**The Effect of Weather Parameters on Triathlon Race Performance: Ironman 70.3 and Full Ironman Analysis**

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**Abstract**

Understanding the impact of environmental conditions on triathlon performance is crucial for athletes across competitive levels. This study assesses the relationship between weather parameters, course characteristics, and triathlon performance in Ironman 70.3 and full Ironman races. Results from 931 races involving 1,480,230 participants were analyzed alongside comprehensive environmental data using multiple statistical and machine learning approaches. Weather variables demonstrated 3-5 times greater impact than elevation features across all race segments, with temperature emerging as the dominant predictor. Optimal performance occurred within moderate temperature ranges (air: 19-27°C, water: 20-24°C). XGBoost models demonstrated superior predictive power (R² = 0.91 for swim segments, 0.61 overall) compared to other approaches. Professional athletes showed stronger correlations between environmental factors and performance, but had approximately 30% less sensitivity to temperature extremes than age-group athletes. Half Ironman events showed higher weather-to-elevation impact ratios than Full Ironman races, challenging assumptions about how environmental effects scale with race distance. Female athletes exhibited greater sensitivity to humidity and temperature variations, while male athletes showed stronger impacts from wind conditions. These findings provide evidence-based guidelines for athletes, coaches, and race organizers to enhance both performance quality and participant safety.

Keywords: Ironman, triathlon, weather parameters, performance, machine learning

**Introduction**

Triathlon is a demanding multi-sport endurance event combining swimming, cycling, and running completed in immediate succession. Among the most prestigious triathlon formats are the Ironman races, known for their extreme distances and worldwide popularity. The full Ironman consists of a 3.8 km swim, 180 km bike ride, and 42.2 km marathon run, while the Ironman 70.3 (Half Ironman) covers half those distances: 1.9 km swim, 90 km bike, and 21.1 km run. Both formats require months of intense training, strategic preparation, and exceptional endurance, making them milestones in any triathlete's journey.

Endurance events are particularly sensitive to environmental conditions, which can significantly affect athlete performance. Weather critically impacts endurance performance because the body must balance intense metabolic heat production with effective thermoregulation. High temperatures and humidity reduce sweat evaporation, causing overheating, accelerating fatigue, and increasing heat illness risk. Conversely, cold conditions increase energy expenditure for warmth and can impair muscle function. Water temperature similarly affects swimmers: cold water risks hypothermia and reduces muscle efficiency, while overly warm water prevents necessary cooling. These factors force the body to divert energy away from propulsion toward temperature management, directly slowing pace, increasing perceived effort, and elevating safety risks.

Previous research on running and cycling indicates that temperature and humidity have optimal ranges for peak performance, with performance decreasing at both high and low extremes. In triathlon contexts, water temperature also plays a crucial role during the swim segment, potentially affecting athlete safety and speed. Although several studies examine either Ironman 70.3 or full Ironman races independently, a unified analysis comparing both distances using a consistent data processing pipeline and advanced predictive modeling is lacking. Moreover, few studies leverage machine learning techniques alongside traditional statistical methods in this context.

The primary purpose of this study is to quantify the effects of weather parameters, altitude, and elevation gain on finish times and split-discipline performance for both Ironman 70.3 and full Ironman athletes. The study addresses the following research questions:

1. How do air temperature, humidity, wind speed, water temperature, and altitude correlate with overall finish times?

2. Is the impact of these parameters similar for age groups and professionals?

3. Are there differential effects of weather on swim, bike, and run segments?

4. How does model performance (statistical vs. machine learning) compare in predicting race outcomes?

**Literature Review**

**Environmental Effects on Endurance Sports**

Environmental conditions, particularly air temperature and wind, have a significant impact on marathon and cycling performance. Higher temperatures consistently lead to slower finishing times and increased withdrawal rates in marathons, with optimal performance occurring at cooler temperatures; humidity, wind speed, and solar radiation also play roles, but their effects are often secondary to temperature and sometimes interrelated with it (Helou et al., 2012; Vihma, 2010; Tan et al., 2022; Gasparetto & Nesseler, 2020; Wang et al., 2024; Nikolaidis et al., 2019; Weiss et al., 2024; Knechtle et al., 2021).

In cycling and long-distance events, microclimatic variations and elevated particulate matter (PM2.5) levels can pose additional risks, highlighting the need for direct environmental monitoring along race routes (Havenga et al., 2024). Overall, both elite and amateur athletes are affected by adverse weather conditions, but slower and less experienced participants tend to be more vulnerable to heat- and pollution-related performance declines (Vihma, 2010; Gasparetto & Nesseler, 2020; Hodgson et al., 2022; Knechtle et al., 2021).

**Prior Studies on Half and Full Ironman Weather Impacts**

Ironman triathlon performance is strongly influenced by environmental conditions, especially temperature and air quality. Analyses of large datasets from professional and age-group races indicate that optimal weather conditions, specifically moderate air and water temperatures, result in the fastest race times, while heat, humidity, and air pollution can significantly impair performance.

Research on Ironman 70.3 events indicates that water temperatures above 22°C can lead to faster swim splits, while bike performance peaks around air temperatures of 20–25°C. Full Ironman studies show similar trends but also highlight that wind conditions disproportionately affect the bike segment due to longer distances.

The fastest Ironman race times are achieved with water temperatures above 22°C and air temperatures between 19–27°C for professionals, and around 24°C (water) and 27°C (air) for age-group athletes. Races held in these conditions, such as Ironman Brazil Florianopolis and Ironman Barcelona, consistently yield better results (Knechtle et al., 2025; Knechtle et al., 2024).

High temperatures (e.g., 29°C dry, 27°C humid) increase core body temperature and fluid loss. Faster athletes tend to tolerate greater body mass loss and higher core temperatures, while slower athletes show more muscle damage and reduced muscle performance (Del Coso et al., 2014; Baillot & Hue, 2015). For every degree above optimal wet bulb globe temperature (WBGT), endurance performance drops by 0.3–0.4% (Mantzios et al., 2021).

Altitude affects performance primarily through reduced partial pressure of oxygen, leading to quicker fatigue in aerobic activities, though lower air density at higher elevations can reduce aerodynamic drag, potentially benefiting cycling. Every 1,000 feet of elevation decreases oxygen availability by approximately 3%, affecting aerobic performance (Bassett & Howley, 2000). Higher elevations trigger EPO production and increased red blood cell concentration (Burtscher et al., 2011). Power output typically decreases 7-10% for unacclimated athletes at moderate altitudes (5,000-8,000 feet) (Burtscher et al., 2011).

**Methodological Approaches in Performance Prediction**

The analysis of performance prediction in endurance sports related to weather conditions uses a variety of advanced methodological methods, mainly focusing on statistical modeling and machine learning algorithms. Studies often use regression analysis, including linear, non-linear (e.g., second-order polynomial), and mixed-effects models, sometimes adding polynomial splines for specific environmental factors like water temperature on swim times (Gibson, 2024).

Quantile Regression (QR) is also used to understand how environmental variables such as temperature, elevation, and water type influence race times across different athlete performance levels (Zhao et al., 2024). Besides traditional statistics, machine learning (ML) algorithms are widely applied, including Decision Tree Regressor, Random Forest Regressor, and XG Boost Regressor to forecast overall race times, with features often including event location, water, and air temperature (Thuany et al., 2023; Knechtle et al., 2025; Mantzios et al., 2022).

For more complex temporal data, models like Recurrent Neural Networks (RNN), Long Short-Term Memory (LSTM), and Gate Recursive Unit (GRU) are used to predict running performance and physiological indicators based on environmental inputs like temperature (Yang et al., 2021). Environmental data such as air temperature, water temperature, relative humidity, wind speed, and solar radiation are typically collected from official race sources or weather stations, with derived metrics like Wet Bulb Globe Temperature (WBGT) and heat index calculated to evaluate overall heat stress (Mantzios et al., 2022; Baillot & Hue, 2015).

Model interpretability tools like SHAP (Shapley Additive Explanations) values and Partial Dependence Plots (PDP) are often employed to explain how various environmental features influence predictions (Thuany et al., 2023; Knechtle et al., 2025).

**Categorical Approach to Environmental Effects**

Recent studies use quantile regression to compare how weather and environmental factors affect triathlon performance across athlete categories such as professionals, recreational athletes, and age groups. For the top 50% of elite (professional) athletes, swim time is the most significant predictor of overall performance, while for slower elite athletes, bike time becomes more influential. Temperature and altitude positively impact race times for all groups, but the degree of influence varies by performance level.

Studies approach weather effects on triathlon performance by categorizing athletes, revealing distinct impacts and optimal conditions for each group (Gibson, 2024; Hermand et al., 2019; Knechtle et al., 2025; Nikolaidis et al., 2023). For full Ironman distances, professional athletes achieve optimal performance in water temperatures warmer than 22°C and air temperatures between 19–26°C (Knechtle et al., 2025). Wind speed is a significant predictor for swimming and cycling (Knechtle et al., 2020). Professionals may experience hyperthermia in extreme conditions (e.g., Kona marathon) (Knechtle et al., 2020; Knechtle et al., 2025).

For Ironman 70.3 age groups, cycling and running are more predictive of overall race performance than swimming (Nikolaidis et al., 2023). The age-related performance decline begins earliest in swimming for these athletes (Nikolaidis et al., 2023). For endurance runners, there is a progressive slowing as Wet Bulb Globe Temperature (WBGT) increases from 5°C to 25°C, with slower runners experiencing larger decrements (Baillot & Hue, 2015; Hermand et al., 2019; Mantzios et al., 2022).

**Identified Gaps and Theoretical Justification**

Research into the impact of weather on triathlons and Ironman races has highlighted several areas requiring further investigation. Most studies focus on professional athletes, with less attention given to recreational or age-group participants, limiting the generalizability of findings across the broader triathlon community (Knechtle et al., 2025). Current triathlon research suffers from a lack of detailed, granular environmental data and fails to sufficiently explore crucial environmental characteristics beyond common variables—such as altitude, terrain specifics, water temperature, and sea currents (Gibson, 2024; Knechtle et al., 2020, 2025; Nikolaidis et al., 2023; Zhao et al., 2024).

A comprehensive understanding of the precise optimal weather conditions for peak performance remains limited, particularly for non-professional athletes (Knechtle et al., 2025). Current research on triathlons is limited by its focus on popular races and regions, neglecting less-studied locations and diverse environments (Knechtle et al., 2025). Existing machine learning models often yield low predictive power (low R² scores), suggesting that additional variables, beyond environmental factors, are necessary to accurately predict Ironman triathlete performance (Knechtle et al., 2025).

The theoretical justification for this research includes recognizing that performance is influenced by a complex interplay of environmental, physiological, and demographic factors. This justifies the use of machine learning and multivariate models to capture these interactions (Knechtle et al., 2025). The need to mitigate health risks (e.g., heat stress) provides a theoretical basis for studying multiple weather and race location parameters, not just temperature, to inform athlete preparation and event management (Mantzios et al., 2021). Understanding how weather affects different athlete groups supports the development of tailored strategies for training, pacing, and heat adaptation, grounded in sports science and environmental physiology (Knechtle et al., 2025; Mantzios et al., 2021).

**Methodology**

**Races Data**

The race data was collected from the website "www.endurance-data.com" for events held between 2015 and 2023. Finish times, split times (swim, bike, and run), and overall placements for both age-group and professional athletes were recorded. Athlete demographic information (age, gender, and category) was also extracted, and personal information (names, bib numbers, and places) was removed to anonymize the data. Results of 1,480,230 athletes participating in 931 races were obtained across 337 locations, with 318 full Ironman races (548,002 athletes) and 613 Ironman 70.3 races (932,228 athletes).

**Race Characteristics**

This study addresses a significant methodological gap in triathlon performance analysis: the absence of a comprehensive study of the effect of race characteristics like venue altitude and elevation gain combined with weather on triathlon races. The elevation profile of an Ironman course represents one of the most significant fixed variables affecting race outcomes. Unlike weather conditions that vary year to year, the fundamental elevation characteristics remain relatively constant, providing a stable basis for comparative analysis and performance prediction.

The elevation data for Ironman triathlon venues was collected using a multi-source web scraping methodology that prioritizes accuracy through cross-validation. The primary parameters collected include venue altitude (elevation above sea level), bike course elevation gain (total climbing in feet), and run course elevation gain (total climbing in feet). The script employs a hierarchical three-tier approach with source prioritization:

1. Tier 1: TriathlonCourseInfo.com (comprehensive course descriptions for global triathlon events)

2. Tier 2: PJammCycling.com (specialized in detailed cycling course analysis)

3. Tier 3: Ironman.com Official Website (official race information from organizers)

**Weather Data**

All weather data was retrieved from the Open-Meteo API, which provides standardized historical weather measurements. The data was collected for all locations and dates based on geographic coordinates (latitude and longitude).

The following weather parameters were collected:

1. Temperature (°C): Maximum temperature (highest temperature recorded during the day), minimum temperature (lowest temperature recorded, usually after sunrise), and 10 AM temperature (representing typical mid-race conditions).

2. Relative Humidity (%): High humidity reduces sweat evaporation efficiency and affects perceived temperature. It's important for hydration planning, performance expectations, and heat management strategies.

3. Wind Speed (m/s): Influences cycling speeds and effort requirements. The average wind speed throughout the day was used since wind direction impact is relatively small due to the loop structure of most Ironman bike and run courses.

4. Air Pressure (hPa): Serves as an indicator of weather conditions and can affect oxygen availability at different elevations.

5. Cloud Coverage (%): Impacts the race conditions by influencing temperature perception and solar radiation exposure.

6. Solar Radiation (W/m²): The total amount of solar energy reaching the Earth's surface, contributing to thermal stress and heightened perceived exertion.

7. Wet Bulb Globe Temperature (WBGT) (°C): A composite temperature used to estimate the combined effect of temperature, humidity, wind speed, and solar radiation on humans. The Australian Bureau of Meteorology approach was adopted due to its superior alignment with official WBGT regulations and thresholds used by governing bodies.

8. Water Temperature (°C): A critical environmental variable with substantial physiological and performance implications. Due to the difficulty of accessing historical data, a mathematical modeling methodology was developed to provide statistically validated water temperature estimates for global Ironman venues.

**Data Preprocessing Workflow**

The data processing workflow traced the transformation of raw race data through seven sequential stages:

1. Initial Data Collection: Collection of Ironman races held between 2015 and 2023, including basic race information and geographic coordinates.

2. Data Transformation and Segregation: Separation of full Ironman and half Ironman races, collection of athletes' results, anonymization, and standardization of data.

3. Elevation Data Extraction: Addition of venue altitude and course-specific elevation data (bike elevation gain, run elevation gain).

4. Basic Weather Data Integration: Addition of temperature metrics, relative humidity, wind speed, atmospheric pressure, and cloud coverage.

5. Solar Radiation Calculation: Addition of solar radiation values.

6. Water Temperature Estimation: Calculation of water temperature estimates.

7. WBGT Calculation: Computation of all races WBGT values.

8. Split Times and Total Time Cleaning: Removal of times below world records and above cut-off times.

**Data Analysis Approach**

The analysis employed multiple statistical and machine learning approaches to ensure robust findings:

1. Statistical Analysis: Descriptive statistics, correlations, and simple linear regression to establish baseline relationships between environmental factors and performance.

2. Linear Regression Models: Applied to assess relationships between environmental factors and performance times, separated by division (professional vs. age group) and gender.

3. Machine Learning Models:

- Decision Trees: Used to identify key environmental thresholds affecting performance.

- Random Forests: Applied to improve prediction accuracy and assess feature importance.

- XGBoost: Employed for maximum predictive power and to quantify complex feature interactions.

- Quantile Regression: Used to examine how environmental effects vary across different performance levels.

All analyses were conducted separately for full Ironman and Ironman 70.3 datasets to enable direct comparison of environmental effects between the two race formats.

**Results**

**Statistical Analysis of Environmental Parameters**

Full Ironman races exhibited considerable variation in environmental conditions. Weather parameters included temperatures ranging from 9.0°C to 42.0°C (average: 24.2°C), relative humidity from 11.0% to 100.0% (average: 68.3%), and water temperature from 5.0°C to 30.0°C (average: 21.0°C). Elevation parameters showed location elevation ranging from -115.0m to 2299.0m (average: 199.6m), bike course elevation gain from 165.0m to 3269.0m (average: 1156.0m), and run elevation from 23.0m to 2122.0m (average: 340.1m).

For Ironman 70.3 races, maximum temperatures ranged from 11.5°C to 40.4°C (average: 24.8°C), relative humidity from 6.0% to 100.0% (average: 66.3%), and water temperature from 5.0°C to 30.0°C (average: 21.9°C). The location elevation ranged from -115.0m to 2408.0m (average: 215.0m), bike course elevation gain from 49.0m to 3277.0m (average: 911.2m), and run elevation from 0.0m to 3067.0m (average: 274.2m).

| **Parameter** | **Full Ironman (Mean ± SD)** | **Ironman 70.3 (Mean ± SD)** |
| --- | --- | --- |
| Max Temperature (°C) | 24.23 ± 4.65 | 24.81 ± 4.95 |
| 10AM Temperature (°C) | 20.77 ± 4.39 | 21.44 ± 4.83 |
| Min Temperature (°C) | 15.92 ± 4.49 | 16.21 ± 4.76 |
| Relative Humidity (%) | 68.28 ± 17.52 | 66.31 ± 16.24 |
| Wind Speed (m/s) | 11.24 ± 6.09 | 11.42 ± 5.21 |
| Pressure (hPa) | 1015.91 ± 5.20 | 1015.24 ± 5.13 |
| Cloud Cover (%) | 52.69 ± 40.21 | 51.79 ± 40.95 |
| Water Temperature (°C) | 20.99 ± 6.47 | 21.87 ± 6.57 |
| WBGT | 21.84 ± 4.07 | 22.24 ± 4.33 |
| Location Elevation (m) | 199.64 ± 341.63 | 215.02 ± 380.83 |
| Bike Elevation (m) | 1155.96 ± 811.08 | 911.17 ± 689.13 |
| Run Elevation (m) | 340.12 ± 518.02 | 274.18 ± 460.05 |

[TABLE 1: Descriptive Statistics for Environmental Parameters in Full Ironman and Ironman 70.3 Races]

Correlation analysis revealed several important relationships in both race formats:

- A strong positive correlation between maximum temperature and WBGT (r = 0.93), indicating that maximum temperature plays a significant role in determining heat stress.

- Temperature variables (max, 10 AM, min) were highly correlated, indicating consistent temperature patterns across race days.

- Location elevation exhibited weak negative correlations with temperature variables, reflecting the cooling effect of higher elevations.

- Bike and run elevation showed a moderate positive correlation (0.51), suggesting that venues with hilly bike courses often have hilly run courses as well.

[FIGURE 1: Correlation Matrix Showing Relationships Between Elevation and Weather Parameters]

**Linear Regression Analysis**

Linear regression models assessed the relationships between environmental factors and performance times across different divisions and genders. The analysis indicated that bike elevation was the strongest predictor of bike times, while temperature and WBGT were the most significant for running times.

For Full Ironman races, temperature showed a complex relationship with performance:

- For every 1°C rise in temperature, run time increased by about 0.91 minutes (54.65 seconds), with R²=0.034.

- For bike performance, course elevation was the most significant predictor, with bike time increasing by approximately 0.24 seconds per meter of elevation gain (R²=0.012).

Professional athletes exhibited stronger correlations between environmental factors and performance compared to age-group athletes. WBGT emerged as a significant predictor for run performance, with every 1 unit increase in WBGT associated with a 1.30-minute increase in run time.

For Ironman 70.3 races, the analysis showed:

- Maximum temperature was the strongest predictor of overall performance.

- Water temperature had a statistically insignificant impact on swim performance, with only a slight trend indicating faster swims in warmer water.

- Elevation factors had a proportionally greater impact on the shorter race format.

Comparative analysis between the two race formats revealed:

- Half Ironman showed higher weather-to-elevation impact ratios than Full Ironman.

- Water temperature had a significant effect on Full Ironman swim performance but virtually no impact on Half Ironman swims.

- Temperature effects were contradictory, with Full Ironman showing counterintuitive benefits with higher temperatures and Half Ironman showing expected performance decline.

[FIGURE 2: Temperature Impact Direction (min/°C) Comparison Between Full and Half Ironman]

**Machine Learning Analysis**

**Decision Tree Analysis**

Decision trees revealed more complex relationships between environmental variables and performance. For swim performance, WBGT emerged as the primary factor (22% importance) followed by water temperature (18% importance). For bike performance, location elevation was the second most important factor (13.9% importance) after minimum temperature. For run performance, relative humidity was identified as the top predictor (17.3% importance). Overall, weather factors dominated over elevation factors across all segments.

**Random Forest Analysis**

Random Forest models consistently outperformed Decision Tree models across all race segments, with the most significant gains in the bike segment. They confirmed the importance of WBGT for swim performance, average wind speed for bike performance, and relative humidity for run performance. Weather factors accounted for 48-59% of predictive power compared to 16-32% for elevation factors.

**XGBoost Analysis**

XGBoost models demonstrated the highest predictive power among all approaches, with R² values of 0.91 for swim segments, 0.63 for bike segments, 0.68 for run segments, and 0.61 for overall times. Maximum temperature consistently emerged as the most influential feature across all segments, with importance scores of approximately 800 for swimming, 350-400 for biking, and 300-320 for running.

For Full Ironman races, weather factors demonstrated substantially higher impact than elevation factors:

- For swim: Weather accounted for ~2700 importance points vs. ~550 for elevation

- For bike: Weather accounted for ~1350 importance points vs. ~370 for elevation

- For run: Weather accounted for ~1180 importance points vs. ~350 for elevation

- For overall time: Weather accounted for ~1250 importance points vs. ~300 for elevation

Similar patterns were observed for Half Ironman races, with weather-to-elevation impact ratios of 12.3x for swimming, 3.6x for biking, 4.6x for running, and 5.1x overall, compared to Full Ironman ratios of 6.1x, 4.2x, 3.8x, and 4.7x respectively.

| **Segment** | **Half Ironman Weather/Elevation Ratio** | **Full Ironman Weather/Elevation Ratio** |
| --- | --- | --- |
| Swim | 12.3x | 6.1x |
| Bike | 3.6x | 4.2x |
| Run | 4.6x | 3.8x |
| Overall | 5.1x | 4.7x |

[TABLE 2: Weather vs. Elevation Impact Ratio Comparison Between Full and Half Ironman]

Division-specific analysis revealed that professional athletes' performance was more predictable based on environmental factors, but age-group athletes showed greater absolute sensitivity to temperature extremes, with professionals demonstrating approximately 30% less sensitivity to temperature deviations.

| **Division** | **Swim** | **Bike** | **Run** | **Overall** |
| --- | --- | --- | --- | --- |
| MPRO | 0.89 | 0.37 | 0.58 | 0.68 |
| FPRO | 0.87 | 0.34 | 0.55 | 0.65 |
| Male\_AG\_Young | 0.76 | 0.28 | 0.49 | 0.56 |
| Male\_AG\_Old | 0.75 | 0.30 | 0.52 | 0.59 |
| Female\_AG\_Young | 0.77 | 0.26 | 0.48 | 0.54 |
| Female\_AG\_Old | 0.74 | 0.28 | 0.51 | 0.57 |

[TABLE 3: Environmental Sensitivity (R² Values) by Division and Race Segment]

**Quantile Regression Analysis**

Quantile regression revealed how environmental factors affected athletes differently depending on their performance level. For Full Ironman, the effect of temperature increased dramatically for slower athletes, reflecting their longer exposure during afternoon heat. For Half Ironman, temperature effects were stronger for faster athletes (lower quantiles) with less variation across quantiles, likely because most athletes finish before peak afternoon temperatures.

The relative importance of race segments also differed between race formats and across performance levels:

- Full Ironman: The run coefficient increased significantly from lower to higher quantiles (1.03 to 1.20), becoming disproportionately important for slower athletes.

- Half Ironman: A similar increasing pattern was observed (1.05 to 1.15) but with a less extreme slope, as the shorter run distance creates less differential impact.

Elevation effects showed different patterns across performance quantiles:

- Full Ironman: More pronounced and consistent effects across all quantiles, with a generally decreasing trend from elite to recreational athletes.

- Half Ironman: U-shaped pattern, with stronger effects at both extremes of the performance spectrum.

Water temperature had a more significant impact on Full Ironman overall performance due to the longer swimming portion, while its effect was minimal in Half Ironman races.

**Discussion**

**Interpretation of Findings across All Models**

Our comprehensive analysis revealed several consistent patterns across different modeling approaches. Temperature emerged as the dominant environmental factor affecting triathlon performance across all race segments and athlete divisions. The relationship between temperature and performance followed a non-linear pattern, with optimal performance occurring in moderate temperature ranges (19-27°C for air temperature, 20-24°C for water temperature). Heat stress metrics (WBGT) proved to be better predictors than absolute temperature alone, particularly for running segments.

Course elevation characteristics showed significant but less dominant effects compared to weather variables. Bike elevation gain consistently emerged as the strongest elevation predictor for bike performance, increasing bike time by approximately 0.01 minutes per meter of elevation gain. Location elevation demonstrated more complex effects, with intermediate altitudes sometimes associated with improved performance.

Wind and humidity emerged as secondary but significant factors. Average wind speed showed particular importance for bike segments, with approximately 0.5 minutes added per 1 km/h increase in wind speed. Relative humidity demonstrated its strongest impact on running performance, particularly for older age-group athletes. Wind effects were proportionally more important in Full Ironman compared to Half Ironman bike segments.

Water temperature analysis revealed a distinct U-shaped relationship with swim performance, with optimal temperature at 22.5°C and performance declining at both higher and lower extremes. Effect size varied by athlete category: professionals showed an effect of 0.38-0.41 minutes per °C deviation from optimal, while age-group athletes showed larger effects of 0.49-0.56 minutes per °C.

Our analysis revealed substantial variations in environmental sensitivity across athlete categories. Professional athletes showed higher R² values in all models, indicating stronger relationships between environmental factors and performance. However, age-group athletes demonstrated greater absolute sensitivity to temperature extremes. Female athletes exhibited higher sensitivity to humidity and temperature variations, while male athletes showed greater impacts from wind conditions.

**Methodological Strengths and Innovations**

This study makes several methodological contributions to the field of environmental impacts on endurance performance. By developing specialized environmental metrics including a validated water temperature estimation model and implementing the Australian Bureau of Meteorology approach for WBGT calculation, we created analytical tools that can be applied in future research. The application of multiple modeling approaches demonstrated the value of methodological triangulation, with each approach revealing complementary insights about environmental impacts on performance.

Our comprehensive dataset, spanning 931 races and over 1.4 million individual performances, represents the largest analysis of environmental impacts on triathlon performance to date. The inclusion of both Half Ironman and Full Ironman events allowed for direct comparison of environmental effects between race formats, revealing important differences in how environmental factors influence performance at different race distances.

The use of advanced machine learning techniques, particularly XGBoost models, significantly improved predictive power compared to traditional statistical approaches. These models were able to capture complex, non-linear relationships between environmental variables and performance that would be difficult to identify using conventional methods.

**Practical Implications**

For Athletes and Coaches

The findings of this study have important implications for training and race preparation. Athletes should prioritize course-specific training that mimics the environmental conditions and elevation profiles of target races. Professional athletes would benefit from data-driven race selection strategies based on personal environmental sensitivities, while age-group athletes should focus on heat acclimation training, particularly older competitors who showed increased sensitivity to heat stress.

Gender-specific training recommendations include more focused heat and humidity adaptation training for female athletes and more wind-resistance training for male athletes, especially for biking. Race strategy should also be adjusted based on environmental conditions, with more conservative pacing in high-humidity conditions for female athletes and adjustments for expected wind conditions for male athletes.

For Race Organizers

Race organizers can use these findings to inform scheduling decisions, safety protocols, and course design. Races with potentially extreme temperatures should incorporate enhanced cooling strategies, especially for run courses where the impact of heat stress is most pronounced. Safety thresholds should be adjusted based on the demographic profile of participants, with more conservative limits for events with higher proportions of age-group and older athletes.

Course design considerations include balancing bike course elevation gain with local climate conditions and providing additional aid stations and cooling resources for run courses in high WBGT conditions. Monitoring and reporting environmental conditions, particularly WBGT values, would help athletes make informed decisions about race strategy and preparation.

**Limitations and Future Research**

While this study provides valuable insights, several limitations should be acknowledged. Water temperature data were partially estimated rather than directly measured for all races, potentially introducing imprecision despite our validation efforts. Weather data relied on daily averages and specific time points rather than continuous race-day monitoring. Some environmental factors, like precipitation and air quality, weren't consistently available across all race venues.

Methodological constraints include the inability to account for individual athlete characteristics beyond basic demographics and potential confounding variables such as athlete experience, equipment choices, and nutrition strategies. The analysis also focused primarily on separate environmental effects rather than their interactions, which may be significant in real-world race conditions.

Future research should incorporate real-time physiological monitoring during competition to better understand how environmental factors affect individual athletes differently. Personalized prediction models could be developed that account for both environmental conditions and athlete-specific characteristics. Research should also examine how climate change may alter the environmental challenges faced by triathletes in coming decades and evaluate the effectiveness of various heat mitigation strategies across different athlete demographics.

**Conclusion**

This study represents the most comprehensive analysis to date of environmental impacts on Ironman and Half Ironman triathlon performance, examining over 1.4 million individual performances across 931 races worldwide. Through the integration of traditional statistical approaches and advanced machine learning techniques, we have quantified the complex relationships between weather parameters, course characteristics, and athlete performance across different demographic groups and race formats.

Our findings conclusively demonstrate that environmental factors significantly influence triathlon performance, with weather variables having 3-5 times greater impact than elevation features across all race segments. Temperature emerged as the dominant predictor, with optimal performance occurring in moderate ranges (19-27°C for air temperature, 20-24°C for water temperature). We identified distinct environmental sensitivity patterns across athlete demographics—professionals demonstrated stronger correlations between environmental factors and performance, but showed approximately 30% less sensitivity to temperature extremes than age-group athletes.

The comparative analysis between Half Ironman and Full Ironman events revealed important format-specific patterns, challenging the assumption that environmental effects simply scale with race distance. Half Ironman events showed higher weather-to-elevation impact ratios than Full Ironman and demonstrated more balanced effects of the three disciplines across performance levels.

The practical implications of this research are substantial for athletes, coaches, and race organizers. For athletes, our findings support the development of individualized environmental preparation strategies based on personal characteristics and targeted race conditions. For coaches, the quantified environmental effects enable more precise performance predictions and race strategy recommendations. For race organizers, our results provide evidence-based guidelines for scheduling decisions, safety protocols, and course design considerations that can enhance both performance quality and participant safety.

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