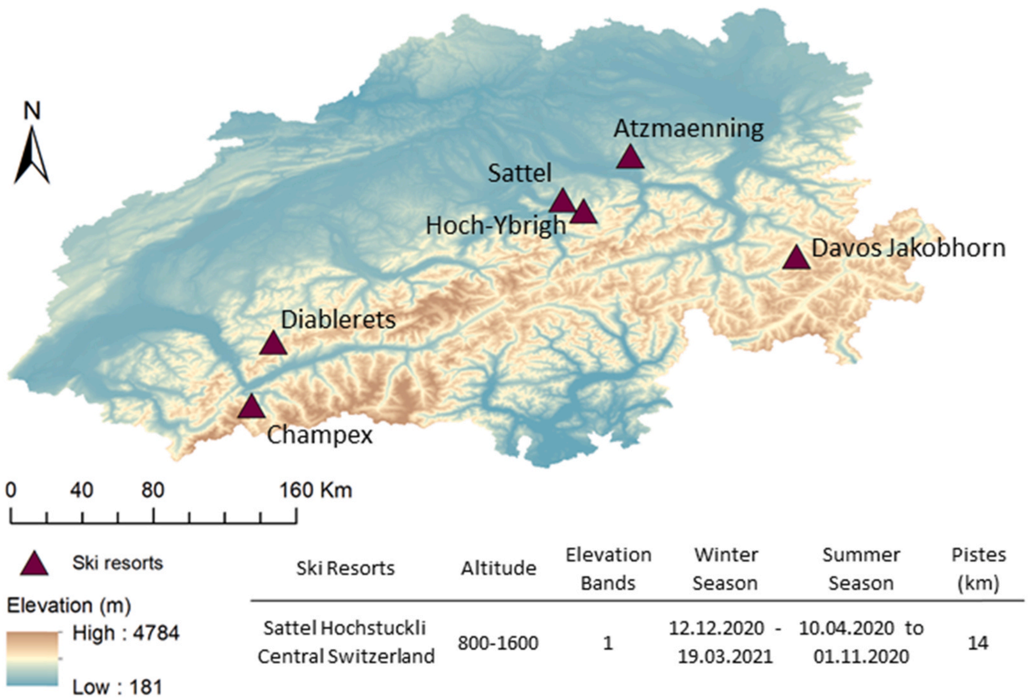
2. Data and method

2.1. Study areas

A total of six ski resorts in the Swiss Alps have been selected to represent a breadth of factors, including elevation, size, facilities, and the number of annual visitors (Fig. 1) (details are provided in the supplementary material (SM, Section A.1)).

2.2. DMDU framework for Swiss Ski Resorts

We use a variety of exploratory modeling techniques (see SM, Section A: Data and Method) to gain insight into the impacts of climate change in ski resorts. The exploratory approach searches a wide range of possible future scenarios (**objective i**). **'Scenario discovery'** (Bryant and Lempert, 2010) identifies the combination of uncertainties and policies with a large probability of tipping points (**objective ii**). **'Feature scoring'** (Guyon and Elisseeff, 2003) illuminate the uncertainties (X) and policies (L) that have the most considerable impact on the number of good snow days (**objective iii**). **Dynamic adaptive policy pathways (DAPP)** (Haasnoot et al., 2013) show which adaptation actions should be taken to avoid future tipping points (**objective iv**). We use the XLRM framework, $\mathbf{M = R\ (X,\ L)}$ (Lempert, 2003), to structure the decision problem and introduce the case. Our decision problem is that ski resorts operators have to decide on the appropriate adaptation options to avoid the tipping points in an uncertain future.



Ski Resorts	Altitude	Elevation Bands	Winter Season	Summer Season	Pistes (km)
Sattel Hochstuckli Central Switzerland	800-1600	1	12.12.2020 - 19.03.2021	10.04.2020 to 01.11.2020	14
Atzmaennig Eastern Switzerland	840-1200	1	10.12.2020 - 20.03.2021	13.04.2019 to 20.10.2019	8
Hoch-Ybrig Central Switzerland	1050-1820	1	12.12.2020 - 19.03.2021	04.07.2020 - 18.10.2020	50
Champex–Lac Valais	1484-2194	1	12.12.2020 - 26.03.2021	13.06.2020 - 14.09.2020	15
Les Diablerets Vaud	1200-3200	4	19.12.2020 - 11.04.2021	04.05.2020 - 18.10.2020	84
Davos Jakobshorn Graubünden	1540-2590	3	04.12.2020 - 18.04.2021	27.06.2020 - 18.10.2020	55

Fig. 1. Alpine topography in Switzerland and location of the ski resorts.

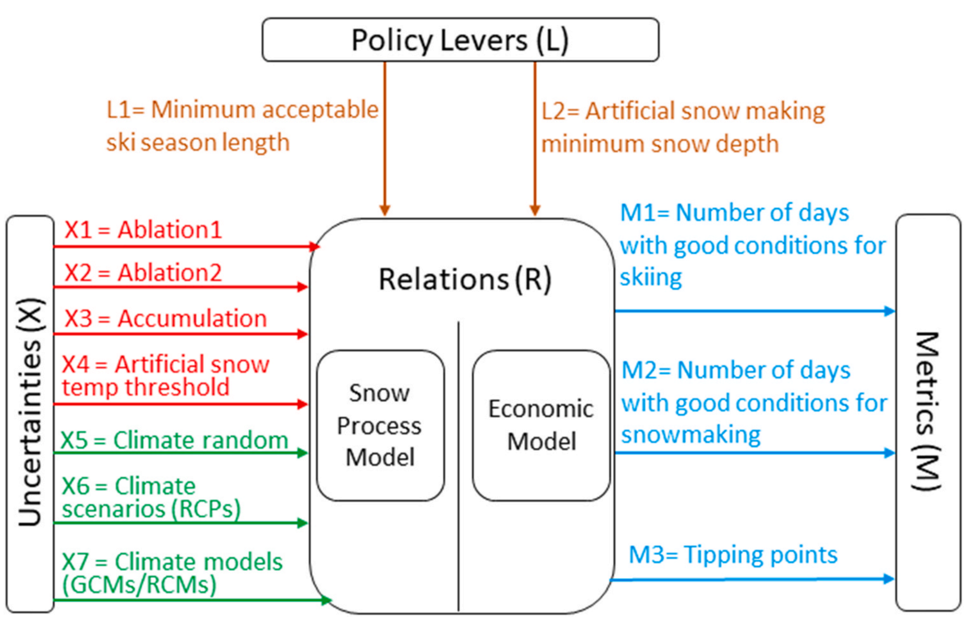


Fig. 2. A schematic framework of XLRM and deep uncertain variables, levers, metrics in ski resorts. X1-X7: 200 options, L1: 5 options, and L2: 9 options.

Our framework defines the resorts' performance metrics (M), the uncertainties (called eXternalities, X), and possible policy actions (called Levers, L); see Fig. 2 and Table 1 for details.

The first performance metric (M1) is the 'number of days with suitable conditions for snowmaking' (GDSM). The second metric (M2) compares the 'seasonal number of suitable snow days for skiing' to a critical threshold for making a profit (GSD). M2 is derived from the '100-day rule: a prominent snow indicator for the ski tourism industry (Abegg et al., 2020; Bürki R, 2000), defined as "A ski resort can be considered snow-reliable if, in 7 out of 10 winters, sufficient snow covering of at least 30–50 cm is available for skiing on at least 100 days between December 1 and April 15" (Bürki R, 2000).

The ski resorts' financial situations depend not only on the full skiing season performance but also on sufficient snow during critical periods such as Christmas, New Year, and school holidays (Abegg, 2012; Elsasser and Bürki, 2002). Ski operators can cope with a limited number of days with snow cover below the 30 cm threshold during the peak time. Therefore, the 100-day rule needs adjustment before it can be considered a robust tipping point indicator. A proper solution is to assume that the Christmas, New Year, and winter holidays rules are fulfilled if the mean snow depth is larger than 30 cm during the given periods (Abegg and Steiger, 2016).

The third metric (M3) is the tipping point at ski resorts. We define our socio-economic tipping point using a fuzzy 100-day rule. We consider a ski resort to be snow-reliable, if in 7 out of 10 winters, sufficient snow covering of at least 30 cm is available for skiing on at least N days (e.g., $60 \leq N \leq 100$) between December 1 and April 15, considering the Christmas and New Year Holidays. We implement the Christmas and New year holiday rules by allowing the snow cover to be above 30 cm not for each day but on average based on literature recommendations (Abegg and Steiger, 2016). Snow reliability is considered here as an indicator for a socio-economic tipping point. We acknowledge that in the past, ski resorts may have tipped when snow reliability could not be guaranteed based on our fuzzy 100 day rule. However, each ski resort's financial bottom-line benefits from subsidies, shares, and other financial instruments, which cannot be explicitly accounted for here. We use the fuzzy 100-day rule as a first-order indicator that can illuminate potential critical thresholds. Therefore, we only calculate the difference between projected and historical tipping points throughout the ski resorts and interpret the differences to the baseline, which is also a standard practice in analyzing climate model impact results (e.g., Rosa et al., 2020).

Table 1
XLRM framework deeply uncertain parameters, policies, metric.

Name	Description	Range (units)
X1 = Ablation_1	Uncertainty due to parameter melt factor (FM) in the ablation	±[10,45] (%) of initial value
X2 = Ablation_2	Uncertainty due to solar radiation impact on the ice-melt (iPot) in the ablation	[900,1200] ($W \quad m^{-2}$)
X3 = Accumulation	Uncertainty due to freezing water contribution to the accumulation	[20,60] (%)
X4 = Art_Snow	Temperature threshold for artificial snowmaking	[−2, −1]°C
X5 = Climate_Random	Uncertainty due to the intra-annual variability of climate models	[1,2,3] 1: CH2018 2: first new climate realization using bootstrap 3: second new climate realization using bootstrap
X6 = RCPs	Uncertainty due to RCPs	RCP2.6, RCP 4.5, RCP 8.5
X7 = GCMs_RCMs	Uncertainty due to the selection of GCM-RCM chain (68 scenarios)	if RCP2.6: [1,12] if RCP4.5: [13,37] if RCP8.5: [38,68]
L1 = Good_Snow	Minimum accepted skiing season length for decision-makers	[60,100] days
L2 = Snow_Threshold	Minimum daily snow depth: (300 mm – 'L_Snow_Threshold'mm) 0–100 mm artificial snowmaking	[200,300] mm
M1 = GDSM	Seasonal number of days with good conditions for snowmaking	(days)
M2 = GSD	Seasonal number of days with good conditions for skiing	(days)
M3 = tipping	tipping points	(frequency)

The model relations, R, cover a snow process model with a highly stylized economic component that simulates daily snow cover depth and the number of days with good snow conditions per skiing season, see Section 2.3. X represents the external or exogenous factors, in other words: the uncertainties that are outside the control of decision-makers, e.g., climate change uncertainties. We include the uncertainty about: the future greenhouse gas emissions (X6 = climate scenario, RCPs); how RCPs affect the regional climate (X7 = climate models, GCMs/RCMs); and how this climate unfolds in intra-annual temperature and precipitation variability (X5 = climate randomness). Besides the climate uncertainty, there is uncertainty in developing the snow cover model even if the climate is known. The snow model uncertainty is reflected by three snow model parameters (X1 and X2 = uncertainty in ablation module, melting factor, X3 = uncertainty in accumulation module due to the contribution of freezing water to the accumulation). Finally, the temperature at which artificial snow can be made is uncertain (X4) due to the wide possible combination of temperature and relative humidity.

The levers (L) reflect the adaptation actions a ski resort can take. The first lever (L1) alters the required number of good ski days, i.e., the minimum accepted ski season length or the 100-day threshold. A resort may survive a shorter winter sports season by economic diversification of their year-round activities. Some winter sports facilities may be used during summers, such as ski lifts for transporting mountain bikes and tourists. whereas other activities (e.g., mountain coasters and alpine slides, indoor climbing walls) may share hotels and restaurants (Hagenstad et al., 2018; Hock et al., 2019). The second lever (L2) is artificial snowmaking (Spandre et al., 2019b), where a lack of natural snow depth is compensated by topping up artificial snow. We assume artificial snowmaking between 0 and 100 mm per skiing season for the second adaptation option to reach a minimum of 30 cm d^{-1} snow depth.

In industry, the wet-bulb temperature index is widely used to decide either a day is suitable for snowmaking or not. Wet-bulb temperature is directly related to relative humidity and outside temperature (e.g., Hartl et al., 2018). Both the industry reports and academic publications inform these reference values of temperature and humidity for snowmaking. Snowmaking is possible when the wet-bulb temperature is equal to or below −2 °C (e.g., Olefs et al., 2010). Therefore, a wide combination of temperature and humidity makes it possible to make artificial snow. In this study, we limit our choices to reduce the uncertainty space. We only consider the situation where −2 °C < temperature <−1 °C. The 2 °C to −1 °C range is the very sensitive set to relative humidity. Thus a slight change in the temperature could change the outcomes and metrics of the XLRM framework.

After defining the elements of XLRM, we set up the scenarios, policies, and experiments of the framework as follows. A scenario is a unique parameter setting for all external factors (X1-X7). We generate 200 scenarios (68 scenarios from CH2018 plus 132 new future climate realization using the bootstrap method (Chernick et al., 2011). A policy is a unique parameter setting for all policy levers (L1-L2). We generate 45 policies (5 alternatives for minimum accepted skiing season (L1) × 9 alternatives for snowmaking (L2)). Detailed information on all parameters and their ranges are summarized in Table 1. The combination of a scenario and policy is called an experiment. We execute a total of 9000 experiments (200 scenarios × 45 policies) per ski resort. The open-source Python library Exploratory Modeling and Analysis Workbench (ema-workbench) is used to coordinate the model simulations and to visualize results (Kwakkel, 2017), see 'code and data availability).

2.3. Snow process model, climate scenarios, and economic model

We use a physically-based snow-process model to simulate (past and future) natural snow cover per ski resort on a daily time step. This mass balance model accounts for site-specific topographic features, including elevation, slope angle, and climatic characteristics, to project natural snow. The model consists of an "Accumulation" module after (Farinotti et al., 2012) and an "Ablation" module after (Hock, 1999). Readers could refer to the SM, section A.4 for more details about our snow process model. For the snow process model, we recognize three sources of uncertainty, with ranges and base values as outlined in Fig. 2, based on the most commonly used settings in the literature (Farinotti et al., 2010; Huss et al., 2008). To assess the goodness of fit of snow process model results with observed data, we compared the satellite snow cover data obtained from satellite images for a reference period (1981–2010) (Hall and Riggs, 2015) with the respective simulated values using the SUFI-2 algorithm (Abbaspour et al., 2004, 2015). As for performance indicators, we used the coefficient of determination (R^2). The results of the snow process calibration are summarized in Table S3. in the SM, section A.7.

Future climate uncertainty is derived from the CH2018 (CH2018, 2018) Switzerland's future projections (Jacob et al., 2014). The CH2018 scenarios consist of 68 EURO-CORDEX simulations (12, 25, and 31 simulations for greenhouse gas scenarios RCP2.6, RCP4.5, and RCP8.5, respectively) (Riahi et al., 2011; Thomson et al., 2011; van Vuuren et al., 2011). We aggregate the nearest climate stations close to the center of the slope of ski resorts where possible or the center of each elevation band and provide a temperature and precipitation representative for that elevation band. We implement a bootstrap resampling technique (Dixon, 2001) and produce new climate realizations to improve the coverage of the uncertainty space and account for the intra-annual variability of the climate models. Resampling is performed over the GCMs-RCMs of each RCPs on an annual basis.

We quantify the changes in the financial status of ski resorts through a simplified economic model that calculates daily income based on and daily revenue and cost at the ski resorts.

$$Income_t = Revenue_t - Cost_t \tag{1}$$

Where $Income_t$ is ski resorts' total earnings or profit per day, $Revenue_t$ is the total amount of income per day generated by ski resorts as the sale of goods or services, and $Cost_t$ is the total amount of daily cost due to infrastructure, maintenance, staff, etc. If the snow depth during the skiing season is above the minimum daily threshold (200–300 mm, considering adaptation options), the ski resorts will earn a maximum possible revenue. We could assume hypothetical values for daily cost and revenue since we calculate the economic balance of future scenarios relative to the reference period. The daily cost is considered constant during the skiing season. This assumption is naive since the operational costs at the beginning of the season are typically higher due to snow-making and reopening costs.

3. Results

We first present future projections of changes in the number of days with good snow conditions (GSD) (Figs. 3 and S1), the number of days with suitable conditions for snowmaking (GDSM) (Fig. S2), and the relative changes in the financial status of the resorts (Fig. S3) for the time horizons we call near-future (2020–2050), mid-future (2050–2080), and far-future (2070–2100). Second, we identify the most relevant features to include in a decision-making model for ski resorts (Figs. 4 and S4), and we present our scenario discovery assessment results that demonstrate the sensitivity of the outcome metrics (M1-M3) to the input parameters (X1-X7 and L1-L2) (Figs. 5 and S5−S14). Third, we show under which adaptation options the ski resorts do not confront more tipping points in the future than the reference period (Fig. 6). Finally, we demonstrate possible adaptation options ranging from "low revenue diversification and moderate snowmaking" to "high revenue diversification and large snowmaking" and indicate when an adaptation action fails and a change to a new plan is needed (Fig. 7).

Ski resorts located in medium-high elevation mountains (1200–3200 m) include Les Diablerets and Davos Jakobshorn and have a wide range of variations in elevation; thus, to analyze more precisely, we divided the resorts into four and three elevation bands, respectively. Due to space constraints, we could not present all results in the main submission. We briefly discuss selected results here for completeness, and for the rest, we refer to SM (see SM, section B to find complementary details).

3.1. Projection of changes in GSD, GDSM, and financial status

The long-term projection of GSD, GDSM, and financial status gives decision-makers a big picture of the trend, seasonality, and noises of outcomes of the XLRM framework. Table 2 presents the declines in GSD, GDSM, and financial status of the resorts compared to the reference period. Generally, the lowest declines in GSD, GDSM, and financial status occurred under RCP2.6, followed by RCP4.5, and the highest decreases are seen under RCP8.5. In Davos-Jakaobhorn and Les Diablerets with different elevation bands, a higher magnitude of change is projected for the lower bands.

The inter-annual fluctuation of the GSD is high in all types of ski resorts (Fig. 3), and a sharp decreasing trend is seen after 2050 under the RCP 8.5 scenarios in all types of ski resorts. Low- and mid-altitude ski

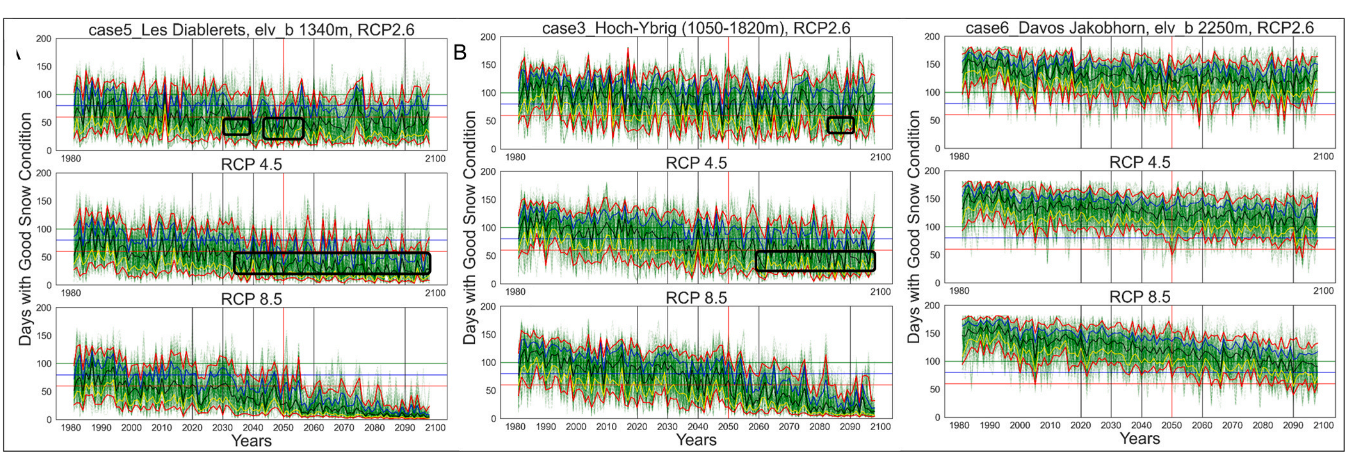


Fig. 3. Annual evolution of the number of days with good snow conditions (GSD) in three types of ski resorts. (A) low-altitude, represented by Les Diablerets (1340 m), (B) mid-altitude, represented by Hoch-Ybrigh, (C) high-altitude, represented by Davos Jakobhorn (2250 m).

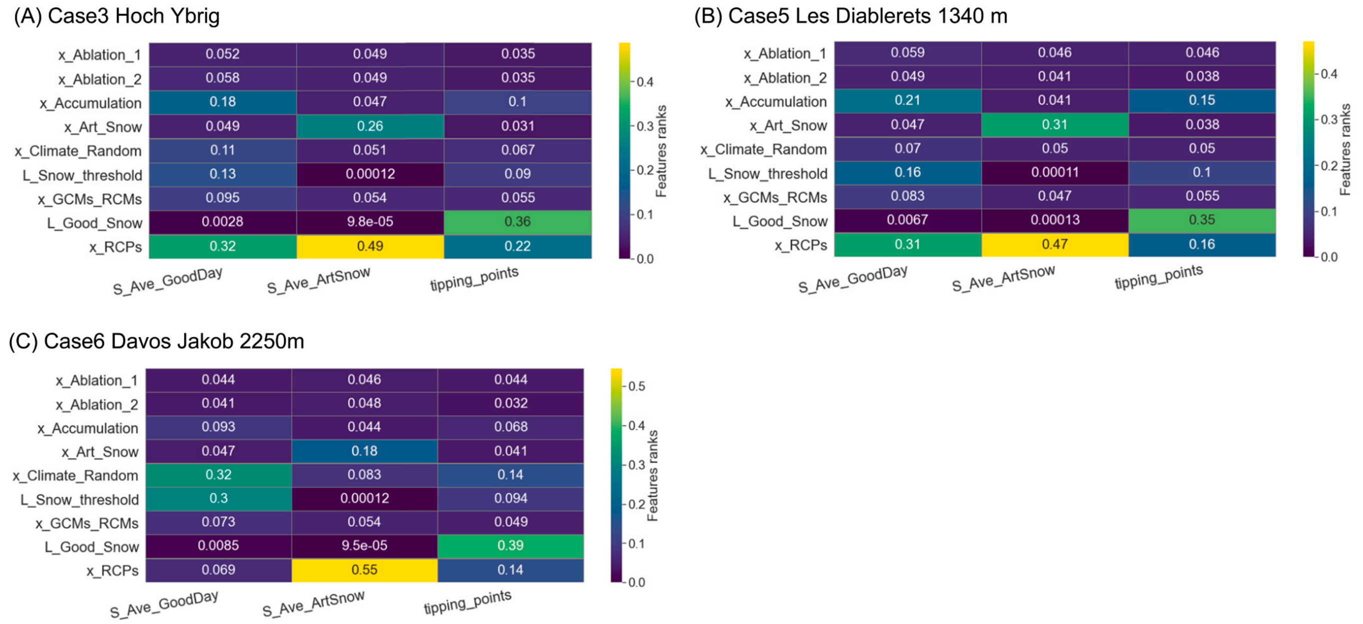


Fig. 4. Feature scoring analysis of ski resorts, showing the relative importance of the choice of measures and uncertainties (y-axis) for the outcomes (x-axis). Higher numbers indicate higher importance. Results correspond to three types of ski resorts. (A) low-altitude, represented by Les Diablerets (1340 m), (B) mid-altitude, represented by Hoch-Ybrigh, (C) high-altitude, represented by Davos Jakobhorn (2250 m).

resorts will face a situation with limited years of GSD >75 days. The green shadow in Fig. 3 shows the uncertainty band in the projection of the GSD. The uncertainty arises due to the various input parameters of 9000 experiments. The area below the GSD = 60 line shows the experiments where even the maximum diversifying options cannot ensure the minimum 60 days length of skiing seasons. Those years with a large portion of the experiments below the GSD = 60 line should be considered the high-risk years for operators. We demonstrate a representative for each low-, mid-, and high-altitude ski resort (see SM section B.2 for more details). Under RCP2.6 and in low- (Fig. 3A) and mid-altitude (Fig. 3B) ski resorts, the median of experiments (black line) is above the GSD = 60 line in many years, showing that ski resorts could safely diversify the revenue and still have the minimum 60 days of the skiing season. However, a few troughs, distinguished by black boxes in the figures, present that there are consecutive years where GSD drops below 60 in more than 50% of possible future scenarios.

In Les Diablerets elevation band 1340 m (Fig. 3A), a representative for low-altitude ski resorts, where GSD and GSDM are low even in the baseline period (74 and 77 days, respectively), we see significant declines in GSD and GDSM in the future. The co-occurrence of less GSD and GDSM (up to 17, 34, and 50 days decrease in GSD and 22, 49, and 71 days decline for GDSM for near-, mid-, and far-future) make a severe situation where the ski resorts' survival is not possible anymore. Many troughs (black boxes) in GSD and GDSM plots support the above interpretation.

In Hoch-Ybrigh, a representative for mid-altitude ski resorts, we project that GSD will decrease to 76 days in the near-future, 62 days in the mid-future, and 53 days in the far-future (Table 2, Fig. 3B). Similarly, GDSM will decrease to 75 days for the near-future, 61 days for the mid-future, and 45 days for the far-future (Table 2, Fig. S2-C). Relative to the resort's income during the reference period, Hoch-Ybrigh could face 10%, 18%, and 38% losses in revenue in the near-, mid-, and far-future, respectively (Fig. S3-C).

In Davos-Jakaobhorn elevation band 2250 m (Fig. 3C), a representative for high-altitude ski resorts, we project a decline of a maximum of nine days in the future that shows 92–99 GSD for RCP 8.5 and RCP2.6. For the GDSM, the slight decrease of up to 11 days is projected, where the baseline GDSM is 145 days. The results show that although the elevation band of 2250 m is hit by climate change, however, the condition remains suitable for skiing and snowmaking. We aggregate the financial status of all elevation bands of Davos-Jakaobhorn to a single indicator which shows up to 5%, 17%, and 31% of declines relative to the baseline condition.

3.2. Sensitivity to input parameters

To evaluate the sensitivity of the outcomes to the input parameters, we use feature scoring to rank the effect of exogenous factors (X) and policy levers (L) on the outcome metrics (M) (Fig. 3, and SM 4). With a high consistency between the low- and mid-altitude ski resorts, results show that the main drivers of the average of seasonal good snow days metric (S_Ave_GoodDay) are RCPs, followed by uncertainty of snow process model in the calculation of accumulation and L_Snow_threshold. However, in the high-altitude ski resorts, the dominant driver is intra-annual climate variability followed by L_Snow_threshold. In all three types of ski resorts, the average of seasonal good snow days for snowmaking metric, S_Ave_ArtSnow, is mainly controlled by RCPs followed by temperature threshold for artificial snowmaking x_Art_snow. For tipping points metrics, the main two drivers of outcome are the length of skiing season (L_Good_Snow) and RCPs, while the third driver varies between low-, mid-, and high-altitude resorts. Some key findings are summarized here:

- Global warming level, which RCPs translate, plays a significant role in determining all outcome metrics.
- The uncertainty in calculating ablation in the snow process model seems less significant than the uncertainty of Climate models, RCPs, and climate intra-model variability.
- Metrics in the low- and mid-altitude ski resorts react similarly to changes in input parameters. In contrast, in high-altitude resorts, the role of intra-annual climate variability is more highlighted.
- The sensitivity of outcomes depends on the metric at which we look.
- Tipping points are influenced by artificial snowmaking, skiing season length, diversification of revenue, and RCPs. However, diversification of revenue only affects tipping points and no other metrics.

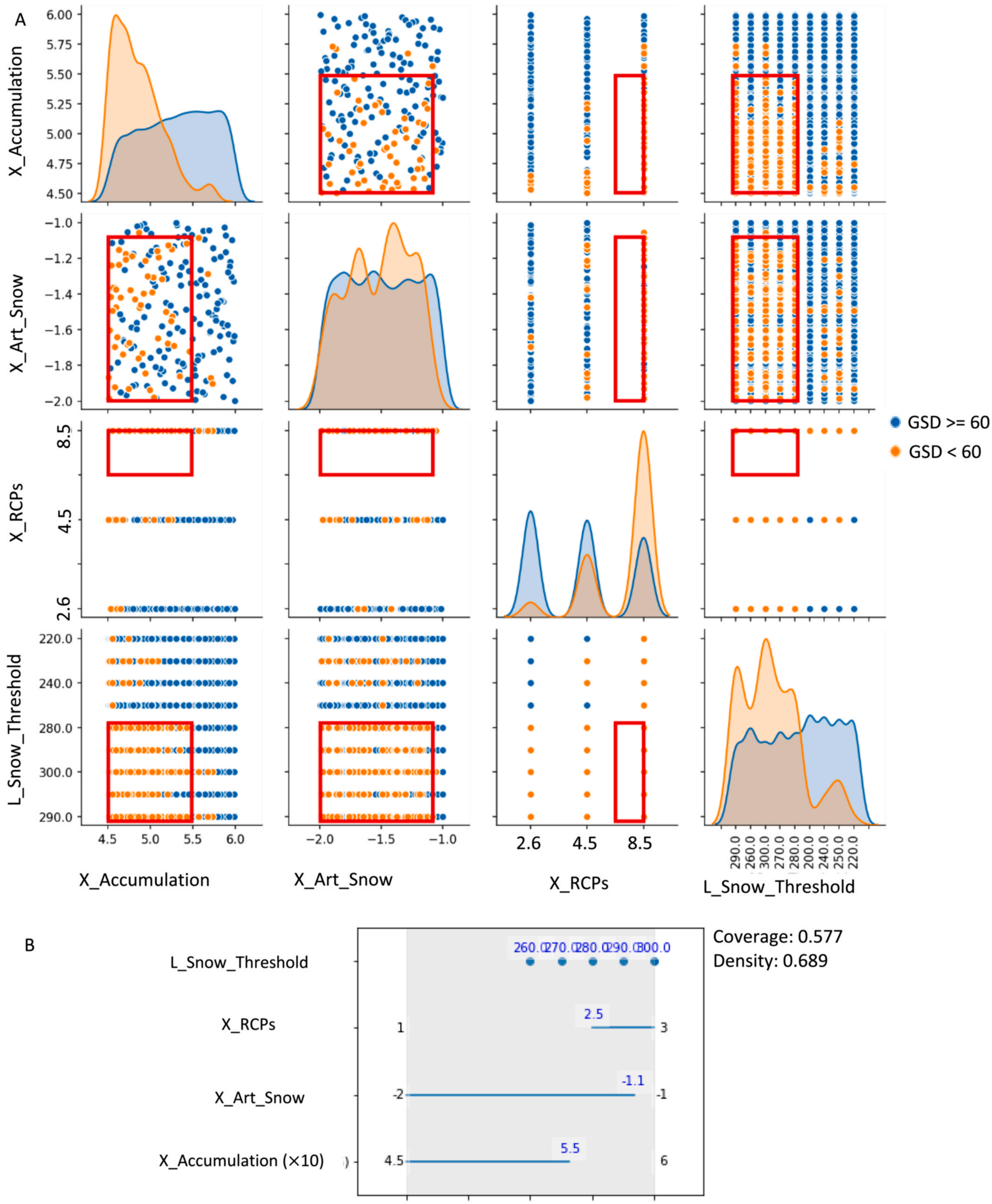


Fig. 5. Scenario discovery analyses of Hoch-Ybrigh. Experiments were plotted as a function of four parameters that best represent the ski resorts' potential vulnerabilities to the GSD metric. The most important parameters are X_Accumulation, X_Art_Snow, X_RCPs, and L_Snow_Threshold (5 A). Orange dots show experiments where GSD falls below 60 days, and red lines show parameters values corresponding to the boundaries of the scenarios. The ranges of parameters that define the condition where GSD $<$ 60 days, density, and coverage for the boxes (5B).

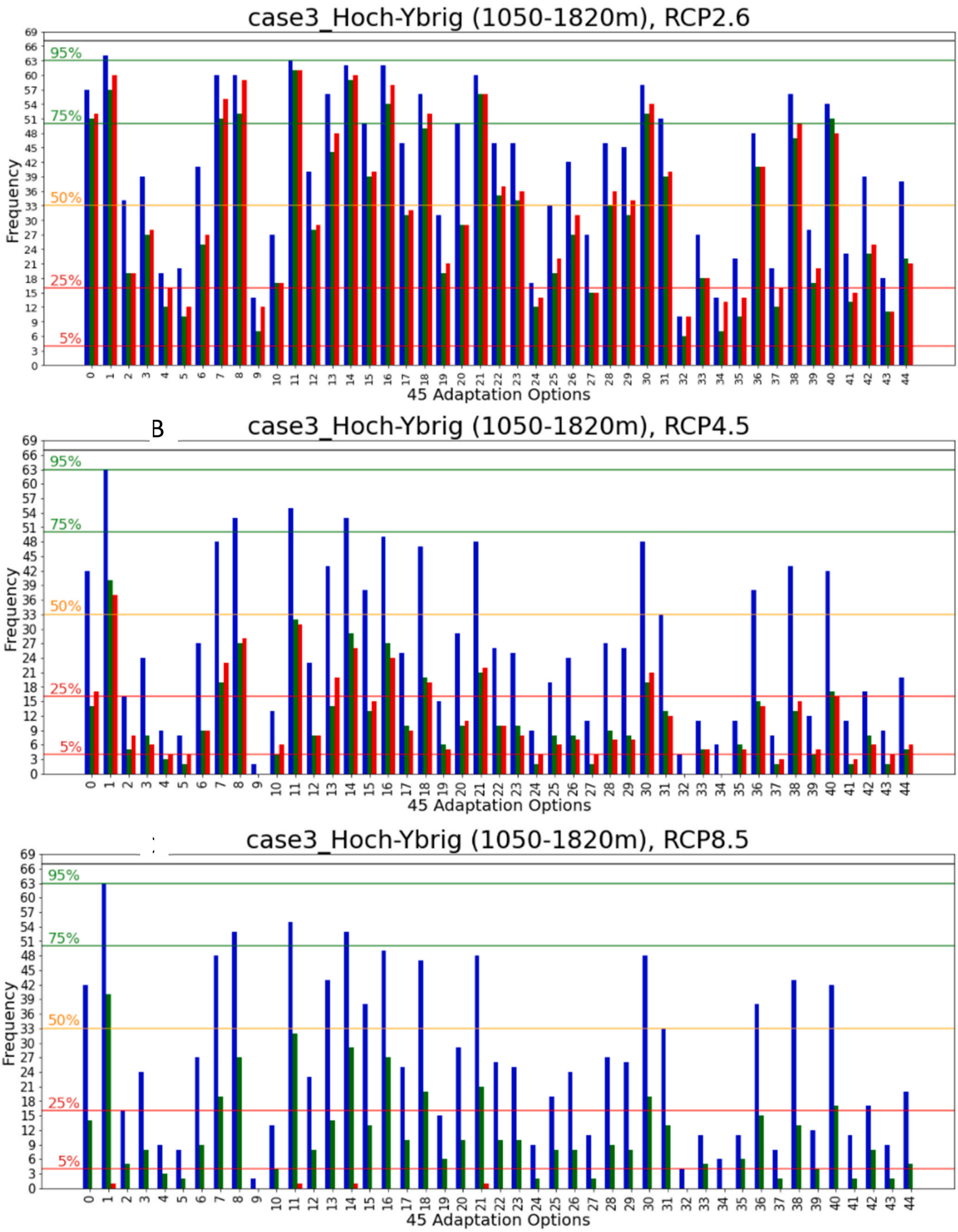


Fig. 6. Frequency of adaptation options at 'Hoch-Ybrigh' ski resort where tipping points remain similar to the reference period. Each adaptation option is used in 200 simulations split equally between RCPs (66 or 67scenarios each). (A) RCP2.4, (B) RCP4.5, (C) RCP8.5. Near, mid, and future time horizons are presented by blue, green, and red bars. The 95%, 75%,50%, 25%, and 5% lines present different confidence levels of decision-making.

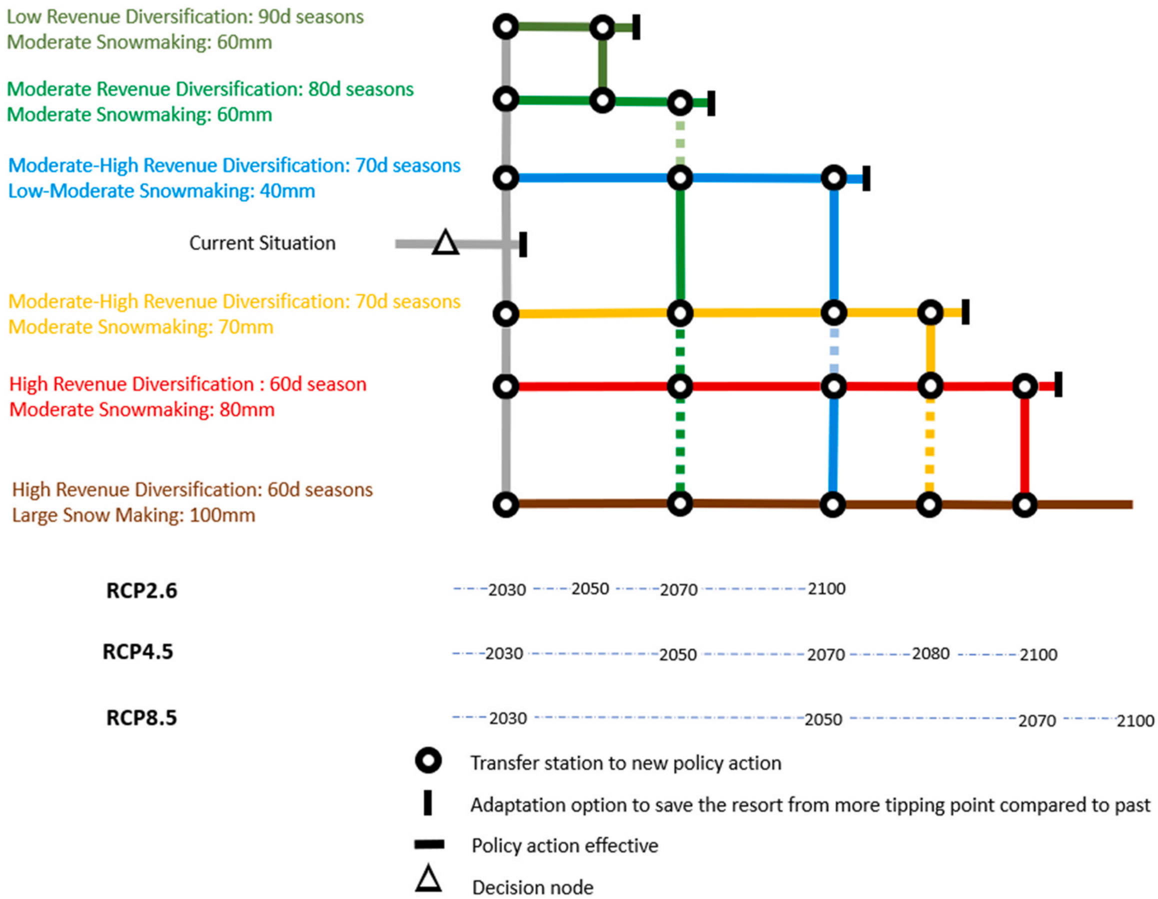


Fig. 7. Adaptive pathways of a Hoch-Ybrigh (known as a metro map), mid-altitude ski resort representative, showing sequences of possible adaptation actions to avoid tipping points under climate change. Note that a transition to income diversification is no longer possible when opting for medium or large snowmaking facilities because of the increased operating costs. Dotted lines are adaptation options that are less probable to be taken.

Table 2
Future projection of declines in the number of days with good snow conditions (GSD), the number of days with suitable conditions for snowmaking (GDSM), and the financial balance of the resorts for near-future (2020–2050), mid-future (2050–2080), and far-future (2070–2100) relative to the reference period (1981–2010).

		Ref	GSD (day)			GDSM (day)			Financial balance (%)		
		GSD, GDSM	2020–2050	2050–2080	2070–2100	2020–2050	2050–2080	2070–2100	2020–2050	2050–2080	2070–2100
Sattel	800–1600 m	94, 95	14 (11–17)	30 (25–34)	42 (34–50)	15 (19–22)	36 (22–49)	48 (25–71)	9.5 (6–13)	14 (10–28)	29 (14–44)
Atzmaennig	840–1200 m	90, 66	19 (15–23)	27 (19–35)	36 (24–48)	20 (11–28)	33 (16–50)	40 (20–60)	9 (7–11)	17 (11–24)	28 (15–41)
Hoch Ybrig	1050–1820 m	90, 91	15 (10–20)	28 (19–36)	37 (22–52)	16 (9–22)	31 (15–46)	45 (21–71)	10 (6–15)	18 (9–26)	28 (13–42)
Champex	1480–2200 m	96 94	10 (8–12)	21 (18–25)	34 (19–50)	21 (17–25)	34 (19–49)	51 (24–79)	8 (5–11)	20 (10–30)	35 (18–52)
Les Diablerets	1340	74, 77	16 (10–21)	29 (18–41)	40 (22–58)	25 (20–30)	41 (29–54)	56 (27–65)	9 (5–13)	22 (10–33)	32 (14–51)
	1800	95, 96	12 (9–15)	23 (10–36)	34 (18–50)	3 (2–4)	17 (2–33)	34 (8–60)			
	2000	98, 97	15 (12–18)	26 (13–39)	37 (21–53)	2 (0–4)	2 (0–4)	22 (6–50)			
	2500	154, 158	25 (20–31)	39 (28–50)	57 (51–62)	11 (10–13)	24 (13–35)	32 (20–45)			
Davos Jakobhorn	1560	96, 97	6 (4–8)	15 (0–29)	28 (10–46)	13 (11–15)	15 (1–29)	22 (12–32)	4 (3–5)	11 (5–17)	20 (9–31)
	2000	97, 127	3 (0–6)	3 (0–6)	12 (7–17)	15 (11–19)	29 (26–31)	37 (35–39)			
	2250	101, 147	2 (0–4)	2 (0–4)	9 (7–11)	15 (12–18)	33 (16–50)	43 (28–57)			

3.3. Finding tipping point scenarios

Scenario discovery results determine scenarios and policies under which ski resorts' DMDU outcomes go below a critical threshold specified by decision-makers. To demonstrate the performance of scenario discovery and to show how decision-makers can benefit from that, we present the results for GSD <60 days for Hoch-Ybrigh (Fig. 5). We choose 60 days threshold for GSD since there is no defined option for diversifying winter tourism activities below this number, and one can interpret it as a minimum accepted length of the skiing season. The axes in Fig. 5 represent key driving forces in Hoch-Ybrigh ski resort that define the scenario representing unacceptably low GSD for the 200 × 45 experiments.

The figure shows the model parameters that distinguish the simulations where the GSD is less than 60 days (Fig. 5A). The length of each blue line represents the subset of the corresponding parameter's uncertainty range leading to these low good snow days scenarios (Fig. 5B). The smaller the subset, the better the parameter can be distinguished. The numbers at the two ends of the grey lines are the lower and upper boundaries of the entire uncertainty range of a parameter, whereas the numbers in blue at the end of the blue lines refer to the identified subset boundary (box limits).

The scenario discovery results suggest that in future scenarios where four conditions hold, the experiments are likely to produce GSD <60 days, irrespective of the value of the other five uncertain parameters in the model (Fig. 5A, B) (see SM, Figs. S5-S14 for other resorts). The conditions follow as (1) RCP 8.5, (2) minimum accepted daily snow depth exceeds 260 mm, (3) the contribution of freezing water in the accumulation module drops below 55% of total accumulation, and (4) temperature where snowmaking could start drops below −1.1 °C.

3.4. An application of DAPP to the future management of ski resorts

Using 9000 experiments, we determine which adaptation options should be implemented under different RCPs (when the future unfolds) to avoid having a worse situation than the reference period. Suppose the ski resorts' operators chose the presented adaptation options in Table 3. We could argue that in the 75% of possible futures (75% confidence level), ski resorts would have an equal or less frequency of tipping points than the reference period in future scenarios. Therefore they can survive with similar business models and governmental supports that they have had in the historical period. Our results could be used for decision-making at various 95%, 75%, 50%, 25%, and 5% confidence levels (Fig. 6 for only Hoch-Ybrig, but the same approach can be applied to other resorts).

For Hoch-Ybrigh under RCP2.6 scenarios, in the near- and mid-future, a 90-day skiing season should be anticipated, while in the far-future, a 60-day skiing season is expected only with 100 mm artificial snowmaking (Table 3, Fig. 6A). Comparison of 45 different adaptation options in 200 plausible future scenarios (split equally between three RCPs) at Hoch-Ybrigh reveals that under RCP2.6, there are 26 out of 45 adaptation options that keep the resort operational at 95% of confidence in the near-future. In contrast, only 10 and 5 options can be used safely for the mid- and far-future (Fig. 6A).

Similarly, we could interpret other confidence levels (e.g. 75% and 50%). Under RCP4.5 (Fig. 6B) and RCP8.5 (Fig. 6C), the resort will face a dramatic situation where there will be no adaptation option at 95% confidence that could keep the resort operational.

When the future unfolds similar to RCP4.5 scenarios, the Hoch-Ybrigh ski resort can survive in the near-future by taking the adaptation 80-day ski season and 60 mm artificial snow (Table 3 and Fig. 6B).

When the future unfolds similar to RCP8.5 scenarios, there are 6 and 24 adaptation options at 95% and 75%, respectively, which could keep the operation of the resort as the reference period. In the mid-future, there are only 3 adaptation options that could be implemented at 75% confidence, while for the far-future, there is no adaptation option that can be used in the resort. Table S3 (see SM) summarizes 45 combinations of adaptation options (Table 3 and Fig. 6C).

We use DAPP to explore specific combinations of options that are adaptive and robust over different future scenarios. We implement this by taking the historical number of tipping points as a benchmark for the survival of the ski resort in the future. This choice is justified by the presence of several tipping points in the reference period. We assume that so-called "historical tipping points" did not prevent the resorts from continuing their operations due to provided support by governments (e.g., subsidies) or alternatives in the business models of ski resorts.

Table 3

Adaptation options for six ski resorts under RCP2.6, RCP4.5, and RCP8.5 scenarios for three future horizons. Adaptation options are presented with two numbers. The first number shows the shortened ski season, e.g., 80-d means that the ski season will be shortened 20 days from the historical 100-day season. The resort needs to generate supplemental revenue in 20 days from other activities than winter sports. The second number presents the required depth of artificial snowmaking (mm) that is needed for the resort.

		RCP2.6			RCP4.5			RCP8.5		
		2020–2050	2050–2080	2070–2100	2020–2050	2050–2080	2070–2100	2020–2050	2050–2080	2070–2100
Sattel	800–1600 m	80-d 80 mm	70-d 50 mm	60-d 60 mm	80-d 40 mm	–	–	–	–	–
Atzmaennig	840–1200 m	90-d 60 mm	80-d 80 mm	70-d 100 mm	60-d 60 mm	–	–	60-d 80 mm	–	–
Hoch Ybrig	1050–1820 m	90-d 20 mm	90-d 50 mm	60-d 50 mm	80-d 60 mm	70-d 40 mm	60-d 80 mm	70-d 20 mm	60-d 100 mm	
Champex	1480–2200 m	90-d 40 mm	80-d 60 mm	70-d 80 mm	80-d 60 mm	70-d 100 mm	60-d 60 mm	80-d 60 mm	60-d 60 mm	–
Les Diablerets	1340 m	70-d 80 mm	60-d 100	–	–	–	–	–	–	–
	1820 m	90-d 30 mm	80-d 20 mm	80-d 20 mm	90-d 60 mm	70-d 60 mm	60-d 80 mm	80-d 40 mm	60-d 60 mm	–
	2000 m	90-d 20 mm	80-d 40 mm	80-d 50 mm	90-d 0 mm	80-d 40 mm	70-d 30 mm	90-d 30 mm	70-d 30 mm	60-d 100
	2500 m	100-d 0 mm	100-d 0 mm	100-d 0 mm	100-d 0 mm	100-d 0 mm	100-d 0 mm	100-d 0 mm	100-d 0 mm	100-d 0 mm
Davos Jakobshorn	1560 m	80-d 40 mm	70-d 50 mm	60-d 60 mm	60-d 70 mm	–	–	–	–	–
	2000 m	90-d 20 mm	80-d 20 mm	70-d 30 mm	90-d 30 mm	70-d 40 mm	70-d 80 mm	80-d 30 mm	80-d 80 mm	70-d 80 mm
	2250 m	90-d 0 mm	90-d 0 mm	90-d 0 mm	90-d 40 mm	90-d 60 mm	80-d 60 mm	80-d 40 mm	70-d 40 mm	70-d 60 mm

The metro map in Fig. 7 combines RDM and DAPP approaches and reflects the different stages of adaptation options and evaluating adaptation pathways for the Hoch-Ybrigh ski resort. A key feature of Fig. 7 is that conditions leading to tipping points can be presented alongside policy options in the metro map to inform decision-makers about the conditions at which individual policies no longer manage avoiding ski resorts from tipping points. From top to down map shows different adaptation options for a range of RCPs and is flexible to further adapt in the future. As the implementation of other options can take resources, decisions will need to be triggered well before the anticipated use-by-year to manage climate change impacts successfully. An adaptation pathways map of Hoch-Ybrigh shows how decision-makers can adjust the resorts to different future scenarios before reaching adaptation tipping points. Following the grey lines of the current situation, one can see six options in the near future. According to the level of global warming, which RCPS translate, decision-makers could change adaption option in the future. Under RCP2.6, Hoch-Ybrigh ski resort could implement the action (90d, 60 mm) to achieve the target for the next 30 years while for the RCP4.5 and RCP8.5 adaptation actions (80d, 60 mm) and (70d, 40 mm) should be applied, respectively. High revenue diversification and large Snowmaking options (60d, 100 mm) is a safe option that can be used in all climate change scenarios up to 2080 (brown line).

4. Discussion

Ski tourism is the most studied segment of the tourism and climate change literature (Fang et al., 2018) due to its strong reliance on good snow conditions, which can become rarer already in the near-future (Scott et al., 2019, 2020). Nonetheless, there is a gap in the effectiveness and timing of adaptation options in dealing with the many socio-economic uncertainties. This study assessed the role and importance of various uncertainties for decision-making and their evolution over time. By explicitly considering uncertainties in the decision problems, we assessed the performance of various adaptation options to prevent socio-economic tipping points for six ski resorts. The problem is spatially explicit and representative of different elevations. This represents an improvement over previous studies that used the single-point representations to assess a given ski resort's snow and meteorological conditions, often using only the median elevation (Abegg et al., 2007; Dawson and Scott, 2013; Gilaberte-Búrdalo et al., 2017; Steiger, 2010).

A chain of GCM-RCMs has been extensively used in the literature to address the impacts of climate change on environmental indicators (Ashraf Vaghefi et al., 2019; Fiddes et al., 2019; e.g., Hausfather and Peters, 2020; Kotlarski et al., 2014; Schmucki et al., 2017). Some studies have used the ensemble (e.g., Ashraf Vaghefi et al., 2019; Schmucki et al., 2017), while others have used regional climate models (e.g., Hausfather and Peters, 2020) to assign a single set of best-estimate probabilities to all future emissions scenarios. This approach could give decision-makers a false sense of certainty, leading to costly adjustments if the world evolves in unanticipated ways. In contrast, this study used an exploratory modeling approach to (1) identify the combination of uncertainties and policies with a high probability of tipping points (2) illuminate the uncertainties and policies that have the largest impact on the metrics of the system (GSD, GDSM, and tipping point), and (3) show which adaptation actions should be taken to avoid future tipping points in ski resorts.

We demonstrated how the main drivers that impose uncertainty on the system change over time (Figs. 3, 8, and S15). To find underlying patterns in the time series of GSD and to avoid misinterpretation due to local peaks and troughs of GSD plots (Fig. 3), we smoothed the time series of GSD with a 10-year rolling window (Fig. 8). Then we investigated if the sensitivity of the output parameters would change in near-, mid-, and far-future horizons. At the beginning of the time series (GSD_10), the number of days with good snow conditions is mainly determined by the uncertainty of the snow process model and the threshold of the accepted skiing season length. However, at the end of the time-series (GSD_100), RCP starts to completely dominate all the uncertainty, indicating that climate change is by far the most important projector for snow conditions by the end of the century, despite all the uncertainty in the other parameters.

Our results show ski resorts located below the 1820–2000 m lines

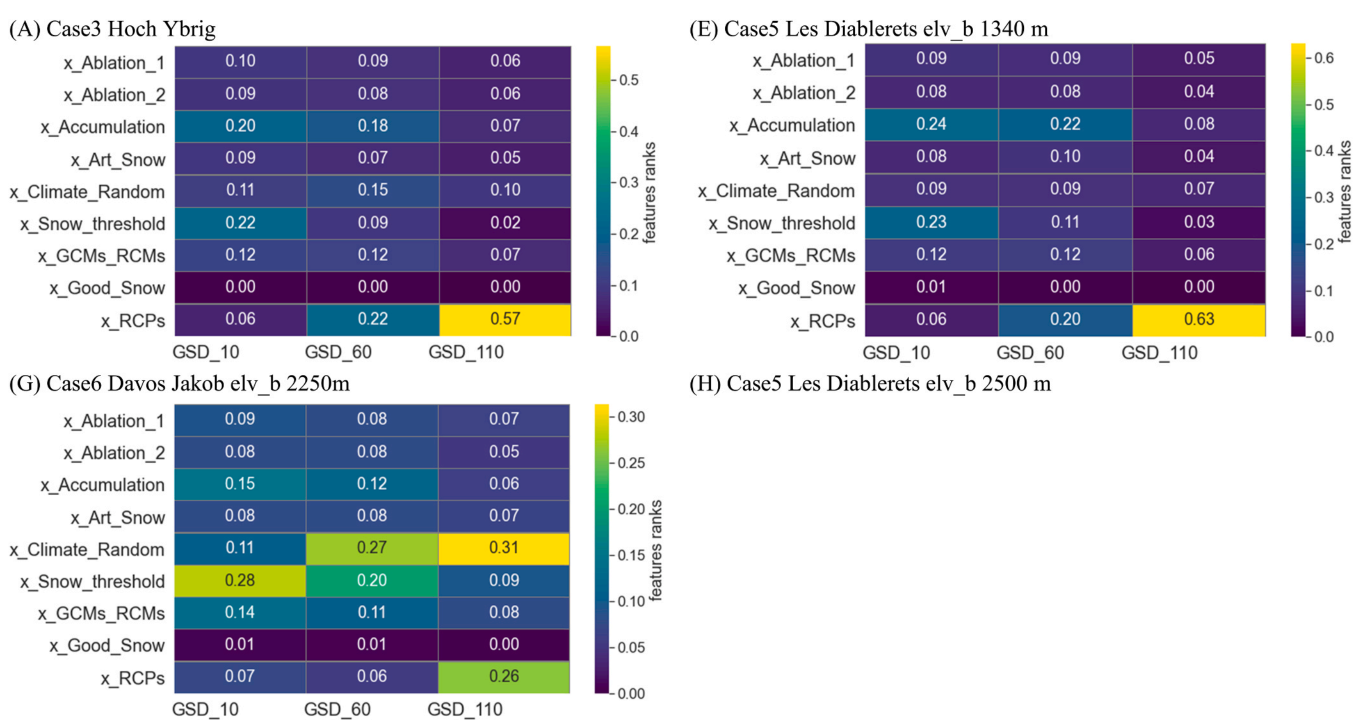


Fig. 8. Feature scoring analyses for GSD with a 10-year rolling window over three future horizons. Results correspond to three types of ski resorts. (A) low-altitude, represented by Les Diablerets (1340 m), (B) mid-altitude, represented by Hoch-Ybrigh, (C) high-altitude, represented by Davos Jakobhorn (2250 m).

will be facing challenges from the 2050 s onwards, and even artificial snowmaking will not be enough to secure their survival (no adaptation option for Hoch-Ybrigh between 2070 and 2100, Fig7, 8 and Table 3). The findings are in line with other studies in Alpine regions (e.g. Bürki R, 2000; Elsasser and Bürki, 2010). The situation is different for ski resorts that extend over several elevation bands, especially for the altitude of above 2000 m. In that case, numerous adaptation options could secure their profitability and survival. We presented an adaptive planning metro map (Fig. 7) for effective adaptation options over time and show how shifting between adaption options could prevent having more critical situations than in the historical period. For the next 30 years, decision-makers could invest in snowmaking of 60 mm combined with diversification of offers for 30 days on different leisure activities such as skiing on grass, mountain biking, and mountain coasters. The selection of activities is based on their preferred business models.

There are a few aspects that need attention in the interpretation of our results. For instance, our model holds the skier visits constantly overtime to isolate the impact of climate change. Future work could calculate a second set of impact estimates accounting for projected population growth. Also, the financial information on daily cost and revenue which we used in this study for the financial status of the ski resorts is, however, too general to yield synchronous economics analysis. We point out that the number of days with good snow (GSD) is intended to capture the general pattern of the future rather than to be accurate representations of the economic situation of the resorts at a specific time. Future studies might consider how winter sport types influence perceptions of warming winters. For example, downhill skiers are well adapted for a warmer climate because of extensive snowmaking that provides skiable terrain even in warmer-than-average winters.

It should be pointed out that "good days for skiing" are not only about a certain snow depth but also other meteorological factors. Eight variables and their required values for considering a day as Optimal Skiing Day (OSD) are summarized as follows (Berghammer and Schmude, 2014): (1) precipitation = 0 mm, (2) ski area entirely operating, (3) (artificial) snow depth on slopes $\geq$30 cm, (4) surrounding snow coverage (scene function) >0 cm, (5) perceived temperature between -5 and $+5$ °C, (6) sunshine duration $\geq$5 h/day, (7) wind speed $\leq$10 m/s, and (8) type of day weekend day/holiday. Only when a day meets all of these conditions concomitantly is it categorized as OSD. In the current study, we focused on snow depth conditions (GSD) and explored how the climate's internal variability will affect GSD. The next step for quantitative analysis of climate change on skiing days is to consider all the factors if the data is available.

Furthermore, the factors that influence the operations of ski resorts are not exclusively limited to the viability in terms of snow conditions. The unique situation in winter 2018 with exceptional snowfall forced ski resorts to close due to the increased risks of wet avalanches. These conditions might become more common in the future, which on top of the overall decline in favorable snow days, could add an extra element of financial risk even for ski resorts located at relatively high elevations (Stoffel and Corona, 2018).

The results shown in this study can be upscaled to the entire alpine region by comparing similar elevation bands using, for example, station data in combination with climate variables from regional climate models at a relatively fine resolution such as CORDEX data (EUR-11, ~12.5 km). Including a more diverse portfolio of adaptation options and a more advanced simulation of socio-economic dynamics would be directions for new research.

In future studies, we suggest to explore more uncertainty space for possible snowmaking condition and cover a wider range from -10 °C < temperature <+4 °C and 0 < humidity <100%. In that case, one can look at the situations where -12 °C < wet bulb temperature <-3 °C.

Finally, scientists, resort operators, and policymakers could co-design a more comprehensive decision option portfolio. These options should be capable of overcoming lines of conflict between different interest groups and providing feasible ways forward, considering local environmental conditions and specific objectives of the ski resorts.

5. Conclusion

This paper used various explorative modeling approaches, including dynamic adaptive policy pathways (DAPP), robust decision making (RDM), and scenario discovery for six ski resorts ranging from low to high elevations. The proposed framework successfully provided insights into the impacts of climate change on tipping points of sky resorts for decision-makers. We offered different adaptation options over time to avoid the occurrence of future tipping points in the resorts.

We summarize the following primary outcomes of the study as follows.

1. Our approach will help decision-makers better understand the combination of uncertainties that most affect their choices, thereby reducing locked-in choices and decision delays that can arise when using a single scenario. Provided DAPP metro map demonstrates when to alter the adaptation options when the future unfolds for avoiding tipping points.
2. All resorts were projected to face reductions in winter recreation season lengths, exceeding 26% by the near-future, 53% by mid-future, and 78% in the far-future. We found that ski resorts in the Swiss Alps will suffer due to climate change more and more severely through the end of the century, especially under RCP8.5 scenarios.
3. We found that higher elevation resorts in the Alps (ski lines > 1820–2000 m ranges) are far more resilient to temperature changes, but every resort will suffer. Our results showed that economic diversification (up to 40days) is indispensable for ski resorts to survive in low elevation mountains after the 2050 s.
4. We determined that the resorts should not only provide activities in the winter but should develop methods to attract people year-round. Now is the time for authorities to plan information campaigns about new adaptations. Ski resort operators should share their thoughts about climate change and its difficulties now or expect in the future.
5. Among the uncertain factors (namely the uncertainty in RCPs; intra-annual climate variability; the snow process model; and adaptation options); the uncertainty in intra-annual climate variability and the snow process model are dominant in the near-future.
6. Our approach can be extended to other regions whose ski resorts might be facing similar challenges (and beyond). It can also be used to explore other tipping points in various decision systems.

CRediT authorship contribution statement

Saeid A. Vaghefi: Prepared data, Adapted the XLRM framework, Performed model runs, Analyzed the results, Developed figures and tables. **Saeid A. Vaghefi, Veruska Muccione, Kees C.H. van Ginkel, Marjolijn Haasnoot:** Designed the study and interpreted the results. **Saeid A. Vaghefi, Veruska Muccione, Kees C.H. van Ginkel**: Wrote the manuscript. **V. Muccione, Kees C.H. van Ginkel**: Developed the initial idea for the Swiss Alps, which led to this study. **Saeid A. Vaghefi**: Wrote the supplementary material.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The developed codes for the DMDU calculations of this study are publicly available in a GitHub repository at https://github.com/saeedashraf/Snow-Ski-Resort-DMDU.

Acknowledgment

We acknowledge the support of Christian Huggel, who made this study financially possible. We are thankful for the initial inputs provided by J. Fiddes to the snow model. Various exchanges with Jan Kwakkel allowed running the ema-workbench for this work successfully.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2021.09.005.

References

Abbaspour, K.C., Johnson, C.A., van Genuchten, M.T., 2004. Estimating uncertain flow and transport parameters using a sequential uncertainty fitting procedure. Vadose Zo. J. 3, 1340–1352. https://doi.org/10.2136/vzj2004.1340.

Abbaspour, K.C., Rouholahnejad, E., Vaghefi, S., Srinivasan, R., Yang, H., Kløve, B., 2015. A continental-scale hydrology and water quality model for Europe: calibration and uncertainty of a high-resolution large-scale SWAT model. J. Hydrol. 524, 733–752. https://doi.org/10.1016/J.JHYDROL.2015.03.027.

Abegg, B., Jetté-Nantel, S., Crick, F., de Montfalcon, A., 2007. Climate Change in the European Alps. OECD. https://doi.org/10.1787/9789264031692-en.

Abegg, B., Morin, S., Demiroglu, O.C., François, H., Rothleitner, M., Strasser, U., 2020. Overloaded! Critical revision and a new conceptual approach for snow indicators in ski tourism. Int. J. Biometeorol. https://doi.org/10.1007/s00484-020-01867-3.

B., Abegg, (2012) Natürliche und technische Schneesicherheit in einer wärmeren Zukunft. In: Swiss Federal Institute for Forest, Snow and Landscape Research WSL (ed) Alpine Schnee- und Wasserressourcen gestern, heute und morgen, Davos, pp 29–35.

AlpNet, 2016, The future of winter travelling in the alps, executive summary.

Ashraf Vaghefi, S., Iravani, M., Sauchyn, D., Andreichuk, Y., Goss, G., Faramarzi, M., 2019. Regionalization and parameterization of a hydrologic model significantly affect the cascade of uncertainty in climate-impact projections. Clim. Dyn. 53. https://doi.org/10.1007/s00382-019-04664-w.

Ashwin, P., Wieczorek, S., Vitolo, R., Cox, P., 2012. Tipping points in open systems: bifurcation, noise-induced and rate-dependent examples in the climate system. Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 370, 1166–1184. https://doi.org/10.1098/rsta.2011.0306.

Bankes, S., Walker, W.E., Kwakkel, J.H., 2013. In: Gass, S.I., Fu, M.C. (Eds.), Exploratory Modeling and Analysis BT - Encyclopedia of Operations Research and Management Science. Springer, US, Boston, MA, pp. 532–537. https://doi.org/10.1007/978-1-4419-1153-7_314.

Beniston, M., Farinotti, D., Stoffel, M., Andreassen, L.M., Coppola, E., Eckert, N., Fantini, A., Giacona, F., Hauck, C., Huss, M., Huwald, H., Lehning, M., López-Moreno, J.-I., Magnusson, J., Marty, C., Morán-Tejéda, E., Morin, S., Naaim, M., Provenzale, A., Rabatel, A., Six, D., Stötter, J., Strasser, U., Terzago, S., Vincent, C., 2018. The European mountain cryosphere: a review of its current state, trends, and future challenges. Cryosph 12, 759–794. https://doi.org/10.5194/tc-12-759-2018.

Bryant, B.P., Lempert, R.J., 2000. Thinking inside the box: A participatory, computer-assisted approach to scenario discovery. Technol. Forecast. Soc. Change 77, 34–49. https://doi.org/10.1016/j.techfore.2009.08.002.

Bürki, R., 2000, Klimaänderung und Anpassungsprozesse im Wintertourismus. Publ. der Ostschweizerischen Geogr. Gesellschaft, H. 6, St. Gall.

CH2018, 2018, CH2018 – Climate Scenarios for Switzerland.

Chernick, M.R., González-Manteiga, W., Crujeiras, R.M., Barrios, E.B., 2011. In: Lovric, M. (Ed.), Bootstrap Methods BT - International Encyclopedia of Statistical Science. Springer, Berlin, Heidelberg, pp. 169–174. https://doi.org/10.1007/978-3-642-04898-2_150.

Collins, M., Knutti, R., Arblaster, J., Dufresne, J.-L., Fichefet, T.P., Friedlingstein, X., Gao, W.J., Gutowski, T., Johns, G., Krinner, M., Shongwe, C., Tebaldi, A., J., W., M., W, 2013. Long-term climate change: projections, commitments and irreversibility. Clim. Chang. 2013 Phys. Sci. Basis Work. Gr. I Contrib. to Fifth Assess. Rep. Intergov. Panel Clim. Chang. 9781107057, 1029–1136. https://doi.org/10.1017/CBO9781107415324.024.

Dawson, J., Scott, D., 2013. Managing for climate change in the alpine ski sector. Tour. Manag. 35, 244–254. https://doi.org/10.1016/j.tourman.2012.07.009.

Debarbieux, B., Oiry Varacca, M., Rudaz, G., Maselli, D., Kohler, T., Jurek, M., 2014, Sustainable Mountain Development Series Hopes, Fears and Realities Tourism in Mountain Regions. https://doi.org/10.7892/boris.63699.

Dessai, S., Hulme, M., Lempert, R., Pielke Jr., R., 2009. Do we need better predictions to adapt to a changing climate? Eos. Trans. Am. Geophys. Union 90, 111–112. https://doi.org/10.1029/2009EO130003.

Dixon, P.M., 2001, Bootstrap Resampling. Encycl. Environmetrics, Major Reference Works. https://doi.org/https://doi.org/10.1002/9780470057339.vab028.

Elsasser, H., Bürki, R., 2010. In: Becker, C., Hopfinger, H., Steinecke, A. (Eds.), Auswirkungen von Umweltveränderungen auf den Tourismus - dargestellt am Beispiel der Klimaänderung im Alpenraum. Oldenbourg, Wissenschaftsverlag, pp. 865–875. https://doi.org/10.1524/9783486700015.865.

Elsasser, H., Bürki, R., 2002. Climate change as a threat to tourism in the Alps. Clim. Res. 20, 253–257. https://doi.org/10.3354/cr020253.

Euronews, 2020, Ski resort under fire for using helicopter to deliver snow.

Fang, Y., Yin, J., Wu, B., 2018. Climate change and tourism: a scientometric analysis using CiteSpace. J. Sustain. Tour. 26, 108–126. https://doi.org/10.1080/09669582.2017.1329310.

Farinotti, D., Magnusson, J., Huss, M., Bauder, A., 2010. Snow accumulation distribution inferred from time-lapse photography and simple modelling. Hydrol. Process. 24, 2087–2097. https://doi.org/10.1002/hyp.7629.

Farinotti, D., Usselmann, S., Huss, M., Bauder, A., Funk, M., 2012. Runoff evolution in the Swiss Alps: projections for selected high-alpine catchments based on ENSEMBLES scenarios. Hydrol. Process. 26, 1909–1924. https://doi.org/10.1002/hyp.8276.

Fiddes, J., Aalstad, K., Westermann, S., 2019. Hyper-resolution ensemble-based snow reanalysis in mountain regions using clustering. Hydrol. Earth Syst. Sci. 23, 4717–4736. https://doi.org/10.5194/hess-23-4717-2019.

Gilaberte-Búrdalo, M., López-Moreno, J.I., Morán-Tejeda, E., Jerez, S., Alonso-González, E., López-Martín, F., Pino-Otín, M.R., 2017. Assessment of ski condition reliability in the Spanish and Andorran Pyrenees for the second half of the 20th century. Appl. Geogr. 79, 127–142. https://doi.org/10.1016/j.apgeog.2016.12.013.

Groves, D.G., Lempert, R.J., 2007. A new analytic method for finding policy-relevant scenarios. Glob. Environ. Chang 17, 73–85. https://doi.org/10.1016/j.gloenvcha.2006.11.006.

Guyon, I., Elisseeff, A., 2003. An introduction to variable and feature selection. J. Mach. Learn. Res. 3, 1157–1182.

Haasnoot, M., Kwakkel, J.H., Walker, W.E., ter Maat, J., 2013. Dynamic adaptive policy pathways: a method for crafting robust decisions for a deeply uncertain world. Glob. Environ. Chang 23, 485–498. https://doi.org/10.1016/j.gloenvcha.2012.12.006.

Hagenstad, M.E.A.B., Hill, R., 2018, Economic Contributions of Winter Sports in a Changing Climate. Protect Our Winters. Boulder, CO, USA.

Hall, D.K., Riggs, G.A., 2015, MODIS/Aqua Sea Ice Extent 5-Min L2 Swath 1km, Version 6. Boulder, Colorado USA. https://doi.org/https://doi.org/10.5067/MODIS/MYD29.006.

Hamarat, C., Kwakkel, J.H., Pruyt, E., 2013. Adaptive robust design under deep uncertainty. Technol. Forecast. Soc. Change 80, 408–418. https://doi.org/10.1016/j.techfore.2012.10.004.

Hartl, L., Fischer, A., Olefs, M., 2018. Analysis of past changes in wet bulb temperature in relation to snow making conditions based on long term observations Austria and Germany. Glob. Planet. Change 167, 123–136. https://doi.org/10.1016/j.gloplacha.2018.05.011.

Hausfather, Z., Peters, G.P., 2020. Emissions – the 'business as usual' story is misleading. Nature 577, 618–620. https://doi.org/10.1038/d41586-020-00177-3.

Hendrikx, J., Hreinsson, E.Ö., 2012. The potential impact of climate change on seasonal snow in New Zealand: part II—industry vulnerability and future snowmaking potential. Theor. Appl. Climatol. 110, 619–630. https://doi.org/10.1007/s00704-012-0713-z.

Hock, R., 1999. A distributed temperature-index ice- and snowmelt model including potential direct solar radiation. J. Glaciol. 45, 101–111. https://doi.org/10.3189/S0022143000003087.

Hock, R., Bliss, A., Marzeion, B., Giesen, R.H., Hirabayashi, Y., Huss, M., Radić, V., Slangen, A.B.A., 2019a. GlacierMIP – a model intercomparison of global-scale glacier mass-balance models and projections. J. Glaciol. 65, 453–467. https://doi.org/10.1017/jog.2019.22.

Hock, R., Rasul, G., Adler, C., Cáceres, B., Gruber, S., Hirabayashi, Y., Jackson, M., Kääb, A., Kang, S., Kutuzov, S., Milner, A., Molau, U., Morin, S., Orlove, B., Steltzer, H., 2019b. High mountain areas. IPCC Spec. Rep. Ocean Cryosphere a Chang. Clim.

Hoogendoorn, G., Stockigt, L., Saarinen, J., Fitchett, J.M., 2020. Adapting to climate change: the case of snow-based tourism in Afriski, Lesotho. Afr. Geogr. Rev. 1–13. https://doi.org/10.1080/19376812.2020.1773878.

Huss, M., Farinotti, D., Bauder, A., Funk, M., 2008. Modelling runoff from highly glacierized alpine drainage basins in a changing climate. Hydrol. Process. 22, 3888–3902. https://doi.org/10.1002/hyp.7055.

Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O.B., Bouwer, L.M., Braun, A., Colette, A., Déqué, M., Georgievski, G., Georgopoulou, E., Gobiet, A., Menut, L., Nikulin, G., Haensler, A., Hempelmann, N., Jones, C., Keuler, K., Kovats, S., Kröner, N., Kotlarski, S., Kriegsmann, A., Martin, E., van Meijgaard, E., Moseley, C., Pfeifer, S., Preuschmann, S., Radermacher, C., Radtke, K., Rechid, D., Rounsevell, M., Samuelsson, P., Somot, S., Soussana, J.-F., Teichmann, C., Valentini, R., Vautard, R., Weber, B., Yiou, P., 2014. EURO-CORDEX: new high-resolution climate change projections for European impact research. Reg. Environ. Change 14, 563–578. https://doi.org/10.1007/s10113-013-0499-2.

Kluger, J., 2020, The Big Melt [WWW Document]. URL ⟨https://time.com/italy-alps-climate-change/⟩.

Kotlarski, S., Keuler, K., Christensen, O.B., Colette, A., Déqué, M., Gobiet, A., Goergen, K., Jacob, D., Lüthi, D., van Meijgaard, E., Nikulin, G., Schär, C., Teichmann, C., Vautard, R., Warrach-Sagi, K., Wulfmeyer, V., 2014. Regional climate modeling on European scales: a joint standard evaluation of the EURO-CORDEX RCM ensemble. Geosci. Model Dev. 7, 1297–1333. https://doi.org/10.5194/gmd-7-1297-2014.

Kwakkel, J.H., 2017. The Exploratory Modeling Workbench: an open source toolkit for exploratory modeling, scenario discovery, and (multi-objective) robust decision making. Environ. Model. Softw. 96, 239–250. https://doi.org/10.1016/J.ENVSOFT.2017.06.054.

Kwakkel, J.H., Haasnoot, M., Walker, W.E., 2015. Developing dynamic adaptive policy pathways: a computer-assisted approach for developing adaptive strategies for a deeply uncertain world. Clim. Change 132, 373–386. https://doi.org/10.1007/s10584-014-1210-4.

Kwakkel, J.H., Pruyt, E., 2013. Exploratory Modeling and Analysis, an approach for model-based foresight under deep uncertainty. Technol. Forecast. Soc. Change 80, 419–431. https://doi.org/10.1016/j.techfore.2012.10.005.
Kwakkel, J.H., Walker, W.E., Marchau, V.A.W.J., 2010. Adaptive airport strategic planning. Eur. J. Transp. Infrastruct. Res. Vol 10 (No 3) https://doi.org/10.18757/ejtir.2010.10.3.2891.
Lempert, R., 2003. Uncertain Science… Uncertain World. Eos. Trans. Am. Geophys. Union 84, 285–286. https://doi.org/10.1029/2003EO300007.
Lempert, R.J., Groves, D.G., Popper, S.W., Bankes, S.C., 2006. A general, analytic method for generating robust strategies and narrative scenarios. Manag. Sci. 52, 514–528. https://doi.org/10.1287/mnsc.1050.0472.
Lenton, T.M., Held, H., Kriegler, E., Hall, J.W., Lucht, W., Rahmstorf, S., Schellnhuber, H. J., 2008. Tipping elements in the Earth's climate system. Proc. Natl. Acad. Sci. 105, 1786–1793. https://doi.org/10.1073/pnas.0705414105.
Lievens, H., Demuzere, M., Marshall, H.-P., Reichle, R.H., Brucker, L., Brangers, I., de Rosnay, P., Dumont, M., Girotto, M., Immerzeel, W.W., Jonas, T., Kim, E.J., Koch, I., Marty, C., Saloranta, T., Schöber, J., De Lannoy, G.J.M., 2019. Snow depth variability in the Northern Hemisphere mountains observed from space. Nat. Commun. 10, 4629. https://doi.org/10.1038/s41467-019-12566-y.
Marchau, V.A.W.J., Walker, W.E., Bloemen, P.J.T.M., Popper, S.W., 2019. Decision Making under Deep Uncertainty: From Theory to Practice. Springer Nature PP, Cham. https://doi.org/10.1007/978-3-030-05252-2.
Marty, C., Schlögl, S., Bavay, M., Lehning, M., 2017. How much can we save? Impact of different emission scenarios on future snow cover in the Alps. Cryosph 11, 517–529. https://doi.org/10.5194/tc-11-517-2017.
Matiu, M., Crespi, A., Bertoldi, G., Carmagnola, C.M., Marty, C., Morin, S., Schöner, W., Cat Berro, D., Chiogna, G., De Gregorio, L., Kotlarski, S., Majone, B., Resch, G., Terzago, S., Valt, M., Beozzo, W., Cianfarra, P., Gouttevin, I., Marcolini, G., Notarnicola, C., Petitta, M., Scherrer, S.C., Strasser, U., Winkler, M., Zebisch, M., Cicogna, A., Cremonini, R., Debernardi, A., Faletto, M., Gaddo, M., Giovannini, L., Mercalli, L., Soubeyroux, J.-M., Sušnik, A., Trenti, A., Urbani, S., Weilguni, V., 2020. Observed snow depth trends in the European Alps 1971 to 2019. Cryosph. Discuss. 2020, 1–50. https://doi.org/10.5194/tc-2020-289.
Pütz, M., Gallati, D., Kytzia, S., Elsasser, H., Lardelli, C., Teich, M., Waltert, F., Rixen, C., 2011. Winter tourism, climate change, and snowmaking in the swiss alps: tourists' attitudes and regional economic impacts. Mt. Res. Dev. 31, 357–362. https://doi.org/10.1659/MRD-JOURNAL-D-11-00039.1.
Riahi, K., Rao, S., Krey, V., Cho, C., Chirkov, V., Fischer, G., Kindermann, G., Nakicenovic, N., Rafaj, P., 2011. RCP 8.5—a scenario of comparatively high greenhouse gas emissions. Clim. Change 109, 33. https://doi.org/10.1007/s10584-011-0149-y.
Rixen, C., Teich, M., Lardelli, C., Gallati, D., Pohl, M., Pütz, M., Bebi, P., 2011. Winter tourism and climate change in the alps: an assessment of resource consumption, snow reliability, and future snowmaking potential. Mt. Res. Dev. 31, 229–236.
Rosa, L., Chiarelli, D.D., Sangiorgio, M., Beltran-Peña, A.A., Rulli, M.C., D'Odorico, P., Fung, I., 2020. Potential for sustainable irrigation expansion in a 3 °C warmer climate. Proc. Natl. Acad. Sci. 117, 29526–29534. https://doi.org/10.1073/pnas.2017796117.
Ruitenberg, R., 2020, As Warm Winter Leaves Ski Slopes Bare, France Promises Aid [WWW Document]. URL ⟨https://www.bloomberg.com/news/articles/2020–02-21/as-warm-winter-leaves-ski-slopes-bare-france-promises-aid⟩.
Schmucki, E., Marty, C., Fierz, C., Weingartner, R., Lehning, M., 2017. Impact of climate change in Switzerland on socioeconomic snow indices. Theor. Appl. Climatol. 127, 875–889. https://doi.org/10.1007/s00704-015-1676-7.
Schöner, W., Koch, R., Matulla, C., Marty, C., Tilg, A.-M., 2019. Spatiotemporal patterns of snow depth within the Swiss-Austrian Alps for the past half century (1961 to 2012) and linkages to climate change. Int. J. Climatol. 39, 1589–1603. https://doi.org/10.1002/joc.5902.
Scott, D., Steiger, R., Dannevig, H., Aall, C., 2020. Climate change and the future of the Norwegian alpine ski industry. Curr. Issues Tour. 23, 2396–2409. https://doi.org/10.1080/13683500.2019.1608919.
Scott, D., Steiger, R., Rutty, M., Pons, M., Johnson, P., 2019. The differential futures of ski tourism in Ontario (Canada) under climate change: the limits of snowmaking adaptation. Curr. Issues Tour. 22, 1327–1342. https://doi.org/10.1080/13683500.2017.1401984.
Spandre, P., François, H., Verfaillie, D., Lafaysse, M., Déqué, M., Eckert, N., George, E., Morin, S., 2019a. Climate controls on snow reliability in French Alps ski resorts. Sci. Rep. 9, 8043. https://doi.org/10.1038/s41598-019-44068-8.
Spandre, P., François, H., Verfaillie, D., Pons, M., Vernay, M., Lafaysse, M., George, E., Morin, S., 2019b. Winter tourism under climate change in the Pyrenees and the French Alps: relevance of snowmaking as a technical adaptation. Cryosph 13, 1325–1347. https://doi.org/10.5194/tc-13-1325-2019.
Spandre, P., Morin, S., Lafaysse, M., Lejeune, Y., François, H., George-Marcelpoil, E., 2016. Integration of snow management processes into a detailed snowpack model. Cold Reg. Sci. Technol. 125, 48–64. https://doi.org/10.1016/j.coldregions.2016.01.002.
Steiger, R., 2010. The impact of climate change on ski season length and snowmaking requirements in Tyrol. Austria Clim. Res. 43, 251–262.
Steiger, R., Damm, A., Prettenthaler, F., Pröbstl-Haider, U., 2020. Climate change and winter outdoor activities in Austria. J. Outdoor Recreat. Tour., 100330 https://doi.org/10.1016/j.jort.2020.100330.
Steiger, R., Scott, D., Abegg, B., Pons, M., Aall, C., 2019. A critical review of climate change risk for ski tourism. Curr. Issues Tour. 22, 1343–1379. https://doi.org/10.1080/13683500.2017.1410110.
Stoffel, M., Corona, C., 2018. Future winters glimpsed in the Alps. Nat. Geosci. 11, 458–460. https://doi.org/10.1038/s41561-018-0177-6.
Thomson, A.M., Calvin, K.V., Smith, S.J., Kyle, G.P., Volke, A., Patel, P., Delgado-Arias, S., Bond-Lamberty, B., Wise, M.A., Clarke, L.E., Edmonds, J.A., 2011. RCP4.5: a pathway for stabilization of radiative forcing by 2100. Clim. Change 109, 77. https://doi.org/10.1007/s10584-011-0151-4.
van Ginkel, K.C.H., Botzen, W.J.W., Haasnoot, M., Bachner, G., Steininger, K.W., Hinkel, J., Watkiss, P., Boere, E., Jeuken, A., de Murieta, E.S., Bosello, F., 2020. Climate change induced socio-economic tipping points: review and stakeholder consultation for policy relevant research. Environ. Res. Lett. 15, 23001. https://doi.org/10.1088/1748-9326/ab6395.
van Vuuren, D.P., Stehfest, E., den Elzen, M.G.J., Kram, T., van Vliet, J., Deetman, S., Isaac, M., Klein Goldewijk, K., Hof, A., Mendoza Beltran, A., Oostenrijk, R., van Ruijven, B., 2011. RCP2.6: exploring the possibility to keep global mean temperature increase below 2°C. Clim. Change 109, 95. https://doi.org/10.1007/s10584-011-0152-3.
Vanat, L. et al., 2020, No Title2020 International Report on Snow & Mountain Tourism - Overview of the key industry figures for ski resorts.
Verfaillie, D., Déqué, M., Morin, S., Lafaysse, M., 2017. The method ADAMONT v1.0 for statistical adjustment of climate projections applicable to energy balance land surface models. Geosci. Model Dev. 10, 4257–4283. https://doi.org/10.5194/gmd-10-4257-2017.
Verfaillie, D., Lafaysse, M., Déqué, M., Eckert, N., Lejeune, Y., Morin, S., 2018. Multi-component ensembles of future meteorological and natural snow conditions for 1500 m altitude in the Chartreuse mountain range. North. Fr. Alps. Cryosph. 12, 1249–1271. https://doi.org/10.5194/tc-12-1249-2018.
Walker, W., Haasnoot, M., Kwakkel, J.H., 2013. Adapt or Perish: a review of planning approaches for adaptation under deep uncertainty. Sustainability 5, 955–979.
Walker, W.E., Rahman, S.A., Cave, J., 2001. Adaptive policies, policy analysis, and policy-making. Eur. J. Oper. Res. 128, 282–289. https://doi.org/10.1016/S0377-2217(00)00071-0.
Wilby, R.L., Dessai, S., 2010. Robust adaptation to climate change. Weather 65, 180–185. https://doi.org/10.1002/wea.543.
Wobus, C., Small, E.E., Hosterman, H., Mills, D., Stein, J., Rissing, M., Jones, R., Duckworth, M., Hall, R., Kolian, M., Creason, J., Martinich, J., 2017. Projected climate change impacts on skiing and snowmobiling: a case study of the United States. Glob. Environ. Change 45, 1–14. https://doi.org/10.1016/j.gloenvcha.2017.04.006.