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Increasing risk of heat stress at the Summer Olympics

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Abstract

Rising temperatures under climate change threaten athlete safety at the Summer Olympics due to increasing heat stress likelihoods. For outdoor sports, suspending activity (i.e. rescheduling or cancelling) is the only possible intervention for mitigating heat stress risk in excessively hot or humid conditions, presenting logistical challenges to organizers. We evaluate the event suspension probability of outdoor Summer Olympic sports in past and potential future host cities due to unsafe climatic conditions for the recent past (1983–2016) and future projected in 2050. Assuming that >50% event suspension probability is logistically

prohibitive, the number of viable host cities decreases from 709 to 595 (16%) in 2050. Remaining viable hosts are more affluent, located at higher elevations and latitudes, or in the Southern Hemisphere. Our results highlight growing heat-related risks at athletic events and can inform planning and adaptation priorities for future Summer Olympics.

Keywords: Extreme Heat, Summer Olympics, Heat Stress, Athletes

Main

Exercising generates metabolic heat that rapidly elevates body temperature if ambient conditions (temperature, humidity, wind, and radiation) do not permit sufficient heat dissipation at the skin surface to the surrounding environment [1]. Protective equipment and apparel hamper the evaporation of perspiration and may further accelerate rises in body temperatures [2, 3]. If an athlete's internal temperature reaches ∼40°C, exertional heat stroke (the most severe form of heat illness) may occur, becoming fatal if not treated properly [4].

Staging athletic competitions in the warm season, such as the Summer Olympics, thus entails managing the complex scheduling and logistics of large sporting events while mitigating heat risks to ensure athlete safety. Meanwhile, climate change is increasing global mean temperatures and the frequency of extremely hot and often humid days [5–7]. As the climate warms, typical protocols for managing athlete heat stress risk (e.g. increasing hydration or implementing cooling strategies) may not be sufficient to prevent critical levels of athlete heat strain [8, 9].

Rescheduling events to avoid the hottest time of the day or relocating them to cooler locations may help; organizers of the Tokyo 2020 Summer Olympics rescheduled events across at least eight sports due to excessively hot and humid conditions and relocated the endurance race walk and marathon events from Tokyo to Sapporo, which has a relatively cooler climate [10]. However, increasing needs for such adaptations in future Summer Olympics could become overly disruptive to the scheduling of events

that often span multiple days and rely on shared facilities. They may even be improbable in cases where even nighttime temperatures are exceedingly warm and humid, such as the 2019 International Association of Athletics Federations World Athletics Championships staged in Doha, Qatar, during which the women's marathon was held at midnight yet 40% of competing athletes still dropped out of the race due to heat [11]. Cities with confirmed interest in bidding to host the 2036 Summer Olympics include Nusantara (Indonesia), Ahmedabad (India), Doha (Qatar), and Riyadh (Saudi Arabia), exemplifying how sport globalization has increased the percentage of submitted and awarded host city bids from low- and middle-income nations that are often in hotter or more tropical climates than past hosts. As the geographic diversity of Summer Olympics hosts thus grows, organizers will face unprecedented challenges in preparing for heat adaptations. Projections of heat stress risk that account for geographic trends in future climate change are therefore necessary to inform decision-making on the suitability of Summer Olympics host cities.

Importantly, climate does not uniformly affect the heat stress risk of athletes due to the differing physiological demands across sports [12]. Although some previous studies assessed heat stress risks for individual events (e.g. the marathon) or in specific Summer Olympics host cities [13, 14], none have comprehensively assessed the projected impact of climate change on athlete heat-health risk across the full range of Summer Olympics sports or potential host cities. Here, we use a biophysical model of heat stress that accounts for sport-specific factors influencing thermoregulation [8] and detailed climate data to systematically analyze heat stress risks related to 27 sports (all outdoor sports where athletes are not immersed in water included in the Paris 2024 Summer Olympics), encompassing 156 medal events (all event competitions—i.e. heats or rounds—of an athletic discipline leading to a unique medal award) (Tables 1, 2), across 880 potential host cities (all global metropolises with populations $\geq$600,000). Details of our analytic approach are described in Methods. In summary, we use high

resolution (0.05°) gridded temperature and relative humidity data from the Climate Hazards Center Coupled Model Intercomparison Project Phase 6 [15] to evaluate city-scale changes in heat stress risk in 2050 under Shared Socioeconomic Pathway (SSP) 2-4.5 relative to a historical period (1983–2016). In each case, we analyze the five months between June–October to understand the potential shift in heat stress risk during the full range of dates over which the Summer Olympics have historically occurred and may occur in the future [16]. Our modeling uses the Sports Medicine Australia Extreme Heat Policy (SMA EHP v1) framework to classify sports into categories (Sport Classifications) based on player heat stress risk given the activity's exertional demands (i.e. due to the intensity and/or duration of play), creation of natural convection through movement, and the insulation and evaporative resistance characteristics of protective equipment and uniforms. The combinations of temperature and relative humidity that correspond to thresholds of heat stress risk—from low to moderate, high, or extreme risk—depend on the Sport Classification (Fig. 1a). The "extreme" risk category corresponds to conditions that are unsafe for exercise and thus for which suspension of physical activity is strongly recommended to prevent heat illness. We define host city viability based on the percentage of days and city area with extreme heat risk for any given outdoor sport weighted by medal events, a proxy for the likelihood of event suspension at any location within the city throughout the months between June–October.

Results

Heat stress risk in past Summer Olympic host cities

Nine Summer Olympics occurred between 1983 and 2016 (the range of available historical data from CHC-CMIP6): Los Angeles 1984, Seoul 1988, Barcelona 1992, Atlanta 1996, Sydney 2000, Athens 2004, Beijing 2008, London 2012, and Rio de Janeiro 2016.

In Fig. 1a, the spatial means of daily maximum temperature (T_{max}) and concurrent relative humidity (Rh_x) for each day of these past Summer Olympics are plotted against the SMA heat stress risk thresholds. Considering all Sport Classifications, the heat stress risk during peak daytime conditions was low across 38% of days, during which adequately hydrating and removing excessive clothing will sufficiently reduce risk, moderate across 35% of days, requiring increased frequency and duration of breaks, and high across 10% of days, necessitating active cooling of the athletes' body (e.g. submerging limbs in cold water, drinking cold fluids) [8, 9]. Peak daytime conditions rarely (2% of days) crossed the extreme heat stress risk threshold, at which point activity suspension should be considered; extreme conditions only occurred during Atlanta 1996 and Beijing 2008. Validating the SMA thresholds with a retrospective analysis of reported incidence rates of heat-related illness at past Summer Olympics is challenging due to inconsistent practices in the collection and dissemination of such data, which often reflects a combination of hazard, exposure, and adaptation and often is reported as a sum total of incidences rather than at daily or subdaily frequencies. Nevertheless, there is anecdotal evidence that days on which T_{max} and Rh_x were in the range of extreme risk (Fig. 1a) corresponded to an increased incidence of heat illness—a third of cyclists did not finish the men's road cycling event that took place on August 9th during Beijing 2008 due to extreme heat [17] while heat-related encounters between medical professionals and spectators and staff peaked on July 20th during Atlanta 1996 [18].

The conditions averaged over space obscure relevant city-scale variations of climate across geographic locales, which we illustrate by comparing conditions during Beijing 2008 and Los Angeles 1984 (Fig. 1b,c). At Beijing 2008, each individual day had generally uniform heat stress risk across the city, though synoptic weather variability led to substantial differences in the day-to-day heat risk (Fig. 1b). In contrast, Los Angeles 1984 experienced larger variations in heat risk across space than from one day

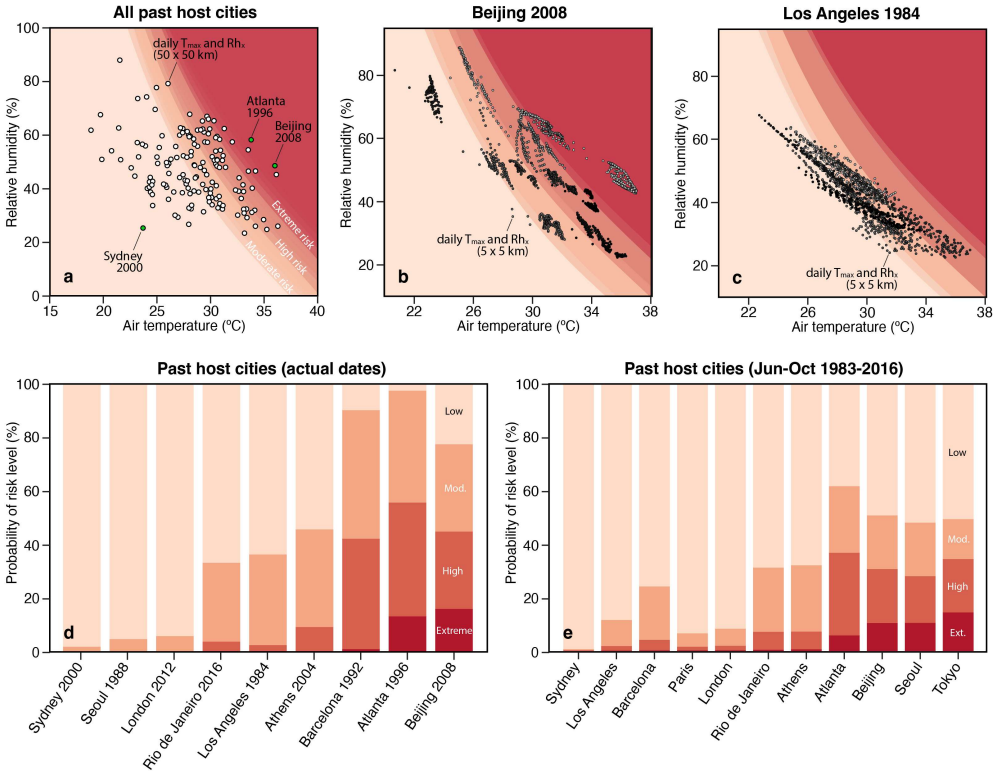


Fig. 1 Heat stress risk at past Summer Olympics. a) Observed daily maximum temperature and corresponding relative humidity for nine past Summer Olympics during their actual dates. Each data point represents one day, averaged over a 50×50 km area centered over a given host city (grid cells over the ocean were omitted). Specific days belonging to Atlanta 1996, Beijing 2008, and Sydney 2000 are highlighted. **b)** Spatial variability in the Beijing 2008 Olympics during its actual dates (Aug. 8–24). Each point represents a 5×5 km grid cell on a particular day, and colors correspond to the day in the Olympics where darker points are later in time. **c)** Same as (b) but for the Los Angeles 1984 Olympics during its actual dates (Jul. 28–Aug. 12). **d)** Risk conditions for historical hosts during the actual dates they occurred (the probability across all sports and spatial grid cells of falling in a given risk level). **e)** Risk conditions for selected past hosts for June–October during the entire historical period (adding in Paris and Tokyo whose actual dates do not fall in the range of CHC-CMIP6). In both panels (d) and (e) cities are ordered by their event suspension probability (extreme risk).

to another due to the city's coastal location and steep gradient in climate from the ocean to semi-arid inland regions (Fig. 1c). These patterns need to be considered for each location individually, as adaptations for cities like Beijing might involve altering the day of the week at which events occur, while for cities like Los Angeles, strategically choosing the location of individual events within the city area might be more advantageous.

As such, we consider the likelihood of conditions on any given day to exceed each heat stress risk threshold in any grid cell within a city's domain to determine the event suspension probability of outdoor Summer Olympics sports. Calculated for these 9 historical host cities across the dates their respective Summer Olympics occurred, extreme risk of heat stress was highest in Atlanta and Beijing, at 16% and 18%, respectively (Fig. 1d). Atlanta and Beijing, along with Barcelona, also had the greatest number of days in the high risk category (Fig. 1d). To better understand how the heat stress risk experienced at these past events compared to the range of probabilities that event organizers and/or the International Olympic Committee (IOC) might have prepared for, we repeated the event suspension probability calculation for the entire 5-month window during which the modern Summer Olympics have occurred (June through October) for the years from 1983–2016 (Fig. 1e). We expanded this analysis to include Tokyo and Paris, as it is reasonable to assume that the 1983–2016 climate of these locations may have informed their selection for host city of the 2020 and 2024 Summer Olympics, respectively. According to this analysis, Tokyo had the highest mean event suspension probability at 14%, exceeding that of Atlanta, Beijing, and Seoul, which had event suspension probabilities of 6%, 10%, and 10%, respectively (Fig. 1e, Table 3). While the mean event suspension probabilities are relatively low due to our inclusion of shoulder season months, we note that there is a large spread in the metric when calculated across discrete 17-day intervals throughout the warm season due to the seasonal cycle and synoptic temperature variability (Table 3). For example, in Tokyo, Beijing, and Seoul, there was a 1% probability that at least 65% of events would be canceled depending on the exact dates chosen and weather conditions.

Though heat was a challenge at the Atlanta 1996, Beijing 2008, and Tokyo 2020 Summer Olympics [19, 20], all medal events concluded successfully in each host city. Therefore, we can assume that a 14% event suspension probability is not sufficiently high to limit a host city's viability during the selection process, nor is managing event

staging during the actual Games when city-area climate corresponds to an 18% event suspension probability.

Current and future host city viability

To evaluate projected changes to the number of climate-viable host cities, we consider a range of event suspension probabilities that are plausible limits from an event management perspective, though the IOC's tolerance for this metric is not publicly known. We consider limits up to a 50% event suspension probability; values >50% suggest that, on eligible Summer Olympics days, over half of outdoor events would need to be suspended to mitigate heat risk. As approximately 11 of 25 Paris 2024 outdoor sports are typically played across 8 or more days, we assume this would pose an excessive burden to the Games' delivery. Projected changes in T_{max} and Rh_x will decrease the number of climate-viable Summer Olympics host cities by 114, 131, 126, 145, and 137 cities for event suspension probability limits of 50%, 40%, 30%, 20%, and 10%, respectively (Fig. 2a). It is also important to consider the diurnal cycle of extreme heat stress risk, since holding events earlier or later in the day is a heat countermeasure organizers may employ. Repeating our event suspension probability calculation with daily minimum temperatures (T_{min}) and corresponding relative humidity (Rh_n) shows that, though more cities overall remain climate-viable under 2050 projections compared to estimates based on T_{max}, warming nighttime temperatures will lead to a greater shift in the proportion of climate-viable to nonviable cities (Fig. 2a). This result is consistent with past observations that nighttime extremes are warming more than daytime extremes [21]. Given that the majority of Olympics events are currently held during the daytime radiative conditions (Fig. 2b), however, we argue that the daytime risk assessment is more relevant to Summer Olympics hosting viability. For remaining results, we consider viable host cities to have peak daytime conditions corresponding to <50% event suspension probability. This limit is less stringent than some used in prior studies (see Methods), though was chosen to be as broad in scope

as possible in terms of future viable host cities while still capturing changing patterns of heat stress risk.

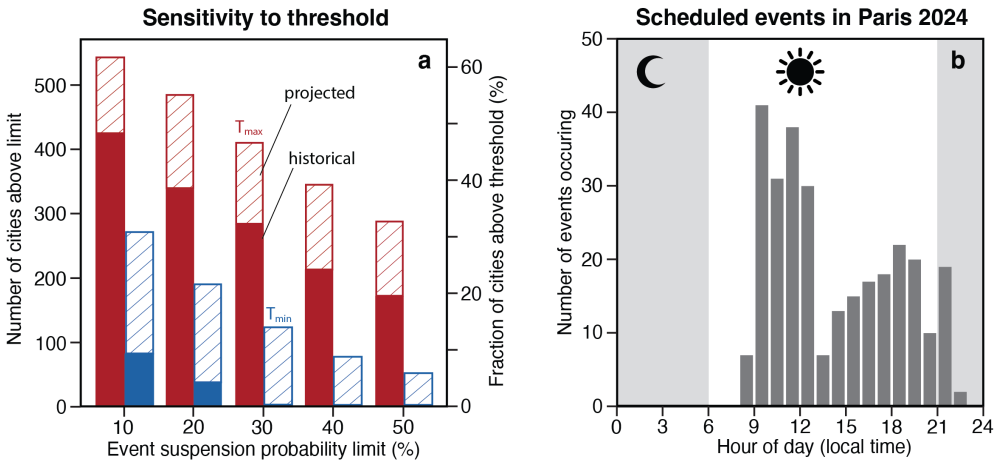


Fig. 2 Role of diurnal cycle and event suspension probability limits on host city viability. a) Percent of potential Summer Olympic host cities that are viable based on event suspension probability in the near recent historical period (1983–2016; solid shading) and mid-century projections (2050; solid plus hatched shading), for thresholds of viability ranging from <10% event suspension probability to <50% event suspension probability. Results are shown for peak daytime (red) and minimum nighttime heat conditions (blue). **b)** Daily scheduling of outdoor sport events at the Paris 2024 Summer Olympics summed across its 19 total days. Nighttime hours (between sunset and sunrise) are shaded in darker grey, highlighting that most events occur during the day.

The latitude and elevation of potential host cities are key determinants of event suspension probability due to extreme heat stress risk. Fig. 3a highlights the geographic trends in event suspension probability across major metropolitan areas for the recent past (1983–2016); cities with climates that exceed the 50% limit (red colors) are concentrated in tropical latitudes and risk broadly decreases with increasing latitude. One exception to this pattern is high-elevation tropical cities, such as those in the Western Ghats (southwest India) or the Mexican Plateau, which have comparatively minimal risk relative to adjacent low-lying cities. In the Southern Hemisphere there is a weaker latitudinal gradient in event suspension probability because the Summer Olympics occur during the hemisphere's cool season (Jun.–Oct.), when extreme risk thresholds are almost never surpassed.

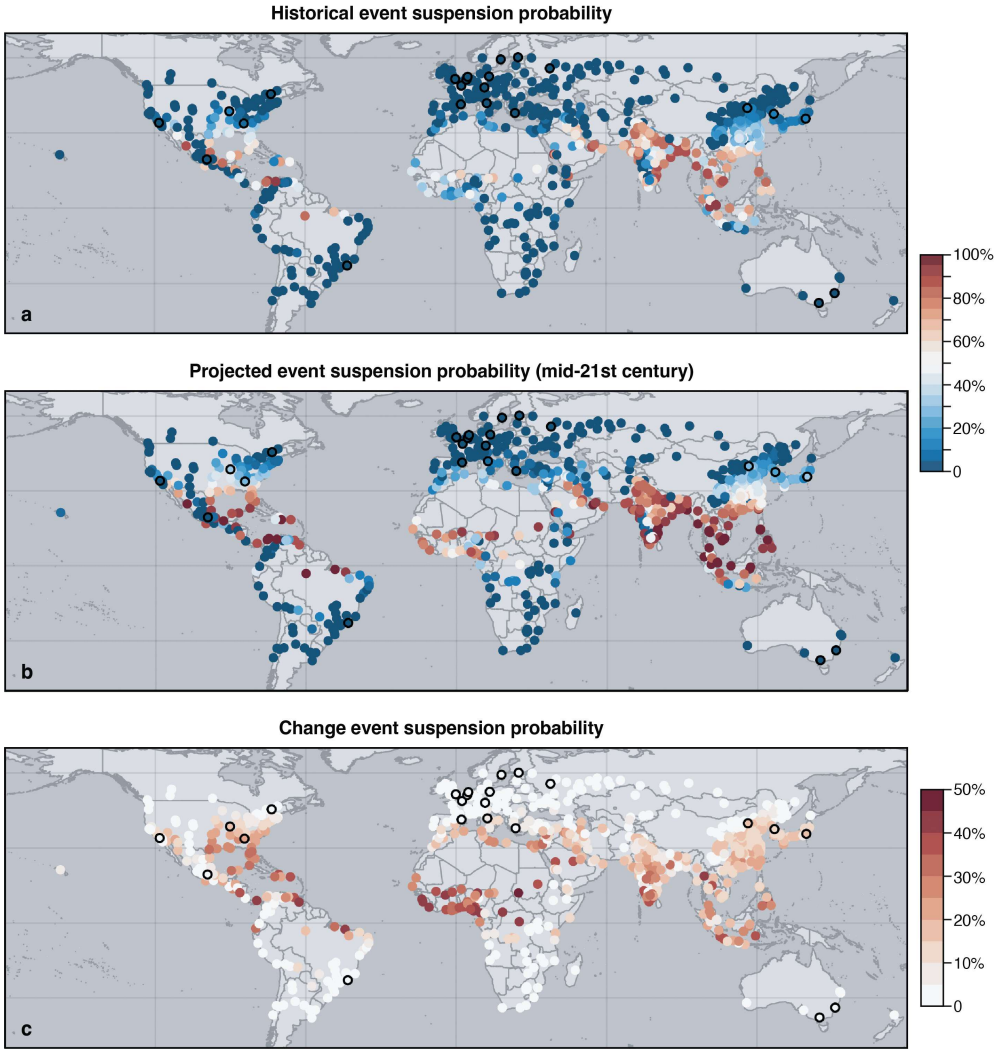


Fig. 3 Geography of event suspension probability across potential host cities. a) Event suspension probability for all potential host cities during the historical period (Jun–Oct, 1983–2016). **b)** Same as (a) but for mid-21st century projections (Jun.–Oct., 33 years with 2045–2055 climatology). **c)** Change in event suspension probability between the historical and projected periods (projection – historical). Black bolded outlines signify that cities have hosted a modern Summer Olympics.

Our results indicate that projected changes in climate by the mid-21st century will increase the event suspension probability for outdoor Summer Olympic sports by 12.4% ± 11.1% (compared to a baseline historical probability of 22.4% ± 27.7%). During the 1983–2016 period, only one city (Johor Bahru, Malaysia) had an event

suspension probability exceeding 95%, meaning outdoor Olympic sports are unsafe in peak daytime conditions nearly every day of the extended summer season. By the mid-21st century, event suspension probability in 58 cities (7% of all potential hosts) will be >95%.

The implications of projected climate change on event suspension probability in all 880 potential host cities ultimately reflects the geographic trends in the historical data (Fig. 3b). The disparate impact of climate change on future risk of athlete heat illness is connected to the likelihood of extreme heat illness risk occurring in a city's historical climatology; cities with climates that currently translate into only low to moderate risk of heat illness are projected to experience little increases in the likelihood of extreme risk conditions while future warming is clearly sufficient to push the edge climates of cities that already experience some likelihood of high or extreme risk of heat illness into the extreme risk category more frequently (Figs. 3c, 4a). Cities with the highest historical event suspension probabilities experience a relatively lower magnitude increase in risk for peak daytime conditions due to climate change (Fig. 4a), though this reflects the fact that nearly 100% summer days in these cities are already unsafe for hosting sporting events. However, these cities will experience the most substantial increases in extreme heat stress risk during nighttime, while cities outside of the humid tropics have projected climates that will likely still be relatively safe for exercise at least during the coolest parts of the day (Fig. 5).

Future climate change will lead to a shrinking of the geographic diversity of viable host cities from a heat risk perspective. While cities in low-income nations are more likely to be nonviable in both the past and projected climate, climate change will increase proportions of nonviable cities from middle- and high-income nations (Fig. 4b). Viable cities in the projected 2050 climate will be more confined to the extratropics and high elevations, particularly in the Northern Hemisphere (Fig. 4c, d). There are only 32 cities where the event suspension probability is zero in the mid-21st century

(compared to 65 cities in the historical period), meaning no grid cells within 25 km of the city center will face temperature and humidity conditions that exceed the extreme risk threshold for any sport. These zero-risk cities all fall within at least one of the three geographic categories discussed above, i.e. located at high extratropical latitudes (e.g. Oslo, Norway 60°N), the Southern Hemisphere (e.g. Melbourne, Australia 37.8°S), or high elevations (e.g. Nairobi, Kenya located near the equator but at ∼1.8 km above sea level).

Discussion and Conclusion

Disruptions or delays to medal events held during the Summer Olympics pose significant logistical challenges to organizers and can adversely impact their economics and legacy. As best practices mandate suspending athletic events when ambient climatic conditions exceed unsafe thresholds of temperature and/or humidity [8, 9, 12], we consider event suspension probability under daily T_{max} and associated Rh_x as a metric for evaluating the viability of potential Summer Olympics host cities. Climatological (1983–2016) values of event suspension probability in past modern Summer Olympics host cities are relatively low (<14%, Fig. 1e), and only reached a maximum of 18% during Beijing 2008 (Fig. 1d) across the approximately two-week period recent Summer Olympics have actually occurred. As such, we reason that levels of this metric tolerable to organizing bodies is >18%. With the assumption that a 50% event suspension probability would sufficiently hamper a city's ability to successfully host the Olympics, we find that projected shifts in climate will decrease the number of viable host cities in 2050 by 16% (from 709 to 595). Low-lying cities in the Northern Hemisphere tropics and subtropics have the greatest historical and projected event suspension probabilities. This trend is consistent with prior work that has established the tropics as experiencing both the highest baseline levels of heat risk and heightened accumulation of humid heat in a warming climate [7]. Cities with historical event

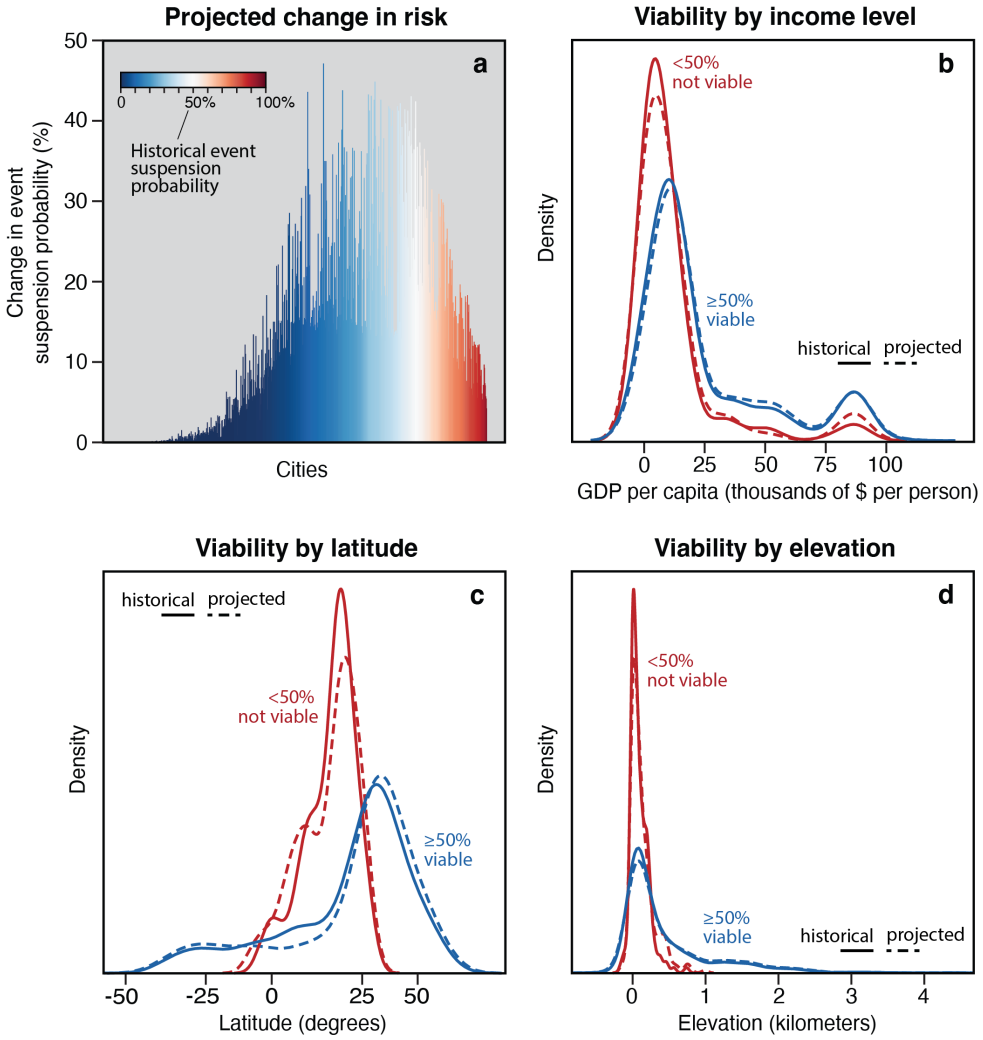


Fig. 4 Characteristics of viable and nonviable potential host cities. a) Change in event suspension probability (in percentage points on the y-axis) between the historical and projected periods (projection − historical) for all potential host cities. Cities on the x-axis are sorted by increasing event suspension probability in the historical period, from 0% to 95.6%, which also shades each bar. **b)** Density of viable and nonviable cities by GDP per capita in 2024 of the country in which each city is located according to an event suspension probability limit of 50%. **c)** Same as (b) but by latitude (°N). **d)** Same as (b) but by elevation (meters above sea level).

suspension probabilities $\gg$50% will experience the largest increases in extreme heat

stress risk during nighttime (Fig. 5), while those that have historical event suspension probabilities around the 50% limit ($\sim \pm 20\%$) will see the greatest increases to extreme risk by 2050 based on projections of T_{max} (Fig. 3, 4a).

Overall, we find that rising greenhouse gases will exacerbate conditions in cities with historically moderate to high risk of heat stress and may thus complicate their viability as potential hosts. Built into our analysis is the assumption that sporting events currently held outdoors will continue to be held outdoors and during peak daytime hours (c.f. Fig. 2b). However, novel and heightened heat adaptations may weaken these assumptions. For example, events might be shielded from the sun to reduce heat exposure, or held in large air-conditioned stadiums such as those constructed for the Qatar 2022 World Cup [22]. Leveraging existing arenas would require balancing the schedule around traditional indoor events while new construction of such facilities may pose a financial barrier for low- to middle-income host cities. Increased construction and use of climate-controlled facilities additionally conflicts with the IOC's stated sustainability initiatives and commitment to reducing their direct and indirect emissions of greenhouse gas emissions [23, 24]. Perhaps, instead, the IOC may consider decentralizing the role of Summer Olympics "host" by holding events in different cities within a host country or region, such as occurred ad hoc in Tokyo 2020 and is planned for Brisbane 2032. Moving events with higher heat risk (e.g. SMA Sport Classifications 4 and 5 for which high activity intensity is coupled with clothing/equipment that impairs heat loss) to cooler parts of the day could also mitigate some risk. Yet, even when considering daily T_{min} and associated Rh_n, 50 cities will be nonviable hosts in 2050 by our metric. Alternatively, adjusting the timing of the Summer Olympics earlier or later in the season—an adaptation largely eschewed by the IOC in the last two decades in hopes of optimizing television ratings [25] but recently floated by IOC president-elect Kirsty Coventry [16]—may broaden the number of viable host cities. The low levels of heat stress risk in Southern Hemisphere cities clearly demonstrate

the heat-health benefits that this adaptation would provide. Ultimately, given that the event suspension probabilities of all past Summer Olympics host cities are below the 56th percentile (Fig. 4a, Table 3), future organizers will likely need to implement unprecedented levels of heat adaptations (c.f. Racinais et al. [12]).

There are some important caveats to our analysis. Our analysis of heat stress risk calculated from T_{max}/Rh_x (or T_{min}/Rh_n) considers only the worst case scenario in regard to solar radiation, i.e. that outdoor athletes are competing under clear skies, and does not account for the effects of cloudiness or wind. The impact of climate warming on these factors is still uncertain, however, so their projected contributions to heightened heat stress risk is an open question. Some cities that are viable from a heat risk perspective may additionally be eliminated because of projected increases in other climate-related hazards, such as sea level rise or extreme precipitation-driven flooding, harmful air quality days, and wildfires [14]. Furthermore, here, we considered only one emissions scenario for mid-century projections. Future work could examine conditions that span further into the future as well as incorporate multiple emissions scenarios to capture the impact of climate change uncertainty on these Summer Olympics heat stress risk projections. Finally, the determination of host city viability is sensitive to the event suspension probability limit that organizers consider tolerable. We have presented most results with a relatively conservative threshold (>50% event suspension probability yields non-viability). Without public guidance from the IOC on this metric, there is ambiguity in our findings on the impact of climate change on the number of viable vs. nonviable cities.

The IOC appears to account for both modern and projected climate in their evaluation of a host city's "Games Delivery" success potential in a limited capacity, as evidenced in the official host city feasibility assessment for the Brisbane 2032 Summer Olympics [26]. This report examines mean July-August temperatures in Brisbane calculated from historical station data and coarse-resolution 2050 projections (under

two possible emissions pathways). The extent to which this information influenced the selection process or planning strategies is unclear as events will be played in 3 cities (Sunshine Coast, Brisbane, Gold Coast) across a ∼150 km stretch of the Queensland region, yet, the IOC only considered climate data for the Brisbane city center [26]. Our analysis revealed significant geographic diversity of historical and future heat stress risk at the sub-city scale by considering high resolution data within a 2500 km^2 region around each urban conglomerate. These nuances underscore the importance of using high-spatial and temporal resolution data in developing heat risk projections to capture the fine-scale patterns that emerge within cities and in day-to-day weather variations. The lack of humidity data included in current IOC assessments of future risk also limits their ability to evaluate heat metrics that are most relevant for human health.

While the focus of this study was on the evolving risk of heat illness in competitive athletes, spectator safety is also a critical concern for "mega-events" such as the Summer Olympics that draw over 5 million attendees [27, 28]. Our analysis suggests that leisurely walking (SMA Sport Classification 1) in 2050 will carry the same heat illness risk as playing rugby or mountain biking (both SMA Sport Classification 4 activities) today (Fig. 6). As the SMA thresholds are designed for healthy adults, we can infer that the heat stress risk is even greater for spectators and staff with comorbidities or advanced aging. This finding underscores the need for future event organizers to also prepare for increased risk of heat-related afflictions in spectators and on-the-ground staff.

We suggest that climate variability and change should be more robustly incorporated into IOC host city evaluation, and evaluation of locations for large sporting events in general. Our study highlights how high-resolution projections and accounting for activity-specific physiological demands are necessary to adequately project future heat stress risk. They may be particularly useful in informing decision making on fine

details of event planning, such as daily scheduling, the impact of Olympic Village and event venue locations on risk exposure, and the heat preparedness of athletes, coaches, and spectators. Our assessment of heat risk across potential host cities reveals how IOC goals to both broaden host city participation and improve sustainability of Summer Olympics may be seriously challenged by both present and projected future heat risk. Finally, although we focused on the Summer Olympics and professional athletes, our results have broader relevance for understanding how climate change will impact daily life in the future. The scientific and epidemiological literature on heat risk has generally focused on survivability and mortality, but our results add to the growing body of literature showing that rising risks of heat illness will increasingly limit where and when outdoor exercise, recreation, and labor will be safe.

Methods

Potential Summer Olympics host cities

Since the beginning of the modern Summer Olympics, only 23 cities have been hosts, but there are significantly more possibilities across the globe. Prior work from [29] identified that, though country-level economic and political indicators are an important determinant in the IOC host city selection process, city size and population were the most robust city-scale predictors of potential host city bid success. We therefore consider all global metropolises with populations greater than 600,000; this value reflects the lowest Summer Olympics host city population since World War II and should reasonably correlate to the structural and financial capabilities of a candidate city [13]. To construct a list of potential host cities, we selected urban agglomerations with populations >600,000 in 2015 based on the United Nations World Urbanization Prospects dataset [30]. Our choice to use urban agglomeration population—defined as "contained within the contours of a contiguous territory inhabited at urban density levels without regard to administrative boundaries" [31]—rather than city population reflects the

tendency for events within one Olympics to be held across greater metropolitan areas rather than strictly confined within city limits. For example, Los Angeles 1984 venues were actually distributed across multiple southern California counties: Los Angeles, Ventura, Riverside, and Orange. This analysis resulted in 880 candidate host cities.

Historical and projected climate data

To calculate heat stress risk, we used daily maximum temperature (T_{max}) and corresponding relative humidity (Rh_x; i.e. the relative humidity co-occurring with T_{max}) and daily minimum temperature (T_{min}) and corresponding relative humidity (Rh_n; i.e. the relative humidity co-occurring with T_{min}) from the ultra-high-resolution (0.05°) University of California Santa Barbara Climate Hazards Center Coupled Model Intercomparison Project Phase 6 (CHC-CMIP6) gridded data product [15]. The dataset leverages high-resolution observations of internal climate variability captured in weather station and satellite data over the historical period (1983–2016) in combination with coarse-resolution direct climate model output to generate daily gridded projections of historical and mid-century climate. The development of the CHC-CMIP6 dataset is detailed in [15]. In brief, they calculated multi-model ensemble mean monthly climatologies of T_{max}, T_{min}, Rh_x, and Rh_n for historical (1850–2014) and future (2015–2100) simulations included in CMIP6, with the ensemble totaling 152 simulations from 25 models. The change (i.e. delta) between the monthly climatologies for the projected mid-century (2045–2055) and near-past (1983–2016) were interpolated to 365 daily delta values. By adding the daily deltas to the corresponding daily observed climate data (i.e. the same delta value was added to each January 1st), their methodology generates high-resolution, bias-corrected future projections that represent a range of possibilities for a 2050 (mid-21st century) climate while still reflecting the range of internal variability during the observational period. The CHC-CMIP6 product contains future projections that are forced with both Shared

Socioeconomic Pathway (SSP) 2-4.5 and 5-8.5 scenarios, but we selected the SSP2-4.5 scenario because it represents a likely, "middle-of-the-road" projection of near-future climate; SSP2-4.5 corresponds to a 2.1°C–3.5°C increase in global mean surface temperature by the end of the century relative to 1850–1900 [32, 33]. Additionally, the high spatial resolution of CHC-CMIP6 enables analysis of climate variability at the sub-city scale relevant to our examination of potential Olympics host cities and their surrounding areas.

For auxiliary geographic analysis, elevation data was obtained from the National Geophysical Data Center 5-min ETOPO05 product [34]. Estimates of gross domestic product per capita for the year 2024 were obtained from the World Economic Outlook Database from the International Monetary Fund [35].

Sports and quantifying heat risk

To quantify the heat stress risk for given ambient climatic conditions, we use the Sports Medicine Australia's Extreme Heat Policy version 1 [8] biophysical model, though it was recently updated in [9].

The SMA EHP v1 framework is unique in its sport-specific approach to quantifying heat stress risk. The 2021 policy categorized 39 of the most popular athletic disciplines into five Sport Risk Classifications (hereafter referred to as Sport Classifications) based on the impact of their exertional demand and clothing worn on thermoregulation under direct solar radiation. Sport Classification 1 (corresponding to leisurely walking) carries the lowest inherent heat stress risk while Sport Classification 5 has the highest inherent heat stress risk. For our analysis, we consider only the outdoor athletic disciplines participating in the Paris 2024 Summer Olympics (Tables 1, 2; [36]), but note that the total number of outdoor events varies across Summer Olympics iterations. "Outdoor" here refers to sports where athletes are exposed to ambient environmental conditions in the absence of climate control and are not predominately immersed

in water (c.f. Tartarini et al. [9]). In Table 1, complex cases where other environmental conditions may impact athlete thermoregulation are denoted with asterisks; two asterisks for events that take place on but not in water (e.g. kayaking) and one asterisk for events likely to take place outdoors but possibly in a shaded area (based on Paris 2024 venue plans). Outdoor events that encompass multiple disciplines (e.g. triathlon which includes swimming, cycling, and running) were classified based on their highest-intensity discipline. The "athletics" discipline was further subdivided to reflect the differences in heat risk based on varying durations of events in this category: sprints and/or intermittent events (hurdles, vaults, jumps, throwing events, and sprint races $\leq$400 m) in Sport Classification 1; middle-distance races (decathlon, heptathlon, and races 800 m–1500 m) in Sport Classification 2; long-distance races (3000 m steeplechase and races 5 km–10 km) in Sport Classification 3; and endurance races (marathon and race walking) in Sport Classification 4. Two disciplines included in Paris 2024 but not explicitly considered in SMA EHP v1 (denoted with a caret in Table 1), skateboarding and breaking, were placed into Sport Classification 3.

The SMA EHP v1 model defines the combined temperature and relative humidity values at which thresholds of heat stress risk occur for each Sport Classification. Their four levels of heat stress risk are associated with specific recommendations for managing athlete heat safety: low risk (maintain hydration and reduce clothing), moderate risk (increase break/rest periods), high risk (implement active cooling strategies, such as submerging limbs in cold water or placing ice packs around the neck), and extreme risk (suspend exercise altogether). Given the greater physical intensity of the higher order Sport Classifications (e.g. 4, 5), these heat stress risk level thresholds are crossed at lower combinations of temperature and relative humidity (Fig. 1a).

An advantage of the SMA approach in determining risk directly from temperature and humidity, rather than using a measure such as wet bulb globe temperature (WBGT, a common heat metric used to estimate exertional heat risk) is that it

accounts for clothing/equipment factors and physiological perspiration restrictions, and helps avoid the shortcomings of WBGT in estimating heat stress risk in environments with restricted evaporation [37]. SMA EHP v1 has been used in the global Lancet Countdown reports on health and climate change since 2022 [38–40], as well as in the regional Lancet Countdown reports for Oceania since 2021 [41–44] and Europe since 2022 [45**?** , 46].

Event suspension probability

Climatic conditions that fall within the "extreme risk" category require suspension of activity to mitigate heat stress risk. As this is likely the most disruptive adaptation from an organizational perspective, we quantify the event suspension probability for each potential host city.

To do so, we selected CHC-CMIP6 data for a 2500 km^2 area (10×10 0.05° grid cells) around the city's center for the five-month period between June to October across all historical and projected years (i.e. 1983–2016 for observations and corresponding "years" in 2050 climate projections). We focus on the extended Northern Hemisphere warm season (rather than just July and August) given the precedence of select Summer Olympics taking place in shoulder seasons (e.g. Seoul 1988 which took place between Sept. 17–Oct. 2 and Sydney 2000 which took place between Sept. 15–Oct. 1) and recent statements from IOC President Kirsty Coventry on the need for flexibility when considering the time of year during which future Summer Olympics will be held [16]. Based on the SMA model, we then determine the corresponding heat risk level category for the climate of each grid cell within the city area for each timepoint and for each sport, using the appropriate heat risk thresholds for its Sport Classification. The city-wide event suspension probability for each outdoor sport is calculated as the sum of non-ocean grid cells with climatic conditions that present extreme heat stress risk given that sport's Sport Classification divided by the total number of non-ocean

Table 1 Outdoor sports (i.e. athletic disciplines) that participated in the Paris 2024 Summer Olympics and the number of unique medal events associated with each discipline and their Sport Classification according to the SMA EHP v1.

Sport Name	Number of Medal Events
Sport Classification 1	
Athletics (hurdles, vaults, jumps, throwing events, track sprints $\leq$ 400 m)	31
Sport Classification 2	
Archery	5
Golf	2
Sailing**	10
Shooting	15
Middle-distance races (Decathlon, Heptathlon, track 800 m and 1500 m)	6
Sport Classification 3	
Basketball 3×3*	2
Beach Volleyball	2
BMX Freestyle	2
BMX Racing*	2
Breaking^	2
Canoe Slalom**	6
Canoe Sprint**	10
Football (Soccer)	2
Long-distance races (3000 m Steeplechase, track 5 km and 10 km)	7
Road Cycling	4
Rowing**	14
Skateboarding^	4
Sport Climbing*	4
Tennis	5
Triathlon	3
Sport Classification 4	
Equestrian	6
Endurance races (Marathon, Race Walking)	4
Pentathlon	2
Rugby	2
Sport Classification 5	
(Field) Hockey	2
Mountain Biking	2

* Possibly occurs under a roof such that athletes are not exposed to direct radiation.

** Occurs on the water.

^ No SMA EHP v1 categorization.

grid cells within the 2500 km^2 area. We repeat the analysis for diurnal maximum and minimum temperatures (and corresponding humidities) to capture the range of daily conditions at which the events occur on each day (Fig. 2).

Table 2 Relative proportions of outdoor sports and associated medal events to all (indoor+outdoor) sports held at the Paris 2024 Summer Olympics.

	Sports			Medal Events		
Sport Classification	**# of outdoor**	**% of outdoor**	**% of all indoor+outdoor**	**# of outdoor**	**% of outdoor**	**% of all indoor+outdoor**
1	1	3.7	2.1	31	19.9	6.1
2	5	18.5	10.4	38	24.4	7.5
3	15	55.6	31.3	69	44.2	13.6
4	4	14.8	8.3	14	9.0	2.8
5	2	7.4	4.2	4	2.6	0.8
Total	27	100	56.3	156	100	47.4

To determine the city-mean event suspension probability for any given sport, we compute the weighted-average of each individual sport's event suspension probability based on the number of medal events within each sport. We use the term "medal event" to refer to all events the sport encompasses for which medals are awarded; for example, golf contains only two medal events, men and women's individual stroke play, while equestrian has six, including individual dressage, individual jumping, team dressage, etc. In other words, the contribution of each sport to the mean event suspension probability is proportional to the number of events the sport encompasses to account for the fact that sports with more medal events would create a greater logistical challenge if they need to be suspended and/or rescheduled. We have chosen to consider each medal event as a singular data point, but we acknowledge that the number of rounds or heats and their duration differs between events and that this could alter the event suspension probability in practice. For example, considering an average duration of one heat of the Men's 100 m sprint spans ∼12 s, the total time required to complete all 18 heats (which includes qualifying rounds) is ∼3.6 mins. In contrast, the Men's Singles Tennis event has 6 rounds that can total ∼36 hours played across 8 days assuming an average match length of 2 hours. As the duration and number of event competition rounds increases, the more likely it is to be played in peak daytime

conditions due to scheduling logistics. A future analysis that takes an alternate view of the likelihood of event suspension might thus consider weighting by duration of play rather than medal event.

Quantification of viability limit

Our analysis of historical Summer Olympics reveals that existing heat adaptations and event scheduling can absorb at least an 18% event suspension probability based on peak daytime conditions (as occurred in Beijing 2008). What the IOC might consider functionally prohibitive heat stress risk is, to the authors' knowledge, not publicly known, but is almost certainly greater than 14% average expected event suspension probability given their selection of Tokyo's bid for the 2020 Summer Olympics. We evaluate the number of viable host cities for a range of event suspension probability limits between 10% and 50%. For most results in this analysis, we define potential host city viability as having event suspension probability lower than a limit of 50%. We note that this is more inclusive than past studies analyzing the impact of climate on the Summer Olympics, which have utilized fairly stringent limits. Some examples from past studies include <10% chance that the WBGT falls above 28°C for 3 consecutive hours in August across a 20-year period [47], or both 10% and 25% probability of WBGT exceeding safe thresholds in July or August [13]. Our limit is more aligned with work focused on the Winter Olympics that have considered an "unreliable host" as the probability of not meeting snow or temperature requirements >25% of the time [48, 49] or the probability of having at least one of four positive climate indicators (snow, rain, temperature, and wet snow) not met >50% of days in February [50].

Table 3 Distribution of event suspension probability (%) statistics when calculated over 17-day windows for all warm season (June through October) dates between 1983 to 2016 for the 11 most recent Summer Olympics host cities.

Host City	Mean	Median	90th	95th	99th	Maximum
Tokyo	14.40	21.3	47.55	59.27	77.79	95.07
Seoul	10.46	0.00	41.18	60.08	87.77	99.89
Beijing	10.41	0.28	36.97	46.35	64.78	91.18
Atlanta	5.76	0.68	17.56	27.42	46.84	60.73
Athens	0.50	0.00	0.62	2.10	9.90	35.30
Rio de Janeiro	0.33	0.00	0.60	2.05	6.91	9.67
London	0.13	0.00	0.00	0.34	3.29	12.88
Paris	0.09	0.00	0.00	0.10	3.90	7.53
Barcelona	0.08	0.00	0.08	0.34	1.06	7.35
Los Angeles	0.04	0.00	0.01	0.08	1.26	2.11
Sydney	0.00	0.00	0.00	0.00	0.00	0.00

Supplementary information.

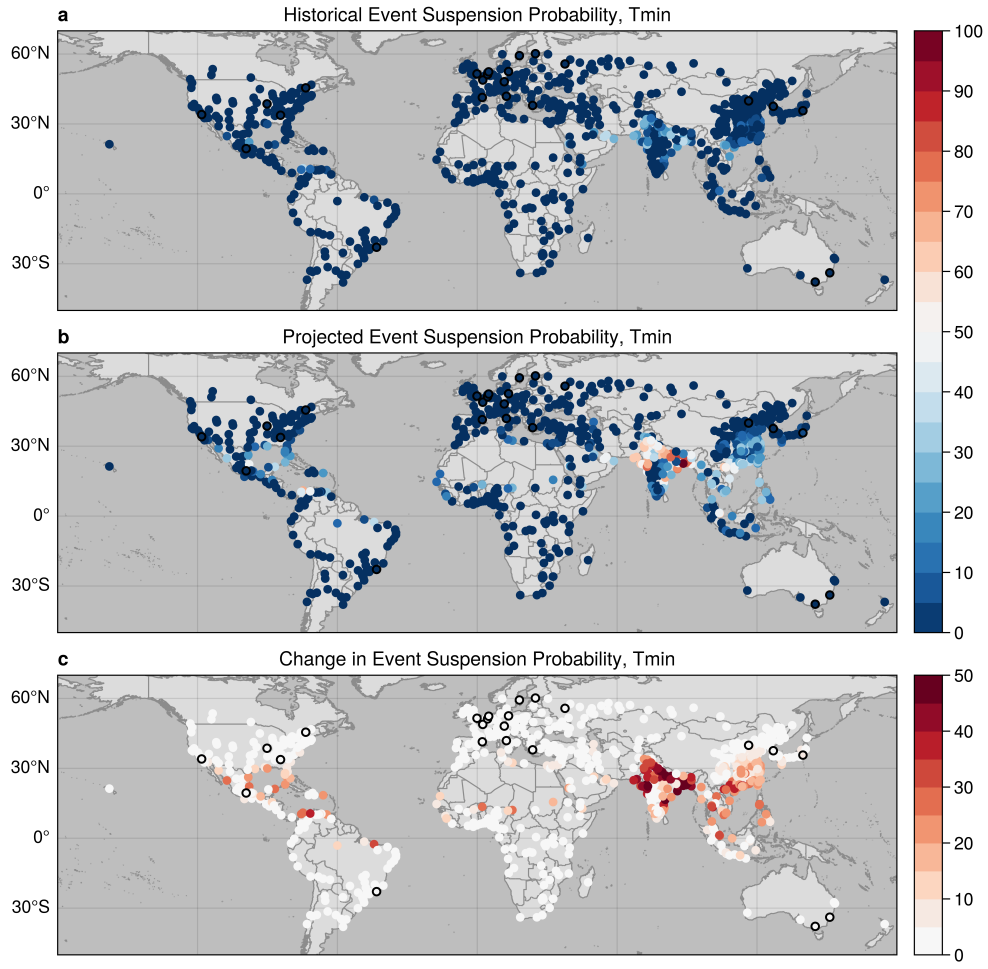


Fig. 5 Geography of event suspension probability across potential host cities based on daily minimum temperature. a) Event suspension probability for all potential host cities during the historical period (Jun.–Oct., 1983–2016). **b)** Same as (a) but for mid-21st century projections (Jun.–Oct., 33 years with 2045–2055 climatology). **c)** Change in event suspension probability between the historical and projected periods (projection – historical). Black bolded outlines signify that cities have hosted a modern Summer Olympics.

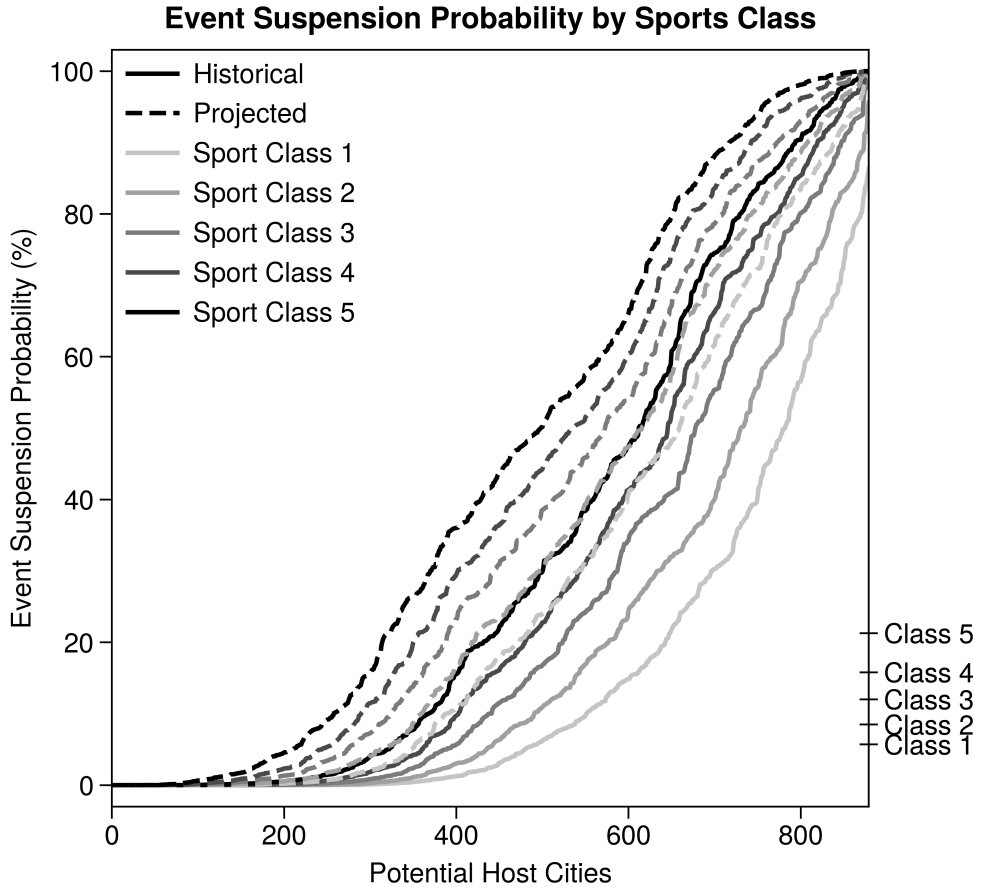


Fig. 6 Historical vs. projected event suspension probability by Sport Classification. Range of event suspension probability for each SMA Sport Classification (1–5) for the months of Jun.–Oct. during the historical period (1983–2016, solid lines) vs. the projected mid-century climate (2050, dashed lines) across all possible host cities. Grey shading encompasses the range of maximum climatological (based on 1983–2016 Jun.–Oct. T_{max} and Rh_x) event suspension probabilities observed among host cities of the nine past Summer Olympics that occurred during the historical CHC-CMIP6 range.

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Declarations

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Competing Interests

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

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Data availability

CHC-CMIP6 historical and projected temperature and relative humidity data [15] is available at https://data.chc.ucsb.edu/products/CHC_CMIP6/. Urban agglomeration population data is freely available to download from the United Nations Department of Economic and Social Affairs https://population.un.org/wup/downloads?tab=Urban%20Agglomerations. National Gross Domestic Product data can be found via the International Monetary Fund (IMF) World Economic Outlook database https://data.imf.org/en. Categorization of Paris 2024 outdoor sports and medal events was sourced from the IOC at https://olympics.com/en/paris-2024/sports and daily event scheduling from the Paris 2024 press office at https://press.paris2024.org/assets/paris-2024-olympic-sports-competition-schedule-pdf-f49c-7578a.html.

Materials availability

Not applicable

Code availability

Data analysis was conducted in python. The python scripts are available via the GitHub repository https://github.com/milrae/olympics-heat-stress.

Author contribution

M.R., D.M.K., J.W.B., and O.J. conceptualized the work. M.R. conducted the analysis advised by D.M.K. and J.W.B. J.W.B. acquired resources to support this work, O.J. provided feedback on usage of the SMA EHP v1 heat thresholds, and S.J.D. assisted with refining analyses and figures. D.M.K. and M.R. wrote the initial draft with contributions from all authors.

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