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ORIGINAL ARTICLE

Modelling the impact of climate change on cultural practices: the future of fen skating (1981–2079)

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Abstract

Cultural practices reliant on the formation of ice are likely to be affected by climate change across the world. Outdoor skating is a popular pastime in many regions of North America, Asia and northern Europe. Fen skating is a traditional sport practiced in the flat area of east England, when shallowly flooded fields and meadows freeze to form large stretches of ice. To assess the future of fen skating, climate metrics were constructed to capture the freezing conditions needed for fen skating to take place. A skating freeze was defined as requiring the daily minimum temperature to be either (i) four nights below -4 °C, (ii) three nights below -5 °C or (iii) two nights below -8 °C. The 12 km resolution UKCP18 dataset was used to assess the frequency and duration of skating freezes in the fens for the period 1981 to 2079. Results from the 12 UKCP18 model members showed notable variability and only four model members successfully captured past skating freezes. Outputs from these four model members showed a rapid decrease in the frequency and duration of skating freezes, raising concerns over the future of this sport.

Keywords Intangible heritage · Cultural practice · Winter sports · Climate change · Freezing events

Introduction

Frost events have long been of interest due to their deteriorative effect on historic materials (Ingham 2005; Hallet 2006; Grossi et al. 2007; Deprez et al. 2020; Richards et al. 2022). However, freezing conditions are also important in enabling cultural practices that rely on cold temperatures (Knoll et al. 2019). The formation of ice changes the way humans interact with landscapes: waterways can become impassable to boats, while the frozen surface can provide a new surface for humans to use for transportation or recreation (Knoll et al. 2019). The formation of ice also allows winter sports such as outdoor ice skating to be undertaken. Such sports can be important in constructing a person's or community's sense of place identity (Ramshaw and Hinch 2008).

Climate change is causing longer warm seasons and shorter cold seasons across the world (IPCC 2013). Ice is particularly sensitive to increases in temperature and warmer winters have caused a reduction in the number of frost events in many regions including Europe (Grossi et al. 2007) and Russia (Vyshkvarkova and Sukhonos 2023), with further reductions projected over the twenty-first century (Richards and Brimblecombe under review; Grossi et al. 2007). Research addressing the effect of warmer winters on cultural practices has been tended to study high-value tourist activities such as skiing (Scott and McBoyle 2007; Pickering 2011; Klein et al. 2016; Rutty et al. 2017; Steiger and Scott 2020) and snowmobiling (Scott et al. 2008; Wobus et al. 2017). However, ice skating is an important cultural practice in many northern regions, including Canada, USA, Russia, China, Japan, South Korea and northern Europe, with for example the 200 km ice skating race through 11 Dutch cities dating back to 1749 (Visser and Petersen 2009). Previous research has assessed change in season length of outdoor skating in countries such as China (Liu et al. 2017) and Canada (Damyanov et al. 2012; Brammer et al. 2014; Robertson et al. 2015), and on the occurrence of ice skating races in Europe (Visser and Petersen 2009; Knoll et al. 2019). Nevertheless, such research has not assessed the impact on the

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traditional practice of fen skating, despite the sport's historic role in founding the International Skating Union that helped establish the Olympic Ice Skating movement, and continued importance for UK ice skating (Atta 2022).

Fen skating is the traditional form of ice skating undertaken in the fenland areas in the east of England. This form of skating utilises the flat, low-lying nature of fenland landscape that makes the area prone to shallow flooding, providing ideal conditions for ice formation in winter months, particularly during the period of cooling in the Little Ice Age. Skating takes place on flooded fields and meadows and was originally undertaken using bone skates with metal blades being used from the seventeenth century (Porter 1969). By the late nineteenth century, several thousand people would attend skating matches (The Littleport Society 2023). It also was influential in the process of establishing the National Skating Association in 1879, which was instrumental in providing greater regulation for the sport (Atta 2022).

Today, the enduring appeal of fen skating is seen with both young and old taking to the ice as soon the conditions permit skating to happen, with many keen to carry on the fenland tradition (Phillips 2021). The local and national newspapers frequently publish news stories on fenland skating when skating conditions occur (e.g. Elliott 2017; Weaver 2018; Phillips 2021) and older generations continue to pass on stories of their fen skating adventures. Furthermore, fen skating is represented in literary pieces and music with for example Philippa Pearce's *Tom's Midnight Garden* (1958) and Duncan Stafford's *Fen-Skating Suite* (1990). Understanding how climate change may affect fen skating could also act as an indicator for the future of other cultural practices that are dependent on specific weather conditions, such as snow being required to create snowy winterscapes associated with Santa Claus and Christmas (Hall 2014), as well as other practices, such as pilgrimages likely to be undertaken in more extreme climates (Yezli et al. 2019; Saeed et al. 2021).

The effect of climate change on heritage has been assessed using a range of methods including the use of archival material, oral histories and interviews (Sloggett and Scott 2022). Computational modelling has also been used but has predominantly been applied to tangible heritage objects and sites (Leissner et al. 2015; Bretti and Ceseri 2022; Hart et al. 2023), although occasionally applied to aspects of intangible heritage (e.g. Brimblecombe and Hayashi 2018). While quantitative modelling methods do not capture the diverse and complex knowledge and experience inherent to cultural practices, they can help us to understand how future climate scenarios may alter environmental conditions that are required for certain cultural practices to be performed. Therefore, this research aims to assess (i) the ability of climate model outputs to capture past freezing events where fen skating is known to have taken place; and (ii) how the frequency and duration of fen skating change between 1981 and 2079. The findings are important for assessing how climate change is likely to affect intangible heritage, both in the UK as well as indicating directions of future change for outdoor skating in other regions.

Method

Study area

The fens are located in the east of England, spanning across an area of around 3900 km^2 in Norfolk, Cambridgeshire and Lincolnshire. The area is characterised by low-lying flat land that is commonly used for agriculture. The fens are naturally marshy but were drained in the seventeenth to nineteenth centuries, resulting in an extensive network of drainage channels.

This study focuses on the area bounded by 52°15′N to 52°48′N and -0°12′E to 0°24′E (Fig. 1a), which includes regions from all three fenland counties. The study area includes key fen skating locations including the villages of Upware, Welney, Whittlesey, Earith and Swavesey (Fig. 1b) and aligns with the grid coordinates of the UKCP18 model data.

Freezing conditions required for fen skating

During winter, shallow flooding is common on low-lying fields and meadows. As ice needs to be a minimum of 40 mm thick to be suitable for fen skating, multiple nights of freezing are required (Bishop 2022). Fen skating news reports published in local newspapers (e.g. Cambridge News and Eastern Daily Press) were used to construct a metric to capture the climate conditions required for fen skating, here named a *skating freeze*. A skating freeze requires the daily minimum temperature to be either (i) four nights below -4 °C (Bishop 2022), (ii) three nights below -5 °C (Elliott 2017; Weaver 2018) or (iii) two nights below -8 °C (Weaver 2018); and for little thawing to not occur during the following day (Bishop 2022), here defined as the average daily temperature not exceeding 2 °C. This metric assumes the presence of shallow flooding in the area.

The conditions required to end a skating period are not easy to measure as it is dependent on factors such as the depth and area of ice (Damyanov et al. 2012). Therefore, instead of calculating the absolute duration of skating freezes, I follow Damyanov et al. (2012) in establishing a proxy for the freeze length. Here, I calculate the number of days before the first thaw day, where average daily temperatures are equal to or greater than 2 °C. The number of actual skating days is likely to be longer than this, particularly if

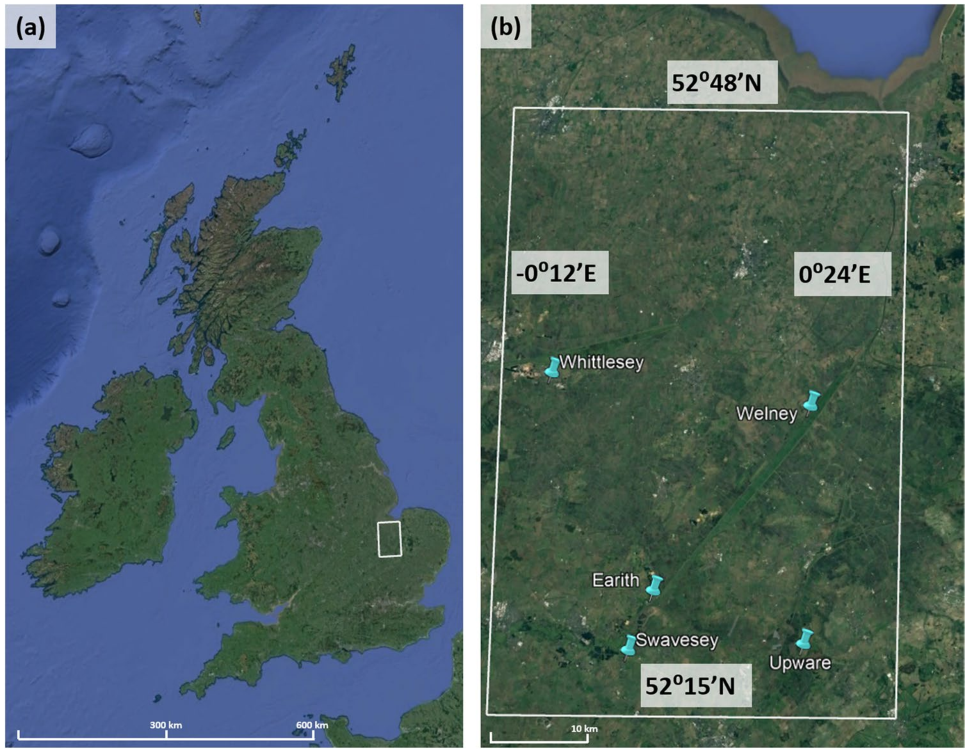

Fig. 1 The location of (**a**) the study area in the UK and (**b**) key fen skating locations in the study area

there is thick ice, but provides an indication of how the duration of skating freezes may change over time.

All parameters are calculated from the start of July to the end of June the following year so events for a whole winter season are considered even if one freeze event was in December and the next in February. For simplicity, the year refers to the year at the start of the winter period (i.e. 1986 is for the winter of 1986/1987).

Model data

Model output data from the UKCP18 project was used to assess changes in skating freezes. The UKCP18 project provides regional climate model projections for the UK, Channel Islands and Isle of Man for the period 1981–2079, with future projections under a high emission scenario (RCP8.5) (Met Office Hadley Centre 2018). The UKCP18 projections have been developed from the UKCP09 project and aim to give the latest assessment of how climate change over the twenty-first century will impact the UK. They use the IPCC standardised representative concentration pathways for their model runs.

Outputs from the 12-km resolution projections were used, meaning the study region was divided into twenty 12 × 12 km cells. The 12-km resolution dataset was chosen to accommodate the need for a continual dataset spanning past and future time periods at a resolution small enough to capture variation within the fenland area. These UKCP18 projections are formed using the HadGEM3-GC3.05 global climate model driven by a perturbed physics ensemble to capture uncertainties in the model's representations of the climate system, coupled with the HadREM3-GA705 regional model and HadREM3-RA11M convection permitting model (Met Office Hadley Centre 2019). Thus, the 12 models, with Member IDs of 01, 04, 05, 06, 07, 08, 09, 10, 11, 12, 13 and 15, were used. Daily fields of minimum and average temperature were obtained from the Centre for Environmental Data Analysis (CEDA) archive [https://catalogue.ceda.ac.uk/uuid/589211abeb844070a95d061c8cc7f604] accessed in January 2023.

Skating freeze metrics were calculated for the 99 complete winters in the dataset between 1981 and 2079 for each of the 20 cells in the 12 regional models. Unless otherwise stated, yearly model average was determined by calculating the mean of the results for the 20 cells. Consequently, if in a given year a skating freeze event was recorded in only one cell, the average number of skating freezes per year would be 1/20 (0.05), while if one skating freeze event had been recorded in every cell in a given year, the average skating freezes per year would be 20/20 (1).

To assess model performance, the number of modelled skating freezes for the years 1981 to 2022 was compared to known skating freezes. A range of sources including local and national newspaper articles, Twitter posts from fen skating groups, videos of fen skating on YouTube and online documentaries were used to compile a database of known times when fen skating had taken place. As fen skating is often recorded by local newspapers, key word searches were undertaken in publications including *Cambridge evening news*, *Eastern Daily Press*, *Watton and Swaffham Times* and *North Norfolk News* using terms "Fen* skating" and "Ice Skating". Cross-referencing of skating dates between sources was undertaken where possible.

Results from this database show that fen skating was found to occur in the winters with a year start of 1985, 1986, 1987, 1995, 1996, 2008, 2009, 2011, 2012, 2017, 2020 and 2022. It was also reported that warm winters between 2011 and 2017 prevented fen skating in these years. A full list of findings is provided in Supplementary Material (Table S1). While additional fen skating events are likely to have occurred in other years, only the years where the status of skating events are known are used to assess model performance.

The database also highlighted that the occurrences of skating freezes were not homogeneous across the whole of the fenland area. Therefore, the criteria for model acceptance were developed so that not all areas of the study area had to experience a skating freeze at the same time. Instead, model acceptance was dependent on the model having (i) an average number of skating freezes of ≥ 0.2 for more than half of years where skating is known to have occurred (excluding years 2011 and 2012 due to conflicting reports); and (ii) an average number of skating freezes of ≤ 0.2 in more than half of years where warm winters limited fen skating opportunities. A value of 0.2 was used to acknowledge spatial variability in freezing across the fens, with one freezing event in 1/5th of model grid cells being seen as enough to satisfy freezing conditions. Outputs from models that passed the acceptance criteria were used to calculate the number, duration and characteristics of skating freezes per year for the complete dataset for winters between 1981 and 2079.

The Mann–Whitney U test was used to assess for significant difference over time and space due to the non-parametric nature of the data sets. All tests were conducted at a 95% confidence level.

Results

Model ability to capture skating freezes

Figure 2 shows the number of modelled skating freezes per year between 1981 and 2022 for each of the 12 regional UKCP18 model members. Outputs from the model ensemble show that between zero and three skating freezes were modelled per year, with the majority of years having one skating freeze or less per year. Model outputs tended to show a greater number of skating freezes in the first two decades and a period of no skating freezes in the 2010s (e.g. Figure 2a, e–g, k, l) although this was not uniformly found (e.g. Figure 2c, j). Outputs from all models also showed that the occurrence of skating freezes was not homogenous across the study area, resulting in the average number of skating freezes to not be an integer amount.

Within the ensemble, there was large variability in the occurrence of skating freezes, and few models consistently captured skating freeze events in years when they are known to have occurred (Fig. 2, Table S1). Only four of the 12 models fulfilled the model acceptance criteria outlined in the "Model data" section. These four models were members 04, 05, 10 and 11 (Fig. 2b, c, h, i).

Frequency and duration of skating freeze events

Results from the four successful models show the number of skating freezes per year decrease over the study period (Fig. 3a). Model results indicate that there has already been a significant decrease in skating freezes per year between 1981–1999 and 2000–2019 (Mann–Whitney U, $n_1 = 19$, $n_2 = 20$, $U = 98.5$, $p < 0.05$). Future projections show that skating freezes will become increasingly infrequent until mid-century. Beyond mid-century, skating freezes are projected to be a rare occurrence, occurring only in localised parts of the study area.

The duration till the first thaw day is also shown to decrease over the study period (Fig. 3b). Similar to the results for the number of skating freezes per year, results also show a significant decrease in the duration till the first thaw day between 1981–1999 and 2000–2019 (Mann–Whitney U, $n_1 = 19$, $n_2 = 20$, $U = 107.5$, $p < 0.05$). Beyond 2040, the average duration till the first thaw day is less than 1 day, suggesting that when skating freeze events do occur, they will rapidly be subjected to thawing conditions.

The model outputs also show a notable reduction in the skating freeze events triggered by temperatures falling below -8 °C, -5 °C and -4 °C for 2, 3 and 4 days, respectively (Fig. 4). The contribution of each event type remains proportionally similar for the four decades, 1980 to 2010, with the -4 °C events causing approximately 40% of the skating freezes. From 2050 onwards, almost all skating freezes are projected to be caused by the -4 °C freezing events.

A declining trend is present across all areas of the study region from more than five skating freezes per decade in each area of the study region to less than one per decade (Fig. 5). However, areas in the west were found to have had significantly more skating freezes than areas in the east in

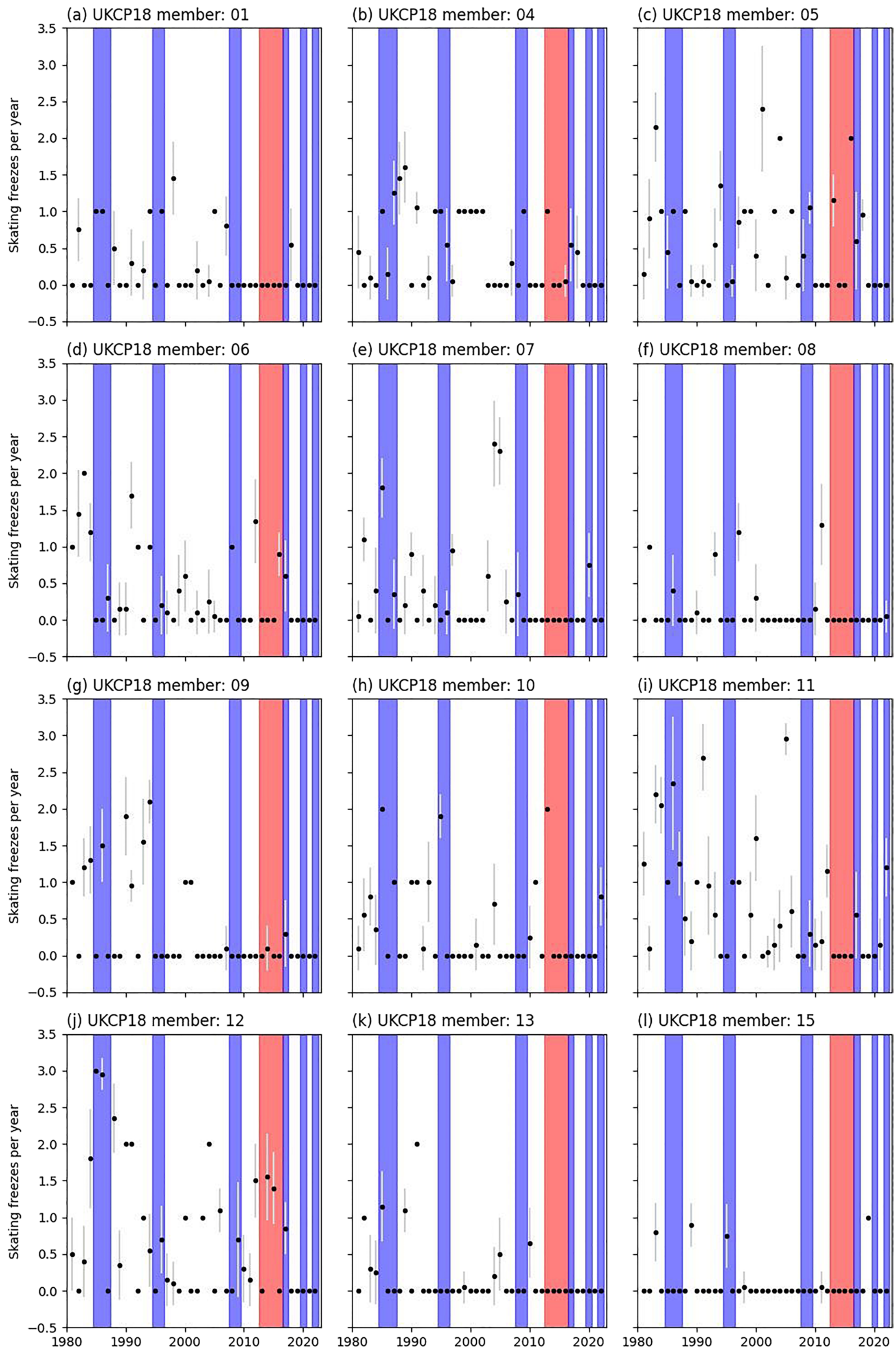

Fig. 2 Average number of modelled skating freezes per year in the study area from 1981 to 2022 for each of the 12 UKCP18 model members. Standard deviations are indicated with light grey lines. Blue indicates periods where fen skating was known to take place and red indicates years where warm winters prevented fen skating from happening

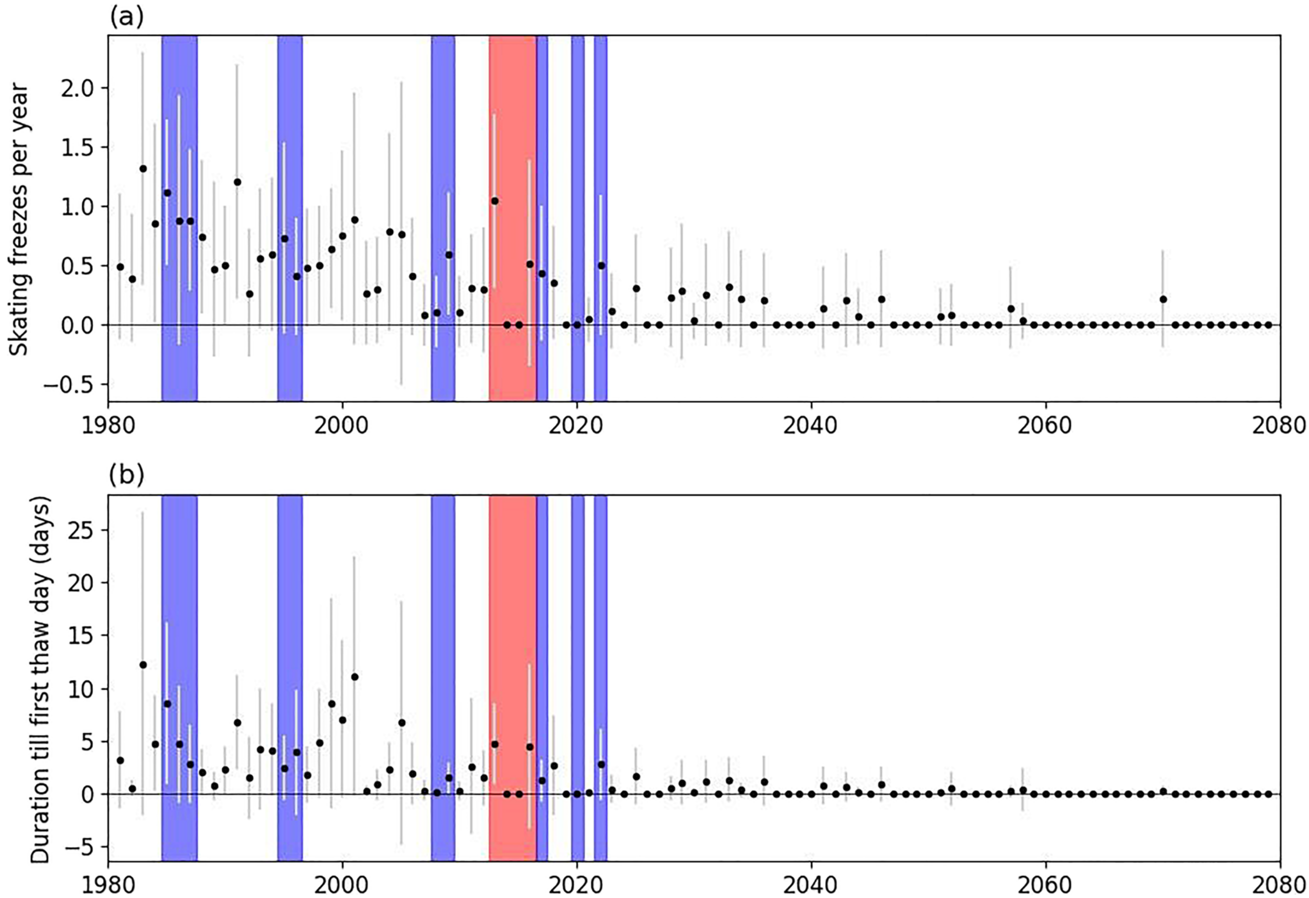

Fig. 3 **a** Average number of skating freezes per year and **b** average duration till first thaw day for the UKCP18 model members 04, 05, 10 and 11 from 1981 to 2079. Standard deviations are indicated with light grey lines. Blue indicates periods where fen skating was known to take place and red indicates years where warm winters prevented fen skating from happening

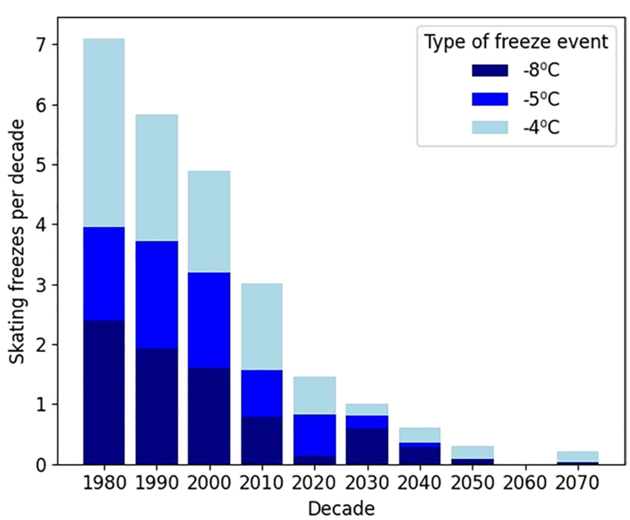

Fig. 4 Average number of modelled skating freezes per decade, calculated from the UKCP18 model members 04, 05, 10 and 11. Results are grouped by the type of freeze event that triggered the skating freeze to occur

the decades 1980, 1990, 2000 and 2040 (Mann–Whitney U, n_{east}=10, n_{west}=10, U_{1980}=5.5, U_{1990}=12, U_{2000}=16.5, U_{2040}=19.5, $p_{1980,\ 1990,\ 2000,\ 2040} < 0.05$), while in warmer past decades such as 2010 and the other projected future decades, a lack of significant difference was found due a reduction in skating freezes across the whole area (Mann–Whitney U, n_{east}=10, n_{west}=10, U_{2010}=33.5, U_{2030}=50, U_{2050}=40, U_{2060}=50, U_{2070}=45, $p_{2010,\ 2030,\ 2050,\ 2060,\ 2070} < 0.05$).

Discussion

Modelling of skating freezes

The UKCP18 dataset was used to assess the number of skating freezes in the fenland region of England. The results from the 12 members showed a substantial variability between models, with only a third of UKCP18 model members successfully capturing skating freezes (Fig. 2). This

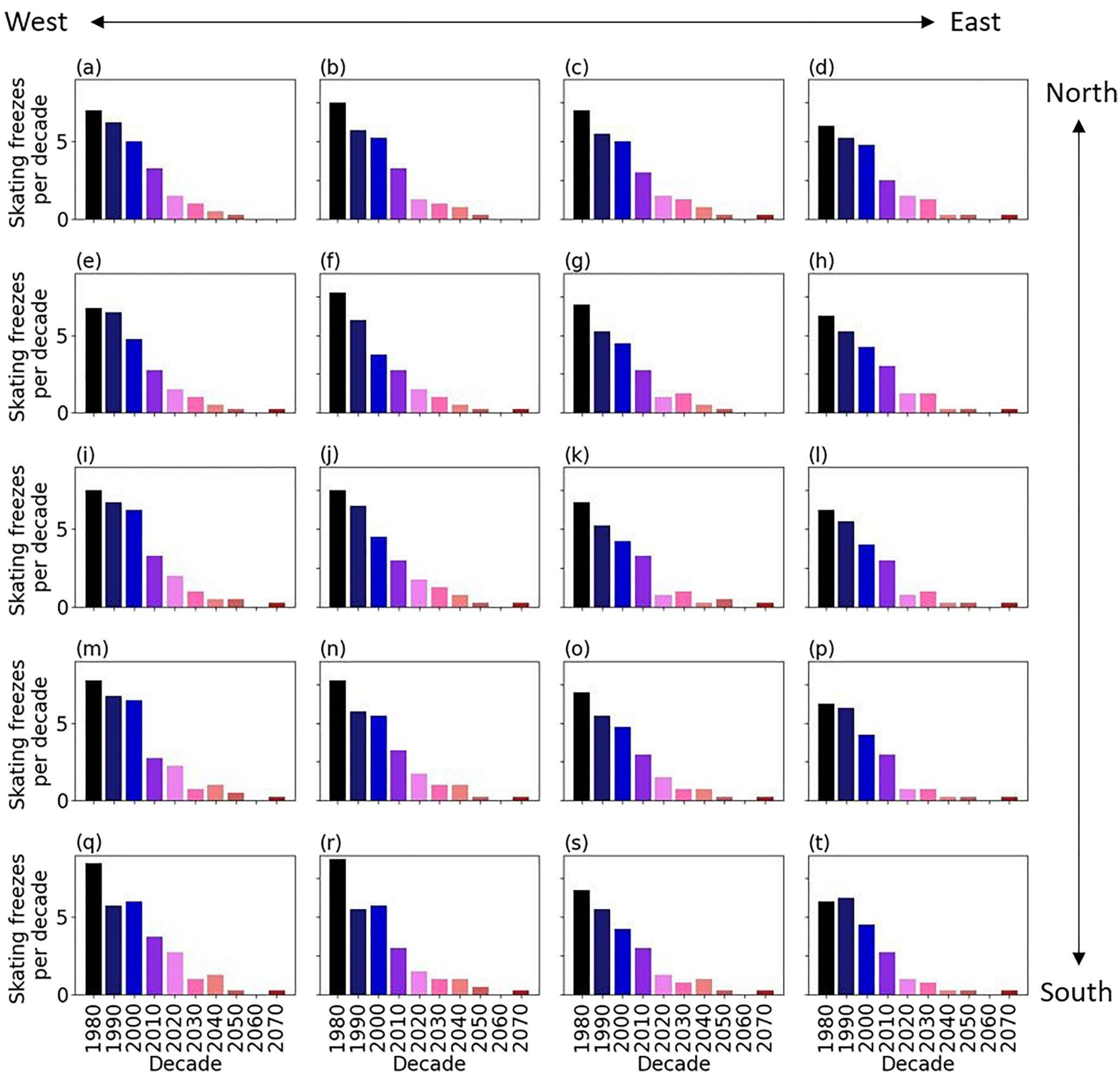

Fig. 5 The number of skating freezes per decade for each of the 12-km resolution model grid squares in the study region with (a) in the north-westerly corner and (t) in the south-easterly corner, calculated from the UKCP18 model members 04, 05, 10 and 11

low rate of model success was somewhat surprising given that temperature is normally well resolved within climate models and that the 12-km resolution UKCP18 dataset has been found to have a small cold bias in the fenland area of up to -1 °C (Barnes et al. 2023). This dataset has also previously been used to assess frost metrics in building research (Lu et al. 2021) and viticulture (Nesbitt et al. 2022; Llanaj and McGregor 2022), without such issues arising. This suggests the occurrence of consecutive days of deep freezes may be less well represented within the UKCP18 dataset. Improvements in modelling skating freezes might be possible if additional parameters such as soil temperature were included. This could be achieved by using a landscape model such as The Joint UK Land Environment Simulator (JULES) (Best et al. 2011; Clark et al. 2011).

The future projections based on a subset of four models show a rapid decline in skating freezes over the next few centuries, following the global trends for an increase in average temperature (IPCC 2021). Barnes et al. (2023) show a greater increase in winter temperatures for the UKCP18 future projections than the EuroCORDEX multi-model ensemble between 1980–2010 and 2050–2080. In the fenland area, the difference is shown to be approximately 1 °C. This finding could suggest that the rate of decrease in skating freezes in this study may be at the upper end of future predictions and so even under a future high-emission scenario, skating freezes may extend into the late twenty-first century.

Modelling-based approaches inherently contain an element of uncertainty. In heritage, understanding this uncertainty is useful to assess the propagation of error into management or policy decision-making (Richards et al. 2023). Here, the complex nature of climate and weather means there is much uncertainty in projecting the absolute number of future skating freezes. However, despite the uncertainty over the exact magnitude, the strength in the direction of change of the number and duration of skating freezes strongly indicates that we are heading towards a future world where opportunities for skating freezes will become few and far between.

Future of fen skating

Results from this study show that the frequency and duration of skating freeze events have and will continue to decrease through the twenty-first century. Cultural practices typically require a continuity of performance for knowledge to be passed on (e.g. Pieroni 2016; Higgins 2022). For fen skating, this knowledge includes both the skating technique, as well as knowing the locations where good skating ice forms. The cold winters of 1890 have been highlighted as a period where there was "enough ice each year to last sufficiently long for the people of the Fens to acquire great skill in the old English pastime of speed skating", with the large stretches of ice in Cambridgeshire providing an ideal area for people to learn to skate (Collingwood 1990, p110). With fewer cold winters in the future, skating technique could be learnt in an indoor rink, and building one in the fens is seen by some as a way of continuing this fenland pastime (Lumby 2018). However, rink skating means that the practice is removed from being embedded in the landscape. Skating on a rink would not provide the same experience of anticipating the formation of ice; nor capture the large expanses of ice that used to link together villages and enabled skaters to cover 40 to 70 miles in a day (Lumby 2018).

Furthermore, without regular natural skating freezes, knowledge of prime skating locations could be lost. Thus, when a freeze event did happen, people might not be aware of where to check for skating conditions. For example, in rural Cambridgeshire, a leaning telegraph pole has become a landmark for people meeting to skate (Moore 2023), but without regular skating freezes such knowledge commonly passed on via word-of-mouth might be forgotten. Therefore, this study's results are potentially even more concerning as projections of skating freezes dropping below one or two events per decade by mid-twenty-first century might mean that the knowledge could be lost, even if the conditions for skating occur.

Conclusion

Climate change is projected to impact both tangible and intangible heritage. While qualitative methods have been used to explore the impact of climate change on individuals and communities, this study uses a modelling approach. The use of climate model data enables us to quantitatively assess how past and projected future changes in climate affect the likelihood of fen skating opportunities. Such results can be incorporated in policy documents to provide robust figures on climate change impacts on local practices. This approach could similarly be applied to other cultural practices that rely on certain climate conditions to be possible, e.g. the celebration of seasonal festivals.

This study also shows the importance for constructing climate metrics that are relevant to specific heritage practices. By constructing a metric for the formation of fen ice, which combines minimum temperatures with the number of consecutive days of occurrence, results calculated from the UKCP18 dataset showed a rapid decrease in the number and duration of skating freezes between 1981 and 2079. Such metrics enable local and site-specific knowledge to be incorporated within the analysis, enabling the metrics to become increasingly tailored to heritage.

Furthermore, as skating freezes become more sporadic, there is an additional risk that the knowledge and skill required to practice fen skating might be forgotten. Therefore, like many other forms of intangible heritage, the practice of fen skating needs to be frequently possible to ensure that knowledge can be passed down between generations, but this could become harder as cold winters become more sporadic. Future work on the future of fen skating should assess other parameters relevant to freeze events, which have not been assessed here, such as flooding depth and soil temperature.

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Author contribution JR completed all work relevant to this manuscript.

Data availability Data is available from the author on reasonable request.

Declarations

Conflict of interest The author declares no competing interests.

References

Atta F (2022) Fen Skating: the Cambridgeshire tradition that sparked an international movement. In: Cambridgeshire Live. Available via https://www.cambridge-news.co.uk/news/history/fen-skating-cambridgeshire-tradition-sparked-25777940. Accessed 22 Feb 2024

Barnes C, Chandler RE, Brierley CM (2023) A comparison of regional climate projections with a range of climate sensitivities. Authorea Preprints [Preprint]. Available via https://doi.org/10.22541/ESSOAR.168056825.50630084/V1. Accessed 22 Feb 2024

Best MJ, Pryor M, Clark DB, Rooney GG, Essery RLH et al (2011) The Joint UK Land Environment Simulator (JULES), model description – Part 1: Energy and water fluxes. Geosci Model Dev 4:677–699. https://doi.org/10.5194/GMD-4-677-2011

Bishop C (2022) Skaters take to the fens as cold spell freezes Welney Washes. In: Eastern Daily Press. Available via https://www.edp24.co.uk/news/23184916.skaters-take-fens-cold-spell-freezes-welney-washes/. Accessed 22 Feb 2024

Brammer JR, Samson J, Humphries MM (2014) Declining availability of outdoor skating in Canada. Nature Clim Change 5(1):2–4. https://doi.org/10.1038/nclimate2465

Bretti G, Ceseri M (2022) Climate change effects on carbonation process: a scenario-based study. Heritage 6:236–257. https://doi.org/10.3390/HERITAGE6010012

Brimblecombe P, Hayashi M (2018) Pressures from long term environmental change at the shrines and temples of Nikkō. Herit Sci 6:1–12. https://doi.org/10.1186/s40494-018-0186-1

Clark DB, Mercado LM, Sitch S, Jones CD, Gedney N, Best MJ et al (2011) The Joint UK Land Environment Simulator (JULES), model description – Part 2: Carbon fluxes and vegetation dynamics. Geosci Model Dev 4:701–722. https://doi.org/10.5194/GMD-4-701-2011

Collingwood F (1990) The fen skaters of Welney Wash. In: Carling C (ed) A fenland Christmas, 1st edn. Alan Sutton, Stroud, UK, pp 110–114

Damyanov NN, Damon Matthews H, Mysak LA (2012) Observed decreases in the Canadian outdoor skating season due to recent winter warming. Environ Res Lett 7:014028. https://doi.org/10.1088/1748-9326/7/1/014028

Deprez M, De Kock T, De Schutter G, Cnudde V (2020) A review on freeze-thaw action and weathering of rocks. Earth Sci Rev 203:103143. https://doi.org/10.1016/j.earscirev.2020.103143

Elliott C (2017) Chilling out on Cambridgeshire's flat old fenland fields. In: Cambridgeshire Live. Available via https://www.cambridge-news.co.uk/news/cambridge-news/chilling-out-cambridgeshires-flat-old-12485211. Accessed 22 Feb 2024

Grossi CM, Brimblecombe P, Harris I (2007) Predicting long term freeze-thaw risks on Europe built heritage and archaeological sites in a changing climate. Sci Total Environ 377:273–281. https://doi.org/10.1016/j.scitotenv.2007.02.014

Hall CM (2014) Will climate change kill Santa Claus? Climate change and high-latitude Christmas place branding. Scand J Hosp Tour 14:23–40. https://doi.org/10.1080/15022250.2014.886101

Hallet B (2006) Why do freezing rocks break? Science 314:1092–1093. https://doi.org/10.1126/science.11352

Hart S, Raymond K, Williams CJ, Rutherford WA, DeGayner J et al (2023) Modeling earthen treatments for climate change effects. Heritage 6:4214–4226. https://doi.org/10.3390/HERITAGE6050222

Higgins N (2022) Changing climate; changing life—climate change and indigenous intangible cultural heritage. Laws 11:47. https://doi.org/10.3390/LAWS11030047

Ingham JP (2005) Predicting the frost resistance of building stone. Q J Eng Geol Hydrogeol 38:387–399. https://doi.org/10.1144/1470-9236/04-068

IPCC (2013) Annex I: Atlas of global and regional climate projections. In: van Oldenborgh, G.J., M. Collins, J. Arblaster, J.H. Christensen, J. Marotzke, S.B. Power, et al (eds) Climate change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 1311–1393. https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_AnnexI_FINAL-1.pdf

IPCC (2021) Summary for policymakers. In: Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, et al (eds) Climate change 2021: the physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 3−32. https://doi.org/10.1017/9781009157896.00

Klein G, Vitasse Y, Rixen C, Marty C, Rebetez M (2016) Shorter snow cover duration since 1970 in the Swiss alps due to earlier snowmelt more than to later snow onset. Clim Change 139:637–649. https://doi.org/10.1007/s10584-016-1806-Y

Knoll LB, Sharma S, Denfeld BA, Flaim G, Hori Y et al (2019) Consequences of lake and river ice loss on cultural ecosystem services. Limnol Oceanogr Lett 4:119–131. https://doi.org/10.1002/LOL2.10116

Leissner J, Kilian R, Kotova L, Jacob D, Mikolajewicz U et al (2015) Climate for culture: assessing the impact of climate change on the future indoor climate in historic buildings using simulations. Herit Sci 3(1):1–15. https://doi.org/10.1186/S40494-015-0067-9

Liu J, Cheng H, Sun X, Huang L, Fan Q et al (2017) Effects of climate change on outdoor skating in the Bei Hai Park of Beijing and related adaptive strategies. Sustainability 9:1147. https://doi.org/10.3390/SU9071147

Llanaj C, McGregor G (2022) Climate change, grape phenology, and frost risk in Southeast England. Aust J Grape Wine Res 2022:1–18. https://doi.org/10.1155/2022/9835317

Lu J, Marincioni V, Orr SA, Altamirano-Medina H (2021) Climate resilience of internally-insulated historic masonry assemblies: comparison of moisture risk under current and future climate scenarios. Minerals 11:271. https://doi.org/10.3390/MIN11030271

Lumby T (2018) Skaters take to the Fens for the first time in eight years. In: Cambridgeshire Live. Available via https://www.cambr idge-news.co.uk/news/local-news/fen-skaters-2018-fenland-tradition-14362544. Accessed 22 Feb 2024

Met Office Hadley Centre (2018) UKCP18 Regional Projections on a 12km grid over the UK for 1980-2080. Centre for Environmental Data Analysis. Available via https://catalogue.ceda.ac.uk/uuid/589211abeb844070a95d061c8cc7f604. Accessed 30 Mar 2023

Met Office Hadley Centre (2019) UKCP18 Guidance: data availability, access and formats. In UKCP18 Guidance. Available via https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/ukcp/ukcp18-guidance-data-availability-access-and-formats.pdf. Accessed 14 Apr 2023

Moore O (2023) The joy of fen skating is a great metaphor for life. In: BBC News East. Available via https://www.bbc.co.uk/news/uk-england-cambridgeshire-64399819. Accessed 22 Feb 2024

Nesbitt A, Dorling S, Jones R, Smith DKE, Krumins M et al (2022) Climate change projections for UK viticulture to 2040: a focus on improving suitability for Pinot noir. OENO One 56:69–87. https://doi.org/10.20870/OENO-ONE.2022.56.3.5398

Phillips B (2021) Skaters take to the local Fens for the first time in years. In: Varsity. Available via https://www.varsity.co.uk/sport/20798. Accessed 22 Feb 2024

Pickering C (2011) Changes in demand for tourism with climate change: a case study of visitation patterns to six ski resorts in Australia. J Sustain Tour 19:767–781. https://doi.org/10.1080/09669582.2010.544741

Pieroni A (2016) The changing ethnoecological cobweb of white truffle (Tuber magnatum Pico) gatherers in South Piedmont, NW Italy. J Ethnobiol Ethnomed 12:1–11. https://doi.org/10.1186/S13002-016-0088-9

Porter E (1969) Fenland skating. Cambridgeshire, Huntingdon and Peterborough Life. February issue

Ramshaw G, Hinch T (2008) Place identity and sport tourism: the case of the heritage classic ice hockey event. Curr Issue Tour 9:399–418. https://doi.org/10.2167/CIT270.0

Richards J, Guo Q, Viles H, Wang Y, Zhang B et al (2022) Moisture content and material density affects severity of frost damage in earthen heritage. Sci Total Environ 819:153047. https://doi.org/10.1016/J.SCITOTENV.2022.153047

Richards J, Brimblecombe P, Engelstaedter S (2023) Modelling temperature-precipitation pressures on African timber heritage. Int J Climatol. https://doi.org/10.1002/JOC.8273

Robertson C, McLeman R, Lawrence H (2015) Winters too warm to skate? Citizen-science reported variability in availability of outdoor skating in Canada. Can Geogr 59:383–390. https://doi.org/10.1111/CAG.12225

Rutty M, Scott D, Johnson P, Pons M, Steiger R et al (2017) Using ski industry response to climatic variability to assess climate change risk: an analogue study in Eastern Canada. Tour Manag 58:196–204. https://doi.org/10.1016/J.TOURMAN.2016.10.020

Scott D, McBoyle G (2007) Climate change adaptation in the ski industry. Mitig Adapt Strateg Glob Chang 12:1411–1431. https://doi.org/10.1007/S11027-006-9071-4

Scott D, Dawson J, Jones B (2008) Climate change vulnerability of the US Northeast winter recreation- tourism sector. Mitig Adapt Strateg Glob Chang 13:577–596. https://doi.org/10.1007/s11027-007-9136-Z

Sloggett R, Scott M (2022) Climatic and environmental threats to cultural heritage. Routledge, London. https://www.routledge.com/Climatic-and-Environmental-Threats-to-Cultural-Heritage/Sloggett-Scott/p/book/9780367756369

Steiger R, Scott D (2020) Ski tourism in a warmer world: increased adaptation and regional economic impacts in Austria. Tour Manag 77:104032. https://doi.org/10.1016/J.TOURMAN.2019.104032

Saeed F, Schleussner C-F, Almazroui M (2021) From Paris to Makkah: heat stress risks for Muslim pilgrims at 1.5°C and 2°C. heat stress risks for Muslim pilgrims at 16:024037. https://doi.org/10.1088/1748-9326/ABD067

The Littleport Society (2023) Fen skating. In: Local history. Available via https://www.littleportsociety.org.uk/local-history/fen-skating/. Accessed 22 Feb 2024

Visser H, Petersen AC (2009) The likelihood of holding outdoor skating marathons in the Netherlands as a policy-relevant indicator of climate change. Clim Change 93:39–54. https://doi.org/10.1007/S10584-008-9498-6

Vyshkvarkova E, Sukhonos O (2023) Climate change impact on the cultural heritage sites in the European Part of Russia over the past 60 years. Climate 11:50. https://doi.org/10.3390/CLI11030050

Weaver M (2018) Ice skaters poised for rare spin on the Fens. In: The Guardian. Available via https://www.theguardian.com/weather/2018/feb/27/ice-skaters-poised-for-rare-spin-on-the-fens. Accessed 22 Feb 2024

Wobus C, Small EE, Hosterman H, Mills D, Stein J et al (2017) Projected climate change impacts on skiing and snowmobiling: a case study of the United States. Glob Environ Chang 45:1–14. https://doi.org/10.1016/J.GLOENVCHA.2017.04.006

Yezli S, Khan A, Bouchama A (2019) Summer Hajj pilgrimage in the era of global warming: a call for vigilance and better understanding of the risks. J Travel Med 26:1–2. https://doi.org/10.1093/JTM/TAZ069

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