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Vulnerability of ski tourism towards internal climate variability and climate change in the Swiss Alps

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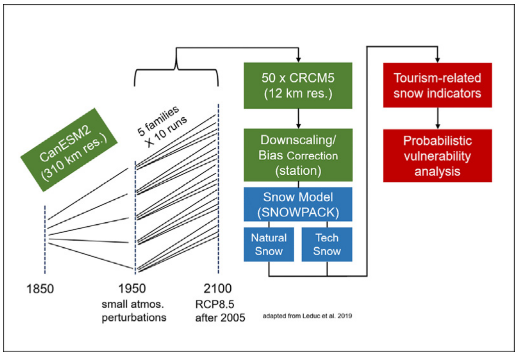
HIGHLIGHTS

- A single model large ensemble is used to drive a physically-based snowpack model.
- Probabilistic vulnerability analysis of tourism-related snow indicators
- Vulnerability analysis towards internal climate variability (ICV) and climate change (CC)
- Certain indicators are more vulnerable to internal climate variability than others.
- Technical snow production is an appropriate adaptation strategy to tackle risks from CC and ICV.

GRAPHICAL ABSTRACT



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ABSTRACT

Increasing temperatures and snow scarcity pose a serious threat to ski tourism. While the impacts of climate change on ski tourism have been elaborated extensively, little is known so far on the vulnerability of winter tourism towards both internal climate variability and climate change. We use a 50-member single model large ensemble from a regional climate model to drive the physically-based snowpack model SNOWPACK for eight stations across the Swiss Alps to model daily snow depth, incorporating both natural snow conditions and including technical snow production. We make a probabilistic assessment of the vulnerability of ski tourism towards internal climate variability in a future climate by analyzing selected tourism-related snow indicators and find significant overall decrease in snow reliability in the future. Further, we show how the sensitivity towards internal climate variability differs among different tourism-related snow indicators and find that certain indicators are more vulnerable to internal climate variability than others. We show that technical snow production is an appropriate adaptation strategy to tackle risks from climate change and internal climate variability. While technical snow production can drastically reduce uncertainties related to internal climate variability, in low elevations, the technique reaches its limits to counteract global warming by the mid of the century.

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1. Introduction

In many alpine regions, tourism, and especially winter tourism is an important source of economic revenue (Berard-Chenu et al., 2020; Bürki et al., 2003), and climate change is generally perceived as a major risk to tourism-dependent destinations. While the global mean temperature shows a warming of approximately 1 °C over the period from 1880 to 2015, warming over the alpine region – with a maximum of up to 2.5 °C - is much more pronounced than in the northern hemisphere (Hansen et al., 2016; IPCC, 2013). Continued warming is expected to cause diverse environmental and socio-economic impacts from regional to global scales (Scott et al., 2012; Scott et al., 2016).

With its high dependency on natural resources, most importantly on snow (Shih et al., 2009), winter tourism was among the first tourism markets investigated for its climate change vulnerability (Gilaberte-Búrdalo et al., 2014; Scott et al., 2012; Scott et al., 2019). The first studies that outline climate change impacts on tourism emerged in the late 1980's to mid-1990's (Abegg, 1996; Abegg and Froesch, 1994; Bürki, 2000; Galloway, 1988; Koenig and Abegg, 1997; McBoyle and Wall, 1987). Many initial studies quantified snow reliability of ski resorts based on the "100-day rule", which is calculated as the number of days per season with a snow depth larger than 30 cm (Bürki, 2000; Witmer, 1986). Koenig and Abegg (1997), for example, estimated that a temperature rise of 2 °C would result in a 300 m rise of the snow reliability line (elevation above which the 100-day rule is fulfilled) in the Alps and the absolute snow line would move up to 1500 m. For North America, Scott et al. (2007) found a reduction in snow depth of 75% under IPCC SRES A1 emissions and a reduction of the ski season length by approximately 30%.

A drawback of those early studies is that the "100-day" indicator alone is not suited to analyze the economic profitability of a ski area, as scientists and stakeholders agree that economic revenues are prevailingly gained during certain key periods, such as school holidays (Abegg et al., 2020). Secondly, those studies often simulated snow conditions using simple degree-day modelling approaches (Dawson and Scott, 2013; Hendrikx and Hreinsson, 2012; Steiger and Abegg, 2013) and only investigated natural snow conditions (Damm et al., 2016; Elsasser and Bürki, 2002). Since the 2000s, technical snowmaking has however become an important adaptation strategy to face global warming and climate variability. Meanwhile also, more and more scientific studies have incorporated machine made snow, in the literature primarily referred to as "technical snowmaking" (Abegg et al., 2020) into their simulations. Several studies found that this technology could significantly reduce climate change impacts on winter tourism (Scott et al., 2003; Spandre et al., 2019). Early studies simulating technical snowmaking used very simple rules for snow production (Hennessy et al., 2008; Scott et al., 2007), but recently snowmaking modules have built their assessments on physically-based snow models with a complex set of rules and better represent the physical characteristics of technical snow (Hanzer et al., 2020; Spandre et al., 2016).

When modelling future impacts of climate change on winter tourism, the vast majority of publications focus on mean changes of tourism-related climate and snow indices. The use of different emission scenarios is commonly applied to tackle uncertainties related to future greenhouse gas emissions and commonly multi-model ensembles are applied to quantify model uncertainty (Damm et al., 2016; Marty et al., 2017; Scott et al., 2019; Spandre et al., 2019; Wobus et al., 2017). While many studies mention the importance of climate variability, weather, or extreme events on winter tourism demand (Gilaberte-Búrdalo et al., 2014; Gonseth, 2013; Njoroge, 2014; Pütz et al., 2011; Rutty et al., 2017; Steiger, 2011), only very few studies actually explore this topic in detail, and the ones that do so typically only focus on certain historical events. For example, Rutty et al. (2017) apply an analogue study of the record warm winter of 2011/2012 in Ontario to assess the impacts of climate variability on the supply-side, such as ski season length, and demand-side, such as overall skier visits, of winter tourism. Steiger (2011) investigates the sensitivity of the ski industry in Tyrol during the record warm winter 2006/2007.

Steiger et al. (2019) reviewed 119 publications that examine the vulnerability of winter tourism towards climate and found that only 14% of overall studies assess past and future climate variability. Those studies primarily try to understand the importance of different weather variables on skiers' demand and use extraordinary winter seasons to estimate potential climate change impacts (Steiger et al., 2019). Even though, on shorter timescales, internal climate variability (ICV), defined as the natural fluctuations in the climate system that arise in the absence of any additional radiative forcing (Hawkins and Sutton, 2009), represents the single most important source of uncertainty with regard to snow depth (Fatichi et al., 2014; Lafaysse et al., 2014), no study investigates how climate variability contributes to uncertainties and vulnerabilities in winter tourism.

One reason for the lack of studies on the impacts of climate variability on winter tourism is the lack of long-term observations and appropriate climate model data. To make a robust probability assessment of ICV, single model large ensembles, generated by small differences in the models' initial conditions, have been developed (Deser et al., 2012; Kay et al., 2015; Leduc et al., 2019). Dynamically downscaled single model large ensembles, using a Regional Climate Model (RCM), are very rare. To our knowledge, only Fyfe et al. (2017) and Willibald et al. (2020) use data from a downscaled single model large ensemble to estimate the impact of ICV on snowpack over the United States and Switzerland, respectively. The single model large ensemble used in this study samples ICV by randomly varying the initial condition of 50 climate simulations and by employing identical climate models (GCM-RCM chain) and an identical external greenhouse gas forcing (RCP8.5). Differences between the 50 model members are hence solely due to potentially unpredictable random variability within the simulated climate system, making each member an equally likely, plausible realization of climate change over the next century. This setup allows the investigation of the combined effects of ICV and a given greenhouse gas forcing scenario on the vulnerability of winter tourism, which has not yet been studied.

The dynamically downscaled single model large ensemble applied in this study was used to drive the state of the art, physically-based snowpack model SNOWPACK for eight stations across the Swiss Alps to model daily snow depth in two setups, one with natural snow only, and one including technical snow. Based on this model framework, we calculate a set of tourism related snow indicators in order to falsify the following hypothesis: First, ICV is an important source of vulnerability for ski tourism. Second, the sensitivity towards ICV differs among different tourism-related snow indicators and changes with anthropogenic forcing. Third, technical snowmaking is an important adaptation strategy to tackle uncertainties due to ICV, and to some extent to climate change.

2. Data and methods

2.1. Observational data and case studies

In a first step, we collected snow measurement data from climate stations in Switzerland, Germany and Austria with at least 10 years of daily snow measurements since 1980 (Fig. 1). The stations are predominantly situated in the Alps, but single German stations are situated in the Black Forest and Bavarian Forest. The data stems from the respective national institutions, namely the Swiss Federal Office of Meteorology and Climatology (MeteoSwiss), the WSL Institute of Snow and Avalanche Research (SLF), the German Meteorological Service (DWD) and the Austrian Central Institute for Meteorology and Geodynamics (ZAMG). Based on data from Openski map (www.openskimap.org), we selected all climate stations in a proximity of ski resorts. The selection was based on the following rules: a maximum distance of 2 km between the ski resort and the climate station. The elevation of the climate

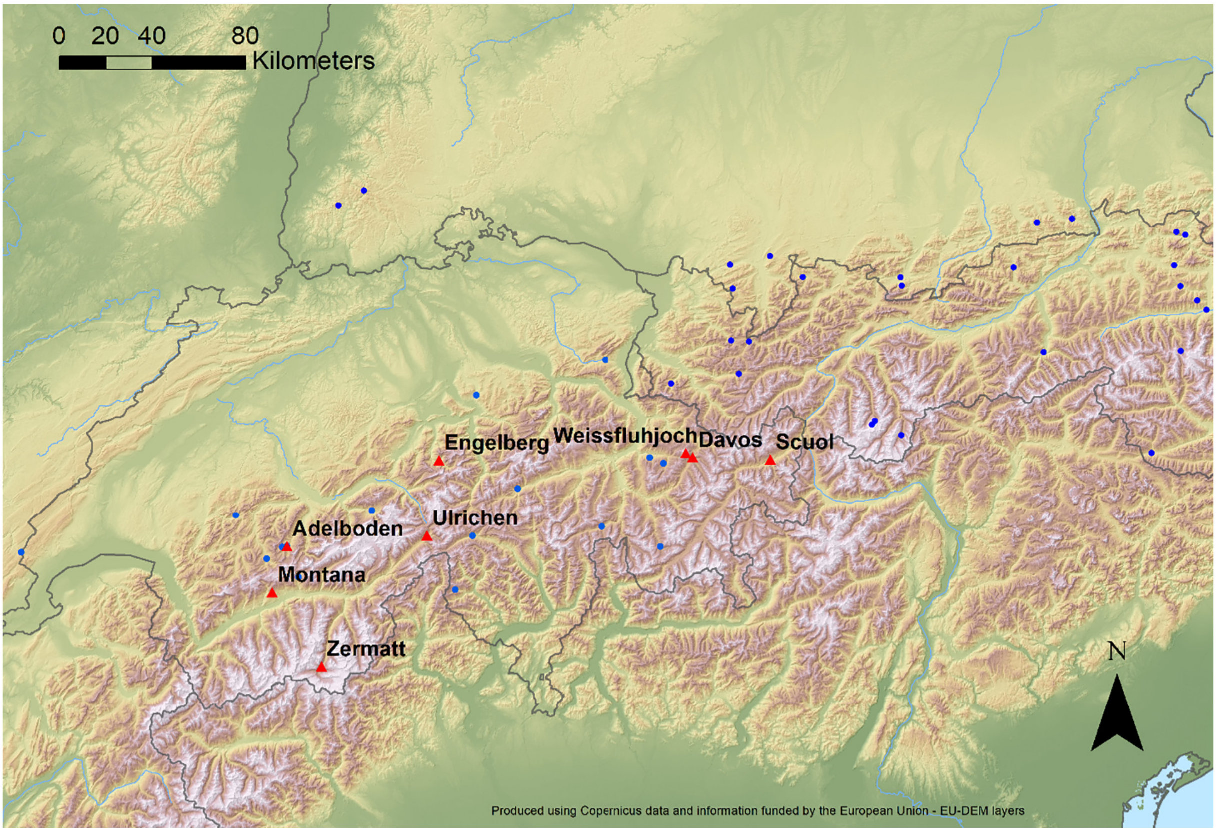

Fig. 1. alpine orography and location of climate stations with long-term snow depth measurements in proximity to ski areas in Switzerland, Austria and Germany (blue dots), case studies used for large ensemble simulations (red triangles). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

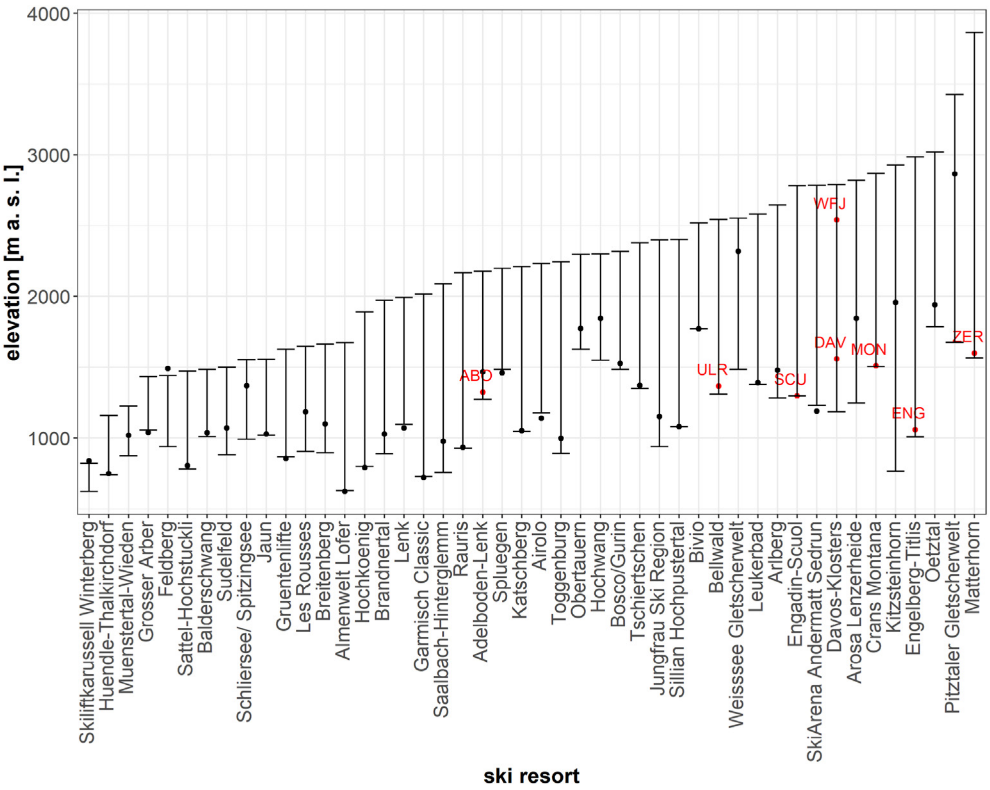

Fig. 2. elevation ranges (black bars) of ski resorts situated in proximity to climate stations (black dots), as well as the corresponding elevations of climate stations used for large ensemble simulations (red dots). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

station must be within the elevation range (+/− 50 m) of the ski resort (Fig. 2) and only ski resorts with at least 10 km of slopes were considered. The selection process results in overall 47 climate stations that fulfill the above mentioned criteria (Fig. 1, Fig. 2). From Fig. 2, we see that most climate stations are situated close to the valley stations of the respective ski resorts. These stations were used to estimate if skiing down to the valley bottom might still be possible in the future, as Unbehaun et al. (2008) found that in contrast to ski resorts and conditions, where skiing is only possible in higher elevations and one has to descend by cable car, winter tourists prefer destinations where skiing all the way down to the bottom of the valley is possible. Additional data in different elevation zones of ski resorts would be preferable, but are rarely available. In Fig. A1 in the Appendix, we show the temporal data availability of these 47 stations between 1980 and 2020.

For the selection of case studies for the large ensemble simulations, additional criteria had to be fulfilled. The choice of these case studies was driven by the availability of long-term observations, not only of snow measurements needed for model validation and index calculation, but also of meteorological input needed for bias adjustment (at least 25 years of observations are recommended for a proper bias adjustment) and SNOWPACK fine tuning and validation. Observational data of temperature, precipitation, wind speed, humidity and incoming shortwave radiation for the purpose of bias adjustment, model calibration and validation was available from MeteoSwiss in a 3-hourly temporal resolution to match the ClimEx-LE output resolution. As explained above, the selection of case studies was limited by the availability of long-term observations of snow and meteorological measurements. Further, the data processing and usage of a single model large ensemble as input for a physically based snow model is computationally highly expensive. For that reason, we focus on eight case studies in the Swiss Alps. The case studies spread over the whole ridge of the Swiss Alps, cover the northern and southern parts of the mountain range and cover elevations between 1040 m a.s.l. and 2540 m a.s.l. (Fig. 1, Table 1).

2.2. The SNOWPACK model

In this study, we make use of the physically-based, one-dimensional snow cover model SNOWPACK (Lehning et al., 1999). Originally developed for avalanche warning (Lehning et al., 2002a), it is also used for long-term climate change studies (Katsuyama et al., 2017; Schmucki et al., 2015; Willibald et al., 2020). SNOWPACK, as a highly advanced snow model, simulates the physical processes (energy balance, mass balance, phase changes, water movement and wind transportation) that take place between the atmosphere, snow and soil. It uses finite elements to solve the partial differential equations regulating the mass-, energy- and momentum-transport within the snowpack. Layers can be added through solid precipitation and subtracted by erosion, melt water runoff, evaporation or sublimation (Lehning et al., 2002a; Lehning et al., 2002b; Lehning et al., 1999). SNOWPACK's preprocessing MeteoIO was provided with the following meteorological forcings: air temperature, relative humidity, incoming short wave radiation, wind speed and precipitation sum. Willibald et al. (2020) describe the exact parameterization and calibration of the model setup used in this study.

Table 1
Case studies used for simulations.

Climate station	ID	Coordinates (lat° N/lon° E)	Elevation (m a.s.l.)	Elevation zone	Snow type simulated Natural	Snow type simulated Technical
Engelberg	ENG	46.8/8.4	1060	Low	✓	✓
Scuol	SCU	46.8/10.3	1298	Low	✓	✓
Adelboden	ABO	46.5/7.6	1325	Low	✓	✓
Ulrichen	ULR	46.5/8.3	1366	Low	✓	✓
Montana	MON	46.3/7.5	1510	Medium	✓	✓
Davos	DAV	46.8/9.9	1560	Medium	✓	✓
Zermatt	ZER	46.0/7.8	1600	Medium	✓	✓
Weissfluhjoch	WFJ	46.8/9.8	2540	High	✓	

SNOWPACK includes a technical snowmaking module. This snowmaking module was developed based on rules adopted from other studies (Demiroglu et al., 2016; Marke et al., 2015; Spandre et al., 2016). Rather than air temperature, wet bulb temperature is commonly used as the decision parameter for technical snow production (Hartl et al., 2018). State-of-the-art snow guns can produce technical snow with a wet bulb temperature < -2 °C, but temperatures above -4 °C provide only low quality snow (Marke et al., 2015). Therefore, as in Demiroglu et al. (2016) and Schneider and Schönbein (2005), we set a wet-bulb temperature threshold of -4 °C, below which technical snow production is possible. This value lies well within the range of thresholds used in other studies, e.g. -2 °C (Hartl et al., 2018) or − 5 °C (Steiger and Mayer, 2008). According to a survey among practitioners by Marke et al. (2015), the snow production season ranges from 1st of November until end of February. We also assume that technical snow production only takes place between 18:00 h and 6:00 h. The technical precipitation rate, season's total water volume available for technical snowmaking and its monthly distribution are based on results by Spandre et al. (2016), who collected data at three operational alpine skiing areas, including the absolute water consumption and its monthly distribution. Based on their empirical results, we set the technical precipitation rate to 4.32 mm h^{-1} m^{-2}. The maximum water availability is 650 mm per season. In November, a maximum of 200 mm can be used for snowmaking, in December 300 mm can be used, in January 100 mm and in February 50 mm, which is also in line with the operational production in Spandre et al. (2016) and measurements in Hanzer et al. (2014). If, due to unfavorable wet-bulb-temperatures, technical snow production is not possible early in the season, we assume that the remaining water is added to the next month. We assume an average water loss due to wind and evaporation of 15% which is in the range provided by the literature (Wolfsperger et al., 2019). Also the density of technical snow is based on experimental results by Wolfsperger et al. (2019) and dependent on the wet-bulb temperature. As soon as conditions are sufficient, technical snow is produced until a snow depth of 60 cm is reached (Marke et al., 2015; Spandre et al., 2016). If simulated snow depth falls below the threshold of 60 cm and if water is available, snow is produced until the snow depth meets the operational threshold again. While the snowmaking module of SNOWPACK is advanced compared to most snow models, it is still in its initial phase and the assumptions are highly simplified, however within plausible ranges.

The technical snow module was applied for all stations but Weissfluhjoch. Due to the high elevation of Weissfluhjoch, technical snow production is not needed to provide a sufficient snow depth for winter sports.

Prior to using climate model data as input for SNOWPACK, the performance of the model was validated by forcing the model with observed meteorological data. The results were compared with observed snow depth. Overall, we obtained a good model fit (Nash-Sutcliff-Coefficiency: 0.51–0.92; coefficient of determination: 0.6–0.92; index of agreement: 0.87–0.98). For detailed results, we refer to Willibald et al. (2020). The model performance with regard to technical snowmaking was validated by Hanzer et al. (2020), however for different case studies and slightly different parameter settings.

2.3. Climate simulation data

We use climate model data from a new single model large ensemble, hereafter referred to as the ClimEx large ensemble (ClimEx LE) (Leduc et al., 2019; von Trentini et al., 2019), as forcing for SNOWPACK. The ClimEx LE consists of 50 members of the global circulation model

Canadian Earth System Model (CanESM2) (Arora et al., 2011), which is dynamically downscaled for a European and North American domain by the Canadian Regional Climate Model (CRCM5) (Šeparović et al., 2013). Each ensemble member is exposed to the same external forcing, but slightly different initial conditions in the atmospheric model. After applying small atmospheric perturbations in the initial conditions, each member evolves randomly over time. The thereby resulting model spread shows how much the climate can vary as a result of natural fluctuations in the climate system (Leduc et al., 2019; von Trentini et al., 2020). This makes each of the 50 members an equally likely, plausible realization of climate change over the next century (Deser et al., 2012; Willibald et al., 2020). Until 2005 the ensemble is driven by observed greenhouse gas forcing, from 2006 to 2099 all simulations are forced with greenhouse gas concentrations according to the IPCC RCP8.5 scenario (Moss et al., 2010). This setup allows us to analyze overall 6000 years of simulations. As the realizations of each member are equally likely, we can therefore make a probabilistic assessment of internal climate variability under RCP 8.5.

The 50 members are then dynamically downscaled to a 12 km resolution using the regional climate model CRCM5. Detailed information on the design of the experiment can be found in Leduc et al. (2019), von Trentini et al. (2019), and Willibald et al. (2020).

An evaluation of the historical simulation period revealed a strong wet bias (1–2 mm/d) with regard to precipitation and a moderate cold bias (0.5–3 °C) with regard to temperature for most grid points covering the Swiss Alps during the winter months.

As we identified this systematic model bias, which nearly all regional climate models have, and as our impact model simulates snow for single point representations in space, a further downscaling/bias adjustment step was performed to bridge the gap between regional climate model simulations and the impact model. Bias adjusting a single model large ensemble requires specific considerations, as the chosen approach should not only adjust the bias of each individual member, but should also retain the individual inter-member fluctuations (Chen et al., 2019). We applied a distribution-based quantile mapping approach, based on the daily translation method by Mpelasoka and Chiew (2009) to bias adjust and downscale the model data to the point scale in one step. For the ClimEx LE simulations, all 50 members were aggregated to compute a single empirical distribution, as a large part of the internal variability would be removed or filtered if the distributions were calculated independently for each member (Chen et al., 2019). We assume that all members have the same systematic bias, as all runs are derived from the same climate model with the same forcing (Chen et al., 2019; Gu et al., 2019; Willibald et al., 2020). Consequently, the distribution was computed based on the pooled ensemble members. A detailed explanation of the bias adjustment, as well as a summary of the performance of the bias adjustment is presented in Willibald et al. (2020).

Results from Willibald et al. (2020) furthermore show that the bias-adjusted ClimEx LE systematically underestimates snowfall fraction in Zermatt and Montana, resulting in a pronounced underestimation of simulated snow depths. For the remaining case studies, the ensemble spread of simulated snow depths encloses observations in the reference period, which implies a good performance of the bias adjustment (see Figs. 3, 4 in Willibald et al. (2020) or Figs. 4, 5 in this publication). As snow depth for Zermatt and Montana is systematically underestimated by the ClimEx LE, we cannot consider absolute snow depth values for those stations. Therefore, we do not discuss

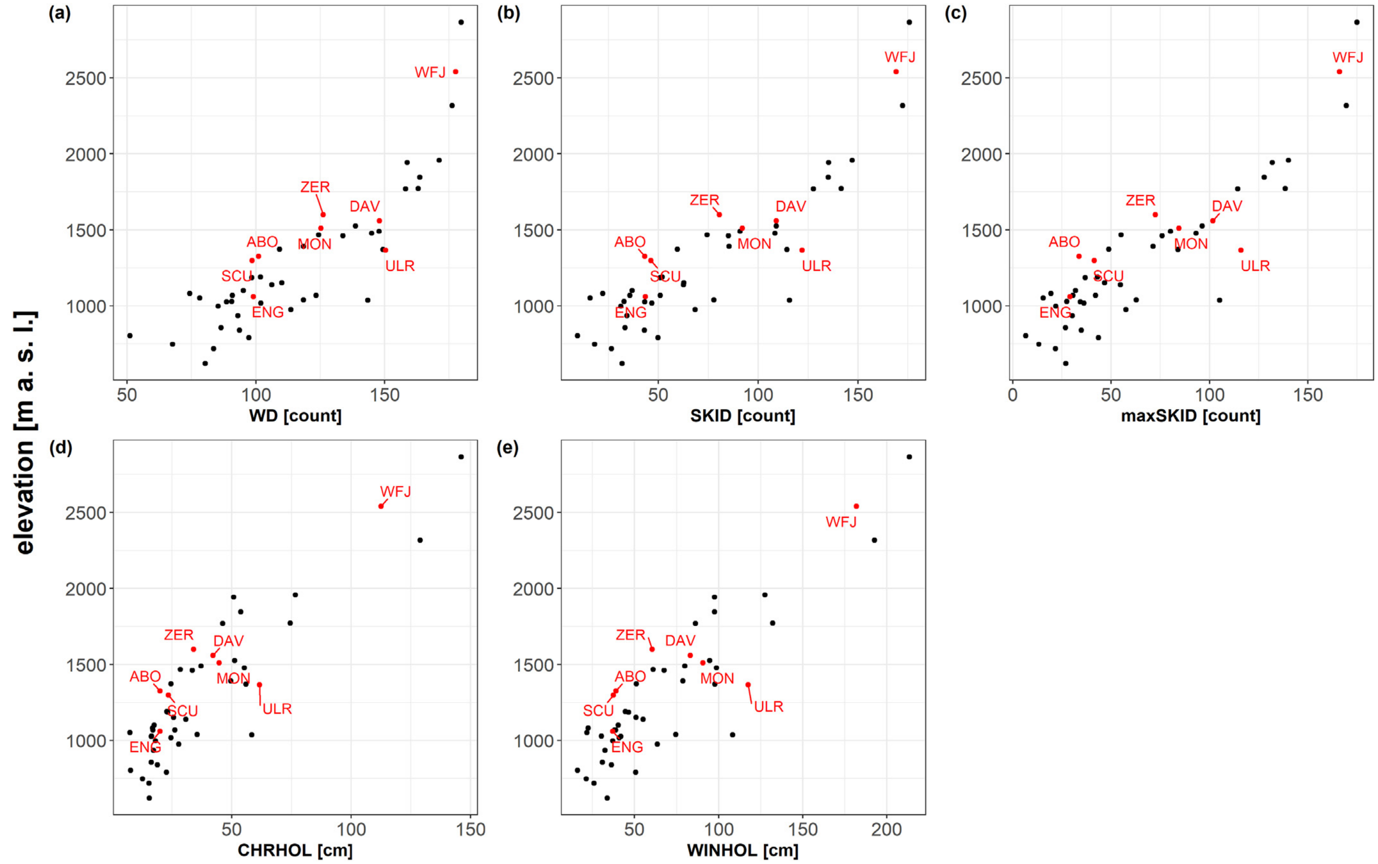

Fig. 3. long-term (1980–2019) season mean snow indicators for the 47 climate stations with at least 10 years of daily observations (black dots; natural snow only). Case studies used for simulations are marked in red. Count of winter days (a), count of ski days (b), maximum consecutive count of ski days (c), mean snow depth during the Christmas period (d), mean snow depth during winter holiday period (e). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

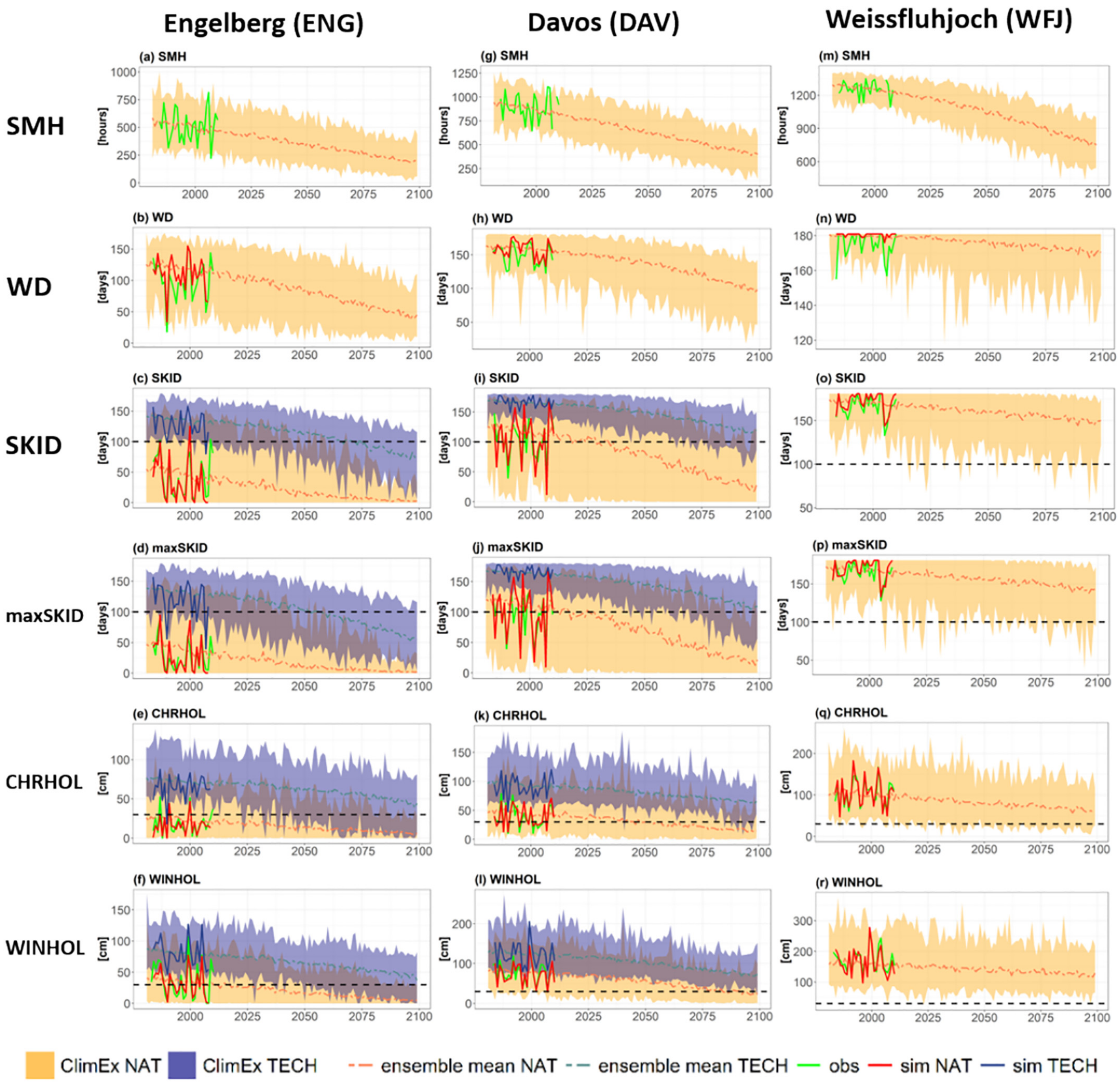

Fig. 4. yearly values of the selected snow indicators snow making potential (SMH), winter days (WD), ski days (SKID), maximum consecutive count of ski days (maxSKID), Christmas holiday indicator (CHRHOL) and winter holiday indicator (WINHOL) from 1980 to 2099 for the low-elevation station Engelberg (ENG), medium-elevation Davos (DAV) and high-elevation Weissfluhjoch (WFJ). Index calculation is based on observed snow depth/wet-bulb temperatures (obs), SNOWPACK simulations using observed meteorological variables (sim) and SNOWPACK simulations using the ClimEx LE as meteorological input (ClimEx). Except for the indicators SMH and WD and for the station Weissfluhjoch, the calculations are based on natural snow only (NAT) and including technical snow production (TECH).

the probability assessment for those two stations. Nevertheless, we can compare the sensitivity of snow indicators towards ICV, as we are using a metric that is independent of absolute values (see Section 2.4.).

2.4. Tourism related snow indicators

The indicators used in this study are measures to represent the snow state of the environment with respect to ski tourism. We summarize the indicators in Table 2. The selection and definition of the indicators are based on several previous studies (Schmucki et al., 2017; Steiger et al., 2020), but primarily on Abegg et al. (2020), who present a critical revision of existing snow indicators. The indicators were chosen to satisfy scientific interests, but also intend to support planning and decision-making in ski tourism at operator, destination and political levels. Nevertheless, they are purely climatic/snow-related and conclusions on economic profitability are generally very limited and not intended in this study.

The index *winter days* is defined as the count of days per season with a minimum snow depth of 5 cm. The threshold of 5 cm for the

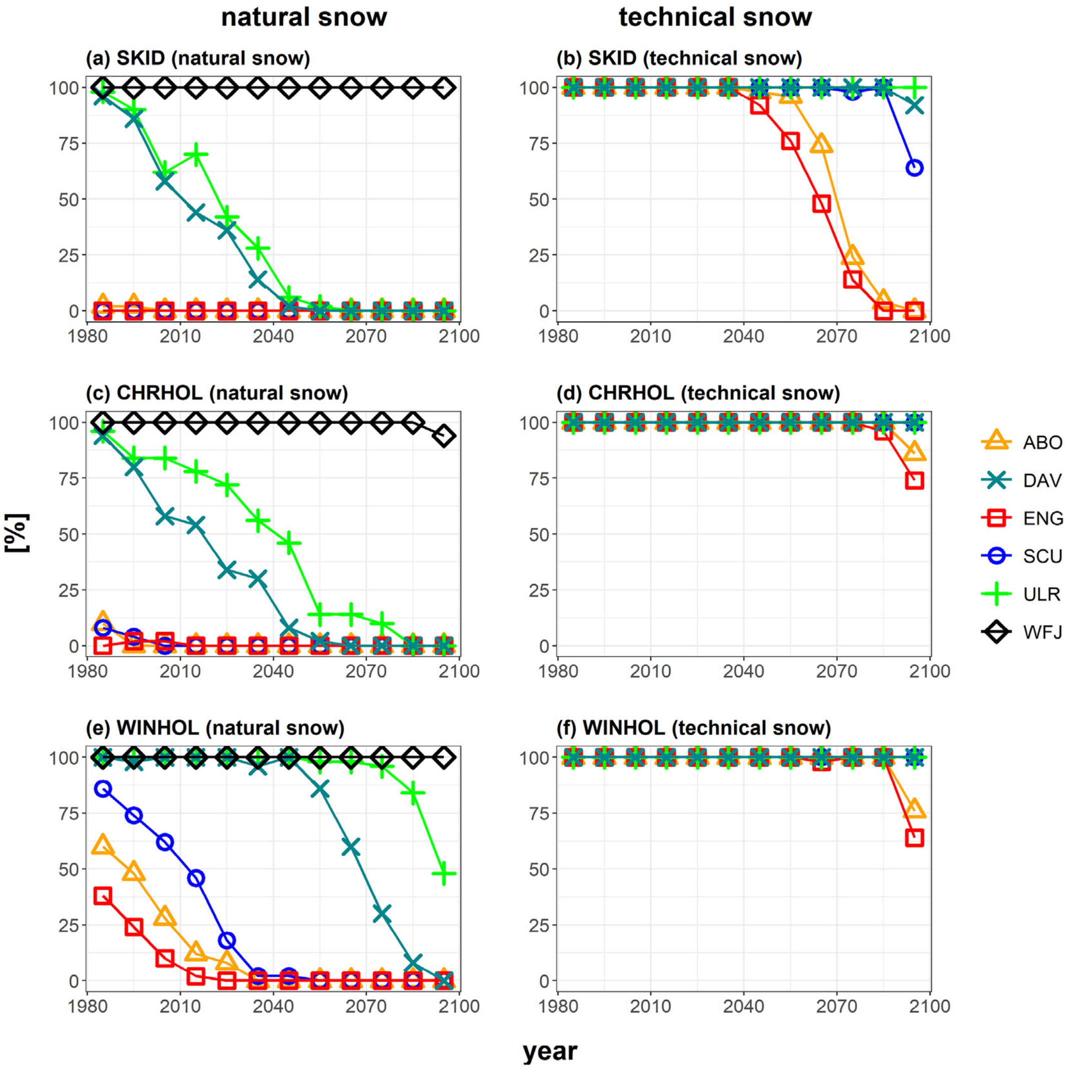

Fig. 5. probability of ClimEx members complying to the given thresholds of 100 days (ski days (SKID)) and 30 cm (Christmas and winter holiday indicators (CHRHOL, WINHOL)) in at least 7 out of 10 years (in each decade) for natural snow only (left) and including technical snow production (right) for the stations Engelberg (ENG), Scuol (SCU), Adelboden (ABO), Ulrichen (ULR), Davos (DAV) and Weissfluhjoch (WFJ).

winter days (WD) is not directly related to the operation of ski resorts, but a snow covered landscape is an important factor for the perception of a winter landscape (Marty, 2008; Schmucki et al., 2017; Witting and Schmude, 2019). The index *skier days* (SKID) is defined as the count of days per season with a minimum snow depth of 30 cm. The threshold of 30 cm is widely accepted as the minimum snow depth needed for downhill skiing (Abegg et al., 2020; Scott et al., 2008; Witmer, 1986). The index *skier days* max (maxSKID) is defined as the maximum consecutive count of days per season with a minimum snow depth of 30 cm. The three indicators above are calculated for each winter sport season that was defined as the period between Nov. 1st and Apr. 30th. In addition to the total season length, the state of the snow during certain key periods is important for ski area operators. The *Christmas index* (CHRHOL) and *winter holiday index* (WINHOL) are defined as the mean snow depth between 24th of December to 6th of January and 15th of February and 2nd of March, respectively. The periods are based on the common school holidays in Switzerland, Germany

Table 2
List of tourism related snow indicators (all indicators but winter days and snowmaking potential were calculated based on natural and technical (TECH) snow conditions.

Acronym	Name	Description	Unit	Snow type	
				Natural	Technical
WD	Winter days	Count of days per season with snow depth > 5 cm	Count	✓	
SKID (TECH)	Ski days	Count of days per season with snow depth > 30 cm	Count	✓	✓
maxSKID (TECH)	Ski days max	Maximum consecutive count of days with snow depth > 30 cm	Count	✓	✓
CHRHOL (TECH)	Christmas Indicator	Mean snow depth between Dec. 24th to Jan. 6th	cm	✓	✓
WINHOL (TECH)	Winter Holiday Indicator	Mean snow depth between Feb. 15th to Mar 2nd.	cm	✓	✓
SMH	Snowmaking potential	Count of hours with wet-bulb temperature < −4 °C	Hours		✓

and Austria. In practice, the winter holidays are not fixed to a certain date (not even within each country), but in many Alpine and neighboring countries, they are commonly situated in the second half of February. The *snowmaking potential* (SMH) is defined as the count of hours with a wet-bulb temperature below −4 °C between November 1st and February 28th (Abegg et al., 2020; Demiroglu et al., 2016; Hartl et al., 2018).

For the *skier days*, the *Christmas*-, and *winter holiday indicator*, we define thresholds to be able to make a probabilistic assessment of the role of ICV on those indicators. The single model large ensemble approach presented in Section 2.3 allows us to calculate probabilities of exceedance of certain indicators in relation to ICV and under a given external forcing (RCP 8.5). With regard to skier days we apply the so-called 100-day rule. The 100-day rule is fulfilled if, during a season, a minimum snow depth of 30 cm is present for at least 100 days between Nov. 1st and Apr. 30th. As ski areas can cope with a limited number of snow scarce seasons, this threshold is not required to be met every season. Commonly, a ski resort is considered snow-reliable if the 100-day rule is fulfilled in 7 out of 10 seasons (Abegg, 1996; Bürki, 2000; Witmer, 1986). The 100-day rule alone cannot be considered a robust economic indicator, as economic success is dependent on sufficient snow during key periods (Abegg, 2012; Elsasser and Bürki, 2002). Therefore, additionally the Christmas- and winter holiday rules are used in this study. The Christmas-, and winter holiday rules are fulfilled if the mean snow depth is larger 30 cm during the given periods (Abegg and Steiger, 2016). According to the 100-day rule, we test if the Christmas and winter holiday rules are fulfilled on a year-to-year basis and in 7 out of 10 years.

In combination with the validation of daily snow depth, we also validated the performance of SNOWPACK with regard to the selected snow indicators. To assess goodness of fit, we compared the observed values of the snow indicators with the respective simulated values. As performance indicators we used mean absolute error (MAE), coefficient of determination (R2) and index of agreement (d) (Krause et al., 2005; Legates and McCabe, 1999). The results are summarized in Table A1 in the Appendix.

As a measure of ICV, for each index, we compute the coefficient of variation between the 50 ClimEx LE members on a yearly basis. The coefficient of variation is computed as:

$$C_v = \frac{s^*100}{M} \tag{1}$$

where *s* is the standard deviation between all 50 members, and *M* is the 50-member mean. The coefficient of variation allows us to compare the variances between indicators with different units. In order to calculate the coefficient of variation, the data must be measured on a ratio scale. If the mean is approaching zero, the coefficient of variation is very sensitive towards small changes in the mean and must be interpreted cautiously (Brown, 1998).

3. Results

3.1. Observed snow indicators

Fig. 3 shows the long-term (1980 to 2019, actual length dependent on data availability, but minimum ten years) season mean of the five snow indicators winter days, ski days, maximum consecutive ski days, mean snow depth during Christmas holidays, and mean snow depth during winter holidays. One can clearly see the strong, mostly linear elevation dependence across all indicators. With regard to ski days, for example, one can observe less than 100 days for most stations below 1500 m. For stations between 1500 m and 2000 m we find 100 to 150 ski days and for stations above 1500 m more than 150. It is also evident that the simulation case studies largely cover the spread of all climate stations with regard to elevation and index values. Only the low elevation stations below 1000 m are underrepresented in our selection of case studies.

3.2. Large ensemble simulations of tourism related snow indicators

3.2.1. Index evaluation

Fig. 4 shows the values of our selected snow indicators calculated based on observed snow depth and wet-bulb temperatures, respectively. The SNOWPACK simulations are derived, using observed meteorological variables (obs, sim NAT, sim TECH), and based on SNOWPACK simulations forced with the bias adjusted ClimEx LE (ClimEx NAT/TECH) for one case study from each elevation zone, namely Engelberg (low-elevation), Davos (medium-elevation) and Weissfluhjoch (high-elevation). For results for the remaining stations, we refer to the Appendix. The blue ribbon represents the ensemble spread generated by the 50 ensemble members. This ensemble spread is solely generated through ICV. For the indicators ski days, maximum consecutive ski days, Christmas indicator and winter holiday indicator the results are shown for natural snow only and including technical snow production. We can see that the observations and simulations using observed meteorological data lie well within the ClimEx LE ensemble spread.

The strongest decrease of winter days is apparent for the low elevation case studies (approx. 60%). Also for the medium elevation case studies a strong decrease of approximately 35% can be found, but even for Weissfluhjoch a small decrease in winter days can be observed (according with Marty and Meister (2012)).

Across all stations, and across all indicators a gradual decrease of the respective metric over time is obtained. This decrease is strongest for the low and medium elevation case studies and less pronounced for the station Weissfluhjoch. The snowmaking potential is approximately halved by the end of the century for all stations. For the low-elevation stations, ski days are halved by the 2050s and approaching zero by 2075. For the medium elevation case studies this decrease is approximately 40% by the 2050s, and until the end of the century a reduction of approximately 80% is found. Including artificial snow making, we find that ski days can be more than doubled or even tripled for the low-elevation case studies compared to natural snow conditions, but also for the medium-elevation case studies a significant increase in absolute skier days can be seen. Nevertheless, even when including technical snowmaking, a gradual decrease of ski days is evident for the low-, and medium-elevation case studies. For Weissfluhjoch, we find a small decrease in ski days, but an overall high number clearly exceeding the 100-day threshold based on natural snow only, which is why we did not use the snowmaking module in this case.

For the Christmas and winter holiday mean snow depths, similar changes are found with a gradual decrease in the mean snow depths towards the end of the century for all stations. Also including technical snowmaking, a similar decrease, differing mainly in the absolute snow depth, is obtained.

With regard to the ensemble spread, we find clear developments over time and also strong differences between natural and technical snow. It must be distinguished between the absolute ensemble spread (see Fig. 4) and the relative ensemble spread. A detailed analysis of the ensemble spread and index sensitivity towards ICV is presented in Section 3.2.3.

3.2.2. Probability assessment of snow indicators

The probability analysis allows us to estimate the vulnerability of ski areas towards ICV in the present and under a future greenhouse gas forcing. We can further quantify how technical snowmaking helps to reduce the uncertainties related to ICV. Fig. 5 shows the probability of ClimEx members exceeding the defined thresholds for ten year windows for six stations (the stations Montana and Zermatt have been excluded because of the underestimated snowfall fraction; see Willibald et al. (2020)). Those thresholds are set to 100 days for the count of ski days per season and to 30 cm mean snow depth over the Christmas and winter holiday periods (see horizontal lines in Fig. 4). We show the probabilities that these thresholds are exceeded in at least 7 out of 10 years.

With regard to ski days and for natural snow conditions only, for the low elevation case studies Adelboden, Engelberg and Scuol, the probability that the 100 day rule is fulfilled in at least 7 out of 10 years is already 0% in the present climate. For the medium elevation case study Davos and low elevation case study Ulrichen, this probability is approximately 90% in 1980 and drops heavily over time. By 2010 the probability falls to approximately 50%. This means that due to natural fluctuations the 100-day rule can be fulfilled in only 50% of cases. By 2030 this value drops to approximately 25% and reaches 0% by 2050. Only for Weissfluhjoch the probability is constantly 100%. For the Christmas holiday rule, we observe a similar development. There is a slight chance of more than 30 cm of snow for the stations Adelboden and Engelberg in the past, but it is very low. This means that ICV can amplify the exceedance of the threshold, but the probability is very low. For Davos and Ulrichen the development is very similar compared to ski days. For Weissfluhjoch, there is a small chance that the mean snow depth can drop below 30 cm in at least 7 out of 10 years by the end of the century. With regard to the winter holiday rule, we find different results for the different stations. For the 1980s, the chance that the rule is fulfilled is 40% in Engelberg, 60% in Adelboden, and 85% in Scuol. By 2010 this probability drops to 5%, 10% and 20% respectively. From the 2030s on, the probability is zero. For the medium elevation station Davos and low elevation station Ulrichen, the probability is 100% until the 2040s. For Davos, it drops drastically to 30% in the 2070s and below 10% by the 2080s. For Ulrichen, the probability starts to drop by the 2070s and reaches 50% by the 2090s.

Including technical snow production in our analysis shows the high potential of compensating anthropogenic climate change and ICV. For the 100-day rule of ski days, we find a 100% probability that the rule is fulfilled in at least 7 out of 10 years for all stations until the mid of the century. This probability stays 100% for all medium elevation study sites until the 2080s. Only by the 2090s there is a slight chance that the 100-day rule is not fulfilled due to ICV in Davos. Also for Scuol, we see a drop to approximately 60% only by the 2090s. For the remaining low elevation case studies, we find a drastic drop starting in the 2050s, resulting in a 20% to 25% chance of enough snow by the 2070s and reaching almost 0% by the 2080s. Further, we find the good potential of technical snowmaking to provide enough snow during key periods. Here the probability is constantly 100%for all case studies until the 2080s. Only by the very end of the century, we find a drop for the stations Adelboden and Engelberg.

3.2.3. Sensitivity of snow indicators towards internal climate variability

The selected snow indicators are commonly used to assess the vulnerability of winter tourism towards climate change, but winter tourism is not only vulnerable to climate change, but also to climate variability. Figs. 4 and 6 show that the ensemble spread differs between indicators and changes with anthropogenic forcing.

To make a better assessment of the sensitivity of our indicators towards ICV, we use the coefficient of variation as measure of variability, as it allows us to compare the relative variability over time, over different stations and between different indicators. The coefficient of variation does not give reliable results if the mean approaches zero. For that reason, for the indices SKID and maxSKID, we only analyze the sensitivities until the year 2070 for the stations Adelboden, Engelberg, Scuol, Zermatt and Montana, as after 2070 the ensemble mean is too close to zero.

Overall, we obtain very different coefficients of variation between the different indicators. Regarding the low-elevation case studies, the highest variability can generally be found for ski days and maximum consecutive count of ski days. This implies that this index is most sensitive towards ICV in low elevations. For the medium elevation case studies Davos and low elevation case study Ulrichen, the Christmas and winter holiday indicators have the highest variability in the past until approximately 2010. The high elevation case study Weissfluhjoch also shows the strongest variabilities for those two indicators. Except for the station Weissfluhjoch, we see a clear increase in the variability of the so far mentioned indicators over time for all stations. This increase is strongest for ski days and maximum consecutive count of ski days, but also evident for the Christmas-, and winter holiday indicator. The results imply that the variability of snow indicators calculated based on natural snow conditions only is significantly increasing in the future. Also for the index snowmaking potential, we see a small increase in the coefficient of variation over time, but a much smaller overall variability. For the index winter days, we find an overall low variability. The smallest changes in variability over time are obtained for Weissfluhjoch, but still a small positive trend can be seen. In contrast to the other stations, this trend is strongest for snowmaking hours.

By comparing the variabilities of indicators based on natural snow only with variabilities of indicators including technical snowmaking, we see the high potential of technical snow production to balance ICV. Compared to natural snow conditions the variability including technical snow production is extremely low, in the range of one-third to one-fourth only. We also find virtually no, or only a very small positive trend over time or by the end of the century. For the stations Ulrichen and Zermatt we find a small decrease in the CV until approximately 2025.

In summary, different sensitivities of different snow indicators towards ICV are obtained, which in turn implies different vulnerabilities towards ICV. The implications of those findings are discussed in the next section.

4. Discussion

Climate change has been identified as a major threat to winter tourism and its impact on the ski industry has been elaborated in numerous publications (Fang et al., 2017; Steiger et al., 2019). This study confirms the general conclusions from previous studies that mean snow cover duration and snow depth in Alpine regions will be drastically reduced in the future (Steiger and Abegg, 2013) and newly tackles the research gap that not only anthropogenic climate change, but also climate variability is a major source of vulnerability for ski tourism. While so far no study investigated the combined effects of climate change and ICV on ski tourism, this study uses unique data from a single regional climate model large ensemble to make a probabilistic vulnerability assessment of ICV in the presence of anthropogenic climate change.

For natural snow, especially the mid-elevation case studies can be considered vulnerable to ICV in the short- to mid-term future. For the 100-day rule and Christmas indicator, by the 2050s, climate change impacts are so severe that these impacts dominate the vulnerability, as the ensemble spread is fully below the given thresholds. For the winter holiday indicator, ICV stays an important source of vulnerability until the end of the century. In contrast, for natural snow and for the low-elevation case studies Adelboden, Engelberg and Scuol, we cannot estimate the vulnerability towards ICV, as the selected indicators are not met at any point in time. Also for the high-elevation case study Weissfluhjoch ICV is not a source of uncertainty with regard to the selected indicators, as the thresholds are met with a probability of 100%.

Including technical snowmaking, we find that the low elevation case studies will have to face the largest vulnerabilities with regard to ICV after 2050. In the case studies Ulrichen and Davos, ICV can be counterbalanced by technical snow production, assuming an economic profitability of the related investments and the availability of water

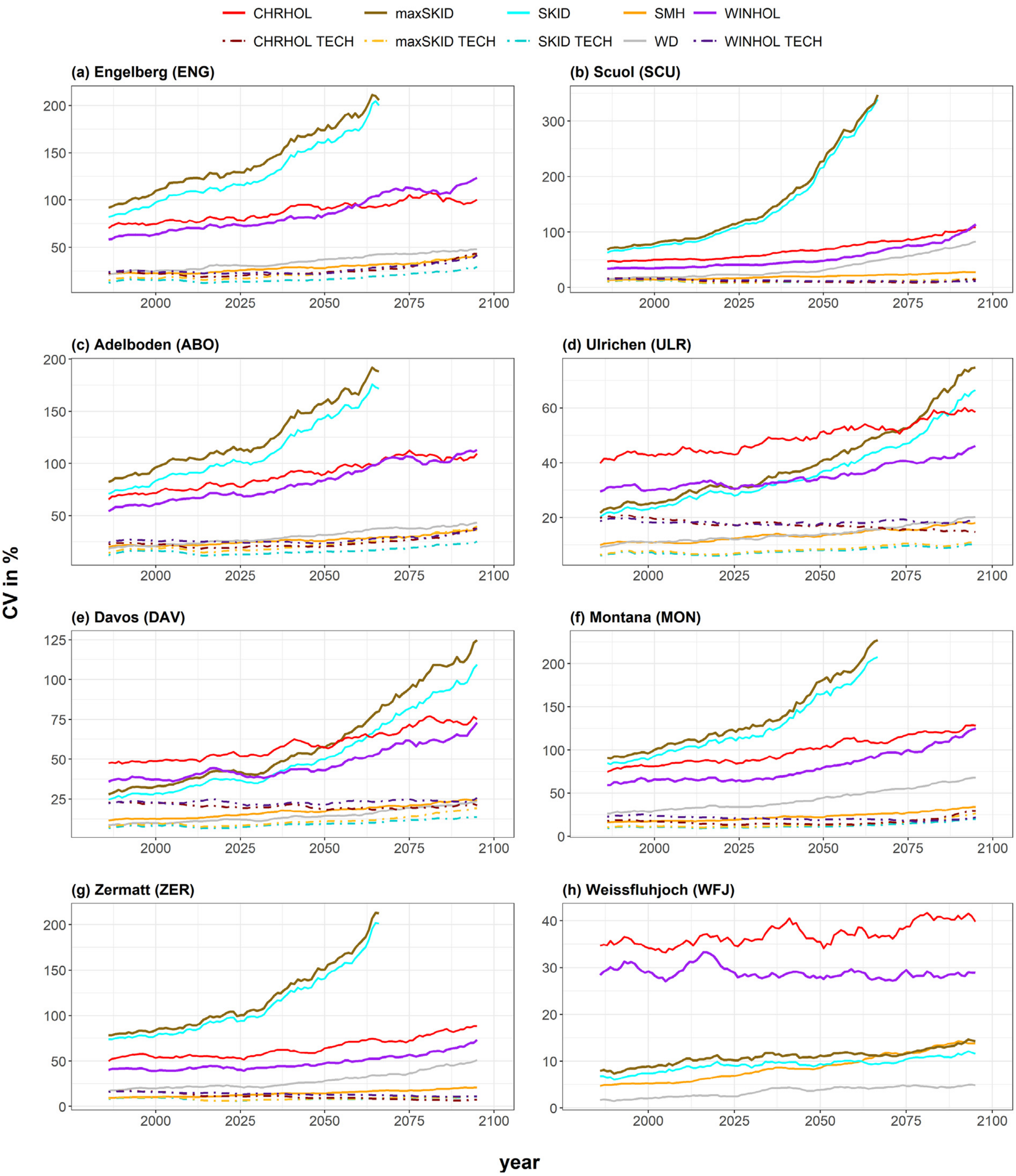

Fig. 6. 10-year running mean for the coefficients of variation [%] between the 50 ClimEx LE members for all tourism-related snow indicators (SMH: snowmaking potential; WD: winter days; SKID: ski days; maxSKID: maximum consecutive ski days; CHRHOL: Christmas holiday indicator; WINHOL: winter holiday indicator) and for each case study for natural snow and including technical snow production (TECH). The panels are arranged according to the station elevations. The coefficient of variation does not give reliable results if the mean approaches zero. For that reason CV values for the stations Adelboden, Engelberg, Scuol, Zermatt and Montana are cut off after the year 2070 for the indices SKID and maxSKID.

resources. Especially in the second half of the century, ICV will be an important driver that determines the exceedance or shortfall of the 100-day rule.

In Section 3.2.3., we estimated the sensitivity of tourism indicators towards ICV and its change over time. Regarding natural snow, and in absolute terms, we find the highest sensitivities for the low-elevation case studies. In relation to elevation, we find that the sensitivity of indicators to ICV varies significantly. Especially the 100-day rule is very sensitive to ICV in low-elevation case studies, while the winter holiday indicator is more robust and less prone to ICV. In the case studies Davos, Ulrichen and Weissfluhjoch, we find that the winter holiday indicator, and especially the Christmas holiday indicator are more sensitive to ICV. Consequently, it is very important to investigate the vulnerability of multiple indicators for a given case study, as its variability and sensitivity can be strongly dependent on the location and elevation.

We find that technical snowmaking is a very effective instrument to counteract ICV, by reducing variability by more than 60%. It is to some extent also capable to buffer climate change, but we find that in low elevation case studies, technical snowmaking will reach its limits by the end of the century. When technical snowmaking reaches its limits, we find an increasing relevance of ICV. The benefits of technical snowmaking for ski resorts are confirmed by Falk and Vanat (2016), who find that large investments in artificial snowmaking have a significantly positive effect on visitor numbers, however this effect cannot be observed for low-elevation ski areas. To cope with rising temperatures, the snowmaking capacities will have to increase in the future. Damm et al. (2014) found that the extension of snowmaking technology in the future will result in a substantial increase in electricity costs for ski operators, which will ultimately lead to increased ticket prices. This development is accompanied by strong interventions in the water balance, resulting in substantial environmental impacts. The expansion of technical snowmaking leads to increased water demand that can have multiple implications on nutrient input and runoff regime through the withdrawal of water from natural and artificial lakes (Teich et al., 2007). It is questionable if future water demand can be provided and conflicts with other users can be expected (Vanham et al., 2009). Further ecological impacts of artificial snowmaking can arise with regard to soil temperature and vegetation (Casagrande Bacchiocchi et al., 2019), as well as erosion and surface runoff (Wronska-Walach et al., 2019).

While this study provides important findings on the interdependencies of climate change and ICV and its impacts on ski tourism, it has multiple limitations and uncertainties that span over the whole process chain, starting with the climate model data, over the snow model, to the selected tourism-relevant snow indicators. With regard to the meteorological process chain, we want to mention only the three main sources of uncertainty and concentrate the discussion of limitations on the SNOWPACK setup and indicator calculation. First, it must be stated that our results are highly dependent on the choice of the emission scenario, as it was performed based on the underlying conditions of the RCP8.5 scenario. Therefore, this scenario represents the most extreme character of greenhouse gas concentrations in the atmosphere. However, expected states and dynamics of other emission scenarios can also be assessed, as these levels are reached earlier in time (Willibald et al., 2020). Second, an important drawback of the single model approach is that it has limited capacity in providing a robust estimate of anthropogenic climate change; this is where multi-model ensemble setups have clear advantages (Tebaldi and Knutti, 2007). With a multi-model ensemble we would expect an overall higher ensemble spread, which is also confirmed by von Trentini et al. (2019). The third large source of uncertainty is the choice of the bias adjustment methodology. Although quantile mapping is widely regarded as a very robust bias adjustment method that is superior to other approaches (Gutiérrez et al., 2019; Ivanov and Kotlarski, 2017; Teutschbein and Seibert, 2012), it has some drawbacks ranging from the assumption of a stationary model bias (Maraun, 2013) to the modification of the raw climate change signal (Ivanov et al., 2018). Those uncertainties within the hydro-meteorological process chain are discussed in detail in Willibald et al. (2020).

While we apply the snowmaking module in SNOWPACK with a uniform setup, snowmaking capacities and technologies differ widely between ski resorts. Therefore, a modelling approach incorporating individual capacities would be desirable, but data on the actual snowmaking behavior in the selected case studies could not be gathered. Further, so far, there exist only very few studies that validate the snowmaking modules of snow models. For example, Hanzer et al. (2020) compare and partly also validate the snowmaking and grooming modules of three different snow models. However, future research is necessary to estimate the effect of snow redistribution by groomers and skiers to validate the snowmaking modules. Our analysis of observed and simulated snow depths and of deviated indicators show no necessity of technical snowmaking for the high elevation case study Weissfluhjoch, as we find that the analyzed indicators clearly exceed the given thresholds. This is also in line with results based on observations by Marty and Meister (2012) and results based on simulations for the future by Schmucki et al. (2017). However, the actual practice looks different. Technical snowmaking at the Weissfluhjoch is already in practice today, primarily to provide sufficient snow early in the season. This is in contradiction to the snow indicators that clearly state sufficient snow for skiing operations and raises the question if the used indicators are meaningful for any elevation band. Due to no vegetation cover and mostly rocky ground cover, higher thresholds should be used in high elevations. Nevertheless, the used indicators have been previously used in a wide variety of publications (Abegg et al., 2020), which allows comparisons to other studies (Steiger and Scott, 2020; Steiger et al., 2019).

Still, a critical review of existing snow indicators is indispensable for a proper interpretation of our results. As we are analyzing climatic and snow cover parameters only, we cannot explain the profitability of ski resorts. Therefore, we stress the fact that an over-interpretation of the applied indicators and of our results needs to be avoided. There are many unpredictable technical, operational and commercial aspects that do not allow drawing conclusions on future profitability. Nevertheless, our results can help explore large uncertainties in winter tourism and support decision making in ski tourism at operator, destination and political levels.

4.1. Transferability

Due to the high computational cost of the entire modelling chain and due to limitations in terms of observational data, we could perform our analysis only for individual station locations, which are well separated in space. Therefore, we cannot account for meso-scale variations in physiographic characteristics, such as slope or aspect (Spandre et al., 2019). This could only be achieved through a distributed modelling approach, which would be computationally unfeasible for multiple study sites and which would also require a regionalization and spatial interpolation of the observed climate and snow cover data. We however assume a basic spatial transferability of our results. The mean elevation of the initial 47 ski resorts in the countries Austria, Germany and Switzerland is 1665 m (compare Fig. 2). With a mean-elevation of 1530 m, the investigated case studies are close to the mean ski resort elevation. Our results in Section 3.1 also show that the selected case studies mostly cover the elevation ranges of Swiss, Austrian and German ski areas. Further, from Fig. 3, we see that the observed tourism-related snow indicator values in our case studies mostly cover the observed spread of indicator values from all 47 climate stations. Only stations in elevations below 1000 m are underrepresented in our study, but also the common thresholds are rarely met in those elevations, which is why an analysis, as performed in this contribution, would not give valuable insights. Therefore, under the current climatology and assuming that elevation is the main factor determining climatic forcing of the snowpack, our selected case studies are a good representation of ski resorts in the Alps in terms of snow indicators. Regarding elevation dependencies of snow indicators, Ulrichen is the only investigated station which does not fit well into the general elevation-dependent pattern (see Fig. 3). The main reason is the fact that the station temperatures are not fully representative for the elevation because the station is located at a known cold pool in the valley bottom. Further exceptions, from the general elevation dependence of the results can be explained, for instance, by specific local factors such as surface coverage and local topography as well as by the effects of the prevailing circulation patterns. Projected frequency changes of the latter are either small or inconsistent across different climate models (Huguenin et al., 2020), and are beyond the scope of the present work. Lastly, we analyzed the spatial pattern of projected temperature and precipitation changes over the whole Alps (see Figures in the Appendix). For temperature, we found that the signal is quite homogeneous for the entire Alpine arch. For precipitation, the sign of winter precipitation change is always positive, but less homogenous. The northern Alps, which are covering all of our 47 climate stations show only a small increase. In the southern part, we find a considerably stronger positive precipitation signal. We conclude that the main findings of this study can at least to some extent be transferred to further locations in the Swiss, German and Austrian Alps.

5. Conclusions

To our knowledge, this is the first probabilistic analysis of the vulnerability of ski tourism towards the combined effects of ICV and climate change. In the present, especially medium-elevation ski resorts are vulnerable to ICV, while low elevation ski resorts cannot comply to certain thresholds of snow reliability regardless of ICV. In contrast, for high-elevation ski areas snow reliability is given at any time. We show that climate change will substantially reduce snow reliability in the future and that technical snow production is an appropriate technique to at least partly buffer the adverse effects of climate change and ICV. Beyond the 2050s technical snowmaking will reach its limit to counteract climate change and ICV will be an important driver that determines snow reliability despite the production of technical snow.

While we could tackle an important research gap, certain open questions remain: In order to identify potential winning and losing destinations, future studies should aim to explore the uncertainties related to ICV, not only over time, but also in greater detail on different spatial scales. As an economic assessment is not possible investigating the indicators in this study, future research should aim at using the results on the supply side and combine it with demand side data, such as skier visits, to be able to monetize the effects of climate change on the one side and the effects of ICV on the other side, or at least estimate the different contributions of climate change and ICV to the economic state of a ski resort. In summary, we could show the overall high relevance of ICV in the vulnerability assessment of ski tourism and its differing contribution across case studies and across the selected indices and could show that our main findings are generalizable over the Swiss, German and Austrian Alps. This knowledge can help winter tourism destinations and local decision makers in the identification of vulnerabilities towards climate change and ICV.

CRediT authorship contribution statement

Fabian Willibald: Conceptualization, Writing – original draft, Methodology, Visualization, Software, Writing – review & editing. **Sven Kotlarski:** Conceptualization, Methodology, Writing – review & editing. **Pirmin Philipp Ebner:** Software, Writing – review & editing. **Mathias Bavay:** Software, Writing – review & editing. **Christoph Marty:** Conceptualization, Methodology, Writing – review & editing. **Fabian V. Trentini:** Visualization, Writing – review & editing. **Ralf Ludwig:** Conceptualization, Methodology, Writing – review & editing. **Adrienne Grêt-Regamey:** Conceptualization, Methodology, Writing – review & editing.

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.

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Appendix

Index validation

As described in Willibald et al. (2020) we received good Snowpack model results with regard to daily snow depth for all case studies (see Fig. 2, Table 2 in Willibald et al. (2020)). Also with regard to the selected snow indicators SNOWPACK provides good simulation results (Table A1).

Table A1
Goodness of fit of selected snow indicators for our eight case studies. We used mean absolute error (MAE), coefficient of determination (R2) and index of agreement (d) as goodness of fit criteria.

	WD [days]			SKID [days]			maxSKID [days]			CHRHOL [cm]			WINHOL [cm]		
	MAE	R2	d	MAE	R2	d	MAE	R2	d	MAE	R2	d	MAE	R2	d
ENG	16.9	0.73	0.87	10.7	0.81	0.94	10.0	0.73	0.92	5.2	0.77	0.92	9.33	0.84	0.94
SCU	23.5	0.56	0.73	17.3	0.64	0.88	17.3	0.6	0.86	7.4	0.56	0.85	10.8	0.67	0.89
ABO	29.0	0.47	0.65	12.8	0.64	0.89	13.0	0.58	0.87	5.0	0.68	0.9	11.4	0.73	0.9
ULR	7.0	0.81	0.91	14.0	0.68	0.89	14.1	0.72	0.89	12.9	0.66	0.86	13.7	0.76	0.93
MON	17	0.61	0.79	13.3	0.72	0.91	10.5	0.84	0.95	12.8	0.9	0.96	7.0	0.88	0.96
DAV	9.22	0.59	0.8	13.9	0.74	0.92	14	0.74	0.92	6.14	0.85	0.95	7.37	0.89	0.97
ZER	16.7	0.63	0.73	16.4	0.75	0.91	16.0	0.75	0.91	7.9	0.78	0.92	10.6	0.65	0.88
WFJ	5.56			5.7	0.78	0.89	6.5	0.67	0.87	10.0	0.86	0.96	14.8	0.89	0.95

Data availability

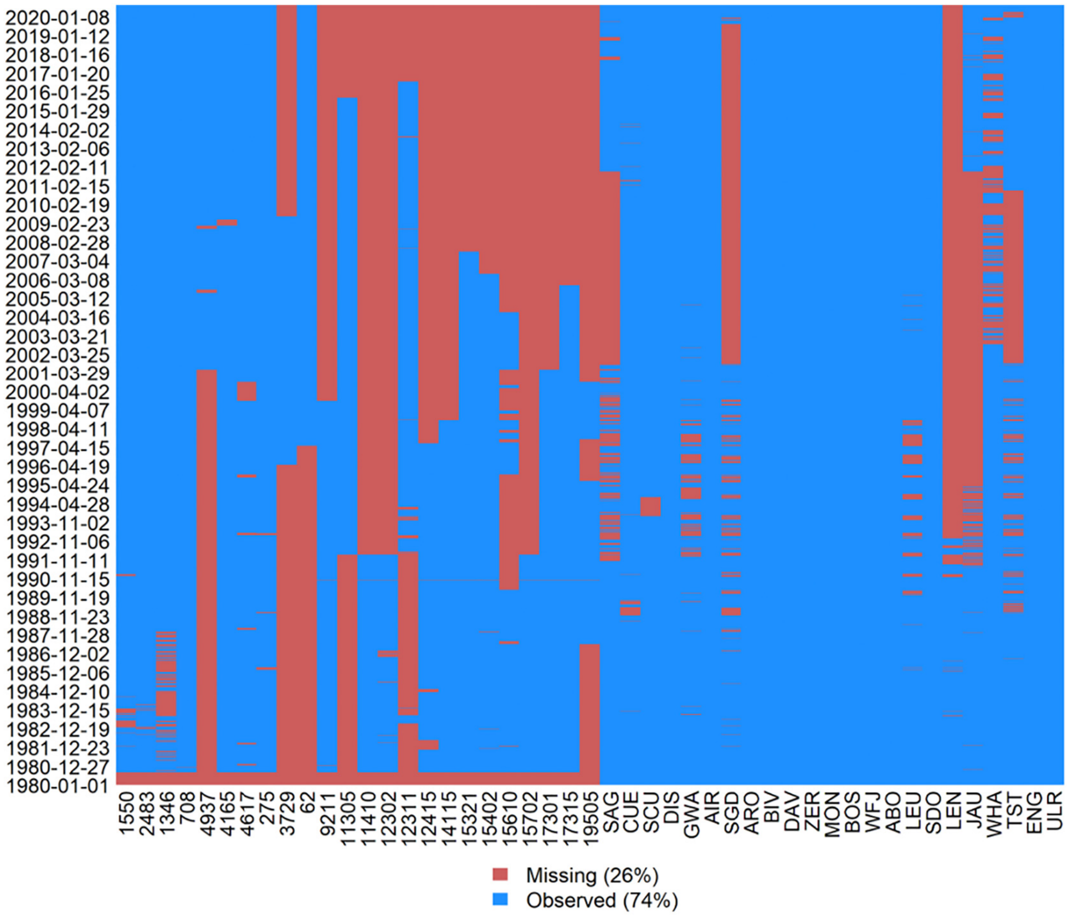

Fig. A1. Visualization of missing data in daily snow depth measurements during the months November to April for 47 climate stations in proximity to ski resorts. IDs on the x-axis represent the official station abbreviations used by the respective meteorological offices.

Index evaluation

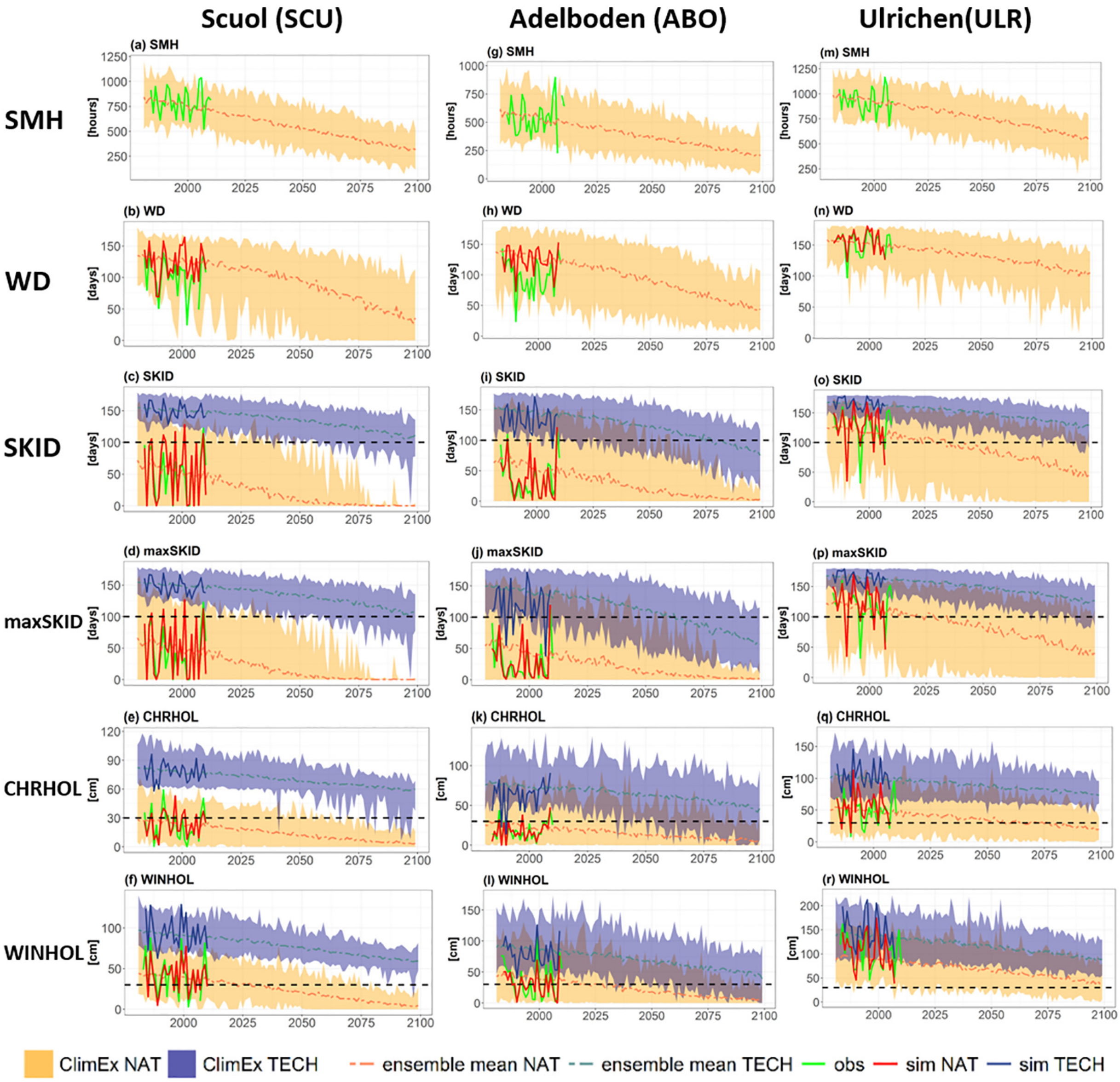

Fig. A2. Yearly values of the selected snow indicators snow making potential (SMH), winter days (WD), ski days (SKID), maximum consecutive count of ski days (maxSKID), Christmas holiday indicator (CHRHOL) and winter holiday indicator (WINHOL) from 1980 to 2099 for the stations Ulrichen (ULR), Scuol (SCU) and Adelboden (ABO). Index calculation is based on observed snow depth/wet-blub temperatures (obs), SNOWPACK simulations using observed meteorological variables (sim) and SNOWPACK simulations using the ClimEx LE as meteorological input (ClimEx). Besides for the indicators SMH and WD the calculations are based on natural snow only (NAT) and including technical snow production (TECH).

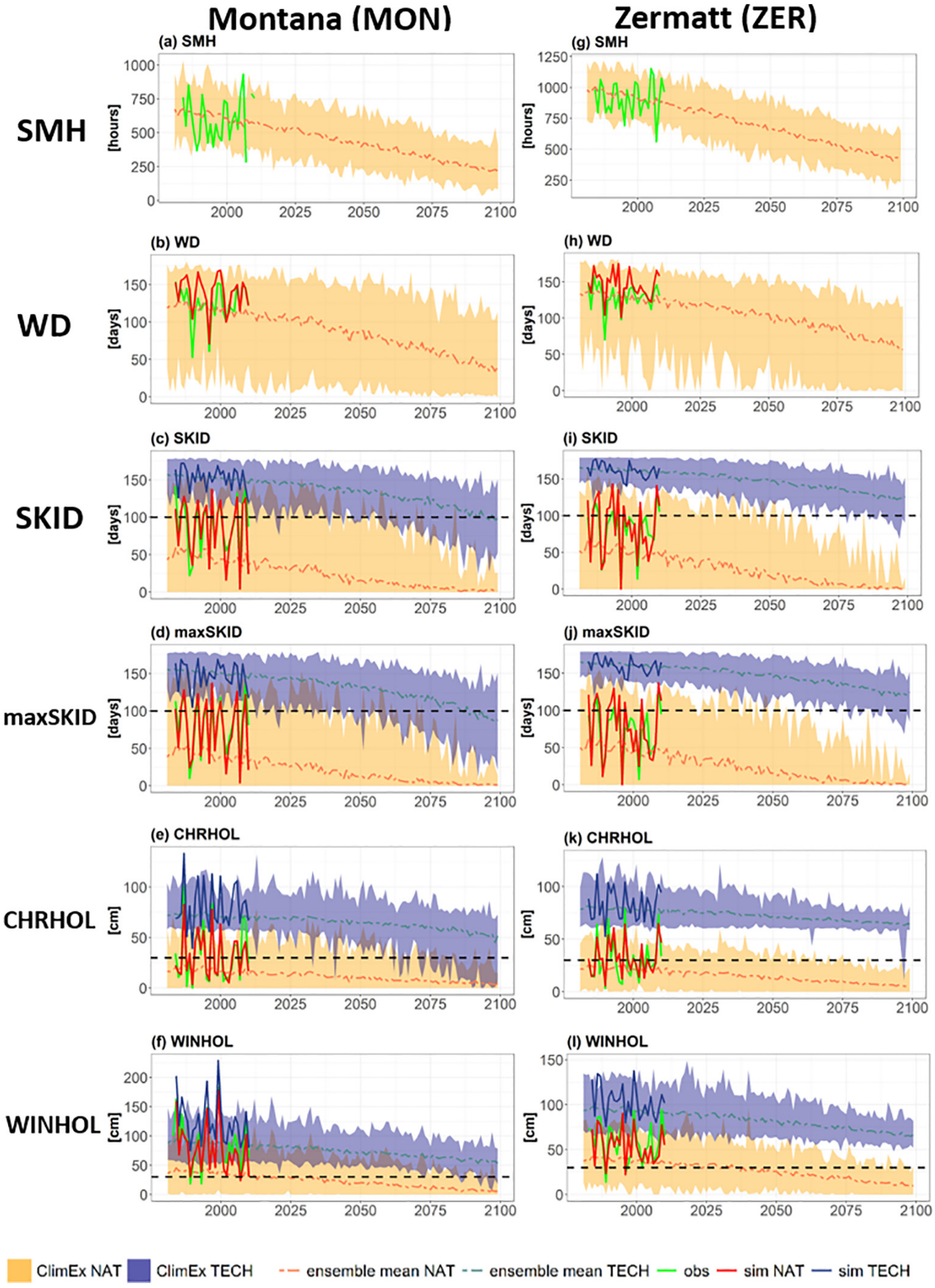

Fig. A3. Same as Fig. A3, but for stations Montana (MON) and Zermatt (ZER).

Climate change signals

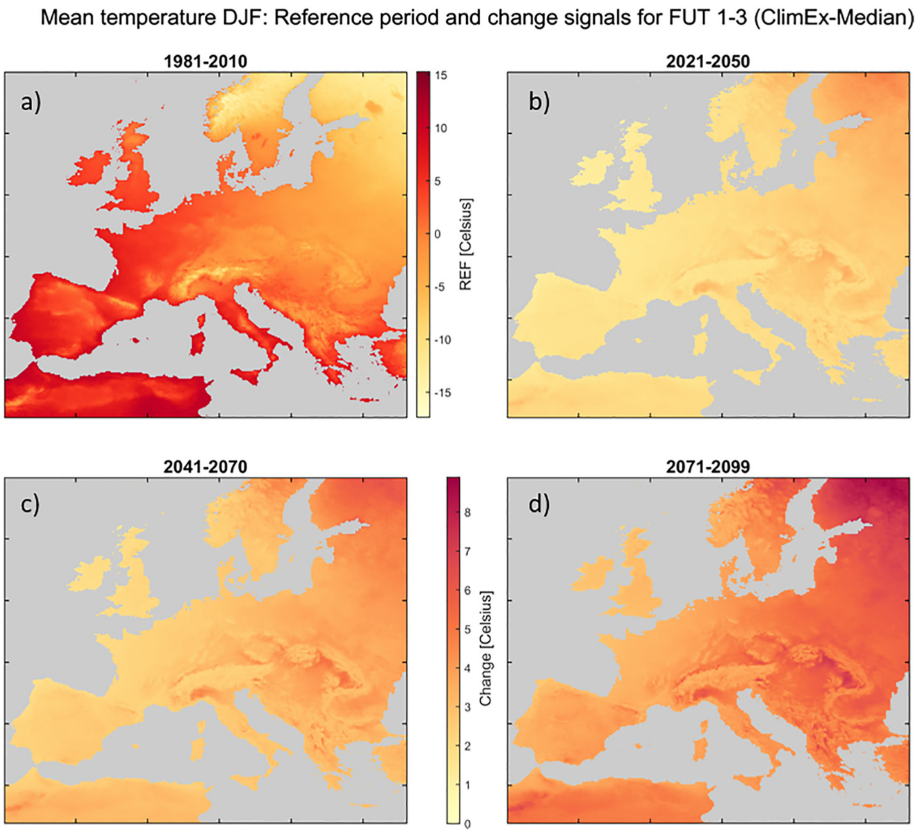

Fig. A4. Climate change signals between the reference period 1981–2010 ClimEx ensemble 50-member median winter mean temperatures (a) and the future periods 2021–2050 (b), 2041–2070 (c), 2071–2099 (d).

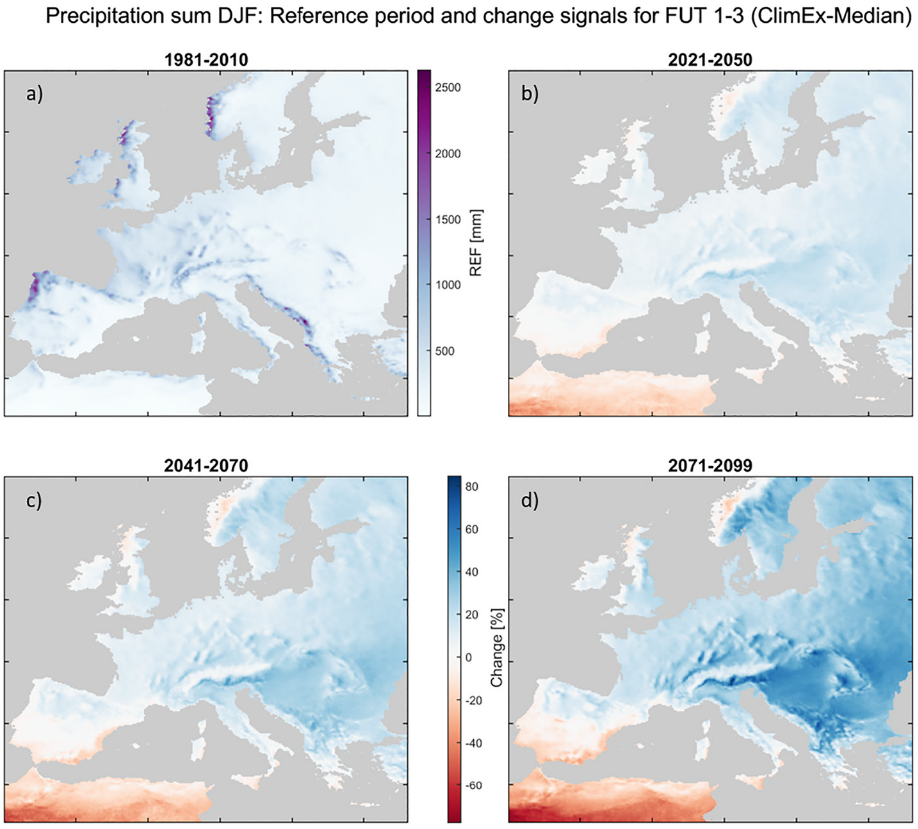

Fig. A5. Climate change signals between the reference period 1981–2010 ClimEx ensemble 50-member median winter precipitation sums (a) and the future periods 2021–2050 (b), 2041–2070 (c), 2071–2099 (d).

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