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Observed warming is shrinking favourable daylight windows for outdoor recreation: evidence from sports facilities across France

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Abstract

Observed warming is changing not only the severity of heat exposure during outdoor recreation, but also the time of day when thermally favourable conditions remain available. We quantify this emerging temporal constraint across metropolitan France from 1991 to 2025 by combining hourly ERA5-Land meteorology, Wet-Bulb Globe Temperature (WBGT), solar geometry and the national Data ES inventory of 226,516 outdoor sports facilities. We define favourable daylight hours as those simultaneously below a WBGT threshold of 28 °C and within civil twilight, and assess trends using Theil–Sen slopes and Mann–Kendall tests. Favourable daylight time declined or remained unchanged across the entire warm-season grid, with the strongest contractions in southern and south-western France and during summer afternoons. In Mediterranean France, the largest recent declines occurred around 14:00–17:00 local time, progressively shifting favourable conditions towards the cooler margins of the day. Regional exposure was highly uneven: more than 60% of outdoor facilities in Nouvelle-Aquitaine and Occitanie were located in highly exposed cells. Current lighting only partly offsets this constraint, leaving substantial shares of highly exposed facilities unlit. Differences among sports largely reflected the geography of facility provision rather than intrinsic thermal sensitivity. These results show that climate change is reducing the temporal accessibility of outdoor recreation and that adaptation capacity is spatially uneven. Incorporating time-of-day into recreation

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planning could help identify where rescheduling, shading, modified opening hours or targeted infrastructure adaptation are most needed.

Keywords: outdoor recreation, climate change, WBGT, daylight, sports facilities, temporal accessibility

1. Introduction

Outdoor recreation and sport are inherently exposed to weather and climate because participation, comfort, safety and the organisation of activities depend on environmental conditions at the time and place where they occur. Weather has long been shown to influence leisure behaviour and participation in outdoor activities (Spinney and Millward, 2011), while recent research has increasingly focused on the consequences of extreme heat for sport and physical activity. Heat stress can affect athlete safety and performance, alter the conditions under which training and competition can be undertaken, and create additional constraints for organisers and facility managers (Racinais et al., 2015; Brocherie et al., 2015). Wet-bulb globe temperature (WBGT), which integrates key meteorological controls on human heat stress, has therefore become widely used in sport heat-safety guidance and environmental assessments. Spatial analyses have shown that WBGT-based risk varies substantially among climatic regions (Grundstein et al., 2015), and climate-change studies indicate that exceedance of heat-safety thresholds is becoming more frequent and geographically widespread (Grundstein et al., 2013). More recent global assessments further suggest that climatic constraints on outdoor sport may increasingly affect not only the warmest part of the day but also morning and evening activity periods (Defrance and Lescure, 2026). These developments raise an important recreation-planning question: as hot conditions increasingly constrain daytime activity, when during the day do favourable opportunities for outdoor participation remain?

Changing the timing of activity is already recognised as one of the most immediate ways to reduce heat exposure. Empirical and modelling studies demonstrate strong within-day variations in thermal conditions and show that training sessions, matches or events scheduled at different hours can experience substantially different levels of heat stress. For example, shifting school-sport practices away from high-risk periods can reduce exposure to hazardous WBGT conditions (Grundstein et al., 2023), while recent analyses of the 2026 FIFA World Cup show that heat exposure can be highly sensitive to kickoff time (Quagraine et al., 2026; Mullan et al., 2025). Similar conclusions emerge from thermal-comfort assessments of sports facilities, where avoiding peak heat periods is proposed alongside physical design measures as an adaptation option (Guo and Sun, 2024). Such evidence establishes scheduling as a practical adaptation lever. However, a thermally favourable hour is not necessarily an equally usable hour for outdoor recreation. Moving activity towards the edges of the day increasingly intersects with another fundamental environmental constraint: the availability of natural light.

Daylight can influence when outdoor physical and recreational activities take place. Studies of children's activity have reported differences in participation between shorter and longer daylight conditions and particularly during the late afternoon and evening (Goodman et al., 2012). Multi-country evidence has likewise examined additional evening daylight as a potential influence on objectively measured physical activity (Goodman et al., 2014). In nature-based recreation, meteorological conditions and daylight have been associated with the amount of recreational physical activity undertaken during leisure visits (Elliott et al., 2019). These relationships should not be interpreted as universal: a natural-experiment analysis of daylight-saving time, for example, found no general increase in moderate-to-vigorous physical activity (Zick, 2014). Nevertheless, the literature demonstrates that daylight availability can shape the timing and usability of outdoor leisure opportunities. This creates a potentially important interaction under climate warming: adaptation to hotter daytime conditions may favour earlier or later activity, while the same temporal shift progressively approaches hours with insufficient natural light.

Infrastructure can partly mediate this constraint. Artificial lighting enables some recreation to continue after sunset and therefore provides a form of temporal flexibility. Illuminated ski slopes, for instance, support distinctive patterns of evening recreational use (Zemla and BoLoz, 2022), while studies of nighttime recreation show that lighting conditions influence perceived safety and the quality of outdoor use (Himschoot et al., 2024). Yet the sports-lighting literature has largely addressed engineering performance, energy use, visual conditions and light pollution rather than climate adaptation (Kim and Kim, 2021). Moreover, infrastructure is not distributed uniformly in space. The geography of sports provision has long revealed differences among facility types and territories (Ahlfeldt and Feddersen, 2010), and recent GIS-based studies continue to document marked spatial inequalities in facility accessibility and provision (Li et al., 2025; Gong et al., 2025). Consequently, the capacity to shift outdoor activity into cooler but darker hours may also be geographically uneven.

These strands of research have mostly addressed heat exposure, activity scheduling, daylight availability, artificial lighting and sports-facility geography separately. Their combined implications for the *temporal accessibility* of outdoor recreation under a warming climate remain poorly quantified. Here, we define a favourable daylight window as the hours that are simultaneously thermally favourable for outdoor activity and naturally illuminated. We examine how this window changed across metropolitan France from 1991 to 2025 using hourly ERA5-Land meteorological data, solar geometry and the national Data ES inventory of outdoor sports facilities. We address three questions: (1) has the number and timing of thermally favourable hours occurring under natural daylight changed since 1991; (2) where has this contraction been strongest, and are favourable conditions increasingly displaced towards hours outside the natural-light window; and (3) how do these emerging temporal constraints intersect with the current geography, lighting status and activity profile of outdoor sports facilities? By linking climatic change to the timing and spatial distribution of recreation opportunities, the analysis aims to provide information directly relevant to facility managers, recreation planners and policymakers considering adaptation to increasingly hot outdoor conditions.

2. Materials and methods

2.1. Study design and analytical framework

The analysis covered metropolitan France over 1991–2025 on the 0.1° ERA5-Land grid (longitude −5.5° to 10.0°E; latitude 41.0° to 51.5°N). The central quantity was the amount of time during which outdoor activity was simultaneously thermally favourable and compatible with natural daylight (Fig. 1). The main analysis focused on May–September (MJJAS), when heat is most likely to constrain outdoor activity in France, and considered local hours from 06:00 to 23:00. April–October (AMJJASO) was retained as a seasonal sensitivity test.

At each grid cell and hour, two binary conditions were evaluated: thermal favourability, defined from Wet-Bulb Globe Temperature (WBGT), and natural-light availability, defined from solar elevation. Their intersection provided hourly counts of favourable daylight conditions. Favourable hours occurring outside the natural-light window were retained separately to quan-

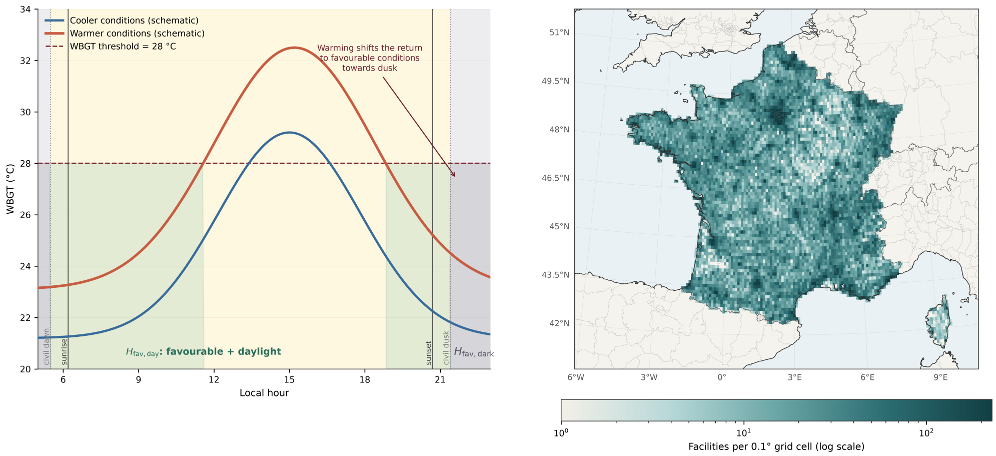

Figure 1: Conceptual framework and study infrastructure. (a) Schematic illustration of the interaction between the diurnal WBGT cycle and the natural-light window. Warming can delay the return to thermally favourable conditions until hours with little or no natural light. (b) Spatial density of outdoor sports facilities from the French Data ES inventory used in the analysis. Panel (a) is conceptual and does not represent a specific observed day.

tify the extent to which thermally suitable conditions were displaced towards darker hours. Climate metrics were then aggregated annually, analysed for monotonic trends over the full 35-year period, and intersected with the present-day national inventory of outdoor sports facilities.

2.2. Hourly ERA5-Land meteorological data

Hourly meteorological fields were obtained from ERA5-Land, the land component of the ERA5 reanalysis (Muñoz-Sabater et al., 2021), retrieved from the Copernicus Climate Data Store (Muñoz Sabater, 2019). We used 2-m air temperature, 2-m dew-point temperature and surface solar radiation downwards (SSRD) for every month from April to October and every year from 1991 to 2025. The native hourly fields were extracted on a regular 0.1° grid over metropolitan France. Timestamps were converted to Europe/Paris local time before hourly aggregation.

Air and dew-point temperatures were converted from K to °C. ERA5-Land SSRD is stored as accumulated energy ($\mathrm{J\,m^{-2}}$) that resets daily at 00:00 UTC; consecutive accumulations were therefore differenced on the native UTC calendar to recover hourly increments, negative increments were set to zero, and the resulting hourly energy was divided by 3600 to obtain a mean radiative flux in $\mathrm{W\,m^{-2}}$. Timestamps were converted to Europe/Paris local time only after this de-accumulation, for the subsequent hourly binning.

2.3. Hourly WBGT reconstruction

Relative humidity (RH, %) was estimated from air temperature (T_a) and dew-point temperature (T_d) using saturation vapour pressure:

$$e_s(T) = 6.112 \exp\left(\frac{17.67T}{T + 243.5}\right), \tag{1}$$

and

$$RH = 100\frac{e_s(T_d)}{e_s(T_a)}. \tag{2}$$

Values were constrained to the physically meaningful range before subsequent calculations.

wet-bulb temperature (T_w), used here as a proxy for the natural wet-bulb temperature, was estimated using the analytical approximation of Stull (2011):

$$\begin{aligned} T_w = {} & T_a \tan^{-1}\left[0.151977(RH + 8.313659)^{1/2}\right] \\ & + \tan^{-1}(T_a + RH) - \tan^{-1}(RH - 1.676331) \\ & + 0.00391838 RH^{3/2} \tan^{-1}(0.023101 RH) - 4.686035. \end{aligned} \tag{3}$$

Because black-globe temperature is not directly available from ERA5-Land, it was estimated from hourly shortwave radiation, air temperature and relative humidity using the empirical regression of Hajizadeh et al. (2017):

$$T_g = 0.01498R_s + 1.184T_a - 0.0789RH - 2.739, \tag{4}$$

where R_s is downward shortwave radiation in $\mathrm{W\,m^{-2}}$. Outdoor WBGT was then calculated as

$$WBGT = 0.7T_w + 0.2T_g + 0.1T_a. \tag{5}$$

This formulation is used here as an environmental outdoor heat-stress proxy rather than as a complete physiological model. In particular, T_g is reconstructed from an empirical meteorological regression rather than from a full radiative–convective globe energy balance. The main analysis defined an hour as thermally favourable when $WBGT < 28$°C. The 28°C value was treated as an operational analytical threshold, not as a universal safety limit for all activities or participants. Sensitivity analyses repeated the trend calculation at 26, 30 and 32°C.

2.4. Solar elevation and definition of natural daylight

Solar elevation was calculated for each hourly timestamp and grid cell from astronomical solar geometry using latitude, longitude and time. The main analysis defined natural-light availability using civil twilight: an hour was classified as naturally illuminated when geometric solar elevation was at least -6°, and as dark when solar elevation was below -6°. This definition includes twilight periods in which outdoor visibility can remain possible without artificial lighting.

For the hour-by-month diagnostics, mean local sunrise and sunset (0° solar elevation) and civil dawn and dusk (-6°) were calculated for each grid cell and month. The probability of thermally favourable conditions at a given local hour was

$$P_{\mathrm{fav}}(h) = \frac{n_{\mathrm{fav,day}}(h) + n_{\mathrm{fav,dark}}(h)}{n_{\mathrm{tot}}(h)}, \tag{6}$$

where the numerator counts all hours below the WBGT threshold irrespective of light status. This diagnostic separates the evolution of the thermal cycle from the astronomical light window.

2.5. Temporal-accessibility metrics

For each year, month, grid cell and WBGT threshold, the hourly classifications were accumulated as (i) favourable daylight hours ($n_{\mathrm{fav,day}}$), (ii) favourable dark hours ($n_{\mathrm{fav,dark}}$), and (iii) all available hours. Seasonal mean favourable daylight hours per day were calculated as

$$H_{\mathrm{fav,day}} = \frac{\sum_{m,h} n_{\mathrm{fav,day}}(m,h)}{\sum_{m} N_{\mathrm{days}}(m)}, \tag{7}$$

with the same definition used for $H_{\mathrm{fav,dark}}$. Total thermally favourable time was

$$H_{\mathrm{fav,tot}} = H_{\mathrm{fav,day}} + H_{\mathrm{fav,dark}}. \tag{8}$$

To describe the increasing importance of favourable conditions occurring outside the natural-light window, we defined a Lighting Dependency metric:

$$LD = 100 \times \frac{H_{\mathrm{fav,dark}}}{H_{\mathrm{fav,tot}}}. \tag{9}$$

LD is therefore a climatic timing indicator rather than a measure of actual electricity use or observed behavioural dependence on lighting. An increase in LD indicates that a greater fraction of thermally favourable time occurs during hours classified as dark.

2.6. Trend and period analyses

Annual MJJAS values of $H_{\mathrm{fav,day}}$ and LD were analysed independently at each grid cell over 1991–2025. Trend magnitude was estimated using the Theil–Sen median slope (Sen, 1968), and significance was assessed using a Mann–Kendall-type monotonic trend test implemented as Kendall's rank correlation against time (Mann, 1945). At least 80% of annual values were required for a grid-cell trend. Statistical significance was defined at $p < 0.05$. $H_{\mathrm{fav,day}}$ slopes were expressed as minutes day^{-1} decade^{-1} and LD slopes as percentage points decade^{-1}.

To visualise changes in the diurnal structure independently of the trend estimator, hourly probabilities were also compared between 1991–2000 and 2016–2025. The main diagnostic focused on Mediterranean France (1°W–7.5°E, 42.0°–44.5°N), averaging only valid metropolitan land cells. Supplementary analyses repeated this comparison for northern, central and Mediterranean latitude bands.

2.7. Outdoor sports facilities and current lighting status

Sports infrastructure was characterised using the complete Data ES national inventory maintained by the French Ministry responsible for sports (Ministère chargé des Sports, 2026). The database provides geolocated equipment-level information including facility type, activities practised, region and whether the activity area is equipped with lighting. We used the current snapshot available for the study rather than a historical time series.

Records with invalid coordinates or region labels inconsistent with metropolitan France were removed. To avoid mixing open-air facilities with covered structures, the main analysis applied a strict outdoor classification retaining equipment explicitly identified as *découvert*, *site naturel*, or *site naturel aménagé*; "extérieur couvert" facilities were excluded. The resulting analytical sample contained 226,516 outdoor facilities across the 13 metropolitan regions. In Data ES, lighting of the activity area is recorded as a complete Boolean field: every facility in the analytical sample carried a lit or unlit value, and no record required an "unknown" category (0 of 226,516). In this snapshot, 65,001 outdoor facilities (28.7%) were recorded as lit and 161,515 (71.3%) as unlit. As a declarative inventory field, an "unlit" value denotes the absence of a recorded lighting installation rather than an independently audited one.

Each facility was assigned the climatic trend of its nearest 0.1° grid cell. Because Data ES describes present-day infrastructure, lighting is interpreted only as a proxy for *current potential temporal flexibility*: the analysis does not infer that lighting was installed in response to climate warming, nor that a lit facility is necessarily available for unrestricted nighttime use.

2.8. Regional exposure and high-exposure classification

Regional distributions were calculated by sampling the $H_{\text{fav,day}}$ trend at every outdoor facility. These distributions are therefore facility-weighted descriptions of the climatic trend experienced by the present-day infrastructure network, rather than population-weighted regional climate statistics.

For the lighting analysis, "high exposure" was defined from climatic cells rather than from the number of facilities. First, unique $0.1°$ grid cells containing at least one outdoor facility were identified. The loss rate, $-\,\text{slope}(H_{\text{fav,day}})$, was calculated for each occupied cell, and the 80th percentile of this cell distribution was used as the high-exposure threshold. This prevented dense urban areas with many co-located facilities from determining the threshold disproportionately. The resulting threshold was 1.4 min day^{-1} decade^{-1}. Facilities located in cells at or above this value were then classified as highly exposed, and regional shares were separated by current lighting status.

2.9. Sport-specific geography and exposure

Sport-specific analyses used the activity descriptions recorded in Data ES. Facilities were assigned to broad activity groups using keyword matching for football, tennis, rugby, basketball, handball, pétanque and equestrian activities; only groups represented by at least 300 facilities were retained. A multi-activity facility could belong to more than one category, so counts across sports are not additive.

To distinguish climatic exposure from the geography of facility provision, we calculated a regional location quotient for each sport:

$$LQ_{s,r} = \frac{N_{s,r}/N_s}{N_{\text{all},r}/N_{\text{all}}}, \tag{10}$$

where $N_{s,r}$ is the number of facilities for sport s in region r, N_s the national number for that sport, $N_{\text{all},r}$ all outdoor facilities in the region, and N_{all} the national outdoor total. $LQ > 1$ denotes regional over-representation relative to the national facility network. We then compared (i) sport-specific location quotients, (ii) facility-level distributions of $H_{\text{fav,day}}$ trends, and (iii) the share of highly exposed facilities by lighting status.

2.10. Sensitivity and robustness analyses

Four complementary checks were used to assess whether the main spatial pattern depended on analytical choices. First, $H_{\mathrm{fav,day}}$ trends were recalculated for WBGT thresholds of 26, 28, 30 and 32°C (Fig. S1). Second, the main MJJAS season was compared with AMJJASO (Fig. S2). Third, the natural-light definition was recomputed directly from the original hourly ERA5-Land fields using geometric sunrise/sunset (0° solar elevation) instead of civil twilight ($-6°$), preserving the exact hourly covariance between WBGT and solar elevation (Fig. S3). Finally, significance maps and north–centre–Mediterranean hour-by-month diagnostics were used to evaluate the spatial coherence of the trends (Figs. S4 and S5).

3. Results

3.1. The favourable thermal window contracted during the warm-season afternoon

The clearest change appeared in the middle of the day, during the hours when summer heat weighs most heavily on outdoor activity. Across Mediterranean France, conditions below the 28°C WBGT threshold were still the rule through almost every daytime hour and every warm-season month in 1991–2000. By 2016–2025 that picture had shifted. Favourable conditions had become noticeably rarer from around midday into the late afternoon, and the change was sharpest in July and August (Fig. 2). The largest drops in the hourly probability of a favourable hour fell between roughly 14:00 and 17:00 local time in midsummer, where individual difference classes reached about -0.04 to -0.06. Early morning and late evening barely moved. What emerges is a hollowing-out of the central part of the day rather than a uniform decline, so that the cooler edges of the day are left carrying a growing share of the usable window.

This afternoon signal is a southern one. Repeating the hour-by-month comparison separately for northern, central and Mediterranean latitude bands shows almost no change in the north, a modest mid-afternoon loss in the centre, and the strong, temporally focused summer-afternoon contraction in the Mediterranean band (Fig. S5). Taken together the three bands make plain that the national picture is driven by what happens in the south during the hottest hours, and that it is the timing of the loss, not only its size, that tightens the window.

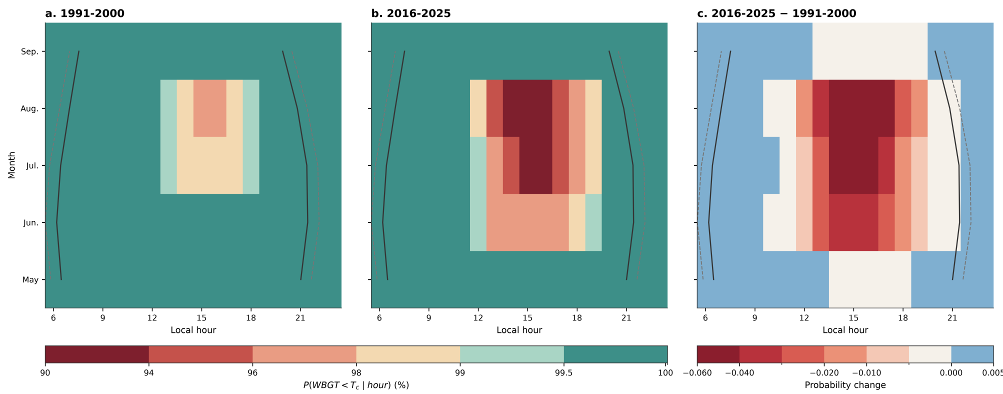

Figure 2: Hour-by-month evolution of thermally favourable conditions in Mediterranean France. The panels show $P(WBGT < 28°\text{C} \mid h)$ for 1991–2000 and 2016–2025 and their difference, with mean sunrise/sunset and civil-twilight limits superimposed. Probabilities are averaged over valid metropolitan land cells within the Mediterranean analysis domain.

3.2. The daylight-compatible window declined most strongly in southern and western France

Accumulated into a seasonal total, the hourly changes translate into a spatially coherent contraction of favourable daylight time over 1991–2025 (Fig. 3). The Theil–Sen slopes of $H_{\text{fav,day}}$ were non-positive everywhere on the MJJAS grid: not a single cell gained favourable daylight hours. The heaviest losses formed a broad southern arc running from the Mediterranean coast across to the Atlantic south-west, with local rates beyond 6 min day^{-1} decade^{-1} and passing 10 min day^{-1} decade^{-1} in the worst-affected cells. Much of the north and north-east stayed close to zero at the 28°C threshold. The monotonic-trend test confirms that this is more than noise: the significant cells (Fig. S4) trace the same southern arc, while the near-zero northern trends are, as one would expect, mostly non-significant.

The contraction was not only a matter of losing daytime hours. In those same southern regions the fraction of favourable time falling outside the natural-light window, our Lighting Dependency metric, tended to rise (Fig. 3b), even though its absolute magnitude remained small. Where the daytime window shrank most, a slightly larger part of what survived was pushed towards hours in which natural light is limited. Warming did two things at once in the south, then: it lowered the favourable daytime total, and it edged the remaining opportunity towards the darker margins of the day, where artificial lighting starts to become the relevant question rather

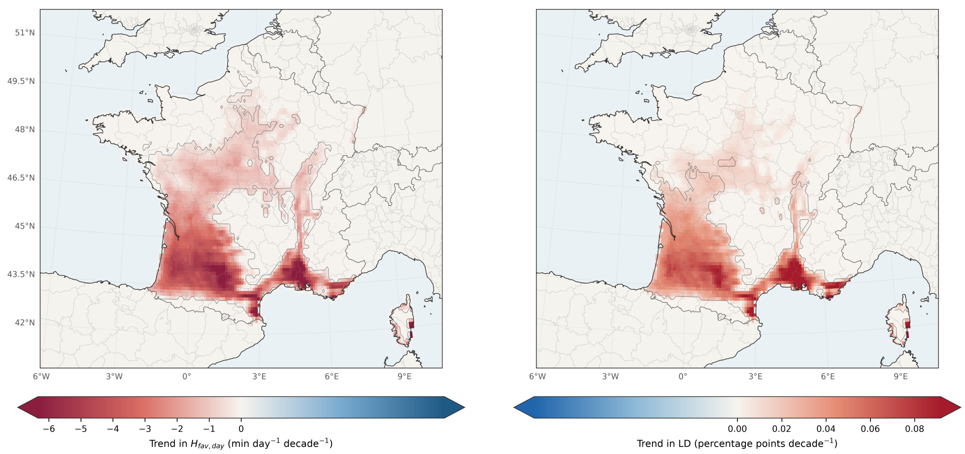

Figure 3: Observed 1991–2025 trends in temporal accessibility during MJJAS. (a) Theil–Sen trend in favourable daylight hours, $H_{\mathrm{fav,day}}$, expressed as min day^{-1} decade^{-1}. (b) Trend in Lighting Dependency (LD), expressed as percentage points decade^{-1}. Thin contours delimit areas with a significant monotonic trend ($p < 0.05$).

than an afterthought.

3.3. Present-day sports facilities face strongly unequal regional exposure

To connect this climatic change to the places where people actually play, we sampled the $H_{\mathrm{fav,day}}$ trend at each of the 226,516 outdoor facilities in the Data ES inventory. The inventory is itself uneven in ways worth holding in view (Fig. S6). Facility counts are highest in Auvergne-Rhône-Alpes, Occitanie and Nouvelle-Aquitaine; the lighting field is close to complete, so that lit and unlit shares can be read directly rather than inferred; and a small number of activity families, large multi-sport grounds, tennis courts, boules pitches and city-stadia, make up most of the outdoor total.

Sampling the trend across this network brought out sharp regional inequalities (Fig. 4). The facility-weighted national median was a modest -0.2 min day^{-1} decade^{-1}, but that single figure hides most of the story. Occitanie carried the largest median contraction at -2.7 min day^{-1} decade^{-1}, followed by Nouvelle-Aquitaine at -2.0, Centre-Val de Loire at -1.1, Île-de-France at -0.8 and Provence-Alpes-Côte d'Azur at -0.7. Provence-Alpes-Côte d'Azur is a revealing case. Its median is only moderately negative, yet its distribution trails a long lower tail, the signature of strong sub-regional hotspots sitting

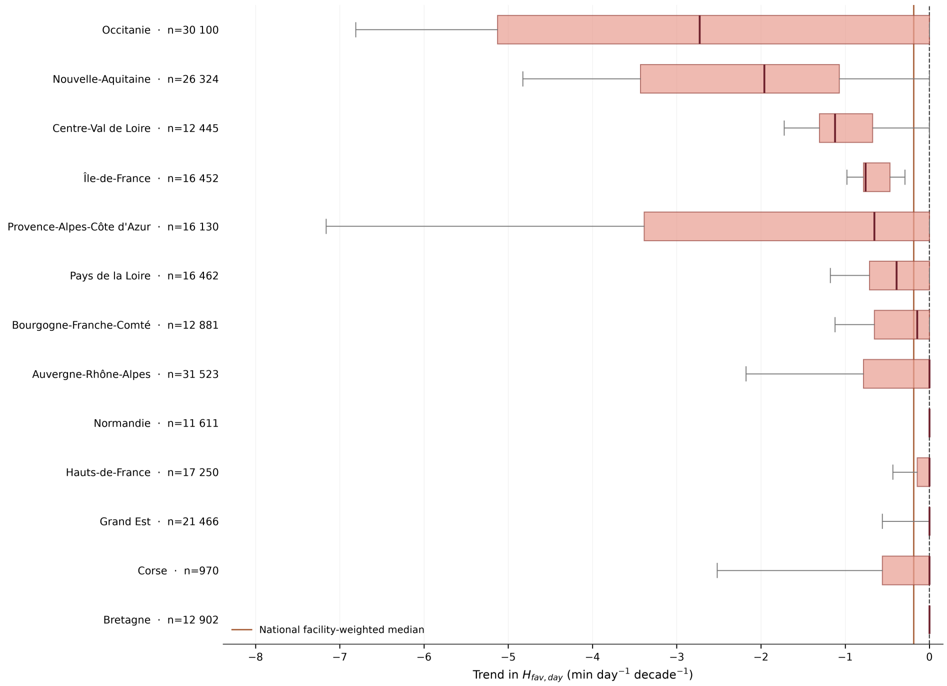

Figure 4: Distribution of the 1991–2025 $H_{\mathrm{fav,day}}$ trend sampled at outdoor sports facilities in each metropolitan region. Boxes show the interquartile range, centre lines the median, and whiskers the 5th–95th percentiles. Each observation is one Data ES facility; therefore, the distributions describe the exposure of the current facility network.

inside an otherwise mixed region. Across much of the northern, eastern and Atlantic regions the median facility barely moved at all.

3.4. High-exposure facilities are concentrated where current lighting capacity is incomplete

Regional medians describe the typical facility, but adaptation planning turns on the tail, on the facilities sitting in the cells that are losing time fastest. We defined high exposure from the climate grid rather than from facility counts, taking the 80th percentile of the per-cell loss rate among occupied cells, which fell at 1.4 min day^{-1} decade^{-1}, and flagging every facility in a cell at or above that value. Anchoring the threshold in the climate field this way keeps dense cities, where many facilities share a single grid cell, from setting it on their own.

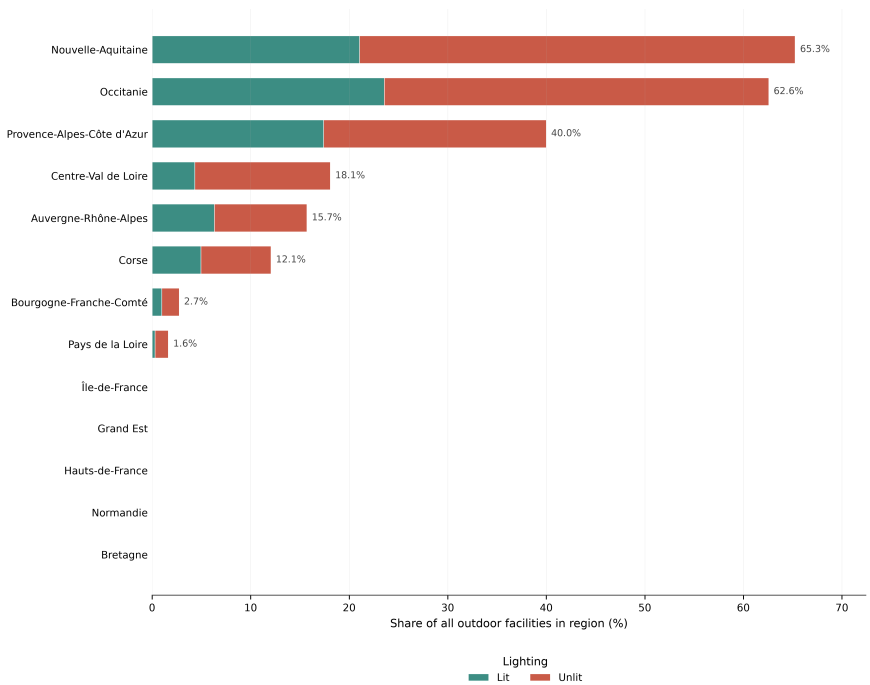

Figure 5: Share of outdoor sports facilities classified as highly exposed to contraction of favourable daylight time, separated by current lighting status and region. High exposure is defined as a loss of at least 1.4 min day^{-1} decade^{-1}, corresponding to the 80th percentile among occupied climate grid cells. Percentages use all outdoor facilities in each region as the denominator.

On this definition the high-exposure share is strikingly concentrated (Fig. 5). Nouvelle-Aquitaine leads, with 65.3% of its outdoor facilities in high-exposure cells, followed by Occitanie at 62.6% and Provence-Alpes-Côte d'Azur at 40.0%. A second tier of Centre-Val de Loire (18.1%), Auvergne-Rhône-Alpes (15.7%) and Corse (12.1%) trails well behind. Current lighting overlaps this exposure only in part, and the gap is exactly the point. In Nouvelle-Aquitaine, 44.2% of all outdoor facilities were both highly exposed and unlit, against 21.0% highly exposed and lit; the same imbalance recurs in Occitanie (39.0% versus 23.5%) and Provence-Alpes-Côte d'Azur (22.6% versus 17.4%). These figures make no claim about whether adaptation has taken place. What they mark out is where the present network offers the least built-in room to move activity into cooler, darker hours.

3.5. Sport-specific exposure largely follows the geography of facility provision

Because activities are not spread evenly across the country, climatic exposure falls unevenly across sports as well (Fig. 6). Ranking activity groups by their median facility-level trend places rugby first at −0.92 min day^{-1} decade^{-1}, ahead of tennis (−0.45), equestrian activities (−0.39), handball (−0.36), basketball (−0.34), football (−0.16) and pétanque (−0.14). The share of facilities lying in high-exposure cells reads in the same order: 41.8% for rugby, then 25.9% for tennis, 25.3% for equestrian activities, 23.0% for handball, 22.6% for basketball, 20.0% for pétanque and 19.4% for football.

The reason is geographic, not physiological. Rugby is heavily over-represented in the two regions that carry the strongest climatic signal, with location quotients of 1.91 in Occitanie and 1.74 in Nouvelle-Aquitaine (Fig. 6a), so its facilities inherit the southern trend even though nothing in the analysis treats rugby players as more heat-sensitive than anyone else. Lighting profiles cut across this in a way worth noting (Fig. 6c). Among rugby facilities, more of the highly exposed ones are already lit than unlit (32.5% versus 9.2%), whereas highly exposed handball and basketball facilities are overwhelmingly unlit (20.1% versus 2.9%, and 19.7% versus 2.9%). The most exposed sport is thus, by circumstance rather than design, somewhat better placed to shift into the evening than several of the less-exposed court sports. All of these contrasts follow from where facilities sit and how they happen to be equipped, and should not be read as intrinsic differences in physiological heat sensitivity between games.

3.6. The main spatial conclusion is robust to threshold, season and daylight definition

Three sensitivity tests bracket the result. The choice of WBGT threshold sets how much signal appears but not its shape (Fig. S1). At the lower, more protective 26°C threshold, 82% of metropolitan grid cells show a significant contraction of $H_{\text{fav,day}}$; that share falls to 39% at 28°C, 5% at 30°C and essentially zero at 32°C. The southern arc is present at every threshold, so what the threshold changes is how far north the contraction reaches, not where it is centred. The robust, national-scale statement therefore belongs at the lower, more protective (recreational) thresholds, and a clearly southern one at the higher, more permissive, acclimatised-athlete end.

Season matters less. Widening the window from MJJAS to AMJJASO damps the southern summer magnitude, because the cooler shoulder months of April and October dilute the seasonal mean, but it leaves the south–north

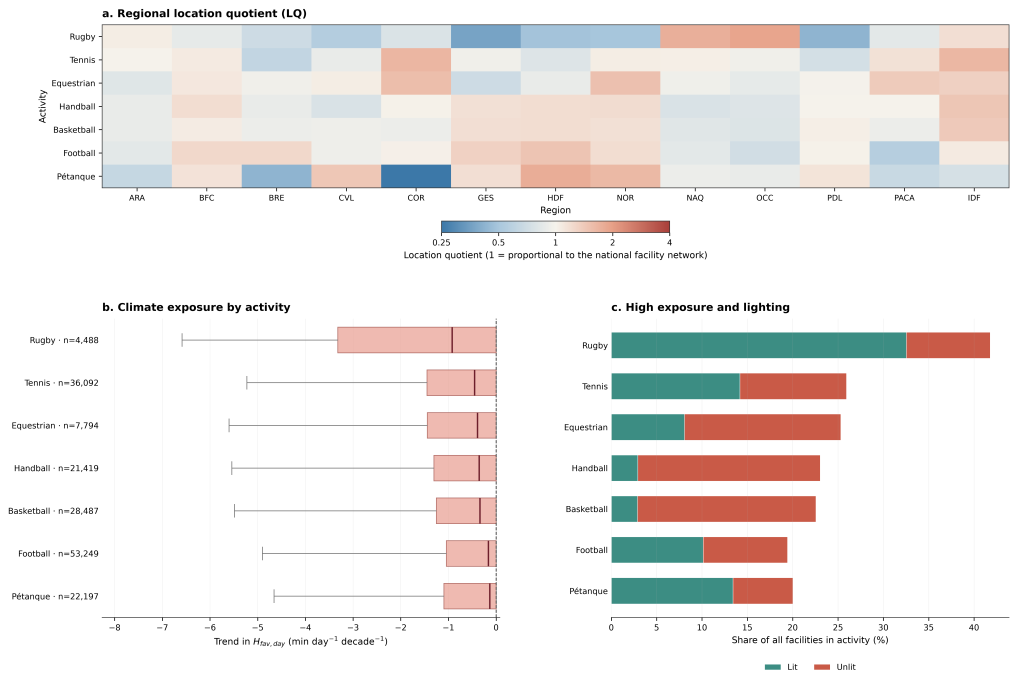

Figure 6: Geography, climatic exposure and lighting by activity. (a) Regional location quotient (LQ) for each activity, where $LQ > 1$ indicates over-representation relative to the national outdoor-facility network. (b) Distribution of $H_{\mathrm{fav,day}}$ trends sampled at facilities by activity. (c) Share of facilities in high-exposure cells, separated by lighting status. Multi-activity facilities can contribute to more than one activity category.

pattern untouched (Fig. S2). The definition of natural light matters least of all. Recomputing the complete hourly intersection with the geometric horizon (0°) instead of civil twilight (−6°), which preserves the exact hour-by-hour covariance between WBGT and solar elevation, leaves the trend maps almost indistinguishable: a spatial correlation of $r = 0.995$, a median absolute slope difference of 0.08 min day^{-1} decade^{-1} and a 95th-percentile difference of 0.30 min day^{-1} decade^{-1} (Fig. S3). The significance maps and the north–centre–Mediterranean diagnostics point the same way, towards a signal that is geographically concentrated and strongest in the Mediterranean warm-season afternoon (Figs. S4 and S5).

4. Discussion

4.1. From heat exposure to temporal accessibility of outdoor recreation

The main contribution of this study is to recast rising heat exposure as a change in the *timing* of outdoor recreation opportunities rather than only in their frequency or severity. A large body of sport-climate research has established heat as an operational constraint on training, competition and event organisation (Racinais et al., 2015; Brocherie et al., 2015), and has shown that the hazard is strongly intra-daily, so that moving a session or a kickoff by a few hours can meaningfully change exposure (Grundstein et al., 2013, 2023; Quagraine et al., 2026; Mullan et al., 2025). Controlled physiological work points the same way, with heat strain during exercise differing markedly between morning and late afternoon (Otani et al., 2020, 2023). What this literature leaves implicit is that the cooler hours towards which activity is nudged are themselves finite, because they run into the edges of natural daylight. Our results make that boundary explicit.

The three questions posed in the introduction can now be answered directly. First, the number and timing of thermally favourable hours occurring under natural daylight have indeed changed since 1991: favourable daylight time has contracted across metropolitan France, the trend is non-positive in every grid cell of the warm-season analysis, and the loss is concentrated in the middle of the summer day rather than spread evenly across it. Second, that contraction is strongly patterned in space, heaviest across the south and south-west, and it is accompanied by a modest but consistent rise in the share of favourable time that falls outside the naturally lit window, so that the remaining opportunity is being pushed towards the darker edges of the day. Third, these emerging temporal constraints intersect unevenly with the present facility network: the regions losing the most favourable daylight time are also those where a large fraction of outdoor facilities remain unlit, and the sports most exposed are so because of where their facilities happen to sit rather than because of any distinct physiological sensitivity. Taken together, the contraction of $H_{\text{fav,day}}$ is not simply another way of saying that heat is increasing; it measures the shrinking part of the day that is at once thermally tolerable and naturally lit, which is the quantity that actually governs when outdoor recreation can take place. A recent global assessment had already hinted that climatic constraints on outdoor sport were reaching beyond the midday peak into morning and evening hours (Defrance and Lescure, 2026);

the present analysis quantifies, at hourly resolution and across a national facility network, what that shift means on the ground.

4.2. Scheduling adaptation increasingly encounters a daylight constraint

The Mediterranean hour-by-month results show why this interaction is more than a technicality. The sharpest recent deterioration falls in the summer afternoon, while early morning and late evening stay comparatively favourable, which is precisely the pattern that makes schedule shifting an attractive, low-regret response to heat (Grundstein et al., 2023; Quagraine et al., 2026; Matzarakis et al., 2019). The difficulty is that the same shift, repeated as warming continues, pushes the usable window towards hours in which natural light is thinning. Daylight is not a neutral backdrop to outdoor activity: day length and evening light have repeatedly been tied to how much outdoor recreation and physical activity people undertake (Goodman et al., 2012, 2014; Elliott et al., 2019), even if the relationship is not universal and natural experiments on clock changes have found no general effect (Zick, 2014). Read against that evidence, our results describe a boundary condition that climate-sport assessments rarely represent: an hour can be thermally preferable and yet, for outdoor recreation, operationally less usable once it slips outside the naturally lit part of the day.

The geography of that boundary deserves emphasis, because it explains why the signal is so clearly southern. Two effects compound in the south rather than cancelling. Summer heat is more intense there, so the midday and early-afternoon window is eroded first and fastest. At the same time, and less obviously, high-summer days are shorter in the south of France than in the north: sunset at the Mediterranean coast falls well before it does near the Channel, so the cool of the evening arrives closer to, or after, dusk. The southern edges of the day are therefore both more needed, because the afternoon is less usable, and less available, because darkness comes sooner. This double squeeze is a genuinely geographical mechanism, not simply a restatement of the north-to-south temperature gradient, and it is what turns a warming signal into a daylight-window signal specifically in the south. The same logic implies that the phenomenon is not peculiar to France. Wherever long, hot summer afternoons coincide with the rapid shortening of the day through late summer, mid-latitude recreation faces the same tightening, which is consistent with the strong sensitivity of heat exposure to time of day already reported for events at comparable latitudes (Quagraine et al., 2026; Mullan et al., 2025).

4.3. Infrastructure creates uneven potential adaptive capacity, at a cost

Artificial lighting is the obvious way to loosen the daylight constraint, and it clearly lets some recreation continue after sunset (Zemla and BoLoz, 2022), with lighting conditions shaping how safe and usable people find outdoor spaces at night (Himschoot et al., 2024). The Data ES analysis shows, though, that this flexibility is unevenly built into the present network. The strongest overlap between climatic contraction and unlit facilities falls in Nouvelle-Aquitaine, Occitanie and Provence-Alpes-Côte d'Azur, the same regions carrying the largest losses, so the places where the daylight window is closing fastest are on average the least equipped to trade daylight for evening use. This should not be read as evidence that lighting has or has not been installed in response to warming, since Data ES is a present-day snapshot; it marks out one component of infrastructure-mediated flexibility as it stands today.

Reading lighting as an adaptation lever also brings its environmental and operational costs into view, which is particularly relevant for recreation planning and facility management. Illuminating more facilities for more of the evening raises electricity demand, so that adapting to a warming-driven constraint would itself add to energy use and, depending on the grid, to emissions. Adaptation of this kind risks feeding the very problem it responds to, which is a poor trade in a sector already asked to lower its footprint. The sports-lighting literature has largely treated illumination as an engineering and energy question rather than a climate-adaptation one (Kim and Kim, 2021; Houser et al., 2011), while a parallel strand documents its contribution to light pollution and the measures needed to contain it (Glaspey, 2003; Bouroussis and Topalis, 2020); disturbance to nocturnal ecology and to neighbouring residents belongs on the same ledger. For these reasons lighting is best seen as one option among several rather than a default. Shade structures, for instance, can lower WBGT at the point of activity and lengthen usable daytime directly, without shifting activity into the dark at all (Grundstein et al., 2026), and thermal-comfort design of semi-outdoor venues works in the same direction (Guo and Sun, 2024). Changes in seasonal programming, surface and vegetation management, access to water and adjusted opening hours may each suit a given facility and activity better than floodlights, and several can be combined.

4.4. The geography of sport redistributes climate exposure

The sport-specific results expose a geographical mechanism that is easy to misread. Rugby stands out as the most exposed activity group not because the analysis grants it a distinct thermal response, but because rugby facilities cluster in Occitanie and Nouvelle-Aquitaine, the two regions where the climatic signal is strongest. Location quotients let us hold the meteorological hazard constant and read the geography of provision on its own terms, and this matters because national, sport-specific adaptation priorities can emerge purely from where facilities happen to sit. The finding connects to a long line of work on the uneven geography of sports provision (Ahlfeldt and Feddersen, 2010; Pascual et al., 2009) and on how spatial access to particular facilities shapes who practises which sport (Karusisi et al., 2013), and it sits alongside evidence that heat-safety thresholds themselves vary systematically across regions (Grundstein et al., 2015).

There is a second, sharper inequality inside this pattern, and it concerns adaptive capacity rather than exposure. The alignment between how exposed a sport is and how well equipped it is to adapt is weak, and at times inverted. Rugby, the most exposed group, is comparatively well lit, whereas several less-exposed court sports such as handball and basketball are predominantly unlit where they are exposed at all. Exposure and the infrastructural means to cope with it are therefore distributed by different logics, so that the communities facing the tightest daylight window are not always those with the built-in flexibility to work around it. Seen this way, the redistribution of exposure by the geography of provision becomes a question of climate equity as much as of recreation planning: warming does not fall evenly across activities or territories, and the unevenness is inherited from where the country chose, over decades, to build and to light its pitches (Li et al., 2026).

4.5. Implications for recreation planning and facility management

Taken together, the results argue for adding time-of-day to the spatial risk maps that already guide adaptation. Conventional heat-risk mapping asks where conditions are becoming dangerous; the analysis here asks, in addition, when in the day favourable conditions still exist and whether that window is naturally lit. One immediate use is to flag the territories where favourable daylight time is contracting fastest and to revisit seasonal opening hours, training schedules and competition calendars there before the constraint bites, since rescheduling remains the lowest-cost response where daylight still allows it. A second is to locate high-exposure facilities that currently lack lighting or another form of temporal flexibility, which is exactly the intersection the Data ES analysis makes visible and which existing accessibility and equity assessments of sports provision could readily absorb (Li et al., 2025; Gong et al., 2025; Xu and Sun, 2026). Folding a climatic-timing layer into those assessments would let planners see exposure and provision together rather than in separate exercises.

Additional lighting should not be the reflex answer. Energy demand, operating cost, light pollution, disturbance to ecology and to neighbours, and the awkwardness of meeting a climate constraint with more consumption all pull against it, and in many settings shade, water, surface management or rescheduling will serve better and more cheaply. The value of the framework proposed here is diagnostic rather than prescriptive: it shows where and when a temporal constraint is emerging, and which facilities sit at the intersection of high exposure and low current flexibility, and it then leaves managers to weigh the response that fits the place, the activity and the local trade-offs. What it adds to current practice is not a single recommended intervention but a way of seeing the problem as one of timing and of unequal capacity, alongside the spatial hazard that is already mapped.

4.6. Limitations and research needs

Several limitations bound the interpretation. ERA5-Land resolves regional exposure at 0.1° but not the microclimate of an individual playing area, its shade, irrigation, urban surroundings or stadium geometry. This matters most for the playing surfaces themselves: synthetic turf can run far hotter than the overlying air and than natural grass, so grid-scale WBGT will understate the strain actually felt at pitch level on artificial surfaces (Jim, 2017; Liu and Jim, 2021; Singh et al., 2024). The WBGT formulation combines the Stull wet-bulb approximation with an empirical globe-temperature regression and should be read as a consistent meteorological proxy rather than an in-situ physiological measurement (Budd, 2008). The 28°C threshold is deliberately generic, whereas real heat policy turns on activity intensity, clothing, age and, not least, acclimatisation, which itself shifts across the season in recreationally active people (Brown et al., 2022, 2023); the threshold sensitivity we report should be read in that light, with the national-scale signal belonging to the lower, more protective (recreational) thresholds and a more southern one to the higher, more permissive, acclimatised limits.

Three further limits concern what the study deliberately does not do. It describes an observed trend over 1991–2025 but does not attribute that trend to anthropogenic forcing; establishing a formal attribution, or projecting the window forward under climate scenarios, is a natural and separable next step rather than part of the present observational design. Because Data ES is a present-day inventory rather than a historical record, the study likewise cannot identify realised adaptation or any causal infrastructure response to warming, and the mere presence of lighting says nothing about its operating hours, illuminance, cost or actual use. Finally, the analysis measures potential temporal accessibility, not observed participation or demand. Demand is itself weather-sensitive and partly self-regulating, since people already adjust when and whether they exercise in response to conditions (Spinney and Millward, 2011), so the realised effect of a contracting daylight window on behaviour need not track the potential effect measured here. The natural next steps follow directly: joining these climatic shifts to high-resolution microclimate observations, to facility operating and usage data, and to participation records (Elliott et al., 2019), and extending the observed diagnosis into a forward-looking one, would together test whether the tightening of the favourable daylight window is already changing, and will change, when and where people play.

5. Conclusions

Climate change is altering not only the intensity and frequency of heat exposure during outdoor recreation, but also *when* thermally favourable conditions remain available within the naturally lit part of the day. Across metropolitan France, favourable daylight time during the warm season contracted or remained unchanged at every analysed grid cell between 1991 and 2025, with the strongest losses concentrated in southern and south-western France and in the summer afternoon. In Mediterranean France, the recent period shows a clear hollowing-out of the central daytime window, leaving the cooler margins of the day to carry a growing share of thermally favourable conditions. The accompanying increase in Lighting Dependency indicates that, where the daylight-compatible window is shrinking fastest, part of the remaining opportunity is progressively displaced towards darker hours. This central result was robust to alternative WBGT thresholds, seasonal definitions and definitions of natural light.

Linking these climatic changes to 226,516 outdoor sports facilities shows that the emerging constraint is also an infrastructure and planning issue. More than 60% of outdoor facilities in Nouvelle-Aquitaine and Occitanie are located in highly exposed cells, and a substantial share of these facilities are currently unlit. Differences among sports likewise reflect the geography of provision: rugby appears most exposed largely because its facilities are disproportionately concentrated in the regions where the climatic signal is strongest. Exposure and the infrastructure available to accommodate temporal shifts are therefore distributed according to different spatial logics.

These findings argue for treating time-of-day as an explicit dimension of climate adaptation for outdoor recreation. The practical implication is not that increasingly exposed facilities should automatically be illuminated. Rather, the favourable-daylight framework provides a screening tool for identifying where temporal constraints are emerging and where managers may need to compare rescheduling, shading, water access, surface and vegetation management, modified opening hours, or, where justified, artificial lighting. More broadly, combining hourly heat stress, solar geometry and facility geography offers a transferable way to move from maps of climatic hazard towards maps of *usable recreation time*. Extending this framework with facility-level microclimate, participation data and future climate projections would allow planners to anticipate not only where outdoor recreation will become more constrained, but when those constraints will be most difficult to accommodate.

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Declaration of AI use

The author used a large language model (Anthropic Claude) to assist with drafting, structuring and editing the manuscript. The author directed all analyses, verified all content, and takes full responsibility for the integrity and accuracy of the work.

Data availability

The ERA5-Land hourly reanalysis data are freely available from the Copernicus Climate Data Store at `https://doi.org/10.24381/cds.e2161bac` (Muñoz Sabater, 2019). The Data ES national inventory of outdoor sports facilities is published by the French Ministry responsible for sports and is publicly available (Ministère chargé des Sports, 2026). The code implementing the WBGT reconstruction, solar-geometry masking and trend analysis is available at `https://doi.org/10.5281/zenodo.22079435`. This study contains modified Copernicus Climate Change Service information 2026; neither the European Commission nor ECMWF is responsible for any use that may be made of the Copernicus information or data it contains. The source code used for WBGT reconstruction, solar-geometry calculations, temporal aggregation, trend analysis, Data ES processing, sensitivity analyses, and figure production is openly available on GitHub at: `https://github.com/cosmosclimae/favourable-daylight-outdoor-recreation-france`.

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