Global Climate Risks for Outdoor Sports Under CMIP6 Scenarios: A Multi-Indicator Assessment Based on WBGT, Heat Index, Heavy Rainfall, and Heatwaves

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Abstract

Outdoor sports are increasingly exposed to climatic conditions that challenge athlete safety, performance and event organisation. Despite extensive physiological and epidemiological evidence on heat stress, no global assessment has yet quantified how multiple climate hazards will jointly constrain outdoor sport under future climate change.

Here we provide the first global, CMIP6-based, multi-indicator assessment of climate-related risks for outdoor sport using bias-corrected daily projections from the NASA NEX-GDDP-CMIP6 dataset at 0.25° resolution. We compute four impact-oriented indicators relevant for sport practice: (i) Wet-Bulb Globe Temperature (WBGT) for morning, afternoon and evening conditions, (ii) dangerous Heat Index days (HI $> 40\,°C$), (iii) heavy rainfall days (precipitation > 20 mm day^{-1}), and (iv) heatwave days defined as sequences of at least three consecutive days with $T_{\max} > 35\,°C$. Indicators are analysed for two contrasted seasons (JJA and DJF) and three 30-year periods (1991–2020, 2031–2060, 2071–2100) under SSP2–4.5 and SSP5–8.5, and combined into a composite Sport Climate Risk Index (SCRI, 0–1).

Results reveal a rapid intensification and spatial expansion of climate constraints on outdoor sport. Under SSP5–8.5, large tropical and subtropical regions exceed 60–80 WBGT extreme-risk days per season by late century, with morning and evening conditions increasingly affected, reducing the effectiveness of time-of-day scheduling as an adaptation strategy. Dangerous Heat Index days frequently exceed two months per season in humid regions, while heatwaves introduce multi-week periods of cumulative thermal stress. Heavy rainfall remains a persistent constraint in monsoonal and equatorial regions, contributing to surface degradation and event cancellations. The SCRI highlights continental-scale hotspots where multiple hazards co-occur, with values exceeding 0.8 across much of the tropics by 2071–2100, indicating that outdoor sport becomes barely viable without major adaptation.

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The divergence between SSP2–4.5 and SSP5–8.5 demonstrates that mitigation choices critically determine the future climatic feasibility of outdoor sport. By providing a coherent global baseline across multiple hazards, seasons and time-of-day exposures, this study establishes a quantitative foundation for climate-aware sport scheduling, infrastructure planning and adaptation strategies in a warming world.

1 Introduction

Outdoor sports are increasingly challenged by environmental conditions that are becoming hotter, more humid and more meteorologically unstable. Around the world, heat-related collapses during marathons, medical time-outs in tennis, hydration crises in football tournaments and heat-modified cycling stages have become visible signals that sport is entering a new climatic era [1, 2]. These events are not anomalies: they reflect a structural shift in the thermal environments in which athletes train, compete and recover.

A substantial body of evidence demonstrates that high temperatures and humidity amplify physiological strain, accelerate dehydration, impair cognitive function and increase the risk of exertional heat illness [3, 4, 5]. Widely used metrics—such as the Wet-Bulb Globe Temperature (WBGT) [6] and the Heat Index [7]—capture these combined stresses, and consistently show that even moderate warming can sharply reduce safe exercise capacity. Sport-specific studies reinforce this pattern: heat impairs technical and tactical performance in football [8], reduces running velocity in marathons [9], affects pacing stability in endurance cycling [10] and increases medical interventions in court sports [2].

Yet despite extensive knowledge on heat physiology, the scientific evidence informing the *future* of outdoor sport remains extremely limited. Our examination of nearly 1,000 sport–climate publications shows a striking imbalance: hundreds of studies analyse heat, WBGT, humidity and hydration under present-day conditions, but only a minority engage with future climate scenarios, and only a handful use global climate models. Heavy rainfall—another major driver of cancellations, unsafe surfaces and injury risk—appears in only a few sport-specific studies [11]. Heatwaves, widely recognised as high-impact hazards in health and labour research [12, 13], have rarely been evaluated in relation to training load, calendar design or athlete recovery.

This gap is consistent with the two major reviews in the field. Bernard et al. (2021) concluded that research on climate and physical activity remains overwhelmingly descriptive, offering little guidance on how risks will evolve under climate change [14]. Orr and Inoue (2023) similarly emphasised that sport organisations face growing climatic pressures but lack robust projections to support long-term adaptation planning [15]. Together, these findings underline a simple point: we know a great deal about how weather affects athletes today, but almost nothing about how climate will constrain sport tomorrow.

Crucially, no global assessment integrates multiple climate hazards relevant for outdoor sport. Existing studies typically consider temperature alone or single indicators in isolation. None evaluate the combined risks of heat, humidity, heavy rainfall and heatwaves under CMIP6 scenarios, and none examine how these risks vary across morning, afternoon and evening—even though adjusting competition times is one of the primary adaptation strategies available to federations.

Meanwhile, analogous fields—including health, agriculture and labour productivity—have already adopted downscaled CMIP6 projections to quantify future climate impacts at global scale [16, 12]. Despite its economic relevance and global reach, the sport sector still lacks a comparable evidence base.

To address this gap, we provide the first global, multi-indicator, CMIP6-based assessment of future climate risks for outdoor sport. Using daily bias-corrected NASA NEX-GDDP CMIP6 projections at 0.25° resolution [17], we analyse four key indicators affecting outdoor sport practice:

- WBGT at three times of day (morning, afternoon, evening),
- Heat Index > 40 °C,
- heavy precipitation (> 20 mm/day),
- heatwaves (≥ 3 consecutive days with $T_{\max} > 35$ °C).

By examining historical (1995–2014), mid-century (2041–2060) and late-century (2081–2100) conditions under SSP2–4.5 and SSP5–8.5, the study identifies emerging hotspots, seasonal shifts in safe practice windows and the changing climatic feasibility of outdoor sport.

Overall, this work provides the first quantitative foundation for anticipating how climate change will reshape the practice, scheduling and global geography of outdoor sport in the coming decades.

2 Data

We use daily climate projections from the NASA NEX-GDDP-CMIP6 dataset [18], a global archive providing bias-corrected and statistically downscaled CMIP6 simulations at 0.25° resolution. The dataset includes daily maximum and minimum temperature (tasmax, tasmin), relative humidity (hurs) and precipitation (pr).

From the 35 CMIP6 global models available, we select five widely used models (GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, UKESM1-0-LL) following the ISIMIP2b protocol for cross-sectoral impact assessment [19]. This subset spans a broad range of climate sensitivities and structural representations within CMIP6, ensuring that our multi-model statistics reflect ensemble diversity rather than clustering around a single model lineage.

We analyse three periods:

- **Historical** (1995–2014): baseline climate.
- **Mid-century** (2041–2060): hereafter “2050”.
- **Late-century** (2081–2100): hereafter “2100”.

Our primary focus is on **SSP5-8.5**, the high-emission pathway used to explore upper-bound risks for human health and labour. A parallel analysis under **SSP2-4.5** provides an intermediate stabilisation trajectory. Together, these scenarios bracket the range of plausible warming relevant for outdoor sport exposure.

3 Methods

3.1 Climate data and temporal aggregation

All indicators are derived from daily NEX-GDDP-CMIP6 temperature, humidity and precipitation. We aggregate results into two seasons relevant for global sport calendars:

- **JJA (June–August)**: boreal summer / austral winter,
- **DJF (December–February)**: boreal winter / austral summer.

These windows capture the dominant competitive periods in both hemispheres and reflect established seasonal patterns of thermal and hydrometeorological stress.

3.2 Multi-model ensemble (MME)

All results are presented as multi-model ensemble means. For each indicator and time period, we compute the ensemble mean from the five selected models. To assess robustness, inter-model agreement is quantified using a 4/5 sign-consistency criterion, whereby stippling indicates regions where at least four models agree on the direction of change. This threshold is aligned with the "medium-to-high confidence" framing used in IPCC AR6 and prevents overinterpretation of model-specific outliers.

3.3 Wet-Bulb Globe Temperature (WBGT)

WBGT is the standard biometeorological index used to assess exertional heat-stress risk in athletes and outdoor workers [6, 7, 20]. We compute WBGT using the classical formulation of **(author?)** [21]:

$$WBGT = 0.7\,T_w + 0.2\,T_g + 0.1\,T_a,$$

where T_a is dry-bulb air temperature, T_w the natural wet-bulb temperature and T_g the globe temperature.

3.3.1 Reconstruction of time-of-day humidity

The NEX-GDDP dataset provides daily mean relative humidity ($\mathrm{RH}_{\mathrm{mean}}$), but WBGT requires humidity that is physically consistent with the temperature at the time of day considered. To obtain **morning** and **afternoon** humidity, we reconstruct RH as follows:

1. We first compute daily vapour pressure:

$$e = RH_{\mathrm{mean}} \times e_s(T_{\mathrm{mean}})/100,$$

where $e_s(T)$ is the saturation vapour pressure from the Tetens formula.

2. For each time window, we recompute RH using:

$$RH_{\mathrm{time}} = 100 \times \frac{e}{e_s(T_{\mathrm{tim}})},$$

where T_{time} is equal to:

- T_{min} for **morning WBGT**,
- T_{max} for **afternoon WBGT**,
- T_{mean} for **evening WBGT**.

3. Reconstructed RH values are constrained to the range 1–99%.

This procedure follows the approach used in large-scale heat–health assessments, ensuring that humidity is consistent with the thermal state of the atmosphere during the relevant sport time window.

3.3.2 Wet-bulb temperature (T_w)

T_w is computed using the analytical approximation of **(author?)** [22], widely used in global WBGT analyses due to its good accuracy across typical sport-relevant temperature–humidity combinations.

3.3.3 Globe temperature (T_g)

We estimate T_g using the simplified radiative–convective formulation of **(author?)** [21]. Shortwave radiation (RSDS) is included for **afternoon** WBGT to represent peak solar load, and set to zero for **evening** WBGT to reflect typical post-sunset conditions.

3.3.4 Time-of-day WBGT

We compute:

- **WBGT-morning**: $T_a = T_{\min}$, RH reconstructed with $T_{\min}$, RSDS = observed.
- **WBGT-afternoon**: $T_a = T_{\max}$, RH reconstructed with $T_{\max}$, RSDS included.
- **WBGT-evening**: $T_a = T_{\text{mean}}$, RH reconstructed with T_{mean}, RSDS = 0.

3.3.5 WBGT thresholds

We quantify heat-stress exposure using the widely applied threshold WBGT > 32 °C, corresponding to the "extreme risk" category for strenuous sport activity [4, 20]. For the composite SCRI index, we use **WBGT-afternoon** only, representing the most hazardous scheduling window.

3.4 Heat Index (HI)

The Heat Index (HI) is computed using the NOAA polynomial algorithm [23]. Daily maximum temperature is converted to Fahrenheit:

$$T_F = (T_{\max} - 273.15) \times \frac{9}{5} + 32,$$

and daily RH is constrained to 1–99%. The raw Heat Index is:

$$HI_F^{\text{raw}} = c_1 + c_2 T_F + c_3 RH + c_4 T_F RH + c_5 T_F^2 + c_6 RH^2 + c_7 T_F^2 RH + c_8 T_F RH^2 + c_9 T_F^2 RH^2,$$

with NOAA coefficients c_1–c_9. The index is applied only when $T_F \geq 80$°F and RH $\geq 40\%$; otherwise HI is approximated by the dry-bulb temperature. We convert back to Celsius:

$$HI_C = (HI_F - 32) \times \frac{5}{9}.$$

Indicator: number of days with HI > 40 °C per season, corresponding to the "danger" category in NOAA guidelines [23, 7].

3.5 Heavy rainfall events

Heavy rainfall days are defined as:

$$P > 20 \text{ mm/day}.$$

This threshold represents precipitation intensities likely to produce waterlogged natural surfaces, reduced friction, degraded footing and increased probability of cancellations [11, 14]. It is also consistent with thresholds used in hydrological impact studies to classify disruptive rainfall.

Indicator: number of P >20 mm/day events per season.

3.6 Heatwaves

Heatwaves are defined as:

$$\text{at least 3 consecutive days with } T_{\max} > 35°C,$$

an absolute-temperature criterion commonly used in global heat-health studies [12, 13]. We count the number of days belonging to heatwave episodes in each season, capturing cumulative thermal load not reflected in single-day metrics [20].

3.7 Composite Sport Climate Risk Index (SCRI)

Each indicator is normalised across all model×scenario combinations:

$$X' = \frac{X - X_{\min}}{X_{\max} - X_{\min}}.$$

The composite index is:

$$SCRI = 0.25X'_{\text{WBGT-afternoon}} + 0.25X'_{\text{HI}} + 0.25X'_{\text{rain}} + 0.25X'_{\text{heatwave}}.$$

Equal weights avoid imposing an arbitrary prioritisation of hazards, reflecting the absence of consensus on sport-specific weighting schemes.

3.8 Model evaluation and limitations

The performance of bias-corrected CMIP6 projections, including NEX-GDDP, has been evaluated in several regional studies [24, 25, 26]. These studies generally show improved skill for temperature and mean precipitation, although regional discrepancies persist. Given these uncertainties, we focus on relative changes rather than absolute values.

Limitations include the simplified WBGT formulation, grid-scale representation of radiation and wind, absence of stadium or urban microclimates and omission of acclimatisation, cooling strategies and behavioural responses. While absolute magnitudes may differ from venue-level conditions, spatial patterns and relative trends remain robust for comparative risk assessment.

4 Results

4.1 Overview of indicator workflow

Figure 1 summarises the indicator workflow and conceptual structure of the multi-hazard framework developed in this study. Daily CMIP6 projections from the NASA NEX-GDDP dataset provide the common foundation for all calculations. From these daily fields, we derive four sport-relevant indicators capturing distinct climatic constraints on outdoor sport: (i) Wet-Bulb Globe Temperature (WBGT) for morning, afternoon and evening match conditions, representing acute heat–humidity–radiation stress; (ii) Heat Index (HI $>$ 40 °C), representing humidity-amplified heat strain; (iii) heavy rainfall days (P $>$ 20 mm/day), associated with surface degradation and cancellations; and (iv) heatwave days, defined as sequences of at least three consecutive days with $T_{\max} > 35°$C, representing cumulative thermal load.

All indicators are aggregated to two seasons relevant for global sport scheduling (JJA and DJF) and three 30-year climate periods (1991–2020, 2031–2060 and 2071–2100). Each indicator is then normalised and combined with equal weight into a composite Sport Climate Risk Index (SCRI), summarising multi-hazard exposure across regions, seasons and emission scenarios. This structure links daily-scale climate physics to seasonal-scale constraints on outdoor sport, providing a coherent and fully integrated assessment framework.

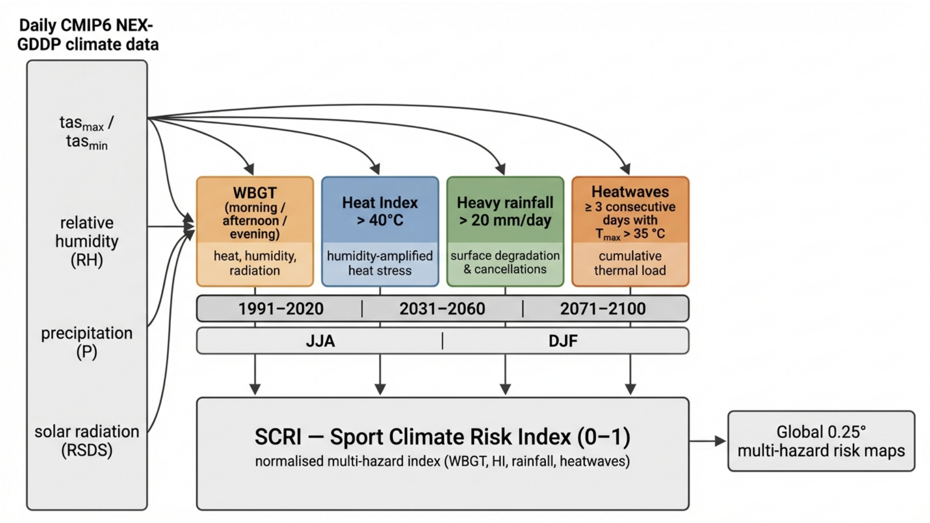

Figure 1: Multi-hazard indicator workflow. Daily CMIP6 NEX-GDDP projections (air temperature, humidity, precipitation and solar radiation) provide the common input for computing four sport-relevant indicators: WBGT (morning/afternoon/evening), Heat Index (HI > 40 °C), heavy rainfall days ($P > 20\,\text{mm}\,\text{day}^{-1}$), and heatwaves (at least 3 consecutive days with $T_{\max} > 35$°C). Each indicator is aggregated for JJA and DJF over three 30-year periods (1991–2020, 2031–2060, 2071–2100), normalised, and combined into a composite Sport Climate Risk Index (SCRI, 0–1). The SCRI enables the production of global 0.25° maps of multi-hazard risk for outdoor sport.

4.2 Seasonal exposure to extreme heat

Across the historical period (1991–2020), exceedances of the WBGT extreme-risk threshold already occur frequently in low-latitude regions. In JJA, afternoon exposure reaches 20–40 days per season across the Sahel, northern India, the Arabian Peninsula and parts of Central America (Figure 2). Morning conditions remain generally below 10 days except in humid equatorial regions, while evening exceedances rarely exceed 5–10 days outside West Africa and northern South America. By mid-century (2031–2060, SSP5–8.5), afternoon extreme-WBGT days intensify and expand poleward: South Asia, the Sahel and Southeast Asia frequently exceed 40–60 days, and southern Europe, southeastern China, the southeastern United States and northern Argentina begin to experience more than 10–20 days per season. By 2071–2100, afternoon extremes surpass 60–80 days across much of the tropics, morning exceedances reach 20–40 days in South Asia and West Africa, and evening exceedances reach 20–30 days in the most humid regions. These trends signal the near-disappearance of a “safe” morning window in several densely populated regions.

In DJF (Figure 3), afternoon WBGT exceedances historically reach 15–30 days in Brazil, 10–20 days in Mozambique and eastern South Africa, and 20–30 days in northern Australia. By mid-century, these regions exceed 30–50 days, with morning values approaching 10–20 days. By 2100, afternoon exposure surpasses 50–70 days across most of Brazil, southern Africa and northern Australia, while morning exceedances commonly reach 20–30 days. Evening conditions exceed 10–20 days in humid tropical regions, indicating persistent 24-hour thermal load. DJF thus becomes as hazardous in the Southern Hemisphere as JJA in the Northern Hemisphere.

Taken together, the JJA and DJF patterns show that by the end of the century, extreme-WBGT conditions become quasi-permanent features of the warm season in many low-latitude regions. Tropical land areas frequently exceed 60–80 dangerous days per season, while subtropical regions such as the Mediterranean Basin, the southern United States, southern Africa and eastern China transition from rare exceedances in the historical climate to 20–40 days per season. The hemispheric complementarity between JJA and DJF further implies that, on a global scale, at least one major sport region is almost always experiencing heightened heat risk, compressing the opportunity for safe scheduling across the annual calendar.

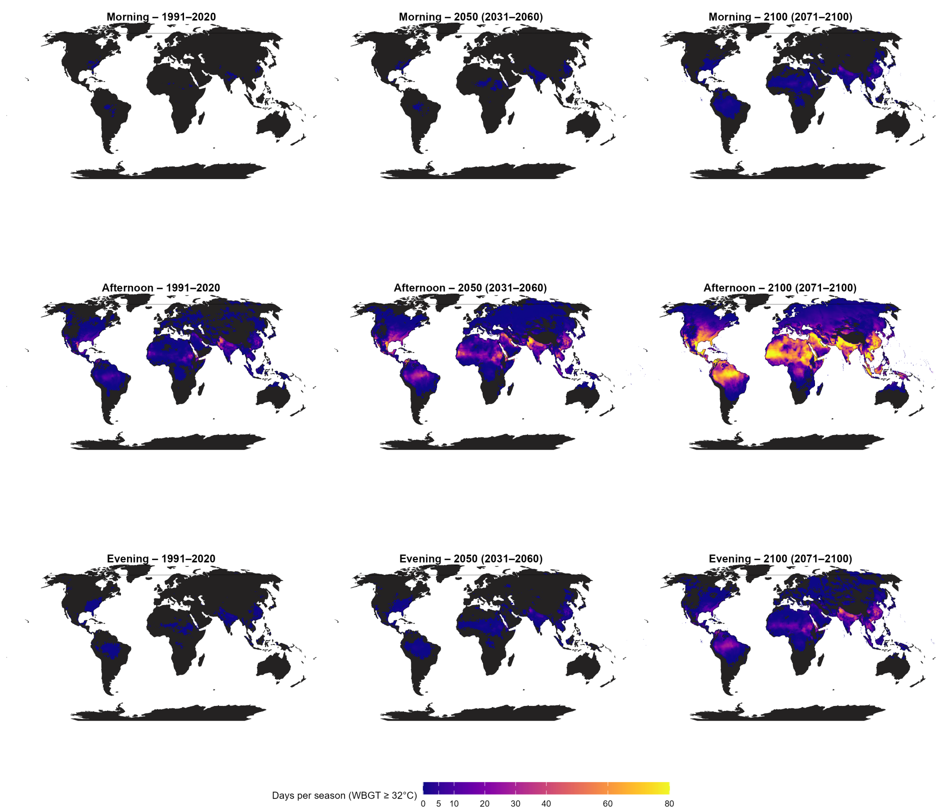

Figure 2: **Seasonal exposure to extreme heat (WBGT > 32 °C) in JJA.** Seasonal number of days above the WBGT extreme-risk threshold for morning, afternoon and evening match conditions (rows), and for 1991–2020, 2031–2060 and 2071–2100 under SSP5–8.5 (columns).

4.3 Adaptation potential and limits of time-of-day scheduling

Seasonal differences between afternoon and morning exposure illuminate the scope—and limits—of scheduling as an adaptation strategy (Figure 4). Historically, most tropical regions show a positive ΔWBGT of 10–20 days, meaning afternoon matches are substantially riskier. Contrasts are strongest across South Asia, the Sahel, northern South America and northern Australia, while dry subtropical regions show near-zero differences.

By mid-century (2031–2060), ΔWBGT increases by 5–15 days across most tropical belts. By 2100, afternoon amplification exceeds 20–35 days in the Indo-Gangetic Plain, West Africa, Central

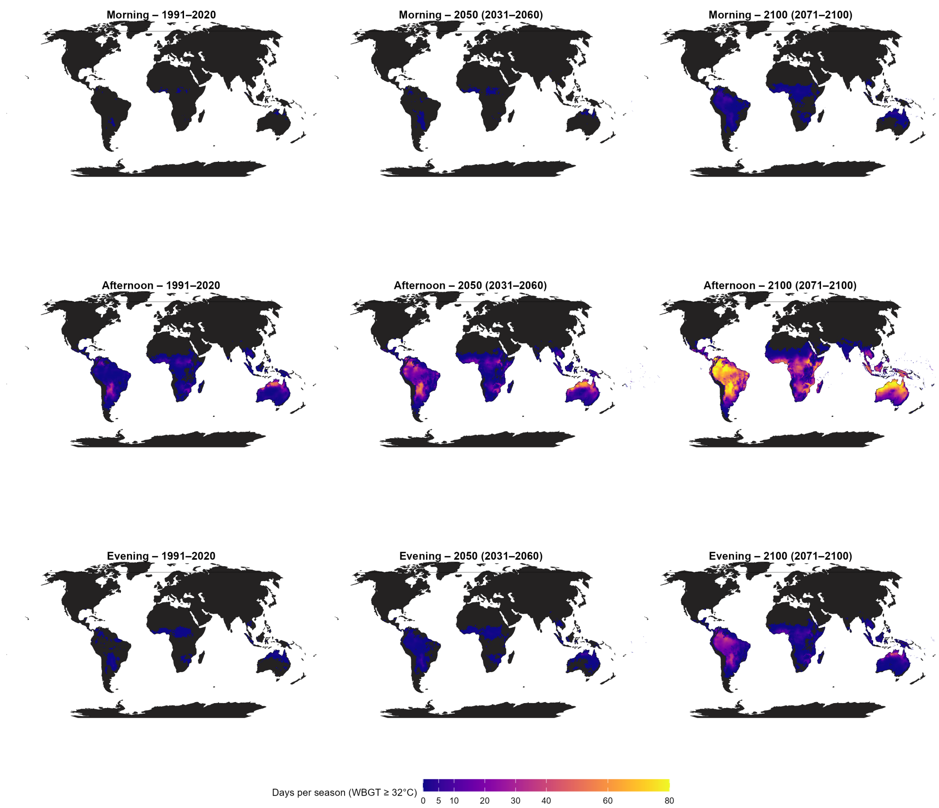

Figure 3: **Seasonal exposure to extreme heat (WBGT > 32 °C) in DJF.** Same layout as Figure 2, highlighting the southward shift of extreme-heat hotspots in austral summer.

America, Brazil and southeastern Africa. In some equatorial regions, however, ΔWBGT declines because mornings also exceed 32 °C, indicating that scheduling loses effectiveness as both morning and afternoon conditions surpass physiological thresholds.

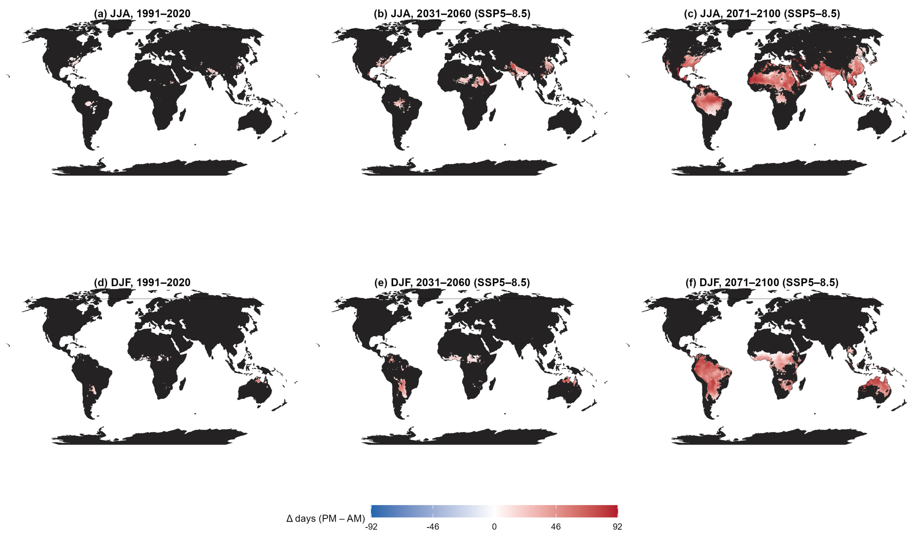

Figure 4: **Difference between afternoon and morning exposure (ΔWBGT-days).** Positive values indicate locations where afternoon matches face greater heat stress; negative values indicate regions where mornings are riskier.

4.4 Dangerous Heat Index conditions

The Heat Index expands faster than WBGT as humidity amplifies thermal stress (Figure 5). Historically, JJA HI > 40 °C occurs 20–40 days per season in West Africa, Amazonia, South Asia and the Arabian Peninsula, and 10–20 days in Central America and Southeast Asia. DJF values reach 10–30 days across Brazil, northern Australia and southern Africa. By mid-century, South Asia, West Africa, Southeast Asia and northern Brazil exceed 40–50 days, while Central America, the Caribbean and the Gulf Coast accumulate 20–40 days. By 2100, Amazonia, West Africa, the Bay of Bengal and Southeast Asia record more than 60 dangerous-HI days per season—two months during which outdoor sport becomes physiologically unsafe regardless of time of day.

4.5 Heavy rainfall days

Heavy rainfall days ($P > 20$ mm/day) show more moderate but spatially coherent increases (Figure 6). Historically, tropical monsoon regions record 10–25 days per season, while subtropical regions remain below five. By 2031–2060, West Africa, the Gulf of Guinea, Southeast Asia and Amazonia increase by 2–5 days per season, with similar changes in DJF across eastern Australia and southeastern Africa. By 2100, tropical regions frequently exceed 20–30 days, Southeast Asia reaches 25–35 days and East Africa surpasses 15–25 days. Even modest increases can disrupt multiple matchdays due to waterlogged surfaces and degraded footing.

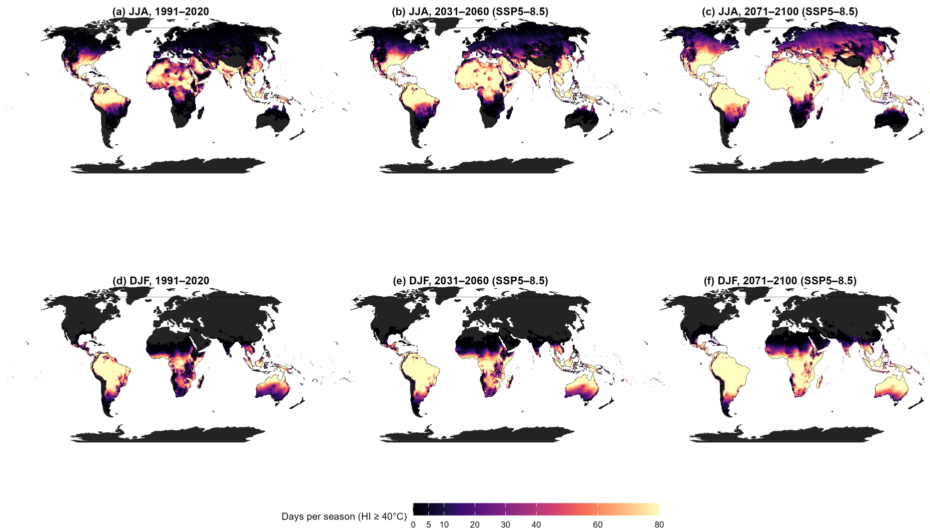

Figure 5: **Seasonal exposure to dangerous Heat Index ($\mathbf{HI > 40\,°C}$).** Seasonal number of dangerous-HI days in JJA and DJF across 1991–2020, 2031–2060 and 2071–2100.

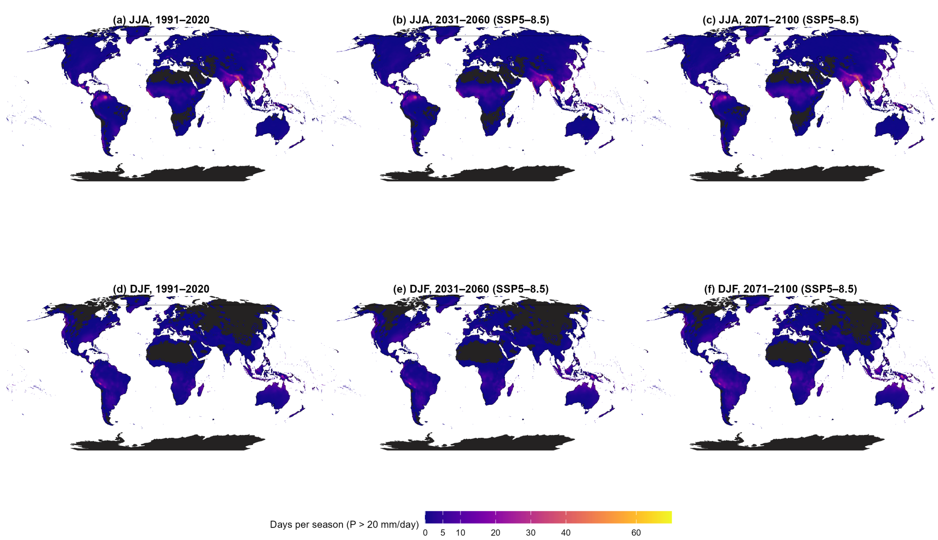

Figure 6: **Seasonal number of heavy rainfall days ($\mathbf{P > 20\,mm/day}$).** JJA and DJF across 1991–2020, 2031–2060 and 2071–2100 under SSP5–8.5.

4.6 Heatwave days

Heatwaves (≥ 3 consecutive days with $T_{\max} > 35$ řC) emphasise cumulative thermal stress (Figure 7). Historically, South Asia, the Middle East, northern Australia, interior Brazil and southern Africa record 10–20 heatwave days per season. By mid-century, the Mediterranean Basin, southwestern United States, South Africa and eastern Australia experience increases of 10–20 days, reaching 20–30 days. By 2100, South Asia and the Gulf reach 40–60 days, inland Australia and central Brazil reach 30–40 days, and the Mediterranean, southern United States and eastern China reach 20–40 days—multi-week sequences with major implications for athlete safety and competition scheduling.

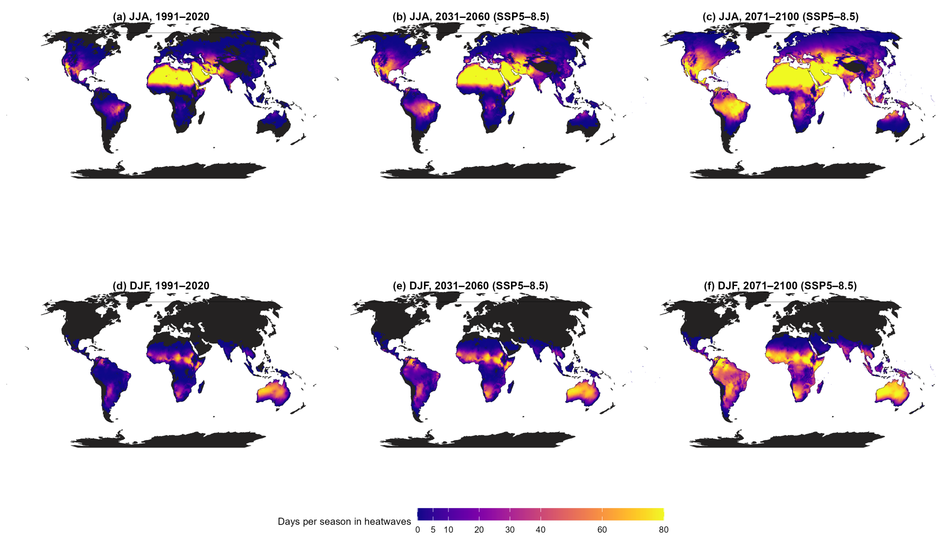

Figure 7: **Seasonal number of heatwave days.** JJA and DJF across 1991–2020, 2031–2060 and 2071–2100.

4.7 Composite Sport Climate Risk Index (SCRI)

The SCRI combines all four hazard dimensions into a 0–1 metric reflecting simultaneous exposure to extreme heat, humidity, heavy rainfall and heatwaves. In 2031–2060, SSP1–2.6 yields SCRI values below 0.4 in most regions, with tropical Africa and South Asia reaching 0.5. Under SSP2–4.5, large regions shift into the 0.5–0.6 range, including northern Brazil, West Africa, Southeast Asia, northern India and parts of the southern United States and Mediterranean Basin. Under SSP5–8.5, most low-latitude regions exceed 0.6, with hotspots reaching 0.7–0.8.

By 2071–2100, scenario divergence becomes marked. SSP1–2.6 stabilises with values below 0.4. SSP2–4.5 yields widespread values of 0.6–0.7 across the tropics and subtropics. Under SSP5–8.5, continental-scale regions reach SCRI values of 0.9–1.0—particularly Amazonia, West Africa, the Bay of Bengal, Southeast Asia and northern Australia—while the Mediterranean, southern United States and East Asia reach 0.6–0.8. Values above 0.8 indicate that multiple hazards are simultaneously severe for more than half the season, implying that outdoor sport becomes barely viable without major adaptation measures.

In practical terms, high-end SCRI values under SSP5–8.5 indicate that large parts of the tropical belt enter a regime where traditional outdoor sport calendars become structurally incompatible with the emerging climate, unless competition periods, training formats and infrastructure design are fundamentally rethought.

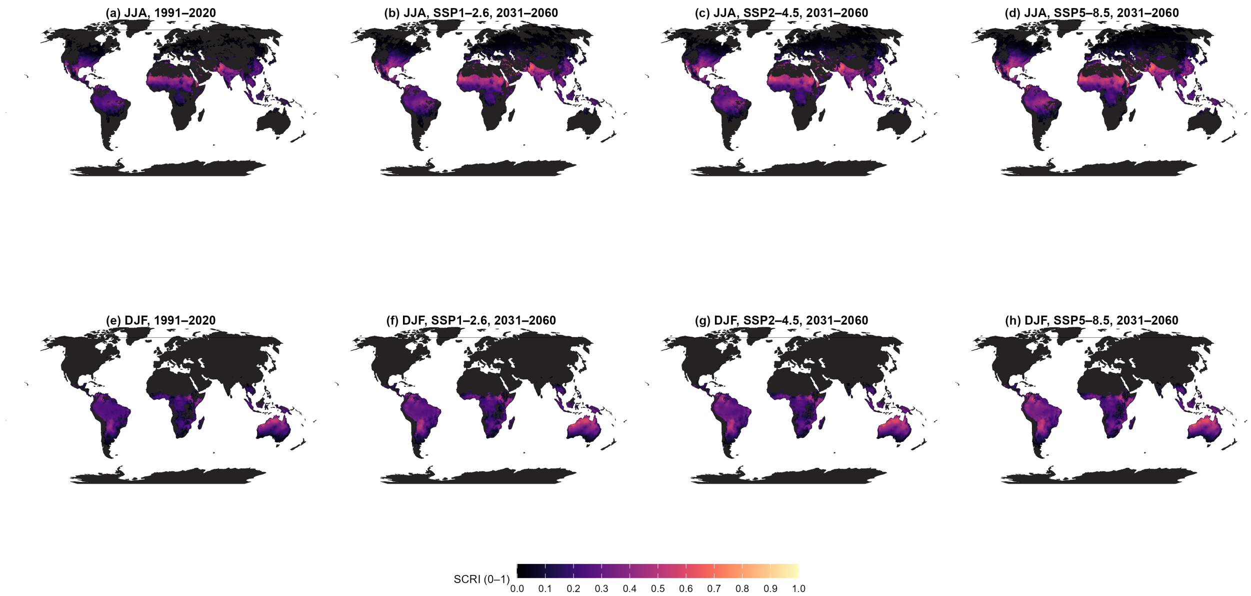

Figure 8: **Composite Sport Climate Risk Index (SCRI), 2031–2060.** JJA (a–c) and DJF (d–f) under SSP1–2.6, SSP2–4.5 and SSP5–8.5.

5 Discussion

Our results provide a first global, CMIP6-based, multi-indicator picture of how climate change is likely to constrain outdoor sport practice over the twenty-first century. In line with recent conceptual and empirical work on climate risks in sport [14, 15, 27, 28, 29], they confirm that the combination of heat, humidity, heavy rainfall and heatwaves will overlap with the spatial and temporal patterns of outdoor sport practice in ways that are difficult to ignore.

5.1 Global and regional hotspots for outdoor sport

A consistent feature across indicators is the emergence of strong hotspots in low-latitude and warm–humid regions, where WBGT and Heat Index frequently exceed safety thresholds already in the historical baseline and rise sharply under future scenarios. These patterns are fully consistent with epidemiological and physiological evidence showing disproportionately high heat-health risks in tropical and subtropical settings [12, 30, 20]. For sport, this means that regions hosting some of the world's densest populations of participants—football, running, school sport and mass-participation events—are also those facing the fastest-growing constraints.

At mid-latitudes, our results suggest substantial increases in the number of days above WBGT or HI safety thresholds during summer, especially under SSP2-4.5 and SSP5-8.5. This is consistent with observed and projected trends in extreme heat across Europe, North America and parts of Asia [12, 13]. These regions currently host many major global events (World Cups, Olympic Games, World Championships, city marathons) and have long been considered "climatically safe" relative to hotter

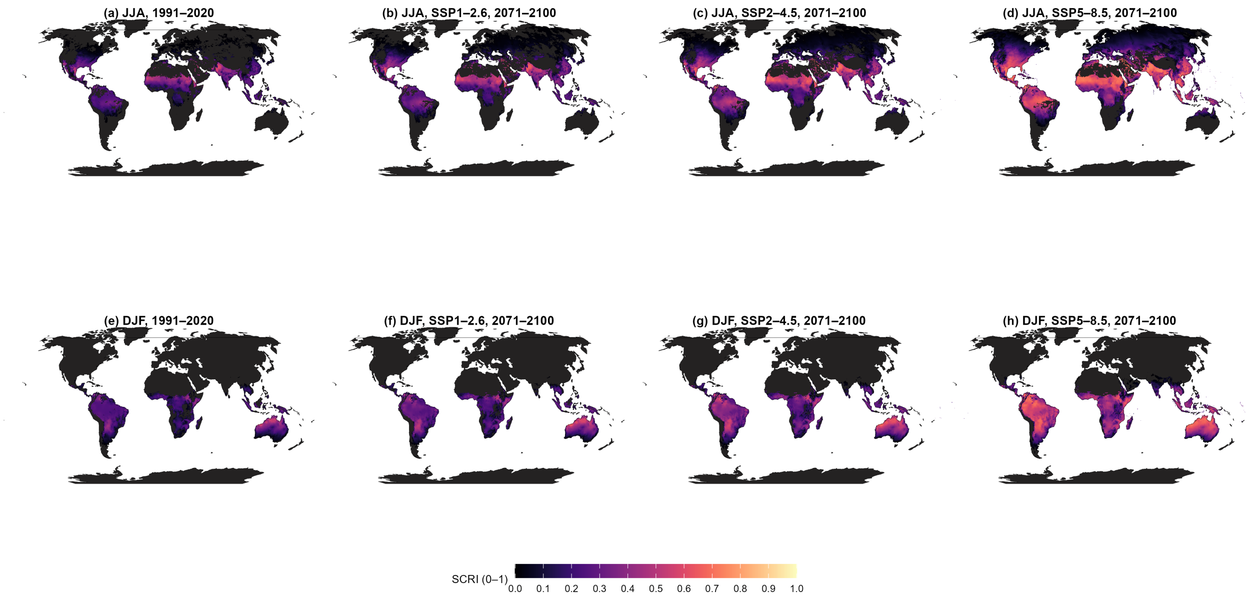

Figure 9: **Composite Sport Climate Risk Index (SCRI), 2071–2100.** JJA (a–c) and DJF (d–f) under SSP1–2.6, SSP2–4.5 and SSP5–8.5.

regions. Our findings show that this assumption is becoming progressively less valid, particularly in a high-emission world, and that mid-latitude regions will increasingly face non-negligible constraints on training, competition and scheduling.

Heavy rainfall and heatwaves exhibit different but overlapping patterns. In temperate regions, increases in heavy rainfall days appear modest, but even small changes can exacerbate pitch degradation, reduced ball roll, poor footing and injury risk [11]. In monsoonal and equatorial regions, heavy-rainfall days remain frequent or increase further, implying that waterlogged surfaces and cancellations will remain recurrent constraints even where heat is not the primary limiting factor. Heatwaves, defined as multi-day runs of very hot conditions, represent cumulative stress episodes that can degrade athlete performance, recovery and safety independently of single-day exceedances [20, 30].

Overall, the multi-indicator perspective confirms recent qualitative assessments that extreme heat is emerging as a structural climate risk to sport [27, 29], while highlighting the additional and interacting roles of humidity, rainfall and multi-day clustering that are rarely examined together.

5.2 Implications for sports scheduling and the geography of play

Our findings have direct implications for sports scheduling at all organisational levels. The projected increases in days with WBGT or HI above recommended safety thresholds suggest that the traditional summer-centred calendar will be increasingly misaligned with safe environmental windows. This echoes calls from governance-focused studies to formally recognise heat as a core climate risk [29] and complements empirical work showing growing athlete, coach and organiser concerns regarding extreme heat [28, 27].

At the elite level, organisers of major competitions may need to consider long-term relocation of events to cooler seasons or cooler venues, particularly under SSP5-8.5. Such changes are already emerging sporadically (e.g. football tournaments shifted to winter, endurance events moved to dawn or dusk), but our results suggest that this may evolve from exception to structural necessity. At community level, local clubs, schools and amateur organisers may experience a significant compression of safe outdoor hours, with consequences for training quality, participation rates and equity of access—particularly in low-income regions where indoor alternatives and cooling infrastructure are limited.

The heterogeneous patterns in our results also imply that some currently marginal regions (e.g. high latitudes) may become more favourable for certain outdoor sports, while others may experience chronic climatic stress. This could gradually reshape the global geography of sport, potentially reinforcing existing inequalities or creating new opportunities depending on adaptation capacity, infrastructure and investment.

5.3 Adaptation via time-of-day: opportunities and limits

One of the most accessible adaptation levers is **time-of-day scheduling**. Our separation of WBGT into morning, afternoon and evening exposures clearly shows that shifting away from afternoon hours—where solar radiation, air temperature and surface heating peak—can substantially reduce the number of days above critical thresholds. This aligns with physiological evidence showing lower thermal strain during cooler parts of the day [3, 5, 20] and with practice-oriented recommendations to "play early or late" [1, 14].

However, our projections also reveal the **limits** of this strategy. In several low-latitude regions under SSP5-8.5, mornings and evenings increasingly exceed safety thresholds, reducing the margin of benefit achievable through temporal shifting alone. Moreover, early-morning scheduling conflicts with athlete sleep, school and work constraints, while late-evening matches can create logistical and safety issues. Time-of-day adaptation is therefore useful but insufficient, particularly in regions where climate change drives WBGT exceedances across the full diurnal cycle.

Additionally, our projections do not include microclimatic effects such as urban heat islands, shading, ventilation or stadium architecture, which may amplify or mitigate heat stress locally. Nonetheless, the broad patterns highlight a structural contraction of safe windows for outdoor activity.

5.4 Rainfall-driven cancellations and surface-related risks

While heat tends to dominate climate–sport discussions, our rainfall indicator underscores the importance of **hydrometeorological constraints**. Days with precipitation above 20 mm can lead to waterlogged natural turf, increased slip risk, reduced ball control and higher injury risk in football, rugby, cricket and other field sports. Even when athletes physiologically tolerate such conditions, surfaces may be unsafe or unplayable.

Although heavy rainfall increases appear modest in many mid-latitude regions, small increments may still lead to substantial operational impacts due to narrower recovery windows and increased pitch saturation. In monsoonal and tropical regions, heavy rainfall remains a dominant constraint, often overlapping with high thermal stress. This **compound hazard**—wet, soft surfaces combined with high temperatures—poses additional injury and scheduling challenges.

From an adaptation perspective, these patterns highlight the value of resilient surface design (drainage, hybrid turf, synthetic options) and flexible scheduling that incorporates both thermal and hydrological forecasts. However, such adaptations are costly and more accessible to professional teams than to community sport organisations, raising clear equity concerns.

5.5 Heatwave interruptions and cumulative stress

Heatwaves represent multi-day periods of elevated thermal load that challenge traditional training cycles and competition calendars. Unlike isolated hot days, heatwaves can impair recovery, elevate cardiovascular strain and increase heat-related illness risk even when individual days remain below acute danger thresholds [20].

Our projections show sharp increases in heatwave days across many regions, particularly under SSP2-4.5 and SSP5-8.5. This implies greater risk of disrupted training blocks, altered tapering, forced rest days and elevated cumulative fatigue. Recreational athletes, older adults and those with underlying conditions are likely to be disproportionately affected [12]. For sport medicine and performance staff, this underscores the need to monitor **cumulative thermal load** and integrate environmental stress into periodisation models—an emerging but underdeveloped area of practice.

5.6 Seasonal patterns (JJA vs. DJF) and hemispheric asymmetries

Our JJA/DJF analysis reveals clear hemispheric asymmetries relevant for sport scheduling. JJA shows the strongest increases in heat-related hazards in the Northern Hemisphere, while DJF becomes increasingly constrained in the Southern Hemisphere where summer sport is predominant.

These patterns intersect structurally with established calendars. Many global events are scheduled to optimise conditions in one hemisphere, but our results show that the concept of a "safe summer" is weakening. Federations may need to revisit long-standing assumptions about seasonal windows and consider cross-hemispheric rotations, shoulder-season scheduling or long-term calendar redesigns.

5.7 Scenario divergence between SSP2-4.5 and SSP5-8.5

The widening gap between SSP2-4.5 and SSP5-8.5 by late century has clear implications for both climate policy and sport governance. Under SSP1-2.6 and, to a lesser extent, SSP2-4.5, many regions experience increases in hazardous days that, while substantial, remain theoretically manageable through adaptation (scheduling shifts, facility upgrades, medical protocols). Under SSP5-8.5, however, several regions cross into regimes where **large fractions of the warm season** exceed thermal safety thresholds even in the coolest parts of the day.

This mirrors broader health and labour impact research [16, 12], which shows that emissions trajectories determine the feasibility of safe outdoor activity. For sport, this means that global mitigation efforts are not simply an environmental imperative but a determinant of whether outdoor sport remains viable in its traditional form in major regions of the world.

5.8 Limitations and future directions

Several limitations must be acknowledged. First, although we use bias-corrected and downscaled CMIP6 projections, we do not perform explicit validation of WBGT, HI, rainfall and heatwave metrics against reanalysis products such as ERA5 or against dense station networks. While NEX-GDDP performs reasonably well for many variables, regional biases remain possible, particularly in complex terrain or coastal domains.

Second, the WBGT formulation uses standard approximations rather than full radiative–wind models. This is common in large-scale assessments but introduces uncertainties when translating grid-cell conditions to venue-specific microclimates (e.g. shade, ventilation, stadium architecture) [6, 7]. Our estimates should therefore be interpreted as **first-order indicators**, not precise diagnostics for specific facilities.

Third, we do not explicitly model acclimatisation, cooling strategies, clothing, hydration protocols or rule changes, all of which can substantially modify real-world risk [1, 5]. Nor do we distinguish between sports with different metabolic loads or protective equipment. As such, our projections define a **climatic envelope of potential stress**, within which sport-specific risks may vary widely.

Fourth, our rainfall and heatwave definitions are intentionally simple and operational. More sophisticated metrics—compound indices, multi-day rainfall accumulations, sport-specific saturation thresholds—could be incorporated in future extensions. Similarly, while our multi-model mean reduces noise, we do not quantify model spread in detail, leaving some uncertainty in regional projections.

Finally, we do not model behavioural, organisational or economic responses. Recent evidence on athlete and organiser behaviour under heat stress [28, 31, 15] suggests that adaptive strategies are heterogeneous and context-dependent. Integrating these behavioural dimensions with physically based hazard projections remains a major research frontier.

Despite these limitations, our study provides an unprecedented global baseline for understanding how climate change may reshape the practice, scheduling and geography of outdoor sport. Future work could build on this foundation by (i) validating and refining indicators with reanalysis and observations, (ii) developing sport-specific thresholds, (iii) exploring alternative adaptation scenarios (e.g. systematic time-of-day shifts, infrastructure upgrades, calendar redesigns), and (iv) coupling climate hazard projections with participation, injury and economic data to develop integrated climate–sport risk assessments.

6 Conclusion

This study provides, to our knowledge, the first global, CMIP6-based, multi-indicator assessment of how climate change will reshape the environmental conditions in which outdoor sports are practiced. By combining WBGT (morning–afternoon–evening), Heat Index $> 40\,°\mathrm{C}$, heavy rainfall days and multi-day heatwaves at 0.25° resolution, we reveal a consistent and substantial intensification of climatic constraints across most regions of the world, with particularly strong impacts in low-latitude and warm–humid environments.

Several key findings emerge. First, heat and humidity together drive a rapid contraction of safe practice windows, especially during afternoon hours when thermal load peaks. While shifting activities to mornings or evenings can partly mitigate risk, this strategy becomes progressively less effective under high-emission scenarios (SSP5–8.5), as even early-morning WBGT values exceed recommended thresholds in many regions. Second, heatwaves introduce cumulative stress that is not captured by single-day indices, underscoring the need for monitoring frameworks that account for multi-day thermal load, not just match-day conditions. Third, heavy rainfall remains a major operational constraint in several climate zones, contributing to surface degradation, injury risk and event cancellations even where thermal conditions are tolerable. Fourth, the divergence between SSP2–4.5 and SSP5–8.5 by late century is substantial: under ambitious mitigation, climatic constraints increase but remain theoretically manageable with robust adaptation; under high emissions, large portions of the warm season become incompatible with safe outdoor sport practice, even with aggressive scheduling changes.

These results have immediate relevance for sport organisers, federations, athlete support staff, public-health authorities and urban planners. They highlight the need for proactive adaptation strategies—including revised scheduling practices, resilient surface and facility design, climate-aware event planning, and strengthened heat–health protocols—and for integrating environmental risk assessments into decision-making in both elite and community sport. At the same time, our findings reinforce a broader message familiar from the health and labour impact literature: global mitigation choices will fundamentally determine whether large regions remain viable for safe outdoor activity, including organised sport.

Our indicators inevitably have limitations. They rely on gridded climate data and cannot capture venue-specific microclimates; WBGT is computed using standard approximations; and we do not represent acclimatisation, cooling strategies, behavioural responses or sport-specific physiological thresholds. Nonetheless, by providing a coherent, global baseline across multiple hazards and future scenarios, this work establishes a foundation on which more detailed, sport-specific and impact-focused studies can build.

Future efforts should integrate high-resolution reanalysis and observational data for validation, refine sport-specific thresholds and injury risk relationships, and couple climate hazards with participation, performance and economic data. Co-developing adaptation pathways with sport organisations, athletes and medical staff will be essential to translate climate information into workable changes to calendars, training practices and infrastructure. As extreme heat, humidity and precipitation become increasingly common, a robust quantitative evidence base will be critical to safeguard health, preserve access to outdoor sport, and support long-term governance decisions in a rapidly changing climate.

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All data used in this study are publicly available. Bias-corrected CMIP6 climate projections were obtained from the NASA NEX-GDDP dataset. Stadium locations were compiled from publicly available information, primarily based on Wikipedia listings of clubs from the top 15 European first-division leagues for the 2024–2025 season.

Processed indicators and all scripts used to generate the results will be made publicly available upon publication via Zenodo and GitHub.

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