nature climate change

Article https://doi.

Climate change exacerbates snow-water-energy challenges for European ski tourism

Received: 24 July 2022

Accepted: 6 July 2023

Published online: 28 August 2023

Check for updates

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Ski tourism is a substantial component of the economy of mountainous regions in Europe and is highly vulnerable to snow scarcity, which is increasing due to climate change. However, the climate change snow supply risk to ski tourism has not been quantified in a consistent way throughout Europe, including the influence and environmental footprint of snowmaking. Here we show that the snow supply risk to ski tourism increases with global warming level, heterogeneously within and across mountain areas and countries. Without snowmaking, 53% and 98% of the 2,234 ski resorts studied in 28 European countries are projected to be at very high risk for snow supply under global warming of 2 °C and 4 °C, respectively. By contrast, assuming a snowmaking fractional coverage of 50% leads to corresponding proportions of 27% and 71%, but with increasing water and electricity demand (and related carbon footprint) of snowmaking. While it represents a modest fraction of the overall carbon footprint of ski tourism, snowmaking is an inherent part of the ski tourism industry and epitomizes some of the key challenges at the nexus between climate change adaptation, mitigation and sustainable development in the mountains, with their high social-ecological vulnerability.

Due to climate change, the mountain seasonal snow cover is decreasing at a rate that depends on the geographical location and the elevation[1–3]. Assessing the extent to which past and future changes in climate affect ski resort operations across Europe is critical to designing meaningful development pathways for this key sector of the European tourism industry[4], particularly in the context of the European Green Deal[5]. This concerns both climate change adaptation and mitigation[6] and needs to take into account related pressures on the local environment and resources such as water and energy[7]. Indeed, ski tourism faces complex and intertwined sustainability challenges in the context of global change[8,9]. Global tourism (not only ski tourism) is responsible for substantial greenhouse gas emissions estimated at 8.1% of global emissions, with 49.1% of this contribution being caused by transport[10]. Tourism strongly influences local and regional social-ecological systems, sustaining livelihoods but also affecting biodiversity and use of resources[11]. The environmental impact of ski tourism is often viewed in terms of water and electricity demand for snowmaking, but only a few studies provide quantitative estimates, most often at the local scale[12,13].

Snow-scarce conditions are detrimental to ski resort operations because snow on ski pistes is the major ingredient of ski tourism

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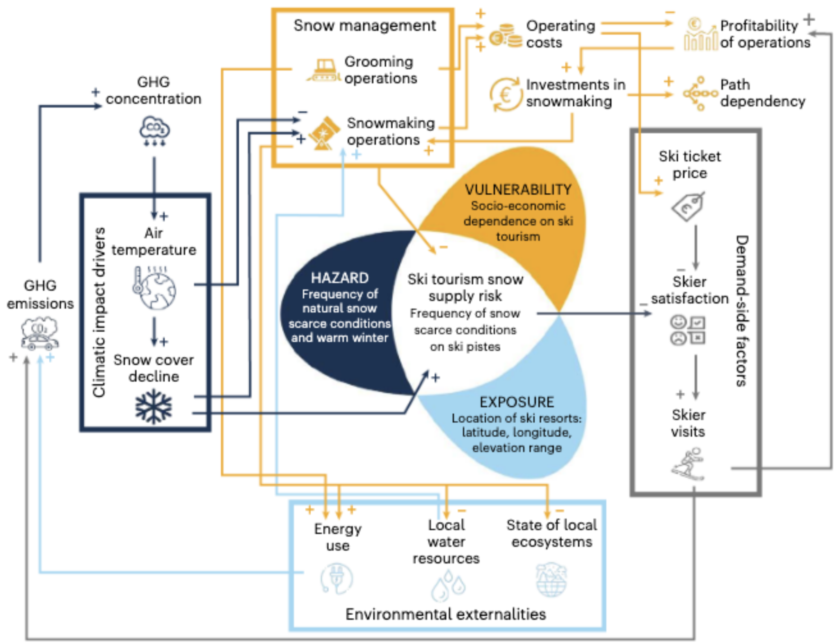

Fig. 1 | Snow supply risk to ski tourism in the context of climate change. Following the IPCC's conceptual framework, risk, which we define as the frequency of snow-scarce conditions on ski pistes, results from the combination of hazard, exposure and vulnerability. Changes in hazard are related to temperature rise and snow cover decline. Snow management is designed to reduce the snow supply risk but is itself influenced by climatic impact drivers. In turn, it induces pressure on environmental externalities, with related greenhouse gas emissions. The risk also influences demand-side factors through skier satisfaction (influencing profitability of operations) and skier visits (contributing to greenhouse gas emissions through transportation, housing and so on). Profitability of operations is influenced by snow management costs but also influences investments in snowmaking and related path dependencies.

supply. An occasional lack of snow has always been contemplated by ski resort operators due to the strong interannual variability of snow conditions[1,2,14,15]. A key concern is how often and to what extent such snow-scarce situations occur, as recurring snow-scarce winters threaten the long-term economic sustainability of ski resorts[14,16–19]. Here we adopt the definition of risk of the Intergovernmental Panel on Climate Change (IPCC)[20], that is, the 'potential for adverse consequences for human or ecological systems' and conceptualize its application to snow supply to ski tourism in Fig. 1. Quantifying long-term climate change impacts and risks pertaining to the snow supply to European ski tourism requires accounting not only for the evolution of climatic impact drivers (temperature increase, snow cover decline) and the related hazards (the frequency of warm and/or snow-scarce winters), but also for their combination with the exposure (geographic location, elevation range) of individual ski resorts and the ski resorts' individual and collective vulnerability.

The risk on snow supply to ski tourism can thus be defined as the frequency of snow-scarce conditions on ski pistes, taking into account snow grooming and snowmaking[1,16,21,22]. Indeed, the climatic impact driver 'snow cover decline' directly leads to a rise in the snow supply risk to ski tourism (Fig. 1). Snowmaking, by contrast, is primarily designed to reduce the snow supply risk to ski tourism by decreasing the frequency of snow-scarce conditions on ski pistes through the addition of machine-made snow[14,18,19,23]. There are multiple interactions between snowmaking, the local climate (snowmaking can only proceed if the temperature remains sufficiently low), the local environment (water resources, local ecosystems), the broader socio-economic functioning of ski tourism within mountain areas and the influence of ski tourism on the climate through greenhouse gas emissions[7,14,18,19,23] (Fig. 1).

Europe (see Fig. 2 for the included mountain ranges) is the largest global ski tourism market, with about 50% of the world's total ski resorts and over 80% of the world's ski resorts with more than 1 million skier visits (that is, number of daily individual use of ski resorts facilities) per year[24]. It accounts for 60% of annual skier visits (43% only for the European Alps) corresponding to 209 million skier visits in 2019 before the coronavirus disease (Covid-19) outbreak[24] and a turnover exceeding €30 billion per year according to media reports[25]. Past studies dedicated to climate change impacts on ski tourism in Europe have either neglected the influence of snow management and in particular snowmaking[4,26–28], or focused on smaller geographical domains, for example, at the scale of individual ski resorts or an aggregation at the national scale[16,17,29–31]. Also, many studies[27–29,31] addressed the demand-side risk resulting from tourists' reactions to future snow-scarce conditions rather than quantifying the risk to snow supply itself. These deficiencies have made it difficult to produce a consistent assessment at the scale of the entire continent. The environmental footprint of snowmaking has seldom been studied[12,32] and never at the scale of the entire continent.

Climate change ski tourism snow supply risk

We study the climate change effects on the snow supply risk to ski tourism at the scale of the entire European ski tourism market. We use numerical simulations of snow conditions, with and without snowmaking, and under past and future climate conditions, at the scale of individual ski resorts (see Methods and Extended Data Figs. 1 and 2). Expanding from previous work[16,18,33], we quantify daily snow conditions at ski resort scale as the fraction of the ski resort's surface area with a snow mass (snow water equivalent) exceeding a threshold of 100 kg m^{-2}. This corresponds to 20 cm of snow with a density of 500 kg m^{-3}, which

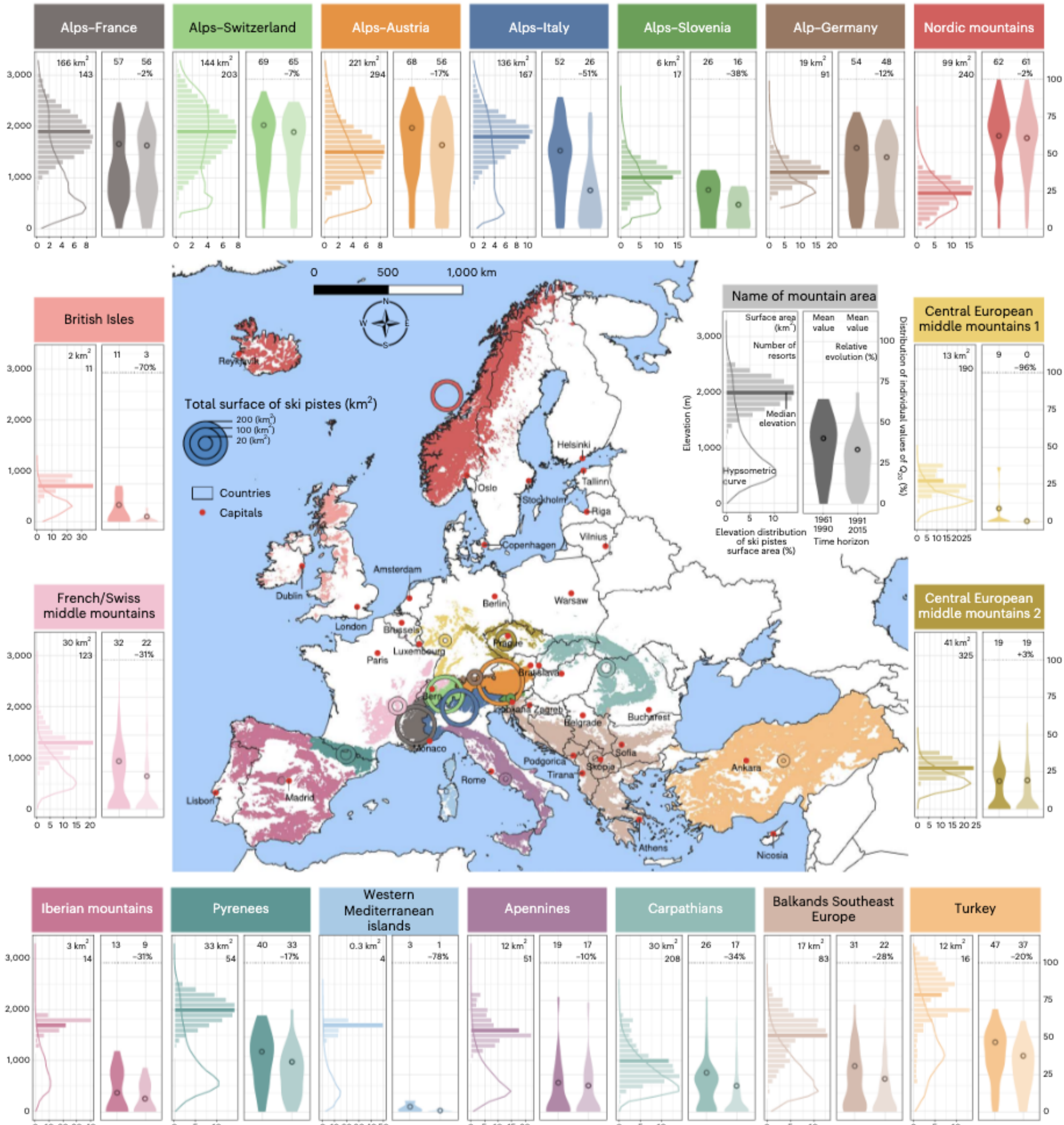

Fig. 2 | Distribution of ski resorts in mountain areas in Europe. Map of Europe, showing the 18 geographical entities (European Environmental Agency mountain areas, 6 subdomains for the European Alps) considered in this study and the corresponding total estimated surface area of ski pistes (total 984 km² as of November 2022). For each geographical entity, subpanels around the map show the vertical distribution of ski pistes, along with the hypsometry and the corresponding number and total surface areas of the ski resorts. The subplots also display the distribution of snow reliability values (from 0 to 100) of snow conditions in ski resorts during snow-scarce winters, corresponding to the 20% worst winter seasons for the time periods 1961–1990 (left) and 1991–2015 (right).

is sufficient for alpine skiing. Averaging this daily value over the critical time period from December to February[14,21] provides a yearly indicator of snow conditions, referred to as the snow reliability index. We define the meaning of 'snow-scarce conditions' for each ski resort as the worst 20% years in terms of groomed natural snow encountered during the reference time period 1961–1990 (Q_{20}^{ref}).

The simulation results used in this study are based on the approach implemented to compute the Copernicus Climate Change Service (CS3) Mountain Tourism Meteorological and Snow Indicators (MTMSI) dataset[34]. This dataset uses the pan-European near-surface meteorological reanalysis UERRA and an ensemble of adjusted EURO-CORDEX regional climate model simulations. Both feed the detailed snow cover model Crocus, which includes a representation of snow grooming and snowmaking[34,35]. In the model, snowmaking depends on operating rules and meteorological conditions, in particular the wet-bulb air temperature[34] (see Methods and Extended Data Fig. 1). The MTMSI dataset provides state-of-the-art estimates of relevant climate data for the ski tourism industry, yet is insufficient for sectoral risk assessment because it does not consider the location of individual ski resorts. We address this gap by combining the data used to produce the MTMSI dataset with geographical information of 2,234 individual ski resorts across Europe (see Methods and Extended Data Figs. 1 and 2). This enables computation of snow cover conditions (including the snow reliability index, expanding its use when snowmaking is taken into account; see Extended Data Fig. 3) and water demand for snowmaking for various values of the snowmaking fractional coverage (that is, the fraction of a resort's ski piste area covered by snowmaking infrastructure) for each ski resort. The results of such calculations are illustrated in Extended Data Figs. 4–7 for contrasted ski resorts located in the French/Swiss middle mountains (Métabief, Jura, France), in the Austrian Alps, in the Nordic mountains and in the British Isles, respectively.

The distribution of Q_{20}^{ref} values for ski resorts in Europe (Fig. 2) reveals the strong heterogeneity in reference snow conditions within and across mountain areas due to the combined effect of the local climate and the location of ski resorts, and provides the baseline upon which future changes can be analysed. It also shows the distribution of the ski resorts' 20th percentile of snow reliability index values (Q_{20}) within a geographical entity for the time period 1991–2015, highlighting that over past decades, natural snow conditions in ski resorts have generally declined, at a rate that differs depending on the mountain area.

On the basis of future climate change scenarios, we investigate how the frequency of snow-scarce winters changes with the global warming level (GWL) for various illustrative values of the snowmaking fractional coverage (0%, 25%, 50% and 75%). The snow supply risk to the European ski tourism is displayed as a function of the global warming level in the form of burning embers in Fig. 3 at the scale of mountain areas[36] (see Methods and Extended Data Fig. 1). We define the risk level as follows: a frequency of 30% of winters below the snow scarcity threshold, corresponding to a 50% increase in the risk compared to the reference value (20%), is referred to as 'moderate' (yellow). A frequency of 40%, corresponding to a doubling of the reference risk value, is referred to as 'high' (red). The risk reaches the 'very high' (violet) domain at a frequency of 50% and above, that is, snow-scarce conditions encountered at least once every 2 yr on average.

Burning embers for groomed natural snow only (left) and including snowmaking (right), consistent with the approach taken in the literature and in recent IPCC reports[36–38] for displaying climate change risk with and without adaptation, shows that in all cases, the risk systematically increases with higher global warming level (Fig. 3). Further, for groomed natural snow conditions only, in most geographical entities, a global warming level of 1.5 °C leads to a high to very high snow supply risk to ski tourism, with only a few entities showing comparatively lower increases in the risk (for example, Turkey, Central European middle mountains 2). Three main patterns emerge from the burning embers analysis taking snowmaking into account. For some mountain areas, mainly in the Alps but also in the Nordic mountains and in Turkey, additional snowmaking fractional coverage reduces the risk. However, the marginal benefit decreases, especially between 50% and 75% (panel **a** in Fig. 3). For other areas, snowmaking has a positive impact on the risk level up to a certain point, but increases in the snowmaking fractional coverage beyond 50% reduce its efficiency and the risk increases (panel **b** in Fig. 3). Last, in some areas, the risk level quickly reaches high values with increasing global warming level regardless of the snowmaking fractional coverage (panel **c** in Fig. 3). Note that these general observations do not necessarily apply to all individual ski resorts within the mountain areas analysed. This illustrates that the snow supply risk to ski tourism under climate change is context-dependent in multiple ways, including the influence of the snowmaking fractional coverage and the geographically and climatically variable efficiency of snowmaking itself[14,39,40]. At 2 °C and 4 °C global warming levels without snowmaking, 53% and 98%, respectively, of the 2,234 ski resorts studied are projected to experience a very high snow supply risk. Assuming a snowmaking fractional coverage of 50%, these figures decrease to 27% and 71%, respectively. Results for individual mountain areas are provided in Extended Data Fig. 8.

Snowmaking water demand and energy footprint

We estimate in Fig. 4 the water and electricity demands for snowmaking under past and future climate conditions, along with the corresponding carbon footprint for the related electricity production (see Methods). Here we focus on the 12 main countries in terms of the total snowmaking amount, comprising 95% of the ski resorts' surface area considered in this study. The median value of the total annual water demand for snowmaking for the reference period 1961–1990 with 50% snowmaking fractional coverage is estimated at 103 Mm^3 (90–119 Mm^3 range spanning the 10th to 90th percentiles). Under these conditions, water demand for snowmaking at the European scale would correspond to 13% of the total annual precipitation falling on ski piste areas equipped with snowmaking facilities. For individual countries, this figure varies between 10% and 32%.

Water demand changes substantially in a warmer climate, both in terms of the total quantity and its seasonal distribution. Our results indicate a general decrease of the water demand for snowmaking in November (decreases in national values range from 0% to −53% at +2 °C, and −5% to −96% at +4 °C) due to increasing temperatures leading to fewer time periods adequate for snowmaking. Projections indicate an overall increase in annual water demand with the global warming level (changes in national values range from +8% to +25% at +2 °C, and +14% to +42% at +4 °C), driven by mountain regions where climate conditions remain sufficiently cold for snowmaking. The corresponding estimates for snowmaking fractional coverages of 25% and 75% are provided in Extended Data Fig. 9.

The median value of the total annual electricity demand for snowmaking in these 12 countries is estimated at 309 ± 103 GWh during the reference time period 1961–1990, assuming a 50% snowmaking fractional coverage (see Methods and Extended Data Fig. 1). This value is in a comparable order of magnitude to a previous estimate of 600 GWh over the European Alps[41]. Using figures on skier visits from 2019, our estimates correspond on average to about 1.5 ± 0.5 kWh per skier visit, devoted to snowmaking. The total electricity demand for snowmaking is projected to increase on average by 18% and 24% for +2 °C and +4 °C global warming, respectively.

On the basis of the carbon intensity of electricity use in 2019, the annual carbon footprint of electricity use for snowmaking in the considered 12 countries is estimated at 78 ± 26 kt CO_2eq for the reference period 1961–1990 and projected to reach 93 ± 31 kt CO_2eq and 97 ± 32 kt CO_2eq at +2 °C and +4 °C global warming levels, respectively. Due to ongoing and future policy changes, the carbon intensity of electricity production is expected to decrease in upcoming decades. Our results illustrate how the carbon footprint of electricity used for snowmaking would evolve in a warmer climate, on the basis of the current energy mix. Due to differences between European countries in both water demand for snowmaking and the current carbon intensity of electricity production (ranging from 0.008 to 1.1 kg CO_2eq kWh^{-1} on annual averages, see Methods), the carbon footprint of electricity demand for snowmaking varies considerably between countries (Fig. 4). Mountainous entities with the highest carbon footprint for snowmaking combine a comparatively high water demand for snowmaking with a high carbon intensity for electricity production. Per skier visit, the carbon footprint of electricity used for snowmaking

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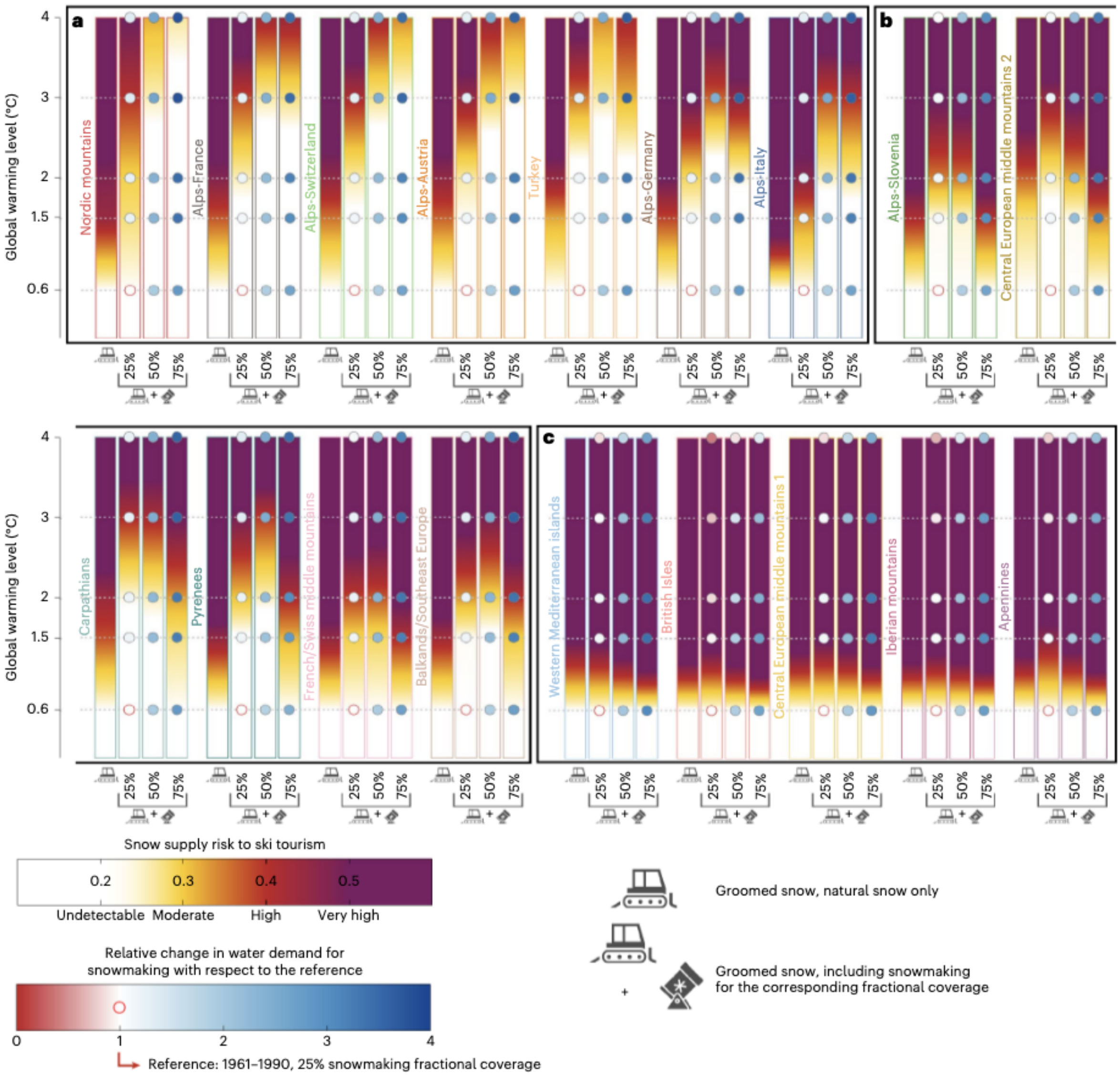

Fig. 3 | Burning ember representation of the snow supply risk to ski tourism in European mountain areas. Burning embers display the risk value, that is, the frequency of snow-scarce winters, using snow conditions without snowmaking for 1961–1990 (corresponding to +0.6 °C global warming level since 1850–1900) as a reference. For each geographical entity, the left bar refers to natural snow only (including grooming) and the three other bars account for different levels of snowmaking fractional coverage. Circles display relative changes in water demand for snowmaking compared to the situation for a fractional snowmaking coverage of 25% during the reference time period 1961–1990. European mountain areas are sorted according to the categories (**a**, **b** and **c**) introduced in the text.

varies between 0.01 and 2.3 kg CO_2eq. These values are consistent with previous estimates at the national scale[42].

Recent studies estimate that the operations of a ski resort (snow management, ski-lift operations and so on), including electricity demand for snowmaking, correspond to 2%–4% of the total carbon footprint of the destination[42,43]. In contrast, more than 50% of the carbon footprint, sometimes even exceeding 80%, is induced by arrival, departure and on-site transportation of skiers[42,43]. However, while the carbon footprint of ski resort operations represents a small share of a destination's total footprint, both are strongly interrelated as ski-related tourism activities are often the main driver for tourist visits. Ski tourism operators, together with other mountain tourism stakeholders, are thus jointly responsible for the broader emissions (for example, accommodation, transportation) related to ski tourism, even if their operations make a small direct contribution.

Discussion

All estimates provided in this study rely on state-of-the-art reanalyses and climate projections of the snow cover reliability and a detailed inventory of ski resort locations in Europe (see Methods and Extended

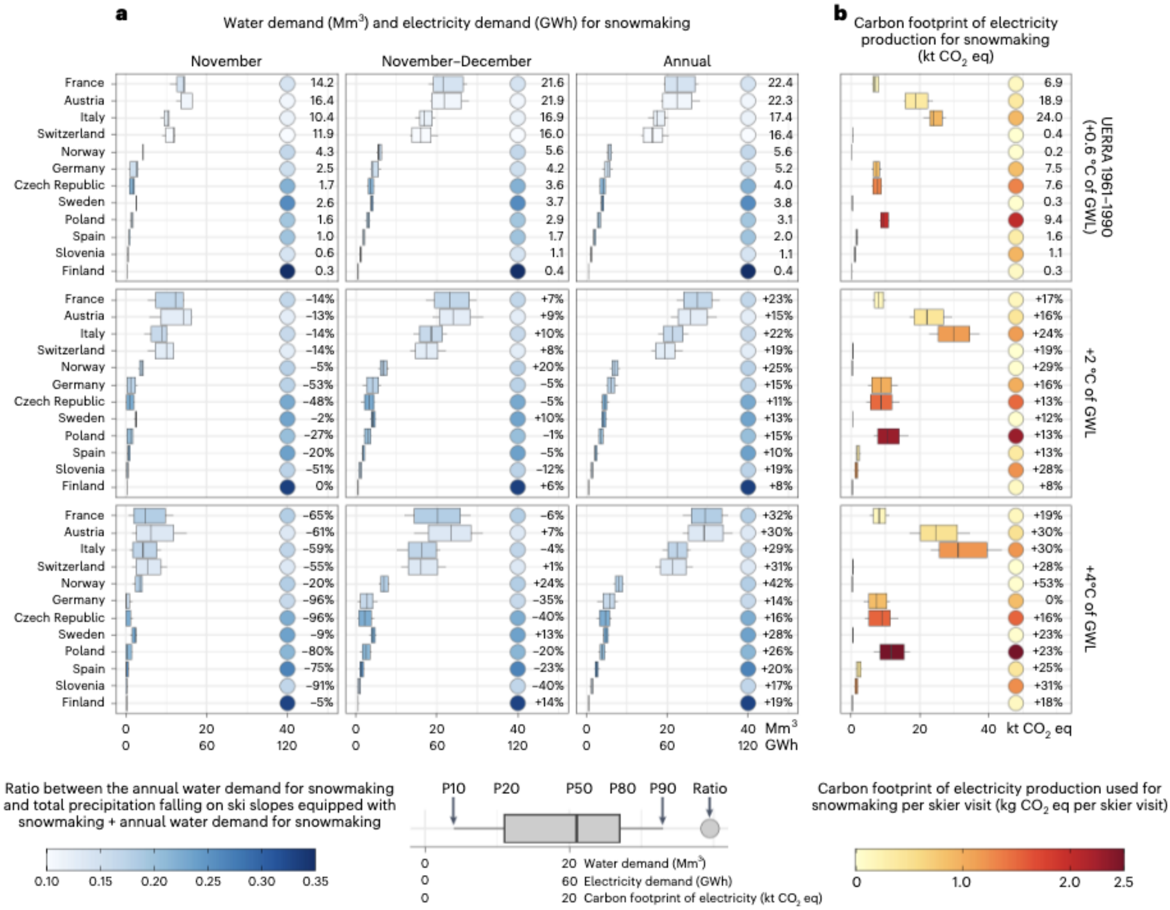

Fig. 4 | Water and electricity demand, and associated carbon footprint for electricity production due to snowmaking. Water demand, corresponding electricity demand and associated carbon footprint for electricity production due to snowmaking only, assuming a uniform 50% snowmaking fractional coverage for the 12 main countries. Rows correspond to global warming levels compared to 1850–1900: +0.6 °C (1961–1990 reference period, top), +2 °C (middle) and +4 °C (bottom). **a**, Water and electricity demand, from left to right, for November, November and December, and hydrological year (summer to summer; snow production occurs between November and February). Boxplots showing the percentiles 10, 20, 50, 80 and 90 are coloured according to the ratio between water demand for snowmaking and total annual precipitation on the ski pistes equipped with snowmaking (colouring also provided in the circles). **b**, Carbon footprint of electricity production for snowmaking. The colouring refers to the carbon footprint per skier visit.

Data Fig. 1). This study comes with inevitable limitations and simplifications implied by our pan-European approach in a context where detailed data are often missing (for example, data on the snowmaking fractional coverage of individual ski resorts and the technology implemented). Our estimates of the water demand for snowmaking assume current technologies and practices of the industry. They reflect neither any limitations in water availability under the current or future climate, nor possible changes in technologies and practices of the industry. Nevertheless, on the basis of a series of reasonable hypotheses and assumptions, we provide a consistent depiction of the current and future state of the snow supply risk pertaining to the ski tourism industry in Europe and some key related environmental externalities.

Although a warmer climate will systematically increase the snow supply risk pertaining to this industry, its magnitude depends on the region. Our results highlight not only the general trend and rising challenges, but also the variability across mountain regions of Europe in this respect, which is further modulated at the local scale due to the strong variability within mountain regions[17,18]. This work provides insights that are primarily relevant for regional-scale mountain development policy[21,44]. Our methods and results also provide a basis for producing local climate change impact studies in Europe at the ski-resort level. However, their local application would require the use of additional local information. This includes the use of a detailed map of the ski resort including the location and characteristics of snowmaking units, an analysis of the availability and use of water under current and future climate conditions, the availability of energy resources for sustaining snowmaking operations and impact studies on local ecosystems[18,32]. Such information is critical for informing climate action in mountainous areas across all relevant scales of decision[44–46]. Our results are also relevant in the context of strengthening EU regulations on climate risk disclosure for all sectors. For planning purposes, such information relevant to the challenges of the ski tourism supply side (operating conditions) needs to be combined with future trajectories on the ski tourism demand side (that is, skiers' preferences and potential changes in practices), which are also heavily dependent on snow conditions and broader socio-economic perspectives including the diversification of mountain economies and avoiding maladaptation[1,6,7,19,27,44,47,48].

The presented results illustrate the interaction between climate change impacts and risks to a given sector (here snow supply to ski tourism) and broader environmental and climate challenges. Indeed, reaching strong reductions in greenhouse gas emissions for ski tourism destinations will chiefly depend on massive reductions of the carbon footprint of transportation and accommodation[6]. This holds implications for tourism development strategies. In particular, it remains questionable whether far-reaching policies required to limit global warming to +2 °C are compatible with carbon intensive tourism activities in their current form, in particular regarding transportation, housing and the carbon intensity of electricity production[7,19]. Even if a substantial fraction of European ski resorts is projected to still be able to operate at 2 °C global warming, the ability of ski tourism destinations, as a whole, to achieve their share of greenhouse gas emission reductions required to remain below this global warming level is a major challenge.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-023-01759-5.

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Methods

Climate data

This study uses meteorological and snow cover simulations underpinning the Copernicus Climate Change Service (CS3) MTMSI dataset[34]. Results are provided for all countries of the European Union, candidate countries and members of the European Free Trade Association. Altogether, the dataset covers all EU member states, Albania, Andorra, Montenegro, North Macedonia, Serbia, Turkey, the United Kingdom, Iceland, Liechtenstein, Norway and Switzerland. Within each country, the data are provided for each NUTS-3 (Nomenclature des unités territoriales statistiques) area by elevation steps of 100 m on flat terrain. Meteorological data were extracted from the UERRA European reanalysis at 5.5 km resolution, spanning the time period 1961–2015. These data were used to adjust 21 pairs (3 RCP2.6, 9 RCP4.5 and RCP8.5) of global (GCM) and regional (RCM) climate models from the EURO-CORDEX dataset, using the ADAMONT adjustment method[34] (see Extended Data Fig. 1).

Snow cover simulations

Using the UERRA near-surface atmospheric reanalysis and the adjusted climate change projections, we performed snow cover simulations using the detailed model Crocus, with and without snowmaking[34,49]. Crocus is a multilayer snowpack model embedded in the ISBA land surface model within the SURFEX model[50]. Beyond natural snow processes including surface energy balance and snow metamorphism, Crocus makes it possible to account for grooming and snowmaking[35], on the basis of physical representations of these snow management practices and operational rules[16,35,51]. For the simulations with snowmaking, the maximum wind speed threshold was set to 4.2 m s^{-1}, the density of machine-made snow to 600 kg m^{-3}, the production rate of machine-made snow to 1.2×10^{-3} kg m^{-2} s^{-1} and the wet-bulb temperature threshold for snowmaking to −5 °C, consistent with previous studies[16,34]. In the simulations, between 1 November and 15 December, up to 150 kg m^{-2} machine-made snow is produced, weather conditions permitting and regardless of natural snowfalls during the period, which corresponds to 25 cm snow depth. Between 15 December and 28 February, snow is produced if meteorologically possible to maintain a total snow depth of 60 cm. After 1 March, no more snow is produced. These threshold values are consistent with typical practices of ski resort operators[49]. All simulations were carried out for flat terrain topographic configuration. The simulation results include not only snow cover data (total depth, snow water equivalent) but also the water demand for snowmaking corresponding to the simulation results.

Inventory of European ski resorts

We used the OpenSkiMap (https://openskimap.org) global database of ski resorts, which is based on the OpenStreetMap (https://www.openstreetmap.org) collaborative geospatial database. Specifically, we used the three files provided by OpenSkiMap (Ski Areas, Lifts and Runs). Information from these three files was combined, involving careful checks and occasional removal from our analysis of lifts that are not associated directly with a ski piste in order to provide a consistent set of ski resorts and ski lifts, together forming a series of 2,959 ski resorts in Europe (see Extended Data Fig. 1).

European mountain areas

The 15 European Environmental Agency (EEA) European mountain areas (https://www.eea.europa.eu/data-and-maps/data/european-mountain-areas) form the core spatial structure of this work. The Atlantic islands, where there is no resort, and the Eastern Mediterranean islands, where there is only one resort, were excluded from the analysis. Thus, we focused on 13 European mountain areas. In this study, the 'Alps' mountain area was split by country due to its dominant position in terms of ski tourism in Europe.

Ski resort geospatial modelling

We combined various geospatial data sources to generate spatial information for ski resorts (see Extended Data Figs. 1 and 2). Using the European Digital Elevation Model (EU-DEM, v.1.1) with a spatial resolution of 25 m (http://land.copernicus.eu/pan-european/satellite-derived-products/eu-dem/eu-dem-v1.1/view) and the ski-lift catalogue from OpenSkiMap (Extended Data Fig. 2a), we computed, for each ski lift in each ski resort, the geographical domain accessible downhill from the top of all the ski lifts (Extended Data Fig. 2b) and from which one can reach the bottom of one of the ski lifts (Extended Data Fig. 2c). Combining these two areas results in the gravitational envelope of the ski resort (Extended Data Fig. 2d,e)[16,18,52,53]. Further, we applied a geospatial modelling framework to infer the location where snowmaking is applied within a given ski resort, depending on the snowmaking fractional coverage value (0%, 25%, 50% and 75%; see Extended Data Fig. 2f)[49,53]. Each pixel of the ski resort gravitational domain was associated with a NUTS-3 region (Extended Data Fig. 2h) and a 100 m elevation band (Extended Data Fig. 2f) from the climate and snow cover dataset for flat terrain conditions.

The limitations of the MTMSI dataset regarding the available elevation bands for each NUTS-3 region compared to the actual elevation ranges or the ski resorts made it necessary to reassign some values. For the resorts fully included in mountain NUTS-3 regions but with missing elevation bands, we assigned the minimum or the maximum available NUTS-3 elevation depending on whether the missing elevations are at the top or at the bottom of the ski resort, within a 300 m difference and with minimum elevation not lower than 500 m. Resorts outside the NUTS-3 areas for which climate data are available were not processed further. This led to 2,625 ski resorts within which only those belonging to EEA mountain areas were considered further, resulting in a final selection of 2,234 ski resorts (see Extended Data Fig. 1).

Resort-level snow cover reliability calculation

The snow cover reliability indicator for a given ski resort on a given day corresponds to the fraction of the surface area (fraction of the pixels) of the gravitational envelope exceeding a snow mass threshold of 100 kg m^{-2} (corresponding to 100 mm water equivalent, that is, 20 cm of snow depth for a typical snow density of 500 kg m^{-3}). The average of the daily values for the months from December to February was used as the snow cover reliability indicator applied in this work. Crocus model runs provide water demand for snowmaking, which are aggregated for each ski resort. Consistent with previous research, we assumed that 10% of the surface area of the gravitational envelope is actually covered with ski pistes[16]. While the full envelope was taken into account for the calculation of the snow reliability index, the 10% ratio was applied only for the calculation of the water volume demand.

Defining whether conditions are snow scarce or not in a given ski resort when snowmaking is taken into account

Snowmaking is implemented in ski resorts to secure snow conditions suitable for skiing. Therefore, snow conditions taking snowmaking into account can be considered snow scarce if the snow reliability index value is lower than the snowmaking fractional coverage considered. For assessing the risk level when snowmaking is taken into account, we therefore defined the snow reliability index threshold $Q_{\text{threshold}}$ as equation (1):

$$Q_{\text{threshold}} = \max\left(Q_{20}^{\text{ref}}, X_{\text{snowmaking}}\right) \quad (1)$$

where $X_{\text{snowmaking}}$ is the snowmaking fractional coverage value considered (25%, 50% or 75%). Extended Data Fig. 3 shows how this calculation was designed and implemented. The snow supply risk to ski tourism was thus expressed as the proportion of snow reliability index values below $Q_{\text{threshold}}$. By design, the risk level was equal to 20% for the reference period without snowmaking. This is illustrated in Extended Data Figs. 4–7.

Computation of the snow supply risk and burning embers

The snow supply risk to ski tourism was defined as the frequency of snow-scarce conditions. These were defined as the 20th percentile of the snow reliability index during the reference period 1961–1990 without snowmaking, based on Crocus model runs driven by the UERRA 5.5 km reanalysis for each ski resort. The frequency of snow-scarce conditions was estimated for each ski resort for 20 yr time periods for each GCM/RCM pair, centred for each pair on the time period when the GCM simulation reached a global warming level for the values +1.5 °C, +2 °C, +3 °C and +4 °C with respect to the time period 1850–1900. Note that in contrast to the discrepancy identified between RCM- and GCM-simulated temperature changes over Europe in summer, there was a good overall consistency for the winter season, which is the main seasonal focus of our study[54,55]. The global warming level dataset providing information for all the GCM results used in this study was obtained from the Santander Meteorology Group (UC-CSIC) (https://github.com/SantanderMetGroup/ATLAS/blob/main/warming-levels/CMIP5_Atlas_WarmingLevels.csv).

For each ski resort, the average value of the frequency of snow reliability index values below the Q_{20}^{ref} across all GCM/RCM pairs corresponding to a given global warming level was used to relate the risk value to this particular warming level. This resort-level risk value was then averaged for each mountain area, using the surface area of the ski resort as a weighting factor. The corresponding risk value for each mountain area and global warming level was then used to build the burning ember diagram. Ultimately, burning embers[36] represent the snow supply risk to ski tourism under different global warming levels, with and without snowmaking.

Due to the lack of a European database on the fraction per ski resort equipped with snowmaking, we applied a homogeneous 25%, 50% and 75% snowmaking fractional coverage to all ski resorts in Europe, notwithstanding actual heterogeneities in snowmaking fractional coverages within and across mountain areas and countries[18].

By design, the risk level was equal to 20% for the reference period without snowmaking. Hence, a frequency of 20% of snow-scarce winters corresponds to an undetectable change in risk level (displayed in white in Fig. 3). A frequency of 30%, corresponding to a 50% increase in the frequency of snow-scarce conditions compared to the reference value (20%), is referred to as 'moderate' risk (yellow), while a doubling in the frequency (40%) is referred to as 'high' risk (red). The risk reaches the 'very high' (violet) domain at a frequency of 50% and above, which corresponds to encountering a situation of snow scarcity at least once every 2 yr, this situation being encountered only once every 5 yr during the reference period.

Water and electricity demand for snowmaking

Water demand values were generated as a diagnostic of the snow cover simulations. Water demand values for snowmaking are illustrated in Extended Data Figs. 4–7. See Extended Data Fig. 8b for more information on the calculation of the uncertainty pertaining to the water demand for various global warming levels and snowmaking fractional coverage values. Here we assumed an electricity consumption of 3 ± 1 kWh m^{-3} of water converted to snow. This value is consistent with recent reports from the ski tourism industry and national and regional reports from local environment and tourism authorities in Europe (https://www.wko.at/branchen/transport-verkehr/seilbahnen/Oekologie_und_Umwelt.html, http://www.observatoire.savoie.equipement-agriculture.gouv.fr/Atlas/4-hydro.htm, https://side.developpement-durable.gouv.fr/ACCIDR/doc/SYRACUSE/152732). In fact, this value depends on the technology used and on the temperature of snow production. However, due to lack of a detailed inventory of the technology deployed in all ski resorts of Europe, which would also require a more detailed modelling framework than currently exists, we considered this central value surrounded by a range from 2 to 4 kWh m^{-3} for this study, with a central estimate of 3 kWh m^{-3}. Since this is a constant parameter in our study, all of the results, in terms of electricity demand and corresponding greenhouse gas emissions, can be updated by means of a simple 'rule of three' using a different value of the electricity demand for water conversion to snow. This value takes into account the entire snowmaking process, including snowguns operations, local water pumping and so on.

Carbon footprint of electrity consumption for snowmaking

The carbon footprints were calculated using amounts of electricity generation by type of production (for example, hard coal, run-of-river hydropower and so on) and country as recorded on the ENTSO-E Transparency Platform for 2018–2022 (https://transparency.entsoe.eu/dashboard/show). The central estimates were computed using the figures for the year 2019, deemed representative of the situation before the outbreak of Covid-19. Data for the years from 2018 to 2022 were used for uncertainty analysis, based on the 6 main countries in terms of water and electricity demand, and for which carbon intensity factors were calculated. Combining electricity demand time series (from past and future climate conditions) with a sampling of the carbon intensity data from these 5 yr leads to an estimate of the uncertainty due to the interannual variability of carbon itensity. The multiannual standard deviation around the mean of the median for the UERRA reanalysis reference time period 1961–1990 varied between 8.8% (Norway, expected to increase up to the values of 12.3% and 13.6% at +2 °C and +4 °C global warming levels, respectively) and 1.2% (Sweden, expected to reach 0.6% and 1.0% at +2°C and +4°C) of the mean value. Values for Italy and Austria, where the mean values were the highest, reached 2.5% and 3.7%, respectively. This uncertainty is thus much lower than the uncertainty due to the electricity demand for snowmaking considered in this study. Production for each generation type and country were multiplied by country-dependent emission factors (kg CO_2eq kWh^{-1}) from the ecoinvent database[56], taking into account life cycle assessment components. The emissions were calculated on an hourly basis and an average emission factor by country and month was used for the conversion of monthly electricity demand for snowmaking into equivalents of CO_2 emissions. Emissions from imported electricity were not included, which is a methodological limitation of this study. The emissions presented are for electricity consumption due to snowmaking only. They do not include emissions for snow grooming and maintenance, snowmaking equipment and its installation, and maintenance and ski-lift operation.

Data availability

The MTMSI dataset is available on the Copernicus Climate Data Store at https://doi.org/10.24381/cds.2fe6a082 under the Copernicus licence. We used the OpenSkiMap (https://openskimap.org) global database of ski resorts, which is based on the OpenStreetMap (https://www.openstreetmap.org) collaborative geospatial database. Description of the 15 European Environmental Agency (EEA) European mountain areas is available at https://www.eea.europa.eu/data-and-maps/data/european-mountain-areas. The European Digital Elevation Model (EU-DEM) (v.1.1, spatial resolution of 25 m) is available at http://land.copernicus.eu/pan-european/satellite-derived-products/eu-dem/eu-dem-v1.1/view. The global warming level dataset is available from the Santander Meteorology Group (UC-CSIC) (https://github.com/SantanderMetGroup/ATLAS/blob/main/warming-levels/CMIP5_Atlas_WarmingLevels.csv). The carbon footprints were calculated using hourly amounts of electricity generation by type of production (for example hard coal, run-of-river hydropower and so on) and country as recorded on the ENTSO-E Transparency Platform for 2019 (https://transparency.entsoe.eu/dashboard/show).

Code availability

The Crocus snow cover model used for this work was developed inside the open-source SURFEX project (http://www.umr-cnrm.fr/surfex/, accessed 7 June 2020). For reproducibility of results, the version used in this work is tagged as 'C3S-European-Tourism-MTMSI-2019' on the SURFEX git repository. The computer code necessary to reproduce the main results is provided on Zenodo at https://doi.org/10.5281/zenodo.8047168.

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Acknowledgements

We are grateful to all organizations and individuals involved in the production and distribution of the datasets used for this work. Work toward this publication has benefitted from funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no. 730203. We thank N. Ribot (Geospatial Solutions) for support on database management and E. Maldonado and F. Bray (INRAE) for operating the DBMS tools. Figures 2 and 3 and Extended Data Figs. 1 and 8 use images from flaticon.com.

Author contributions

H.F. and S.M. conceived the original idea for the paper. R.S. and H.F. carried out the calculations, with input from D.N.B. regarding carbon intensity calculations. S.M., H.F. and R.S. led the analysis. All authors contributed to the analysis, drafting, reviewing and editing of the paper.

Competing interests

The authors declare no competing interests.

Additional information

Extended data is available for this paper at https://doi.org/10.1038/s41558-023-01759-5.

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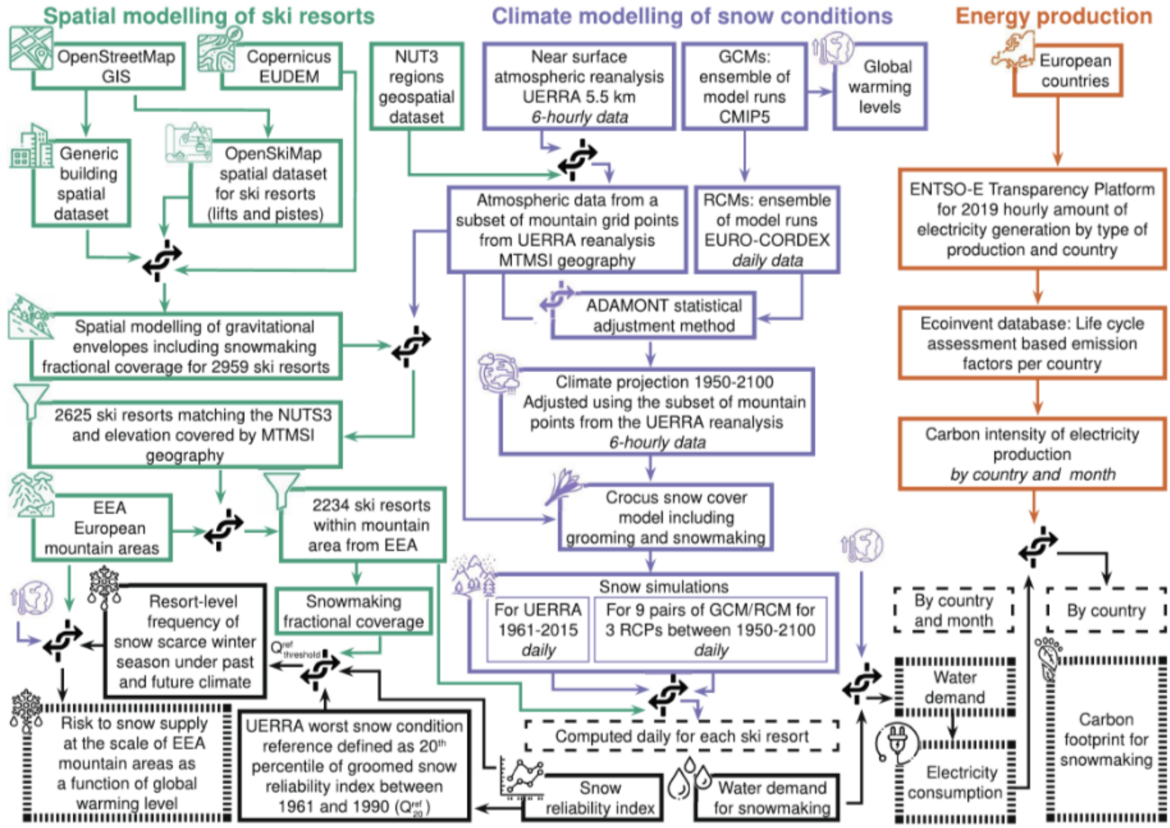
Peer review information *Nature Climate Change* thanks Daniel Farinotti, Christoph Marty, Paul Peeters and Daniel Scott for their contribution to the peer review of this work.



Extended Data Fig. 1 | Methodological approach to compute the snow conditions on ski pistes and related externalities. The method brings together advanced spatial modelling of the ski resorts (left), modelling of snow conditions in ski resorts taking into account grooming and snowmaking (middle) and estimates of the carbon intensity of snowmaking (right). Results, primarily computed for individual ski resorts and providing annual values, are aggregated at the scale of EEA mountain areas and countries, for past climate conditions and for various global warming levels.

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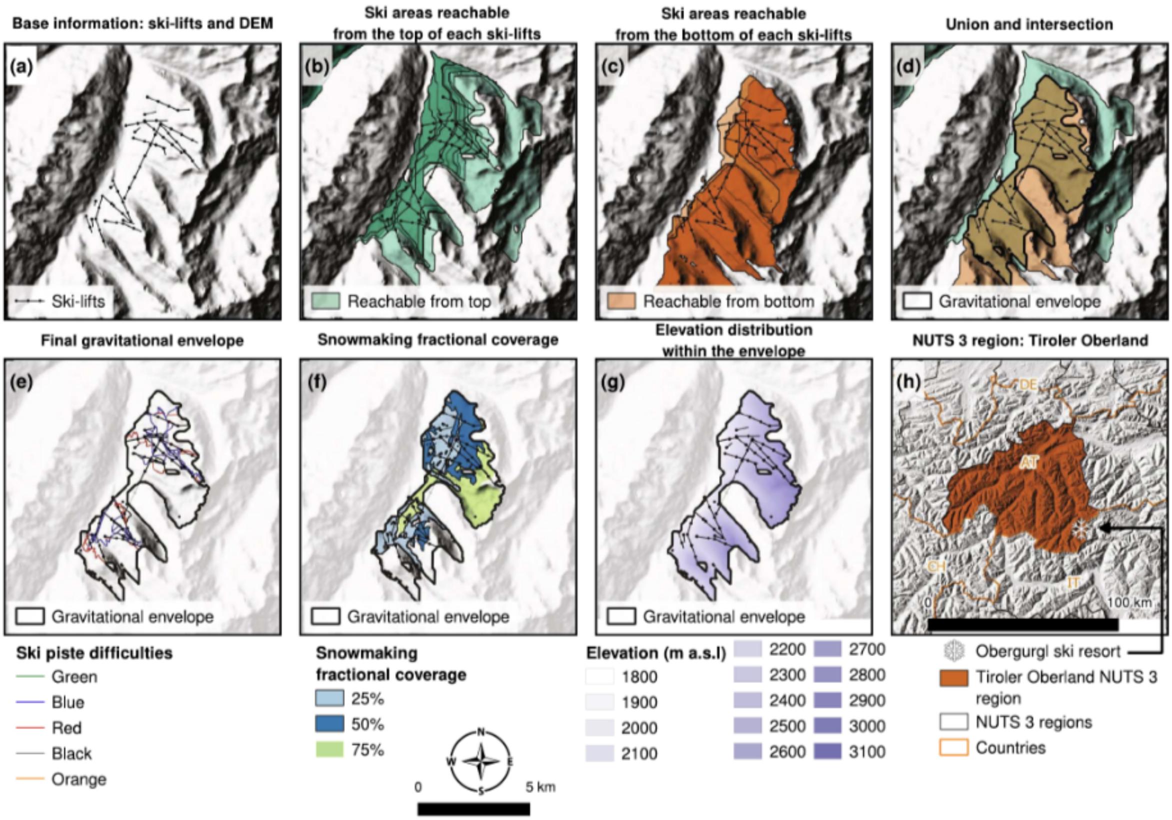

Extended Data Fig. 2 | Methodological approach for the spatial modelling of ski resorts. Using the European Digital Elevation Model (EU-DEM), version 1.1, with a spatial resolution of 25 m and the ski-lift catalogue from OpenSkiMap (a), we compute, for each ski lift in each ski resort, the geographical domain accessible downhill from the top of all the ski lifts (b) and reaching the bottom of one of the ski lifts (c). Combining these two areas results in the gravitational envelope of the ski resort (d and e). Further, we apply a geospatial modelling framework to infer the location where snowmaking is applied within a given ski resort, depending on the snowmaking fractional coverage value (0%, 25%, 50% and 75%) (f). Each pixel of the ski resort gravitational domain is associated to a (NUTS-3, elevation) pair from the climate and snow cover dataset, by steps of 100 m elevation and for flat terrain conditions (g). The modelling approach is illustrated here using the Obergugl ski resort in Austria (European Alps), in the NUTS-3 region 'Tiroler Oberland' (h).

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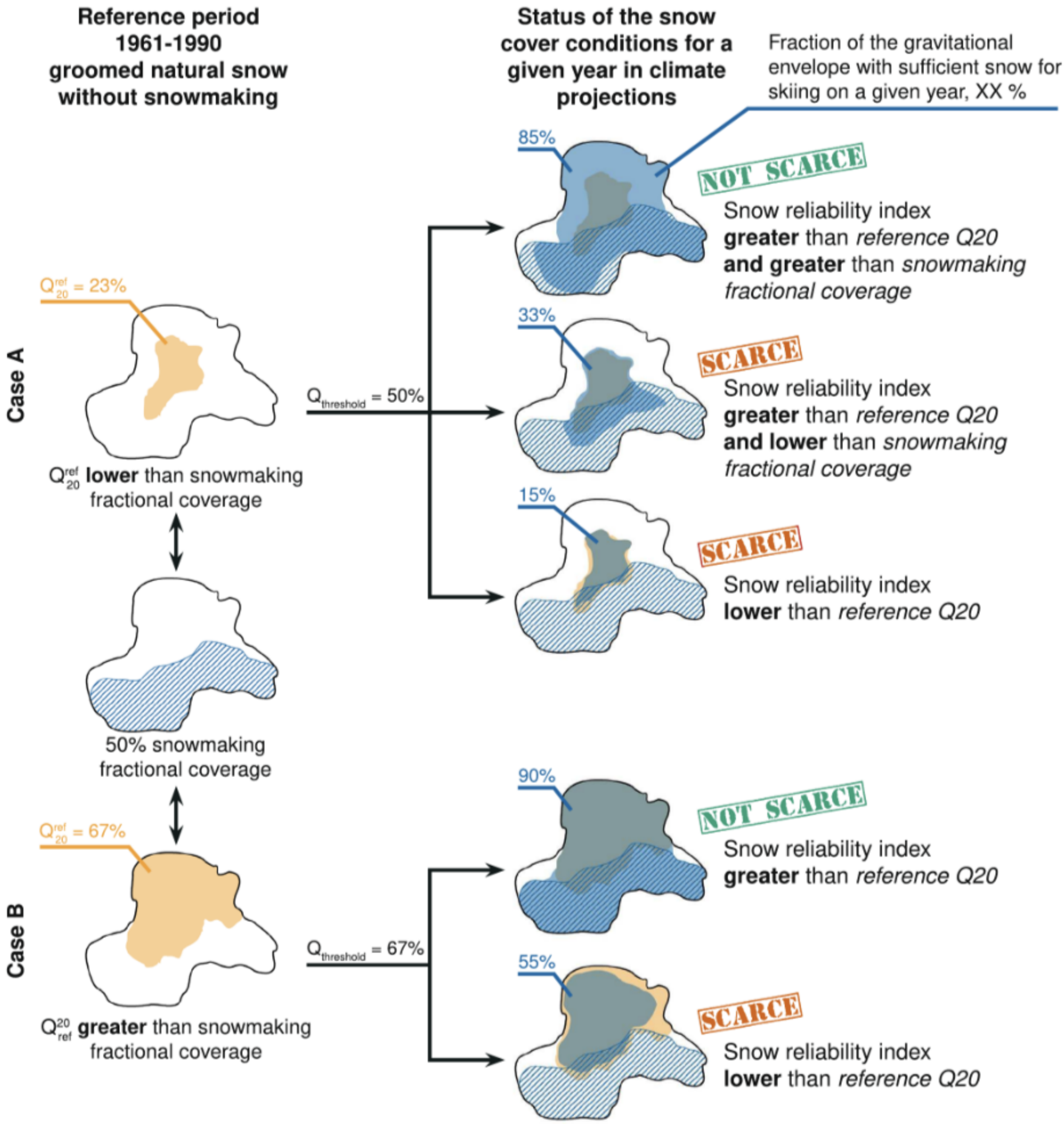

Extended Data Fig. 3 | Methodological approach employed to determine whether snow conditions are snow scarce or not, in a given ski resort, when snowmaking is taken into account. The reference snow reliability index Q_{20}^{ref} is computed based on groomed natural snow simulations for the reference period 1961-1990, bounding the 20% worst values of the snow reliability index. A snow reliability index value for a given year is considered snow scarce if it falls below a threshold value $Q_{threshold}$, equal to the maximum between Q_{20}^{ref} and the snowmaking fractional coverage. In case A (top), Q_{20}^{ref} (here 23%) is lower than the snowmaking fractional coverage (here 50%). If for a given year the snow reliability index value is larger than both, it is not considered snow scarce. If it is lower than both, it is considered snow scarce. In the intermediate case (here 33%), it is considered snow scarce, because it is lower than the snowmaking fractional coverage. In case B (bottom), Q_{20}^{ref} (here 67%) is higher than the snowmaking fractional coverage (here 50%). There are then only two possible situations, simply comparing the snow reliability index with the Q_{20}^{ref}.

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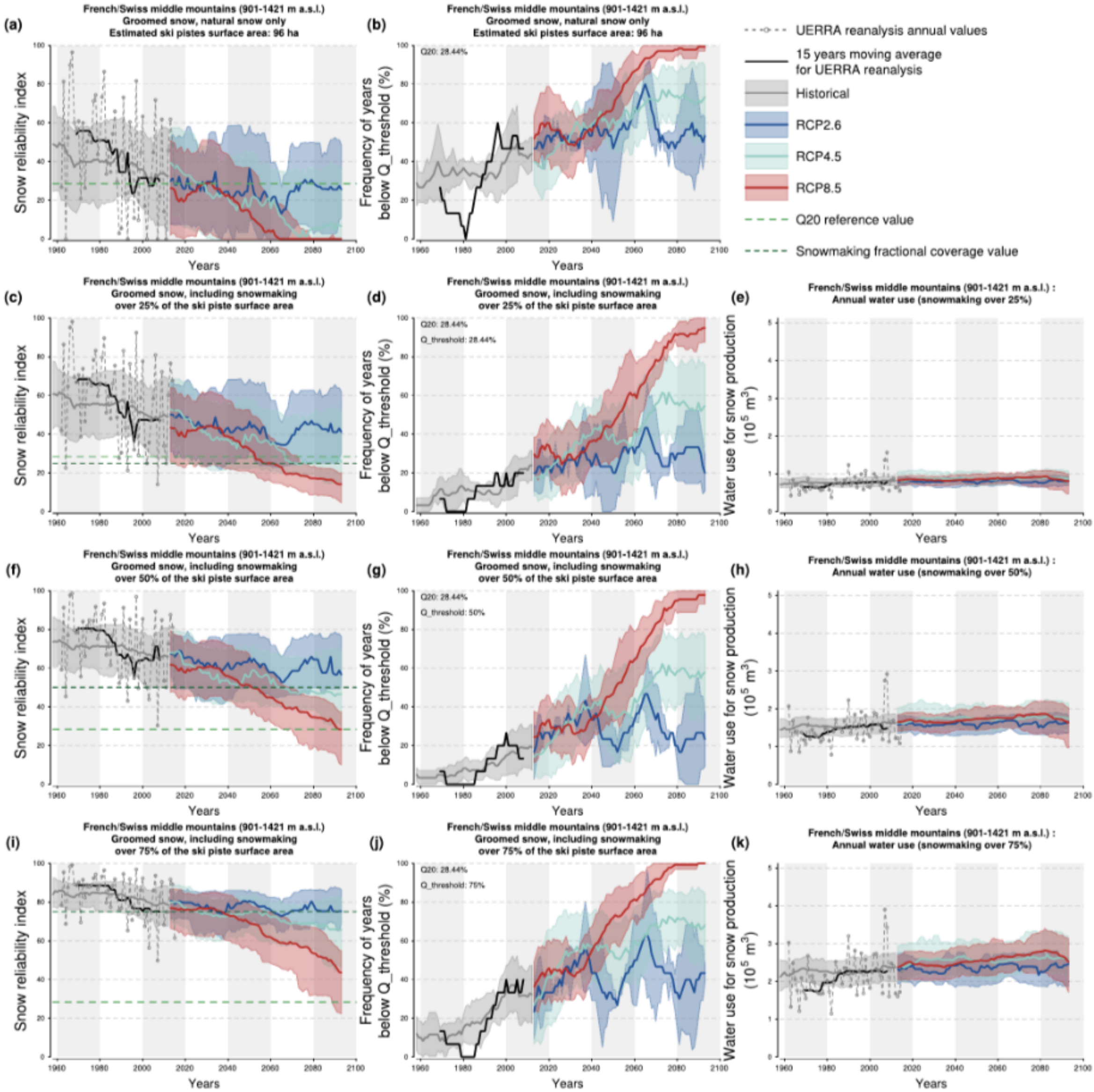

Extended Data Fig. 4 | Illustration of the results of the simulations for a given ski resort, here the Métabief ski resort (French Jura mountain region). All panels display past simulations (based on the UERRA reanalysis), and climate projections (historical from 1950 to 2005 and future projections for RCP2.6, RCP4.5 and RCP8.5 for 2006 to 2100). Panels are organized horizontally as a function of snowmaking fractional coverage (0% on the top row, panels a and b; 25% for panels c, d and e; 50% for panels f, g, and h; 75% for panels i, j and k). Panels on the left hand side (a, c, f and i) display the time series of the snow reliability index values. Individual annual values are displayed for UERRA reanalysis. For climate projections, the panels show the median (solid line) and 20/80 percentile values (colored area) for all simulations of the same RCP, on 15-years sliding windows. The black solid line displays the median value based on UERRA reanalysis. Panels in the middle column (b, d, g and j) display the frequency of years below the snow reliability threshold $Q_{threshold}$ (computed based on the values obtained using the UERRA reanalysis from 1961 to 1990). Here, the solid line refers to the mean of the frequency values obtained for each GCM/RCM pair for each 15-years periods, and the colored area displays the standard deviation around the mean. Panels on the right side (e, h and k) display the computed water demand for snowmaking. The solid line refers to the median and the colored area spans the 20/80 percentile range, on 15-years sliding windows.

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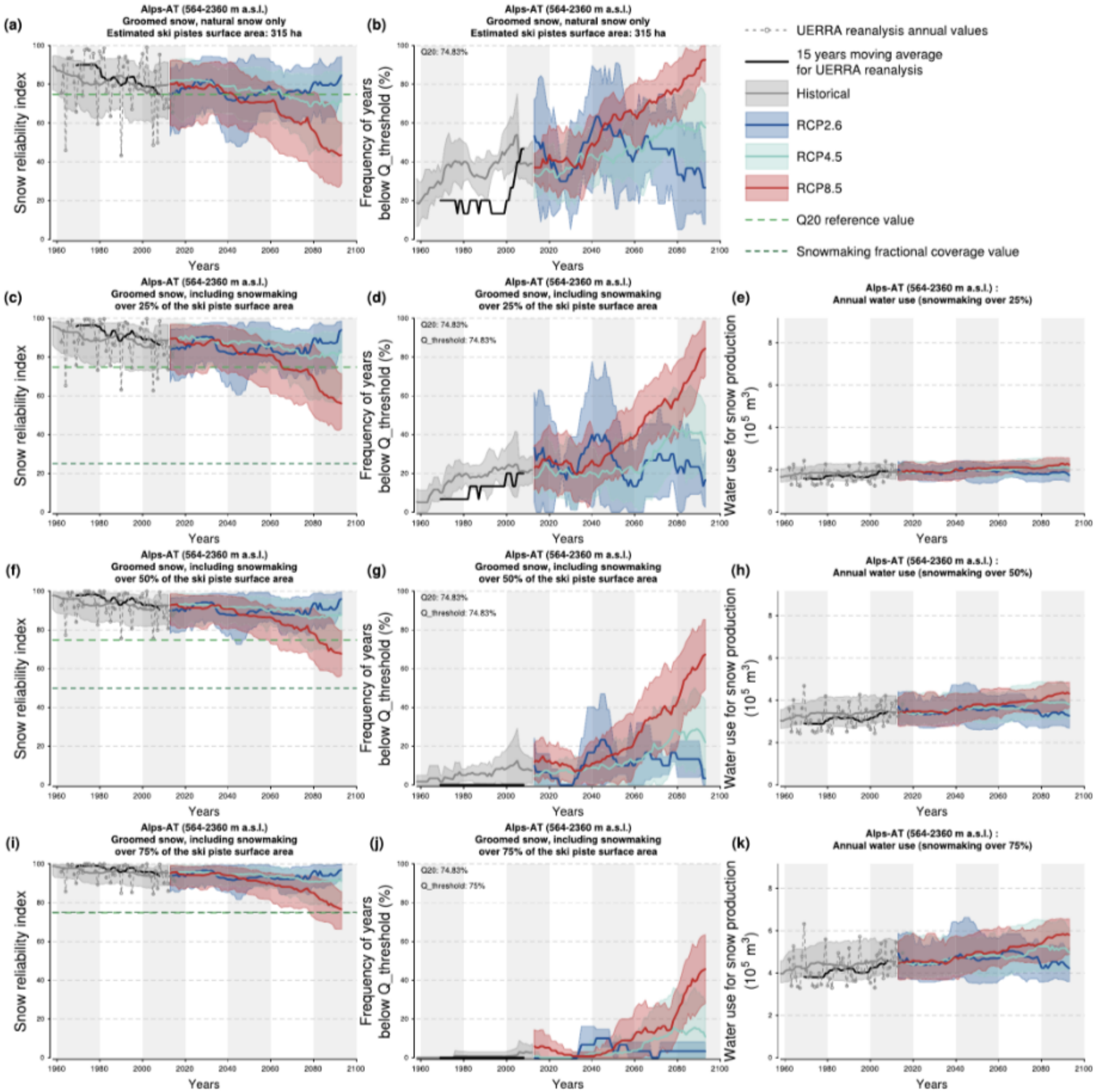

Extended Data Fig. 5 | Illustration of the results of the simulations for a given ski resort in the Austrian Alps. Same as Extended Data Figure 4 but for a ski resort located in the Austrian Alps.

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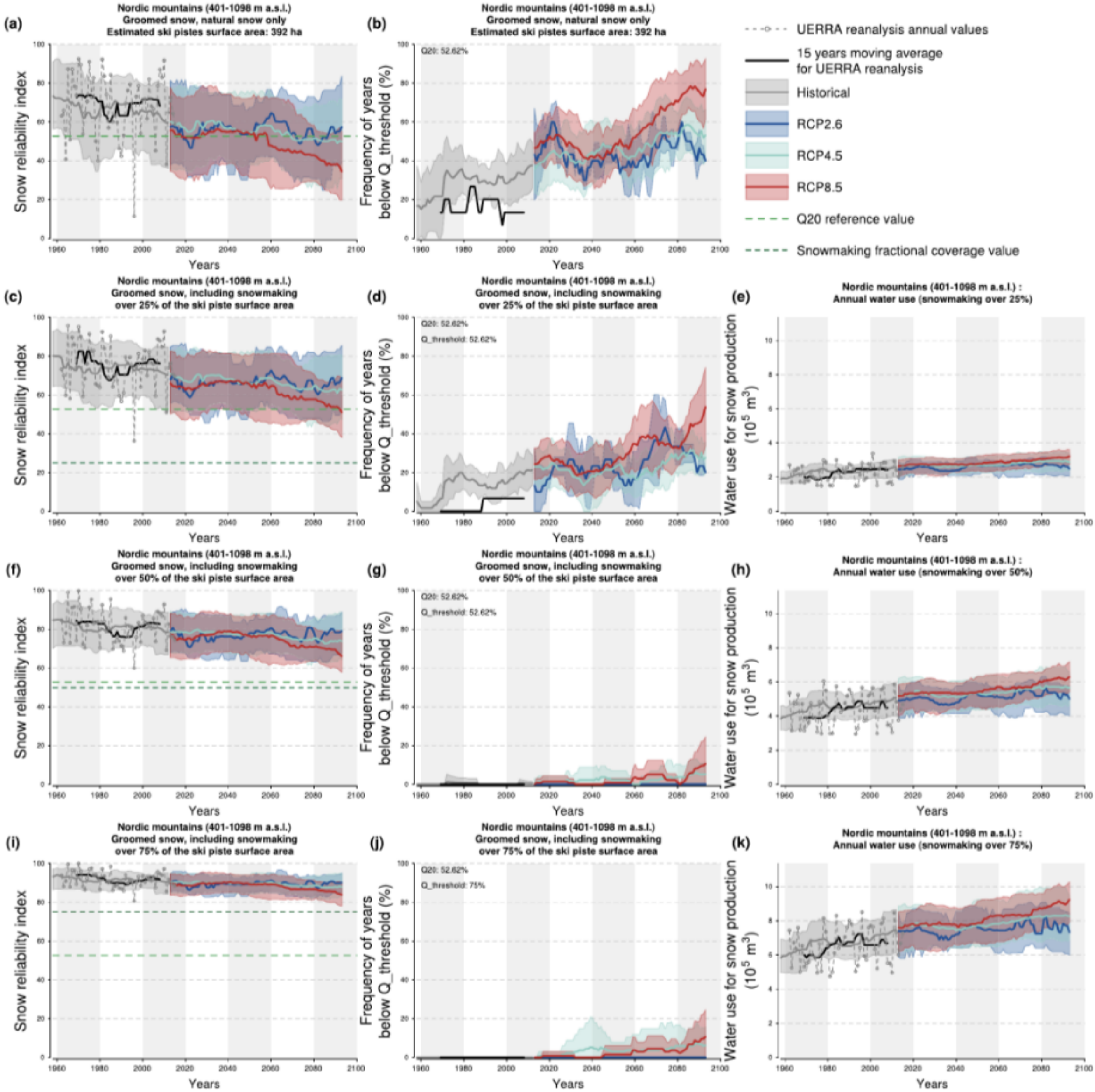
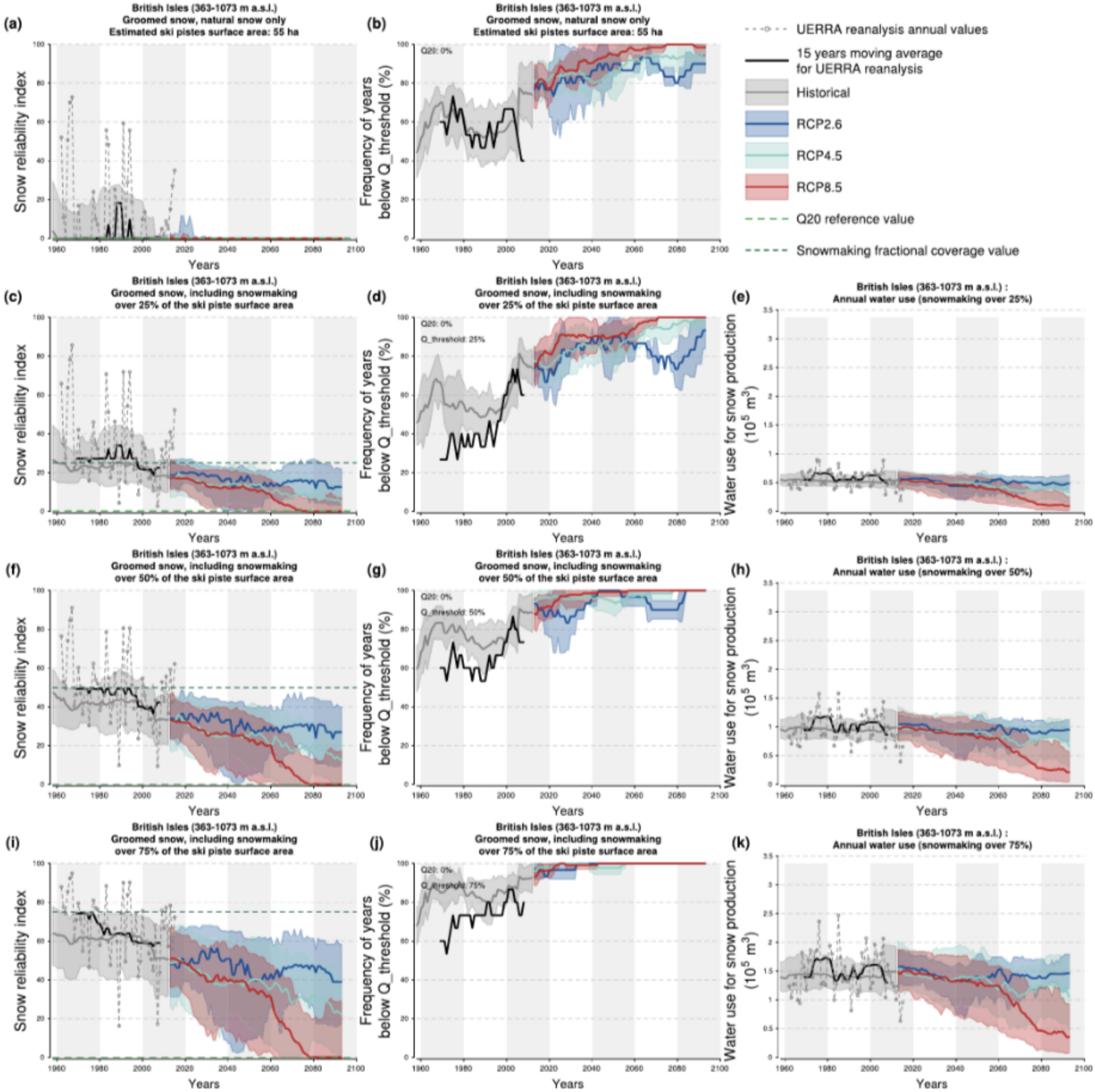
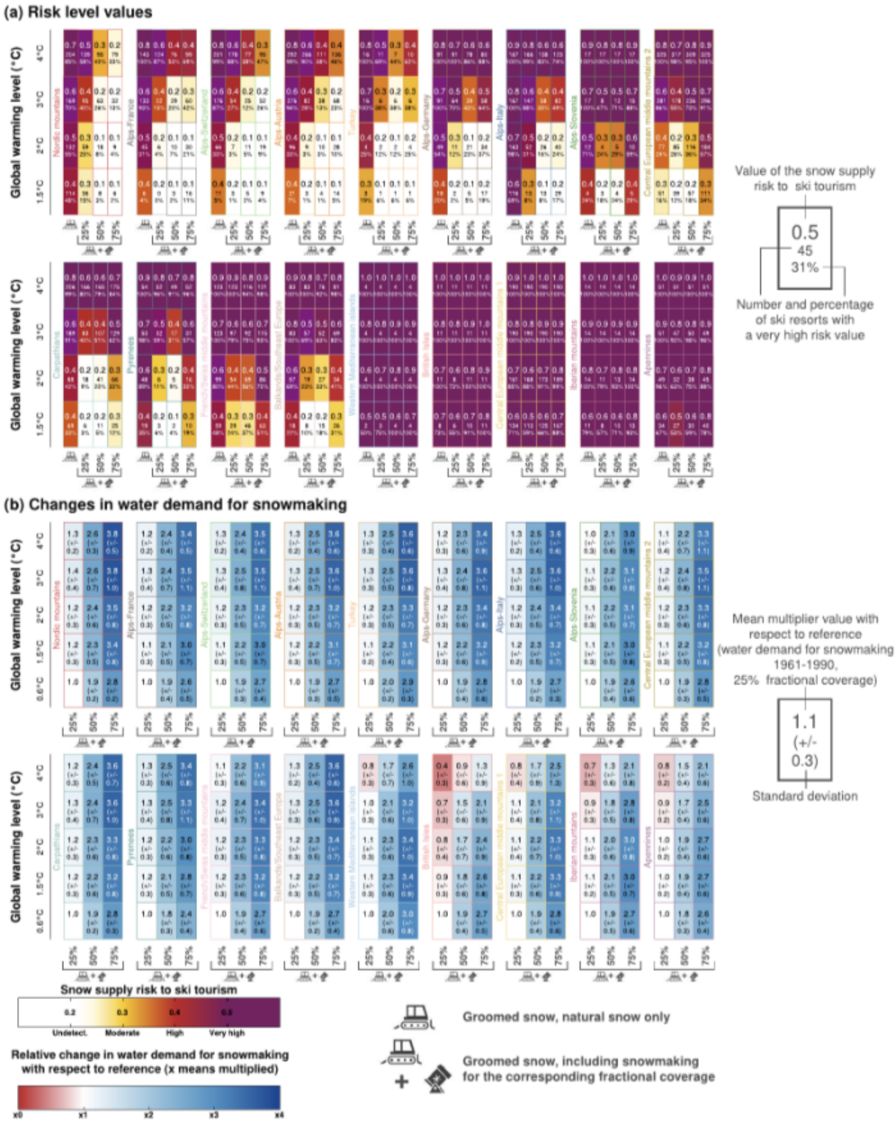


Extended Data Fig. 6 | Illustration of the results of the simulations for a given ski resort in Norway. Same as Extended Data Figure 4 but for a ski resort located in Norway.



Extended Data Fig. 7 | Illustration of the results of the simulations for a given ski resort in the British Isles. Same as Extended Data Figure 4 but for a ski resort located in the British Isles.



Extended Data Fig. 8 | Numerical values of the snow supply risk levels displayed on the burning ember figure, including the proportion of individual ski resorts belonging to the 'very high risk' category for each mountain area, for various global warming levels and snowmaking fractional coverage values and changes in water demand for snowmaking. Numerical values of the snow supply risk levels from Fig. 3, including the proportion of individual ski resorts belonging to the 'very high risk' category for each mountain area, for various global warming levels and snowmaking fractional coverage values (a) and changes in water demand for snowmaking (b), used in the burning embers diagram displayed in Fig. 3. The uncertainty shown in panel (b) is calculated based on the standard deviation around the mean of the water demand calculated for each global warming level with respect to the reference mean value (mean water demand for a snowmaking fractional coverage of 25% during the reference time period 1961-1990).

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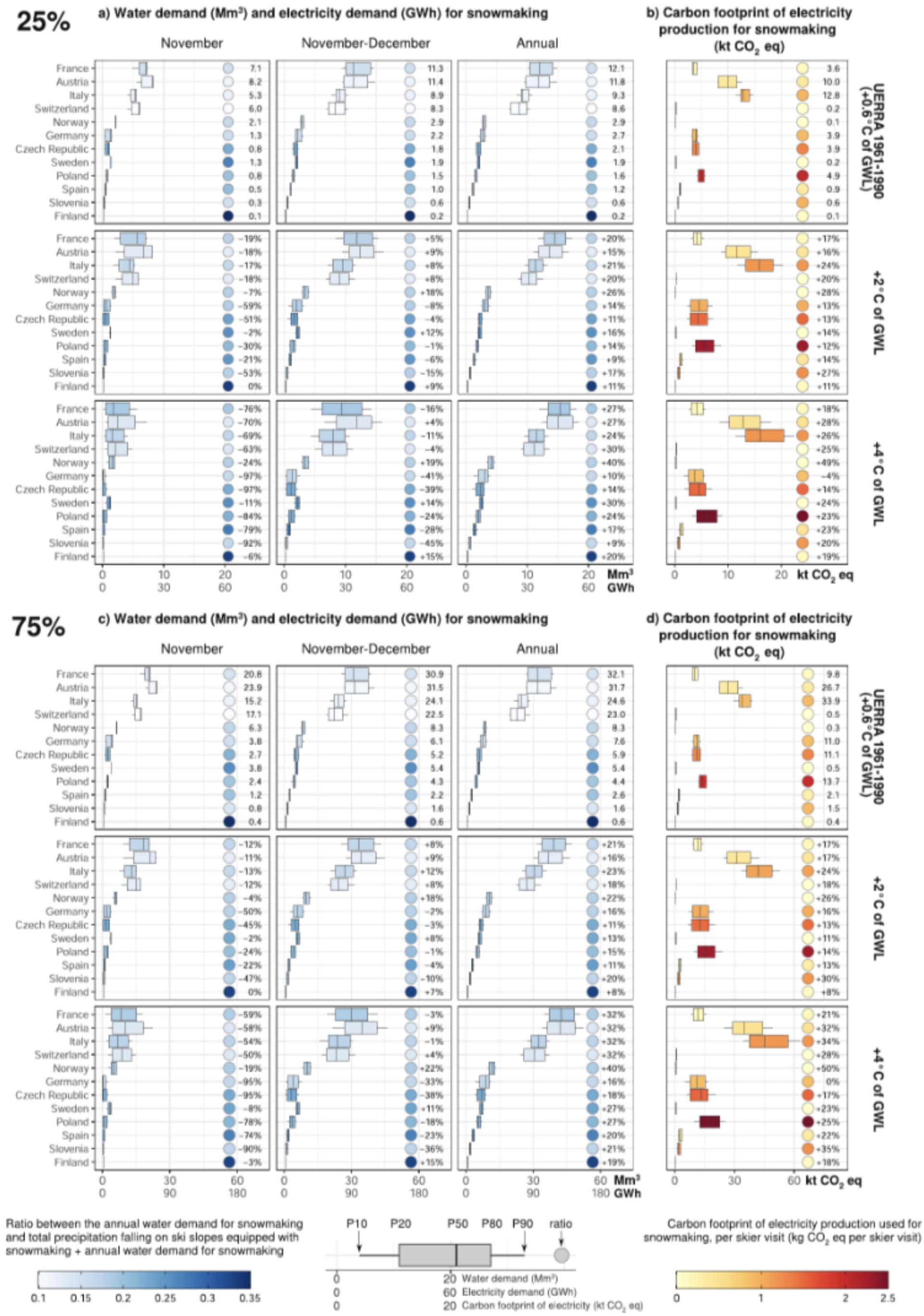

Extended Data Fig. 9 | Water demand, corresponding electricity demand and associated carbon footprint for electricity production, due to snowmaking only, assuming a uniform snowmaking fractional coverage of 25% and 75%, for the main 12 countries. Same as Fig. 4 but for 25% snowmaking fractional coverage (a and b) and 75% snowmaking fractional coverage (c and d).