

Review

Climate Change and Geotourism: Impacts, Challenges, and Opportunities

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Abstract: Climate change and rising sea levels present significant challenges for geotourism destinations and activities. Accelerated changes in geomorphological processes threaten or diminish both the physical existence and aesthetic qualities of geoheritage assets, and hence the visitor experience, as well as presenting increased or new risks from natural hazards. This is particularly a concern in mountain and coastal areas, and also where greater extremes of temperature and precipitation affect visitor comfort. A literature review was conducted to assess the extent to which the consequences of climate change have been recognised in geotourism research. With the exception of glacier-based geotourism, few studies have considered the impacts of climate change and reported the planning or development of adaptation measures. However, the didactic potential of geotourism in raising awareness of climate change has been commonly recognised. A review of the wider tourism literature identified additional destination-supply and visitor-demand issues that will affect the sustainability of geotourism in the face of climate change. These include changes in visitor motivations, travel behaviour, perceptions of destination image, and reactions to local, national, and international mitigation and adaptation responses, as well as geoethical considerations around carbon footprints and sustainable modes of travel. Situating geotourism within a broader body of multidisciplinary tourism research should help inform adaptation strategies in conjunction with measures to adapt to the physical impacts of climate change on geotourism sites.

Keywords: geoheritage; geoparks; risk assessment; adaptation; sustainability; geoethics; research gaps



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1. Introduction

Climate change is one of the major issues facing society and presents challenges and constraints both for geoconservation [1–7] and for geotourism [8]. It is identified as a ‘main focus area’ for UNESCO Global Geoparks (UGGps), which have an important role in raising public awareness of climate change and promoting mitigation and adaptation, adopting nature-based solutions, reducing natural disaster-related risks, encouraging behavioural change, and establishing good environmental governance [9–11]. However, in contrast to the wider tourism literature [12], there has been limited evaluation and critical analysis of the impacts of climate change on geotourism, which will compound existing pressures on sites and the visitor experience. Moreover, there is little evidence-based guidance available in official documents or strategies for geopark managers and managers of geotourism attractions and destinations in the form of frameworks and methods for dealing with the challenges of planning for, and adapting to, the impacts of climate change [5].

Geotourism has developed globally over the last few decades, becoming an established component of tourism with a particularly strong presence in Europe and Asia and expanding elsewhere [13–16]. As reflected in various definitions, the fundamental basis of geotourism involves a focus on geological and geomorphological features and sites as tourist attractions both in natural/semi-natural landscapes and in the built environment. Geotourism promotes awareness, understanding, and conservation of geodiversity and geoheritage through appropriate interpretation and sustainable activities [17–19]. The

ecological, cultural, and aesthetic values of geodiversity and geoheritage can also play an important part in enhancing geotourism attractions [18,20–22]. In a broad sense, as adopted in this study, geotourism may be viewed as encompassing both a specific type of geo-based tourism and an approach to tourism based on the geological and geomorphological features and characteristics of a landscape [18]. Geotourists may therefore span a broad spectrum of categories from ‘dedicated’ and ‘educational’ to ‘casual’ and ‘recreational’ geotourists, with a corresponding range of interests and motivations [17,20,23]. Because of their intrinsic geoheritage values, geotourism attractions frequently occur in protected and conserved areas (e.g., national and state parks, nature reserves, national monuments, geoparks, and World Heritage Sites (WHSS)), but they are not limited to these areas.

While not exclusive to geoparks, geotourism has been significantly encouraged and facilitated through the growth and spread of national and UNESCO Global Geoparks (UG-Gps) [11,24–26]. Through geoparks, geotourism has been widely proposed as a pathway to local and regional employment creation and sustainable local and regional socio-economic development in particular territories, helping deliver the UN Sustainable Development Goals (SDGs), particularly SDGs 1, 4, 5, 8, 11, 12, 13, and 17 [11,24,27], while at the same time promoting geoheritage values and geoconservation. The expanding interest in geotourism is reflected in a commensurate growth in the number of publications in the scientific literature [15,18,28–30]. There has been a strong focus on regional geosite inventories, including criteria for geotouristic value assessment [21,31–33]. Inventories have enabled identification of sites with geotourism potential and have often been accompanied by calls for geopark designation, e.g., [34–40]. However, there has generally been a lack of research on actual and potential constraints and outcomes, visitor motivations and preferences, the challenges faced by destination managers, the impacts of geotourism on the natural environment, and economic and social issues [15,41,42]. All of these gaps are directly relevant to the topic of climate change and geotourism.

According to Hall and Saarinen ([43], p. 77), “the broader effects of geotourism-related travel throughout the tourism system have been ignored, along with the potential role of climate change in affecting geosites and attractions”. Both in relation to geotourism and the heritage tourism sector more generally, climate change impacts (including those of sea-level rise) will affect not only attractions and visitor experiences but also access to, infrastructure at, and comfort at destinations and visitor travel patterns, motivations, and behaviours [44]. Moreover, not only is tourism affected by climate change but it also contributes to climate change [45]. Therefore, there are wider geoethical concerns and tensions to be considered; for example, there is the tension between encouraging geotourism as a source of sustainable economic development in line with the SDGs, particularly as a vital source of income in many countries, and reducing greenhouse gas emissions from national and international travel and tourism activities and infrastructure [46]. This paper examines the extent to which the above issues have been addressed in geotourism studies. First, it reviews the academic literature on geotourism to assess the degree to which threats and impacts from climate change have been identified and factored into adaptation strategies and planning. Second, from a selective review of the wider tourism literature, it explores issues and challenges that geotourism operators and geopark managers will need to consider, together with some lessons that arise and areas for future research. In doing so, it seeks to encourage more critical analysis and discourse in geotourism studies contextualised within the broader tourism research frame.

2. Methods

The aim was to conduct an initial scoping review, rather than a full bibliometric analysis, of the academic literature on climate change and geotourism. Three main questions were addressed: (1) What are the impacts of climate change on geotourism sites and activities? (2) To what extent are they acknowledged in the scientific literature? (3) What are the principal themes emerging from studies on climate change and geotourism and do they address the risks and challenges? A systematic literature search was conducted

using the Clarivate™ Web of Science Core Collection and Elsevier Scopus. A broadly defined query string, 'Climate change' AND 'Geotourism', was employed to cover the scope of the topic, and a four-phase work flow was followed: identification, screening, selection of eligible articles, and synthesis of the findings; see [47]. The literature search was conducted on 13 February 2023 for publications within title, abstract, and keyword categories and was limited to journal articles, book chapters, and official publications in English and French; review articles were included. No date limit was applied in order to capture the full timeframe of geotourism studies. The search produced 29 publications from Web of Science and 37 from Scopus. After elimination of duplicates, 41 publications remained. Following screening by reading abstracts and, in some cases, the full papers, 19 publications were considered relevant. Publications were excluded where there was no clear connection between climate change and geotourism. Publications on winter sports, mountaineering (unless related to more widely used visitor trails) and those relating to sites with records of Earth climate history but not specifically to education about climate change through geotourism were also omitted. Similarly, those on the effects of climate change on geomorphological processes, hazards (e.g., rockfalls and glacier lake outburst floods), and physical damage to geoheritage were excluded unless they specifically referred to geotourism although some are cited in the following text, where they illustrate potential impacts on geotourism. Publications on broader landscape and nature-based tourism, including studies on polar tourism, were omitted unless related to specific geofeatures. Also omitted were publications on local perceptions of climate change unless they were related specifically to geotourism.

A second literature search was conducted on 20 February 2023, on the Web of Science Core Collection only, using the following query string: 'Climate change' AND 'Tourism'. The search included publications within title, abstract, and keyword categories and was limited to journal articles, book chapters, and official publications in English and French with no date limit, including review papers. The purpose was twofold: (i) to identify additional publications that fall under the category of geotourism activities but are not explicitly labelled as such in the publications; and (ii) to identify more general climate change issues and challenges relevant to the geotourism sector. This search produced 4296 articles. These were screened by using a manual search of keywords and abstracts for relevance in relation to activities that could be interpreted as geotourism but did not include the word 'geotourism' (e.g., glacier tourism). Similar exclusions were applied as for the first search. Also, articles on rapidly shrinking glaciers were omitted unless they were linked to effects on tourism and/or climate change education. This search produced a further 61 relevant publications. Subsequently, this list was supplemented from references in, and citations of, the 21 publications in the first search and the 61 publications on geotourism-related activities in the second search, and also by the author's own knowledge of publications up to end of June 2023. This produced a final total of 136 articles that were examined in the study.

The publications from the second search were also screened by using a manual search of keywords and abstracts, and judgements were made of their relevance in relation to broader issues that might present challenges or lessons for geotourism (e.g., destination risk assessment, supply and demand issues, visitor motivation and perceptions, climate comfort, destination image issues and adaptation strategies). This produced 301 publications. These were not examined systematically for the present paper, but this body of literature was used to inform the discussion in Section 4, with a focus on more recent publications.

There are several limitations to the methodology employed. First, not all studies that apply to the scope of geotourism include that word in their titles, abstracts, or keywords. This was often the case in relation to glacier and mountain tourism studies. This highlights that under a broad definition of geotourism, many relevant publications may be overlooked by a narrow search. As far as possible, this was addressed through the second search, from the reference lists in known publications, and from the author's own knowledge. Second, the searches were limited to journal articles, book chapters, and other official

publications published in English and French. Project reports, theses, and working papers were not examined. Third, the wider tourism literature is vast, and it is likely that some publications will have been missed in the second search. Fourth, given the strong tourist appeal of glaciers and the widespread evidence of their retreat, there is a relatively large number of publications in this area. This may have led to some bias in literature citations. Fifth, publications that included brief acknowledgements of climate change impacts on geotourism, as well as substantive research papers, were included since the purpose was a qualitative review to identify the main issues and the extent to which they have been acknowledged or need to be addressed; a full bibliometric analysis was outside the scope of this paper.

3. Results

From the 136 articles, four principal themes and several sub-themes were identified in terms of the foci of research on climate change and geotourism (Table 1); publications were assigned to particular themes and sub-themes based on the author's judgement of the content. Publications were counted more than once where they were found to span several categories. The greatest number of publications, 103, addressed impacts on geotourism sites, activities, and visitors; 34 addressed didactic potential through opportunities for education about climate change through geotourism, including understanding climate change in the geological record and from the retreat of glaciers; 31 addressed adaptation or the need for adaptation; and 23 addressed impacts on visitor motivations and perceptions. Note that not all publications are cited in the following text.

Table 1. Summary of the principal research themes/sub-themes and the numbers of publications assigned to each.

Research Theme	Sub-Theme	Numbers of Publications ¹
1. Impacts on geotourism, including sites, activities and visitors	Glacier and mountain tourism including: loss of features, aesthetic value and access; increased risk of natural hazards from glacier and permafrost melting (including impacts on infrastructure and trails); decreased visitor numbers at visitor centres	87
	Coastal sites and features at risk from sea-level rise; loss or reduction of access; increased risk of hazards from sea-level rise and adjacent slope failures	3
	Palaeontological sites at risk from adverse climate conditions and climate change	1
	Vulnerability of karst systems to climate change	3
	Geoheritage sites and features with related cultural interests (e.g. rock art) in semi-arid/arid areas at risk from adverse climate conditions and climate change	6
	Impact on visitor comfort from extreme climate conditions and exacerbation of these conditions	3
2. Didactic potential through opportunities for education about climate change through geotourism	Based on understanding climate change in the geological record, including Quaternary climate change and dynamic landscape processes and natural hazards	18
	Based on evidence of glacier retreat as a visible indicator of climate change	16
3. Need for adaptation and diversification, including strategies	Glacial and mountain environments	28
	Non-glacial environments	3
4. Impacts on visitor motivations (including last chance tourism), perceptions, values and destination image		23

Note: ¹ Some articles span multiple themes and have been counted more than once.

3.1. Climate Change Impacts on Geotourism

Climate change impacts emerged as the most commonly studied theme. Gordon et al. [5] reviewed both direct and indirect potential physical impacts on geoheritage, including features and sites with value for geotourism. In brief, direct impacts on geoheritage will principally arise through changes in geomorphological processes resulting from the progressive melting of glaciers and permafrost, sea-level rise, and increased frequency and severity of extreme weather events including flash floods, droughts, storm surges at the coast, hurricanes, and tropical storms. The degradation or loss of rock outcrops and landforms will result from accelerated weathering, erosion, and landslides while increased accumulation of talus at the bases of rock faces or soft-sediment exposures will conceal the interest. Some natural features such as glaciers and sea stacks will be lost completely, while many coastal sites will become inaccessible. Increased vegetation cover under warmer and/or wetter climates may impede the access to and visibility of features.

Indirect impacts from human responses to increased natural hazards include interventions in the form of hard coast protection and river management to mitigate erosion and flooding and, in some places, may represent a greater threat to geoheritage [1]. The installation or extension of hard coastal defences conceals cliff and foreshore exposures, reducing sediment supply to beaches, sand dunes, and saltmarshes, and leads to the loss of these features, coastal steepening, enhanced coastal erosion down-drift, and the disruption of geomorphological processes. Changes in land use, such as afforestation to enhance carbon capture and offsetting or to mitigate flooding, may affect visibility and access, as will changes in sediment and/or water discharges into rivers and cave systems. The consequences for geotourism are the deterioration or loss of geotourism assets and their cultural values; loss or reduction of access to geoheritage features or their visibility; and loss of Earth-history knowledge where rock and sediment exposures or landforms are damaged or destroyed or climate history records are lost from melting glaciers.

Glaciers have a strong tourism appeal for their scenic and aesthetic values (Figure 1a). Their retreat is highly visible in the landscape and has become emblematic of the effects of climate change [48–51]. The impacts on glacier and mountain tourism have attracted much greater focus in the literature than other topics, represented in 101 individual publications identified in the present study (including, with overlaps, 87 under the impacts theme, 16 under the didactic theme, and 28 under the adaptation theme). For a broad comparison, Welling et al. [52] identified 53 publications up to December 2014; Salim et al. [49] found 61 peer-reviewed papers between 1984 and 2020. Note, however, that there are differences in methodology and search questions in the different studies. From the papers accessed, this topic drew increasing attention in the first decade of the 21st century, notably in relation to the Canadian Rockies [53], Glacier National Park in the USA [54–56], the Alps in Europe [57,58], and Yulong Mountain in China [59]. Since then, and particularly since 2015, an increasing number of papers have been published on the topic of glacier tourism [49,60] and over 100 glacier tourism destinations have been identified [61,62], many in national parks and WHSs [63,64]. The principal areas of study have been in New Zealand [65–69], Norway [70–72], China [60,73–78], the Alps [57,58,79–83], Iceland [79,84–87], the Rockies [53,54,56,88], the Andes [89,90], and Nepal [91]. Impacts of glacier retreat on Antarctic tourism appear not to have been considered, although glacier recession is widespread in the more frequently visited areas of the Antarctic Peninsula and South Georgia and clearly demonstrates the effects of recent climate change [92,93].

Glacier retreat and shrinkage are occurring globally [94–96] (Figure 1b), often accompanied by increased covers of rock debris, leading many authors to comment on the loss or depreciation of visitor attractions and reduced scenic, aesthetic, and cultural values of landscapes [60,75,78,97–102]. Some smaller glaciers have disappeared completely, for example in Iceland (Okjökull), the Pyrenees (Gourgs Blancs glacier), and the Andes (Chacaltaya glacier) and in Glacier National Park in the USA. This is likely to become a more frequent occurrence in most of the world's mountain ranges in the next few decades, resulting in a significant loss of geoheritage [89,94,103,104] and hence geotourism attractions. For

example, the retreat of Portage Glacier and its loss of visibility has contributed to a drop in visitor numbers at Begich, Boggs Visitor Center in Alaska [105]. Vulnerable glaciers have been equated with ‘endangered species’ [106,107], leading to their becoming ‘last chance tourism’ (LCT) attractions [49,72,86,88,108,109]. On the other hand, new attractions, such as developments or extensions of glacier lakes with icebergs, have appeared, as in Iceland, New Zealand, and the Alps [67,110–112], and the evolution of proglacial areas may provide new landforms and geomorphological processes of interest to visitors and have educational value [113,114].

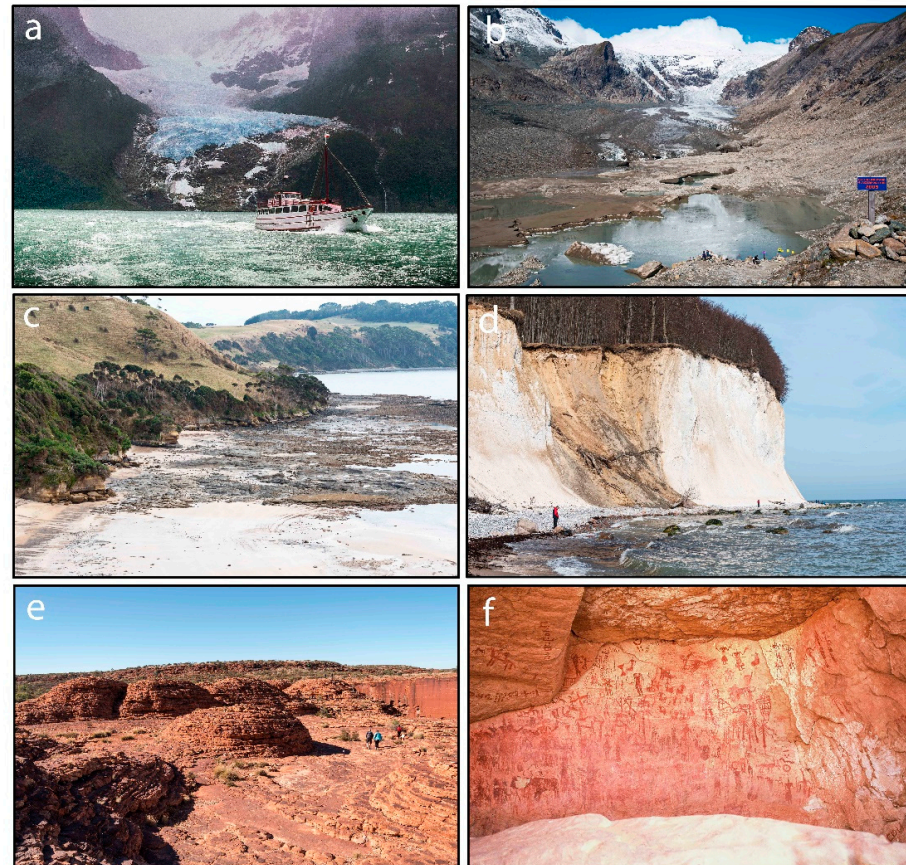


Figure 1. Examples of geotourism sites vulnerable to climate change and its effects. (a) Balmaceda Glacier in Bernardo O’Higgins National Park, Chile, is a popular day trip reached via boat tour from Puerto Natales. Globally, accelerated glacier retreat is a threat to geotourism. (b) Interpretative signs along the footpath to Pasterze Glacier, Hohe Tauern National Park, Austria, indicate former positions of the icefront and highlight the extent of glacier retreat. (c) Exposure of the Wynyard Tillite Formation on an intertidal shore platform at Wynyard on the north coast of Tasmania. The tillite was deposited by a tidewater glacier during Permo-Carboniferous glaciation when Australia was part of Gondwana. Unconformably overlying the tillite in the adjacent cliff section are fossiliferous sandstones and basalt dating from the Miocene. The site forms part of a geotrail, ‘Created from Chaos’, developed and promoted by local communities, but is vulnerable to sea-level rise. (d) Chalk cliffs in Jasmund National Park on the island of Rügen, Germany, have been a visitor attraction popularised in art since the 19th century but are susceptible to rockfalls and landslides. (e) Kings Canyon Rim Walk, Watarrka National Park, Northern Territory, Australia, includes interpretation of the geology and evolution of the landscape and their role in supporting biodiversity and cultural heritage. Climate comfort is a significant consideration for visitors to semi-arid and desert environments. (f) Prehistoric rock art in the Tadrart Acacus World Heritage Site, Libya, has cultural geoheritage value, depicting past changes in the flora and fauna, and is indicative of past climate change and human activity. Such sites are vulnerable to weathering and erosion. (Photos: John Gordon).

Climate change also impacts glacier geotourism in other ways. Glacier retreat and shrinkage can make access more difficult for walking tours and vehicular access, as in the case of the Athabasca Glacier in Canada and in New Zealand, the Alps, Norway, and the Himalayas [56,67,69,71,91,115,116]. Of the 22 papers identifying increased levels of risk to visitors from geomorphological hazards, 21 are related to glacial and periglacial environments. Such hazards include rockfalls, landslides, slope failures from thawing permafrost and ice-cored moraines, and avalanches from cold-based hanging glaciers [81,87,100,114]. These may also adversely affect access routes and itineraries while high-intensity rainfall events, erosion, and mass movements may damage trails [113,117,118]. Where glacier retreat is accompanied by lake formation or expansion, there is enhanced risk of glacial lake outburst floods triggered by rock or ice avalanches into the lakes, with cascading effects downvalley [119,120]. It has also been suggested that increasing visitation and the development of visitor facilities may increase the local tourism heat footprint, contributing to glacier retreat [76,121].

The net effect of these impacts is an actual or projected reduction in visitor demand with consequent economic impacts [56,59,64,69,86,101,102,122].

In other environments, geosites and features located on the coast and adjacent to rivers are likely to be most susceptible to climate change, particularly through the effects of sea-level rise and increased erosion or flooding [1,3]. Coastal geosites are particularly at risk from sea-level rise, compounded by likely changes in the intensity, frequency, and magnitude of storms and storm surges, with associated impacts from augmented coastal erosion and flooding [1,5–7]. They may undergo accelerated cliff retreat, resulting in the loss of features such as sea stacks [123] as well as foreshore lowering, possible burying of foreshore exposures by landslide debris or increased longshore sediment transfer, and loss of access through submergence (Figure 1c). Greater incidence of rockfalls and landslides from adjacent cliffs will increase the risks to access for education and geotourism [124] (Figure 1d). Surprisingly, therefore, the impacts of sea-level rise and coastal change have received relatively little attention specifically in the geotourism literature, and only three publications addressed coastal impacts and hazards [123–125] although globally, the latter will be a significant constraint on geotourism resource management. In the wider tourism literature, studies of climate impacts on coastal tourism have typically focused on sun, sea, and sand recreation, including the effects of weather on visitor comfort and physical impacts on destinations [126]. The loss of beaches and amenities, accompanied by coastal squeeze and pressures on infrastructure, is recognised through erosion, inundation, coastal retreat, and saltwater intrusion, which will adversely affect both tourism access, infrastructure, and attractions [127] as well as cultural heritage [128]. Such changes will also impinge on coastal geotourism destinations and attractions.

In semi-arid and arid areas, increasing temperatures and frequency of droughts in summer and flooding in winter will directly affect geotourism sites through accelerated weathering, erosion, soil desiccation, and desertification, impacting natural geomorphological features (e.g., unusual rock outcrops) that capture the attention of visitors and representing additional risks to their safety [129,130]. Increased aeolian activity and sand movements may cover or erode geoheritage features [129], and there will be an increased risk of flash flooding and erosion during extreme precipitation events [131]. Where droughts persist, the loss of vegetation cover from increased frequency and magnitude of wildfires will enhance soil vulnerability to erosion and there will be diminished visitor comfort due to increased heat and aridity and extreme climates [132,133] (Figure 1e). In conjunction with other factors such as atmospheric pollution, the risk of damage to geo-cultural heritage through accelerated weathering and the erosion of heritage stone monuments, buildings, and rock art is widely recognised, e.g., in [130,134–137] (Figure 1f). However, only six publications identified threats in the context of geotourism.

Cave and karst systems are vulnerable to climate change, particularly from changes in hydrology arising from increased precipitation and flooding or occurrence of droughts, and to increased soil erosion from more intense precipitation and loss of vegetation in

their catchments [138–140]. Consequences include physical damage to features from increased sedimentation in caves, the potential blocking of passageways and contamination of speleothems, and the loss of aesthetic value in show caves.

Only one publication referred to climate threats to palaeontological sites and those under the current climate conditions [141].

Urban geotourism is of growing interest, particularly in Europe, e.g., [142–144]. However, visitor comfort in the summer season under increasing incidence of heatwaves was not identified as a concern in the geotourism literature.

3.2. *The Role of Geotourism in Education about Climate Change*

A second main theme identified is the potential opportunities that geosites, geoparks, and geotourism offer for education about climate change e.g., [67,125,145–151]. This includes learning about past environmental and climate change [152,153], how human activity may result in warmer climates and higher sea levels in the future [145] and how Earth's past provides potential comparisons for modern climate change [58,148,154,155]. The retreat of glaciers is frequently highlighted as having an important educational role as a powerful visible indicator demonstrating the reality of climate change and raising tourists' awareness of climate change, as in 16 of the 34 papers under this theme, e.g., [67,74,79,82,88,109,146,151,156]. For example, at a number of glaciers, signposts have been erected along visitor trails marking past positions of retreating glaciers [88,107] (Figure 1b). Geo-interpretation also has a significant part to play in promoting sustainable behaviour by geotourists [67,108].

3.3. *Adaptation Strategies*

The need for adaptation has been recognised mainly in relation to mountain and glacier tourism (Table 1), and a range of adaptation measures have been identified [49,52,60,67,81,157]. In a survey at six glacier sites in the Alps [81], stakeholders identified six main concerns related to management, itineraries, infrastructure, attractiveness, safety, and activity issues, resulting in the adoption of 29 adaptation strategies, categorised under management change, technical change, mitigation measures, diversification, access and itinerary maintenance, heritage development, planning, and the implementation of transformation projects. Similar issues and related measures have been suggested or implemented in other glacier tourism studies. They include:

- making changes to visitor access to mitigate hazards, adapting trails or developing new trails or itineraries, adding new infrastructure such as bridges, adding security equipment, closing some viewpoints, and changing or relocating some activities [97,100,117];
- the diversification or replacement of activities [60,69,74,78,89,158,159];
- the temporal and spatial substitution of activities [49,69,71,157];
- enhancing conservation measures [74,97];
- the development of educational activities and tourism planning [85,88,91,110,156];
- the attenuation of glacier retreat [52,74] and destination management strategies to reduce the impacts of tourism activities on glaciers, including reducing local energy consumption [76];
- the preparation of risk management plans to address natural hazards [87,160];
- changing the focus of glacier tourism from landscape appreciation to understanding landscape evolution [161].

Enhancing conservation measures and the attenuation of glacier retreat include the experimental application of artificial covers to reduce ablation [50,162–166] and legal protection for glaciers [50]. The former is essentially impractical at scale and in terms of economics; the latter aims partly to protect glaciers from other human impacts such as mining that, *inter alia*, might reduce tourist appeal [167], but does not really address the root cause of the problem (anthropogenic global warming) [50].

Diversification activities include the development of museums and exhibition/interpretation centres, as in Norway and the Alps [70,72,168–171]; boat tours in Iceland and boat tours and fixed-wing and helicopter scenic flights and glacier landings in New Zealand [66,67,69]; rafting and canyoning [172]; e-bike tours [162]; and the use of digital tools and virtual tours [173–176]. There are also opportunities to diversify as new destinations emerge (e.g., as the extent of sea ice recedes in the Arctic and Antarctic), but these may present ecological and environmental risks [177,178], and some adaptations may not be sustainable such as the increasing use of fixed-wing and helicopter flights over New Zealand glaciers [179].

Apart, possibly, from New Zealand [68,69,157], the majority of the measures adopted have largely been reactive and are coping or incremental strategies that enable stakeholders to maintain their activities but do not ensure the longer-term sustainability of glacier tourism [49,81,110]. In the longer term, more transformative strategies will be required [80,81]. Both Salim et al. [80] and Welling et al. [85] recommended anticipatory scenario planning involving all stakeholders, including those with public, commercial, private, and conservation interests, to plan appropriate adaptation strategies as part of destination governance, echoing the recommendation of Diolaiuti and Smiraglia [97] that managers of geotourism sites and destinations must integrate climate change issues into management plans, including risk preparedness, adaptive design, and management planning.

Although risks to coastal geotourism have attracted limited attention, as noted above, the wider tourism literature has recognised the need for coastal adaptation strategies, e.g., [180,181]. Nature-based solutions (NbS) are recommended as sustainable [182–184], but these will not necessarily protect vulnerable geoexposures in the long term, so the loss or inaccessibility of features will need to be accepted and rescue and record measures adopted where practical [5]. However, destinations exemplifying NbS may in themselves become geotourism attractions for their educational value in demonstrating sustainable options for coastal management.

3.4. Impacts on Visitor Motivations and Perceptions

Much of the geotourism research literature on climate change has focused on supply-side impacts and adaptations, particularly in relation to glacier-based tourism. The demand side has received relatively less attention, although 22 of the publications on glacier tourism have addressed visitor motivations (including LCT), values, and perceptions of destination image. These highlight negative impressions of glacier retreat and loss of landscape aesthetic quality and glacier visibility, leading to lowered likelihood of repeat visits and strengthening the case for adaptive measures, the development of alternative attractions, and improved education about climate change to promote pro-environmental behaviours, e.g., [56,64,67,69,83,88,101,102,108,109,115]. These studies, and that by Amaro et al. [23] in the Arouca UGGp in Portugal, demonstrate the diversity of motivations across the spectrum of geotourists and a requirement for further research on the demand side of geotourism to help inform education, communication, and adaptation planning [52,83,86].

4. Discussion

From an economic viewpoint, tourism is a globally important sector [185,186]. Outdoor recreation and nature-based tourism (including geotourism) also provide essential benefits, both to participating individuals and hosting communities, and thereby contribute to delivering the SDGs. At the same time, however, tourism-based economies are particularly sensitive to climate change and associated hazards [187]. Climate change could potentially have significant direct and indirect impacts on the global geotourism industry through damage to destination assets from extreme weather events and sea-level rise and from changes in visitor accessibility and comfort levels, leading to degradation of the visitor experience. There will likely be geographic and seasonal changes in visitation, compounded by a range of vulnerabilities in physical assets, operating costs, demand issues, risk deterrents, and adaptive capacity [186]. The Intergovernmental Panel on Climate

Change (IPCC) Special Report on the Ocean and Cryosphere in a Changing Climate [95] identified the tourism sector as one of the main systems influenced by climate change in these environments, in particular affecting high mountain areas, polar regions, low-lying islands, and coastal areas. Dealing with climate extremes and rapid-onset events, not only progressive changes, will be a challenge for the industry [188]. However, tourism activities make a significant contribution to global greenhouse gas emissions, estimated at ~8% of the world's total [189], which are drivers of anthropogenic climate change. Managing tourism sustainably requires a comprehensive set of policies and practices to reduce the environmental impact and high dependency on fossil fuel-based energy consumption.

The implications of climate change for tourism in general have been studied for several decades [45,190,191]. However, while there is general recognition that geoheritage features and sites represent a finite natural resource vulnerable to climate-driven processes (such as erosion and sea-level rise), there have been few studies, except in the glacier sector, that have examined the impacts of climate change on geotourism and the need for adaptation measures in specific territories. In contrast, cultural heritage studies have recognised the vulnerability of tangible coastal cultural heritage to increased weathering, erosion, and sea-level rise and, increasingly, the need for adaptation measures [128,137,192–196].

The wider literature on climate change and tourism highlights a number of issues pertinent to geotourism and geoparks. These studies point to the need for geotourism studies to make adequate assessments not only of the potential of the resource, but also the risks to it, the adaptive capacity of the industry and local communities, and the potential responses of geotourists. The geotourism sector will need to anticipate and adapt both to the direct impacts on geoheritage assets and to changes in environmental conditions, safety, and infrastructure needs as well as to shifts in visitor behaviours and perceptions of likely changes in destination assets and their attitudes and reactions to the need to travel sustainably to reduce greenhouse gas emissions [197]. This will require adapting existing, or developing new, tourism products that help leverage benefits from the changed climate [198]. It will mean addressing whole supply and value chains [188] and two fundamental challenges in particular: (1) decarbonising tourism as part of the transition to a net-zero global economy by 2050, and developing a vision for its place in that economy; and (2) adapting to the increasingly complex environmental and socio-economic impacts of climate change [199]. Markham et al. [63] provide a useful starting point in the form of an overall response framework and recommendations for WHSs and tourism in a changing climate across a range of levels from the international community to government policy makers, the tourism industry, and site management authorities.

4.1. Destination Risk Assessment and Response

Destination risk assessment includes several components involving analysis of the offers on the supply side of geotourism and will need to be based on downscaled climate change projections. First, there are the risks to destination geoheritage assets, as outlined in Section 3.1. Gordon et al. [5] provided a framework for the evaluation of impacts and risk-assessment and adaptation planning and implementation. Site condition monitoring will be essential to inform the adaptation planning and implementation steps [3]. Adaptation options in response to threats to geoheritage sites and features range from non-intervention to various forms of proactive management depending on the specific interests and local circumstances [5]. As exemplified in Section 3 above, they may also include infrastructure changes and soft interventions that involve education and awareness-raising, changing behaviour and practices, capacity building, institutional reforms, and technical solutions such as early warning systems for natural hazards [200]. Adaptation may also mean accepting the loss of sites and features, although opportunities may exist for innovative virtual substitution and 'second chance' tourism [201].

Second, there are risks to destination assets and the safety of geotourists from weather extremes and the increased frequency and magnitude of natural hazards including extreme weather events, flash floods, tropical cyclones, landslides, and wildfires. Increased erosion,

debris flows, and landslides will impact geotourism infrastructure including buildings and footpaths. Access to many coastal and mountain sites will become more prone to natural hazards, requiring clear lines of risk communication [87].

Third, changing weather patterns and weather extremes are important in shaping a destination image and influencing visitor perceptions and expectations and will also have an impact on climate comfort and health for both visitors and staff (e.g., rangers). Consequently, there are likely to be changes in the spatial and temporal patterns of climatic suitability for geotourism; see [45,184,202]. Some areas will become too hot and humid in summer, resulting in changes in seasonal demand and visitors favouring alternative, more comfortable destinations. Investment in indoor facilities and attractions may become increasingly necessary for summer visitors, and part of the geotourism demand may shift from summer to shoulder seasons, attenuating peak seasons. Climate comfort and cross-cultural studies of tourist climate indices could better inform geotourism development and help to understand the potential impacts of future climate change [203]. Tourists' aversion in general to inclement weather may pose some challenges for geotourism operators. Dedicated geotourists are likely to be more resilient than casual geotourists, but decreased destination attractiveness for the latter may have a critical impact on the economic viability of some destinations.

Fourth, health risks to both visitors and destination staff may arise not only from extremes of heat and humidity but also from the spread of viruses and changes in geographic ranges of mosquitoes and other vectors of pathogens, while future pandemics will affect the vulnerability and resilience of geotourism destinations if lockdowns and travel restrictions are imposed as precautionary or reactive measures [8,204–206]. Nevertheless, European Geoparks proved relatively resilient to the COVID-19 pandemic [207].

Fifth, managing geotourism sustainably requires a comprehensive set of strategies, policies, and practices to reduce environmental impact, carbon footprints, and greenhouse gas emissions [63,208] in line with the 2015 Paris Agreement on climate change [209] and the Glasgow Declaration [210]—but see [211]. These strategies, policies, and practices need to address effective risk reduction and disaster response and be updated regularly according to the latest climate projections [63]. Strategies should be anticipatory, not reactive, based on projecting downscaled future climate scenarios for a destination and then assessing the tourism products that the future climate will support and implementing adaptation measures. Forecasting visitor numbers and monitoring the environmental impacts of infrastructure and operations to reduce greenhouse gas emissions will be required, based on environmental indicators and benchmarking [212] and linked to certification [213]. In UGGps, this should be addressed as part of the quadrennial review process. Assessments of carrying capacity may also be required at sensitive sites [214], particularly where the effects of climate change compound those of other pressures such as overtourism and lead to negative visitor experiences [215–218].

Geotourism adaptation strategies should dovetail with wider regional and national adaptation strategies [200,219] and involve all stakeholders, including local communities, tourism operators, and policy-makers. Community resilience and adaptive capacity are still not well known, such as regards the critical role of emotional stability and residents' perceptions of change [220]; for example, glaciers have different cultural and spiritual meanings in local societies [156,221–223], so local perspectives need to be addressed in framing responses to climate change and developing geotourism adaptations [50,224]. There may also be other issues such as impacts on water resources and water management for geotourism developments, which may be in conflict with other water demands [225,226]. Exploring solutions and developing and prioritising adaptations through community-based scenario planning is a priority [227]. Institutional barriers may need to be overcome and long-term goals distinguished from short-term ones. This may mean a shift from trying to preserve the status quo towards long-term planning for future change and embracing adaptive evolution [128]. For example, access to some coastal assets will undoubtedly be lost, but, as part of the development of innovative strategies to diversify tourist offers and

enhance territorial development [42], geotourism might incorporate opportunities related to alternative values of geoheritage, such as the health, well-being, and restorative benefits of access to 'blue spaces' [184].

Adaptation will require evaluating trade-offs and addressing the purposes and values of tourism, including equity and ethical issues and the balance between different SDGs (e.g., between poverty alleviation and environmental impacts) [186,228]. Tourism has been highlighted in SDGs 8, 12, and 14, and recognised by UGGPs, as a tool for sustainable economic growth, sustainable consumption and production practices, and the conservation and sustainable use of nature and natural heritage. However, "[f]or tourism to really contribute towards security and sustainable development it needs to be placed within the bigger picture of human mobility, lifestyle, consumption and production" ([188], p. 315). Consequently, there is a geoethical dimension to ensure a just transition to responsible and sustainable geotourism practice in a global net-zero economy [229]. This will require balancing economic development and decarbonising the sector, addressing the LCT paradox, reducing carbon-intense travel to tourism-dependent destinations, and ensuring social justice [46,230,231].

4.2. Visitor-Demand Issues

Climate change will not only physically affect natural and cultural resources for geotourism within protected and conserved areas but is also likely to have complex effects on visitor behaviour, motivations, preferences, and visitation patterns [232,233]. However, it is less clear, on the demand side, how geotourists will perceive and respond to climate change and to what extent calls for more sustainable tourism and carbon footprint reductions will form part of their decision making considerations [41,232]. De Urioste-Stone et al. [234] found that climate change most likely will influence travel behaviour to national parks and other protected area categories, affect how visitors perceive potential personal risks and threats associated with their travel, and have an impact on the natural environment and infrastructure on which geotourism depends. Jedd et al. [235] examined how summer visitation has changed in response to temperature and precipitation extremes in four national parks in the Rockies in the USA, noting a decline in extremely dry years. Studies of visitor experiences at glacier destinations in New Zealand and at the Athabasca Glacier in Canada and Mendenhall Glacier in Alaska have shown negative visitor responses to the likely disappearance of glaciers or loss of future glacier visibility, but non-natural adaptations and commercial developments may be equally important in influencing such responses [64,69,101,236]. Similarly, a decline in the aesthetic value of alpine landscapes as glaciers recede will likely diminish their attractiveness [102]. Hence, changes in destination image as a consequence of climate change impacts and the degradation of attractions need to be considered [62]. Probably, dedicated geotourists have higher resilience and motivation to visit particular destinations than casual geotourists. However, many geotourism destinations depend on visits not only from dedicated geotourists but also from a wider range of visitors, so impacts on landscape aesthetics and cultural heritage are essential considerations in assessing likely changes in appeal for the wider spectrum of geotourists [20,21].

Understanding geotourist perceptions and reactions to the impacts of climate change will be essential to anticipating both the potential geographic and seasonal shifts in demand as well as the changing appeal of specific attractions. Linked to this is the need to understand visitor levels of satisfaction, not only with the attractions on offer but also with respect to the climate comfort of the destination in question and level of acceptance of, and compliance with, necessary adaptation measures while maintaining positive visitor experiences [237]. This includes acquiring insights into the weather sensitivity of geotourism activities and stakeholders and their ability to deal both with currently variable conditions and potential future changes under scenarios of more extreme conditions. Destination management is also a further factor in visitor satisfaction, and for many geotourists the level of decarbonisation is likely to be a consideration. Yet, despite a wide range of

publications assessing reactions of tourists to various environmental and climate-related changes, little is known about the complexity of demand responses, and there has been relatively little research on geotourists' values and motivations and the factors that affect destination choice.

A further consideration is the motivation of LCT and its effects [49,69,83,88,108,109,238]. While LCT can help to provide climate change education, increase tourists' environmental awareness, and encourage pro-environmental behaviour [82,108,109], LCT attractions are often in remote locations that require carbon-intensive air travel. This raises ethical issues [239,240], particularly if visitors to LCT destinations are not inclined to pay for carbon offsetting despite their apparent high level of environmental awareness [241]. Hence there is something of a paradox or 'cognitive dissonance' [108] although LCT is promoted more by the media than by the tourism industry [238,242]. There may be lessons from polar tourism through the transformative experiences of visitors [243–245], but effective communication based on educational, experiential, and emotional aspects will be essential [109].

The implications of variations in tourism demand induced by climate change include the redistribution of tourism flows and likelihood of destination substitution [246]. Seekamp et al. [127] identified several research requirements to enable destinations to become better prepared for climate change. These apply equally to geotourism and include the factors that influence geotourists' trip decision making, their perceptions of potential enhanced risks, their tolerance thresholds of negative changes (e.g., in weather extremes; with changes in temperature or humidity, or the deterioration of geoheritage features or their access; responses to the installation of hard coast defences; and the loss of associated attractions such as beaches) and their readiness to substitute alternative destinations. Also unclear is the level of willingness of geotourists to accept substitute activities or attractions (e.g., boat trips or glacier museums as glaciers retreat and disappear). Another issue is the degree of readiness of geotourists to pay site entrance fees or enhanced fees to help fund adaptation and mitigation [184,247]. Individuals' attitudes, views, and beliefs about adopting sustainable practices on their travel and visits to destinations need to be taken into account when examining visitors' stated responses to climate change and projecting subsequent potential shifts in tourism demand. For example, to what extent are geotourists environmentally conscious and make environmentally informed vacation choices, and how do attitudes vary across different segments of the geotourist spectrum [83,86,248]?

There is also the question of how national and international climate policies might affect tourism demand [249]. Few studies have investigated the impacts of such policies on tourism, leading to an ambiguous understanding of tourism adaptation to emissions policy changes [250]. To reduce travel-related greenhouse gas emissions significantly, tourism cannot only rely on local solutions (e.g., use of electric vehicles); for example, Clivaz and Savioz [251] noted that 80% of emissions related to activities in the Chamonix valley were attributable to external travel by visitors and were outwith local hands. It is unclear how geotourists will respond to national and international measures aimed at reducing fossil-fuel dependent travel, as part of decarbonising the global economy, and likely involving increased costs of long-haul air travel and a shift to rail and public transport. This could see a shift to more domestic geotourism and change from short-break to slow-travel patterns [252]. Furthermore, there is again a geoethical dimension to these issues to ensure a just transition to more sustainable, decarbonised geotourism [229].

4.3. Research Requirements and Opportunities

Geoparks emphasise sustainability activities and values [8,27,253], but the effects of climate change add a further dimension that will need to be addressed, both in terms of managing assets for geotourism and in the response to the net-zero transition. While geotourism destinations will be directly affected, to a greater or lesser degree, by the physical effects of climate change and issues of destination comfort for visitors and employees, all will need to adapt to a net-zero carbon world, with an emphasis on transformative adaptation rather than short-term reactive or incremental responses. In their review of the

IPCC Sixth Assessment Report and the implications for tourism development, Scott et al. ([254], p. 13) concluded that: “climate change will transform tourism worldwide over the next three decades and beyond. Unavoidable changes in climate and society’s collective mitigation and adaptation responses will alter the competitiveness and sustainability of destinations and reshape demand”. Consequently, to anticipate the net-zero transition and climate disruption that will transform tourism over the coming decades [199,254], there is an urgent requirement for geotourism studies to progress from the inventory and identification of potential geotourism sites in particular territories and to develop more critical forecasting and evaluation of longer-term sustainability in the face of destination- and demand-side risks arising from climate change and sea-level rise and assess how geotourism might be sustained under net-zero carbon constraints. The issues involve both complex human and socio-economic considerations that span local to global scales within which tourism and geotourism are situated [64,179,180,255–257] as well as managing and adapting to the direct and indirect impacts on geosites [5]. This is particularly challenging since geoparks and other destinations attract not only dedicated geotourists but a wider spectrum of tourists with a range in motivations and, likely, in responses to climate change issues. Addressing the challenges will demand collaborative working by the geotourism research community and destination managers and operators, including geoparks. It will require framing geotourism in the wider context of sustainability and resilience and the broader tourism research agenda [157,179,254,258] to achieve a better understanding of geotourists’ values, motivations, preferences, destination experiences, responses to destination mitigation strategies, and the environmental, social, and ethical aspects of their travel; see [15,41,42]. It will also require situating geotourism in wider national and international adaptation and mitigation strategies and policies for a just transition to a green economy, net-zero goals, the decarbonisation of travel, and the consequences of these along the whole supply and demand chains. Encouragingly, some of these issues are identified in a ‘Roadmap on Climate Change’, part of a proposed multiple-goal, post-COVID-19 roadmap for UGGps [8].

Particular requirements and opportunities from a research perspective include:

- anticipating physical changes to geoheritage assets based on downscaled climate projections and the assessment of the risk of degradation of these assets from the effects of climate change;
- providing the evidence base for multi-stakeholder anticipatory scenario adaptation planning and monitoring, including developing transformative adaptations and realistic assessments of the likely effectiveness and limits of existing and proposed adaptations;
- assessing changes in climate suitability for geotourists and the implications for temporal and spatial patterns of visitation;
- achieving a better understanding of visitor motivations and behaviour in response to climate change and decarbonisation, including modelling future tourism demand and segmentation analysis across the spectrum of geotourists;
- informing the setting of realistic decarbonisation targets, measuring and monitoring emissions, positioning geoparks and other geotourism destinations within the decarbonisation target corridors identified by the World Travel & Tourism Council [259], and addressing the implications of national and international emission-reduction strategies;
- assessing the carrying capacities of destinations, both in relation to the physical impacts of visitor numbers compounded by the effects of climate change and visitor tolerance of changes in physical assets/infrastructure, climate conditions, crowding, and adaptation measures adopted;
- balancing geotourism, sustainable development, and social justice in a net-zero world;
- developing evidence-based, best-practice guidance and case studies.

While understanding the future motivations and behaviour of visitors is complex, it is a priority for attention in adaptation planning and decision making by geotourism destination managers and geotourism stakeholders [64]. At the same time, however, the geoconservation objectives of geotourism must not be overlooked (see [111,260]), bearing in

mind that IUCN Resolution WCC-2016-Res-060: 'Improving standards in ecotourism' [261], inter alia, encourages the adoption of standards and norms to ensure positive conservation outcomes in landscapes and seascapes of conservation value.

5. Conclusions

Geotourism is widely viewed and promoted both as a source of sustainable development for local communities as well as a means to deliver geoconservation, particularly through the establishment of geoparks. Through learning from the past and demonstrating present landscape changes, geotourism can also help to raise awareness of both the impacts of climate change on society and the environment as well as the impacts of society on climate. The global expansion of geotourism has been remarkable, but, as for tourism generally, the future of many destinations will depend on how they respond to the major challenges, both of adapting to changing climate conditions and the effects on assets and visitor responses as well as reconciling the impacts of tourism and sustainable development in a socially just way.

The present review has revealed limitations in the existing engagement of geotourism studies with climate change. Impacts, hazards, and the role of geoheritage sites in demonstrating climate change, both present and past, are broadly recognised, together with the need for adaptation, particularly in the case of mountain and glacier studies but less so in other fields. However, with the exception of glacier-related tourism, the wider implications of climate change for geotourism, and particularly the lessons from the substantial body of tourism research on both supply and demand issues, have not been addressed, including the chain of physical, economic, and social interconnections. While understanding these connections is complex, it is a priority for attention to inform adaptation planning and decision making by geoparks, geotourism destination managers and other stakeholders. As well as adapting to the physical impacts of climate change on geotourism sites, preparing the sector for the transition to a net-zero world, while continuing to deliver geoconservation outcomes, will require situating geotourism within the broader multidisciplinary frame of tourism research to enable a better understanding of geotourists' values, motivations, preferences, and responses to the economic, social, and ethical issues presented by climate change. Ultimately, the long-term viability of geoparks and geotourism destinations will depend on how they diversify and adapt to changing supply- and demand-side conditions informed by evidence-led research.

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