

# A ticket to where? Dwindling snow cover impacts the winter tourism sector as a consequence of climate change

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## ABSTRACT

Climate change affects human activities, including tourism across various sectors and time frames. The winter tourism industry, dependent on low temperatures, faces significant impacts. This paper reviews the implications of climate change on winter tourism, emphasising challenges for activities like skiing and snowboarding, which rely on consistent snowfall and low temperatures. As the climate changes, these once taken-for-granted conditions are no longer as commonplace. Through a comprehensive review supported by up-to-date satellite imagery, this paper presents evidence suggesting that the reliability of winter snow is decreasing, with findings revealing a progressive reduction in snow levels associated with temperature and precipitation changes in some regions. The analysis underscores the need for concerted efforts by stakeholders who must recognize the reality of diminishing snow availability and work towards understanding the specific changes in snow patterns. This should involve multi-risk and multi-instrument assessments, including ongoing satellite data monitoring to track snow cover changes. The practical implications for sports activities and the tourism industry reliant on snow involve addressing challenges by diversifying offerings. This includes developing alternative winter tourism activities less dependent on snow, such as winter hiking, nature walks, or cultural experiences.

## 1. Introduction

The evolving climate is posing new and sometimes subtle challenges to winter resorts, exposing both renowned and local destinations to structural fragilities and inherent vulnerabilities (Frigo et al., 2021), in part because these locations and attractions were planned at a time when snow precipitation was taken as a stable landscape factor (Bilgin et al., 2024). Therefore, the whole economic sector around winter destinations – whose turnover exceeded US\$ 180 billion in Europe in 2022 (Kim et al., 2024) – faces somewhat 'existential' complexities.

The tourism sector's contribution to climate change is significant, totalling ~8% of greenhouse gas emissions, releasing significant amounts of carbon dioxide (CO<sub>2</sub>) into the atmosphere, mainly through

air travel and consuming goods and services (Lenzen et al., 2018). Tourism spans various aspects of the industry, including local transportation, food production and consumption, waste disposal and accumulation, accommodation, and other services (Lenzen et al., 2018; Leal Filho, 2022; Mota et al., 2024).

Climate change accelerates infrastructure wear, impacting roads, airports, and railways. Extreme weather disrupts travel plans, affecting accessibility due to landscape instability (Gariano and Guzzetti, 2016) impacting both domestic and international tourism. Climate change significantly affects the tourism industry, impacting destination appeal, sustainability of practices, and infrastructure resilience. Adapting and minimizing environmental impact is crucial for the sector's long-term viability as climate change progresses (Tanrisever et al., 2024).

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Tourism's impact on climate change varies based on location, type, and practices employed by tourists and the industry (Leal Filho, 2022).

Since the 1990s, the rise of mean temperatures worldwide – with 2023 being the hottest year on record (Hersbach et al., 2023) – has caused the elevation at which snowfall occurs, i.e., the snowline, to steepen over the recent decades (Lorrey et al., 2022), in part due to human influence (Gottlieb and Mankin, 2024). In fact, across crucial tourist locations throughout the Eastern Alps (Kloos et al., 2024), the extent of snow cover and depth has been declining since as early as the 1960s (Olefs et al., 2020) – despite common perception. In addition, the winter season starts later and ends earlier than usual (Bausch and Gartner, 2020), with diminishing snow cover affecting the amount of prospective water attainable for human use (Mankin et al., 2015). Global warming threatens winter tourism by impacting snow availability and quality, altering the winter season's duration, and influencing the costs and benefits of related activities (Damm et al., 2017; Bassetti and Michielin, 2023). Such impact is so meaningful that literature reviews (Steiger et al., 2019, 2021) show that the number of works straddling climate change and winter tourism has steadily increased since 1998, peaking after 2018.

Decreased snowfall and shorter seasons may cause financial instability for winter tourism-dependent businesses, potentially resulting in job losses and economic decline (Bassetti and Michielin, 2023; NSW, 2023; Moreno-Gené et al., 2018). Although some studies maintain that the winter tourism industry would see a ca. 64% drop in demand under global temperatures rise throughout skiing seasons if snowfall reduction is limited to the beginning and end of the seasons, only an 18% decline in demand may occur (Leal Filho, 2022). Recent estimates indicate that, at least for the Eastern Alps, the deteriorating snow conditions expected to happen over the 2020/21–2049/50-time horizon could lead to a 6–28% decline in ski-related visits, depending on the forecasted CO<sub>2</sub> emission – temperature rise scenario, even including snow availability provided by artificial snowmaking. A game-changing 22–64% loss is estimated if only natural snow cover is considered (Damm et al., 2014). Concerning the benchmarks based on former evidence, the latter, up-to-date estimates provide more complex and nuanced scenarios. Although these estimates are not straightforward to compare due to their different space and time patterns and underlying analytic strategies and data structure, the recent forecasts are alarmingly consistent with the above time-honed ones (Arsenault and Houser, 2018; Shulgina et al., 2023), highlighting just how much such projections have gone unattended in policymaking. The studies offer valuable insights into the past behaviour of skiing enthusiasts through cumulative figures. However, it is essential to acknowledge the limitations, including the use of parametric data like natural snowfall, such as snow depth or the length of the snow season, in regression models.

Urgent collaborative efforts are crucial to address challenges in winter tourism caused by changing climatic conditions. Despite its prevalence in ski resort operations, natural snow remains a vital driver of demand, and manufactured snow serves only as a partial substitute (Steiger et al., 2023). This study provides insights into the magnitude of these challenges, especially concerning winter leisure activities and the broader industry. It highlights a research gap by underscoring the inadequacy and environmental drawbacks of relying on snowmaking as a solution. This research critically examines climate change's profound impact on winter tourism, particularly the diminishing reliability of winter snow. Utilizing literature review and satellite imagery, the study reveals a concerning trend with implications beyond the physical realm, extending to socio-economic consequences such as revenue loss and negative effects on the well-being of the industry and the populace.

In the upcoming sections, challenges in winter tourism are introduced, criteria are presented, climate change impacts on the industry are analysed, coping measures are proposed, and key findings with recommended strategies for stakeholders to mitigate climate change impact on winter tourism are summarised, translating a novelty in comparison with existing works, due to the practical approach of this article to the

winter tourism industry.

## 2. Methods

The study adopts a multifaceted approach, utilizing a comprehensive literature review and parameterized snow data from satellite imagery, to investigate the impacts of climate change on winter tourism. The literature review explores the complex relationship between winter tourism and climate change, providing insights into historical context, trends, and documented impacts. The satellite imagery, covering physical Europe and its surroundings, offers a spatial and temporal understanding of winter snow reliability, allowing for the identification of patterns and variations. This data, chosen for its self-consistency and accuracy, serves as crucial evidence illustrating the consequences of climate change on winter tourism. The integration of literature review and visual evidence provides a comprehensive overview of the evolving challenges faced by the winter tourism sector, contributing to a nuanced understanding of the decreasing reliability of winter snow and its implications.

## 3. The impacts on the winter tourism industry

### 3.1. Physical consequences

Climate change is significantly impacting winter tourism in various ways, as mentioned. Leisure activities classically associated with winter tourism, ranging from skiing to snowboarding and from ice skating to snowmobiling, thoroughly rely on snowfall both consistent and widespread and on low temperatures that can ensure snow precipitation over a) a sufficiently long-time window, b) varied landscapes, i.e., not just peaks but valleys too, depending on altitude and exposure, and c) areas within reach of transportation. As the climate changes, these activities and the tourism industry that depends on them are affected by several challenges and uneasy space-time patterns, depending on the diverse landscape physical conditions and the infrastructure and organisation available at specific winter locations.

Rising global temperatures can reduce snowfall in many regions, causing shorter and less reliable winter seasons (Damm et al., 2017; Leal Filho, 2022). They contribute to increasing the occurrence of hazards with potentially adverse effects and ensuing disasters, e.g., avalanches, landslides, floods, and wildfires, that may ultimately jeopardise the environmental contexts and natural scenery at the heart of winter tourism destinations, including the infrastructures serving them, such as energy and transportation (Ombadi et al., 2023; WEF, 2023).

Fig. 1, by one of the Copernicus Sentinel-3 satellites on March 5, 2023 (Copernicus, 2023), shows the reduced snow cover across the Italian and Swiss Alps. According to Copernicus data, the daily Snow Water Equivalent evaluated in the region for the 2022/2023 winter has consistently and significantly been below the previous record of 2021/2022, consistently with evidence of steadily dwindling snow coverage (Carrer et al., 2023). The reduced amount of snow affects the duration and quality of snow-based activities, making it difficult for businesses to attract visitors and operate successfully. As temperatures rise, so does the elevation at which snowfall occurs (snowline). This can further limit the number of ski resorts and winter sports areas with sufficient snow cover, reducing tourist options (Bassetti and Michielin, 2023).

Fig. 2 shows the stark difference between snow cover conditions, spanning the 2002–2022 time range. The period results from the balance between highlighting the steadily diminishing snow availability documented by the records (NOAA, 2023) and the need to employ a time-space consistent dataset offered across several payloads and sensors. A benchmark as back in time as possible, depending on the respective sensors' operational time windows, was used. A diverse set of indexes and data collections was utilized, stemming from both contemporary Landsat (USGS-NASA) and Sentinel (Copernicus)

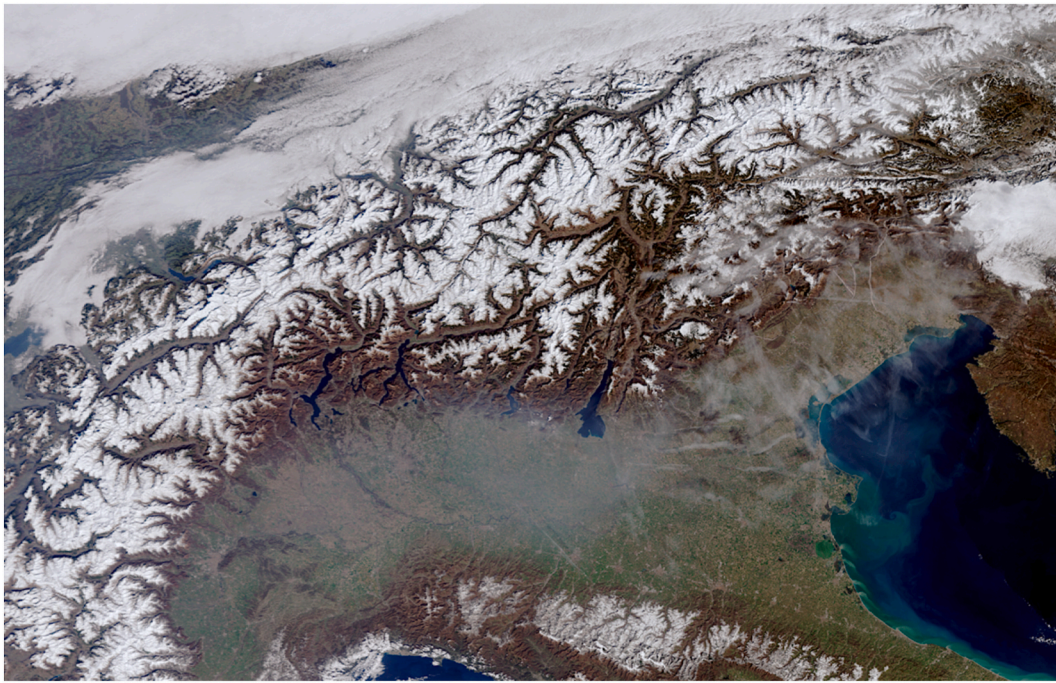


Fig. 1. Reduced snow cover in the Italian and Swiss parts of the Alps in March 2023 (Copernicus, 2023).

missions, along with elaborations from MODIS (NASA) sensors aboard Aqua and Terra missions, supplied by NASA's Earthdata (<https://www.earthdata.nasa.gov/>).

Snow extent, cover, and associated physical indexes across a relatively short period of 20 years tell two remarkably different stories. The former, dated 2002, is reminiscent of how snow cover "should be" in October, i.e., at the early onset of the snow season. Although in parametric form, such data convey the image of snow occurrence in full swing, even in locations less renowned for snow precipitation, such as southern Spain and southern France, while western and eastern Europe were quite dotted, not to mention northern Europe. Conversely, the latter image, dated 2023, is unpleasantly consistent with what can be witnessed right in the weeks at the time of writing across Europe. Overall, the trends related to snow coverage seem to be negative in Europe also in the Arctic (Bokhorst et al., 2016), as they seem to be in other parts of the world, as indicated by Notarnicola (2022) and Young (2023) who have performed similar studies on snow cover. This is consistent with the findings from the 2022 IPCC report (Bednar-Friedl et al., 2022), which predicts future changes in snow cover in Europe, which may reduce their levels even further.

### 3.2. The socio-economic bigger picture

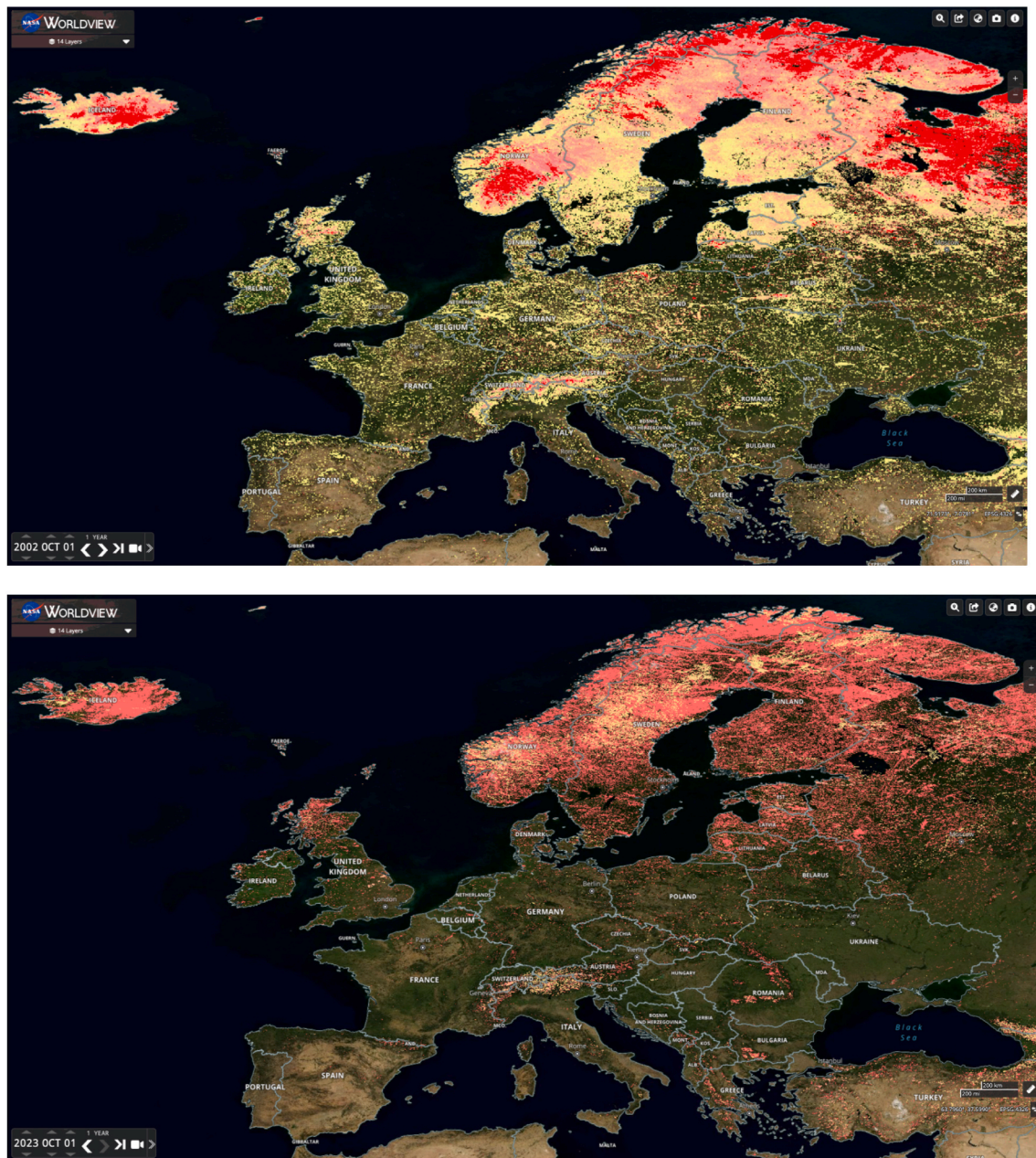
The differences in snow cover conditions described above are conspicuous and come with numerous consequences. Among these, there is a significant economic impact since winter tourism is a pivotal source of revenue for many resorts, mountain communities, and, ultimately, countries; for instance, it contributes to the ca. 10% of Gross Domestic Product (GDP), either directly or indirectly, that tourism cumulatively provides across the European Union (EU) (Matei et al., 2023). Global warming substantially impacts the winter tourism sector, leading to non-ideal snow conditions, potentially reducing the duration of the winter season and raising the likelihood of suboptimal conditions occurring during peak demand periods (Steiger and Scott, 2020). With winter tourism being an essential piece of ski markets for specific countries income, e.g., European alpine destinations (Witting et al., 2021), such potential impacts deserve increasing attention (Steiger et al., 2023) and, possibly, novel planning strategies, in part including

some predictive repurposing. Therefore, it is more important to underline the linkages threatening this sector at the global level, including diminished snow reliability, decreasing operating days (supply-side), and rising operational expenses (Witting et al., 2021), as much as the reaction of tourists willing to changing destination or activity. For example, snowmobiling in the northeastern United States may undergo a 65% decrease or even cease altogether (Xiao et al., 2020), under +3 °C, i.e., the mean of SSP2-4.5 IPCC AR6 scenario (Lee et al., 2021). Notably, two decades ago, prescient forecasts estimated that skiing visits in Japan would decline by ~30% (Fukushima et al., 2002) and that +2 °C warming (baseline: 1971–2000) would cause a loss of 10.1 million ski-tourism-related overnight stays worth 557 million EUR of turnover in Europe (Damm et al., 2017).

Indeed, the ski industry has long implemented essential artificial snowmaking infrastructure in an effort to maintain ski conditions during snow-poor winters (Steiger and Abegg, 2018). For many, winter is associated with skiing, one of the most valued winter sports and recreational activities. In colder regions, skiing is pivotal in driving local economies (Moreno-Gené et al., 2018), even as a local means of transportation. However, evidence indicates that this treasured winter pastime is being challenged by climate change. Alterations in weather patterns and the warming climate can undermine the predictability of snowfall, potentially threatening ski resorts and the associated tourism market they rely on for sustenance (Climate Adaptation Platform, 2022). While snowmaking is viewed as a viable climate adaptation strategy, it may not be suitable or economically sustainable in the long term, due to persistent changes in weather patterns caused by climate change. Additionally, its considerable carbon and water footprints are likely incompatible with the sensitivities of both winter resorts' inhabitants and visitors in the medium term (Scott et al., 2022).

Despite the recent snowfall in Europe, tempering any false optimism is essential because the region has experienced one of its warmest winters on record, in agreement with global mean trends (NOAA, 2023). The limited snowfall has resulted in grass covering the central mountains of the continent, raising concerns for the winter sports organisers (Bassetti and Michielin, 2023). This situation has amplified discussions about climate change's impact on skiing's future. The ever-changing Alpine Ski World Cup calendar reflected this snow-scarce winter.





**Fig. 2.** Variations of snow cover from 2002 to 2023. It shows the net difference across snow index, snow cover, and snow extent throughout Europe and adjacent areas in the 2002 (**top**) - 2023 (**bottom**) period. Darker tones indicate heavier snow cover. Data content and imagery are from NASA Worldview (<https://worldview.earthdata.nasa.gov>). Readers can access the full legend explanation and breakdown of layers' content in Supplementary Material SM1.

Events in Zermatt and Cervinia were cancelled in October 2022 due to the lack of snow, and the Zürs stage in November 2022 suffered the same fate. Snowmaking equipment rescued events like the surreal January 2023 slalom in Garmisch, where artificial snow contrasted with green pastures. Other events were also rescheduled, illustrating the dramatic implications of snow levels imposed by a changing climate in winter professional sporting events (Bassetti and Michielin, 2023). The outlook for winter tourism is challenging, necessitating a fundamental shift in the industry's approach that traditionally centred around a seemingly permanent 'snow identity'. To adapt to the changing circumstances, winter tourism must transition towards offering meaningful experiences that foster a deeper connection between snow-based tourism regions and the broader tourism sector through differentiation. The inherent importance of snow, whether natural or artificially produced and the diverse impacts of marginal snow conditions across different seasons

pose numerous implications for the management of winter tourism. These implications are further accentuated by the ongoing shifts in climate patterns, requiring a reevaluation of strategies to navigate the evolving landscape of the winter tourism industry.

#### 4. Coping with the problem

As described above, the future of winter tourism is critical to specific regions and markets globally. Climate change worldwide has implications in this respect, which need to become a multi-national concern precisely because the change in tourists' behaviour may become permanent, and tourists will seek other activities and markets. Thus, to evaluate the influence of climate change on the winter tourism economy, it is essential to assess current and future trends related to temperature increases. Snowmaking, for instance, has long been a form of

'artificial adaptation', but besides being intrinsically impactful on the environment, it elicits mixed reactions depending on the stakeholder (Moser and Baulcomb, 2020), and consensus cannot be taken for granted.

Contradictory as it may seem, tourism as a whole could be seen as a 'win-win' endeavour, where humans commercially exploit the results of a pre-existing commodity that will be there anyway - until it is no longer. After all, winter tourism exists as long as snow is sufficiently reachable, is widespread, and highlights attractive locations. While not precisely a 'nature-based solution', it indeed relies on, or instead, it used to rely on a naturally occurring element of communal, shared, and profitable benefit.

Yet multiple, stark evidence of consistently dwindling snow extents and exploitation potential of winter resorts suggests that, because of the changing climate, stakeholders in the tourism industry need to focus on sustainable practices and the diversification of the tourism market offer to both reduce its footprint and adapt to a changing climate - regardless of anticipated scenarios. Three approaches may exemplify potential solutions to the issue that was probed. First and foremost, to slow the pace of rising temperatures due to climate change, curbing CO<sub>2</sub> emissions and stock is an inescapable target. Achieving this complex global long-term goal lacks a brief, economical, or readily available solution. Nevertheless, as an overarching objective, any improvement made will also benefit the challenges faced by winter tourism.

Furthermore, given the anticipated complex climate scenarios and the precipitation patterns, winter tourist infrastructure is expected to undergo a significant overhaul to be less snow-dependent. While this will require a sort of collective adjustment upfront from the perceived image of snowy, white environments - so deeply ingrained in the human experience - to one encompassing more rocky and grassy terrain, such transformation is somehow already undergoing, as economic options that entirely depend on snow cover started to dwindle - a long time ago.

Last but not least, the needed diversification in winter tourism already includes activities quite away from 'classic', high-intensity sports, i.e., skiing, snowboarding, and bobbing. Such activities range from indoor, i.e., spa, yoga, wellness, to outdoor, i.e., trekking, hiking, cross-country walking, ones, which also have the significant advantage of being available irrespective of the season, i.e., of the snow cover. Moreover, although in varied fashions, i) the environmental footprint of 'low-intensity' outdoor activities in winter contexts can range from minimal (i.e., hiking) to negligible (i.e., walking), and ii) active time spent in green, natural environments delivers overall benefits to human health (White et al., 2019). Such activities may ensure tourists' on-site presence, unlike those associated with 'classic' winter sports, with potential, continuing benefit to the tourist sector.

## 5. Conclusions

Winter tourism, reliant on snow availability, faces a substantial threat from climate change. The analysis utilized a dual approach to investigate this challenge. Through a comprehensive literature review, publications to delve into the historical context and trends on how climate change profoundly impacts winter tourism and the ensuing consequences, including those on the socio-economic fabric of societies that will not dissipate as quickly as snow, were examined. Additionally, up-to-date satellite imagery that provided parametric data to assess changes in snow cover over time, was analysed. This integration provided a spatial and temporal understanding of winter snow reliability. Satellite data selected for self-consistency, timeliness, and accuracy offered a tangible representation of climate change effects on winter tourism. The resulting evidence presents a nuanced insight into decreasing snow reliability and its implications for the winter industry.

It is emphasised that the reliability of winter snow is diminishing, posing a threat to winter tourism. The risk of climate change has both physical and socio-economic ramifications. The physical aspect affects the area and the period of snow covers available for leisure activities.

Loss of revenue and impacts on social well-being affect both the industry and the populace. Thus, stakeholders need concerted efforts to develop mitigation and transformative adaptation strategies (Leal Filho et al., 2023) to address these challenges. Innovative approaches should explore alternative activities and nature-based solutions for reducing the impacts.

The analysis highlights threats and challenges to winter tourism stemming from the changing climate while examining potential solutions. The necessity to scrutinize these challenges is deemed essential due to their implications for winter leisure activities and the industry. While this study offers an initial overview of the challenges faced by winter tourism due to climate change, future research should delve into decoding and dissecting these challenges, evaluating potential solutions, and exploring alternatives that are both more sustainable and resilient over the coming decades. Given that climate change impacts are unlikely to diminish in the foreseeable future, a continued examination of these issues is imperative. For instance, from a practical perspective, the reliance on snowmaking as a potential solution is both insufficient and environmentally detrimental. On the strategic front, although skiing and related activities serve as significant economic drivers and popular sports, promoting alternative, snow-independent healthy sports activities deserves recognition and encouragement.

Limitations of this study include the reliance on existing literature and satellite imagery, which may not capture all nuances of the impacts of climate change on winter tourism. The scope of the study is also limited to certain regions and may not fully represent the global diversity of winter tourism contexts. Additionally, the analysis primarily focuses on the physical and socio-economic aspects of climate change impacts on winter tourism, potentially overlooking other relevant factors such as cultural implications or policy interventions. Future research could address these limitations by conducting more extensive empirical studies covering a wider geographical scope and incorporating a broader range of factors influencing winter tourism resilience and adaptation strategies. Further studies could also focus on providing detailed temperature change analyses during the studied period and comparing them with a specific period in the future, enhancing the understanding of the relationship between temperature variations and snow cover changes, and contributing to a more accurate interpretation of the future outlook for snow cover.

## CRedit authorship contribution statement

**Walter Leal Filho:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Maria Alzira Pimenta Dinis:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Gustavo J. Nagy:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Umberto Fracassi:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Yusuf A. Aina:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation.

## Declaration of competing interest

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

## Data availability

Data available publicly on NASA's website.



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## Appendix A. Supplementary data

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