CosmosClimae
Climat, indicateurs, adaptation

PREPRINT
Version prépublication - manuscrit soumis pour évaluation

Heat-stress exposure at European football venues under climate change: the limits of timing-based adaptation

Dimitri Defrance, Tiffanie Lescure
CosmosClimae, Montpellier, France
Auteur correspondant : dimitri@cosmosclimae.com

Note de prépublication

Ce document est une version préprint diffusée sur CosmosClimae.
Il n'a pas encore été accepté par une revue ni relu par les pairs.
Le contenu, les figures, les résultats et les formulations peuvent évoluer avant une éventuelle publication scientifique finale.
Merci de citer la version publiée lorsqu'elle sera disponible.

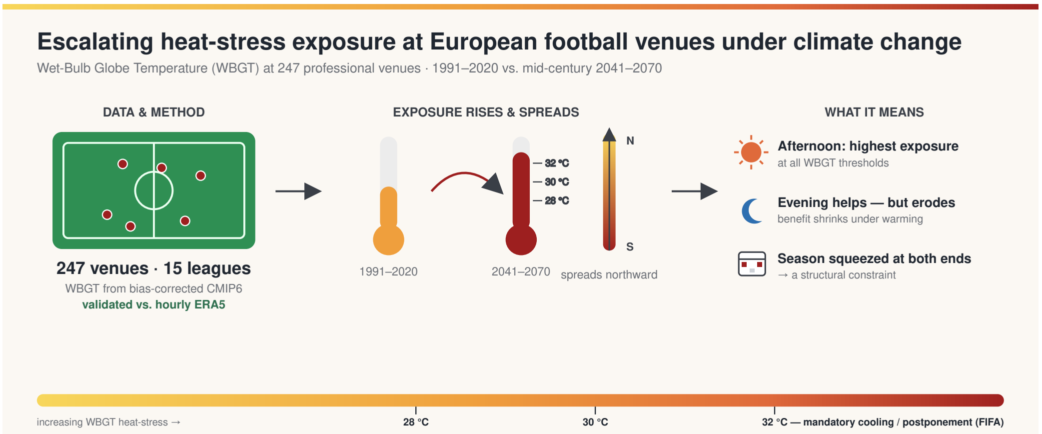
Statut : soumis à Sustainable Cities and Society

Date du préprint : juin 2026

Graphical Abstract

Heat-stress exposure at European football venues under climate change: the limits of timing-based adaptation

Dimitri Defrance, Tiffanie Lescure



Highlights

Heat-stress exposure at European football venues under climate change: the limits of timing-based adaptation

Dimitri Defrance, Tiffanie Lescure

- Heat-stress exposure is assessed at 247 European professional football venues.
- Daily WBGT reconstruction is validated against hourly ERA5 reanalysis.
- WBGT exceedances already occur in southern Europe and increase by mid-century.
- Evening scheduling reduces exposure, but its protective effect weakens under warming.
- Heat stress increasingly constrains both match timing and the football calendar.

Heat-stress exposure at European football venues under climate change: the limits of timing-based adaptation

Dimitri Defrance[a,*], Tiffanie Lescure[a]

[a] *CosmosClimae, Montpellier, France*

Abstract

Heat stress is becoming an increasingly important constraint for outdoor sport under climate change, especially where intense physical activity, fixed venues, and rigid competition calendars interact. Professional football is particularly exposed because matches are played in open or semi-open stadiums, players sustain high metabolic heat loads, and opportunities for behavioural thermoregulation during play remain limited. While extreme heat during summer tournaments has been widely studied, less is known about heat-stress exposure across the regular European football season and the extent to which timing-based adaptation can reduce future risk.

Here we quantify present and future heat-stress exposure at 247 professional football venues across 15 European top-tier leagues using the Wet-Bulb Globe Temperature (WBGT). Daily WBGT was computed from an ensemble of five bias-corrected CMIP6 models for a historical reference period (1991–2020) and a mid-century horizon (2041–2070). SSP2-4.5 is used as the central scenario, with SSP1-2.6 and SSP5-8.5 bracketing the plausible range. Exposure is measured as the cumulative number of days per football season, from July to May, exceeding WBGT thresholds of 28, 30, and 32 °C, and is reported separately for afternoon and evening conditions. The daily WBGT reconstruction is validated against hourly ERA5 reanalysis at all stadium locations.

Heat-stress exposure already occurs during the current European football calendar, mainly in southern Europe, and is projected to intensify and spread by mid-century. Afternoon conditions consistently show the highest

*dimitri@cosmosclimae.com

exposure across thresholds and scenarios. Evening scheduling substantially reduces exceedance frequency, but its protective effect weakens under warming, with non-negligible evening exposure emerging at the warmest venues. Monthly results further show that heat stress increasingly affects both the beginning and the end of the football season, reducing the number of thermally favourable windows within the existing calendar.

These findings indicate that heat stress is emerging as a structural constraint on professional football in Europe. Later kick-off times remain a useful adaptation measure, but they are unlikely to be sufficient on their own under continued warming. Integrated strategies that combine match scheduling, calendar design, stadium heat management, and health-protection protocols for players and spectators will be needed to maintain safe and resilient football operations in a warming climate.

Keywords: Heat stress, Wet Bulb Globe Temperature (WBGT), Climate change, Professional football, Match scheduling, Climate adaptation, Urban heat exposure

---

1. Introduction

Climate change is increasingly altering the environmental conditions under which outdoor sport is played, organised, and attended. Rising temperatures, more frequent heat extremes, and changes in atmospheric humidity are increasing the likelihood of thermally stressful conditions during physical activity IPCC (2023); Perkins-Kirkpatrick and Lewis (2020); Mora et al. (2017). These changes are particularly relevant for organised sport, where competition schedules, athlete-health requirements, stadium infrastructure, and event-management constraints interact within tightly structured socio-technical systems Orr and Inoue (2019); Orr et al. (2022); Schneider and Mücke (2024).

Professional football is especially exposed to this tension. Matches are played in open or semi-open venues, require repeated high-intensity activity, and are embedded in fixed domestic and international calendars. During competition, players experience high metabolic heat production, limited opportunities for behavioural thermoregulation, and only short interruptions for cooling or hydration Casa et al. (2015); Nybo et al. (2014); Gouttebarge et al. (2023). Heat stress can therefore affect not only acute health risk, but also physical performance, pacing behaviour, and competitive conditions. Football-specific studies have shown that elevated environmental temperatures and Wet Bulb Globe Temperature (WBGT) are associated with changes in match running performance, high-intensity activity, and performance maintenance under extreme heat Nassis et al. (2015); Schwarz et al. (2025); Carmo et al. (2026).

At the same time, professional football is not only a physiological exposure setting. It is also an urban and economic system. Stadiums concentrate players, staff, spectators, transport flows, security services, and media operations in fixed locations, while match timing is constrained by broadcasting, policing, travel, commercial, and competitive requirements. Heat exposure in football should therefore be understood not only as a sports-medicine issue, but also as a challenge for the climate resilience of urban sport infrastructure and event scheduling.

Thermal exposure in sport is commonly assessed using the Wet Bulb Globe Temperature, a biometeorological index that integrates air temperature, humidity, solar radiation, and convective heat exchange Budd (2008); International Organization for Standardization (2017). WBGT-based thresholds are widely used in occupational health and sports settings to guide activity modification, cooling interventions, and event-postponement decisions Jacklitsch et al. (2016); Hosokawa et al. (2019); Racinais et al. (2023); Gouttebarge et al. (2023). Time-of-day is a primary modulator of this exposure: WBGT typically peaks in mid-afternoon and declines through the evening, so that afternoon kick-offs concentrate the highest heat-stress risk, and moving activity out of the afternoon can substantially reduce extreme-heat exposure Grundstein et al. (2014); Mullan et al. (2025); Lindner-Cendrowska et al. (2024). Recent studies have applied heat-stress metrics to major football tournaments and shown that host-city climate, kick-off time, and calendar design strongly modulate exposure Lindner-Cendrowska et al. (2024); Mullan et al. (2025); Sawadogo et al. (2025). These assessments, however, target discrete tournaments held in a single host region over a few weeks. The structural, season-long heat exposure of the regular professional football calendar, where the same fixed venues are used week after week across an extended season, has not been assessed at continental scale.

This gap is important for European football. Most top-tier domestic leagues operate from late summer to late spring, with matches beginning as early as July or August and continuing until May. This seasonal structure has historically reduced direct overlap with peak summer heat, but it does not eliminate heat exposure, particularly during early-season and late-season matches. Moreover, under climate change, thermally stressful conditions may expand beyond the traditional summer peak and increasingly affect months that are currently considered operationally safe. Evening scheduling is often treated as a practical adaptation, yet its long-term effectiveness remains uncertain as evening and night-time temperatures rise.

From a climate-adaptation perspective, the key question is therefore not only whether individual matches may exceed heat-stress thresholds, but whether the current geography and timing of professional football remain compatible with future thermal conditions. Stadiums are fixed infrastructures, whereas match calendars are constrained by institutional, commercial, and logistical requirements. That even the calendar is no longer immovable is illustrated by the relocation of the 2022 FIFA World Cup from its traditional June–July window to November–December (the first such shift in the tournament's history) to avoid extreme summer heat. As warming continues, comparable pressures may increasingly act on domestic kick-off times, season boundaries, venue management, and player-protection protocols Orr et al. (2022); Racinais et al. (2023). This creates a planning problem similar to that faced by other climate-sensitive urban systems, in which adaptation may require not only operational adjustments, such as later kick-off times, but also more structural changes to season timing, infrastructure, and urban heat-mitigation strategies.

Here, we assess present and future heat-stress exposure at European professional football venues using the WBGT index and bias-corrected CMIP6 climate projections. We analyse 247 stadiums from top-tier domestic leagues in 15 UEFA-affiliated associations over an 11-month football period from July to May. Exposure is quantified as the number of days exceeding WBGT thresholds of 28, 30, and 32 °C, distinguishing between afternoon and evening conditions to evaluate the potential and limits of timing-based adaptation. We focus on a historical reference period (1991–2020) and a mid-century planning horizon (2041–2070), with SSP2–4.5 used as the central scenario and the low- and high-emission pathways SSP1–2.6 and SSP5–8.5 bracketing the plausible range. To our knowledge, this is the first continental-scale, multi-venue, full-season assessment of climate-driven heat-stress exposure in professional football. By shifting the focus from isolated heat events to repeated exposure at fixed urban football venues, this study evaluates how climate change may challenge the long-term sustainability, scheduling, and governance of professional football infrastructure in Europe.

2. Materials and Methods

2.1. Climate data and scenarios

Daily climate projections were obtained from the NASA NEX-GDDP-CMIP6 dataset, which provides statistically bias-corrected and spatially downscaled outputs from CMIP6 global climate models at a horizontal resolution of 0.25° Thrasher et al. (2022). NEX-GDDP-CMIP6 is based on a daily variant of the bias-correction spatial disaggregation (BCSD) method, originally developed for monthly climate projections, in which model outputs are adjusted against an observational reference over a common historical period and then interpolated to a finer spatial grid. Bias correction relies on an empirical quantile-mapping procedure: for each variable and calendar day, the cumulative distribution of the historical model output is compared with that of the observational reference using a ±15-day moving window over the 1960–2014 calibration period, and each modelled value is mapped to the corresponding observed quantile. The observational reference used for this correction is the Global Meteorological Forcing Dataset (GMFD), at 0.25° daily resolution Thrasher et al. (2022).

This procedure corrects systematic biases across the modelled distribution while preserving the large-scale climate-change signal produced by the original GCMs, including monthly temperature trends that are removed prior to bias correction and added back afterwards Thrasher et al. (2022). However, the BCSD approach does not add physical information beyond that contained in the original CMIP6 simulations, apart from bias correction and spatial interpolation. It also assumes that the relative spatial patterns observed during the reference period remain valid under future climate change. Consequently, although the temporal occurrence of anomalously high or low values within each scenario is retained, the magnitude of downscaled extremes may be underestimated in some regions because of spatial smoothing during the translation from coarse to finer resolution Thrasher et al. (2022). This limitation is particularly relevant for heat-stress indicators, whose upper-tail behaviour depends jointly on temperature and humidity extremes.

Five CMIP6 models were used: GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, and UKESM1-0-LL. These constitute the primary General Circulation Model ensemble of the ISIMIP3b framework Lange (2019), selected for their availability across all Shared Socioeconomic Pathways and because they span a wide range of equilibrium climate sensitivities, from lower-sensitivity models (e.g. GFDL-ESM4) to higher-sensitivity models (e.g. UKESM1-0-LL). This spread ensures that the ensemble does not systematically over- or under-estimate the projected warming signal.

Three emission scenarios were analysed (SSP1-2.6, SSP2-4.5, and SSP5-8.5) spanning low, intermediate, and high-emission trajectories. The intermediate SSP2-4.5 pathway, most consistent with current policies and pledges, is used as the central scenario in the main text, while SSP1-2.6 and SSP5-8.5 bracket the plausible range. Two periods were compared: a historical reference period (1991–2020) and a mid-century period (2041–2070), the latter providing a decision-relevant planning horizon for adaptation. The reference period combines the CMIP6 historical experiment (1991–2014) with the SSP1-2.6 projection (2015–2020).

Daily maximum (T_{max}), minimum (T_{min}) and mean (T_{mean}) air temperature, near-surface relative humidity (RH), and surface downward shortwave radiation (RSDS) were extracted for all models and scenarios. Multi-model results are reported as the ensemble mean to reduce single-model uncertainty.

2.2. Football stadium dataset

The analysis focuses on clubs competing in the top-tier domestic league during the 2024-2025 season in 15 UEFA-affiliated European football associations (Table 1). The selected leagues combine high competitive relevance, assessed using the UEFA association coefficient as a league-level indicator, with broad geographical coverage across the European continent. The selection was therefore not intended to reproduce the exact UEFA association ranking, but to retain a set of prominent domestic leagues while avoiding an overly concentrated sample in Western and Southern Europe.

A database of 247 professional football stadiums was compiled. Geographic coordinates were collected from publicly available sources and visually checked for consistency. In this study, stadiums are treated as fixed urban exposure points rather than as proxies for national climate conditions, because their operation depends on location-specific climatic constraints, transport flows, crowd management, and event scheduling. Where several clubs share a home stadium, each club was treated as a distinct exposure point. The complete list of stadiums, clubs, countries, and coordinates is provided in the Supplementary Information.

Each stadium was mapped to the nearest 0.25° grid cell of the climate dataset using a nearest-neighbour approach. All analyses are performed at stadium locations only: results are presented as stadium-level values and as country-level distributions, and *no spatial interpolation between stadiums is* *performed*. Country-level statistics aggregate the stadiums located within each country and therefore represent climatic exposure at professional football venues rather than national mean climate conditions.

Table 1: Top-tier domestic leagues and number of professional football venues analysed (2024–2025 season). Each club is treated as a distinct exposure point.

Country	Top division	Venues
Spain	La Liga	20
Italy	Serie A	20
England	Premier League	20
Turkey	Süper Lig	19
Portugal	Primeira Liga	18
Netherlands	Eredivisie	18
Germany	Bundesliga	18
France	Ligue 1	18
Norway	Eliteserien	16
Czechia	Chance Liga	16
Belgium	Pro League	16
Switzerland	Super League	12
Scotland	Scottish Premiership	12
Denmark	Superliga	12
Austria	Bundesliga	12
Total	**15 leagues**	**247**

2.3. Wet Bulb Globe Temperature

Heat-stress exposure was quantified using the outdoor Wet Bulb Globe Temperature (WBGT), a biometeorological index recommended by international sport and occupational-health guidelines Racinais et al. (2023); Hosokawa et al. (2018). We adopt the same WBGT formulation recently applied by Sawadogo et al. (2025) to assess climate-related heat risk for the Africa Cup of Nations, computed as

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

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

Because T_w and T_g are not provided by climate models, they were estimated from standard meteorological variables. The natural wet-bulb temperature was computed using the analytical psychrometric approximation of Stull (2011), which is valid at standard sea-level pressure with a mean deviation below 0.3 °C. The black-globe temperature was estimated from the empirical regression of Hajizadeh et al. (2017):

$$T_g = 0.01498\, RSDS + 1.184\, T_a - 0.0789\, RH - 2.739$$

This combination of T_w and T_g formulations is identical to that used by Sawadogo et al. (2025) for a comparable football climate-risk assessment.

2.4. Time-of-day reconstruction

Match exposure was evaluated for two representative kick-off times, 15:00 (afternoon) and 21:00 (evening), expressed in local solar time. Because the climate models provide daily rather than sub-daily fields, the air temperature, humidity, and radiation entering the WBGT at each kick-off time were reconstructed from the daily variables.

Air temperature was reconstructed using the sinusoidal diurnal model of Parton and Logan (1981), with the daily maximum assumed to occur at 15:00 solar time:

$$T_a(h) = \frac{T_{max} + T_{min}}{2} + \frac{T_{max} - T_{min}}{2} \cos\left(\frac{\pi\,(h - 15)}{12}\right)$$

which yields $T_a = T_{max}$ at 15:00 and $T_a = (T_{max} + T_{min})/2$ at 21:00.

Time-of-day relative humidity was derived assuming a conserved daily vapour pressure: the mean vapour pressure was computed from daily mean temperature and relative humidity, and the relative humidity at each kick-off time was recovered from the saturation vapour pressure at the reconstructed temperature, constrained to 1–99%.

Incoming shortwave radiation was set to the daily-mean RSDS for the afternoon, representing daytime solar exposure, and to zero for the evening, representing the near-absence of direct solar radiation at the latitudes and seasons of typical evening matches.

2.5. Validation against hourly reanalysis

Because the WBGT is intrinsically a sub-daily quantity, the daily-data reconstruction was validated against hourly ERA5 reanalysis Hersbach et al.

(2020) at the 247 stadium locations over 2016–2025. For each day, a reference WBGT was computed directly from hourly ERA5 2 m temperature, 2 m dew point, and surface shortwave radiation at 14:00 and 20:00 UTC, approximating the afternoon and evening kick-off times across the European domain, and compared with the WBGT obtained by applying the identical daily reconstruction to ERA5 daily aggregates derived from the same hourly data. Using the same dataset on both sides isolates the error of the daily reconstruction from any climate-model bias. Mean bias, root-mean-square error, and the error in the number of days exceeding 28, 30, and 32 °C are reported in Section 3.1 (Figure 1) stratified by month and by latitude band.

2.6. Heat-stress thresholds and exposure metrics

Heat-stress exposure was quantified as the cumulative number of days exceeding three WBGT thresholds over the 11-month football period (July–May): 28 °C (moderate heat stress and reduced performance), 30 °C (high heat stress and increased health risk), and 32 °C (very high heat stress with elevated risk of heat illness). These thresholds follow international sport and occupational heat guidelines and have been applied in recent football- and tournament-scale climate-risk assessments Racinais et al. (2023); Hosokawa et al. (2018); Sawadogo et al. (2025). For each stadium, model, and scenario, exceedance days were summed over July–May; multi-model results are reported as the ensemble mean, and country-level values aggregate stadium-level exposure.

2.7. Limitations

Several limitations are noted explicitly. First, WBGT is reconstructed from daily climate fields rather than sub-daily data; the resulting error is quantified by the ERA5 validation and is concentrated in the warm months that drive threshold exceedances. Second, the black-globe temperature relies on an empirical regression Hajizadeh et al. (2017) that does not include wind speed and was originally calibrated under warm, low-latitude conditions; its application to European venues is supported by the validation but remains an approximation. Third, the assumption of zero evening shortwave radiation may underestimate exposure at high-latitude venues in early summer, when the sun remains above the horizon at 21:00; this renders the evening estimates conservative. Fourth, WBGT derived from gridded data does not resolve microclimatic modifiers such as stadium geometry, crowd density, ventilation, or urban heat-island effects, so the estimates should be interpreted as a conservative lower bound of in-stadium exposure. Finally, exposure metrics are not weighted by the actual number of matches played per month and therefore represent potential rather than event-specific risk.

3. Results

3.1. Validation of the daily WBGT reconstruction

Because every result that follows is based on a WBGT reconstructed from daily fields, we first quantify how well that reconstruction reproduces the sub-daily quantity. Figure 1 compares, at the 247 stadium locations over 2016–2025, the WBGT from the daily reconstruction with the WBGT computed directly from hourly ERA5 at the same solar times.

On warm days (truth WBGT $\geq 25\,^\circ$C, the range relevant for exceedances), the afternoon reconstruction reproduces the hourly WBGT closely, with values tightly distributed around the 1:1 line (Figure 1a) and an RMSE of 0.94 °C. It carries a small cold bias of $-0.70\,^\circ$C, consistent with the use of a daily-mean rather than instantaneous shortwave flux, which underestimates the mid-afternoon radiant load. The evening reconstruction is essentially unbiased (+0.11 °C, RMSE 0.84 °C), although warm evenings are rare and the evening sample is correspondingly small. The bias has a clear seasonal structure (Figure 1b): the afternoon cold bias is largest in the warm months that generate exceedances and vanishes in the cool months, while the evening bias stays small and slightly positive throughout the season.

The reconstruction also reproduces the metric used throughout this study, the number of threshold-exceedance days (Figure 1c). At the most severe threshold, 32 °C, on which our headline results rest, the per-stadium counts fall on the 1:1 line and the reconstruction is essentially unbiased. At the lower thresholds the afternoon cold bias translates into an underestimate of afternoon exceedance-days of about a quarter at 28 and 30 °C, concentrated at the most exposed southern venues. Because this bias is systematic rather than random, it largely cancels when periods and scenarios are compared: the projected increases and the spatial and seasonal patterns reported below are therefore more robust than the absolute day counts, which should be read as a conservative lower bound on true exposure.

The afternoon cold bias is of comparable magnitude across latitude bands (between about -0.4 and $-0.8\,^\circ$C, with RMSE $< 1\,^\circ$C in every band; values not shown), so it affects southern and northern venues alike and cannot, by itself, account for the north–south gradient reported below.

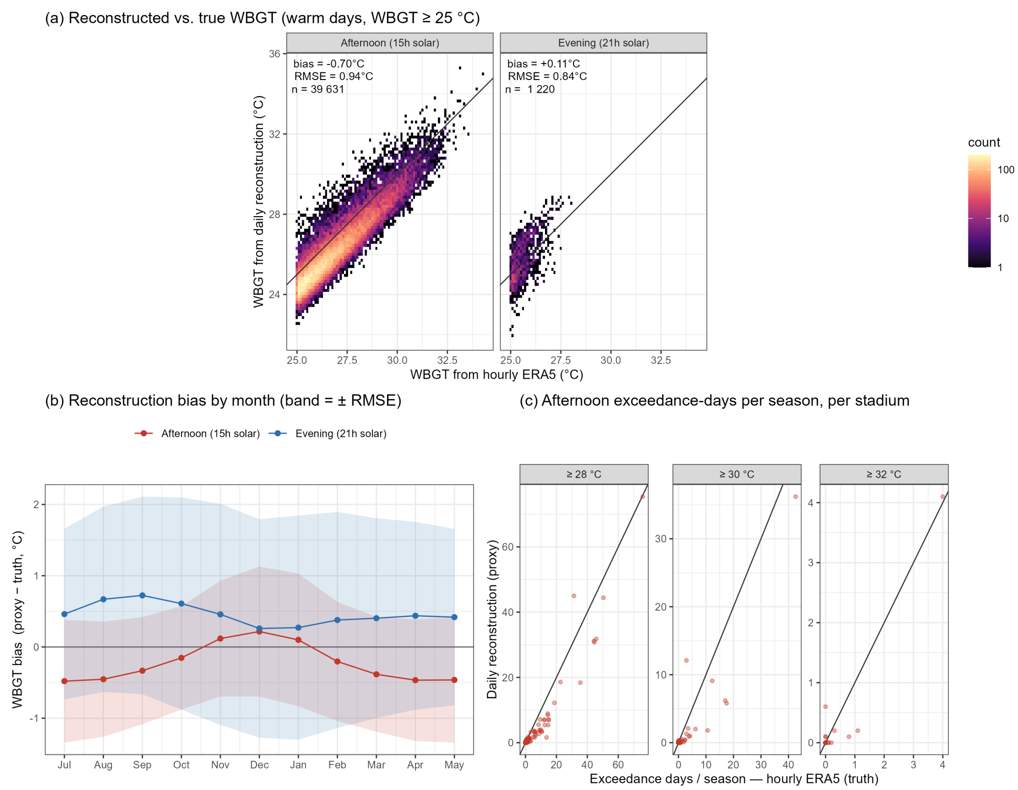


Figure 1: Validation of the daily WBGT reconstruction against hourly ERA5 at the 247 stadium locations over 2016–2025. (a) Density of reconstructed vs. true WBGT on warm days (WBGT $\geq 25\,^{\circ}$C), afternoon and evening, with the 1:1 line and the mean bias and RMSE. (b) Reconstruction bias by month (line) with $\pm$RMSE band. (c) Afternoon exceedance-days per season per stadium, reconstruction vs. hourly truth, for the 28, 30 and 32 $^{\circ}$C thresholds, with the 1:1 line.

3.2. Spatial distribution of heat-stress exposure at European football venues

Figure 2 maps cumulative heat-stress exposure at 247 European professional football venues, expressed as the number of days per football season from July to May on which WBGT exceeds 32 °C. This threshold corresponds to very high heat stress and to conditions for which the most stringent heat-mitigation measures may be required in football Bandiera et al. (2024); Racinais et al. (2023). Results are shown at stadium locations only, so no value is interpolated between venues. Columns compare the historical reference period (1991–2020) with mid-century projections (2041–2070) under SSP2-4.5 and SSP5-8.5. Rows distinguish afternoon and evening conditions.

Under present-day conditions, WBGT rarely reaches 32 °C at European professional football venues. Afternoon exceedances are confined to a small number of southern venues, mainly in southern Iberia, southern Italy, and Turkey, while evening exceedances are effectively absent. The most severe heat-stress threshold is therefore currently an edge condition of the European football calendar rather than a routine constraint.

By mid-century, exposure to this threshold increases. Under SSP2-4.5, afternoon exceedances emerge at a growing set of southern venues, with the highest counts along the Mediterranean fringe and in south-eastern Europe. Under SSP5-8.5, the same spatial pattern intensifies, both in terms of the number of venues affected and the number of exceedance days. Isolated evening exceedances also appear at the hottest southern stadiums. The results for SSP1-2.6 are shown in Supplementary Information (Figure A.1).

Two features are robust across the scenarios shown in Figure 2. First, exposure to WBGT above 32 °C remains strongly concentrated in southern Europe. Unlike the lower thresholds analysed in Figures 3-5, this very high heat-stress threshold does not become a pan-European condition by mid-century. Second, evening conditions remain substantially less exposed than afternoon conditions across the continent. Evening scheduling therefore keeps the most severe threshold largely avoidable, except at the hottest southern venues under stronger warming.

3.3. Country-level distributions across WBGT thresholds

Figures 3-5 show country-level distributions of cumulative heat-stress exposure at European professional football venues, derived from stadium locations only. Exposure is expressed as the number of days exceeding WBGT thresholds of 28 °C, 30 °C, and 32 °C over the July to May football period.

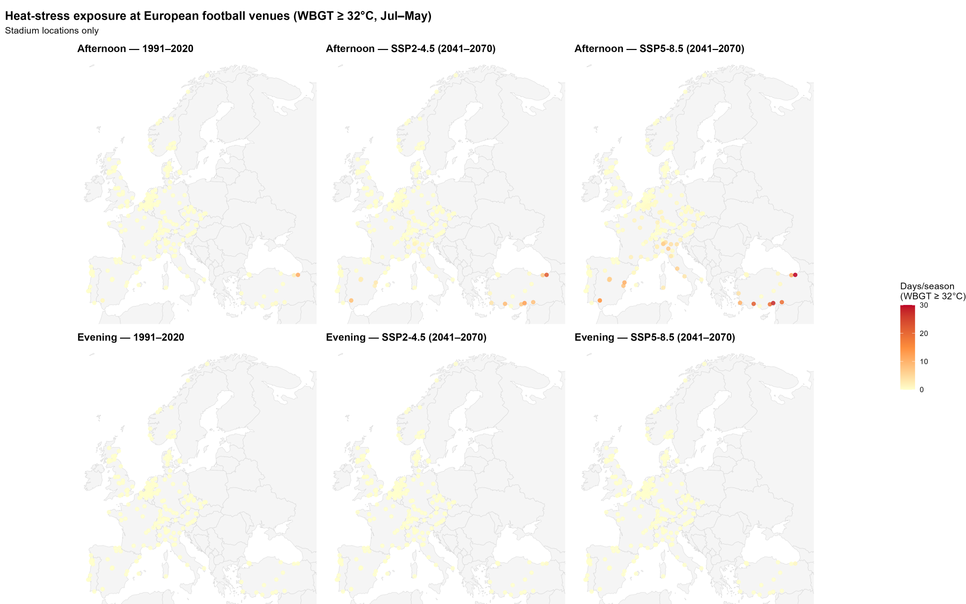


Figure 2: Spatial distribution of cumulative heat-stress exposure at European professional football venues, expressed as the number of days per football season from July to May exceeding a WBGT threshold of 32 °C. Each point represents a stadium and no spatial interpolation is performed. Columns show the historical reference period (1991–2020), SSP2-4.5 at mid-century (2041–2070), and SSP5-8.5 at mid-century (2041–2070). Rows show afternoon and evening conditions. Values represent multi-model ensemble means across five bias-corrected CMIP6 models.

Results are shown separately for afternoon and evening conditions and compare the historical reference period (1991–2020) with mid-century projections (2041–2070) under SSP1-2.6, SSP2-4.5, and SSP5-8.5.

At the 28 °C threshold (Figure 3), moderate heat-stress exposure is already present during the current football calendar, particularly under afternoon conditions. The highest present-day values are concentrated in southern and south-eastern Europe, notably in Spain, Italy, Turkey, and Portugal. Northern and western countries, including England, Germany, Belgium, the Netherlands, and the Scandinavian leagues, show lower historical exposure, although some stadium-level values are already non-zero.

Future projections show a clear scenario-dependent increase in exceedance days. SSP1-2.6 produces a limited but visible increase in several countries, while SSP2-4.5 leads to broader exposure across southern and central Europe. Under SSP5-8.5, the increase becomes much larger, with southern countries reaching the highest medians and widest country-level spreads. These spreads indicate substantial variation among stadiums within the same country, especially in geographically diverse leagues such as Spain, Italy, and Turkey.

Evening conditions strongly reduce the number of 28 °C exceedance days relative to afternoon conditions. However, the evening panels show that this reduction does not eliminate exposure under future warming. Under SSP2-4.5 and especially SSP5-8.5, non-zero evening exceedances become more frequent in the warmest countries, particularly in southern Europe. Later kick-off times therefore remain an effective mitigation option, but they are not sufficient to fully suppress moderate heat-stress exposure at the warmest venues.

At the 30 °C threshold (Figure 4), present-day exposure is more spatially restricted. Afternoon exceedances remain limited in most countries and are mainly concentrated in the warmest southern and south-eastern leagues. Spain, Italy, Turkey, and Portugal show the clearest current exposure, whereas most northern and central European countries remain close to zero during the reference period.

Future projections indicate a marked expansion of high heat-stress exposure. The increase remains moderate under SSP1-2.6, becomes more evident under SSP2-4.5, and is strongest under SSP5-8.5. Under the highest scenario, several southern countries show large increases in both median values and upper ranges, meaning that some stadiums within these countries experience many more exceedance days than the national median. Central European

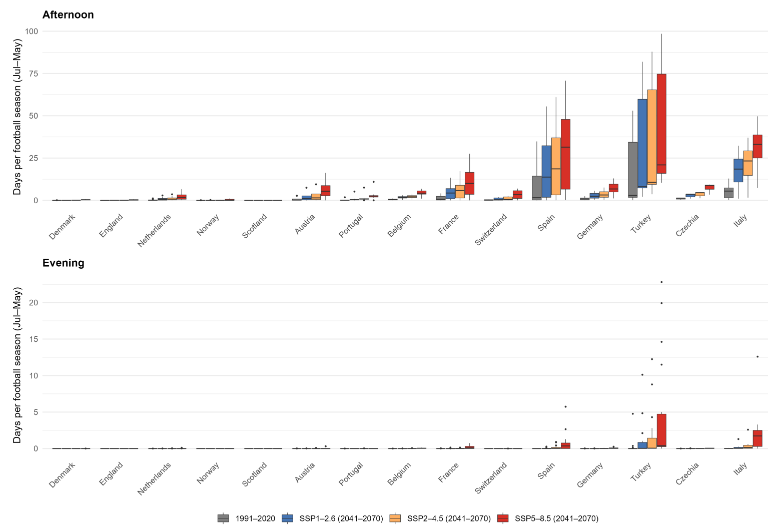


Figure 3: Country-level distributions of cumulative heat-stress exposure at European professional football venues for a WBGT threshold of 28 °C, expressed as the number of exceedance days over the July to May football period. Results are derived from stadium locations only and shown for afternoon and evening conditions. Boxplots compare the historical reference period (1991–2020) with mid-century projections (2041–2070) under SSP1-2.6, SSP2-4.5, and SSP5-8.5.

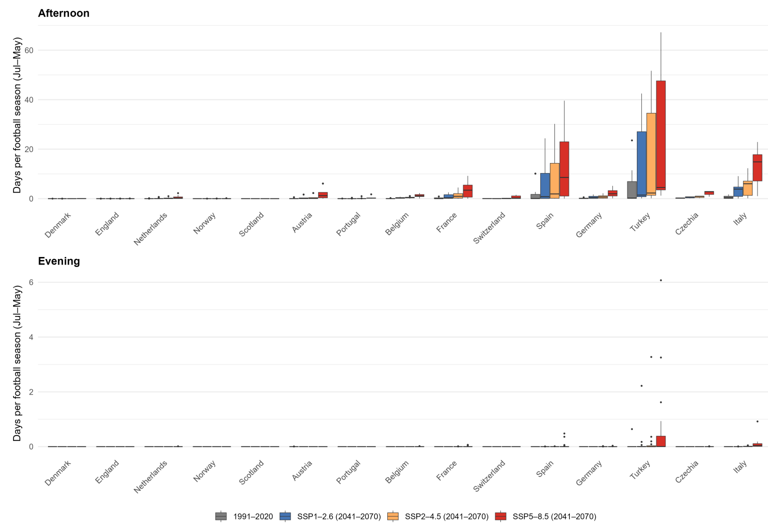


Figure 4: Same as Figure 3, but for a WBGT threshold of 30 °C, corresponding to high heat-stress conditions associated with increased health and performance risks.

countries also begin to show non-zero values, indicating that high heat stress is no longer confined to the warmest parts of the continent.

Evening exposure at 30 °C remains close to zero for most countries in the historical period. Nevertheless, future scenarios show the emergence of non-negligible evening exceedances in several warm countries, particularly under SSP5-8.5. This pattern confirms that evening scheduling substantially reduces high heat-stress exposure, but its protective effect weakens as the full WBGT distribution shifts upward.

Exceedances of the 32 °C threshold (Figure 5), corresponding to very high heat stress, remain rare under present-day conditions. Historical values are close to zero in most countries and are largely restricted to isolated stadiums in the warmest regions, mainly under afternoon conditions. This confirms that very high WBGT exposure is not yet a regular feature of most European professional football venues during the July to May calendar.

Future projections nevertheless show the emergence of 32 °C exceedance days, with a strong scenario dependence. Under SSP2-4.5, afternoon exceedances become detectable in several southern countries, especially around the Mediterranean and south-eastern Europe. Under SSP5-8.5, the increase is much larger, with the highest values and widest spreads again found in Spain, Italy, Turkey, and Portugal. These results indicate that the most

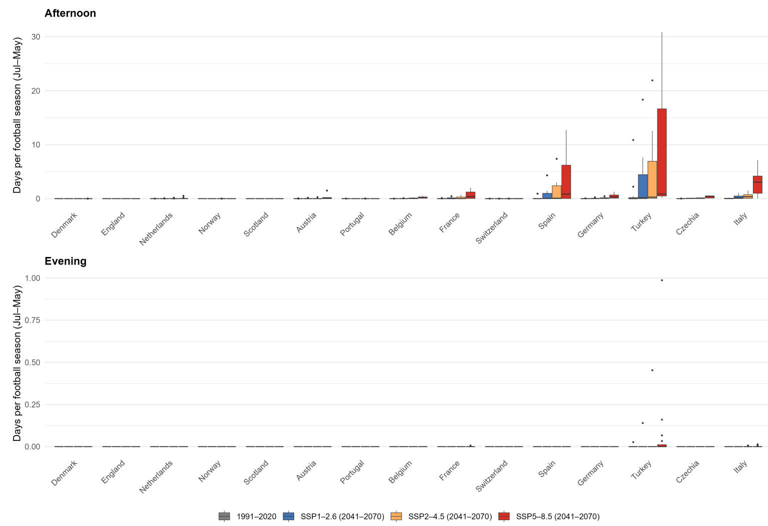


Figure 5: Same as Figure 3, but for a WBGT threshold of 32 °C, corresponding to very high heat-stress conditions for which mandatory cooling breaks, stronger mitigation measures, or match postponement may be required under heat-safety protocols.

severe heat-stress conditions remain geographically concentrated, but they become more frequent and affect a larger set of venues under stronger warming.

Evening exceedances at 32 °C remain much less frequent than afternoon exceedances and are close to zero in most countries. However, isolated nonzero values appear under SSP5-8.5 in the warmest countries. This suggests that very high heat stress would still be primarily an afternoon problem, but that the most exposed venues may no longer be fully protected by evening scheduling under high warming.

3.4. Effectiveness of evening scheduling as an adaptation strategy

Figure 6 assesses the effectiveness of evening scheduling as an adaptation strategy by quantifying the difference in cumulative heat-stress exposure between afternoon and evening conditions at the WBGT 30 °C threshold. The metric is computed as afternoon minus evening exceedance days over the July to May football period. Positive values therefore indicate a reduction in the number of high heat-stress days when matches are scheduled in the evening rather than in the afternoon.

Under present-day conditions, evening scheduling substantially reduces heat-stress exposure in the countries where afternoon exceedances already occur. The largest current benefits are concentrated in southern and south-eastern Europe, notably in Spain, Italy, Turkey, and Portugal. In northern and western countries, the benefit is smaller because afternoon exceedances of the 30 °C threshold remain limited during the historical period.

Future projections show that the absolute benefit of evening scheduling increases with warming. This is particularly visible under SSP2-4.5 and SSP5-8.5, where the difference between afternoon and evening exposure becomes larger in the warmest countries. Later kick-off times therefore continue to avoid a substantial number of high heat-stress days, especially in Mediterranean and south-eastern European venues.

However, the figure also shows that this benefit becomes increasingly heterogeneous across countries and stadiums. Under SSP5-8.5, several countries exhibit wide distributions, indicating that the effectiveness of evening scheduling varies strongly among venues within the same national league. This is especially relevant for geographically diverse countries, where stadiums are distributed across contrasting climatic zones.

These results indicate that evening scheduling remains a robust short-term adaptation measure, but also that it should not be interpreted as a complete solution. The benefit of moving matches to the evening increases because afternoon exposure rises strongly, yet evening exceedances do not disappear entirely in the warmest countries. Evening scheduling therefore reduces high heat-stress exposure, but under stronger warming it cannot fully offset the upward shift in WBGT conditions across the football season.

3.5. Seasonal redistribution of heat-stress exposure and implications for calendar adaptation

Figure 7 illustrates the monthly distribution of cumulative heat-stress exposure aggregated across professional football stadiums for five representative countries: Norway, England, Germany, Italy, and Spain. Exposure is expressed as total stadium-days exceeding a WBGT threshold of 30 °C for each month of the July to May football period. Results are shown for afternoon conditions and compare the historical reference period (1991–2020) with mid-century projections (2041–2070) under SSP1-2.6, SSP2-4.5, and SSP5-8.5.

Under present-day conditions, heat-stress exposure is concentrated in the warmest months of the football calendar. In Norway and England, WBGT 30 °C exceedances remain very limited or absent throughout most of the

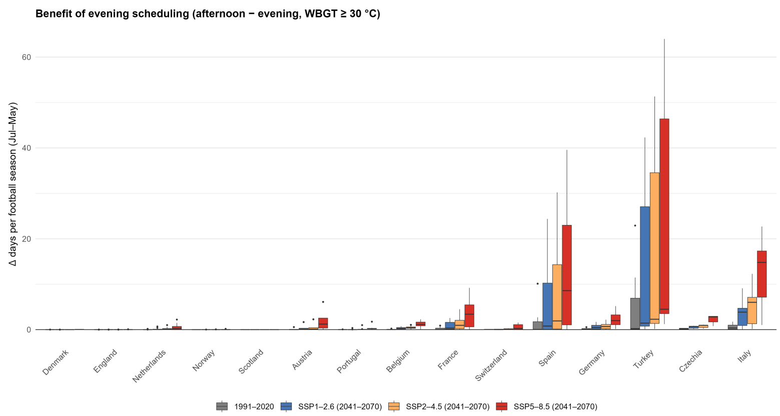


Figure 6: Country-level distributions of the reduction in cumulative heat-stress exposure achieved by evening scheduling, expressed as the difference in the number of WBGT 30 °C exceedance days between afternoon and evening conditions over the July to May football period. Results are derived from stadium locations only and compare the historical reference period (1991–2020) with mid-century projections (2041–2070) under SSP1-2.6, SSP2-4.5, and SSP5-8.5. Positive values indicate a benefit of evening scheduling.

season. Germany shows low exposure overall, with only sporadic exceedances during the warmest part of the calendar. By contrast, Italy and Spain already exhibit clear early-season exposure, especially in July and August, indicating that high heat stress is already relevant for southern European football venues during the opening phase of the season.

Future projections show both an intensification and a seasonal redistribution of heat-stress exposure. Under SSP1-2.6, changes remain limited in northern and western countries, while Italy and Spain show increased exceedances during the early-season months. Under SSP2-4.5, exposure becomes more pronounced and extends further into the football calendar, particularly in southern Europe. Under SSP5-8.5, the seasonal signal becomes much stronger, with high heat-stress exposure no longer confined to July and August. In Spain and Italy, exceedances extend into late-season months, including April and May, while Germany and England begin to show more visible exposure during months that are currently close to zero.

This redistribution is important because it reduces the number of thermally favourable windows within the existing football calendar. The problem is not only that peak summer months become hotter, but that high heat-stress conditions increasingly encroach on the margins of the season.

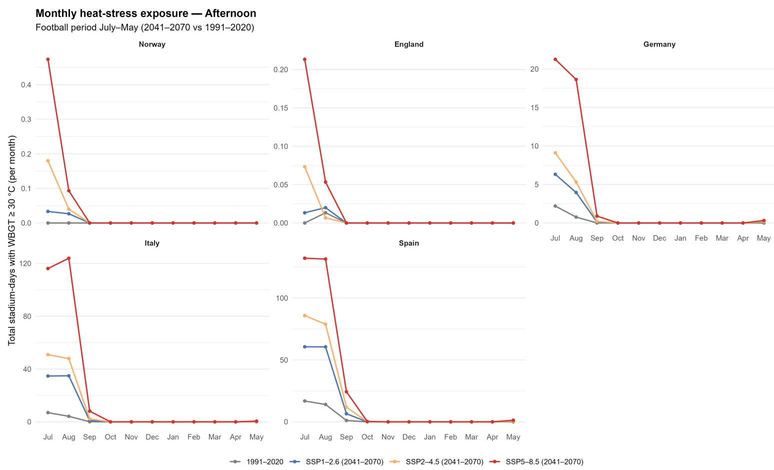


Figure 7: Monthly distribution of cumulative heat-stress exposure across professional football venues for selected European countries (Norway, England, Germany, Italy, and Spain), expressed as total stadium-days exceeding a WBGT threshold of 30 °C over the July to May football period. Results are shown for afternoon conditions and compare the historical reference period (1991–2020) with mid-century projections (2041–2070) under SSP1-2.6, SSP2-4.5, and SSP5-8.5.

Early-season matches become more exposed, and late-season matches that currently occur under relatively safe thermal conditions may also become affected under stronger warming.

These results indicate that adaptation strategies based only on shifting kick-off times are likely to face increasing limitations. Evening scheduling can reduce exposure on a given day, but it does not address the broader seasonal expansion of heat stress across the football period. As WBGT exceedances progressively spread into both the beginning and the end of the season, calendar-level adaptation may become relevant alongside operational measures such as later kick-off times, cooling breaks, hydration protocols, and stadium-level heat mitigation.

4. Discussion

4.1. Heat stress as an emerging structural constraint for European football

This study shows that heat stress, measured here with the Wet-Bulb Globe Temperature (WBGT), is no longer limited to isolated summer events. It increasingly overlaps with the regular July to May calendar of European professional football. WBGT exceedances already occur at a non-negligible number of venues under present-day conditions, and by mid-century (2041–2070) exposure intensifies and spreads across countries and thresholds, both under the central SSP2-4.5 scenario and under SSP5-8.5, which we treat as an upper bound.

The most severe threshold we examine, 32 °C, deserves particular attention because it is the level at which football heat guidelines call for the strongest measures, from mandatory cooling breaks to match postponement Bandiera et al. (2024); Racinais et al. (2023). Such conditions are still rare in European professional football today. Their emergence at southern venues under warming therefore signals where these interventions are likely to shift from an exceptional safeguard to a more routine part of match management.

Earlier WBGT assessments have concentrated on individual international tournaments, each held in a single host region over a few weeks, such as the African Cup of Nations Sawadogo et al. (2025) or the 2026 FIFA World Cup Hosokawa et al. (2018); Lindner-Cendrowska et al. (2024); Mullan et al. (2025). Our analysis instead examines the season-long exposure of the regular professional calendar across an entire continent. Read in this light, and in line with policy-oriented work arguing that climate change threatens the long-term viability of football governance and competition formats rather than representing a passing operational nuisance Orr et al. (2025), heat stress is best understood as an emerging structural constraint on European professional football.

For cities hosting professional football venues, this also means that heat risk is not confined to exceptional tournament events. It becomes embedded in the routine operation of urban sport infrastructure, affecting match scheduling, stadium management, player-protection protocols, and potentially the wider organisation of match-day services.

4.2. North–south gradient and geographical expansion of risk

Exposure follows a clear latitudinal gradient. Southern European venues accumulate the most WBGT exceedances, while northern and western venues show little exposure today but a distinct emergence of risk by mid-century. This pattern is consistent with evidence that anthropogenic warming is pushing dangerous heat into mid-latitude regions once considered thermally safe Raymond et al. (2020).

For football, the consequence is a gradual convergence of risk profiles across the continent. Southern leagues face heat that is more frequent and more intense, whereas northern leagues meet exposure regimes that are new to them, and for which current operational practices and player-protection protocols are poorly prepared. Similar conclusions have been drawn for other continental competitions, in particular the African Cup of Nations, where climatic constraints are narrowing the set of viable host regions and kick-off windows Sawadogo et al. (2025). At the 32 °C threshold the picture is more localised: exposure stays concentrated in southern Europe even at mid-century, so the conditions that demand the strongest interventions will first become a routine concern for southern venues.

4.3. Health relevance of WBGT thresholds and existing mitigation protocols

WBGT is a useful health indicator because it brings air temperature, humidity, and radiant load together into a single quantity closely tied to physiological strain (a fully instrumented measurement also accounts for wind). Consensus statements and applied football studies place WBGT values of roughly 28 to 32 °C in a range of progressively higher risk of heat exhaustion, heat illness, and impaired performance during intense activity Racinais et al. (2023); Hosokawa et al. (2018); Bandiera et al. (2024).

In football, these thresholds underpin the measures already in use: extra hydration and cooling breaks, longer half-time intervals, and, as a last resort, rescheduling or postponement. Reviews of football-specific guidance note that such measures lower acute risk but do not remove physiological strain when WBGT stays high for long periods Gouttebarge et al. (2023). The more frequent exceedances we project therefore imply growing reliance on in-match mitigation, with knock-on effects for match flow, competitive fairness, and cumulative player load.

4.4. Limits of timing-based adaptation: evening scheduling

Moving kick-off times into the evening is one of the most frequently proposed adaptations in professional football. Our results confirm that it substantially reduces WBGT exceedances today and stays beneficial at mid-century (Figure 6). The principle is well established: when activity is moved out of the mid-afternoon, when WBGT peaks, extreme-heat exposure can fall by roughly 90 % Grundstein et al. (2014).

The benefit weakens, however, as background temperatures rise. Warming shifts the whole WBGT distribution upward for both afternoon and evening conditions, so evening scheduling reduces exposure without eliminating it, and the first scattered evening exceedances of the 32 °C threshold appear at the hottest southern venues. This echoes tournament-scale analyses showing that, under sustained warming, scheduling changes alone cannot keep every venue and every match within safe limits Mullan et al. (2025); Lindner-Cendrowska et al. (2024). Evening scheduling thus slows, but does not stop, the spread of unsafe conditions through the season.

4.5. Seasonal redistribution and constraints on the football calendar

The monthly analysis points to a second, slower process: a seasonal redistribution of exposure. By mid-century, exceedances rise not only in the early-season months of July and August but also in April and May, leaving fewer thermally safe windows inside the existing calendar (Figure 7). Adaptation that acts only on kick-off times is increasingly hemmed in by this calendar-level exposure.

The calendar itself is not fixed, as the 2022 FIFA World Cup showed when it was moved from its usual June–July slot to November–December to avoid the summer heat, the first such shift in the tournament's history. Comparable pressure may build on domestic season boundaries, fixture density, and venue management. The same tension between warming and rigid seasonal structures has been reported for major tournaments Mullan et al. (2025); Sawadogo et al. (2025), and from a governance standpoint climate change challenges not just match timing but the long-term organisation of the European football calendar Orr et al. (2025).

4.6. Players versus spectators: an asymmetry of exposure and protection

Players are comparatively well protected, with medical oversight, heat-acclimatisation strategies, and threshold-based intervention protocols Racinais et al. (2023); Gouttebarge et al. (2023). Spectators are not. They are a heterogeneous population with long, passive exposure, limited freedom to move, and uneven vulnerability, including elderly people and those with chronic conditions. Direct epidemiological evidence for football crowds remains scarce, but studies of sports tourism at major events report substantial thermal-stress risk for attending audiences under future climates Craig and Karabas (2024).

This spectator dimension is central for sustainable city planning because match-day heat exposure extends beyond the pitch to queues, transport nodes, concourses, fan zones, and surrounding public spaces. The stadium's urban setting can further amplify this risk. Urban-climate research shows that evening and night-time heat stress can be increased by heat stored in built environments and by urban heat-island effects Huang et al. (2021); Tuholske et al. (2021), which are precisely the conditions of an evening match in a dense city. Because our WBGT values come from gridded climate data, they do not resolve this local amplification and probably understate what spectators actually experience. As warming continues, spectator heat risk may become as critical as player heat risk, even though players generate far more metabolic heat during play.

4.7. Methodological robustness and conservative risk estimates

Two features keep our estimates on the conservative side. First, the WBGT is reconstructed from daily fields, and the validation against hourly ERA5 (Figure 1) shows that this introduces a small afternoon cold bias (about $-0.70\,^{\circ}\mathrm{C}$ on warm days, RMSE $< 1\,^{\circ}\mathrm{C}$) which underestimates exceedance-days at the lower thresholds while remaining essentially unbiased at $32\,^{\circ}\mathrm{C}$. Because the bias is systematic, it largely cancels in period-to-period and scenario comparisons, so the increases and patterns we report hold even though the absolute counts are a lower bound. Second, the values are derived from gridded climate data at stadium locations and do not resolve microclimatic modifiers such as stadium geometry, crowd density, ventilation or surface materials, which urban-climate studies link to higher local heat stress, particularly on warm evenings when radiative cooling is limited Huang et al. (2021). Both effects point the same way: true in-stadium exposure is likely higher than reported here. The qualitative conclusions, namely rising exposure, the diminishing benefit of evening scheduling and the seasonal narrowing of safe windows, are therefore robust to these limitations.

4.8. Towards integrated adaptation strategies

Taken together, these results suggest that warming is turning heat stress into a structural constraint on European professional football. Evening scheduling remains a useful tool, but on its own it cannot offset the rise in exposure expected by mid-century, which is the central tension between the potential and the limits of timing-based adaptation. Managing heat will instead call for a combination of measures that reach beyond match timing: calendar design, stadium microclimate management, and health-protection protocols for players and spectators alike.

Such strategies should be understood as part of broader urban climate-adaptation planning, linking stadium design, shading, ventilation, public transport, emergency services, and event governance. This broader framing is important because football heat risk is not confined to the pitch: it also affects the urban systems that make match-day operations possible.

5. Conclusion

This study provides a health-focused, continental-scale assessment of present and future heat-stress exposure at European professional football venues, based on the Wet-Bulb Globe Temperature (WBGT) index, bias-corrected CMIP6 projections, and a stadium-resolved analysis of the full July–May calendar. We show that heat-stress conditions already occur during the current season, predominantly at southern venues, and that exposure intensifies and expands geographically by mid-century (2041–2070) under both the central SSP2–4.5 scenario and the high-emission SSP5–8.5 upper bound.

Afternoon conditions consistently carry higher exposure than evening conditions, confirming that timing-based adaptation such as later kick-off times is presently effective. However, this protective effect erodes under warming: evening WBGT exceedances emerge at the hottest southern venues by mid-century, and the most severe threshold (32 °C) (the level triggering mandatory cooling breaks or postponement in football) begins to appear where it is virtually absent today. Adjusting match timing alone is therefore unlikely to be sufficient to contain heat-related health risks.

The seasonal redistribution of exposure compounds this limitation. Rising exceedances at the start (July–August) and end (April–May) of the competition period narrow the thermally safe window within the existing calendar, so that calendar-level adaptation may become as relevant as daily scheduling. While such measures raise broader institutional questions, the climatic signal quantified here provides an objective basis for anticipatory, health-oriented planning.

Overall, heat stress is emerging as a recurrent and structurally embedded constraint on professional football in Europe rather than an occasional summer disruption. Integrating climate-exposure assessment into preventive strategies, spanning match scheduling, calendar design, stadium microclimate, and player- and spectator-protection protocols, will be essential to safeguard health in a warming climate, and the approach is readily transferable to other forms of intense outdoor physical activity.

Acknowledgements

The authors acknowledge the climate modelling groups participating in CMIP6 and the NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) initiative for providing access to bias-corrected climate projections. All analyses were conducted using open-source software on the authors' own computing resources.

Funding

This research received no external funding.

Conflict of interest

The authors declare that they have no competing interests.

Data availability

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

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

Author contributions

Conceptualization: D.D., T.L., **Methodology:** D.D., T.L., **Software:** D.D., **Formal analysis:** D.D., **Data curation:** D.D., **Validation:** D.D., **Visualization:** D.D., **Writing – original draft:** D.D. and **Writing – review & editing:** D.D., T.L.

Appendix A. Spatial distribution of heat-stress exposure at European football venues for SSP1-2.6

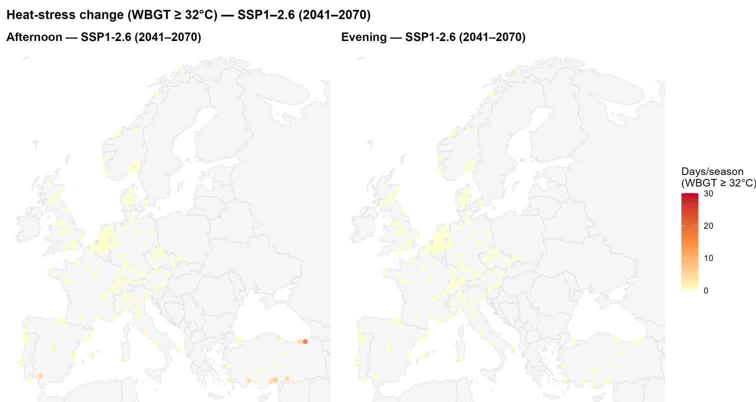


Figure A.1: Spatial distribution of cumulative heat-stress exposure at European professional football venues, expressed as the number of days per football season from July to May exceeding a WBGT threshold of 32 °C. Each point represents a stadium and no spatial interpolation is performed. The figures show at the left the afternoon conditions and at the right the evening conditions for SSP1-2.6 scenario at mid-century (2041–2070). Values represent multi-model ensemble means across five bias-corrected CMIP6 models.

References

Bandiera, D., Racinais, S., Garrandes, F., Adami, P.E., Bermon, S., Pitsiladis, Y.P., Tessitore, A., 2024. Heat-related risk at Paris 2024: a proposal for classification and review of International Federations policies. British Journal of Sports Medicine 58, 860–869. doi:10.1136/bjsports-2024-108310.

Budd, G.M., 2008. Wet-bulb globe temperature (WBGT): its history and its limitations. Journal of Science and Medicine in Sport 11, 20–32. doi:10.1016/j.jsams.2007.07.003.

Carmo, A.A.L., Souza-Junior, R.C.S., Ferretti, P.H.S., Gontijo, L.A., Prado, L.S., Teixeira-Coelho, F., Wanner, S.P., et al., 2026. Physical performance in elite male soccer under extreme heat: A case study of the 2025 fifa club world cup. Temperature 13, 71–87. doi:10.1080/23328940.2026.2623745.

Casa, D.J., DeMartini, J.K., Bergeron, M.F., Csillan, D., Eichner, E.R., Lopez, R.M., Ferrara, M.S., Miller, K.C., O'Connor, F., Sawka, M.N., Yeargin, S.W., 2015. National athletic trainers' association position statement: Exertional heat illnesses. Journal of Athletic Training 50, 986–1000. doi:10.4085/1062-6050-50.9.07.

Craig, C., Karabas, I., 2024. Forecasting thermal stress for sports tourists at the 2026 FIFA World Cup. International Journal of Biometeorology 68, 2731–2742. doi:10.1007/s00484-024-02785-4.

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 & Exercise Medicine 9, e001608. doi:10.1136/bmjsem-2023-001608.

Grundstein, A., Cooper, E., Ferrara, M., Knox, J.A., 2014. The geography of extreme heat hazards for American football players. Applied Geography 46, 53–60. doi:10.1016/j.apgeog.2013.10.007.

Hajizadeh, R., Farhang Dehghan, S., Golbabaei, F., Jafari, S.M., Karajizadeh, M., 2017. Offering a model for estimating black globe temperature according to meteorological measurements. Meteorological Applications 24, 303–307. doi:10.1002/met.1631.

Hersbach, H., Bell, B., Berrisford, P., et al., 2020. The ERA5 global reanalysis. Quarterly Journal of the Royal Meteorological Society 146, 1999–2049. doi:10.1002/qj.3803.

Hosokawa, Y., Grundstein, A., Casa, D.J., 2019. Activity modification in heat: critical assessment of guidelines across athletic, occupational, and military settings in the USA. International Journal of Biometeorology 63, 405–427. doi:10.1007/s00484-019-01673-6.

Hosokawa, Y., Grundstein, A.J., Casa, D.J., 2018. Extreme heat considerations in international football venues: the utility of climatologic data in decision making. Journal of Athletic Training 53, 860–865. doi:10.4085/1062-6050-361-17.

Huang, K., Lee, X., Stone Jr., B., Knievel, J., Bell, M.L., Seto, K.C., 2021. Persistent increases in nighttime heat stress from urban expansion despite heat island mitigation. Journal of Geophysical Research: Atmospheres 126, e2020JD033831. doi:10.1029/2020JD033831.

International Organization for Standardization, 2017. Ergonomics of the thermal environment: Assessment of heat stress using the WBGT (wet bulb globe temperature) index. ISO 7243:2017.

IPCC, 2023. Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland. doi:10.59327/IPCC/AR6-9789291691647.

Jacklitsch, B., Williams, W.J., Musolin, K., Coca, A., Kim, J.H., Turner, N., 2016. Criteria for a Recommended Standard: Occupational Exposure to Heat and Hot Environments. Technical Report DHHS (NIOSH) Publication No. 2016-106. National Institute for Occupational Safety and Health. Cincinnati, OH. doi:10.26616/NIOSHPUB2016106.

Lange, S., 2019. Trend-preserving bias adjustment and statistical downscaling with ISIMIP3BASD (v1.0). Geoscientific Model Development 12, 3055–3070. doi:10.5194/gmd-12-3055-2019.

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. Scientific Reports 14, 26976. doi:10.1038/s41598-024-77540-1.

Mora, C., Dousset, B., Caldwell, I.R., Powell, F.E., Geronimo, R.C., Bielecki, C.R., Counsell, C.W.W., Dietrich, B.S., Johnston, E.T., Louis, L.V., Lucas, M.P., McKenzie, M.M., Shea, A.G., Tseng, H., Giambelluca, T.W., Leon, L.R., Hawkins, E., Trauernicht, C., 2017. Global risk of deadly heat. Nature Climate Change 7, 501–506. doi:10.1038/nclimate3322.

Mullan, D., Barr, I., Brannigan, N., Flood, N., Gibson, O.R., Hambly, C., Kennedy-Asser, A.T., Kielt, A.C., Matthews, T., Orr, M., et al., 2025. Extreme heat risk and the potential implications for the scheduling of football matches at the 2026 FIFA World Cup. International Journal of Biometeorology 69, 753–763. doi:10.1007/s00484-025-02852-4.

Nassis, G.P., Brito, J., Dvorak, J., Chalabi, H., Racinais, S., 2015. The association of environmental heat stress with performance: analysis of the 2014 fifa world cup brazil. British Journal of Sports Medicine 49, 609–613. doi:10.1136/bjsports-2014-094449.

Nybo, L., Rasmussen, P., Sawka, M.N., 2014. Performance in the heat: physiological factors of importance for hyperthermia-induced fatigue. Comprehensive Physiology 4, 657–689. doi:10.1002/cphy.c130012.

Orr, M., Inoue, Y., 2019. Sport versus climate: Introducing the climate vulnerability of sport organizations framework. Sport Management Review 22, 452–463. doi:10.1016/j.smr.2018.09.007.

Orr, M., Inoue, Y., Seymour, R., Dingle, G., 2022. Impacts of climate change on organized sport: A scoping review. WIREs Climate Change 13, e760. doi:10.1002/wcc.760.

Orr, M., Murfree, J.R., Ross, W.J., 2025. Football on the frontlines: the unjust burden of the climate crisis on pacific island nations. Leisure Studies 1, 1–16. doi:10.1080/02614367.2025.2490547.

Parton, W.J., Logan, J.A., 1981. A model for diurnal variation in soil and air temperature. Agricultural Meteorology 23, 205–216. doi:10.1016/0002-1571(81)90105-9.

Perkins-Kirkpatrick, S.E., Lewis, S.C., 2020. Increasing trends in regional heatwaves. Nature Communications 11, 3357. doi:10.1038/s41467-020-16970-7.

Racinais, S., Hosokawa, Y., Akama, T., Bermon, S., Bigard, X., Casa, D.J., Grundstein, A., Jay, O., Massey, A., Migliorini, S., Mountjoy, M., et al., 2023. IOC consensus statement on recommendations and regulations for sport events in the heat. British Journal of Sports Medicine 57, 8–25. doi:10.1136/bjsports-2022-105942.

Raymond, C., Matthews, T., Horton, R.M., 2020. The emergence of heat and humidity too severe for human tolerance. Science Advances 6, eaaw1838. doi:10.1126/sciadv.aaw1838.

Sawadogo, W., Bliefernicht, J., Faye, A., Kunstmann, H., 2025. Where should sports events be held under global warming? A case study of the African Cup of Nations. Sustainable Cities and Society 119, 106091. doi:10.1016/j.scs.2024.106091.

Schneider, S., Mücke, H.G., 2024. Sport and climate change: how will climate change affect sport? German Journal of Exercise and Sport Research 54, 12–20. doi:10.1007/s12662-021-00786-8.

Schwarz, E., Duffield, R., Novak, A.R., Görres, T., Meyer, T., 2025. Associations between match running performance and environmental temperatures in 4 professional football leagues. International Journal of Sports Physiology and Performance 20, 109–119. doi:10.1123/ijspp.2024-0248.

Stull, R., 2011. Wet-bulb temperature from relative humidity and air temperature. Journal of Applied Meteorology and Climatology 50, 2267–2269. doi:10.1175/JAMC-D-11-0143.1.

Thrasher, B., Wang, W., Michaelis, A., Melton, F., Lee, T., Nemani, R., 2022. NASA global daily downscaled projections, CMIP6. Scientific Data 9, 262. doi:10.1038/s41597-022-01393-4.

Tuholske, C., Caylor, K., Funk, C., Verdin, A., Sweeney, S., Grace, K., Peterson, P., Evans, T., 2021. Global urban population exposure to extreme heat. Proceedings of the National Academy of Sciences 118, e2024792118. doi:10.1073/pnas.2024792118.