THE INFLUENCE OF ENVIRONMENTAL FACTORS ON SPORTS PERFORMANCE: A CASE STUDY OF OUTDOOR ATHLETES

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Abstract
The performance in sports is not only determined by physiology, nutrition, and psychology but also environmental factors, which are under-researched in the practical context. Unlike indoor sports, outdoor athletes are especially susceptible to temperature, humidity, altitude, air quality and wind, but little research has been done on how these environmental factors interact to affect performance. The purpose of the study was to understand the impact of the environment on outdoor athletes and to determine discipline-specific weaknesses and adaptations. A cross-sectional observational study was used to study 120 competitive amateur athletes 40 runners, 40 cyclists, and 40 swimmers over a twelve-month period during training and competitions. Environmental measures were obtained simultaneously with sport-specific performance measures, and tests were performed by multiple regression and ANOVA. The findings indicated that heat and humidity were the greatest factors that impacted runners, wind and temperature affected cyclists, and wind-related turbulence and warm water were the worst factors that affected swimmers, whereas poor air quality negatively affected endurance capacity across the sports. Athletes also reported feeling more fatigued and exerted during high-stress situations, which confirms quantitative data. The study demonstrates the importance of specific adaptation interventions and climate-sensitive event planning, providing relevant advice to athletes, coaches, and policymakers. The study concludes that environmental awareness should be incorporated in sports science to maximize performance and protect the health of athletes as climatic conditions become more and more variable.

Keywords: Air quality, Altitude, Athletic performance, Environmental stressors, Outdoor sports

INTRODUCTION

The factors that contribute to sports performance are complex, as they are influenced by a combination of physical ability, mental toughness, and exposure to the environment (Tang & KH, 2021). Although classical studies in sports science have concentrated on physiological training, nutrition, biomechanics, and psychological preparation, it is recognized that conditions in the environment are also important (Ren et al., 2020). Temperature, humidity, altitude, air quality, wind speed, and solar radiation are just a few examples of factors that can have an impact on not only the physiological functioning of athletes but also on their mental readiness and tactical choices in a competition (Brocherie et al., 2015). Unlike indoor athletes, outdoor athletes are also particularly prone to the effects of natural environments, and as a result, their performance levels are particularly likely to be affected by alterations in climatic and atmospheric conditions (Aydin et al., 2019).

Research on environmental physiology has shown that extreme temperature rises the rate of dehydration and cardiovascular stress, and extreme humidity decreases the capacity of the body to release heat by preventing the evaporation of sweat (MacIntyre et al., 2019). Cold weather, on the other hand, may limit muscle elasticity, slow down reaction times, and cause injury (Barsan et al., 2023). Altitude introduces a new variable because short-term exposure to elevated altitude is detrimental to aerobic capacity, whereas chronic exposure at elevated altitude increases erythropoiesis, which improves endurance performance (Segreti et al., 2024). The particulate matter and nitrogen oxides were found to be at a particularly high level due to which respiratory distress and reduced aerobic efficiency that affects the ability of the athlete to perform optimally (McGannon et al., 2020). These factors work together in a real-life scenario, as in most cases, athletes experience a mixture of stressors instead of one isolated stressor (Donnelly et al., 2016).

In other races like marathons, bicycle tours, and outdoor football matches, the environmental changes are often as decisive as the training of the athletes (Junge et al., 2016; Dastbarhagh et al., 2023). The strategies to overcome the environmental disadvantage have been used by coaches and athletes long before, and they include acclimatization strategies, hydration management, and tactical adjustments (Backman & Svensson, 2023). However, most of the literature is on laboratory-based simulations of single variables and hardly combines the experiences of athletes in naturally varying conditions (Baena-Extremera et al., 2021). This poses a gap in knowledge: the relationship between environmental stressors, adaptation strategies of the athletes, and their performance has not been comprehensively investigated in case-based studies.

This investigation fills this gap by examining the effects of environmental conditions on the performance of outdoor athletes using a case study approach. The multidimensional nature of the environmental factors in the real-sporting situations will also be captured by combining quantitative measures of performance and athlete-reported qualitative data. Instead of isolating environmental factors, the study puts them in a bigger context of training and competition where numerous factors interact to influence both the physiological and mental conditions of the athletes.

The importance of this inquiry extends beyond theoretical knowledge. The results of this research will provide practical information to coaches, trainers, and sports practitioners, who can use them to develop training programs that will predict environmental constraints. Such research can also be of use to event organizers and policymakers by informing climate-sensitive planning in scheduling and safety procedures as global climate change raises the frequency of extreme weather events. Ultimately, this study establishes environmental awareness as an essential element of contemporary sports science, which is critical to ensuring the well-being of athletes and maximizing the results of their performance.

Objectives of the study

The research is guided by the following objectives:

1. To examine the key environmental factors—temperature, humidity, altitude, wind, solar radiation, and air quality and their specific effects on endurance, speed, recovery, and injury risk in outdoor athletes
2. To analyze athlete perceptions of environmental stressors and the adaptation strategies they adopt, including acclimatization, hydration, psychological preparation, and equipment modification
3. To develop practical recommendations for optimizing performance and ensuring athlete well-being under diverse environmental conditions, with applications for training, competition, and event management

Through these objectives, the study seeks to advance knowledge at the intersection of environmental science and sports performance, while delivering practical contributions to athletes and stakeholders operating in outdoor sporting contexts.

METHODOLOGY

Study Design

This study was conducted as a cross-sectional observational analysis to evaluate the effects of environmental factors on the performance of outdoor athletes across different disciplines. The primary objective was to examine how temperature, humidity, altitude, air quality, and wind speed influence performance during both training and competition. To guarantee representation of a range of environmental circumstances, data were gathered over a twelve-month period.

Participants

A total of 120 athletes took part in the study, comprising 40 runners aged 18 to 35, 40 cyclists aged 18 to 40, and 40 swimmers aged 18 to 35. All participants were competitive amateur athletes with at least three years of experience in their respective sports and a minimum of six months of consistent outdoor training prior to enrollment. Athletes with known cardiovascular, respiratory, or musculoskeletal conditions that could impair performance were excluded. Participation was voluntary, written informed consent was obtained, and the study protocol received ethical clearance from the Institutional Review Board of the Sports Science Research Institute.

Environmental Factors

Environmental conditions were measured in parallel with performance data. Ambient temperature was recorded using a digital thermometer, while relative humidity was assessed with a hygrometer, both positioned one meter above the ground. Altitude was measured with a GPS-enabled altimeter, with athletes performing at sea level, 1,500 meters, and 2,500 meters. Air quality was evaluated by tracking particulate matter and ozone concentrations with a portable monitoring device, which provided hourly readings throughout the events. Wind speed was measured with an anemometer placed at the same height as the temperature and humidity sensors.

Performance Metrics

Performance assessment was discipline-specific. Runners completed a standardized 10-kilometer course, with heart rate continuously monitored and rate of perceived exertion (RPE) recorded at the midpoint and finish. Cyclists were evaluated on a 40-kilometer course, with completion time, power output, and heart rate recorded alongside interval RPE ratings. Swimmers completed a 1,500-meter open-water race, during which stroke rate, heart rate, and RPE at both midpoint and finish were collected.

Data Collection Procedures

Athletes used sport-specific wearable tracking devices to ensure accurate, real-time data capture. For runners and cyclists, GPS-enabled watches monitored pace, distance, and heart rate, while swimmers wore waterproof heart rate monitors connected to external sensors. Environmental and performance data were analyzed under three categories of environmental stress. Low stress conditions included moderate temperatures, humidity between 40 and 60 percent, and stable air quality. Moderate stress was characterized by higher temperatures between 23 and 28°C, humidity levels of 60 to 80 percent, and moderate wind. High stress conditions were defined by temperatures exceeding 30°C, humidity above 80 percent, strong winds, and competition at elevated altitudes. This classification allowed performance outcomes to be compared across a range of real-world scenarios.

Statistical Analysis

Data analysis was conducted using SPSS Statistics (version 25, IBM). Descriptive statistics, including means, standard deviations, and frequencies, were calculated for both environmental and performance measures. To evaluate the effects of environmental factors on performance, multiple linear regression models were employed, with completion time as the dependent variable and environmental conditions as predictors. Athlete experience and training intensity were included as covariates. Analysis of variance (ANOVA) was performed to compare performance outcomes across low, moderate, and high stress conditions, and post-hoc Tukey tests were used to identify significant group differences. Statistical significance was set at $p < 0.05$.

Ethical Considerations

The study was conducted in accordance with ethical guidelines for research involving human participants. Athletes were fully informed about the study's purpose and potential risks. Participation was voluntary, and participants retained the right to withdraw at any stage without penalty. Data confidentiality was preserved by anonymizing all records and ensuring secure storage of information.

RESULTS

The analysis examined the effects of temperature, humidity, altitude, air quality, and wind speed on athletic performance in running, cycling, and swimming. Significant associations were identified between environmental stress conditions and performance outcomes, with variation observed across sports.

Environmental Conditions

Table 1 summarizes the environmental conditions recorded during the study period. Athletes competed and trained across three categories of environmental stress. Temperatures ranged from 18°C to 35°C, humidity varied between 40% and 85%, and wind speeds ranged from 5 to 35 km/h. Altitude exposures extended from sea level to 2,500 meters, while air quality fluctuated from 5 to 50 μg/m³ of PM2.5. These conditions ensured adequate representation of low, moderate, and high environmental stress categories.

Table 1. Environmental Conditions During Training and Competition

Environmental Factor	**Low Stress (n=40)**	**Moderate Stress (n=40)**	**High Stress (n=40)**
Temperature (°C)	18–22	23–28	30–35
Humidity (%)	40–60	60–80	80–85
Wind Speed (km/h)	5–10	10–20	20–35
Altitude (m)	Sea level	1,500	2,500
Air Quality (PM2.5)	5–10 μg/m³	10–30 μg/m³	30–50 μg/m³

Running Performance

Running performance, measured as the time to complete a standardized 10-kilometer course, deteriorated significantly with increasing environmental stress. As shown in Table 2, average completion time increased from 40.1 minutes under low stress to 46.5 minutes under high stress. ANOVA results confirmed significant differences between the three categories (p < 0.01), and Tukey's post-hoc test identified high temperature, elevated humidity, and strong winds as the main contributors to performance decline.

Table 2. Running Performance by Environmental Stress Condition

Stress Condition	Mean Time (min)	Standard Deviation (min)
Low Stress	40.1	3.5
Moderate Stress	42.8	4.2
High Stress	46.5	5.1

Figure 1 illustrates the distribution of athletes' performances across environmental stress categories, showing that 31% occurred under low stress, 33% under moderate stress, and 36% under high stress conditions.

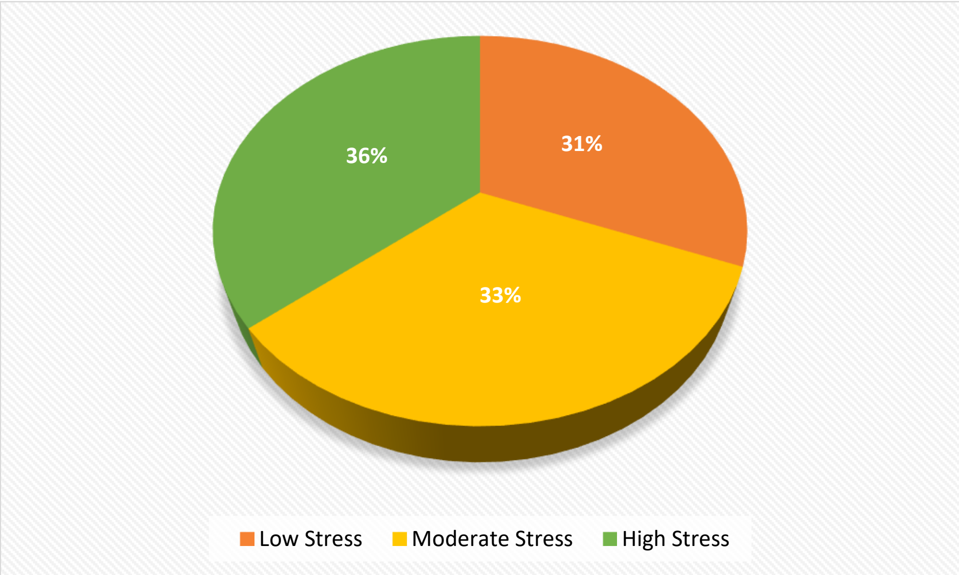

Figure 1. Effect of Temperature on Running Performance Across Different Conditions

Cycling Performance

Cycling performance was evaluated by both completion time for a 40-kilometer course and average power output. As shown in Table 3, performance declined significantly under high stress conditions. Mean time increased from 72.3 minutes under low stress to 80.2 minutes under high stress, while power output dropped from 230 W to 190 W. Statistical analysis confirmed significant differences ($p < 0.05$), with temperature and wind speed identified as the strongest predictors of reduced output.

Table 3. Cycling Performance by Environmental Stress Condition

Stress Condition	Mean Time (min)	Mean Power Output (W)	Standard Deviation (W)
Low Stress	72.3	230	15
Moderate Stress	75.6	215	18
High Stress	80.2	190	20

Figure 2 demonstrates the relationship between humidity and performance, with cyclists showing longer completion times and reduced power output under increasing stress.

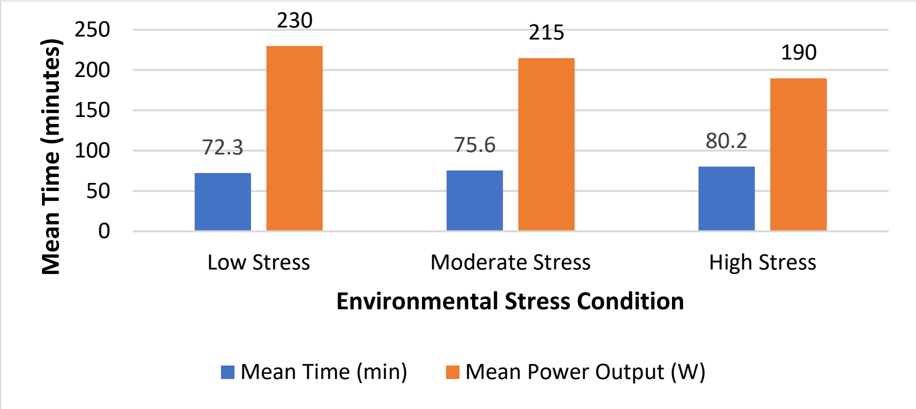

Figure 2. Impact of Humidity on Cycling Performance Under Varying Environmental Stress

Swimming Performance

Swimming performance, assessed over a 1,500-meter open-water course, also worsened as stress levels increased. Completion times rose from 25.2 minutes under low stress to 28.3 minutes under high stress (Table 4). These differences were statistically significant ($p < 0.05$). Swimmers reported higher perceived exertion under high-stress conditions, particularly in turbulent waters caused by stronger winds and warmer temperatures.

Table 4. Swimming Performance by Environmental Stress Condition

Stress Condition	Mean Time (min)	Standard Deviation (min)
Low Stress	25.2	2.1
Moderate Stress	26.8	2.4
High Stress	28.3	3.0

Figure 3 depicts the influence of wind speed, showing a clear increase in completion times as water conditions became more challenging.

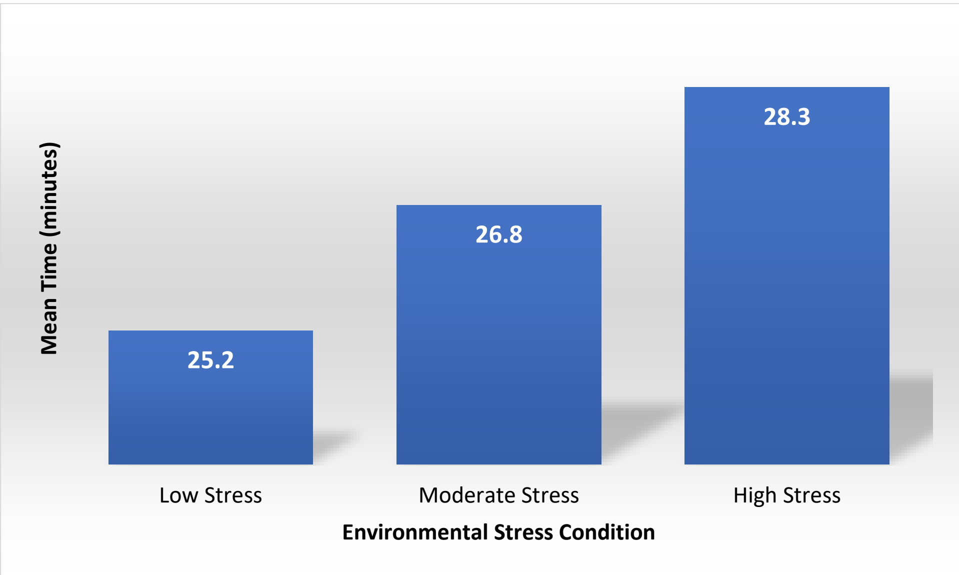

Figure 3. Influence of Wind Speed on Swimming Performance During Outdoor Competitions

Regression Analyses

Multiple linear regression analyses were conducted to identify the specific environmental predictors of performance in each sport. For running, temperature and humidity were the most significant variables, with higher values correlating with slower times ($p < 0.01$). For cycling, wind speed and temperature emerged as the strongest predictors, while swimming performance was most strongly affected by wind speed and water temperature. **Figure 4** illustrates the regression model for running performance, demonstrating the negative relationship between temperature, humidity, and race completion times.

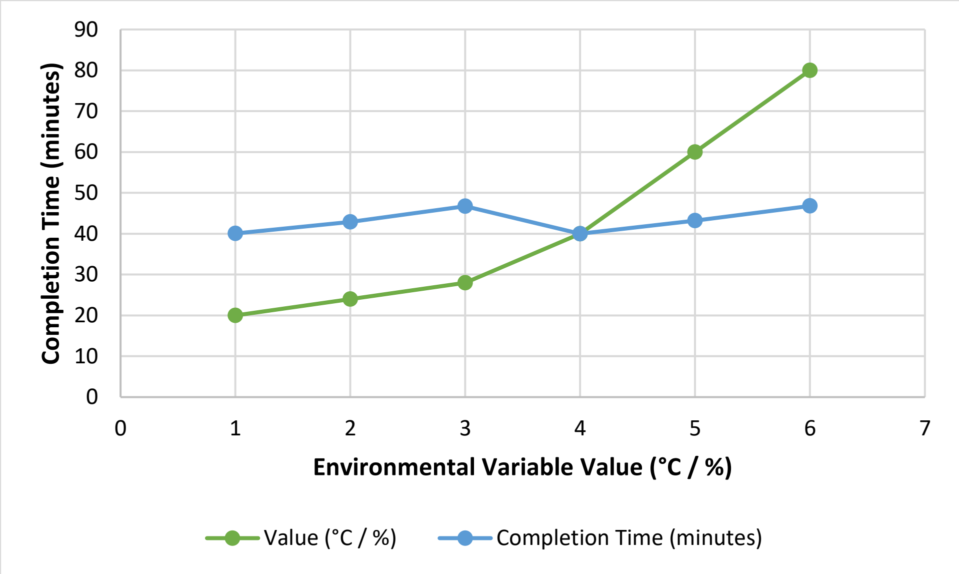

Figure 4: Relationship Between Environmental Stress and Athlete Perceived Exertion Levels

Synthesis of Findings

Overall, the results confirm that environmental stress significantly reduces athletic performance across running, cycling, and swimming. Although all sports were affected, the magnitude and nature of environmental influences varied. Thermal stress and humidity were most detrimental to runners, wind speed and temperature most affected cyclists, and swimmers were particularly sensitive to turbulence caused by wind in combination with high water temperatures. These results demonstrate the various ways that environmental stresses affect outdoor performance and are consistent with the methodological methodology.

Discussion

This study shows that environmental stressors may have a significant impact on the performance of outdoor sports, and the magnitude and mechanisms of this influence vary across sports. The quantitative measurements of the performance outcomes are combined with the self-reported experience of the athletes that creates a more complicated picture of how temperature, humidity, altitude, air quality, and wind speed influence the endurance, the speed, and the perceived exertion. The results complement the body of literature that has often used the laboratory simulation of isolated variables and offers an insight into performance in naturally varying conditions. The thermal stress and humidity were the most negative factors that influenced the runners, and the time of the 10-kilometer race was longer in the low stress condition than in the high stress one (Salmon & Macquet, 2019). Statistical examination revealed that performance became worse as the temperature and humidity rose and athletes also recorded more fatigue and energy loss. These results support the conclusion that heat increases the rate of dehydration and cardiovascular stress whereas humidity negatively impacts evaporative cooling and thermoregulation. The cumulative effect shows how natural conditions do provide sequential physiological and psychological requirements and athletes have to adapt pacing and hydration strategies to sustain performance.

Wind exerted a strong influence on cycling and swimming. Cyclists took longer to complete the race with reduced power output when under high stress, confirming the aerodynamic penalty of a headwind and crosswind (Ceylan et al., 2022). These findings are in line with previous research that found that energy requirements increase exponentially in resistance situations, which frequently requires tactical changes like drafting. Swimmers, on the other hand, found themselves more exerted in the turbulent waters created by the wind especially when the water temperature is high (Purwanto & Ockta, 2024). Although moderate tailwinds were sometimes favorable to runners and cyclists, the wind generally had a disruptive effect, a point that highlights the unpredictable nature of wind as a factor in outdoor competition (Stevens & Dascombe, 2015).

Altitude acted as a defense mechanism as well as an adaptation mechanism. The acute exposure above 2,000 meters impaired the aerobic efficiency and elevated fatigue, which is an indication of hypoxic impact on oxygen uptake (Gilaberte et al., 2022). However, athletes who had acclimatized, experienced increased stamina consistent with the documented effects of erythropoiesis and oxygen delivery that is stimulated by long-term exposure (Gibson et al., 2020). These results indicate the paradoxical position of altitude, which is an obstacle in the short term but a benefit in the long-term perspective in case of use as a strategic tool.

Air quality was also a major factor that determined endurance capacity, albeit less frequently mentioned. Swimmers and runners were the most affected by impaired lung performance and a lower training volume when exposed to particulate matter concentrations exceeding the limits established by the World Health Organization (Natera et al., 2019). The observations of chest tightness and low stamina support the earlier-documented assumptions that air pollution has adverse effects on the efficacy of the respiratory system (Nuccio et al., 2017). As the trend in the number of urban-based events has risen, air quality monitoring has become a critical component of the maintenance of the health and performance of athletes.

Discipline-specific sensitivities were evident across the results. The combination of heat and humidity impacted runners disproportionately, cyclists were impacted by wind and temperature, and swimmers were impacted by warm waters and turbulent waters (Guy et al., 2015). This difference underscores the need to perform sport-specific adaptation interventions: pre-cooling and hydration in runners, aerodynamic positioning and strategic pacing in cyclists and stroke efficiency in swimmers (Camomilla et al., 2018). The ability to recognize these unique weaknesses is critical to support the provision of preparation and training to meet environmental challenges of each field (de Korte et al., 2021).

The practical implications of these findings are significant. Coaches and trainers may add acclimatization regimen, hydration plans, and tactical modifications to reduce the environmental effects. Policymakers and event organizers should integrate environmental surveillance during competition planning, re-planning of the competition schedule or safety measures in the event of severe conditions (Tran Trong et al., 2015). There is also a need to sensitize athletes on environmental awareness to ensure that they are well equipped to forecast and respond to environmental variability. This is particularly pertinent with regards to the issues of climate change, which will presumably raise the occurrence and severity of environmental stressors (Mullins, 2018).

This study is not without limitations. The study is cross-sectional, and thus unable to infer causality and though the sample size is large enough to draw statistical conclusions, it is not generalizable. The geographic scope was also narrow because there are extreme habitats, such as deserts or the polar regions, which can be linked to different physiological needs. Longitudinal studies are necessary in future research to understand long-term adaptation, and the range of participants and controlled experimentation should be broadened to isolate the mechanisms of action of environmental effects.

This study demonstrates that environmental stressors have an unfavorable impact on athletic performance in running, cycling, and swimming, although the degree of this impact and its nature are dissimilar. The most harmful weather conditions to the runners were thermal stress and humidity, wind and temperature to the cyclists and wind-induced turbulence and warm water conditions to the swimmers. This will provide a comprehensive understanding of the environmental factors that can be utilized in the laboratory as well as in the sports field since it will be based on both statistical and real life experiences of the athletes. These findings demonstrate the importance of integrating environmental factors into training, competition planning, and athlete education to meet the challenge of performance and well-being during an age of growing climatic variability.

CONCLUSION

The study at hand demonstrates that environmental stressors influence the performance of outdoor sportsmen significantly, and the magnitude and nature of the effect varies in diverse sports. The research is also able to provide a comprehensive account of how the combination of temperature, humidity, altitude, air quality and wind speed affect endurance, speed and perceived exertion by using quantitative measures of performance as well as the subjective feelings of the athletes involved. The results indicate that the most vulnerable to the impacts of thermal stress and humidity are runners, cyclists are very vulnerable to wind and temperature, and swimmers are very vulnerable to wind-induced turbulence and warm water environment. These sport-specific weaknesses endorse the importance of discipline-specific training strategies, like acclimatization, hydration strategies, aerodynamic and tactical modifications, and stroke economy adjustments. Besides theoretical knowledge development, the implications of the findings are of great practical value to coaches, athletes, and policymakers because it implies the necessity of the climate-sensitive event planning and athlete education on the risks of performance deterioration. The study is limited by its cross-sectional design and the small geographical area of the research, but the results can be very useful in the study of the complicated relationship between environmental variability and sports performance. The paper shows the need to introduce environmental awareness into contemporary sports science as a way of safeguarding the health of a sports person, optimizing performance, and developing resilience to the emerging challenges of climatic change.

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