Title

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ARTICLE

Unequal weather exposure across teams and groups at the 2026 FIFA World Cup: an event-based analysis using hourly reanalysis

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ABSTRACT
The connection between climate change and sports is evident, as sports contribute to environmental challenges, while climate change impacts the conditions for playing, organizing, and enjoying sports. In professional football, heat, humidity, rain, wind, and insufficient recovery time at night can influence player health, physical stress, and game performance. Evaluations of the 2026 FIFA World Cup have pointed out significant environmental risks in host cities, especially concerning heat stress, but these assessments are focused on specific locations. This research examines whether the environmental exposure during the 2026 FIFA World Cup is unevenly distributed due to the interaction between climate conditions and the tournament's schedule. We propose an event-based framework where each match is evaluated based on venue, date, and local kick-off time. Hourly ERA5-Land and ERA5 data are used to calculate probabilities of exceeding thresholds for heat stress, rainfall, wind gusts, and night-time recovery constraints, assessed through tropical nights. For each match, conditions are assessed within a timeframe starting one hour before and ending two hours after kick-off, combined with two-days calendar window, resulting in 75 sampled events per match for each 15-year period. Comparing 1996–2010 and 2011–2025 reveals that exposure varies across matches, groups, and teams. Heat stress is most pronounced, particularly for afternoon games in southern and inland locations, while rain, wind, and tropical nights exhibit unique spatial and temporal patterns. Thus, environmental exposure is not just a backdrop for outdoor football but an emerging aspect of mega-event planning, affecting tournament fairness, sports management, and climate adaptation.

KEYWORDS
FIFA World Cup; climate change; sport management; mega-events; heat stress; WBGT; tournament design; competitive fairness; environmental exposure

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1. Introduction

1.1. Climate change, sport, and environmental exposure

Climate change is increasingly altering the environmental conditions under which outdoor activities take place, with rising temperatures, more frequent heatwaves, and increasing hydroclimatic extremes affecting both human health and physical activity (Fischer & Knutti, 2015; IPCC, 2021; Perkins-Kirkpatrick & Lewis, 2020). These changes are particularly relevant for sport, which both depends on climatic conditions and contributes to broader environmental challenges (Bernard et al., 2021; Orr, Inoue, Seymour, & Dingle, 2022; Schneider & Mücke, 2024).

Recent reviews have highlighted that climate change affects organized sport through multiple pathways, including heat exposure, extreme weather events, air quality degradation, infrastructure disruption, and scheduling constraints (Orr & Inoue, 2019; Orr et al., 2022; Schneider & Mücke, 2024). These impacts concern not only athletes, but also spectators, staff, volunteers, and urban populations involved in large sporting events. As a result, climate change is increasingly recognised as a major challenge for the sustainability and governance of sport systems (Mabon, 2023).

Among climate-related hazards, heat stress has emerged as a major concern for outdoor sports, particularly during summer competitions when climatic conditions can approach or exceed physiological limits (Périard, Eijsvogels, & Daanen, 2021; Racinais et al., 2015). The combination of high air temperature, humidity, and solar radiation can substantially increase thermal strain and affect both health and performance.

1.2. Football, heat stress, and adaptation strategies

In football, environmental conditions such as temperature, humidity, solar radiation, wind, and precipitation influence both physiological strain and match performance. Heat stress, commonly quantified using the Wet Bulb Globe Temperature (WBGT), reduces high-intensity running capacity, alters pacing strategies, and increases cardiovascular strain (Nybo, Rasmussen, & Sawka, 2014; Périard et al., 2021; Racinais et al., 2015). Observational studies in football show that players adapt their activity profiles under heat exposure, with reductions in sprint distance, high-intensity actions, and modifications in tactical behaviour (Girard, Brocherie, & Bishop, 2015; Nassis, Brito, Dvorak, Chalabi, & Racinais, 2015).

Extreme conditions also increase the risk of exertional heat illness, requiring mitigation strategies such as cooling breaks, heat acclimation, hydration protocols, or match rescheduling (Casa et al., 2015; Gouttebarge, Duffield, den Hollander, & Maughan, 2023). Recent analyses of elite competitions confirm that environmental conditions can directly affect match outputs. Matches played under elevated thermal stress are associated with reduced physical performance, while evening matches allow higher work rates compared to afternoon matches (Carmo et al., 2026).

Environmental constraints also extend beyond the match itself. In congested tournament schedules, recovery conditions between matches are a critical component of performance maintenance and player health. Elevated night-time temperatures can impair sleep quality, thermoregulation, and physiological restoration (Obradovich, Migliorini, Mednick, & Fowler, 2017). In climate science, such conditions are commonly characterised using tropical nights, defined as nights during which minimum temperature remains above 20 °C (ETCCDI, 2009). While widely used in climatology as an indicator of nocturnal heat stress, tropical nights are also directly relevant for elite sport because they may limit overnight cooling and recovery following competition in hot environments.

Several recent studies have therefore questioned the sustainability of summer football competitions under climate change and highlighted the growing tension between broadcasting constraints, tournament calendars, player health, and environmental exposure (Mabon, 2023). Similar concerns have already prompted calls for calendar and scheduling adaptations in major sporting events, a dynamic that has been documented across the Olympic Winter Games, endurance competitions, and sports events more broadly (DeChano-Cook & Shelley, 2017; Scott, Steiger, Rutty, & Johnson, 2015; Steiger & Scott, 2025; Werner, 2024).

1.3. Mega-events, tournament structure, and environmental inequality

Increasing attention has consequently been paid to environmental risks associated with mega sporting events (Collins, Jones, & Munday, 2009; Müller, 2015; Orr et al., 2022). Mega-events such as the FIFA World Cup combine large spectator flows, complex scheduling systems, extensive travel, and strong exposure to local climatic conditions (Müller, 2015). Several authors have argued that climate change may progressively challenge the organisation and viability of such events, particularly during summer periods (Mabon, 2023).

Recent studies have specifically assessed heat exposure at host cities of the 2026 FIFA World Cup, showing that many venues are likely to experience WBGT levels exceeding recommended thresholds during June and July (Craig & Karabas, 2024; Esh et al., 2026; Mullan et al., 2025). These studies have raised concerns regarding player safety, tournament scheduling, and adaptation strategies under a warming climate.

However, existing assessments remain largely location-based. They typically describe climatic conditions at host cities without considering how environmental exposure is experienced within the structure of the tournament itself. In practice, teams experience climate as a sequence of matches defined by specific venues, dates, and kick-off times. Environmental exposure is therefore dynamic and may vary substantially across teams depending on the tournament schedule.

This issue is particularly relevant for large multi-host competitions (Collins et al., 2009; Müller, 2015; Orr & Inoue, 2019). The 2026 FIFA World Cup spans a wide geographical domain across North America, exposing teams to diverse climatic regimes ranging from arid to humid subtropical and continental climates (Esh et al., 2026). In parallel, scheduling decisions—especially kick-off times—strongly modulate environmental conditions within a given day (Mullan et al., 2025). The interaction between spatial climatic variability and tournament design therefore creates the potential for unequal environmental exposure across matches, groups, and teams.

Previous work on fairness in multi-host tournaments has primarily focused on logistical factors such as travel distance, basecamp location, or home advantage (Brocherie, De Larochelambert, & Millet, 2022). By contrast, the distribution of environmental constraints within the competition structure has received far less attention, despite the fact that climatic conditions may interact with competitive balance, recovery, and health protection.

More broadly, while climate change impacts on sport are increasingly documented, important gaps remain regarding the role of tournament organisation itself in shaping exposure inequalities. Climate-related burdens are also known to disproportionately affect vulnerable populations and regions (Callahan & Mankin, 2024; Diffenbaugh &

Burke, 2020; Hsiang et al., 2017), raising broader questions regarding environmental justice and adaptation capacities in global sporting systems.

1.4. Objectives of the study

In this study, we address these gaps using an event-based framework to quantify environmental exposure at the match level and assess how it is distributed across groups and teams during the 2026 FIFA World Cup.

Using hourly ERA5-Land and ERA5 reanalysis data, we estimate the probability of exceeding thresholds for heat stress, rainfall, wind, and night-time recovery conditions. We further compare two recent climate periods (1996–2010 and 2011–2025) to assess recent changes in exposure.

From a sport management perspective, the study contributes by showing that environmental exposure is not only a climatic condition affecting sport events, but also a managerial outcome of decisions about venue selection, match allocation, kick-off times, and tournament expansion.

By shifting the focus from host locations to tournament structure, this study provides a new perspective on environmental risk in major sporting events and raises the question of whether environmental conditions should be considered as an additional dimension of competitive fairness (Brocherie et al., 2022; Mabon, 2023; Orr & Inoue, 2019).

2. Methods

2.1. Data

2.1.1. Tournament data

The analysis is based on the official match schedule of the 2026 FIFA World Cup, obtained from the official FIFA website(FIFA, 2026). The dataset includes match dates, local kick-off times, venues, group assignments, and participating teams. All times are expressed in local time at each venue.

2.1.2. Reanalysis data

Hourly meteorological variables are derived from the ERA5-Land reanalysis dataset at 0.1° spatial resolution (Muñoz-Sabater et al., 2021), accessed through the Copernicus Climate Data Store (CDS)(Copernicus Climate Change Service (C3S), 2024b). The ERA5-Land time series product is used to extract point-based hourly data at stadium locations.

The following variables are used from ERA5-Land:

- 2-m air temperature (`t2m`)
- 2-m dew point temperature (`d2m`)
- surface solar radiation downwards (`ssrd`)
- total precipitation (`tp`)
- 10-m zonal and meridional wind components (`u10`, `v10`)

These variables are used to compute heat stress indicators and precipitation metrics.

Wind gusts are extracted from the ERA5 atmospheric reanalysis at 0.25° spatial resolution (Hersbach et al., 2020), using the CDS time series product(Copernicus Climate Change Service (C3S), 2024a). ERA5 provides consistent global estimates of atmospheric variables and is used here specifically for wind gust diagnostics.

2.1.3. Study periods

Two 15-year periods are considered: 1996–2010 and 2011–2025. These periods allow for a comparison between past and more recent climatic conditions while ensuring a sufficient sample size for robust statistical analysis.

2.2. Design of the study

This study adopts an event-based framework to quantify environmental exposure at the match level. The methodology consists of five main steps: (i) spatial localization of stadiums and extraction of meteorological data at match locations, (ii) temporal alignment of match schedules in local time, (iii) event-based sampling of environmental conditions around each match, (iv) computation of climate indicators, and (v) estimation of exceedance probabilities and aggregation across tournament levels.

2.2.1. Stadium localization and data extraction

All stadiums hosting the 2026 FIFA World Cup matches are geolocated using their latitude and longitude coordinates and present on figure 1. Meteorological variables are extracted at each stadium location using the nearest grid point from ERA5-Land and ERA5 reanalyses.

Stadium-specific infrastructure, such as air conditioning, is not explicitly accounted for in the analysis. Environmental exposure is therefore assessed based on outdoor atmospheric conditions, with potential mitigation effects discussed separately.

2.2.2. Temporal alignment

Match schedules are processed in local time at each venue. All meteorological variables are therefore analyzed in local time to ensure consistency with match conditions and human exposure.

Night-time conditions are defined over a fixed 22:00–06:00 local-time window. For each match, the night immediately following the match day is considered to assess recovery conditions.

2.2.3. Event-based sampling

For each match, environmental conditions are sampled over a time window extending from one hour before to two hours after kick-off. This match-time window is combined with a $\pm$2-day window around the calendar date.

This results in 5 days per year over 15 years, corresponding to 75 sampled events per match. This sampling strategy provides a robust empirical distribution of environmental conditions representative of the match timing and season.

2.3. Climate indicators

2.3.1. Heat stress (WBGT)

Heat stress is estimated using the Wet Bulb Globe Temperature (WBGT). The wet-bulb temperature (T_w) is approximated following Stull (2011):

$$
\begin{aligned}
T_w = T \cdot \arctan\left(0.151977\sqrt{RH + 8.313659}\right) & \quad (1)\\
+ \arctan(T + RH) & \quad (2)\\
- \arctan(RH - 1.676331) & \quad (3)\\
+ 0.00391838 \cdot RH^{3/2} \cdot \arctan(0.023101 RH) & \quad (4)\\
- 4.686035 & \quad (5)
\end{aligned}
$$

WBGT is then estimated under outdoor conditions as:

$$WBGT = 0.7\,T_w + 0.2\,T_g + 0.1\,T \quad (6)$$

where T_g is approximated from solar radiation.

For each match, the maximum WBGT over the match window is retained. Two thresholds are considered: 28°C and 32°C, corresponding to moderate and high heat stress conditions, respectively (Casa et al., 2015; FIFPRO, 2023; Gouttebarge et al., 2023).

2.3.2. Rainfall

Rainfall during matches is defined as accumulated precipitation over the 3-hour match window, with a threshold of 1 mm. This threshold corresponds to measurable precipitation (World Meteorological Organization, 2018).

Antecedent wet conditions are defined as total precipitation over the 24 hours preceding kick-off, with a threshold of 5 mm, representing non-negligible wet conditions that may affect pitch properties.

2.3.3. Wind

Wind exposure is assessed using maximum wind gusts over the match window. A threshold of 12 m s^{-1} is used, corresponding approximately to Beaufort force 6 (strong breeze), conditions that may interfere with ball trajectory and gameplay (World Meteorological Organization, 2008).

2.3.4. Night-time recovery

Night-time recovery conditions are evaluated using tropical nights, defined as minimum temperature exceeding 20°C during the night following the match (22:00–06:00 local time), following the ETCCDI definition (ETCCDI, 2009).

2.4. Probability estimation

For each match and climate period, environmental exposure is estimated using an event-based sampling strategy. Match conditions are sampled over a ± 2-day window around the scheduled calendar date and repeated for each year within the considered 15-year period. This results in 75 event realizations per match and per period (5 calendar days $\times$ 15 years).

For each indicator, probabilities are estimated empirically as the frequency of threshold exceedance across these sampled realizations. Probabilities therefore represent the fraction of match-event realizations for which environmental conditions exceed a predefined threshold under the considered tournament configuration.

For example, a probability of 0.20 for WBGT $\geq 28\,^{\circ}$C indicates that 15 out of 75 sampled realizations exceed the selected heat-stress threshold. Similarly, a probability of 0.30 for rainfall indicates that precipitation exceeding the selected threshold occurs in 30% of sampled match windows.

Because indicators represent different environmental dimensions, their interpretation differs slightly. Heat-stress probabilities reflect the likelihood of exposure to physiologically stressful thermal conditions during play, whereas rainfall and wind probabilities characterize the occurrence of potentially disruptive weather conditions during matches. Tropical-night probabilities quantify the frequency of warm nocturnal conditions that may impair overnight recovery between matches.

Changes in probability between periods therefore represent changes in the frequency of environmentally stressful conditions under recent climate conditions relative to the earlier baseline period.

2.5. Aggregation

Environmental exposure is aggregated at three levels: match, group, and team. This allows assessing how tournament structure distributes environmental constraints across competition levels.

3. Results

3.1. Tournament structure

The 2026 FIFA World Cup is characterized by a geographically dispersed multi-host structure, spanning North America across 16 stadiums located in Canada, the United States, and Mexico (Fig. 1). The majority of matches are hosted in the United States, with a smaller number in Mexico and Canada, leading to a heterogeneous spatial distribution of venues across a wide range of climatic conditions.

Match allocation is also uneven across stadiums, with several venues hosting a higher number of matches, thereby increasing their relative contribution to overall tournament exposure.

The temporal structure of the tournament reveals a strong concentration of matches during the group stage, which spans approximately two weeks in mid to late June. Subsequent knockout phases occur over a shorter time period in early to mid-July.

Kick-off times exhibit a marked clustering in the late afternoon and evening, with a secondary peak around midday. A limited number of matches are scheduled at late evening hours. This distribution reflects broadcasting constraints but also implies that teams are exposed to a wide range of diurnal environmental conditions.

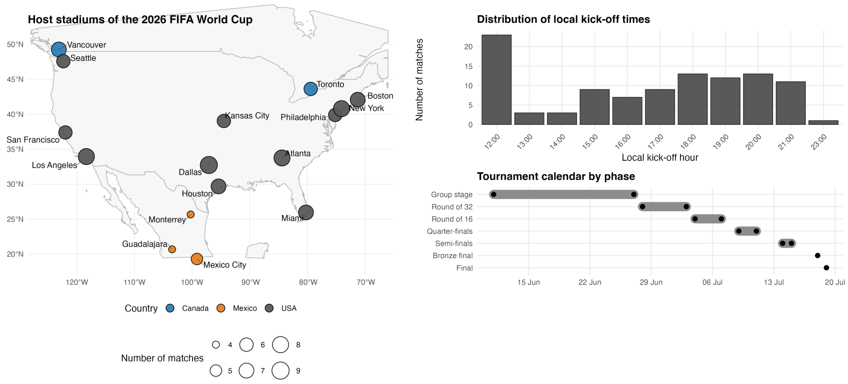

Figure 1. Spatial distribution of stadiums, number of matches, and distribution of local kick-off times.

Overall, the combination of spatial dispersion, uneven match allocation, and heterogeneous kick-off times suggests that environmental exposure during the tournament is inherently non-uniform, providing a structural basis for unequal climatic constraints across matches, groups, and teams.

3.2. Climatic context

Host stadiums are distributed across a wide range of climate regimes, from arid and semi-arid environments in Mexico and the southwestern United States to humid subtropical and continental climates in the eastern United States and Canada (Fig. 2).

This climatic diversity reflects the large spatial extent of the tournament and implies substantial differences in baseline environmental conditions across venues. In particular, several stadiums are located in regions characterized by high summer temperatures and humidity, while others are situated in milder or more temperate climates.

This heterogeneity provides a structural basis for contrasting environmental exposures across matches, independent of scheduling effects.

3.3. Changes in exposure between periods

Substantial changes in environmental exposure are observed between the 1996–2010 and 2011–2025 periods, with strong spatial variability across stadiums (Fig. 3).

Heat stress exhibits the most pronounced increase, particularly in southern and inland stadiums such as Dallas, Houston, and Atlanta, where the probability of exceeding WBGT thresholds increases markedly under outdoor atmospheric conditions. In contrast, changes remain limited or near zero in several coastal or northern venues. Because this analysis is based on reanalysis-derived outdoor conditions, these results do not account for potential mitigation associated with partially enclosed or climate-controlled stadium infrastructure.

Changes in rainfall exposure are more heterogeneous, with both increases and decreases depending on location. This reflects the higher spatial variability of precipitation compared to temperature-driven indicators.

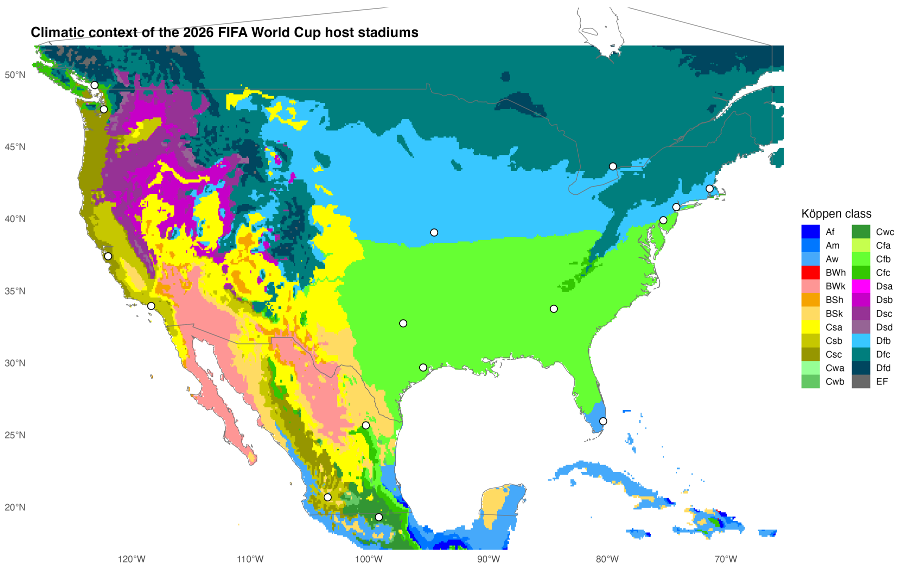

Figure 2. Köppen–Geiger climate classification across North America (1991–2020 baseline) with locations of the 2026 FIFA World Cup host stadiums. Stadiums are distributed across a wide range of climate types, including humid subtropical (Cfa), arid (BWh, BSk), Mediterranean (Csa), and continental climates (Dfa, Dfb), highlighting the strong climatic heterogeneity of the tournament environment.

Wind gust exposure shows moderate changes overall, with localized increases in certain stadiums, although the magnitude of change remains smaller than for heat stress.

These results indicate that recent climatic conditions have already altered the environmental constraints experienced during matches, with heat stress emerging as the dominant and most consistently increasing hazard.

3.4. Match-level variability

Environmental exposure varies substantially across matches, with large differences in probability distributions for all indicators (Fig. 4).

Heat stress shows the highest variability, with some matches exhibiting very high probabilities of exceeding WBGT thresholds, while others remain close to zero. This variability is strongly structured by kick-off time, with early afternoon matches associated with the highest exposure levels.

Rainfall exposure displays a more compact distribution, although several matches show elevated probabilities, reflecting localized precipitation patterns.

Wind gust exposure remains generally low across matches, with limited variability compared to heat stress and rainfall.

Overall, match timing emerges as a key driver of environmental exposure, with scheduling decisions directly influencing the level of climatic constraints experienced during the tournament.

3.5. Group-level inequality

Environmental exposure is not uniformly distributed across tournament groups (Fig. 5). Marked differences are observed for all indicators, although the strongest

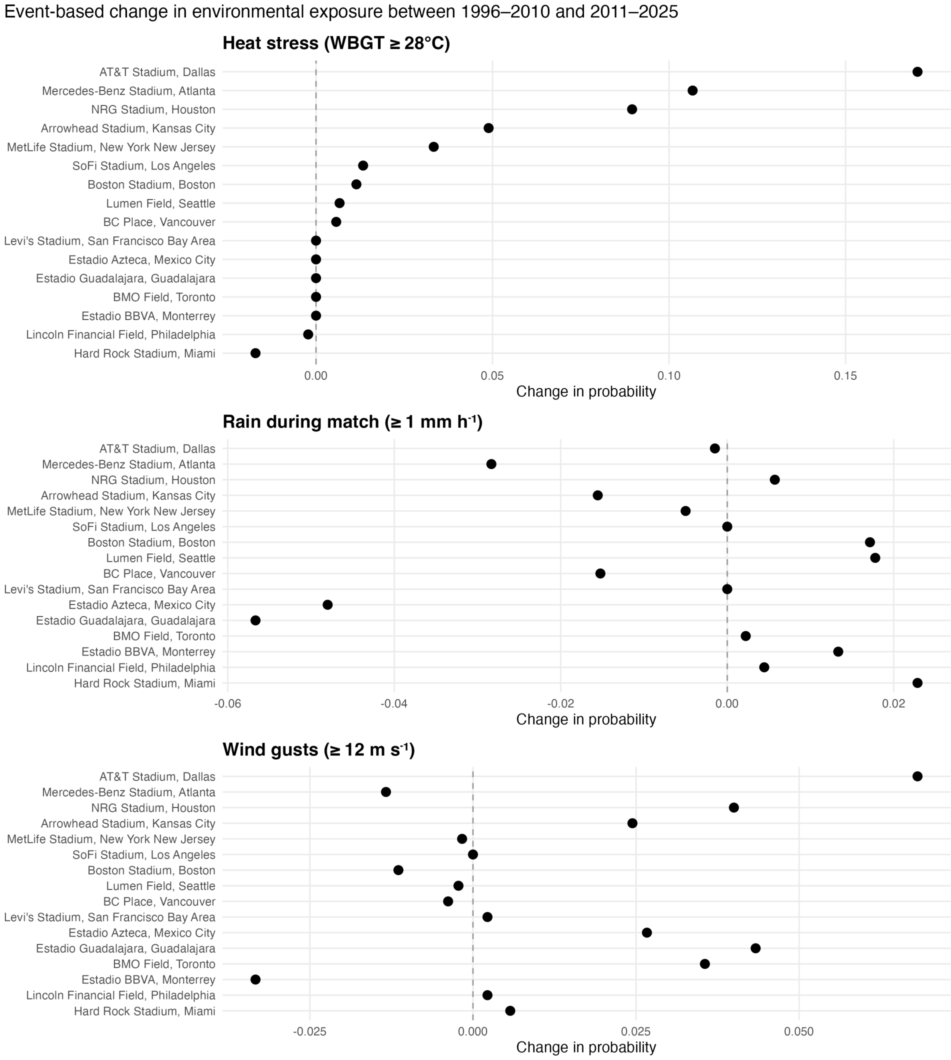

Figure 3. Event-based changes in environmental exposure between 1996–2010 and 2011–2025 across host stadiums. Each point represents the change in the probability of exceeding predefined thresholds for heat stress (WBGT $\geq$ 28°C), rainfall during matches (1 mm h^{-1}), and wind gusts (12 m s^{-1}). Positive values indicate increased exposure in the recent period.

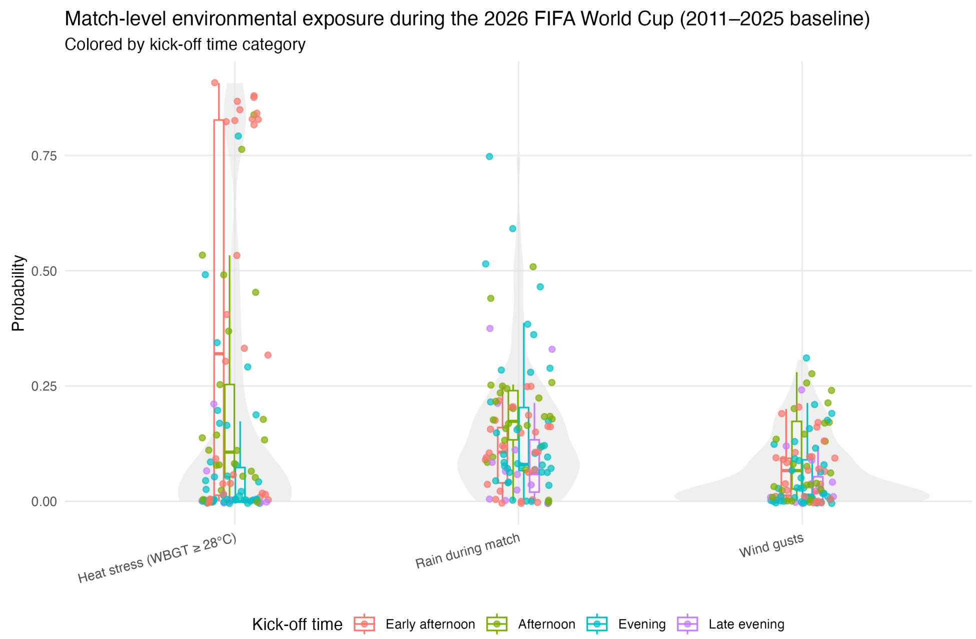

Figure 4. Match-level environmental exposure during the 2026 FIFA World Cup based on the 2011–2025 baseline. Distributions of probabilities are shown for heat stress (WBGT $\geq$ 28°C), rainfall during matches, and wind gusts. Points are colored by kick-off time category, highlighting the influence of match timing on exposure.

contrasts emerge for heat stress.

Groups F and K exhibit the highest exposure to heat stress, with several matches showing high probabilities of exceeding the WBGT 28°C threshold. Group H also displays elevated heat exposure, although with lower central values than Groups F and K. In contrast, Groups A, B, D, and G remain close to zero for most matches, indicating substantially lower heat-related constraints.

Wet conditions are distributed differently. Antecedent rainfall probabilities are highest in Groups H, K, and A, while Groups C and I also show relatively elevated values. Rain during matches is most pronounced in Groups K and H, with moderate exposure in Groups A and I. Several groups, such as D and G, show consistently low rainfall-related exposure.

Wind gust exposure is generally lower than heat or rainfall exposure, but still varies across groups. Groups F, I, and L show the highest central values and widest variability, whereas Groups D and G remain close to zero. Although not explicitly represented in Fig. 5, night-time recovery conditions also display substantial variability between tournament pathways, with some groups more frequently exposed to tropical-night conditions that may impair post-match recovery.

Overall, these results show that tournament groups are associated with distinct environmental profiles, indicating that the group-stage draw is not only a competitive structure but also a climatic one.

3.6. Team-level inequality

The unequal distribution of environmental exposure becomes even clearer at the team level (Fig. 6). Considerable contrasts are observed between teams for heat stress, wet

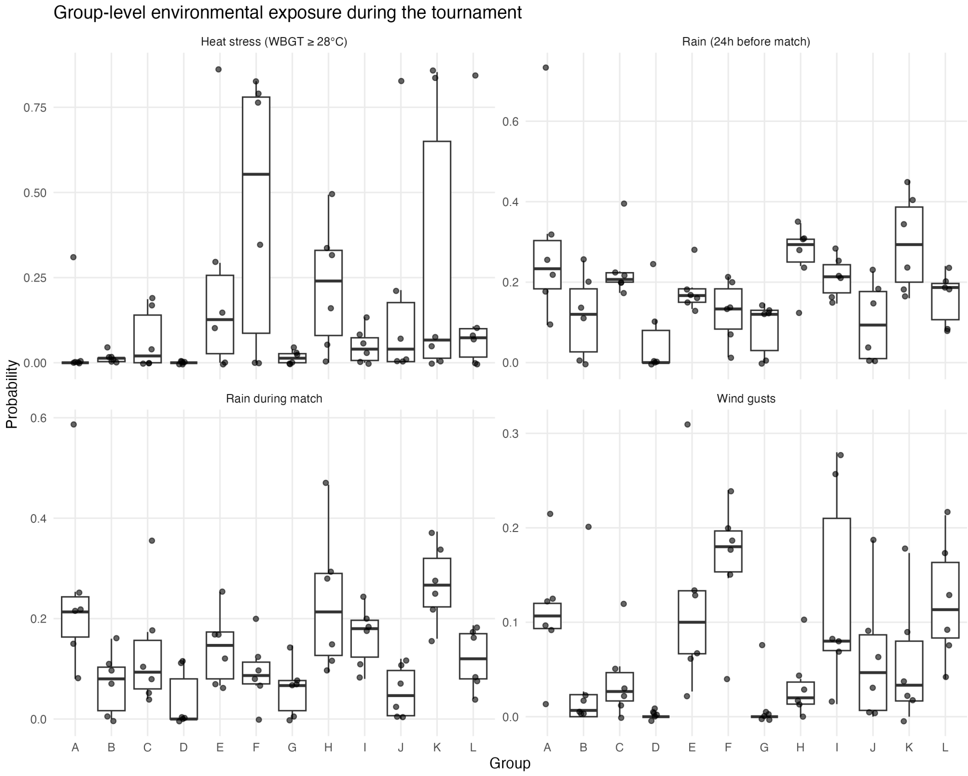

Figure 5. Group-level environmental exposure during the group stage of the 2026 FIFA World Cup based on the 2011–2025 baseline. Boxplots show the distribution of match-level probabilities within each group for heat stress (WBGT $\geq 28°C$), antecedent rainfall (24 h before match), rainfall during matches, and wind gusts.

conditions, and night-time recovery constraints.

The strongest differences are found for heat stress. Teams such as the Netherlands, Portugal, Sweden/Poland, Japan, and Curaçao display the highest mean probabilities of exposure to WBGT $\geq$ 28°C across their three group-stage matches. By contrast, teams such as Australia, Kosovo/Turkiye, Mexico, Paraguay, and the Republic of Korea remain close to zero. Exposure to the higher WBGT threshold (32°C) is much less frequent overall, but the same teams remain among the most exposed.

Wet conditions show a different ranking. For rainfall during the match and antecedent rainfall, teams such as the Netherlands, Portugal, Colombia, Mexico, and Czechia/Denmark are among the most exposed, whereas Australia, Kosovo/Turkiye, Paraguay, and several North American teams show comparatively lower probabilities.

Night-time recovery constraints also vary strongly. The highest probabilities of tropical nights are found for teams such as Portugal, the Netherlands, Sweden/Poland, Argentina, and Japan, while the lowest values are found for teams such as Australia, Kosovo/Turkiye, Mexico, Paraguay, and Qatar.

Taken together, these results show that teams are not only exposed to different average conditions, but also to different combinations of climatic constraints. Some teams experience predominantly heat-related burdens, whereas others are more affected by wet conditions or night-time recovery constraints. The tournament schedule therefore translates climatic heterogeneity into unequal team-level exposure.

4. Discussion

4.1. Environmental exposure as an implicit dimension of tournament fairness

This study shows that environmental exposure during the 2026 FIFA World Cup is not uniformly distributed across matches, groups, and teams. The mechanisms underlying this inequality can be conceptualized as a cascade of interactions between climate conditions and tournament design (Fig. 7). While climatic variability is an inherent feature of outdoor football, our results indicate that tournament design translates this variability into structured inequalities. In this sense, environmental exposure appears as an additional, implicit dimension of tournament fairness.

This perspective complements previous work on fairness in multi-host competitions, which has mainly focused on travel distance, basecamp location, and home-advantage effects (Brocherie et al., 2022; Müller, 2015; Orr & Inoue, 2019). In the case of the 2020 UEFA European Championship, teams with basecamps close to match venues improved their match outcomes, even though travel distance and bio-meteorological conditions were not clearly associated with progression through the tournament (Brocherie et al., 2022). Our results extend this line of thinking by showing that, even without directly analysing match outcomes, the tournament environment itself is unevenly allocated.

This unequal allocation also resonates with broader discussions on climate justice and social justice. Climate change impacts are rarely distributed evenly, and vulnerability depends not only on physical exposure but also on the capacity of individuals and institutions to anticipate, absorb, and adapt to environmental stressors (Callahan & Mankin, 2024; Diffenbaugh & Burke, 2020; Hsiang et al., 2017; Preston et al., 2014; Venn, 2019). In sport, this is particularly relevant because teams do not enter tournaments with equal adaptive resources. Wealthier federations may benefit from

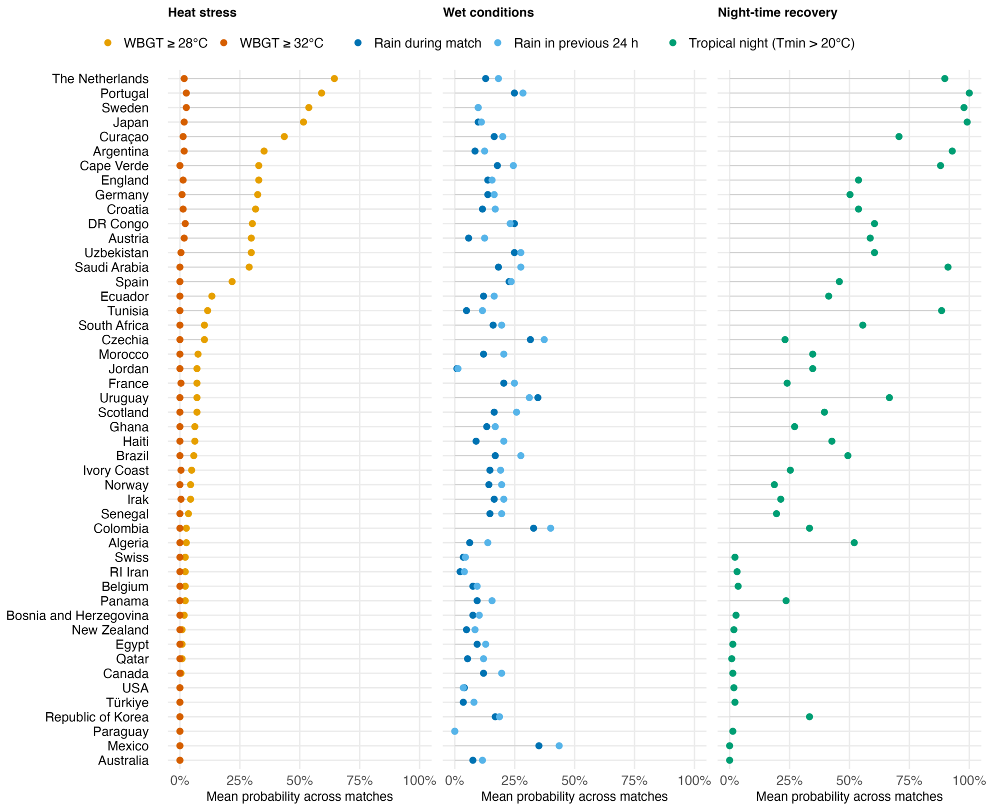

Figure 6. Team-level environmental exposure during the group stage of the 2026 FIFA World Cup based on the 2011–2025 baseline. Each value represents the mean probability of exposure across the three group-stage matches of a given team. Panels show heat stress (WBGT $\geq 28°C$ and WBGT $\geq 32°C$), wet conditions (rain during the match and in the previous 24 h), and night-time recovery constraints (tropical nights).

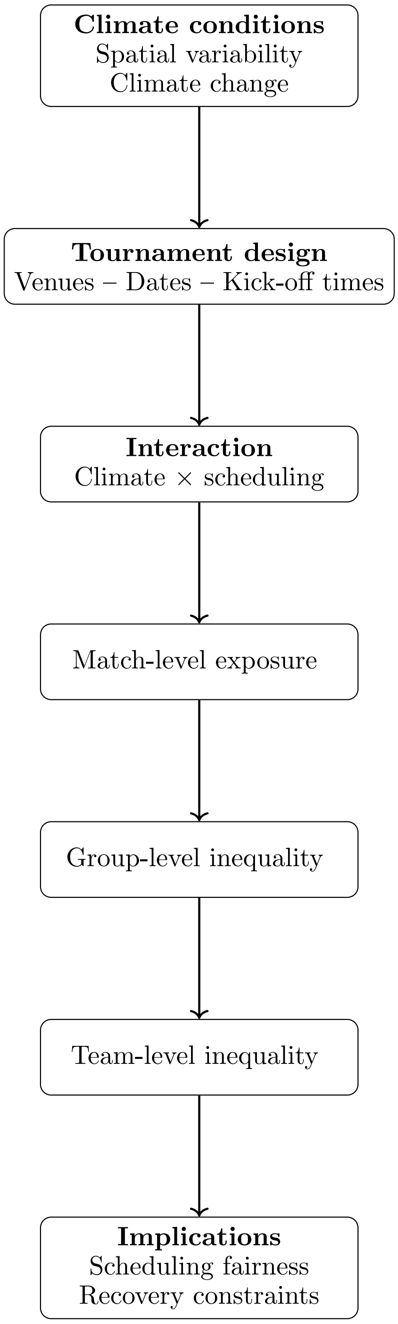

Figure 7. Conceptual framework of unequal environmental exposure in tournament settings. Climate conditions and tournament design interact to shape match-level exposure, which propagates into inequalities across groups and teams, with implications for scheduling fairness and recovery.

better medical staff, heat-acclimation protocols, recovery facilities, travel logistics, and access to controlled indoor environments, whereas less-resourced teams may face more limited adaptive capacity. Environmental exposure should therefore not be interpreted only as a natural background condition: it becomes part of a broader socio-technical system in which climate, infrastructure, institutional capacity, and tournament design interact.

Yet the concept of fairness itself warrants more careful theoretical grounding. In sport management, fairness is commonly treated as an intuitive standard, but it encompasses at least two analytically distinct dimensions that have different implications for governance. *Procedural fairness* concerns the rules and processes by which outcomes are generated: a tournament draw is procedurally fair if it follows transparent, pre-established rules applied equally to all participants (Capeheart & Milovanovic, 2020). *Substantive fairness*, by contrast, concerns the distribution of actual burdens and advantages among participants, irrespective of the procedural neutrality of the process that generated them (Preston et al., 2014; Venn, 2019). These two dimensions can diverge sharply. A draw may be procedurally irreproachable and yet produce substantially unequal environmental exposures, precisely because the procedural mechanism operates on a pre-existing and climatically non-neutral schedule. Our results illustrate this divergence: no team is disadvantaged by a biased draw, yet some teams systematically face higher probabilities of heat stress, disruptive weather, and impaired recovery.

A further distinction is necessary between *equality of exposure*—the raw probability of encountering stressful environmental conditions—and *equality of effective constraint*—the actual physiological and competitive burden produced by that exposure, which depends critically on adaptive capacity. As highlighted in the climate justice literature, vulnerability to environmental stressors is not only a function of physical exposure but also of the institutional, financial, and technical resources available to absorb and respond to those stressors (Diffenbaugh & Burke, 2020; Preston et al., 2014; Venn, 2019). In the context of football, wealthier national federations can invest in heat-acclimation protocols, climate-controlled training facilities, specialist medical staff, and tailored recovery infrastructure, thereby converting the same nominal exposure into a lower effective constraint. Less-resourced federations, by contrast, may lack these adaptive buffers, such that identical climatic probabilities translate into greater actual burdens. Environmental exposure in a mega-event therefore does not operate on a blank competitive slate: it interacts with pre-existing inequalities in institutional capacity, reproducing at the tournament level the broader pattern whereby climate-related burdens fall disproportionately on those least equipped to manage them (Callahan & Mankin, 2024; Diffenbaugh & Burke, 2020; Hsiang et al., 2017).

This intersection with social justice is further sharpened when one considers the geographical origin of the most exposed teams. Evidence from previous tournaments suggests that teams from tropical or subtropical environments—many of them from the Global South—are not necessarily advantaged by warm conditions at competitions held elsewhere. Teams habituated to playing at altitude or in heat may benefit from partial acclimatization in some circumstances (McSharry, 2007; Nassis, 2013; Taylor & Rollo, 2014), but this advantage is context-dependent and does not straightforwardly offset the compounded burdens of limited recovery infrastructure, long travel distances, and condensed preparation periods. Conversely, teams from temperate climates with high institutional capacity—and therefore greater access to acclimation protocols and recovery resources—may be more exposed in absolute terms at the 2026 FIFA World Cup while remaining better equipped to manage that exposure. The tournament thus risks reproducing, in microcosm, the wider socio-environmental pattern in which those who have contributed least to the problem bear the greatest share of its costs (Preston et al., 2014; Venn, 2019).

This pattern takes on additional significance when read against the political economy of the tournament's design. The expansion of the FIFA World Cup to 48 teams and 104 matches was explicitly motivated by projected revenue gains of approximately one billion US dollars in additional broadcasting and sponsorship income compared to the preceding 32-team format as documented in analyses of FIFA's governance model. The selection of North America as host region, and the distribution of kick-off times across the tournament schedule, reflects the primacy of media markets in the Global North—particularly the United States—whose prime-time windows structurally determine when matches are played (Pielke, 2013; Sugden & Tomlinson, 1998). In this sense, the climatic conditions to which teams are exposed are not simply a byproduct of geography: they are partly produced by commercial and broadcasting logics that govern tournament design upstream of any scheduling or draw decision. The expansion of the tournament simultaneously increases the inclusion of teams from the Global South—through additional qualification places for Africa, Asia, and CONCACAF—and embeds those teams in a competitive structure whose temporal architecture was shaped by interests largely external to those confederations. Environmental inequality in the 2026 FIFA World Cup is therefore not only a climatic phenomenon: it is also a governance outcome, produced at the intersection of commercial tournament design and geographically uneven climate risk (Müller, 2015; Pielke, 2013).

This does not mean that climatic variability should be eliminated from outdoor football. Heat, humidity, altitude, wind, rain, and surface conditions have always been part of the game, and previous work has shown that football performance can be shaped by environmental contexts such as heat and altitude (Nassis, 2013; Taylor & Rollo, 2014). However, in a highly commercialised multi-host mega-event, the question is no longer simply whether teams play in different climates, but whether the distribution of these constraints is transparent, predictable, and compatible with competitive fairness. This issue becomes even more important when some adaptation measures, such as climate-controlled or roofed stadiums, may reduce heat exposure in selected venues while leaving other matches fully exposed to outdoor atmospheric conditions.

4.2. From climatic variability to structured inequality

Climatic conditions have long been recognised as a relevant constraint in football. Heat stress impairs physical performance, reduces high-intensity running, alters pacing, and increases physiological strain and health risk (Carmo et al., 2026; Casa et al., 2015; Gouttebarge et al., 2023; Nybo et al., 2014; Périard et al., 2021; Racinais et al., 2015). The issue is therefore not whether climate matters, but how its effects are distributed across the competition.

Our results suggest that climatic exposure is not simply a random background factor. Rather, it emerges from the interaction between (i) spatial climatic heterogeneity, (ii) tournament geography, and (iii) scheduling decisions. This is particularly clear for WBGT, which shows both the strongest signal of recent increase and the largest match-, group-, and team-level contrasts. Hence, climate is not only "part of the game"; under a multi-host format, it becomes part of the competition structure itself.

This distinction matters for sport management because tournament fairness is usually considered through sporting and logistical dimensions: group balance, travel burden, rest days, venue allocation, and competitive advantage. Our results suggest that environmental exposure should be added to this list. A team's climatic burden is not only determined by where the tournament is hosted, but by the sequence of venues, dates, kick-off times, and recovery conditions assigned to that team. In this sense, climate becomes an organisational variable.

4.3. Mechanisms: climate heterogeneity, scheduling, and tournament design

The unequal exposure identified here arises through several interacting mechanisms as illustrated in Fig. 7.

First, the 2026 tournament spans a very large geographical domain across Canada, the USA, and Mexico. This exposes teams to markedly different climatic regimes and environmental stressors, including heat, humidity, altitude, air pollution, allergens, and travel-related disruption (Esh et al., 2026). Recent work has emphasised that the 2026 FIFA World Cup presents an unprecedented combination of environmental challenges compared with previous men's World Cups (Esh et al., 2026).

Second, kick-off timing strongly modulates exposure. This was already suggested in recent work on the 2025 FIFA Club World Cup, where early afternoon matches were scheduled partly for broadcasting reasons and where environmental conditions were shown to affect physical performance, with longer distances covered in evening matches than in afternoon matches (Carmo et al., 2026). Our event-based framework confirms that exposure during the 2026 FIFA World Cup is strongly structured by local kick-off time, especially for heat stress.

Third, the interaction between venue allocation and match timing amplifies disparities. Recent prospective studies of 2026 have already shown that many host cities are exposed to substantial WBGT risk during June and July, especially during afternoon hours (Craig & Karabas, 2024; Esh et al., 2026; Mullan et al., 2025). Our contribution is to translate this city-scale risk into a match-scale probability and then into group- and team-level inequality. In that sense, exposure is not determined by climate alone, but by climate *multiplied by scheduling.*

This interaction may be further amplified by acclimatization constraints. As highlighted by Esh et al. (2026), many players are likely to enter the 2026 FIFA World Cup shortly after the end of domestic leagues and continental competitions, with limited time available for heat acclimatization before the tournament. This issue is particularly relevant during the group stage, when teams may face rapid transitions between climatic regimes, repeated exposure to hot or humid venues, and short recovery periods. Consequently, the same match-level climatic probability may not translate into the same physiological constraint for all teams. Its actual impact may depend on recent training environment, acclimatization status, travel sequence, squad rotation, and recovery conditions.

This point is important because match schedules in major tournaments are not climatically neutral objects. They result from a combination of sporting, logistical, security, broadcasting, and commercial constraints. In the FIFA World Cup, the allocation of teams to already scheduled fixtures means that part of the environmental exposure faced by a team depends on the interaction between the draw and a pre-existing temporal structure. This study does not assess whether specific teams are deliberately favoured or disadvantaged by kick-off times. However, it shows that once dates, venues, and hours are fixed, the draw translates this structure into unequal environmental exposure. Climate therefore becomes an additional layer of tournament design, even when it is not explicitly considered as such.

This observation points to a governance distinction that has received little attention in the sport management literature: the sequential layering of tournament design decisions and its implications for where remediation is possible. The overall format of the competition—number of teams, number of venues, geographical distribution—is fixed years in advance through FIFA's hosting decision. The match calendar and kick-off times are subsequently determined through negotiations involving broadcasting partners, security authorities, and logistical constraints, and are largely finalised before any team qualification is known. The group draw then allocates qualified teams to already-scheduled fixtures. These three layers—*format*, *calendar*, and *draw*—operate at different temporal horizons and involve different decision-making actors. Environmental inequalities that arise from format and calendar decisions cannot be corrected at the draw stage, because the draw operates on a structure that is already climatically non-neutral. Conversely, if climatic equity were considered at the format and calendar stages, it could inform venue selection, match sequencing, and kick-off allocation in ways that would reduce the range of environmental exposure before the draw takes place. Recognising this sequential structure is important for sport governance because it clarifies where responsibility lies and at which decision point intervention is most effective. Treating environmental inequality as a problem of the draw alone—as might be implied by comparing team-level exposure after the fact—misattributes the source of the problem and obscures the upstream decisions that produced it.

4.4. Implications for performance, health, and recovery

These inequalities have several practical implications.

First, they are relevant for performance. The recent 2025 FIFA Club World Cup study showed that WBGT and air temperature significantly reduced total distance and distance covered at different speeds, while relative humidity specifically reduced high-speed running distance; longer distances were observed in the evening and in clubs from colder climates (Carmo et al., 2026). That result is important because it suggests that environmental exposure is not merely theoretical: it can alter the physical demands of elite male football matches, including running distance and high-intensity activity.

Second, the results are relevant for player health. The 2026 evidence-based review by Esh et al. notes that 14 of the 16 host cities are expected to experience June–July WBGT values above 28 °C, with some locations reaching 30–35 °C, and summarises how such conditions increase thermoregulatory strain, reduce physical and cognitive performance, and elevate the risk of exertional heat illness (Esh et al., 2026). Similarly, recent scheduling-oriented work has highlighted that several 2026 host venues exceed WBGT levels at which football governing bodies recommend match delay, cooling breaks, or postponement (Mullan et al., 2025). Our results show that these risks are not evenly distributed across the tournament.

Third, night-time recovery matters. Tropical nights are a standard climatic indicator, but they are also directly relevant to athlete recovery because elevated night-time temperatures may impair sleep quality, thermoregulation, and physiological restoration, although direct evidence in elite athletes remains limited. (Obradovich et al., 2017). Our team-level results suggest that recovery conditions, like match conditions, are unequally distributed. This matters because recovery is not a secondary issue in tournament football: teams repeatedly compete under short intervals, and impaired nocturnal recovery may accumulate across the group stage.

Taken together, these results suggest that environmental probabilities should be interpreted as decision-relevant exposure metrics. A probability of threshold exceedance is not a prediction that a specific match will be dangerous, nor a direct measure of match outcome. Rather, it quantifies how often a team or group is placed in conditions that are more likely to increase physiological strain, disrupt match conditions, or compromise recovery. From a management perspective, this makes such probabilities useful for comparing the environmental burden embedded in the tournament structure.

4.5. Adaptation strategies and the emergence of new inequalities

Several adaptation strategies are already available to reduce heat-related risks in football, including cooling breaks, revised kick-off times, heat acclimation protocols, hydration strategies, and the use of partially enclosed or climate-controlled stadium infrastructure (Esh et al., 2026; Gouttebarge et al., 2023; Mullan et al., 2025; Orr et al., 2022; Schneider & Mücke, 2024). However, our results suggest that adaptation should not be interpreted only as a technical response to environmental risk. In a multi-host tournament, adaptation may also redistribute exposure and create new forms of inequality.

This is particularly relevant when mitigation measures are not applied uniformly across venues. Cooling breaks or medical protocols may be standardized at the competition level, but other forms of adaptation, such as roof closure, shading, ventilation, or climate control, are venue-specific. As a result, two teams facing similar outdoor climatic conditions may experience very different effective playing environments depending on stadium infrastructure and operational decisions.

This creates a new problem. If some matches are played in moderated environments while others remain fully exposed to outdoor heat and humidity, adaptation does not eliminate climatic inequality; it partially transforms it. Mitigation may reduce heat stress for selected matches, but it also introduces an artificial correction that applies only to some venues and therefore only to some teams. In this sense, adaptation can become part of the tournament structure itself.

This raises a fundamental question for tournament design: should environmental conditions be standardized across venues as much as possible, or accepted as part of the inherent variability of outdoor international football? The answer is not straightforward. Football has historically incorporated environmental variability as part of the game, including altitude, rain, wind, pitch conditions, and crowd environments. Yet climate change and expanded multi-host formats increase the scale and unevenness of this variability. The issue is therefore no longer only whether teams can adapt to different conditions, but whether tournament organizers should actively limit avoidable environmental disparities when they are amplified by scheduling and venue allocation.

4.6. What should be considered an acceptable environmental constraint?

A broader normative question follows. Climatic variability has always been part of football, just as altitude, travel, or crowd effects have been part of tournament conditions. However, the issue is not whether such constraints exist, but at what point they become incompatible with minimum expectations of player safety and competitive fairness.

The literature suggests that this threshold is not only physiological but organisational. The 2026 review by Esh et al. and the scheduling-focused work of Mullan et al. both argue that the combination of large geographic spread, extreme heat risk, and tournament expansion creates an environment in which scheduling choices become a central mitigation tool rather than a secondary logistical decision (Esh et al., 2026; Mullan et al., 2025). Our results support that argument by showing that the tournament calendar itself is one of the main mechanisms through which environmental burden is allocated.

For sport managers and governing bodies, this raises a practical issue: environmental exposure should not be considered only after the schedule has been fixed. If climatic constraints are evaluated too late, mitigation options become reactive and uneven. If they are considered upstream, they can inform venue selection, kick-off allocation, match sequencing, recovery planning, and communication with teams and spectators. This does not imply that all environmental variability can or should be removed, but it does imply that avoidable disparities should be identified and made explicit.

4.7. Strengths and limitations

This study has several strengths. First, it shifts the analysis of environmental risk from a host-city perspective to an event-based tournament perspective. Rather than characterising climatic conditions at venues in general, the framework explicitly combines venue, date, kick-off time, and match sequence. This allows environmental exposure to be quantified under the actual temporal and spatial structure of the tournament.

Second, the approach provides a multi-level assessment of exposure. By estimating probabilities at the match level and then aggregating them across groups and teams, the analysis shows how climatic constraints propagate through the tournament structure. This is particularly relevant for multi-host competitions, where unequal exposure may arise not only from geographical differences between venues, but also from the draw, match allocation, and scheduling decisions.

Third, the use of hourly reanalysis data allows exposure to be assessed at the relevant time scale for football matches. This is important because several environmental stressors, especially heat stress, vary strongly within the day. The method therefore captures differences between afternoon, evening, and late-evening matches, rather than relying only on daily or monthly climatic averages.

Finally, the study considers multiple dimensions of environmental exposure, including heat stress, rainfall during matches, antecedent rainfall, wind gusts, and night-time recovery conditions. This multi-indicator perspective is useful because tournament constraints are not limited to heat alone. Wet conditions, wind, and impaired recovery may also contribute to unequal playing and preparation conditions, even if their mechanisms differ.

Several limitations should nevertheless be acknowledged.

First, the analysis relies on ERA5-Land and ERA5 reanalysis data at relatively coarse spatial resolution. These products do not resolve stadium-scale microclimates, shading, ventilation, urban heat island effects, pitch-level radiative conditions, or the actual thermal conditions experienced inside partially enclosed or climate-controlled venues. Consequently, the results should be interpreted as estimates of outdoor atmospheric exposure at stadium locations, not as direct measurements of in-stadium conditions.

Second, the study focuses on environmental exposure rather than causal effects on technical, tactical, or competitive outcomes. This is deliberate. Previous work has shown that linking environmental conditions directly to match outcomes is difficult because team quality, tactics, and contextual factors remain dominant drivers (Brocherie et al., 2022). The objective here is therefore not to infer whether climate determines results, but to quantify whether environmental constraints are evenly or unevenly distributed across the tournament. This choice also has a theoretical justification that goes beyond the methodological. Exposure-based assessments and outcome-based assessments address different research questions and operate at different levels of causal inference. Outcome-based studies—linking match conditions to physical performance metrics or competitive results—are valuable for quantifying the magnitude of environmental effects on individual matches (Carmo et al., 2026; Nassis et al., 2015). However, they require observed outcomes and are therefore necessarily retrospective. By contrast, an exposure-based framework is prospective and structural: it characterises the distribution of environmental risk *embedded in the competition architecture* before matches are played, independently of team quality, tactical choices, or chance. The two approaches are therefore complementary rather than substitutable. The present study does not claim that environmental exposure will determine competitive outcomes. It claims that the tournament design systematically places some teams in conditions that are more likely to increase physiological strain, disrupt playing conditions, or impair recovery—and that this structural asymmetry is a relevant input for governance, regardless of whether its effects on results can be isolated in any particular case. Future work combining event-based exposure estimates with post-tournament performance data could bridge these two levels of analysis and provide a more complete picture of how environmental constraints propagate through competition outcomes.

Third, some operational thresholds, particularly for rainfall and wind, should be interpreted as competition-relevant thresholds rather than universal hazard thresholds. They are intended to capture potentially disruptive match and field conditions, not absolute injury, cancellation, or safety cut-offs. Similarly, tropical nights are used as a proxy for potentially impaired night-time recovery, but they do not directly measure sleep quality, hotel conditions, travel fatigue, or access to recovery infrastructure.

Fourth, stadium infrastructure and operational decisions are not explicitly represented. Some 2026 venues include permanent or retractable roofs and may operate under climate-controlled conditions. Recent literature notes that venues such as Atlanta, Dallas, Houston, and Vancouver may reduce heat-stress challenges when such systems are used (Esh et al., 2026). This means that our estimates may overestimate effective heat exposure for matches played under moderated stadium conditions. However, this limitation is also conceptually important: if only some venues provide climate-controlled environments, mitigation itself becomes unevenly distributed across the tournament.

Finally, the analysis does not incorporate other relevant 2026 environmental and logistical challenges such as altitude, air pollution, allergens, long-distance travel, base-camp location, or acclimatization status, all of which have been identified as important stressors for this tournament (Esh et al., 2026). These dimensions could interact with the climatic inequalities documented here. Future work should therefore combine event-based climate exposure with travel sequences, team preparation environments, player acclimatization, and stadium-specific operational conditions.

4.8. Implications for mega-event governance and tournament design

The findings have implications beyond the 2026 FIFA World Cup. They suggest that climate exposure should be considered as a governance issue in the design of large multi-host sporting events. Mega-events are not only exposed to climate risk because they take place in specific locations; they also produce exposure through their spatial format, match allocation, calendar structure, and kick-off times. This complements broader work showing that mega-events are complex socio-spatial systems whose impacts extend beyond the sporting field itself (Collins et al., 2009; Müller, 2015).

This is particularly important as major tournaments expand in size and geographical scope. The 2026 FIFA World Cup, with 48 teams, 104 matches, and 16 venues across three countries, illustrates how expansion can increase climatic heterogeneity within a single competition. From a sport management perspective, environmental exposure therefore becomes part of event design, alongside travel, broadcasting, security, commercial, and sporting considerations. This perspective is consistent with recent work framing climate change as an organizational vulnerability for sport, rather than only as an external environmental hazard (Orr & Inoue, 2019; Orr et al., 2022).

Our results do not imply that all climatic variation should be removed from outdoor football. Weather has always been part of the game. However, when environmental constraints are unevenly structured by tournament design, they become more than background variability. They raise questions of fairness, risk allocation, and responsibility. The issue is therefore not whether football should be protected from all weather variability. Rather, it is whether tournament organisers should account for the fact that some weather-related constraints are no longer random once they are systematically shaped by venue allocation, scheduling, broadcasting, and infrastructure decisions. In this sense, climate exposure should be treated as an additional dimension of mega-event planning, particularly for competitions staged across large climatic gradients or during seasons of elevated heat risk. This is especially relevant for football, where climate-related challenges are increasingly discussed in relation to governance, scheduling, infrastructure, and evidence-informed adaptation (Mabon, 2023; Schneider & Mücke, 2024).

This also complicates adaptation. Measures such as cooling breaks, revised kick-off times, heat acclimation protocols, or climate-controlled stadiums may reduce acute risks, but they may also redistribute advantages if they are applied unevenly across venues or teams. For future tournaments, sport governing bodies may therefore need to consider whether environmental risk should be explicitly incorporated into scheduling criteria, venue selection, and competitive fairness assessments. This extends previous discussions of fairness in multi-host tournaments, which have mainly focused on travel, basecamp location, and logistical inequalities (Brocherie et al., 2022).

More broadly, the results point to a changing governance challenge for international sport. Climate change is not only increasing the frequency of hazardous conditions; it is also exposing the hidden assumptions behind existing tournament formats. In a warming climate, the design of mega-events will increasingly need to account for who is exposed, when, where, and under what competitive conditions.

5. Conclusion

This study shows that environmental exposure during the 2026 FIFA World Cup is not uniformly distributed, but emerges from the interaction between climate conditions and tournament design. Differences in venue location, match timing, and scheduling result in substantial variability in exposure to heat stress, wet conditions, wind, and night-time recovery constraints across matches, groups, and teams.

These findings suggest that environmental conditions should be considered as an additional dimension of tournament fairness, alongside more traditional factors such as travel, rest time, and scheduling. Climatic variability is inherent to outdoor football, but under large multi-host formats it can be transformed into structured inequality through the allocation of matches across venues, dates, and kick-off times.

The analysis does not imply that environmental inequalities are deliberately produced by tournament organisers. Rather, it shows that once venues, dates, kick-off times, and group allocations are fixed, environmental exposure becomes an implicit consequence of tournament design. This distinction is important for sport governance: even when environmental exposure is not intentionally assigned, it can still become measurable, foreseeable, and part of the competitive structure once the tournament calendar is fixed.

More broadly, the results highlight the need to integrate environmental risk into mega-event planning, particularly in the context of climate change, which is expected to increase the frequency and intensity of extreme conditions during summer competitions. Future tournament design should therefore consider not only where and when matches are played, but also who is exposed, under which conditions, and with what implications for fairness, performance, health, and recovery.

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Data availability statement

ERA5 and ERA5-Land reanalysis data are publicly available from the Copernicus Climate Data Store. The FIFA World Cup 2026 match schedule was obtained from publicly available FIFA information. The processed event-level datasets and analysis code will be deposited in a public repository upon publication. Until then, they are available from the corresponding author upon reasonable request.

Author contributions

D.D.: Conceptualization, Methodology, Data curation, Formal analysis, Visualization, Writing – original draft. D.F.: Conceptualization, Interpretation P.B.: Sport management framing, Writing – review and editing. T.G.: Sport management framing, Writing – review and editing. All authors approved the final manuscript.

Ethics statement

This study used publicly available climate reanalysis data and publicly available tournament schedule information. No human participants, personal data, or animal subjects were involved.

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