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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 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 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%

2 *Climate change challenges European ski tourism*

047 leads to a proportion of 27% and 71%, respectively, but with increasing
048 water and electricity demand (and related carbon footprint) of snow-
049 making. While it represents a modest fraction of the overall carbon
050 footprint of ski tourism, snowmaking is an inherent part of the ski tourism
051 industry and it epitomizes some of the key challenges at the nexus
052 between climate change adaptation, mitigation, and sustainable devel-
053 opment in the mountains, with their high social-ecological vulnerability.

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

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

076 Snow scarce conditions are detrimental to ski resort operations, because
077 snow on ski pistes is the major ingredient of ski tourism supply. An occasional
078 lack of snow has always been contemplated by ski resort operators, due to
079 the strong interannual variability of snow conditions [1, 2, 14, 15]. A key con-
080 cern is how often and to what extent such snow scarce situations occur, as
081 recurring snow scarce winters threaten the long term economic sustainability
082 of ski resorts [14, 16–19]. Here we adopt the definition of risk of the Inter-
083 governmental Panel on Climate Change (IPCC) [20], i.e. the "potential for
084 adverse consequences for human or ecological systems", and conceptualize its
085 application to snow supply to ski tourism on Figure 1. Quantifying long term
086 climate change impacts and risks pertaining to the snow supply to European
087 ski tourism requires accounting not only for the evolution of climatic impact-
088 drivers (temperature increase, snow cover decline), the related hazards (the
089 frequency of warm and/or snow scarce winters), but also for their combina-
090 tion with the exposure (geographic location, elevation range) of individual ski
091 resorts, and the ski resorts' individual and collective vulnerability.

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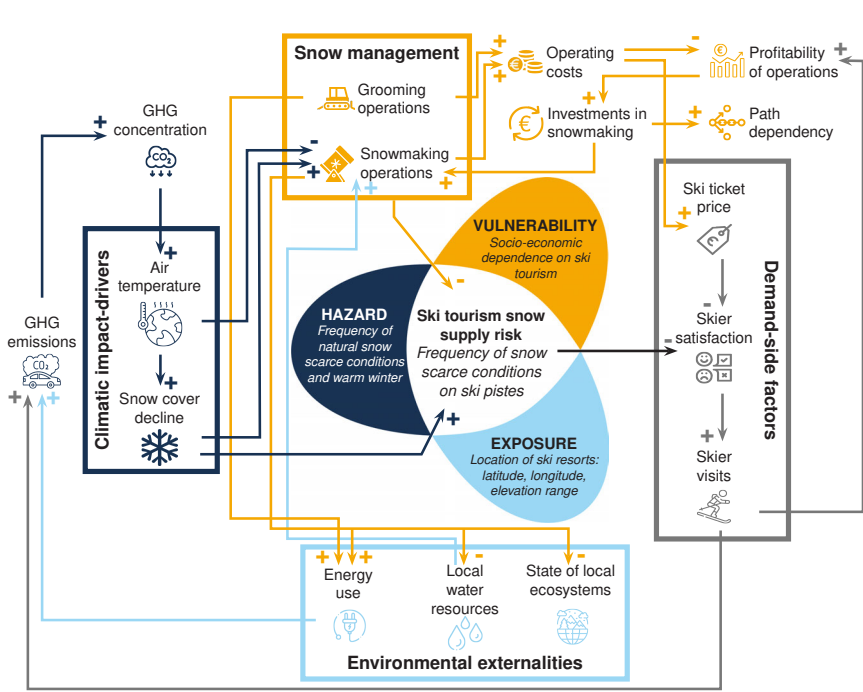


Fig. 1 Snow supply risk to ski tourism in the context of climate change.

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 the 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 etc.). Profitability of operations are influenced by snow management costs but also influence investments in snowmaking and related path dependencies.

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 (Figure 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] (see Figure 1).

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139 Europe (see Figure 2 for the included mountain ranges) is the largest global
140 ski 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
142 of daily individual use of ski resorts facilities) per year [24]. It accounts for 60%
143 of annual skier visits (43% only for the European Alps) corresponding to 209
144 million skier visits in 2019, before the Covid-19 outbreak [24], and a turnover
145 exceeding 30 billion euros per year according to media reports [25]. Past studies
146 dedicated to climate change impacts on ski tourism in Europe have either
147 neglected the influence of snow management, and in particular snowmaking
148 [4, 26–28], or focused on smaller geographical domains, e.g. at the scale of
149 individual ski resorts or an aggregation at the national scale [16, 17, 29–31].
150 Also, many studies [27–29, 31] addressed the demand side risk resulting from
151 tourists' reactions to future snow scarce conditions rather than quantifying the
152 risk to snow supply itself. These deficiencies have made it difficult to produce
153 a consistent assessment at the scale of the entire continent. The environmental
154 footprint of snowmaking has seldom been studied [12, 32], and never at the
155 scale of the entire continent.

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157 **1 Climate change ski tourism snow supply risk**

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

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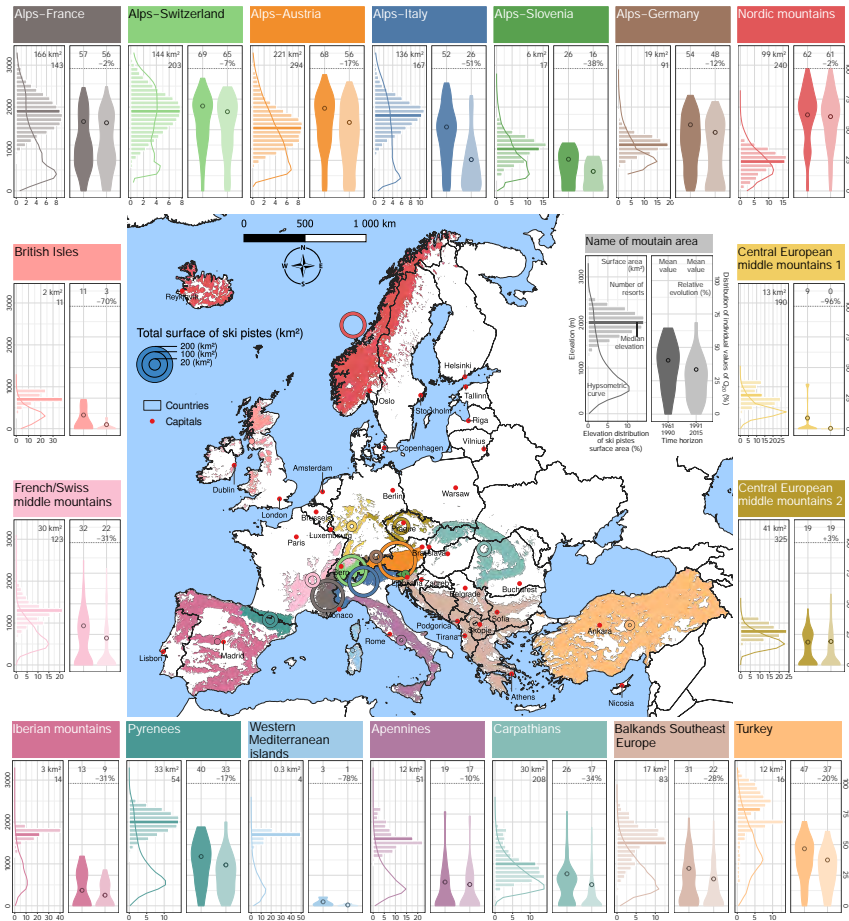


Fig. 2 Distribution of ski resorts in mountain areas in Europe.

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).

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

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231 coverage (i.e. the fraction of a resort's ski piste area covered by snowmak-
232 ing 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.

236 The distribution of Q_{20}^{ref} values for ski resorts in Europe, shown on Figure
237 2, reveals the strong heterogeneity in reference snow conditions within and
238 across mountain areas, due to the combined effect of the local climate and the
239 location of ski resorts, and provides the baseline upon which future changes can
240 be analyzed. It also shows the distribution of the ski resorts' 20th percentile
241 of snow reliability index values (Q_{20}) within a geographical entity for the time
242 period 1991-2015, highlighting that over past decades natural snow conditions
243 in ski resorts have generally declined, at a rate which differs depending on the
244 mountain area.

245 Based on future climate change scenarios, we investigate how the frequency
246 of snow scarce winters changes with the global warming level for various illus-
247 trative values of the snowmaking fractional coverage (0%, 25%, 50% and 75%).
248 The snow supply risk to the European ski tourism is displayed as a function
249 of the global warming level in the form of burning embers in Figure 3 at the
250 scale of mountain areas [36] (see Methods and Extended Data Figure 1). We
251 define the risk level as follows: a frequency of 30% of winters below the snow
252 scarcity threshold, corresponding to a 50% increase in the risk compared to
253 the reference value (20%), is referred to as "moderate" (yellow). A frequency
254 of 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
256 of 50% and above, i.e. snow scarce conditions encountered at least once every
257 two years on average.

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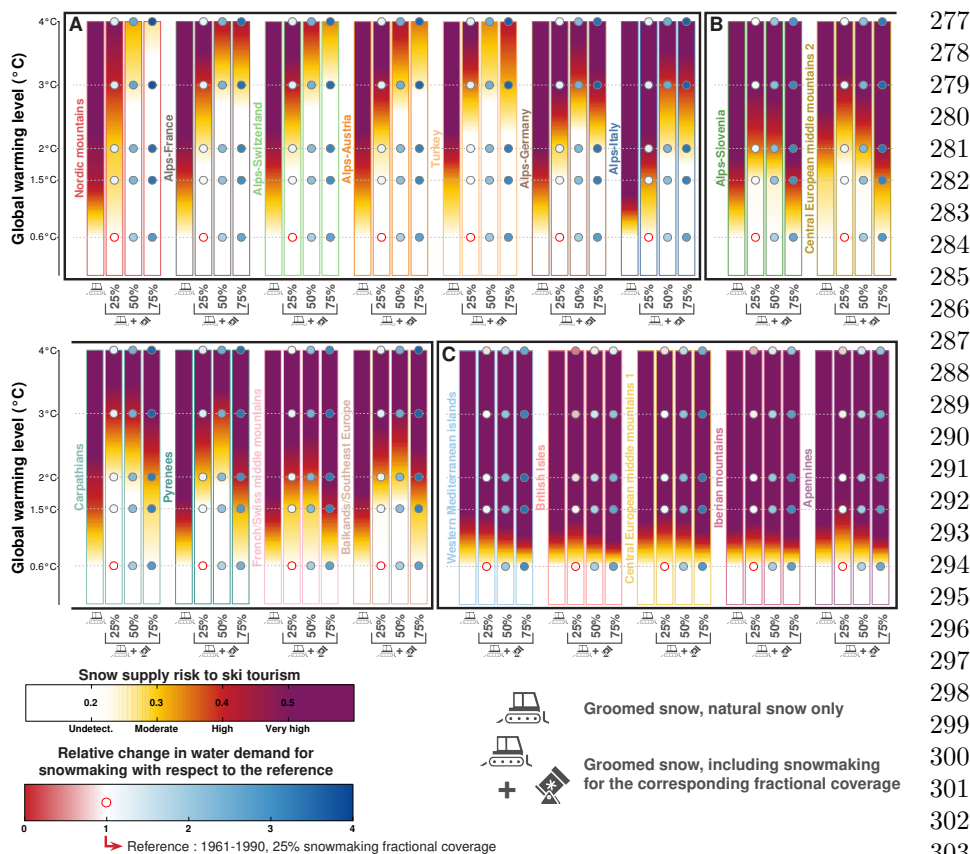


Fig. 3 Burning ember representation of the snow supply risk to ski tourism in European mountain areas.

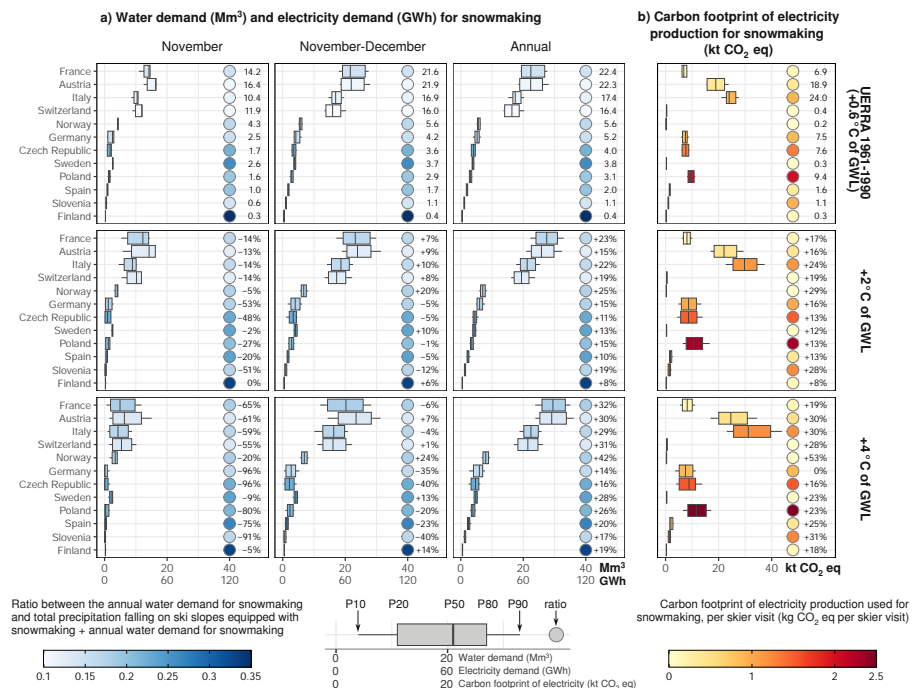
Burning embers replay the risk value, i.e. the frequency of snow scarce winters, using snow conditions without snowmaking for 1961-1990 (corresponding to $+0.6^{\circ}\text{C}$ global warming level since 1850-1900) as a reference. For each geographical entity, the left bar refers to natural snow only (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.

3). Note that these general observations do not necessarily apply to all individual ski resorts within the mountain areas analyzed. 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, respectively, without snowmaking, 53% and 98% of the 2,234 ski resorts studied are projected to experience 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.

326 2 Snowmaking water demand and energy 327 footprint



353 **Fig. 4 Water and electricity demand, and associated carbon footprint for electricity production, due to snowmaking.**

355 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 main 12 countries. Rows correspond to global warming levels compared to 1850-1900: +0.6°C (1961-1990 reference period, top), +2°C (middle), and 359 +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). Box plots, showing the percentiles 10, 20, 50, 80 and 361 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 362 in the circles). b) Carbon footprint of electricity production for snowmaking. The colouring refers to the carbon footprint per skier visit.

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366 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 367 368

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 Mm³ (90 - 119 Mm³ 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%, respectively, are provided on Extended Data Figure 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 Figure 1). This value is in a comparable order of magnitude to a prior estimate of 600 GWh over the European Alps [41]. Using figures on skier visits from 2019, our estimates corresponds 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.

Based on the carbon intensity of electricity in 2019, the annual carbon footprint of electricity use for snowmaking in the considered 12 countries is estimated at 78±26 kt CO₂eq for the reference period 1961-1990, and projected to reach 93±31 kt CO₂eq and 97±32 kt CO₂eq at +2°C and +4 °C global warming level, 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, based on 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 CO₂eq kWh⁻¹ on annual averages, see Methods), the carbon footprint of electricity demand for snowmaking varies considerably between countries, as shown in Figure 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 varies between

415 0.01 and 2.3 kg CO₂ 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-
418 ment, ski lift operations etc.), including electricity demand for snowmaking,
419 correspond to 2% to 4% of the total carbon footprint of the destination [42, 43].
420 In contrast, more than 50% of the carbon footprint, sometimes even exceed-
421 ing 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.
425 Ski tourism operators, together with other mountain tourism stakeholders, are
426 thus jointly responsible for the broader emissions (e.g. accommodation, trans-
427 portation) related to ski tourism, even if their operations make a small direct
428 contribution.

429

430 **3 Discussion**

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

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

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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 (i.e., 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.

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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 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 the paper.

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 510 at: <https://doi.org/10.1038/s41558-023-01759-5>.

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512 **Competing interests**

513

514 The authors declare no competing interests.

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516 **References**

517

518 [1] Hock, R. *et al.* High Mountain Areas. In Pörtner, H.-O. *et al.* (eds.) *IPCC*
 519 *Special Report on the Ocean and Cryosphere in a Changing Climate*, 131–
 520 202 (Cambridge: Cambridge University Press, 2019).

521

522 [2] Matiu, M. *et al.* Observed snow depth trends in the European Alps: 1971
 523 to 2019. *The Cryosphere* **15**, 1343–1382 (2021).

524

525 [3] Kotlarski, S. *et al.* 21st century alpine climate change. *Clim. Dyn.* 65–86
 526 (2022).

527

528 [4] Abegg, B., Agrawala, S., Crick, F. & de Montfalcon, A. *Climate change*
 529 *impacts and adaptation in winter tourism*, 25 – 60 (OECD, Paris, 2007).

530

531 [5] European Commission. The European Green Deal. Tech. Rep.
 532 (2019). URL [https://ec.europa.eu/info/strategy/priorities-2019-2024/
 533 european-green-deal_en](https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en).

534

535 [6] Filho, W. L. *et al.* Global tourism, climate change and energy sustain-
 536 ability: assessing carbon reduction mitigating measures from the aviation
 537 industry. *Sustain. Sci.* 1–14 (2022).

538

539 [7] Knowles, N., Scott, D. & Steiger, R. Sustainability of snowmaking as
 540 climate change (mal)adaptation: an assessment of water, energy, and
 541 emissions in Canada’s ski industry. *Current Issues in Tourism* 1–18
 542 (2023).

543

544 [8] Scott, D., Hall, C. M. & Gössling, S. Global tourism vulnerability to
 545 climate change. *Annals of Tourism Research* **77**, 49–61 (2019).

546

547 [9] Scott, D. Sustainable tourism and the grand challenge of climate change.
 548 *Sustainability* **13** (2021).

549

549 [10] Lenzen, M. *et al.* The carbon footprint of global tourism. *Nature Clim.*
 550 *Change* (2018).

551

552 [11] OECD. *Rethinking tourism success for sustainable growth* (2020).

- [12] Rixen, C. *et al.* Winter tourism and climate change in the Alps: An assessment of resource consumption, snow reliability, and future snowmaking potential. *Mountain Research and Development* **31**, 229–236 (2011). 553
554
555
556
- [13] Vignié, V. *et al.* When adaptation increases energy demand: A systematic map of the literature. *Environ. Res. Lett.* (2021). 557
558
559
- [14] Steiger, R., Scott, D., Abegg, B., Pons, M. & Aall, C. A critical review of climate change risk for ski tourism. *Current Issues in Tourism* **22**, 1343–1379 (2019). 560
561
562
563
- [15] Willibald, F. *et al.* Vulnerability of ski tourism towards internal climate variability and climate change in the swiss alps. *Science of The Total Environment* **784**, 147054 (2021). 564
565
566
- [16] Spandre, P. *et al.* Climate controls on snow reliability in French Alps ski resorts. *Sci. Rep.* **9** (2019). 567
568
569
- [17] Steiger, R. & Scott, D. Ski tourism in a warmer world: Increased adaptation and regional economic impacts in Austria. *Tourism Management* **77**, 104032 (2020). 570
571
572
573
- [18] Berard-Chenu, L., François, H., George, E. & Morin, S. Past changes in natural and managed snow reliability of French Alps ski resorts from 1961 to 2019. *The Cryosphere* **16**, 863–881 (2022). 574
575
576
577
- [19] Scott, D., Knowles, N. & Steiger, R. Is snowmaking climate change maladaptation? *Journal of Sustainable Tourism* 1–22 (2022). 578
579
580
- [20] on Climate Change (IPCC), I. P. *Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press). 581
582
583
584
- [21] Abegg, B. *et al.* Overloaded! Critical revision and a new conceptual approach for snow indicators in ski tourism. *International Journal of Biometeorology* (2020). 585
586
587
588
- [22] Scott, D., Steiger, R., Ruttty, M., Knowles, N. & Rushton, B. Future climate change risk in the us midwestern ski industry. *Tourism Management Perspectives* **40**, 100875 (2021). 589
590
591
592
- [23] Steiger, R., Knowles, N., Pöll, K. & Ruttty, M. Impacts of climate change on mountain tourism: a review. *Journal of Sustainable Tourism* 1–34 (2022). 593
594
595
596
597
598

- 599 [24] Vanat, L. 2021 International Report on Snow and Mountain Tourism.
600 Overview of the key industry figures for ski resorts. Tech. Rep., Laurent
601 Vanat (2021). URL <http://www.vanat.ch/RM-world-report-2021.pdf>.
602
- 603 [25] <https://www.swissinfo.ch/eng/business/the-importance-of-white-gold-to-the-alpine-46233650> (2020). [Online; accessed 28-March-2023].
604
- 605 [26] Tranos, E. & Davoudi, S. The regional impact of climate change on winter
606 tourism in europe. *Tourism Planning & Development* **11**, 163–178 (2014).
607
- 608 [27] Damm, A., Greuell, W., Landgren, O. & Prettenhaler, F. Impacts of
609 +2°C global warming on winter tourism demand in Europe. *Climate*
610 *Services* **7**, 31–46 (2017).
611
- 612 [28] Prettenhaler, F., Kortschak, D. & Woess-Gallasch, S. Modelling tourists’
613 responses to climate change and its effects on alpine ski tourism – a com-
614 parative approach for european regions. *Journal of Outdoor Recreation*
615 *and Tourism* **39**, 100525 (2022).
616
- 617 [29] Toegelhofer, C., Eigner, F. & Prettenhaler, F. Impacts of snow conditions
618 on tourism demand in austrian ski areas. *Climate Research* **46**, 1–14
619 (2011).
620
- 621 [30] Scott, D., Steiger, R., Dannevig, H. & Aall, C. Climate change and the
622 future of the Norwegian alpine ski industry. *Current Issues in Tourism*
623 1–14 (2019).
624
- 625 [31] Scott, D., Steiger, R., Ruttu, M., Pons, M. & Johnson, P. Climate
626 change and ski tourism sustainability: An integrated model of the adaptive
627 dynamics between ski area operations and skier demand. *Sustainability*
628 **12** (2020).
629
- 630 [32] Gerbaux, M., Spandre, P., François, H., George, E. & Morin, S. Snow reli-
631 ability and water availability for snowmaking in the ski resorts of the Isère
632 département (French Alps), under current and future climate conditions.
633 *Journal of Alpine Research* **108-1** (2020).
634
- 635 [33] Steiger, R. & Stötter, J. Climate change impact assessment of ski tourism
636 in tyrol. *Tourism Geographies* **15**, 577–600 (2013).
637
- 638 [34] Morin, S. *et al.* Pan-European meteorological and snow indicators of
639 climate change impact on ski tourism. *Climate Services* **22**, 100215 (2021).
640
- 641 [35] Spandre, P. *et al.* Integration of snow management in a detailed snowpack
642 model. *Cold Regions Science and Technology* (2016).
643
644

- [36] Zommers, Z. *et al.* Burning embers: towards more transparent and robust climate-change risk assessments. *Nature Reviews Earth & Environment* **1**, 516 – 529 (2020). 645
646
647
648
- [37] IPCC. Summary for policymakers. In *The Ocean and Cryosphere in a Changing Climate: Special Report of the Intergovernmental Panel on Climate Change*. (Cambridge University Press, 2019). 649
650
651
652
- [38] Hicke, J. A. & et al. Chapter 14 : North america. In *IPCC 6th Assessment Report, Working Group 2 “Impacts, adaptation and vulnerability”*. (2022). 653
654
655
- [39] Scott, D., McBoyle, G. & Mills, B. Climate change and the skiing industry in southern ontario (canada): exploring the importance of snowmaking as a technical adaptation. *Climate research* **23**, 171–181 (2003). 656
657
658
- [40] IPCC. *Impacts of 1.5°C Global Warming on Natural and Human Systems*, 175–312 (Cambridge University Press, 2018). 659
660
661
- [41] Hahn, F. *L’enneigement artificiel dans l’arc alpin - Rapport de synthèse* (Commission Internationale pour la Protection des Alpes, 2004). URL <http://www.cipra.org/fr/publications/2709>. 662
663
664
665
- [42] Guide sectoriel 2022: filière sport, montagne et tourisme. Tech. Rep. (2022). URL <https://bilans-ges.ademe.fr/fr/ressource/guide-sectoriel-list/index/idElement/16/siGras/1>. 666
667
668
- [43] Neger, C., Prettenhaler, F., Gössling, S. & Damm, A. Carbon intensity of tourism in austria: Estimates and policy implications. *Journal of Outdoor Recreation and Tourism* **33**, 100331 (2021). 669
670
671
672
- [44] Adler, C. *et al.* Cross-Chapter Paper 5 : Mountains. In *IPCC 6th Assessment Report, Working Group 2 “Impacts, adaptation and vulnerability”*. (2022). 673
674
675
676
- [45] McDowell, G. *et al.* Closing the Adaptation Gap in Mountains. *Mountain Research and Development* **41** (2021). 677
678
679
- [46] Tschanz, L. *et al.* A transdisciplinary method, knowledge model and management framework for climate change adaptation in mountain areas applied in the Vercors, France. *Regional Environmental Change* **22**, 15 (2022). 680
681
682
683
684
- [47] Dawson, J., Scott, D. & Havitz, M. Skier demand and behavioural adaptation to climate change in the US Northeast. *Leisure/Loisir* **37**, 127–143 (2013). 685
686
687
688
689
690

- 691 [48] Sun, Y.-Y., Gossling, S. & Zhou, W. Does tourism increase or decrease
692 carbon emissions? a systematic review. *Annals of Tourism Research* **97**,
693 103502 (2022).
694
695
696
697
698
699
700
701
702
703
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4 Methods

Climate data

This study uses meteorological and snow cover simulations underpinning the Copernicus Climate Change Service (CS3) Mountain Tourism Meteorological and Snow Indicators (MTMSI) dataset [1]. 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 is provided for each NUTS-3 (Nomenclature des unités territoriales statistiques) area, by elevation steps of 100 m, on flat terrain. Meteorological data are extracted from the UERRA European reanalysis at 5.5 km resolution, spanning the time period 1961–2015. This data was 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 [1]. See Extended Data Figure 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 [1, 2]. Crocus is a multi-layer snowpack model embedded in the ISBA land surface model within the SURFEX model [3]. Beyond natural snow processes including surface energy balance and snow metamorphism, Crocus makes it possible to account for grooming and snowmaking [4], based on physical representations of these snow management practices and operational rules [4–6]. For the simulations with snowmaking, the maximum wind speed threshold was set to 4.2 ms^{-1} , the density of machine-made snow to 600 kg m^{-3} , the production rate of machine made snow to $1.2 \cdot 10^{-3} \text{ kg m}^{-2} \text{ s}^{-1}$, and the wet-bulb temperature threshold for snowmaking to -5°C , consistent with previous studies [1, 5]. In the simulations, between November 1 and December 15, 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 December 15 and February 28, snow is produced if meteorologically possible so as to maintain a total snow depth of 60 cm. After March 1, no more snow is produced. These threshold values are consistent with typical practices of ski resort operators [2]. 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 use the OpenSkiMap (<https://openskimap.org>) global database of ski resorts, which is based on the OpenStreetMap (<https://www.openstreetmap>).

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783 [org](#)) collaborative geospatial database. Specifically, we use the three files pro-
784 vided by OpenSkiMap (Ski Areas, Lifts and Runs). Information from these
785 three files was combined, involving careful checks and occasional removal of
786 lifts from our analysis, which are not associated directly with a ski piste, in
787 order to provide a consistent set of ski resorts and ski lifts, together forming a
788 series of 2,959 ski resorts in Europe. See Extended Data Figure 1.

789 *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.

799 *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/eu-dem/eu-dem-v1.1/view>)
804 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
816 terrain 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).
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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 w.e. , i.e. 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 is 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 assume that 10% of the surface area of the gravitational envelope is actually covered with ski pistes [5]. While the full envelope is taken into account for the calculation of the snow reliability index, the 10% ratio is 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 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)):

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

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 conditions. These are 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 is estimated for each ski resort for 20-year time periods for each GCM/RCM pair, centered for each pair on the time period when the GCM simulation reaches a global warming level for the values $+1.5^\circ\text{C}$, $+2^\circ\text{C}$, $+3^\circ\text{C}$ and $+4^\circ\text{C}$ 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 is a good overall consistency for the winter season, which is the main seasonal focus of our study [10, 11]. The global warming level dataset, providing information for all of the

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

878 For each ski resort, the average value of the frequency of snow reliability
 879 index values below the Q_{20}^{ref} , across all GCM/RCM pairs corresponding to a
 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.

887 Due to the lack of a European database on the fraction per ski resort
 888 equipped with snowmaking, we apply a homogeneous 25%, 50% and 75% snow-
 889 making fractional coverage to all ski resorts in Europe, notwithstanding actual
 890 heterogeneities in snowmaking fractional coverages within and across mountain
 891 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 (yellow), 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 ± 1 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
 912 local environment and tourism authorities ([https://www.wko.at/branchen/](https://www.wko.at/branchen/transport-verkehr/seilbahnen/Oekologie_und_Umwelt.html)
 913 [transport-verkehr/seilbahnen/Oekologie_und_Umwelt.html](https://www.wko.at/branchen/transport-verkehr/seilbahnen/Oekologie_und_Umwelt.html), [http://www.](http://www.observatoire.savoie.equipement-agriculture.gouv.fr/Atlas/4-hydro.htm)
 914 [observatoire.savoie.equipement-agriculture.gouv.fr/Atlas/4-hydro.htm](http://www.observatoire.savoie.equipement-agriculture.gouv.fr/Atlas/4-hydro.htm), [https://](https://side.developpement-durable.gouv.fr/ACCIDR/doc/SYRACUSE/152732)
 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 m³ 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 etc.

Carbon footprint of electricity consumption for snowmaking

The carbon footprints are calculated using amounts of electricity generation by type of production (e.g. hard coal, run-of-river hydropower, etc.) and country as recorded on the ENTSO-E Transparency Platform for 2018 to 2022 (<https://transparency.entsoe.eu/dashboard/show>). The central estimates were computed using the figures for the year 2019, deemed representative of the situation prior to 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 years leads to an estimate of the uncertainty due to the interannual variability of carbon intensity. The multiannual standard deviation around the mean of the median shows, for the UERRA reanalysis reference time period 1961-1990, varies 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 value is the highest, reach 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 are multiplied by country dependent emission factors (kg CO₂eq kWh⁻¹) from the ecoinvent database [13], taking into account life cycle assessment (LCA) components. The emissions are calculated on an hourly basis and an average emission factor by country and month is used for the conversion of monthly electricity demand for snowmaking into equivalents of CO₂ emissions. Emissions from imported electricity are 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, snow making equipment and its installation and maintenance and ski lift operation.

Data availability

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

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>.
 971 The European Digital Elevation Model (EU-DEM), version 1.1, with a
 972 spatial resolution of 25 m, is available online [http://land.copernicus.eu/](http://land.copernicus.eu/pan-european/satellite-derived-products/eu-dem/eu-dem-v1.1/view)
 973 [pan-european/satellite-derived-products/eu-dem/eu-dem-v1.1/view](http://land.copernicus.eu/pan-european/satellite-derived-products/eu-dem/eu-dem-v1.1/view). The
 974 global warming level dataset is available from the Santander Meteorol-
 975 ogy Group (UC-CSIC) ([https://github.com/SantanderMetGroup/ATLAS/](https://github.com/SantanderMetGroup/ATLAS/blob/main/warming-levels/CMIP5_Atlas_WarmingLevels.csv)
 976 [blob/main/warming-levels/CMIP5_Atlas_WarmingLevels.csv](https://github.com/SantanderMetGroup/ATLAS/blob/main/warming-levels/CMIP5_Atlas_WarmingLevels.csv)). The carbon
 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 Code availability

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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](https://zenodo.org/record/105281)) [15].

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991 Methods references

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993 References

994

- 995 [1] Morin, S. *et al.* Pan-European meteorological and snow indicators of
 996 climate change impact on ski tourism. *Climate Services* **22**, 100215 (2021).
 997
- 998 [2] Spandre, P., François, H., George-Marcelpoil, E. & Morin, S. Panel based
 999 assessment of snow management operations in French ski resorts. *Journal*
 1000 *of Outdoor Recreation and Tourism* (2016).
 1001
- 1002 [3] Vionnet, V. *et al.* The detailed snowpack scheme Crocus and its
 1003 implementation in SURFEX v7.2. *Geosci. Model. Dev.* **5**, 773–791 (2012).
 1004
- 1005 [4] Spandre, P. *et al.* Integration of snow management in a detailed snowpack
 1006 model. *Cold Regions Science and Technology* (2016).
 1007
- 1008 [5] Spandre, P. *et al.* Climate controls on snow reliability in French Alps ski
 1009 resorts. *Sci. Rep.* **9** (2019).
 1010
- 1011 [6] Spandre, P. *et al.* Winter tourism under climate change in the Pyrenees
 1012 and the French Alps: relevance of snowmaking as a technical adaptation.

- The Cryosphere* **13**, 1325–1347 (2019). 1013
1014
- [7] François, H., Morin, S., Lafaysse, M. & George-Marcelpoil, E. Crossing numerical simulations of snow conditions with a spatially-resolved socio-economic database of ski resorts: A proof of concept in the French Alps. *Cold Regions Science and Technology* **108**, 98–112 (2014). 1015
1016
1017
1018
1019
- [8] François, H., Morin, S., Spandre, P., Lafaysse, M. & George-Marcelpoil, E. Croisement de simulations numériques des conditions d’enneigement avec une base de données socioéconomiques spatialisée des stations de sports d’hiver : description de l’approche et application aux Alpes françaises. *La Houille Blanche* **4** (2016). 1020
1021
1022
1023
1024
1025
- [9] Berard-Chenu, L., François, H., George, E. & Morin, S. Past changes in natural and managed snow reliability of French Alps ski resorts from 1961 to 2019. *The Cryosphere* **16**, 863–881 (2022). 1026
1027
1028
- [10] Taranu, I. S., Somot, S., Alias, A., Boé, J. & Delire, C. Mechanisms behind large-scale inconsistencies between regional and global climate model-based projections over Europe. *Climate Dynamics* (2022). 1029
1030
1031
1032
- [11] Ribes, A. *et al.* An updated assessment of past and future warming over France based on a regional observational constraint. *Earth System Dynamics* **13**, 1397–1415 (2022). 1033
1034
1035
1036
- [12] Zommers, Z. *et al.* Burning embers: towards more transparent and robust climate-change risk assessments. *Nature Reviews Earth & Environment* **1**, 516 – 529 (2020). 1037
1038
1039
1040
- [13] Wernet, G. *et al.* The ecoinvent database version 3 (part i): overview and methodology. *Int. J. Life Cycle Assess.* (2016). 1041
1042
- [14] Morin, S., Samacoïts, R., François, H. & Abegg, B. Mountain tourism meteorological and snow indicators for europe from 1950 to 2100 derived from reanalysis and climate projection. <https://doi.org/10.24381/cds.2fe6a082> (2020). 1043
1044
1045
1046
1047
- [15] François, H. & Samacoïts, R. European ski resorts snow reliability. <https://doi.org/10.5281/zenodo.8047168> (2023). 1048
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1059 **Extended Data**

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1062 **Spatial modelling of ski resorts**

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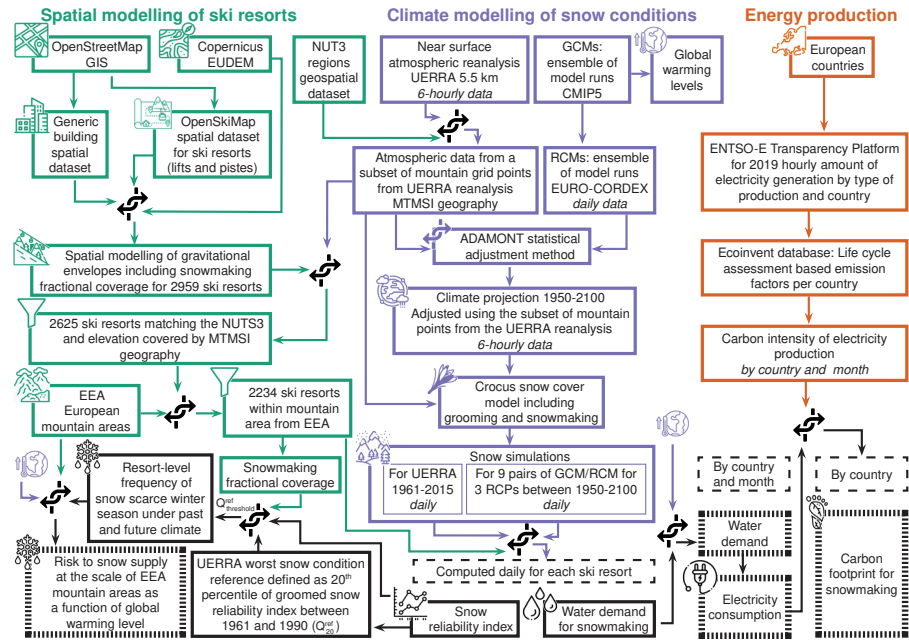


Fig. 1 Methodological approach to compute the snow conditions on ski pistes and related externalities.

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.

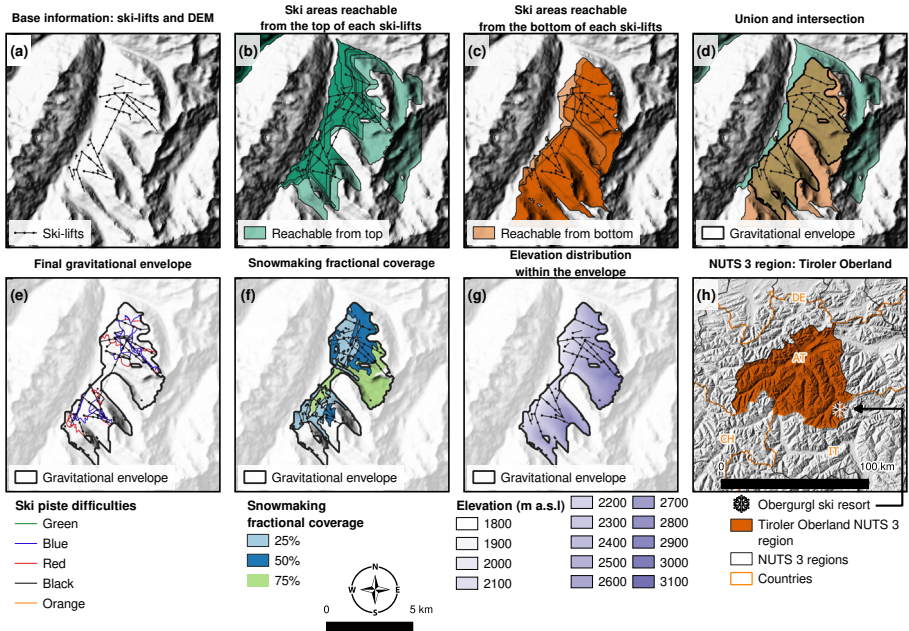
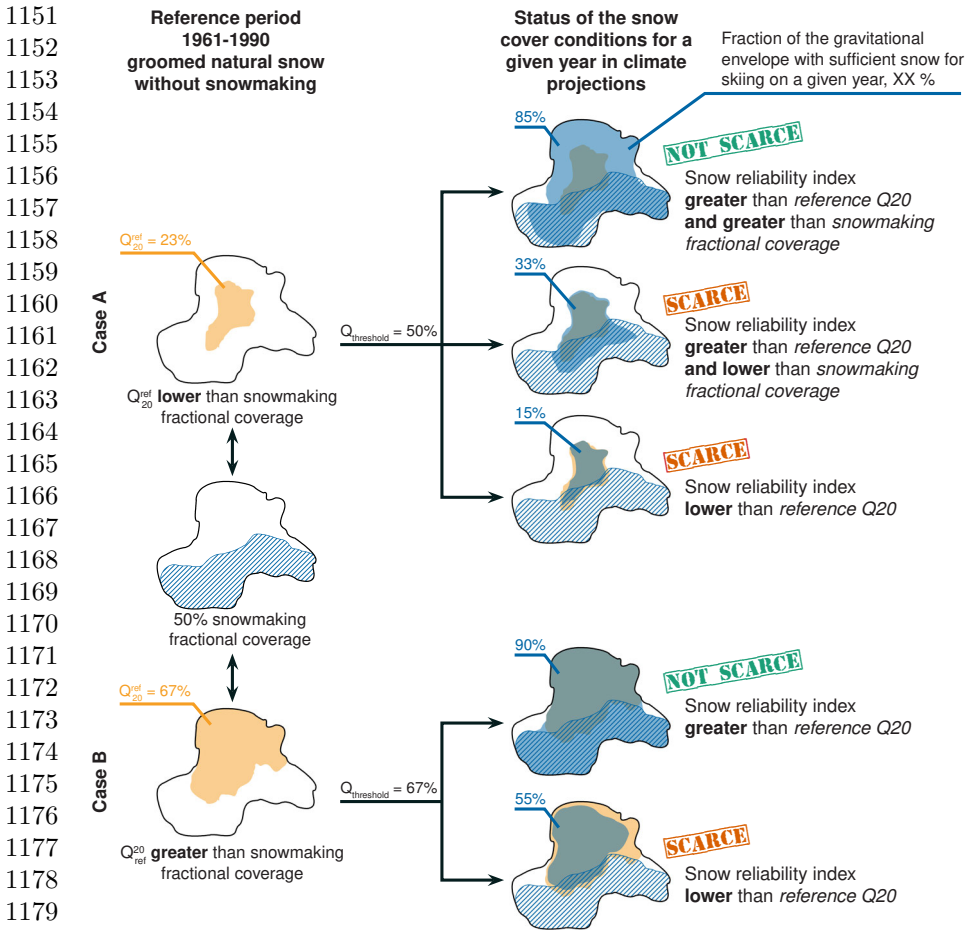


Fig. 2 Methodological approach for the spatial modelling of ski resorts.

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 Obergurgl ski resort in Austria (European Alps), in the NUTS-3 region "Tiroler Oberland".



1181 **Fig. 3 Methodological approach employed to deter-**
 1182 **mine whether snow conditions are snow scarce or not.**

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.
 1187 A snow reliability index value for a given year is considered snow scarce if it falls below a
 1188 threshold value $Q_{threshold}$, equal to the maximum between Q_{20}^{ref} and the snowmaking frac-
 1189 tional coverage. In case A (top), Q_{20}^{ref} (here 23%) is lower than the snowmaking fractional
 1190 coverage (here 50%). If for a given year the snow reliability index value is larger than both,
 1191 it is not considered snow scarce. If it is lower than both, it is considered snow scarce. In
 1192 the intermediate case (here 33%), it is considered snow scarce, because it is lower than the
 1193 snowmaking fractional coverage. In case B (bottom), Q_{20}^{ref} (here 67%) is higher than the
 1194 snowmaking fractional coverage (here 50%). There are then only two possible situations,
 1195 simply comparing the snow reliability index with the Q_{20}^{ref} .

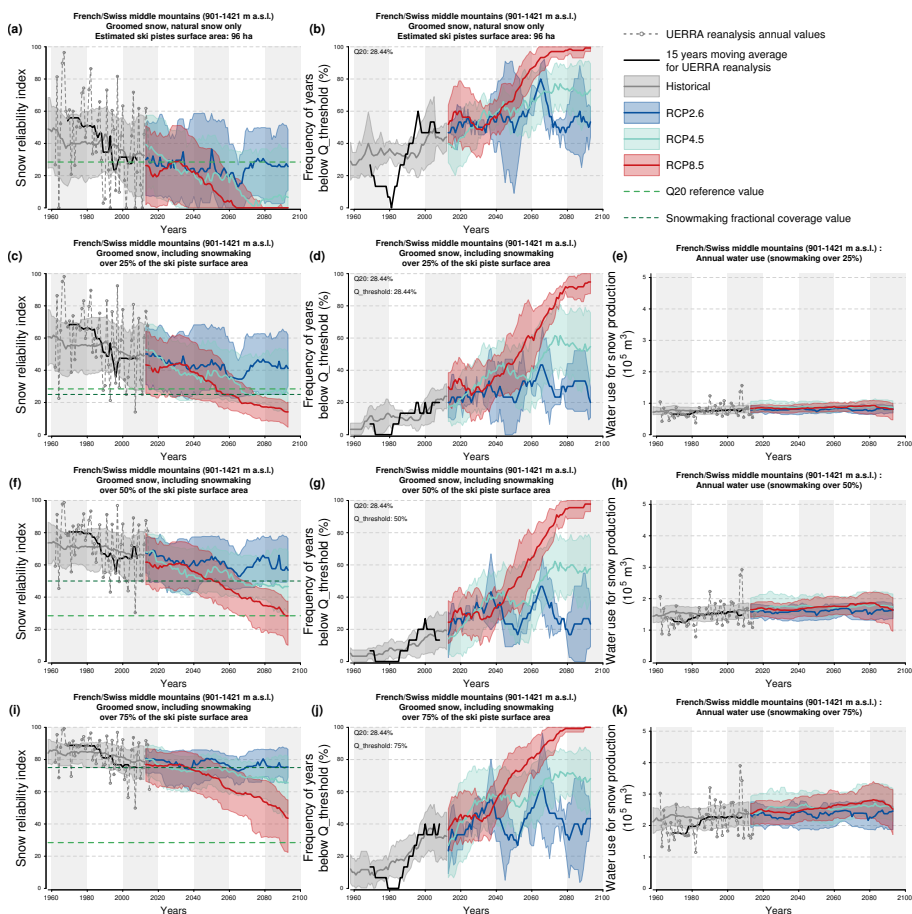


Fig. 4 Simulation results for the Metabief ski resort (French Jura mountain regions).

Simulation results for the Metabief ski resort (French Jura mountain regions. 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 same information 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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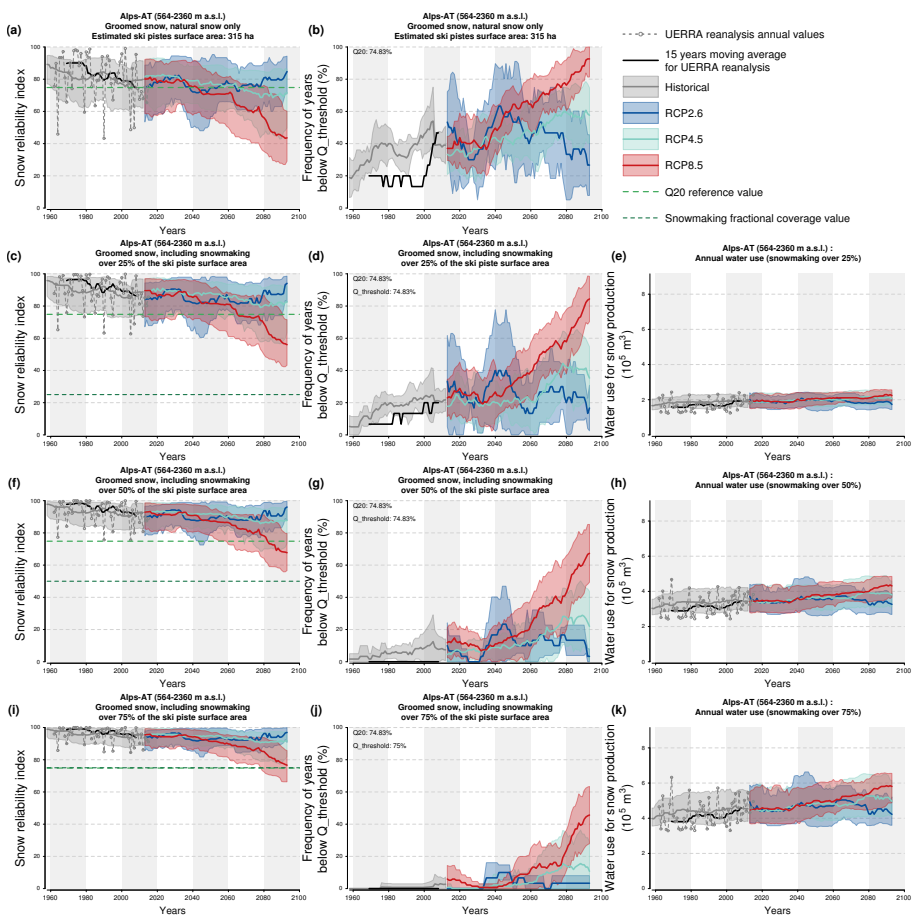


Fig. 5 Simulation results for a given ski resort in the Austrian Alps.

Same as Extended Data Figure 4 but for a ski resort located in the Austrian Alps.

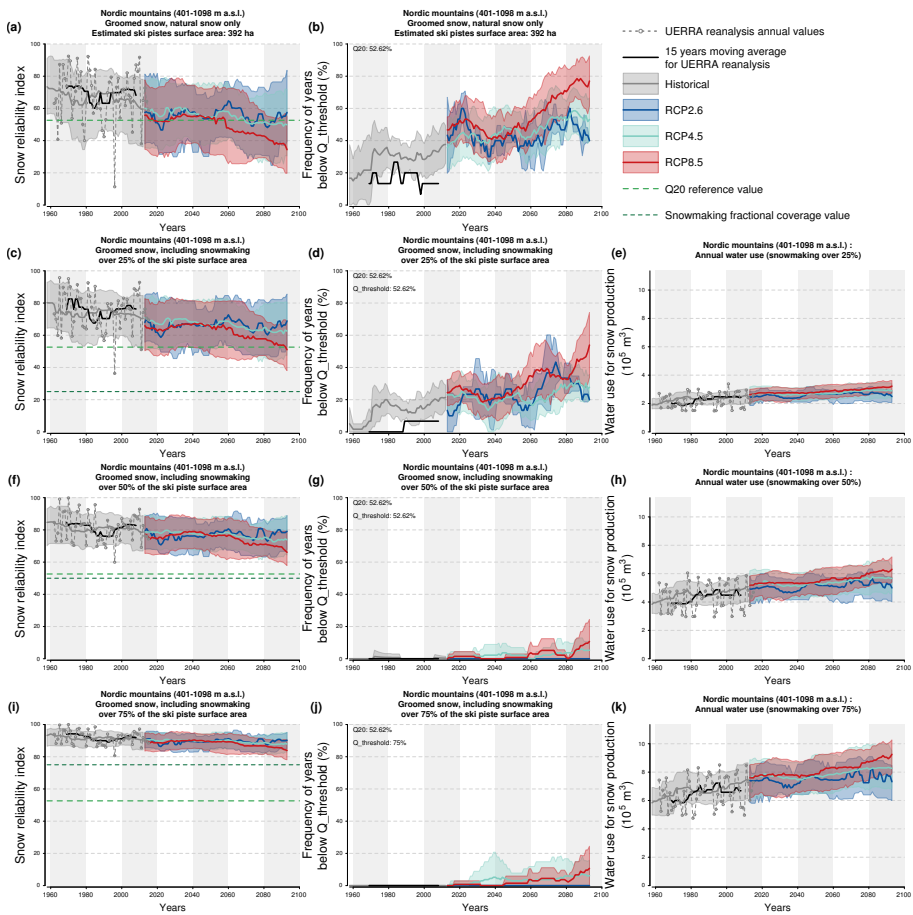
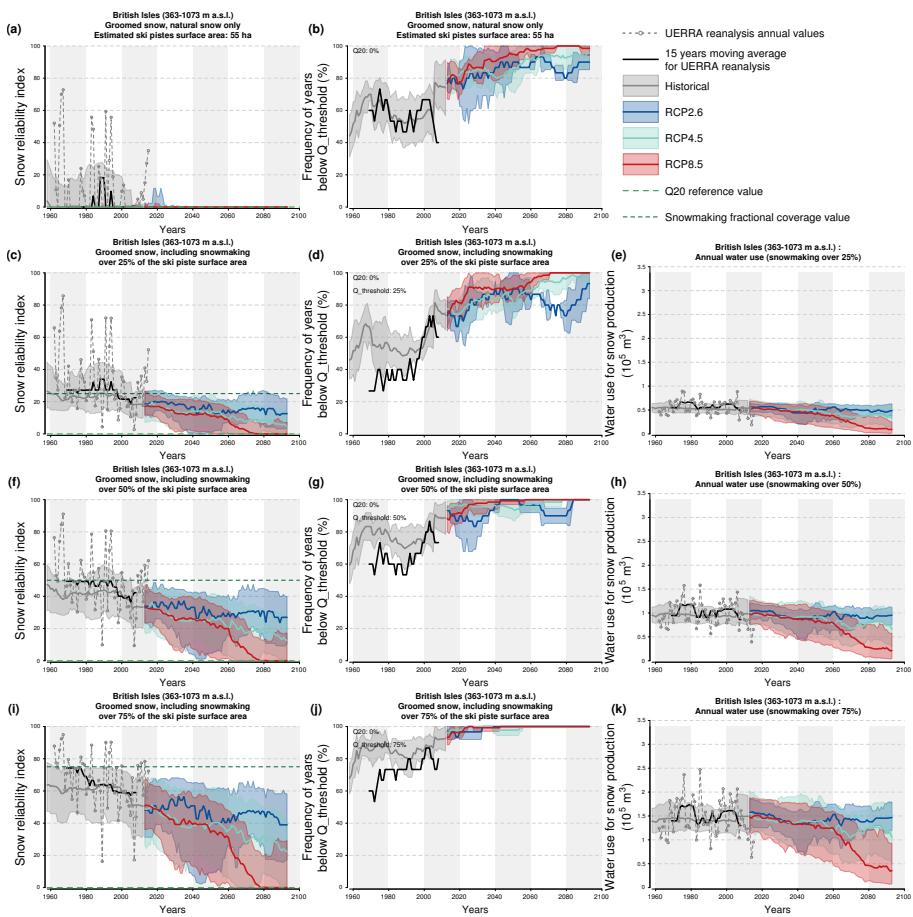


Fig. 6 Simulation results for a given ski resort in Norway.

Same as Extended Data Figure 4 but for a ski resort located in Norway.

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1371 **Fig. 7** Simulation results for a given ski resort in the British Isles.

1372 Same as Extended Data Figure 4 but for a ski resort located in the British Isles.

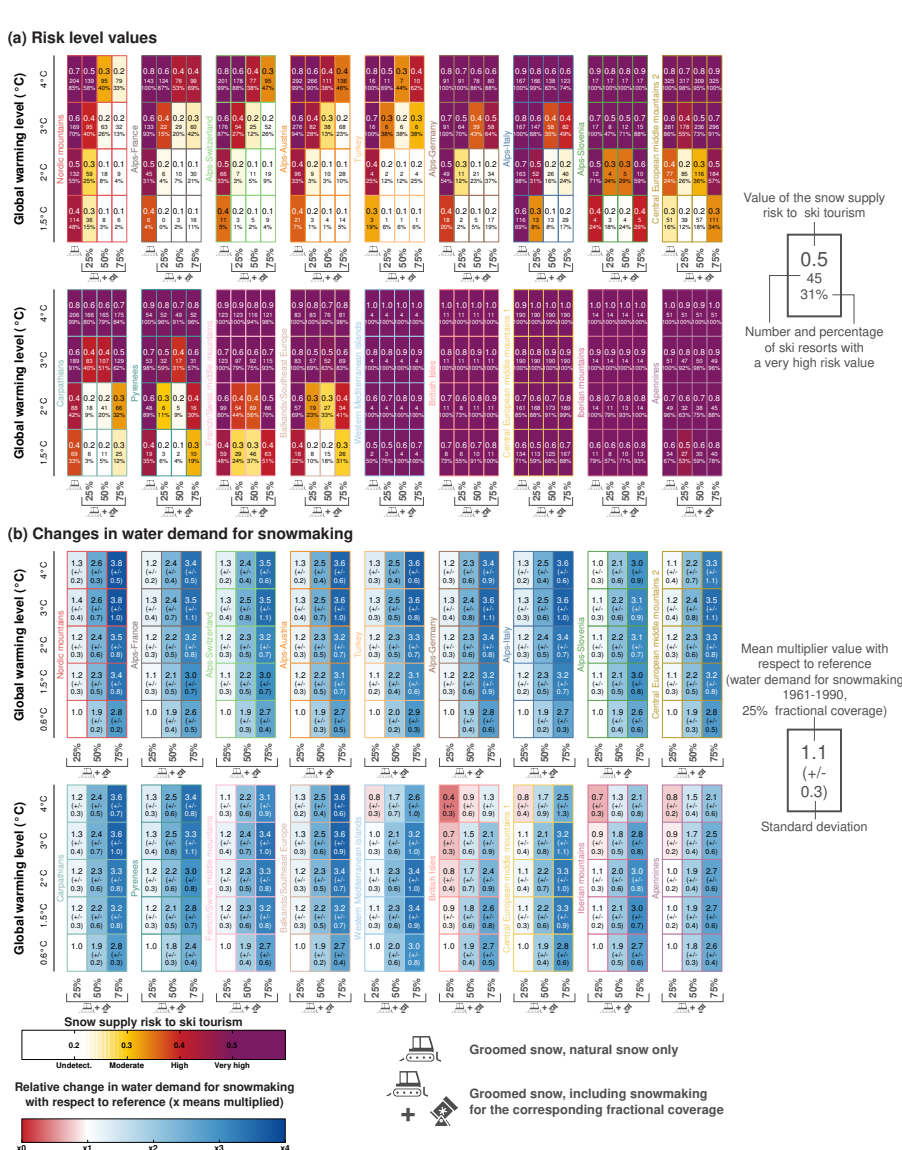


Fig. 8 Numerical values of the snow supply risk levels and proportion of individual ski resorts belonging to the "very high risk" category.

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).

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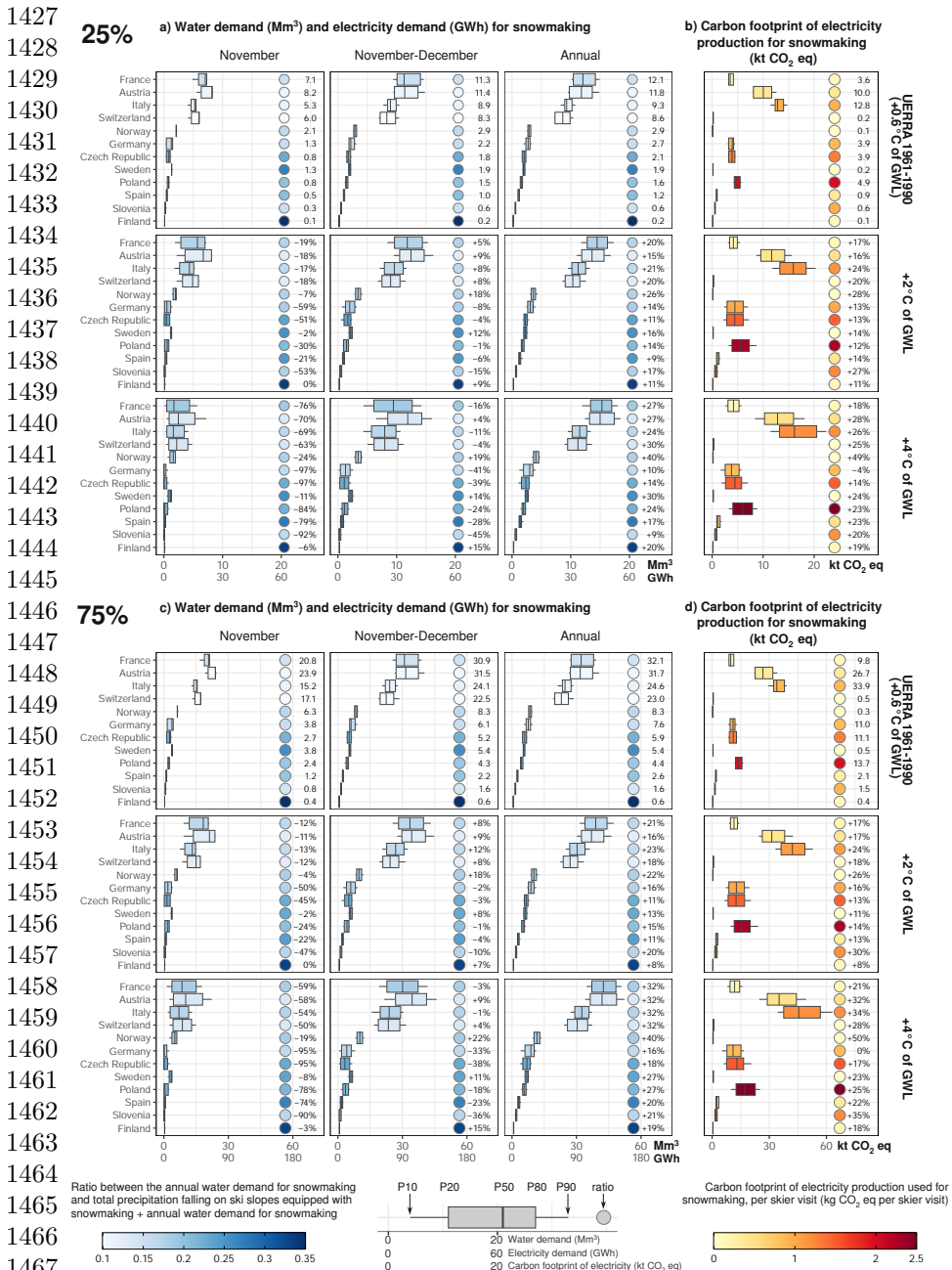


Fig. 9 Water and electricity demand and associated carbon footprint for electricity production, due to snowmaking only, assuming a uniform snowmaking fractional coverage of 25% and 75%.

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