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Climate change exacerbates
snow-water-energy challenges for European
ski tourism
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Abstract
Ski tourism is a substantial component of the economy of mountainous
regions in Europe and highly vulnerable to snow scarcity, which increases
to ski tourism has not been quantified in a consistent way throughout
Europe, including the influence and environmental footprint of snow-
making. 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 at yory high
risk for snow supply under global warming of 2°C and 4°C, respec-
tively. By contrast, assuming a snowmaking fractional coverage of 50%

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047leads to a proportion of 27% and 71%, respectively, but with increasing048water and electricity demand (and related carbon footprint) of snow-049making. While it represents a modest fraction of the overall carbon050footprint of ski tourism, snowmaking is an inherent part of the ski tourism051industry and it epitomizes some of the key challenges at the nexus052between climate change adaptation, mitigation, and sustainable development in the mountains, with their high social-ecological vulnerability.

054Keywords: snow, tourism, ski, snowmaking, Europe, climate change, water,055carbon footprint

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059Due to climate change, the mountain seasonal snow cover decreases, at a rate which depends on the geographical location and the elevation [1-3]. Assessing 060 the extent to which past and future changes in climate affect ski resort opera-061 tions across Europe is critical to design meaningful development pathways for 062 this key sector of the European tourism industry [4], particularly in the context 063 064 of the European Green Deal [5]. This concerns both climate change adaptation and mitigation [6], and needs to take into account related pressures on 065the local environment and resources such as water and energy [7]. Indeed, ski 066 tourism faces complex and intertwined sustainability challenges in the context 067 of global change [8, 9]. Global tourism (not only ski tourism) is responsible for 068 069 substantial greenhouse gas emissions, estimated to 8.1% of global emissions with 49.1% of this contribution caused by transport [10]. Tourism strongly 070 influences local and regional social-ecological systems, sustaining livelihoods 071but also affecting biodiversity and use of resources [11]. The environmental 072 impact of ski tourism is often viewed in terms of water and electricity demand 073 074 for snowmaking, but only a few studies provide quantitative estimates, most often at the local scale [12, 13]. 075

Snow scarce conditions are detrimental to ski resort operations, because 076 snow on ski pistes is the major ingredient of ski tourism supply. An occasional 077 lack of snow has always been contemplated by ski resort operators, due to 078 079 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 080 recurring snow scarce winters threaten the long term economic sustainability 081 of ski resorts [14, 16–19]. Here we adopt the definition of risk of the Inter-082 governmental Panel on Climate Change (IPCC) [20], i.e. the "potential for 083 084 adverse consequences for human or ecological systems", and conceptualize its application to snow supply to ski tourism on Figure 1. Quantifying long term 085climate change impacts and risks pertaining to the snow supply to European 086 ski tourism requires accounting not only for the evolution of climatic impact-087 drivers (temperature increase, snow cover decline), the related hazards (the 088 089 frequency of warm and/or snow scarce winters), but also for their combination with the exposure (geographic location, elevation range) of individual ski 090 resorts, and the ski resorts' individual and collective vulnerability. 091



Fig. 1 Snow supply risk to ski tourism in the context of climate change.

117 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 118vulnerability. Changes in the hazard are related to temperature rise and snow cover decline. 119Snow management is designed to reduce the snow supply risk, but is itself influenced by 120climatic impact-drivers. In turn, it induces pressure on environmental externalities, with related greenhouse gas emissions. The risk also influences demand-side factors, through 121skier satisfaction (influencing profitability of operations) and skier visits (contributing to 122greenhouse gas emissions through transportation, housing etc.). Profitability of operations 123are influenced by snow management costs but also influence investments in snowmaking 124and related path dependencies.

126The risk on snow supply to ski tourism can thus be defined as the frequency 127of snow scarce conditions on ski pistes, taking into account snow grooming 128and snowmaking [1, 16, 21, 22]. Indeed, the climatic impact-driver "snow cover 129decline" directly leads to a rise in the snow supply risk to ski tourism (Figure 1301). Snowmaking, by contrast, is primarily designed to reduce the snow supply 131risk to ski tourism by decreasing the frequency of snow scarce conditions on ski 132pistes through the addition of machine-made snow [14, 18, 19, 23]. There are 133multiple interactions between snowmaking, the local climate (snowmaking can 134only proceed if the temperature remains sufficiently low), the local environment 135(water ressources, local ecosystems), the broader socio-economic functioning 136of ski tourism within mountain areas, and the influence of ski tourism on the 137climate through greenhouse gas emissions [7, 14, 18, 19, 23] (see Figure 1). 138

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139Europe (see Figure 2 for the included mountain ranges) is the largest global 140ski tourism market, with about 50% of the world's total ski resorts and over 141 80% of the world's ski resorts with more than 1 million skier visits (i.e. number 142of daily individual use of ski resorts facilities) per year [24]. It accounts for 60% 143of annual skier visits (43% only for the European Alps) corresponding to 209 144million skier visits in 2019, before the Covid-19 outbreak [24], and a turnover 145exceeding 30 billion euros per vear according to media reports [25]. Past studies dedicated to climate change impacts on ski tourism in Europe have either 146147neglected the influence of snow management, and in particular snowmaking [4, 26–28], or focused on smaller geographical domains, e.g. at the scale of 148149individual ski resorts or an aggregation at the national scale [16, 17, 29–31]. 150Also, many studies [27–29, 31] addressed the demand side risk resulting from 151tourists' reactions to future snow scarce conditions rather than quantifying the 152risk to snow supply itself. These deficiencies have made it difficult to produce 153a consistent assessment at the scale of the entire continent. The environmental 154footprint of snowmaking has seldom been studied [12, 32], and never at the 155scale of the entire continent.

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$\begin{array}{c} 157 \\ 158 \end{array}$

1 Climate change ski tourism snow supply risk

159We study the climate change effects on the snow supply risk to ski tourism 160at the scale of the entire European ski tourism market. We use numerical 161simulations of snow conditions, with and without snowmaking, and under past 162and future climate conditions, at the scale of individual ski resorts (see Method 163and Figures 1 and 2). Expanding from previous work [16, 18, 33], we quantify 164daily snow conditions at ski resort scale as the fraction of the ski resort's surface 165area with a snow mass (snow water equivalent) exceeding a threshold of 100 166kg m⁻². This corresponds to 20 cm of snow with a density of 500 kg m⁻³, which 167is sufficient for alpine skiing. Averaging this daily value over the critical time 168period from December to February [14, 21] provides a yearly indicator of snow 169conditions, referred to as the snow reliability index. We define the meaning of 170"snow scarce conditions" for each ski resort as the worst 20% years in terms of 171groomed natural snow encountered during the reference time period 1961-1990.

172The simulation results used in this study are based on the approach imple-173mented to compute the Copernicus Climate Change Service (CS3) Mountain 174Tourism Meteorological and Snow Indicators (MTMSI) dataset [34]. This 175dataset uses the pan-European near-surface meteorological reanalysis UERRA 176and an ensemble of adjusted EURO-CORDEX regional climate model sim-177ulations. Both feed the detailed snow cover model Crocus, which includes 178a representation of snow grooming and snowmaking [34, 35]. In the model, 179snowmaking depends on operating rules and meteorological conditions, in par-180ticular wet bulb air temperature ([34], see Methods and Extended Data Figure 1811). The MTMSI dataset provides state-of-the-art estimates of relevant climate 182data for the ski tourism industry, yet is insufficient for sectoral risk assess-183ment because it does not consider the location of individual ski resorts. We 184

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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 cor-
responding total estimated surface area of ski pistes (total 984 km², as of November 2022).217
218For 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).210
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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 Method and Extended Data Figures 1 and 2). This enables to compute snow cover conditions (including the snow reliability index - expanding its use when snowmaking is taken into account, see Extended Data Figure 3) and water demand for snowmaking, for various values of the snowmaking fractional 230

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231 coverage (i.e. the fraction of a resort's ski piste area covered by snowmaking infrastructure) for each ski resort. The results of such calculations are 233 illustrated on Extended Data Figures 4, 5, 6 and 7 for contrasted ski resorts 234 located in the French/Swiss middle mountains (Metabief, Jura, France), in the 235 Austrian Alps, in the Nordic mountains and in British Isles, respectively.

The distribution of Q_{20}^{ref} values for ski resorts in Europe, shown on Figure 2362372, reveals the strong heterogeneity in reference snow conditions within and 238across mountain areas, due to the combined effect of the local climate and the 239location of ski resorts, and provides the baseline upon which future changes can be analyzed. It also shows the distribution of the ski resorts' 20^{th} percentile 240241of snow reliability index values (Q_{20}) within a geographical entity for the time 242period 1991-2015, highlighting that over past decades natural snow conditions 243in ski resorts have generally declined, at a rate which differs depending on the 244mountain area.

245Based on future climate change scenarios, we investigate how the frequency of snow scarce winters changes with the global warming level for various illus-246247trative 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 248249of the global warming level in the form of burning embers in Figure 3 at the 250scale of mountain areas [36] (see Methods and Extended Data Figure 1). We 251define the risk level as follows: a frequency of 30% of winters below the snow 252scarcity threshold, corresponding to a 50% increase in the risk compared to 253the reference value (20%), is referred to as "moderate" (vellow). A frequency 254of 40%, corresponding to a doubling of the reference risk value, is referred to as 255"high" (red). The risk reaches the "very high" (violet) domain at a frequency 256of 50% and above, i.e. snow scarce conditions encountered at least once every 257two years on average.

258Burning embers for groomed natural snow only (left), and including snow-259making (right), consistent with the approach taken in the literature and in recent IPCC reports [36–38] for displaying climate change risk with and with-260out adaptation, shows that, in all cases, the risk systematically increases with 261262higher global warming level (Figure 3). Further, for groomed natural snow 263conditions only, in most geographical entities, a global warming level of 1.5° C 264leads to a high to very high snow supply risk to ski tourism, with only a few 265entities showing comparatively lower increases in the risk (e.g. Turkey, Central European middle mountains 2). Three main patterns emerge from the burning 266267embers analysis taking snowmaking into account. For some mountain areas, mainly in the Alps but also in the Nordic mountains and in Turkey, addi-268269tional snowmaking fractional coverage reduces the risk. However the marginal 270benefit decreases, especially between 50% and 75% (block A in Figure 3). For 271other areas, snowmaking has a positive impact on the risk level up to a cer-272tain point, but increases in the snowmaking fractional coverage beyond 50%273reduce its efficiency and the risk increases (block B in Figure 3). Last, in some 274areas, the risk level quickly reaches high values with increasing global warm-275ing level regardless of the snowmaking fractional coverage (block C in Figure 276

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Burning embers risplay the risk value, i.e. 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, 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. 300 307 308 309 310 311 312

314 3). Note that these general observations do not necessarily apply to all indi-315vidual ski resorts within the mountain areas analyzed. This illustrates that 316 the snow supply risk to ski tourism under climate change is context-dependent in multiple ways, including the influence of the snowmaking fractional cover-317 318age and the geographically and climatically variable efficiency of snowmaking 319 itself [14, 39, 40]. At 2°C and 4°C global warming levels, respectively, without snowmaking, 53% and 98% of the 2,234 ski resorts studied are projected to 320 321experience a very high snow supply risk. Assuming a snowmaking fractional

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323 coverage of 50%, these figures decrease to 27% and 71%, respectively. Results
324 for individual mountain areas are provided in Extended Data Figure 8.
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³²⁶ 2 Snowmaking water demand and energy footprint



Water demand, corresponding electricity demand and associated carbon footprint for 356electricity production, due to snowmaking only, assuming a uniform 50% snowmaking 357 fractional coverage, for the main 12 countries. Rows correspond to global warming levels compared to 1850-1900: $+0.6^{\circ}$ C (1961-1990 reference period, top), $+2^{\circ}$ C (middle), and 358 +4°C (bottom). a) Water and electricity demand, from left to right, for November, Novem-359 ber and December, and hydrological year (summer to summer; snow production occurs 360 between November and February). Box plots, showing the percentiles 10, 20, 50, 80 and 36190, 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 362 in the circles). b) Carbon footprint of electricity production for snowmaking. The colouring 363refers to the carbon footprint per skier visit. 364

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We estimate on Figure 4 the water and electricity demand 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. 369 comprising 95% of the ski resorts' surface area considered in this study. The 370 median value of the total annual water demand for snowmaking, for the refer-371 ence period 1961-1990 with 50% snowmaking fractional coverage, is estimated 372at 103 Mm³ (90 - 119 Mm³ range spanning the 10th to 90th percentiles). 373 Under these conditions, water demand for snowmaking at the European scale 374would correspond to 13% of the total annual precipitation falling on ski piste 375areas equipped with snowmaking facilities. For individual countries, this figure 376 varies between 10% and 32%. 377

Water demand changes substantially in a warmer climate, both in terms 378 of the total quantity and its seasonal distribution. Our results indicate a gen-379 eral decrease of the water demand for snowmaking in November (decreases in 380 national values range from 0% to -53% at $+2^{\circ}C$, and -5% to -96% at $+4^{\circ}C$). 381 due to increasing temperatures leading to fewer time periods adequate for 382snowmaking. Projections indicate an overall increase in annual water demand 383 with the global warming level (changes in national values range from +8% to 384 +25% at $+2^{\circ}$ C, and +14% to +42% at $+4^{\circ}$ C), driven by mountain regions 385where climate conditions remain sufficiently cold for snowmaking. The cor-386 responding estimates for snowmaking fractional coverages of 25% and 75%, 387 respectively, are provided on Extended Data Figure 9. 388

The median value of the total annual electricity demand for snowmak-389 ing in these 12 countries is estimated at 309 ± 103 GWh during the reference 390 time period 1961-1990, assuming a 50% snowmaking fractional coverage (see 391 Methods and Extended Data Figure 1). This value is in a comparable order 392 of magnitude to a prior estimate of 600 GWh over the European Alps [41]. 393 Using figures on skier visits from 2019, our estimates corresponds on average 394to about 1.5 ± 0.5 kWh per skier visit devoted to snowmaking. The total elec-395tricity demand for snowmaking is projected to increase on average by 18% and 396 24% for $+2^{\circ}C$ and $+4^{\circ}C$ global warming, respectively. 397

Based on the carbon intensity of electricity in 2019, the annual carbon 398 footprint of electricity use for snowmaking in the considered 12 countries is esti-399 mated at 78 ± 26 kt CO₂eq for the reference period 1961-1990, and projected to 400reach 93 ± 31 kt CO₂eq and 97 ± 32 kt CO₂eq at $+2^{\circ}$ C and $+4^{\circ}$ C global warm-401 ing level, respectively. Due to ongoing and future policy changes, the carbon 402intensity of electricity production is expected to decrease in upcoming decades. 403 Our results illustrate how the carbon footprint of electricity used for snowmak-404 ing would evolve in a warmer climate, based on the current energy mix. Due to 405differences between European countries in both water demand for snowmak-406 ing and the current carbon intensity of electricity production (ranging from 4070.008 to $1.1 \text{ kg CO}_2 \text{eq kWh}^{-1}$ on annual averages, see Methods), the carbon 408footprint of electricity demand for snowmaking varies considerably between 409countries, as shown in Figure 4. Mountainous entities with the highest car-410bon footprint for snowmaking combine a comparatively high water demand for 411 snowmaking with a high carbon intensity for electricity production. Per skier 412413visit, the carbon footprint of electricity used for snowmaking varies between

415 0.01 and 2.3 kg CO_2 eq. These values are consistent with previous estimates at 416 the national scale [42].

417 Recent studies estimate that the operations of a ski resort (snow manage-418ment, ski lift operations etc.), including electricity demand for snowmaking, correspond to 2% to 4% of the total carbon footprint of the destination [42, 43]. 419 420 In contrast, more than 50% of the carbon footprint, sometimes even exceed-421ing 80%, is induced by arrival, departure and on-site transportation of skiers 422 [42, 43]. However, while the carbon footprint of ski resort operations represents 423 a small share of a destination's total footprint, both are strongly interrelated 424 as ski-related tourism activities are often the main driver for tourist visits. 425Ski tourism operators, together with other mountain tourism stakeholders, are 426thus jointly responsible for the broader emissions (e.g. accommodation, trans-427 portation) related to ski tourism, even if their operations make a small direct 428contribution.

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${}^{430}_{431}$ 3 Discussion

432All estimates provided in this study rely on state-of-the-art reanalyses and 433climate projections of the snow cover reliability and a detailed inventory of 434ski resort locations in Europe (see Methods and Extended Data Figure 1). 435This study comes with inevitable limitations and simplifications implied by 436our pan-European approach in a context where detailed data are often missing 437(e.g. data on the snowmaking fractional coverage of individual ski resorts, 438and the technology implemented). Our estimates of the water demand for 439snowmaking assume current technologies and practices of the industry. They 440neither reflect any limitations in water availability under the current or future 441climate, nor possible changes in technologies and practices of the industry. 442Nevertheless, based on a series of reasonable hypotheses and assumptions, we 443provide a consistent depiction of the current and future state of the snow 444supply risk pertaining to the ski tourism industry in Europe, and some key 445related environmental externalities.

446Although a warmer climate will systematically increase the snow supply 447risk pertaining to this industry, its magnitude depends on the region. Our 448results highlight not only the general trend and rising challenges, but also 449the variability across mountain regions of Europe in this respect, which is 450further modulated at the local scale due to the strong variability within moun-451tain regions [17, 18]. This work provides insights, which are primarily relevant 452for regional scale mountain development policy [21, 44]. Our methods and 453results also provide a basis for producing local climate change impact stud-454ies in Europe at the ski-resort level. However, their local application would 455require the use of additional local information. This includes the use of a 456detailed map of the ski resort including the location and characteristics of 457snowmaking units, an analysis of the availability and use of water under current 458and future climate conditions, the availability of energy resources for sustain-459ing snowmaking operations, and impact studies on local ecosystems [18, 32]. 460

Such information is critical for informing climate action in mountainous areas, 461across all relevant scales of decision [44-46]. Our results are also relevant in 462the context of strengthening EU regulations on climate risk disclosure for all 463sectors. For planning purposes, such information relevant to the challenges of 464 the ski tourism supply side (operating conditions) needs to be combined with 465future trajectories on the ski tourism demand side (i.e., skiers preferences and 466 potential changes in practices), which are also heavily dependent on snow con-467 ditions and broader socio-economic perspectives including the diversification 468of mountain economies and avoiding maladaptation [1, 6, 7, 19, 27, 44, 47, 48]. 469

The presented results illustrate the interaction between climate change 470impacts and risks to a given sector (here snow supply to ski tourism) and 471 broader environmental and climate challenges. Indeed, reaching strong reduc-472473tions in greenhouse gas emissions for ski tourism destinations will chiefly depend on massive reductions of the carbon footprint of transportation and 474475accommodation [6]. This holds implications for tourism development strategies. In particular, it remains questionable whether far-reaching policies 476required to limit global warming to $+2^{\circ}$ C are compatible with carbon intensive 477tourism activities in their current form, in particular regarding transporta-478tion, housing, and the carbon intensity of electricity production [7, 19]. Even 479if a substantial fraction of European ski resorts is projected to still be able to 480 operate at 2°C global warming, the ability of ski tourism destinations, as a 481 whole, to achieve their share of greenhouse gas emission reductions required 482to remain below this global warming level is a major challenge. 483

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Author contributions

498H.F. and S.M. conceived the original idea for the paper. R.S. and H.F. carried out the calculations, with input from N.B. regarding carbon intensity calcu-499lations. S.M., H.F. and R.S. led the analysis. All authors contributed to the analysis, drafting, reviewing and editing the paper. 501

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$_{513}^{512}$ Competing interests

- 514 The authors declare no competing interests.
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4 Methods

Climate data

This study uses meteorological and snow cover simulations underpinning the 740 Copernicus Climate Change Service (CS3) Mountain Tourism Meteorologi-741 cal and Snow Indicators (MTMSI) dataset [1]. Results are provided for all 742countries of the European Union, candidate countries and members of the 743 European Free Trade Association. Altogether, the dataset covers all EU mem-744ber states, Albania, Andorra, Montenegro, North Macedonia, Serbia, Turkey, 745the United Kingdom, Iceland, Liechtenstein, Norway and Switzerland. Within 746 each country, the data is provided for each NUTS-3 (Nomenclature des unités 747 territoriales statistiques) area, by elevation steps of 100 m, on flat terrain. 748Meteorological data are extracted from the UERRA European reanalysis at 749 5.5 km resolution, spanning the time period 1961-2015. This data was used 750to adjust 21 pairs (3 RCP2.6, 9 RCP4.5 and RCP8.5) of global (GCM) and 751 regional (RCM) climate models from the EURO-CORDEX dataset, using the 752ADAMONT adjustment method [1]. See Extended Data Figure 1. 753

Snow cover simulations

756 Using the UERRA near-surface atmospheric reanalysis and the adjusted cli-757 mate change projections, we performed snow cover simulations using the 758detailed model Crocus, with and without snowmaking [1, 2]. Crocus is a multi-759layer snowpack model embedded in the ISBA land surface model within the 760SURFEX model [3]. Beyond natural snow processes including surface energy 761balance and snow metamorphism, Crocus makes it possible to account for 762grooming and snowmaking [4], based on physical representations of these snow 763management practices and operational rules [4-6]. For the simulations with 764snowmaking, the maximum wind speed threshold was set to $4.2 \,\mathrm{m \, s^{-1}}$, the 765density of machine-made snow to $600 \,\mathrm{kg}\,\mathrm{m}^{-3}$, the production rate of machine 766 made snow to 1.210^{-3} kg m⁻² s⁻¹, and the wet-bulb temperature threshold 767 for snowmaking to -5° C, consistent with previous studies [1, 5]. In the simula-768tions, between November 1 and December 15, up to 150 kg m^{-2} machine-made 769 snow is produced, weather conditions permitting and regardless of natural 770snowfalls during the period, which corresponds to 25 cm snow depth. Between 771December 15 and February 28, snow is produced if meteorologically possible 772so as to maintain a total snow depth of 60 cm. After March 1, no more snow 773is produced. These threshold values are consistent with typical practices of ski 774resort operators [2]. All simulations were carried out for flat terrain topographic 775configuration. The simulation results include not only snow cover data (total 776depth, snow water equivalent) but also the water demand for snowmaking 777 corresponding to the simulation results. 778

Inventory of European ski resorts

780We use the OpenSkiMap (https://openskimap.org) global database of ski 781resorts, which is based on the OpenStreetMap (https://www.openstreetmap. 782

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org) collaborative geospatial database. Specifically, we use the three files provided by OpenSkiMap (Ski Areas, Lifts and Runs). Information from these three files was combined, involving careful checks and occasional removal of lifts from our analysis, which 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 Figure 1.

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790 European mountain areas

791 The 15 European Environmental Agency (EEA) European mountain areas 792 (https://www.eea.europa.eu/data-and-maps/data/european-mountain-areas) 793 form the core spatial structure of this work. The Atlantic islands, where 794 there is no resort, and the Eastern Mediterranean islands, where there is only 795 one resort, were excluded from the analysis. Thus we focus on 13 European 796 mountain areas. In this study, the "Alps" mountain area is split by countries 797 due to its dominant position in terms of ski tourism in Europe.

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$\frac{799}{5}$ Ski resort geospatial modelling

800 We combine various geospatial data sources to generate spatial information 801 for ski resorts (see Extended Data Figures 1 and 2). Using the European 802 Digital Elevation Model (EU-DEM), version 1.1, with a spatial resolution 803 of 25 m (http://land.copernicus.eu/pan-european/satellite-derived-products/ 804 eu-dem/eu-dem-v1.1/view) and the ski-lift catalogue from OpenSkiMap 805 (Extended Data Figure 2a), we compute, for each ski lift in each ski resort, 806 the geographical domain accessible downhill from the top of all the ski lifts 807 (Extended Data Figure 2b) and reaching the bottom of one of the ski lifts 808 (Extended Data Figure 2c). Combining these two areas results in the gravita-809 tional envelope of the ski resort (Extended Data Figures 2d and 2e) [5, 7–9]. 810 Further, we apply a geospatial modelling framework to infer the location where 811 snowmaking is applied within a given ski resort, depending on the snowmak-812 ing fractional coverage value (0%, 25%, 50%) and 75%, see Extended Data 813 Figure 2f) [2, 8]. Each pixel of the ski resort gravitational domain is associated 814 to a NUTS-3 region (Extended Data Figure 2h) and a 100 m elevation band 815 (Extended Data Figure 2f) from the climate and snow cover dataset, for flat 816terrain conditions. 817

The limitations of the MTMSI dataset regarding the available elevation 818 bands for each NUTS-3 region compared to the actual elevation ranges or the 819 ski resorts made it necessary to reassign some values. For the resorts fully 820 included in mountain NUTS-3 regions, but with missing elevation bands, we 821 assigned the minimum or the maximum available NUTS-3 elevation, depending 822 on whether the missing elevations are at the top or at the bottom of the 823 ski resort, in the limit of a 300 m difference and with minimum elevation not 824 less than 500 m. Resorts outside the NUTS-3 areas, for which climate data 825 are available, were not processed further. This led to 2,625 ski resorts, within 826 which only those belonging to EEA mountain areas were considered further, 827 resulting in a final selection of 2,234 ski resorts (see Extended Data Figure 1). 828

Resort-level snow cover reliability calculation

830 The snow cover reliability indicator for a given ski resort on a given day cor-831 responds to the fraction of the surface area (fraction of the pixels) of the 832 gravitational envelope exceeding a snow mass threshold of 100 kg m^{-2} (corre-833 sponding to 100 mm w.e., i.e. 20 cm of snow depth for a typical snow density 834 of 500 kg m⁻³). The average of the daily values for the months from December 835 to February is used as the snow cover reliability indicator applied in this work. 836 Crocus model runs provide water demand for snowmaking, which are aggre-837 gated for each ski resort. Consistent with previous research, we assume that 838 10% of the surface area of the gravitational envelope is actually covered with 839 ski pistes [5]. While the full envelope is taken into account for the calculation 840 of the snow reliability index, the 10% ratio is applied only for the calculation 841 of the water volume demand. 842

Defining whether conditions are snow scarce or not, in a given ski resort, when snowmaking is taken into account 843 844 845

Snowmaking is implemented in ski resorts in order 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 define the snow reliability index threshold $Q_{threshold}$ as (Equation (1)):

$$Q_{threshold} = max(Q_{20}^{ref}, X_{snowmaking}) \tag{1}$$

where $X_{snowmaking}$ is the snowmaking fractional coverage value considered (25%, 50% or 75%). We exemplify on Extended Data Figure 3 how this calculation is designed and implemented. The snow supply risk to ski tourism is thus expressed as the proportion of snow reliability index values below $Q_{threshold}$. By design, the risk level is equal to 20% for the reference period without snowmaking. This is illustrated on Extended Data Figures 4, 5, 6 and 7.

Computation of the snow supply risk and burning embers

The snow supply risk to ski tourism is defined as the frequency of snow scarce 863 conditions. These are defined as the 20^{th} percentile of the snow reliability index 864 during the reference period 1961-1990 without snowmaking, based on Crocus 865 model runs driven by the UERRA 5.5 km reanalysis, for each ski resort. The 866 frequency of snow scarce conditions is estimated for each ski resort for 20-year 867 time periods for each GCM/RCM pair, centered for each pair on the time 868 period when the GCM simulation reaches a global warming level for the values 869 $+1.5^{\circ}C$, $+2^{\circ}C$, $+3^{\circ}C$ and $+4^{\circ}C$ with respect to the time period 1850-1900. 870 Note that, in contrast to the discrepancy identified between RCM and GCM 871 simulated temperature changes over Europe in summer, there is a good overall 872 consistency for the winter season, which is the main seasonal focus of our study 873 [10, 11]. The global warming level dataset, providing information for all of the 874

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875 GCM results used in this study, is obtained from the Santander Meteorology
876 Group (UC-CSIC) (https://github.com/SantanderMetGroup/ATLAS/blob/
877 main/warming-levels/CMIP5_Atlas_WarmingLevels.csv).

878 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 879 880 given global warming level, is used to relate the risk value to this particular 881 warming level. This resort-level risk value is then averaged for each mountain 882 area, using the surface area of the ski resort as a weighting factor. The corre-883 sponding risk value for each mountain area and global warming level is then 884 used to build the burning ember diagram. Ultimately, burning embers [12] 885 represent the snow supply risk to ski tourism under different global warming 886 levels, with and without snowmaking.

Due to the lack of a European database on the fraction per ski resort equipped with snowmaking, we apply 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 [9].

892 By design, the risk level is equal to 20% for the reference period without 893 snowmaking. Hence, a frequency of 20% of snow scarce winters corresponds 894 to an undetectable change in risk level (displayed in white on Figure 3). A 895 frequency of 30%, corresponding to a 50% increase in the frequency of snow 896 scarce conditions compared to the reference value (20%), is referred to as 897 "moderate" risk (vellow), while a doubling in the frequency (40%) is referred 898 to as "high" risk (red). The risk reaches the "very high" (violet) domain at a 899 frequency of 50% and above, which corresponds to encountering at least once 900 every two years a situation of snow scarcity, which was only encountered once 901 every 5 years during the reference period.

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903 Water and electricity demand for snowmaking

904 Water demand values are generated as a diagnostic of the snow cover sim-905 ulations. Water demand for snowmaking is illustrated in Extended Data 906 Figures 4, 5, 6 and 7. See Extended Data Figure 8b for more informa-907 tion on the calculation of the uncertainty pertaining to the water demand 908 for various global warming levels and snowmaking fractional coverage 909 values. Here we assume an electricity consumption of $3\pm1\,\mathrm{kWh}$ per m³ 910 of water converted to snow. This value is consistent with recent reports 911 from the ski tourism industry and national and regional reports from 912local environment and tourism authorities (https://www.wko.at/branchen/ 913transport-verkehr/seilbahnen/Oekologie_und_Umwelt.html. http://www. 914observatoire.savoie.equipement-agriculture.gouv.fr/Atlas/4-hydro.htm, https: 915//side.developpement-durable.gouv.fr/ACCIDR/doc/SYRACUSE/152732).

916 In fact, this value depends on the technology used and on the temperature of

⁹¹⁷ snow production. However, in lack of a detailed inventory of the technology

⁹¹⁸ deployed in all ski resorts of Europe, which would also require a more detailed

- ⁹¹⁹ modelling framework than currently exists, we consider this central value
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surrounded by a range from 2 to 4 kWh per m^3 for this study with a central 921 estimate of 3 kWh m⁻³. Since this is a constant parameter in our study, all 922 of the results, in terms of electricity demand and corresponding greenhouse 923 gas emissions, can be updated by means of a simple "rule of three" using a 924 different value of the electricity demand for water conversion to snow. This 925 value takes into account the entire snowmaking process, including snowguns 926 operations, local water pumping etc. 927

Carbon footprint of electrity consumption for snowmaking

930 The carbon footprints are calculated using amounts of electricity generation 931 by type of production (e.g. hard coal, run-of-river hydropower, etc.) and coun-932 try as recorded on the ENTSO-E Transparency Platform for 2018 to 2022 933 (https://transparency.entsoe.eu/dashboard/show). The central estimates were 934 computed using the figures for the vear 2019, deemed representative of the sit-935 uation prior to the outbreak of Covid-19. Data for the years from 2018 to 2022 936 were used for uncertainty analysis, based on the 6 main countries in terms 937 of water and electricity demand, and for which carbon intensity factors were 938 calculated. Combining electricity demand time series (from past and future 939 climate conditions) with a sampling of the carbon intensity data from these 5 940 years leads to an estimate of the uncertainty due to the interannual variabil-941 ity of carbon itensity. The multiannual standard deviation around the mean 942 of the median shows, for the UERRA reanalysis reference time period 1961-943 1990, varies between 8.8% (Norway, expected to increase up to the values of 944 12.3% and 13.6% at $+2^{\circ}C$ and $+4^{\circ}C$ global warming levels, respectively) and 945 1.2% (Sweden, expected to reach 0.6% and 1.0% at $+2^{\circ}C$ and $+4^{\circ}C$) of the 946 mean value. Values for Italy and Austria, where the mean value is the highest, 947 reach 2.5% and 3.7% respectively. This uncertainty is thus much lower than 948 the uncertainty due to the electricity demand for snowmaking, considered in 949 this study. Production for each generation type and country are multiplied 950 by country dependent emission factors $(\text{kg CO}_2\text{eq kWh}^{-1})$ from the ecoinvent 951 database [13], taking into account life cycle assessment (LCA) components. 952The emissions are calculated on an hourly basis and an average emission factor 953 by country and month is used for the conversion of monthly electricity demand 954for snowmaking into equivalents of CO₂ emissions. Emissions from imported 955 electricity are not included, which is a methodological limitation of this study. 956 The emissions presented are for electricity consumption due to snowmaking 957 only. They do not include emissions for snow grooming and maintenance, snow 958making equipment and its installation and maintenance and ski lift operation. 959

Data availability

962 MTMSI dataset is available on the Copernicus Climate The Data 963 https://doi.org/10.24381/cds.2fe6a082 Store this doi: [14]following 964under the Copernicus licence. We use the OpenSkiMap (https: 965 //openskimap.org) global database of ski resorts, which is based on 966

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967 the OpenStreetMap (https://www.openstreetmap.org) collaborative 968 geospatial database. The description of the 15 European Environ-969 mental Agency (EEA) European mountain areas is available online: 970 https://www.eea.europa.eu/data-and-maps/data/european-mountain-areas.

The European Digital Elevation Model (EU-DEM), version 1.1, with a 971 972 spatial resolution of 25 m, is available online http://land.copernicus.eu/ 973 pan-european/satellite-derived-products/eu-dem/eu-dem-v1.1/view. The 974 global warming level dataset is available from the Santander Meteorol-975ogy Group (UC-CSIC) (https://github.com/SantanderMetGroup/ATLAS/ blob/main/warming-levels/CMIP5_Atlas_WarmingLevels.csv). The carbon 976 977 footprints are calculated using hourly amounts of electricity generation 978 by type of production (e.g. hard coal, run-of-river hydropower, etc.) and 979 country as recorded on the ENTSO-E Transparency Platform for 2019 980(https://transparency.entsoe.eu/dashboard/show).

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982 983 Code availability

984 The Crocus snow cover model used for this work is developed inside the 985 open-source SURFEX project (http://www.umr-cnrm.fr/surfex/, last access : 986 7 June 2020). For reproducibility of results, the version used in this work is 987 tagged as "C3S-European-Tourism-MTMSI-2019" on the SURFEX git repos-988 itory. The computer code necessary to reproduce the main results is provided 989 at the Zenodo repository (10.5281/zenodo.8047168) [15].

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${}^{991}_{992}$ Methods references

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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 res-olution 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".



1183 Methodological approach employed to determine whether snow conditions are snow scarce 1184 or not, in a given ski resort, when snowmaking is taken into account. The reference snow 1185 reliability index Q_{20}^{ref} is computed based on groomed natural snow simulations for the 1186 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 1187 threshold value $Q_{threshold}$, equal to the maximum between Q_{20}^{ref} and the snowmaking frac-1188 tional coverage. In case A (top), Q_{20}^{ref} (here 23%) is lower than the snowmaking fractional 1189 coverage (here 50%). If for a given year the snow reliability index value is larger than both, 1190 it is not considered snow scarce. If it is lower than both, it is considered snow scarce. In 1191 the intermediate case (here 33%), it is considered snow scarce, because it is lower than the 1192 snowmaking fractional coverage (here 50%). There are then only two possible situations, 1193 simply comparing the snow reliability index with the Q_{20}^{ref} .

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Simulation results for the Metabief ski resort (French Jura mountain regions. All panels 1229display past simulations (based on the UERRA reanalysis), and climate projections (his-1230torical from 1950 to 2005 and future projections for RCP2.6, RCP4.5 and RCP8.5 for 2006 1231to 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; 123275% for panels i, j and k). Panels on the left hand side (a, c, f and i) display the time series 1233of the snow reliability index values. Individual annual values are displayed for UERRA 1234reanalysis. For climate projections, the panels show the median (solid line) and 20/80percentile values (colored area) for all simulations of the same RCP, on 15-years sliding 1235windows. The black solid line displays the same information based on UERRA reanalysis. 1236 Panels in the middle column (b, d, g and j) display the frequency of years below the snow 1237 reliability threshold $Q_{threshold}$ (computed based on the values obtained using the UERRA 1238reanalysis 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 1239the standard deviation around the mean. Panels on the right side (e, h and k) display 1240the computed water demand for snowmaking. The solid line refers to the median and the 1241 colored area spans the 20/80 percentile range, on 15-years sliding windows. 1242



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Numerical values of the snow supply risk levels from Figure 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 Figure 3. The uncertainty shown in panel (b) is calculated based on the standard deviation around the mean of the water demand calculated for each level of climate warming with respect to the reference mean value (mean water demand for a snowmaking fractional coverage of 25% during the reference time period 1961-1990). 1420 1421 1422 1423

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1472 Same as Figure 4 but for 25% snowmaking fractional coverage (a and b) and 75% snowmaking fractional coverage (c and d).