CORRESPONDENCE:

Declining availability of outdoor skating in Canada

To the Editor — Climate change is, and will continue, altering the supply of ecosystem services[1,2]. Cultural ecosystem services provide important societal benefits but are challenging to operationalize[2–5]. The impact of warming on these cultural activities, such as ice skating, are likely to be among the most broadly obvious and compelling impacts of climate change[6]. Here we report that the availability and benefits of skating on the world's largest outdoor ice skating facility: declined from 1972 to 2013, was strongly dependent on weather, and is projected to continue declining with an accelerated rate between 2020–2090.

Ecosystem services, or the "benefits people obtain from ecosystems", can be categorized as provisioning, regulating, supporting, or cultural services[2,3]. Cultural ecosystem services, or "non-material benefits"[2], include aesthetics, spirituality, education, and recreation. These are often intangible, subjective, and difficult to quantify[2–5,7,8], particularly in the context of human benefits[3]. Cultural ecosystem services are generally underrepresented within ecosystem service research[5,8], and climate change projections[1]. Yet these services are amongst the most recognized and acknowledged by the general public[3–6].

We projected local weather-mediated declines in the availability and benefit of a recreational cultural ecosystem service: outdoor ice-skating. Clearly ice[9], and by extension, ice-based recreation[6,10], will be impacted by a changing climate[11]. The Rideau Canal in Ottawa, Canada, is the world's largest outdoor ice-skating surface and a UNESCO heritage site, with up to 1.3 million visitors annually (Supplementary Fig. 1). We used season length, or the days between opening and closing, to represent ecosystem service availability, and user number to represent service benefit[3]. We evaluated weather as a predictor of availability, and fitted ecological models to the relationship between use and availability[12]. Treating user numbers as analogous to resource consumption, and skating days as analogous to resource density, we compared three responses: constant increase in use with more skating days (type I); saturating increase in use with more skating days (type II); and accelerating increase in use initially, followed by saturating increase in use with more skating days[12] (type III, Supplementary Fig. 2). Combining these models with MarkSim weather projections[13] (Supplementary Methods), we projected the availability and use of this cultural ecosystem service to 2090.

Unsurprisingly, service availability was highly weather dependent. From 1972–2013, season length varied substantially year-to-year (35–90 days) with an overall decline (-5.2 ± 2.9 days per decade; 95% CI; Fig. 1; Supplementary Table 1) driven by later opening dates (6.3 ± 2.0 days per decade), not earlier closing dates (1.0 ± 2.6 days per decade). Among top models (maximum variance explained, $R^2_{max} = 0.53$), the most important explanatory variable was mean daily temperatures of the 100 coldest days of the year (Supplementary Methods). Using skating days (season length minus within-season closures) as the response variable had the same result (Supplementary Table 2).

As with availability, use varied substantially interannually (400,000–1,300,000 users), and declined overall from 1992 to 2013 (−84,000 ± 187,000 users per decade, 95% CI; Fig. 2b). User numbers were nonlinearly related to availability ($R^2_{max} = 0.82$), with use increasing marginally in long seasons but decreasing dramatically in short seasons (Fig. 2a). Use also depended on opening date with late opening seasons having fewer users than early opening seasons, independent of season length. Including both skating days and opening date, the relationship between use and availability was either type III (Akaike's corrected information criterion for model comparison[15], AICc = 478.4; $R^2 = 0.82$), or type II (AICc = 480.3;

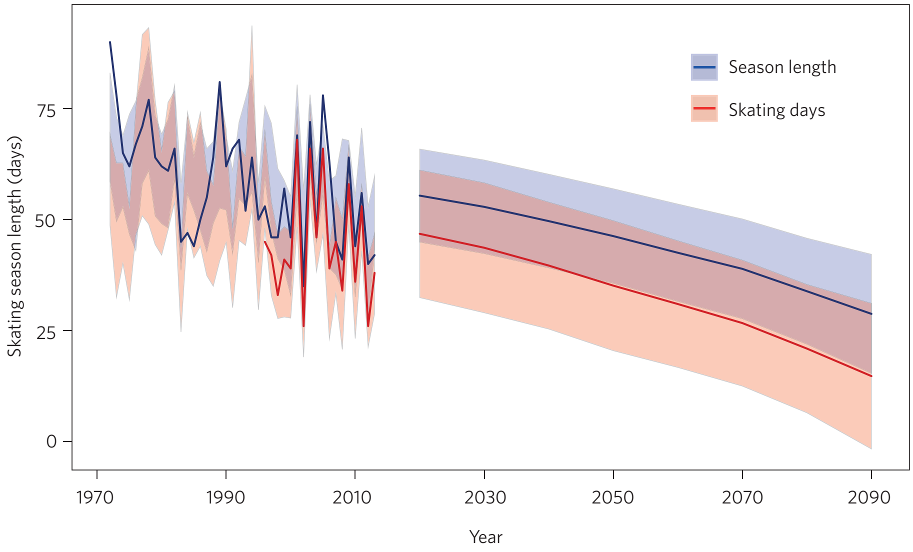

Figure 1 | Historical and projected season length and skating days at the Ridea Canal Skateway. Season length (opening to closing; n = 42) and skating days (opening to closing minus within season closures; n = 18) at the Rideau Canal Skateway are shown in blue and red respectively. Prediction intervals (80%) for the model and projections are shaded. Projections were based on simulated weather from the MarkSim Weather Generator using an average of six IPCC general circulation models and the A2 emissions scenario (see Supplementary Methods)[13].

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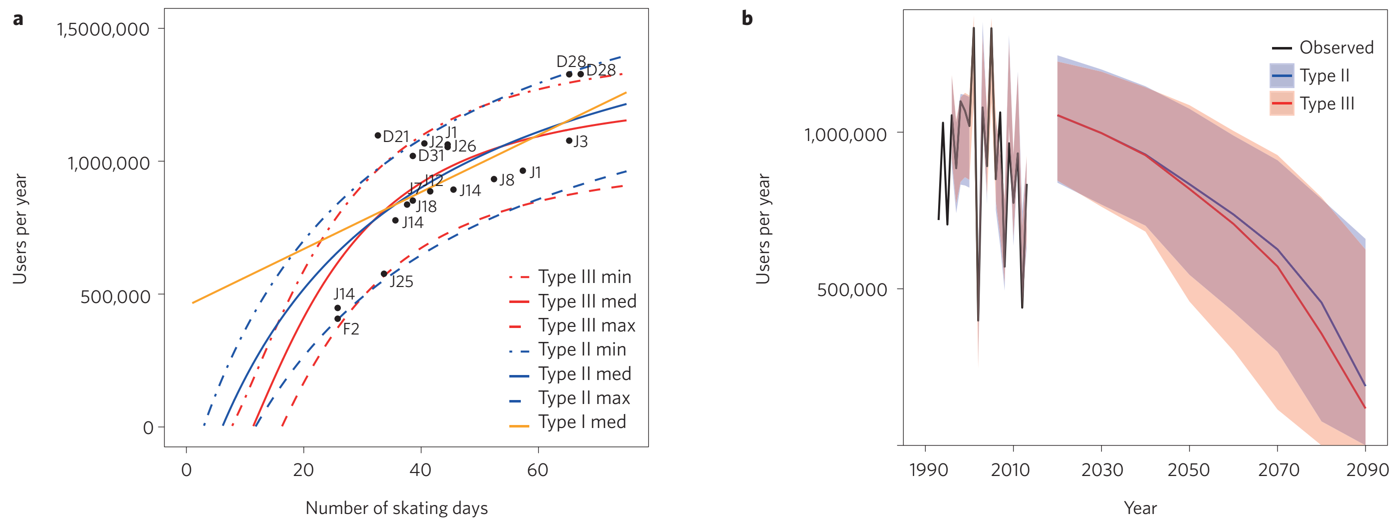

Figure 2 | Comparing different models of cultural ecosystem service benefit in terms of user numbers. **a**, Use of the Rideau Canal is plotted against availability (n = 18 years). **b**, Use of the Rideau Canal over time. All models include opening date. Points in **a** are labelled with their opening date (for example, J1 = 1 January). Holling's functional responses[11] are type: I $f(x) = ax + b$); II $f(x) = ax/(b+x)$; III $f(x) = ax^2/(b^2+x^2)$. The solid and dashed three lines in **a** plotted for types II and III represent earliest (min), median (med), and latest (max) opening dates. Shading in **b** represents 80% prediction intervals.

$R^2 = 0.80$), but probably not type I (AICc = 483.5, $R^2 = 0.77$) (Fig. 2a). Types II and III are not strongly differentiated (III is 2.6 times more likely) due to few data from very short seasons. Regardless, in either model benefits are compromised more by short seasons than they are enhanced by long seasons.

Combining models of availability and use with MarkSim weather projections based on the high-emission business-as-usual A2 scenario[13] (Supplementary Methods), we forecasted the availability of this service to decline with shorter seasons (−3.8 ± 2.0 days per decade; 95% CI), later opening dates (2.6 ± 1.5 days per decade), but not earlier closing dates (−0.6 ± 0.7 days per decade). In 1972–2013, the mean season at the canal was 58.4 ± 3.9 days (95% CI). For the 2040 horizon, all else being equal, we projected seasons of 49.7 ± 10.6 days (80% prediction interval, PI); for 2090, 28.8 ± 13.4 days. Incorporating within-season closures, mean skating days at the canal was 44.5 ± 6.5 days (95% CI) for 1996–2013. We projected 39.6 ± 14.0 days (80% PI) skating days for the 2040 horizon, and 14.7 ± 16.4 days for 2090. How use will be impacted by this reduced availability depends on the form of the relationship between use and availability (Fig. 2a): all else being equal, initial declines are identical between types II and III (−5.4% ± 1.4% mean decline in users per decade; 95% CI), but type III is more pessimistic later in the century (−67.0% ± 9.1% versus −58.5% ± 8.3% mean decline in 2080–2090). Alternatively, if measures are taken to limit global mean temperature increase to 2 °C, the projected use and availability of the canal would correspond to approximately the 2040 time horizon.

In our projections based on the high-emission business-as-usual A2 scenario, the declines are probably underestimated. Since 1970, the Rideau Canal has experienced an accelerating rate of warming with mean winter temperatures increasing 0.51 °C per decade between 1970–1990 and 1.3 °C per decade between 1991–2013 (Supplementary Fig. 3). Similarly, other analyses of ice-based recreation have found accelerating rates of warming, leading to accelerating declines in ice skating indicators persisting since the 1970s[6,10]. Meanwhile, the general circulation models used by MarkSim have consistently underestimated the accelerating rate of global warming since 1983[14] (Supplementary Discussion). As a result, our temperature projections appear optimistic given the historical trend (Supplementary Fig. 3). Since season length and use are highly sensitive to errors in temperature, an underestimation of warming will lead to overly optimistic forecasts in both. Projections of use in particular seem discontinuous with the historical trend (Fig. 2b). Simple extrapolation suggests a more rapid decline in both is possible.

Here we presented a case study of the importance of weather in determining recreational cultural ecosystem service availability and use historically, and projected an accelerating decline in both due to warming. Recreation is a more readily quantified cultural ecosystem service[5]; as such it represents an opportunity to quantify the linkages between physical drivers, cultural ecosystem services, and human well-being[2,7]. Many other cultural ecosystem services are not so easily quantified (for example, spirituality)[5], and their connections with human well-being and the physical environment are complex[2]. Nevertheless, using visitor numbers as a quantitative index of human benefit[3] in this case enabled the demonstration of a nonlinear relationship between service benefits and availability. Other recreational ecosystem services may also have low availability thresholds below which their use rapidly declines, and high availability thresholds above which their use saturates. Cultural ecosystem services that are responsive to weather may emerge as among the most compelling indicators of long-term climate trends. ❐

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Author Contributions
J.B. conceived the study and gathered data from the National Capital Commission. J.S. simulated future weather data using MarkSim. J.B., in consultation with J.S. and M.H., conducted the analysis and wrote the manuscript. J.S. and M.H. edited the manuscript.

Additional information
Supplementary information is available in the online version of the paper.

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COMMENTARY:

Institutional coordination of global ocean observations

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A sustainable global ocean observation system requires timely implementation of the framework for ocean observing. The recent Qingdao Global Ocean Summit highlighted the need for a more coherent institutional response to maintain an integrated ocean-observing system.

Approximately 93% of the additional heat associated with global warming is stored in the ocean[1], and recent discoveries show that an enhanced heat storage in the subsurface ocean over the past decades contributed to the global surface warming hiatus[2–5]. This is just one example that highlights the importance of ocean observations in understanding, monitoring and detecting global climate change, and providing the basis to assess the impacts of climate and environmental change on the ocean.

Ocean observations, the 'bread and butter' of ocean and climate change science, are predominantly conducted by a limited number of large ocean research institutions. At the international level, the World Climate Research Program (WCRP) provides the framework to coordinate climate and ocean science, the Partnership for Observing the Global Ocean (POGO) and the intergovernmental Group on Earth Observations (GEO) offers a venue for discussion and collaboration on ocean observing, and the Global Climate Observing System (GCOS) with its Global Ocean Observing System (GOOS) produces a framework to identify and globally coordinate observations that are critically needed. However, the level of global commitment to sustained ocean observing is falling short of the requirements. This challenge was highlighted at the recently held Global Ocean Summit, on 25–26 October in Qingdao, initiated by newly elected member of the Chinese Academy of Sciences, Lixin Wu of the Ocean University of China. We call for such a summit to continue.

At the summit, leaders from 61 universities and research institutions, from both developing (22 institutions) and developed (39 institutions) nations, presented their needs and capabilities in ocean science and the required underpinning ocean observations. Their work in the development of new technologies and their ocean observation activities in the open ocean (surface and deep) and below sea ice, both on-going and planned, was highlighted at this summit. Importantly, leading world ocean researchers discussed collaboration methods for inter-institutional scientific and logistic coordination. Such coordination is particularly challenging because of the differences in funding cycles between nations. However, a globally coordinated effort will reap enormous benefits — improved international coordination will help to deliver both a great return on investment and strong science outcomes, and facilitate the emergence of technologies and capabilities for observing deep and unknown parts of the ocean. The international Argo program[6] provides an example of the success of such coordination. A collaborative partnership of more than 30 nations, the Argo program has built a global array of more than 3,500 free-drifting profiling floats that measure the upper 2,000 metres of the ocean every 10 days. This program, for the first time, allows continuous monitoring of ocean temperature and salinity on a global scale, with all data relayed and made publicly available within hours after collection. The 10 years of data with over 1,000,000 profiles have been used widely, including studies that examine the distribution and changes in heat and water cycles[7–9].

Such international collaboration is rare though and there is much a regular global ocean summit could do. Firstly, it can be a forum to promote implementation and coordination of the existing framework of ocean observations[10]. This framework (Fig. 1) was established as a result of the OceanObs'09 conference (http://www.oceanobs09.net), which took

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