Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Where You Sit Matters More Than Where You Play: Systemic Thermal Exposure Inequality Across the 2026 FIFA World Cup

Francisco Armas

alu0101330327@ull.edu.es

Universidad de La Laguna

Serafin Corral

Universidad de La Laguna

Alejandro Herrera

Universidad de La Laguna

Emilio Bonal Pérez

Universidad de La Laguna

Research Article

Keywords: thermal exposure, inter-venue heterogeneity, WBGT, mega-events, FIFA World Cup, spectator-degree-hours

Posted Date: November 1st, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11152012/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Abstract

Geographically distributed mega-sporting events create systemic variations in spectator thermal exposure that traditional venue-level risk assessments fail to capture. Adopting a system-level perspective, this study investigates whether ambient thermal exposure emerges as a property of tournament design by quantifying inter-venue thermal exposure heterogeneity at the 2026 FIFA World Cup using surface weather observations and spectator-weighted exposure metrics. Our findings show that thermal risk was a structural property of tournament design, with inter-venue spatial variance dominating intra-venue temporal variability. Geographic venue assignment accounted for 71% of the variance in ambient Wet-Bulb Globe Temperature (WBGT), generating a 12.5°C disparity between the hottest and coolest host cities. This inequality translated into a highly asymmetric population-level health risk: 95% of the cumulative thermal burden (spectator-degree-hours above 28°C) was concentrated in just three venues—a concentration that remained robust across thresholds (85% at 26°C, 100% at 30°C; Table 4). Our analyses identify match scheduling as the primary modifiable driver of within-venue exposure, while validation against ERA5 reanalysis reveals that global models systematically underestimate aggregate thermal exposure at the venue level, with individual match classifications near risk thresholds remaining sensitive to methodological assumptions—reinforcing the operational case for complementing reanalysis with local station data. Future spectator heat management therefore depends not only on forecasting weather, but on understanding how tournament design distributes thermal exposure across populations.

1. Introduction

1.1 The Systemic Nature of Thermal Risk at Mega-Events

The geographic scale of mega-sporting events has fundamentally altered the nature of thermal risk. As tournaments transition from single host cities to continent-wide footprints, spectators are distributed across drastically different climatic zones within a single event framework. While the physiological hazards of high Wet-Bulb Globe Temperature (WBGT) — including impaired thermoregulation, cardiovascular strain, and heat stroke — are well established for both athletes and spectators (Epstein and Roberts 2011; Hifumi et al. 2018), our conceptualization of this risk has remained geographically static. Thermal risk is no longer solely a property of weather; it is increasingly a property of tournament design.

1.2 From Venue-Level Assumptions to Systemic Exposure

Current biometeorological research predominantly treats thermal risk as an independent, venue-level attribute. Studies have focused on whether athletes will face unsafe conditions at specific sites (Racinais et al. 2023; Vanos et al. 2020) or whether individual host cities are climatically suitable (Craig and Karabas 2024; Lindner-Cendrowska et al. 2024; Mullan et al. 2025). The 2022 FIFA World Cup in Qatar demonstrated that thermal extremes can reshape scheduling, forcing a shift to a winter tournament (Nybo et al. 2021).

Although extreme heat has been extensively studied, virtually all previous assessments implicitly assume that thermal risk can be evaluated independently for each venue. This assumption becomes increasingly problematic as tournaments expand geographically. The 2026 FIFA World Cup, for example, distributed 104 matches across 16 stadiums spanning three countries — from tropical-humid Miami to temperate-highland Ciudad de México. Spectators navigating a unified ticketing platform faced systematically different thermal environments, constrained purely by the tournament draw and scheduling. Yet, the scientific literature lacks a framework to understand how a mega-event, acting as a single structural system, concentrates or distributes this thermal burden across its population. We use the term *inter-venue thermal exposure heterogeneity* to conceptualize and measure this systemic variance.

Existing studies have successfully identified heat risk at individual venues. However, they cannot answer whether thermal exposure at a geographically distributed tournament emerges as a property of the tournament system itself. Addressing this question requires shifting the analytical perspective from individual stadiums to the event as an integrated spatial system

1.3 Study Objectives

This study transitions the analysis of mega-event thermal risk from venue-level prediction to system-level observation. Using post-tournament surface observations from the 2026 FIFA World Cup, our objectives are to:

(1) determine whether ambient thermal exposure is distributed uniformly across the event or structurally concentrated in a limited number of venues;

(2) quantify the fraction of total exposure variance attributable to the tournament's geographic assignment versus daily weather or scheduling; and

(3) evaluate how identifying this systemic heterogeneity changes the operational mitigation levers available to organizers, while validating the reliability of historical reanalysis data (ERA5) for future pre-tournament planning.

2. Materials and Methods

2.1 Study Design and Data Sources

The study analyzed thermal exposure across all 104 matches of the 2026 FIFA World Cup (June 11–July 19 2026). Meteorological conditions were assessed over a spectator exposure window spanning from two hours before kickoff to four hours after kickoff, approximating the period from early arrival and queuing through post-match dispersal. Match-level attendance data, used to calculate population exposure metrics, were compiled from official FIFA reports and Transfermarkt.

The primary meteorological dataset consisted of hourly observations (air temperature, dew point, relative humidity, and wind speed) retrieved from 15 surface weather stations archived by the Iowa Environmental Mesonet (IEM), comprising 11 U.S. NOAA ASOS stations and 4 international equivalents (2 Canadian 2 Mexican; Online Resource 1)For brevity, this observational dataset is referred to as 'NOAA' throughout, reflecting the majority data source. Stations were selected based on proximity to the host stadiums (mean distance: 16 km, range: 2–40 km), characterizing the ambient thermal environment of the event perimeter (e.g., transit hubs, fan zones) rather than the architecturally modified stadium interior. NOAA data provided coverage for 100 matches; the four matches in Guadalajara were excluded from the primary observational analysis due to a lack of archived local station data in the IEM repository.

As a secondary source, ERA5 global reanalysis data (~ 31 km resolution; Hersbach et al. 2020) were retrieved via the Open-Meteo API for all 104 matches. This dataset served a dual purpose: providing coverage for the unmonitored Guadalajara matches and enabling a systematic, post-tournament validation of reanalysis reliability against surface observations.

2.2 WBGT Computation and Risk Thresholds

Outdoor ambient WBGT was computed using a structural energy-balance approach based on the architecture of Liljegren et al. (2008). Solar radiation for the NOAA dataset was estimated using clear-sky global horizontal irradiance models adjusted for atmospheric transmittance, and anemometer wind speeds were logarithmically scaled to a 2-meter reference height. (Full mathematical formulations, including iterative Newton-Raphson solvers, heat transfer coefficients, and surface property constants, are detailed in the Supplementary Material).

Thermal risk was classified using the maximum hourly WBGT observed within each match's exposure window and categorized using a four-tier scheme constructed for this study, informed by existing sports-medicine thresholds: Low (< 28°C), Moderate (28.0–30.0°C), High (> 30.0 to < 32.0°C), and Extreme (≥ 32.0°C). The 28°C threshold corresponds to the WBGT level at which FIFPRO recommends match postponement or rescheduling (FIFPRO 2021; Gouttebarge et al. 2023), while 32°C is the FIFA operational trigger for mandatory cooling breaks (FIFPRO 2021). The intermediate 30°C boundary follows the ACSM activity-modification guidelines for high-risk conditions (Armstrong et al. 2007). Sensitivity to this particular scheme is assessed in Table 4.

2.3 Sensitivity Analyses

To ensure findings were robust to methodological choices, three sensitivity analyses were performed:

- *Radiation Source*: NOAA WBGT values were recomputed utilizing ERA5 shortwave radiation to isolate bias introduced by clear-sky assumptions.
- *WBGT Formulation*: The empirical sWBGT model (Stull 2011) was computed alongside the energy-balance model to validate the stability of inter-venue disparities.
- *Risk Frameworks*: Exposure classifications were re-evaluated across alternative sports medicine thresholds (ACSM 26°C, ACSM High 30°C, FIFA operational 32°C)

All mixed-model p-values were derived from z-approximations. Given the small number of venue groups (k = 15), these should be interpreted as liberal estimates; Satterthwaite-corrected degrees of freedom would yield slightly more conservative inference, though the magnitude of the reported effects makes qualitative changes in significance unlikely.

AI-assisted tools were used for editorial review, numerical cross-checking, and copy editing of the manuscript. All analytical decisions, interpretations, and conclusions are the authors' own.

2.4 Statistical Analysis

All statistical procedures were designed to evaluate thermal exposure as a systemic, tournament-wide property. Inter-venue thermal exposure heterogeneity was quantified using the intraclass correlation coefficient (ICC(1,1); Shrout and Fleiss, 1979), with 95% confidence intervals derived from the F-distribution approximation for unbalanced designs, assessing the proportion of total WBGT variance driven strictly by geographic venue assignment. The 95% confidence interval for the inter-venue disparity (maximum minus minimum venue mean) was estimated via stratified bootstrap (10,000 replicates, percentile method), resampling matches independently within the hottest and coolest venues. The robustness of this variance structure was confirmed via leave-one-venue-out resampling (15 iterations).

To evaluate the public health impact, we introduced a novel spectator-weighted exposure metric: *spectator-degree-hours* above 28°C (spectator-dh_{28}). This metric was calculated by integrating the degree-hours above the 28°C threshold over the exposure window of each match, multiplied by recorded attendance, allowing us to pinpoint the spatial concentration of population thermal burden.

To identify the modifiable drivers of within-venue heat exposure, a linear mixed-effects model (fitted by REML) was constructed. Ambient WBGT was regressed on kickoff hour (local 24-h format), altitude, and latitude as fixed effects, with venue included as a random intercept. (Note: An initial parametric stadium shadow model was computed, but this variable was excluded from the final mixed model to prevent the methodological mismatch of testing stadium-interior shading against exterior airport observations; see Supplementary Material).

Finally, the reliability of ERA5 for future event planning was assessed against NOAA observations using Pearson R^2, root mean square error (RMSE), mean signed bias, and Bland–Altman limits of agreement. All analyses were conducted in Python 3.12 (statsmodels, scipy, pandas, numpy). Code and datasets are available in the deposited replication package.

3. Results

3.1 Thermal exposure was highly unequal across the tournament

Geographic assignment shaped the thermal environment spectators experienced, creating substantial inequalities across the tournament footprint. Rather than thermal risk being driven by random daily weather fluctuations, we found it to be a systemic property of the tournament's spatial organization.

Venue grouping alone accounted for 71% of the total variance in ambient WBGT across the 100 matches analyzed (ICC = 0.707, 95% CI: 0.528–0.866). Knowing where a spectator attended a match was fundamentally more predictive of their thermal exposure than any other variable.

The magnitude of this structural inequality was substantial. Mean maximum WBGT within the spectator exposure window ranged from a peak of 28.8°C in Houston to a low of 16.3°C in San Francisco. This 12.5°C disparity (95% bootstrap CI: 9.0–15.1°C) spanned three separate physiological risk categories within a single sporting event. Furthermore, leave-one-venue-out resampling confirmed that this marked heterogeneity was a systemic feature of the tournament's geographic configuration, rather than a statistical artifact driven by a single outlier venue.

3.2 Population thermal burden was concentrated in a small number of venues

This structural inequality translated into a highly asymmetric population-level health risk. Rather than a widespread hazard, the physical danger was heavily concentrated in a fraction of the host cities. Across the tournament, spectators endured a cumulative 5,286,952 spectator-degree-hours above the 28°C FIFPRO threshold (n = 100 NOAA-covered matches; Table 4). 95% of this total cumulative burden was absorbed by just three venues (Houston, Dallas, and Atlanta), despite these locations hosting only 25% of the total tournament attendance.

This concentration was equally stark when evaluating discrete match-level risk. Of the 100 matches analyzed with surface observations, 17 exceeded the 28°C threshold. Every single one of these 17 matches (including all 4 classified as High risk) occurred in just five venues: Houston, Dallas, Miami, Atlanta, and Philadelphia **[Table 1; Fig 2]**. The remaining 10 venues produced zero matches above 28°C. This binary distribution confirms that severe ambient heat exposure at this mega-event was not a generalized condition, but a highly localized phenomenon constrained to a specific subset of the venue roster.

Table 1. Thermal exposure by venue (NOAA observations, energy-balance WBGT).

Venue	ICAO	Dist(km)	Mean	Max	n	Risk	Bias (NOAA–ERA5, °C)
Houston	KHOU	15	28.8	31.7	7	3M+2H	+0.95
Dallas	KDFW	20	28.0	30.2	9	4M+1H	+0.66
Miami	KMIA	25	27.5	28.9	7	3M	+0.49
Atlanta	KATL	15	27.0	30.7	8	2M+1H	+2.05
Filadelfia	KPHL	7	24.3	29.1	6	1M	+0.66
Monterrey	MMMY	25	24.7	24.9	4	OM + 0H	+0.13
Kansas City	KMCI	20	23.1	25.0	6	—	-0.82
Nueva York/NJ	KEWR	10	23.1	26.0	8	—	+0.88
Boston	KBOS	40	21.4	26.7	7	—	+0.43
Toronto	CYTZ	2	20.4	27.1	6	—	+0.49
Seattle	KSEA	18	19.3	24.2	6	—	+0.60
Los Angeles	KLAX	10	18.6	20.6	8	—	-0.60
Vancouver	CYVR	15	18.3	21.8	7	—	+1.43
Ciudad de Mexico	MMMX	10	16.5	21.4	5	—	+0.17
San Francisco	KSJC	8	16.3	23.6	6	—	-0.36

3.3 Tournament organization explained this concentration

The observed inequality was not simply the consequence of hot summer weather. Instead, it emerged from the interaction between tournament geography and kickoff scheduling.

Match scheduling acted as the most powerful modifiable driver of within-venue heat exposure. Specifically, each hour of delayed kickoff reduced ambient WBGT by approximately 0.33°C ($p < 0.001$). For a venue like Dallas, this scheduling effect meant the difference between a high-risk afternoon match (30.2°C at 15:00) and a low-risk evening match (26.0°C at 22:00).

Geographic coordinates were included as level-2 controls. Latitude reduced WBGT by 0.375°C per degree north ($p = 0.004$). The model also estimated a cooling effect of 5.0°C per 1,000 m of altitude ($p = 0.007$); however, this coefficient is effectively identified by a single venue (Ciudad de México 2,195 m), as the remaining 14 venues range from 2 to 540 m. It should therefore be interpreted as a description of the Ciudad de México effect rather than a generalizable altitude–WBGT relationship.

Notably, the model-adjusted ICC (0.620) decreased only modestly from the unconditional value (0.707) despite the inclusion of two venue-level predictors. This indicates that altitude and latitude—the observable geographic coordinates—explain relatively little of the between-venue variance. The bulk of the systematic thermal heterogeneity is driven by local climatic factors (coastal proximity, prevailing wind regimes, urban heat island intensity) that these predictors do not capture, consistent with the parsimony constraints noted in §4.1. The venue-assignment effect is therefore largely irreducible by simple geographic covariates, reinforcing the conclusion that thermal inequality was structurally embedded in the tournament's spatial design [Table 2].

Table 2. Mixed-effects model: WBGT ~ kickoff hour + altitude + latitude, (1\|venue).

Variable	β	SE	z	p
Intercept	43.021	5.308	8.11	< 0.001
Kickoff hour (local 24h)	−0.328	0.080	−4.13	< 0.001
Altitude (m)	−0.005	0.002	−2.61	0.007
Latitude (°N)	−0.375	0.133	−2.82	0.004
σ^2(venue)	9.670			
σ^2(residual)	5.926			
ICC (model-adjusted)	0.620			

Shapiro-Wilk W = 0.975, p = 0.050. Given this marginal result, fixed-effect inference was verified using cluster-robust standard errors (grouped by venue); all three predictors remained significant (kickoff hour p = 0.018, altitude p < 0.001, latitude p < 0.001) and all substantive conclusions were unchanged. VIFs: hour 1.06, altitude 1.57, latitude 1.52. P-values based on z-approximation (see §2.3). Note: An initial specification included shadow fraction; it was excluded because it describes stadium-interior shading tested against airport-exterior WBGT (see §2.5, §4.4).

3.4 Robustness of the findings

The systemic inequality and concentration of thermal risk observed across the tournament were not artifacts of methodological choices. The profound 12.5°C inter-venue disparity and the spatial concentration of burden in three cities remained fundamentally unchanged regardless of the WBGT formulation (sWBGT vs. energy-balance) or the operational risk threshold applied (28°C vs. 30°C) [Tables 3 and 4]. Crucially, the spatial concentration of spectator thermal burden was also robust to threshold choice: the same three venues (Houston, Dallas, Atlanta) dominated population exposure at every threshold tested, concentrating 85% of spectator-degree-hours at 26°C, 95% at 28°C, and 100% at 30°C (Table 4). This stability confirms that the concentration pattern is a structural property of the tournament's geographic design, not an artifact of the selected threshold.

Furthermore, evaluating the primary data source revealed that global reanalysis (ERA5) reliably captures the tournament's thermal macro-structure (R^2 = 0.933, RMSE = 1.35°C) but systematically underestimates aggregate venue-level exposure by 0.52°C on average. Radiation sensitivity analysis (Table 5) confirmed that 81% of this bias stems from genuine differences in temperature, humidity, and wind fields rather than from clear-sky radiation assumptions. However, while the aggregate bias was robust, individual match classifications near risk thresholds were sensitive to the radiation source: substituting ERA5 radiation into the NOAA computation shifted the number of High-risk matches from 4 to 5 and Moderate from 13 to 10. While the mean absolute per-match difference between radiation configurations was small (0.15°C, median 0.08°C), seven matches exceeded 0.5°C and individual shifts reached 2.0°C. These perturbations were bidirectional (42 positive, 40 negative, 18 unchanged), canceling in the aggregate but producing category reclassifications for three matches near thresholds: one Moderate match in Houston (29.99°C) crossed into High with ERA5 radiation (30.05°C), while two Moderate matches (Houston 28.15°C, Miami 28.08°C) dropped to Low. This explains the counterintuitive increase from 4 to 5 High-risk matches and underscores that individual classifications within ~0.5°C of a threshold boundary should be treated as uncertain—reinforcing the operational recommendation that reanalysis-based planning must be complemented with local station data [Fig 3; Table 5].

Collectively, these sensitivity analyses demonstrate that the central findings of this study—the dominance of venue assignment, the extreme concentration of spectator burden, and the structural nature of tournament-wide thermal inequality—remain stable regardless of methodological specification or data source.

Table 3. WBGT formulation comparison: sWBGT vs energy-balance model over NOAA data.

Metric	sWBGT (Stull)	Energy-balance	Difference
Mean WBGT (°C)	22.07	22.75	+0.68
Max WBGT (°C)	29.73	31.67	+1.94
≥18.4°C (Craig threshold)	74.0%	76.0%	+2.0%
Matches ≥28°C	9	17	+8 (17 − 9 = 8)
Matches ≥30°C	0	5	+5 (5 − 0 = 5)
Disparity (°C)	11.8	12.5	+0.7 (12.5 − 11.8 = 0.7)
R^2 (mutual)			0.986

Table 4. Threshold sensitivity analysis.

Threshold	Source	Matches ≥	% of 100	Venues	Spectator-dh	Disparity	% top 3
26°C	ACSM	31	31.0%	7	19,421,179	12.5 85.1%	85.1%
28°C	FIFPRO	17	17.0%	5	5,286,952	12.5 94.6%	94.6%
30°C	ACSM High	5	5.0%	3	517,543	12.5	100% ---
32°C	FIFA	0	0.0%	0	0	12.5	

All match classifications use the peak hourly WBGT within the exposure window, consistent with the primary classification in §2.2. At the 30°C boundary, the ≥30°C count includes one match at exactly 30.00°C (Dallas), which is classified as Moderate under the §2.2 convention (High: >30.0°C). This explains the difference between 5 matches ≥30°C in these tables and the 4 High-risk matches reported in §3.1 and Table 1.

Table 5. Radiation sensitivity analysis (NOAA branch).

Configuration	Bias vs ERA5	Mean WBGT	Moderate	High
NOAA + clear-sky	+0.52	22.75	13	4
NOAA + ERA5 radiation	+0.42	22.65	10	5
ERA5 (reference)	—	22.23	5	0
Radiation component	0.10°C			18% of total bias
Genuine component	0.42°C			81% of total bias

4. Discussion

4.1 From Local Weather to Systemic Inequality

Our findings suggest that thermal exposure should no longer be conceptualized solely as an environmental condition, but also as a consequence of tournament design. By analyzing the 2026 FIFA World Cup as an integrated spatial system, we demonstrated that geographic venue assignment

accounted for 71% of ambient WBGT variance. Previous prospective assessments asked: "Which individual venues are hot?" (Craig and Karabas 2024; Mullan et al. 2025). In contrast, our study asks: "How is thermal exposure distributed across the tournament as a whole?"

These are fundamentally different scientific questions. The 12.5°C disparity between venues confirms that modern, multi-venue mega-events create substantial inter-venue thermal heterogeneity. We deliberately avoid the term “thermal equity” in its normative sense; our data document a measurable, structural heterogeneity in physical exposure. Whether this heterogeneity constitutes an inequity depends on normative judgments about acceptable variation and compensating factors that observational designs cannot adjudicate. However, establishing that this inequality is structurally baked into the event's geographic footprint transitions thermal risk from a localized meteorological problem to a system-level governance challenge.

The residual venue-level variance (model-adjusted ICC = 0.620) likely reflects additional local factors—coastal proximity, urban heat island intensity, prevailing wind patterns—that cannot be reliably estimated as level-2 predictors with only 15 venue groups. With a ratio of 15 groups to 2 level-2 predictors already at the conventional limit, we retain the three-predictor specification as the maximum that the group structure supports, and note the unexplained venue-level variance as a target for future studies with denser venue networks.

4.2 The Perimeter Dimension of Spectator Exposure

This systemic inequality becomes particularly critical when evaluating where spectators are actually exposed to heat. All four High-risk matches in our dataset occurred at stadiums with full enclosure and climatization (Houston, Dallas, Atlanta). This is not paradoxical, but partly a consequence of geography—the hottest host cities build enclosed stadiums precisely because of their climate—and partly the result of deliberate FIFA scheduling policy. Following heat-related incidents during the 2025 Club World Cup, FIFA publicly announced that daytime matches at the 2026 tournament would be preferentially assigned to air-conditioned venues (AT&T Stadium, NRG Stadium, Mercedes-Benz Stadium). This means the scheduling counterfactual in § 4.3 operates within a system where part of the rescheduling margin was already consumed by a mitigation policy whose beneficiary was the stadium interior, not the event perimeter

However, this creates a "perimeter paradox." While climatization protects spectators inside the bowl, the 2–4 hours spent in queues, transit hubs, and fan zones remain fully exposed to ambient conditions. The Houston Fan Festival incident—over 100 medical incidents among 30,000 attendees at an open-air fan zone (Fox Weather 2026)—illustrates this perimeter risk. Our airport-based measurements capture precisely this exposure, demonstrating that the relevant public-health challenge is increasingly located outside the stadium walls.

4.3 Operational Implications for Future Mega-Events

Recognizing thermal risk as a systemic, perimeter-level property fundamentally changes operational decision-making. First, the marked concentration of spectator thermal burden—with nearly 94% of spectator-degree-hours above 28°C localized in just three venues—argues for asymmetric mitigation. Rather than applying uniform, tournament-wide protocols, organizers can target capital and resources precisely where the burden mathematically falls (e.g., pre-positioning cooling stations at specific transit hubs, extending venue opening hours, and reinforcing medical staffing based on projected spectator-dh).

Second, our analyses indicate that match scheduling constitutes a primary, evidence-based mitigation lever. Delaying kickoffs reduced ambient WBGT by approximately 0.33°C per hour, and nighttime scheduling at historically hot venues (e.g., Monterrey) produced zero thermal exceedances—though Monterrey's low observed variability may partly reflect station-level data limitations (see § 4.4).

These systemic levers are directly relevant to the 2030 (Morocco, Spain, Portugal) and 2034 (Saudi Arabia) FIFA World Cups. Organizers can deploy the spectator-degree-hours metric prospectively using reanalysis data—calibrated by the systematic ERA5 underestimations identified in this study—to optimize schedule configurations before the tournament draw is finalized.

To quantify this lever, we applied the mixed-model scheduling coefficient (− 0.328°C per hour) to all 30 daytime matches (kickoff before 19:00) at the five venues with observed exceedances. Under a counterfactual scenario in which these matches were rescheduled to 20:00 local time, 13 of the 17 matches classified as Moderate or High risk would have been reclassified as Low. All four High-risk matches would have been eliminated as a category (three downgraded to Moderate, one to Low), and the tournament would have recorded zero High-risk matches. At least 2.77 million spectator-degree-hours above 28°C (52% of the tournament total) would have been avoided. The seven evening matches already played at these same five venues were internally consistent with this estimate, as none produced exceedances of 28°C—though these observations are not independent of the model, since they contributed to the coefficient estimation, and kickoff-time assignment is itself non-random (influenced by broadcast windows, tournament phase, and team rest schedules).

This counterfactual carries important caveats. The linear extrapolation over a 5-hour shift (implying a 1.64°C reduction) may overestimate the benefit at humid venues where nocturnal humidity sustains WBGT after sunset. Additionally, FIFA scheduling operates within strict broadcast, rest, and logistical constraints. The estimate therefore represents an upper bound on the thermal benefit of scheduling adjustments rather than a directly implementable reduction.

Table 6
Summary of quantitative findings and operational implications.

Key Finding	Operational Lever	Associated Metric≥
95% of spectator-dh_{28} concentrated in 3 venues	Asymmetric allocation of cooling/medical resources	Spectator-dh per venue
−0.33°C reduction per hour of kickoff delay	Nighttime rescheduling for historically High-risk venues	Number of matches in 12:00–16:00 window
ERA5 underestimates aggregate WBGT by ~ 0.5°C on average; individual match classifications near thresholds sensitive to radiation assumptions	Complement reanalysis with local station data for planning	Bias by venue

4.4 Limitations and Future Research

Several limitations contextualize these findings. First, surface weather stations characterize the ambient perimeter environment but cannot resolve dynamic spectator microclimates influenced by architectural shading, localized crowd density, or surface materials. (Consequently, our initial geometric shadow model was excluded from the final specification, as testing interior shading against exterior airport observations precludes causal interpretation). Second, attendance data represent stadium entry counts rather than precise spatiotemporal mobility patterns, meaning the spectator-dh metric assumes uniform exposure duration. Third, while WBGT is operationally standard, its applicability to seated or queuing spectators—who present different metabolic rates and vulnerabilities than exercising athletes—requires further epidemiological validation (de Korte et al. 2023). WBGT was selected over alternative thermal indices (UTCI, PET/mPET) because it remains the regulatory standard adopted by FIFA, the IOC, and ACSM for sport-specific heat management decisions (Racinais et al. 2023), and because its known limitations—particularly the absence of direct solar radiation measurement in standard implementations (Budd 2008)—are explicitly addressed through the radiation sensitivity analysis in Table 5.

The low variability at Monterrey (WBGT range: 0.9°C across four matches [24.0–24.9°C], compared to 6–12°C at comparable venues) warrants scrutiny. Although the MMMY station record was verified against IEM archives (1,224 hours, 100% coverage), the near-constant WBGT despite varying temperature (27–29°C) and humidity (69–86%) is difficult to explain. This contrasts with Lindner-Cendrowska et al. (2024), who identified Monterrey among the three highest-stress venues using UTCI climatological normals. The discrepancy may reflect the specific 2026 tournament window, the differing thermal index, or a data-quality issue at MMMY. Monterrey's observed profile may therefore underestimate its climatological risk.

A Monte Carlo simulation (5,000 iterations) confirmed that the ICC was robust to measurement uncertainty: even under ± 2.0°C noise (far exceeding typical station precision), the ICC averaged 0.605 (95% interval: 0.528–0.681) and the inter-venue disparity remained between 11.2°C and 14.9°C.

Overcoming these limitations requires future research deploying in-situ micro-sensor networks and dynamic crowd tracking. However, the macro-level conclusions remain highly robust. Future tournaments should not only ask where extreme heat will occur, but also how tournament design distributes that exposure across millions of spectators.

Finally, this study evaluates observational data from a single tournament year; future assessments should contextualize these findings against 1991–2020 climatological normals to determine if the exposure observed in 2026 was representative of long-term average conditions or driven by anomalous meteorological events.

5. Conclusions

Post-tournament observations from the 2026 FIFA World Cup demonstrate that ambient thermal exposure across a geographically distributed mega-event is highly unequal and fundamentally driven by tournament organization rather than by random weather variability. By analyzing the tournament as an integrated spatial system, we found that geographic venue assignment explained the vast majority of exposure variance, creating a structural disparity in the thermal conditions experienced by different segments of the spectator population.

This systemic inequality challenges the traditional approach of evaluating host cities as independent climatic entities. Venue assignment, match scheduling, and crowd size must be evaluated simultaneously. While traditional threshold-based classifications obscure how risk is distributed, integrating these variables through a spectator-degree-hours metric reveals that population-level thermal burden is intensely concentrated in a minimal fraction of the venue roster.

Three methodological elements distinguish this system-level approach from the venue-by-venue assessments that preceded the tournament. First, the ICC framework reveals that venue assignment explained more thermal exposure variance than kickoff time and daily weather combined. Second, the spectator-degree-hours metric exposes an extreme concentration of population burden (95% in three venues) that binary threshold classifications are structurally incapable of detecting. Third, the post-tournament NOAA–ERA5 comparison provides venue-specific bias estimates that future reanalysis-based planning can use for calibration. Organizers can directly manage population exposure through strategic match scheduling and by asymmetrically allocating cooling and medical resources to the specific event perimeters where the quantifiable burden lies. These tools are transferable to the 2030 and 2034 FIFA World Cups, where comparable or greater climatic gradients are expected. Ultimately, protecting spectators at future mega-events depends not only on forecasting the weather, but on understanding how tournament design itself generates and distributes thermal risk across populations.

Declarations

Data Availability Statement

Surface observations: Iowa Environmental Mesonet (mesonet.agron.iastate.edu). ERA5: Open-Meteo API (open-meteo.com). Attendance: FIFA/Transfermarkt. The analytical dataset (100 NOAA-covered matches × 22 variables), Python notebooks, and WBGT computation code are provided as Supplementary Material accompanying this submission (Online Resource 1: analytical dataset and station assignment; Online Resource 2: Python notebook and WBGT computation code).The four Guadalajara matches, which lack surface station coverage (see §2.1), are excluded from the primary dataset; their ERA5-derived values are available from the corresponding author upon request.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Author Contributions (CRediT)

F.A. Conceptualisation, analysis, wrote the main manuscript

S.C. Methodology, wrote the main manuscript

A.H. Data collection

E.B. Data collection

All authors reviewed the manuscript.

Declaration of Competing Interests

The authors declare no competing interests.

Ethics Statement

This study used publicly available meteorological data and aggregated attendance figures. The medical incident data cited (Houston Fan Festival, June 11 2026) were sourced from published news reports and official public communications; no individual-level health data were accessed or processed. No ethical approval was required.

Acknowledgements

The authors thank Alejandro S. Herrera Hernández and Emilio Bonal Pérez (PENSARes-ULL) for their support throughout this research.

References

1. Armstrong LE, Casa DJ, Millard-Stafford M, Moran DS, Pyne SW, Roberts WO (2007) American College of Sports Medicine position stand: Exertional heat illness during training and competition.

Med Sci Sports Exerc 39:556–572. https://doi.org/10.1249/mss.0b013e31802fa199

2. Bland JM, Altman DG (1986) Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 327:307–310. https://doi.org/10.1016/S0140-6736(86)90837-8
3. Budd GM (2008) Wet-bulb globe temperature (WBGT) — its history and its limitations. J Sci Med Sport 11:20–32. https://doi.org/10.1016/j.jsams.2007.07.003
4. Craig CA, Karabas I (2024) Forecasting thermal stress for sports tourists at the 2026 FIFA World Cup. Int J Biometeorol 68:2731–2742. https://doi.org/10.1007/s00484-024-02785-4
5. de Korte JQ, Eijsvogels TMH, Hopman MTE, Bongers CCWG (2023) Thermoregulatory, cardiovascular and perceptual responses of spectators of a simulated football match in hot and humid environmental conditions. Sports 11:78. https://doi.org/10.3390/sports11040078
6. Epstein Y, Roberts WO (2011) The pathophysiology of heat stroke: An integrative view. Scand J Med Sci Sports 21:742–748. https://doi.org/10.1111/j.1600-0838.2010.01224.x
7. FIFPRO (2021) Extreme Weather in Football. https://fifpro.org/en/supporting-players/health-and-performance/extreme-weather-and-climate-change/extreme-weather-in-football. Accessed 15 Jul 2026
8. Fox Weather (2026) 100+ suffer from heat exhaustion during fan festival for 2026 FIFA World Cup. https://www.foxweather.com/weather-news/over-100-people-heat-exhaustion-2026-fifa-world-cup-opening-day. Accessed 15 Jul 2026
9. Gouttebarge V, Duffield R, Den Hollander S, Maughan R (2023) Protective guidelines and mitigation strategies for hot conditions in professional football: starting 11 Hot Tips for consideration. BMJ Open Sport Exerc Med 9:e001608. https://doi.org/10.1136/bmjsem-2023-001608
10. Hersbach H, Bell B, Berrisford P et al (2020) The ERA5 global reanalysis. Q J R Meteorol Soc 146:1999–2049. https://doi.org/10.1002/qj.3803
11. Hifumi T, Kondo Y, Shimizu K, Miyake Y (2018) Heat stroke. J Intensive Care 6:30. https://doi.org/10.1186/s40560-018-0298-4
12. Liljegren JC, Carhart RA, Lawday P, Tschopp S, Sharp R (2008) Modeling the wet bulb globe temperature using standard meteorological measurements. J Occup Environ Hyg 5:645–655. https://doi.org/10.1080/15459620802310770
13. Lindner-Cendrowska K, Leziak K, Bröde P, Fiala D, Konefał M (2024) Prospective heat stress risk assessment for professional soccer players in the context of the 2026 FIFA World Cup. Sci Rep 14:26976. https://doi.org/10.1038/s41598-024-77540-1
14. Mullan D, Barr I, Brannigan N, Flood N, Gibson OR, Hambly C, Kennedy-Asser AT, Kielt AC, Matthews T, Orr M (2025) Extreme heat risk and the potential implications for the scheduling of football matches at the 2026 FIFA World Cup. Int J Biometeorol 69:753–763. https://doi.org/10.1007/s00484-025-02852-4
15. Nybo L, Flouris AD, Racinais S, Bogerd CP, Garg GG, Havenith G (2021) Football facing a future with global warming. Br J Sports Med 55:297–298. https://doi.org/10.1136/bjsports-2020-102736

16. Racinais S, Hosokawa Y, Akama T et al (2023) IOC consensus statement on recommendations and regulations for sport events in the heat. Br J Sports Med 57:8–25. https://doi.org/10.1136/bjsports-2022-105942
17. Shrout PE, Fleiss JL (1979) Intraclass correlations: Uses in assessing rater reliability. Psychol Bull 86:420–428. https://doi.org/10.1037/0033-2909.86.2.420
18. Stull RB (2011) Wet-bulb temperature from relative humidity and air temperature. J Appl Meteorol Climatol 50:2267–2273. https://doi.org/10.1175/JAMC-D-11-0143.1
19. Vanos JK, Thomas WM, Grundstein AJ, Hosokawa Y, Liu Y, Casa DJ (2020) A multi-scalar climatological analysis in preparation for extreme heat at the Tokyo 2020 Olympic and Paralympic Games. Temperature 7:191–214. https://doi.org/10.1080/23328940.2020.1737479

Figures

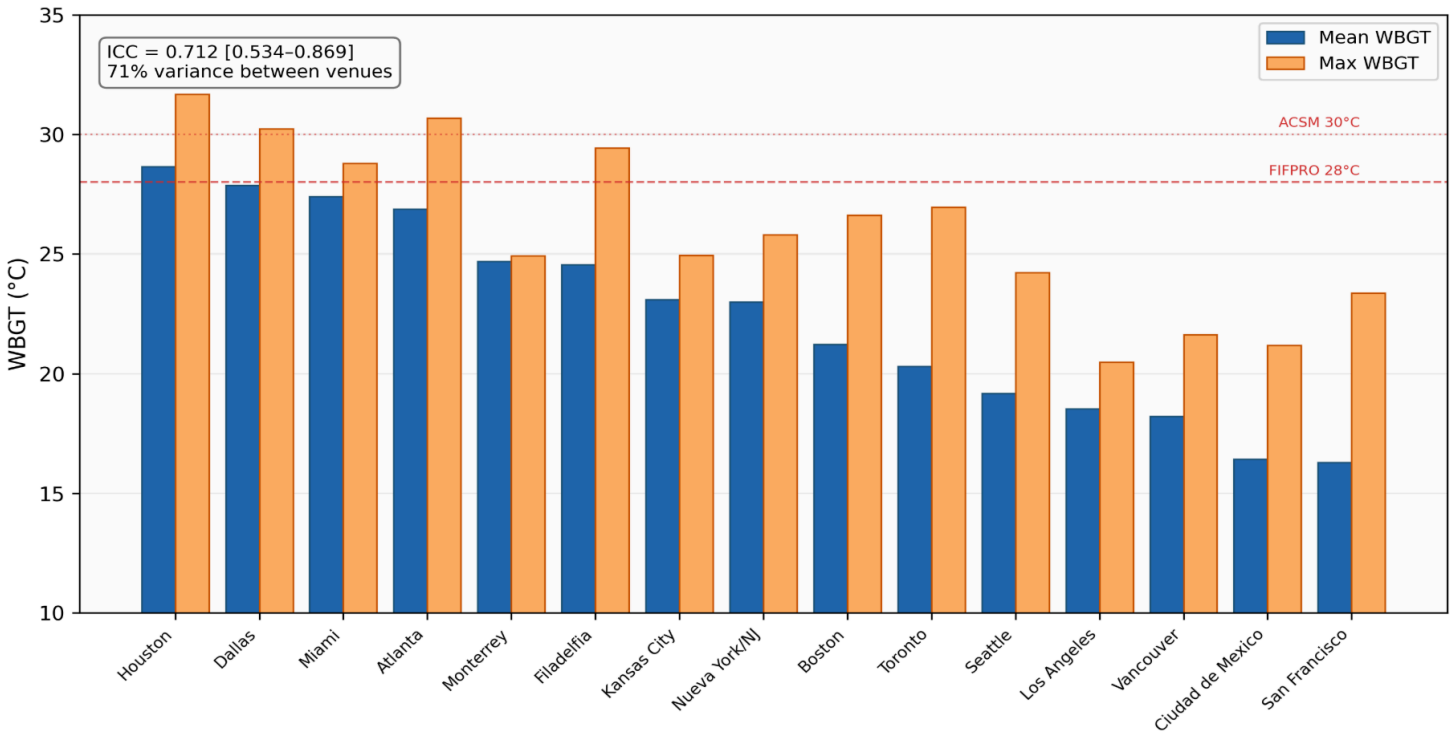


Figure 1

Mean and max WBGT by venue (15 NOAA stations). ICC = 0.707.

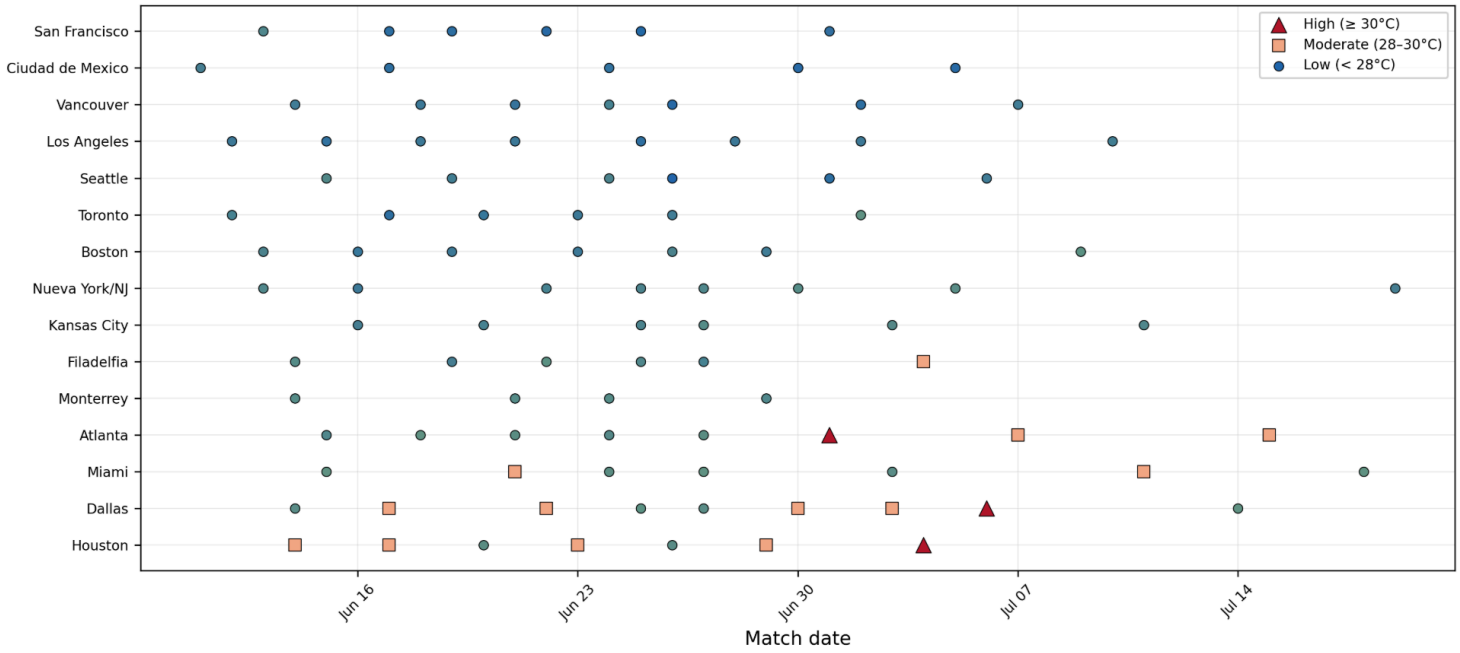


Figure 2

Mean WBGT (NOAA observations) across 15 venues. Red border = High-risk; orange = Moderate.

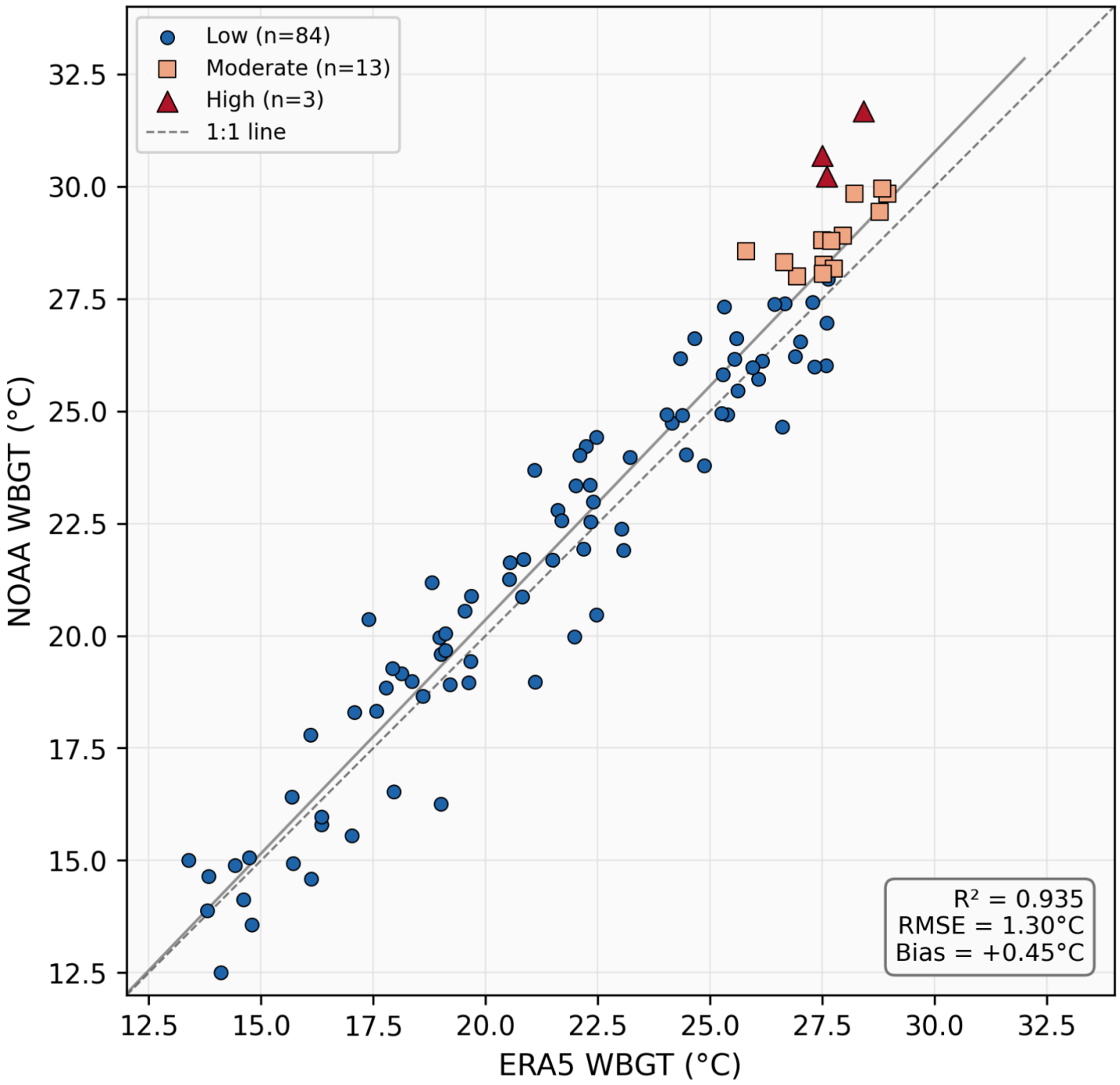


Figure 3

NOAA vs ERA5 validation (n=100). R²=0.933, RMSE=1.35°C. Red points: High-risk matches undetected by ERA5.

A radiation sensitivity analysis confirmed that 81% of this discrepancy reflected genuine differences in temperature, humidity, and wind between station observations and grid-level reanalysis, rather than artifacts of the clear-sky radiation assumption. Therefore, the structural heterogeneity we observed is real, but relying

solely on reanalysis data during the planning phase may blind organizers to the most extreme local hazards.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Mundial2026WBGTNOAA15sedesDEFINITIVO1.xlsx
- Mundial2026NOAADEFINITIVO1.ipynb