

The Heat of Competition: Assessing Climate Vulnerabilities and Adaptive Governance in Endurance, Winter, and Youth Sports

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Abstract

Background: Climate change is fundamentally reshaping the environmental parameters of global sport, posing unprecedented risks to athlete health, safety, and performance. As rising temperatures, frequent extreme heat events, and deteriorating air quality become the new normal, athletic environments from community fields to elite international arenas face an existential threat. Purpose: This study provides an interdisciplinary synthesis of the multifaceted impacts of climate change on athletes, integrating evidence from sports medicine, environmental health, and climate science. It examines the physiological burden of environmental stressors specifically heat-related illness (HRI), cardiovascular strain, and respiratory distress alongside the psychological stressors triggered by disrupted seasons and unsafe competitive conditions. Methodology: Using a mixed-methods design, the research investigates the specific vulnerabilities of endurance, winter, and youth athletics. Findings: The results highlight a stark Adaptation Gap. While tactical adaptation by coaches is high (80%), a significant Governance Gap persists: although 75% of athletes recognize climate change as a direct threat, only 40% believe governing bodies are responding adequately. Data reveals that 72% of endurance athletes report heat-related symptoms, and 65% of youth athletes who possess immature thermoregulatory systems struggle with heat-load management. Vulnerabilities are disproportionately concentrated in endurance disciplines and resource-constrained settings that lack climate-resilient infrastructure. Conclusion: Through an analysis of case studies from major international competitions, the research identifies an urgent need for a paradigm shift in sports governance. Safeguarding athlete well-being must transition from a peripheral medical concern to a core requirement of sustainable event planning. The study concludes that the future of sport depends on moving beyond reactive measures toward structural, policy-driven resilience. By positioning the athlete at the centre of the climate crisis, this research advocates for the sporting world to transition from a vulnerable sector to a powerful platform for public health resilience and climate advocacy. Future research should examine interdisciplinary studies that integrate climate science, sports medicine, and organizational governance.

Keywords: Climate change, Athlete health, Heat-related illness, Environmental stressors, Sports medicine, Climate adaptation, Physiological strain, Global health, Sports governance.

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INTRODUCTION

The intersection of climate change and athlete health represents a critical new frontier in both sports medicine and public health. As the global sports industry faces unprecedented environmental volatility from receding snowlines threatening winter sports to humidity-saturated stadiums hosting summer championships, the geographic comfort zone for athletics is rapidly shrinking. [1]

While early climate discourse largely focused on infrastructure and economic loss, this research shifts the focus toward the industry's most vital asset: the athlete. By examining the synergy between physiological strain and institutional response, this study positions athlete well-being as the primary casualty of climate-induced inertia. [2] Athletes serve as canaries in the coal mine for heat-related illnesses; their bodies generate significant metabolic heat that must be dissipated into increasingly hostile, warm, and humid environments. When ambient conditions exceed the body's thermoregulatory capacity, the risk of Exertional Heat Stroke (EHS), cardiovascular collapse, and chronic respiratory damage transitions from a theoretical concern to a clinical reality [3] (Figure 1).

This study sought to analyze the physiological mechanisms through which heat exposure and air pollution impair both athletic performance and long-term health outcomes. Attention was paid to the vulnerabilities of youth, endurance, and winter sports athletes, who represent distinct populations facing heightened risks from climate stressors. In addition, this study evaluated the current state of climate adaptation policies within major sports governing bodies, examining the adequacy of institutional responses to escalating environmental challenges. Finally, the study identified the governance gap that exists between athletes' perception of climate-related risks and the level of institutional action, thereby highlighting the misalignment between lived experiences on the ground and organizational preparedness at the policy level. [4-6]

Recent scholarship has highlighted the direct physical impact of climate change on sporting environments. Maunder [7] (2025) documented how extreme heat waves and humidity increase the risk of heatstroke and respiratory illness among athletes, particularly in endurance sports. Nagabhoina and Verma P. [8-15] (2025) showed that unpredictable rainfall patterns in India have disrupted cricket and football matches, underscoring the global reach of climate-related challenges. Winter sports are especially vulnerable, with declining snow cover shortening seasons and forcing reliance on artificial snow, which raises sustainability concerns due to high energy and water demands.

Evidence from recent literature and case studies, such as Maunder's [7] (2024) work on heat stress, Steiger et al.'s [12] (2023) projections for winter sports, and Wirth's [11] (2022) analysis of the Tokyo Olympics, confirms that sports are highly vulnerable to climate variability. Simultaneously, the sector is beginning to respond through adaptive strategies, including event rescheduling, climate-resilient infrastructure, and institutional commitments, such as the UN Sports for Climate Action Framework.

On Winter Sports and Snow Reliability Research by Steiger et al. [12] (2023) highlight that up to 50% of ski resorts in Europe may face operational challenges by 2050 if warming trends continue. Although artificial snow production is adaptive, it raises ecological concerns, including water scarcity and increased carbon emissions (Scott et al. [12] 2025; Cayolla et al. [3] (2025); Moore [10] (2026)). The Tokyo 2020 Summer Olympics offered a clear example of adaptation to extreme heat. The organizers implemented shaded rest areas, misting stations, and rescheduled endurance events to early mornings to mitigate heat stress. Wirth [11] (2022) showed that these measures reduced heat-related incidents among athletes and spectators, demonstrating how large-scale sporting events can integrate climate resilience into planning.

The FIFA World Cup in Qatar (2022) faced scrutiny for hosting matches in one of the hottest regions of the world. As argued by Cayolla et al. [3] (2025), the industry is entering the Sports 5.0 era, where environmental resilience has become a non-negotiable prerequisite for hosting. The data points to the wholesale rescheduling of the 2022 FIFA World Cup to winter and the midnight start times of the 2019 World Athletics Championship as definitive proof that traditional scheduling norms have been superseded by the thermal windows dictated by the changing climate. Organizers responded with climate-adaptive stadiums featuring advanced cooling technologies powered, in part, by renewable energy. While effective in maintaining safe playing conditions, scholars such as Boykoff [2] (2023) have argued that such technological fixes highlight the tension between short-term adaptation and long-term sustainability.

Esh et al. [4] (2024) emphasized that evidence-based heat acclimation strategies and environmental monitoring are becoming essential components of competition preparation as global temperatures rise. In addition to thermo-physiological strain, heat stress alters the metabolic processes relevant to endurance adaptation. Bennett et al. [1] (2024) demonstrated that elevated thermal load influences substrate utilization and training adaptations, potentially affecting long-term performance outcomes. In addition to temperature, climate-driven wildfire events increasingly expose endurance athletes to hazardous air quality during outdoor training and competitions, compounding cardiopulmonary strain.

The discussion highlights a central tension: while technological adaptations, such as cooling systems and artificial snow production, provide short-term solutions, they often reinforce unsustainable practices. Long-term resilience requires sports organizations to embed sustainability into governance, infrastructure, and cultural practices. This includes investing in renewable energy, eco-friendly stadium design, and resource-efficient operations, as emphasized by Liebhart et al. [6] (2025).

Youth athletes are uniquely vulnerable to injuries owing to physiological and structural factors. Children and adolescents exhibit less efficient thermoregulation, lower sweat rates, and greater susceptibility to dehydration than adults, placing them at a heightened risk during extreme heat exposure. Hylton-Pelaia et al. [5] (2025) identified climate change as an emerging public health concern in adolescent sports, particularly for girls and youth in under-resourced communities lacking adequate cooling infrastructure or environmental safeguards. Climate stressors also disrupt participation patterns, and extreme heat days, poor air quality alerts, and weather-related facility damage increasingly result in cancelled practices and shortened seasons. These disruptions may negatively influence physical literacy development, psychosocial well-being, and long-term athletic pathways.

Esh et al. [4] (2024) emphasized that evidence-based heat acclimation strategies are critical for endurance competitions in warming climates. According to Hylton-Pelaia et al. [5] (2025), climate change introduces structural and physiological barriers to adolescent sports participation. Youth athletes also face a disproportionate vulnerability to climate-related heat stress (Hylton-Pelaia et al., [5] 2025). Bennett et al. [1] (2024) demonstrated that heat stress influences metabolic responses relevant to endurance training adaptations. Heat exposure significantly impairs endurance performance and increases thermo-physiological strain, and heat stress may alter substrate metabolism and training adaptations (Esh et al., [4] 2024; Bennett et al., [1] 2024).

Equally important is the role of sports as a platform for climate advocacy. Athletes and organizations are increasingly using their visibility to raise awareness and influence public behavior, aligning with McCullough's [9] (2023) argument that sports can mobilize climate resilience through their cultural significance. By embracing this dual role of adapting to climate risks and advocating for sustainability, sports can safeguard their future while contributing meaningfully to global climate action.

Ultimately, the future of sports in a warming world will depend on proactive adaptation, sustainable innovation and climate advocacy. Sports must navigate the tension between immediate safety and long-term ecological responsibility while leveraging their unparalleled visibility to inspire climate-conscious values. If these pathways are pursued, the sector can transform from a victim of climate change into a catalyst for resilience, ensuring that the spirit of play endures in a sustainable and equitable future.

METHODOLOGY

To address the complex intersection of physiological strain and organizational governance, this study used a mixed-methods research design. This approach allowed for the quantification of health impacts while providing the qualitative depth necessary to understand the institutional barriers to adaptation. This study employed a convergent parallel design, in which quantitative and qualitative data were collected simultaneously, analyzed independently, and then merged to identify points of

convergence or contradiction. This design is particularly effective in sports medicine for validating subjective athlete experiences against objective health metrics. The initial phase focused on gathering broad-scale data from a sample of 500 athletes. These participants represented three distinct domains particularly vulnerable to environmental shifts: endurance (marathon runners and cyclists), winter sports (skiers and snowboarders), and Youth Athletics (ages 12–18).

To gather this data, a validated online questionnaire was deployed to measure three critical variables: the frequency of self-reported Heat-Related Illness (HRI) symptoms, the perceived impact of declining air quality on training and aerobic capacity, and athlete confidence in the efficacy of climate policies established by sports governing bodies. Quantitative metrics were benchmarked against the Wet Bulb Globe Temperature (WBGT) index to accurately correlate the experiences of athletes with established environmental stress thresholds. To provide deeper context to the survey findings, semi-structured interviews were conducted with 20 key stakeholders, including sports physicians, elite coaches, and climate policy advisors from international federations. This was supplemented by a longitudinal analysis of case studies on climate vulnerabilities and adaptive governance in endurance, winter, and youth sports (Figure 3).

To ground the primary research in a historical context, the team performed a retrospective analysis using data from the Copernicus Climate Change Service. This historical climate data were cross-referenced with injury reports and event cancellation records spanning the last decade to identify long-term trends. The final stage involved synthesizing all data streams using specialized software. Quantitative survey data were processed to identify statistical significance ($p < 0.05$), specifically focusing on the correlation between an athlete's age, sport type, and physiological vulnerability to heat. Simultaneously, qualitative data, including interview transcripts and case notes, underwent thematic content analysis using NVivo software. This allowed the research team to identify recurring institutional challenges, such as systemic inertia and the difficult economic-safety trade-offs faced by event organizers in a changing climate.

RESULTS

This study's findings confirm a significant disconnect between the escalating environmental risks faced by athletes and the current level of institutional preparedness. Climate stressors have emerged as primary health concerns rather than peripheral risks for active populations. Among endurance athletes, 72% reported experiencing symptoms of heat-related illness, such as dizziness, extreme exhaustion, or heat cramps, during the previous competitive season. Youth athletes are particularly vulnerable, with 65% struggling to regulate their body temperature during peak summer months. This cohort also recorded the highest frequency of near-miss exertional incidents, often linked to the absence of age-specific heat policies.

The empirical data paint a stark picture of a sporting world in transition, where environmental limits increasingly dictate athletic potential. Analysis of the survey data revealed that endurance athletes are at the vanguard of this crisis, with an overwhelming 72% of respondents reporting acute heat-related symptoms, ranging from heat syncope to severe exhaustion, during the most recent competitive cycle. This suggests that the Goldilocks Zone for endurance performance, traditionally defined by ambient temperatures between 7°C and 15°C is vanishing in favor of high-heat environments that challenge human homeostatic limits.

In the realm of youth athletics, these results underscore a physiological mismatch. A total of 65% of youth athletes struggled with thermoregulation, which aligns with the biological reality that children possess a higher surface area-to-mass ratio and less efficient sweat mechanisms than adults. This vulnerability is compounded by operational failures, and 40% of outdoor events were either rescheduled or truncated due to unsafe Wet Bulb Globe Temperature (WBGT) readings.

The crisis in winter sports is equally profound, although structural rather than physiological. Athletes reported a 25% reduction in usable snow days, leading 58% of participants to note a significant shortening of their competitive and training periods. This seasonal squeeze has forced a reliance on artificial snow, which athletes identified as a primary factor in increased orthopaedic injury risk due to its higher density and inconsistent texture (Figure 4).

While 80% of coaches have implemented tactical changes, such as shifting training times to avoid peak heat, institutional responses remain lackluster. The most critical finding is the 35-point disparity between athlete concern and institutional trust: while 75% of athletes recognize climate change as a direct threat to their sport and safety, only 40% believe their governing bodies are responding with adequate policy frameworks. This Governance Gap suggests that athletes and coaches are operating on the front lines of the climate crisis, while leadership remains largely reactive, tethered to legacy schedules and commercial interests that do not reflect the new environmental normal.

Finally, the study identified a significant Governance Gap. While 75% of the total athlete population acknowledged that climate change had fundamentally altered their sport, only 40% expressed confidence in their governing bodies' ability to mitigate the risks. This 35-point disparity suggests that while athletes are feeling the heat, institutions remain largely reactive (Figure 2).

Ultimately, the sports world is at a crossroads. By positioning the athlete at the center of the climate crisis, this research advocates for a transition from a vulnerable sector to a powerful platform for public-health resilience. If sports organizations embrace structural and policy-driven resilience, they can leverage their immense global visibility to inspire climate advocacy, ensuring that the pursuit of athletic excellence remains possible on a warming planet.

Figure 1 quantifies the tangible logistical consequences of escalating environmental instability on the global sports calendar. Event Disruptions are common, and this comparative bar chart shows that outdoor endurance events are more frequently disrupted (40%) than winter sports (25%).

Figure 2 captures the psychological and institutional core of the study, highlighting a profound disconnect between the athlete's subjective lived experience and the organization's objective policy response. This Governance Gap serves as a primary barrier to long-term resilience, as it erodes the trust necessary for effective risk management. The bar chart shows a strong consensus among athletes (75%) that climate change has impacted their sport, contrasted with low confidence (40%) in the responses of governing bodies.

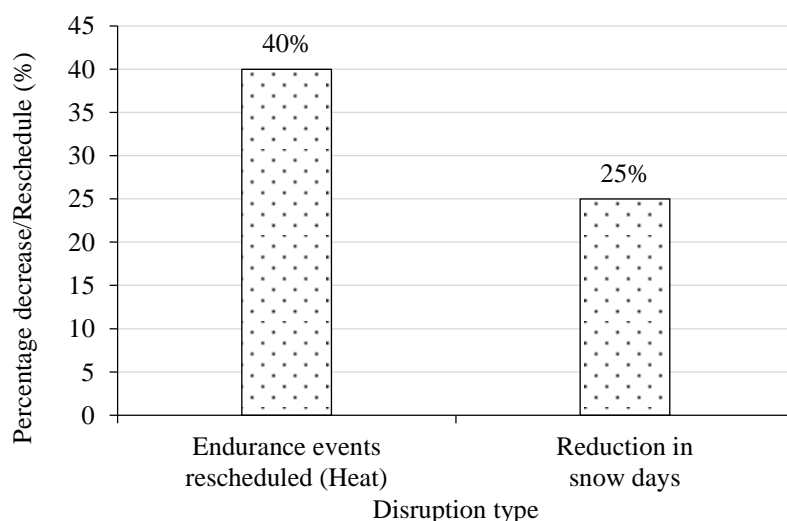


Figure 1. Operational disruption and climate volatility.

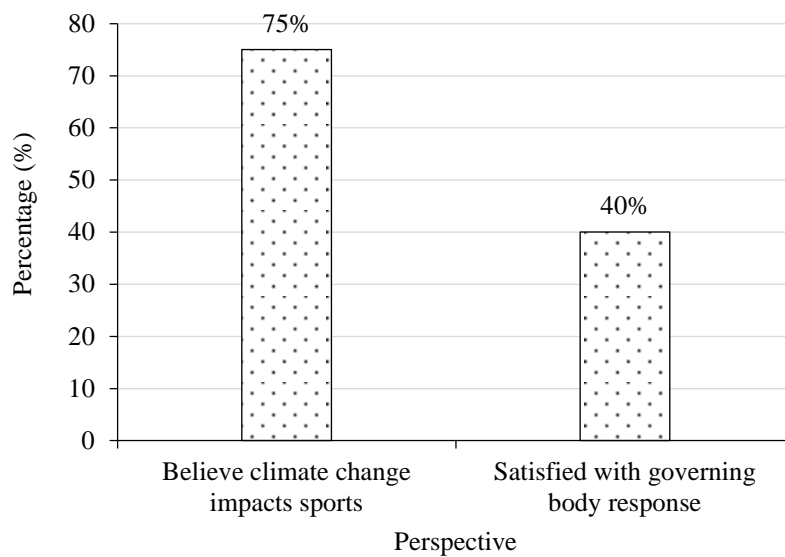


Figure 2. The governance gap: athlete perception versus policy efficacy.

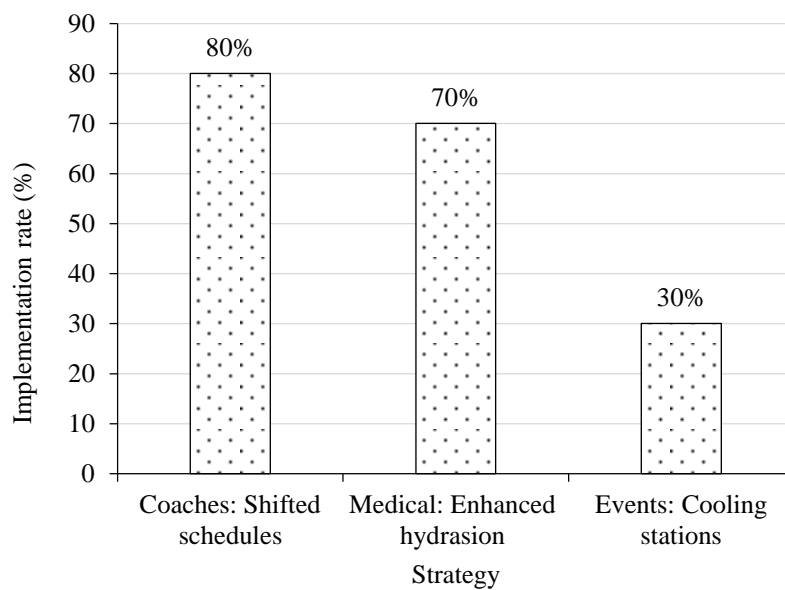


Figure 3. Adoption of adaptive strategies by stakeholders.

Figure 3 illustrates the Ground-Up Adaptation model, which currently defines the sports industry's response to climate change. It highlights the critical disparity between behavioral changes made by individuals on the front lines and the physical investments required at the institutional level. The figure reveals that 80% of coaches have implemented tactical shifts to mitigate environmental risks. Following coaching shifts, 70% of the medical staff enhanced their on-field protocols. These strategies include standardized pre-cooling routine. In stark contrast to behavioral changes, only 30% of events and venues have introduced dedicated cooling infrastructure such as misting fans, shaded recovery zones, or high-capacity immersion baths.

Figure 4 illustrates that endurance athletes were the most affected group (72%), followed by youth athletes (65%) and winter athletes (58%). The data illustrate a critical shift, where climate stressors have moved from occasional inconveniences to primary drivers of event volatility, particularly within endurance and winter disciplines.

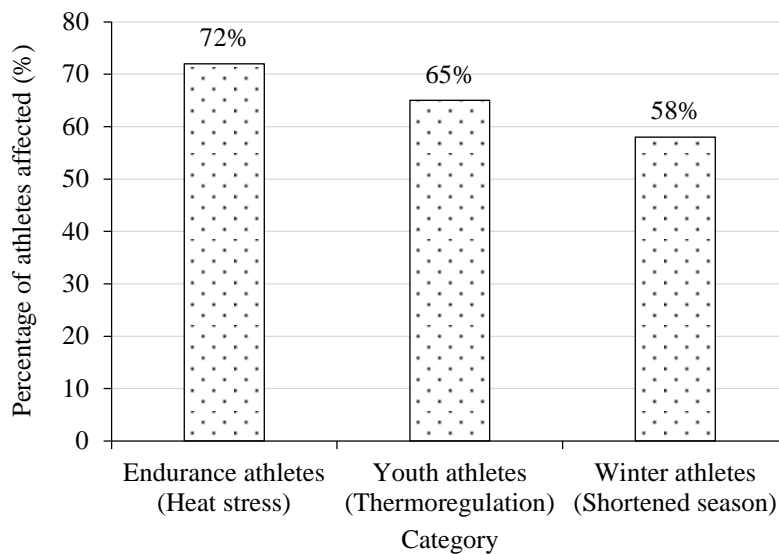


Figure 4. Physiological and operational impacts of climate stressors.

DISCUSSION

The findings of this study reinforce the growing consensus in the literature that sports are both highly vulnerable to climate change and uniquely positioned to act as agents of climate change advocacy. Rising temperatures, declining snow reliability, and increasingly frequent extreme weather events are already reshaping the conditions under which athletes train and compete in the Winter Olympics. These results align with Maunder E [7] (2024) analysis of heat stress in endurance sports, which documents the heightened risks of heat exhaustion and respiratory illness during prolonged exposure to extreme heat. Similarly, Nagabhoina and Verma [15] (2025) highlighted how unpredictable rainfall patterns in South Asia have disrupted cricket and football matches, underscoring the global reach of climate-related disruptions.

The vulnerability of winter sports is well documented. Steiger et al. [12] (2023) projected that up to half of European ski resorts may face operational difficulties by 2050 owing to declining snow cover, with artificial snow production becoming increasingly necessary. While this adaptation allows events to continue, it raises ecological concerns because of its heavy water and energy demands. This tension between short-term adaptation and long-term sustainability reflects Boykoff's [2] (2023) argument that mega sporting events often rely on technological fixes that address immediate risks but fail to resolve underlying environmental challenges.

The adaptive strategies identified in this study also resonate with existing literature. Wirth [11] (2022) showed that the Tokyo 2020 Olympics successfully reduced heat-related risks by rescheduling endurance events to cooler times of day and implementing shaded rest areas and misting stations. Similarly, the FIFA World Cup in Qatar demonstrated the use of advanced cooling technologies in stadiums, partially powered by renewable energies. These safety measures, while effective, underscore the paradox identified by Boykoff [2] (2023), in which immediate risk mitigation serves to entrench inherently unsustainable practices.

At the institutional level, adopting frameworks such as the UN Sports for Climate Action reflects the growing recognition of the need for systemic change. McCullough [9] (2023) and Liebhart et al. [6] (2025) argue that organizational sustainability in sports requires a bifurcated approach to mitigate carbon footprints and adapt operational strategies to a volatile environment. This dual responsibility is evident in the increasing investments in renewable energy, eco-friendly stadium design, and resource-efficient practices documented by Shu et al., who highlighted the significant carbon emissions associated with international sporting events and the emerging measures to reduce them.

The socio-economic dimensions of climate change in sports are also consistent with the broader literature. Infrastructure damage from storms and floods imposes financial burdens on clubs and communities, and rising insurance costs threaten the viability of smaller organizations. The World Economic Forum (2024) notes that the sports industry is experimenting with adaptive strategies, such as shifting event times, rescheduling tournaments, and investing in climate-resilient infrastructure. These findings suggest that sustainability is not only an environmental imperative but also an economic strategy for safeguarding the future of sport.

Finally, the role of sports as a platform for climate advocacy has been widely recognized. Athletes and organizations are increasingly using their visibility to raise awareness of climate issues, a trend supported by the UNFCCC's [16] (2018) Sports for Climate Action Framework. By leveraging their global reach, sports can influence fan behavior and public discourse, positioning themselves as catalysts for broader social change. This aligns with McCullough's [9] (2023) argument that sports have a unique capacity to mobilize climate awareness and resilience through their cultural significance.

In summary, the discussion underscores that the future of sports in a warming world will depend on proactive adaptation, sustainable innovation, and climate advocacy. The literature consistently highlights the tension between immediate adaptation and long-term sustainability while emphasizing the potential of sports to inspire climate-conscious values. By embracing this dual role, the sports sector can safeguard its future and contribute meaningfully to global climate resilience.

RECOMMENDATIONS

The findings of this study highlight the need for coordinated action at multiple levels in the sporting world. For athletes, the priority must be to safeguard their health through proactive measures. Strict hydration protocols, the use of cooling aids such as ice vests or shaded rest areas, and careful monitoring of symptoms such as dizziness or fatigue are essential for reducing the risk of heat-related illness. Athletes should also adapt their training routines by scheduling sessions during cooler hours and adjusting their intensity in response to environmental conditions.

Coaches play a critical role in shaping these adaptations by implementing climate-conscious scheduling to minimize exposure to extreme heat and other stressors. Coaches should also integrate climate resilience into training programs, educating athletes about the risks posed by climate change, and equipping them with practical strategies to cope. Collaboration with sports medicine staff is vital to ensure that rapid response protocols are in place during competitions and that medical monitoring is embedded into everyday practice.

At the organizational level, governing bodies must take responsibility for embedding climate resilience into policies and infrastructure. This includes revising official guidelines to incorporate climate considerations, investing in sustainable facilities equipped with shaded areas, cooling technologies, and renewable energy solutions, and promoting equitable access to protective measures across all levels of sports, including youth programs. Sports organizations also have a unique opportunity to leverage their visibility to advocate for climate action by using athletes and events as platforms to raise public awareness and inspire collective responsibility.

CONCLUSION

This study demonstrates that climate change is no longer a distant concern for the sporting world but an immediate and escalating challenge. Rising temperatures, declining snow reliability, and increasingly frequent extreme weather events are already disrupting athletic performance, competition schedules, and infrastructure. This study demonstrates that climate change is already exerting significant impacts on athlete health, with endurance athletes, youth athletes, and winter sports participants facing distinct vulnerabilities. Rising temperatures, deteriorating air quality, and shortened seasonal windows are compromising performance, safety, and long-term well-being. The results confirm earlier findings in the literature that heat stress, dehydration, and respiratory

challenges are among the most pressing risks, while event disruptions highlight the systemic nature of climate impacts on sports. Future research should expand on these findings by examining long-term health outcomes, evaluating the effectiveness of adaptation measures, and exploring the role of sports as platforms for climate advocacy. Future research should also examine the long-term health outcomes of athletes exposed to repeated climate stressors. Again, there is a need to evaluate the effectiveness of adaptation strategies. Finally, interdisciplinary studies that integrate climate science, sports medicine, and organizational governance will be essential. By bridging these fields, researchers can develop holistic frameworks that not only explain vulnerabilities but also guide systemic adaptation.

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