

# Effects of Weather Parameters on Endurance Running Performance: Discipline-specific Analysis of 1258 Races

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## ABSTRACT

MANTZIOS, K., L. G. IOANNOU, Z. PANAGIOTAKI, S. ZIAKA, J. D. PÉRIARD, S. RACINAIS, L. NYBO, and A. D. FLOURIS. Effects of Weather Parameters on Endurance Running Performance: Discipline-specific Analysis of 1258 Races. *Med. Sci. Sports Exerc.*, Vol. 54, No. 1, pp. 153–161, 2022. **Introduction:** This study evaluated how single or combinations of weather parameters (temperature, humidity, wind speed, and solar load) affect peak performance during endurance running events and identified which events are most vulnerable to varying weather conditions. **Methods:** Results for the marathon, 50-km racewalking, 20-km racewalking, and 10,000-, 5000-, and 3000-m steeplechase were obtained from the official Web sites of large competitions. We identified meteorological data from nearby ( $8.9 \pm 9.3$  km) weather stations for 1258 races held between 1936 and 2019 across 42 countries, enabling analysis of 7867 athletes. **Results:** The wet bulb globe temperature (WBGT) across races ranged from  $-7^{\circ}\text{C}$  to  $33^{\circ}\text{C}$ , with 27% of races taking place in cold/cool, 47% in neutral, 18% in moderate heat, 7% in high heat, and 1% in extreme heat conditions, according to the World Athletics classification. Machine learning decision trees ( $R^2 = 0.21\text{--}0.58$ ) showed that air temperature (importance score = 40%) was the most important weather parameter. However, when used alone, air temperature had lower predictive power ( $R^2 = 0.04\text{--}0.34$ ) than WBGT ( $R^2 = 0.11\text{--}0.47$ ). Conditions of  $7.5^{\circ}\text{C}\text{--}15^{\circ}\text{C}$  WBGT (or  $10^{\circ}\text{C}\text{--}17.5^{\circ}\text{C}$  air temperature) increased the likelihood for peak performance. For every degree WBGT outside these optimum conditions, performance declined by 0.3%–0.4%. **Conclusion:** More than one-quarter of endurance running events were held in moderate, high, or extreme heat, and this number reached one-half when marathons were excluded. All four weather parameters should be evaluated when aiming to mitigate the health and performance implications of exercising at high intensities in a hot environment with athletes adopting heat mitigation strategies when possible. **Key Words:** MARATHON, HEAT, COLD, OLYMPICS, RACE, COMPETITION

The implications of weather conditions on athletic performance have raised considerable attention, owing to the escalating climate change (1–3), the desire to go

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beyond existing levels of human performance (4,5), and the safe globalization of sports across all continents and climates (e.g., first Youth Summer Olympics in Africa in 2026). The effect of weather parameters such as temperature (i.e., heat or cold), relative humidity (i.e., dry or humid), wind speed, and solar radiation can undermine both athletic performance and event organization (2–4,6). It is clear that heat stress affects several parameters of importance for exercise endurance with associated performance impairment in both middle distance and marathon races, but with large variation in the average reported effect from ~3% to 14% (7,8). Translating this to Eliud Kipchoge's 2018 World Record at the Berlin Marathon in temperate conditions ( $17^{\circ}\text{C}$  wet bulb globe temperature [WBGT]) means an additional 3 min and 16 s, which would make his race only the seventh fastest in the world at that time, had he ran in warmer conditions (i.e.,  $25^{\circ}\text{C}$  WBGT—calculation based on a 2.7% performance decrement as suggested by Ely et al. [8]).

To date, the handful of studies on the topic have clearly shown a strong link between weather parameters and endurance

running performance, but this is mainly derived from studies on marathon running and its application in other endurance events is unclear (7–12). Also, the focus has been primarily on the effects of high temperatures, although low temperatures (13,14) as well as high relative humidity (10), wind speed (15), and solar radiation (16) can also affect race finishing times. Understanding the effects of the different weather parameters can be critical for athletes and coaches aiming to optimize running performance as well as for event organizers and officials wishing to mitigate the risk of heat illness to competitors. Additionally, this knowledge will improve sports science education and create opportunities for companies that develop wearables and sports-related technologies and applications. In this retrospective study, we analyzed the endurance running events included in the list of Olympic sports: marathon, 50-km racewalking, 20-km racewalking, 10,000-m run, 5000-m run, and 3000-m steeplechase. We aimed to determine 1) the weather conditions observed in previously held endurance events, 2) the weather parameters associated with peak performance, and 3) the events most vulnerable to varying weather conditions.

## METHODS

**Performance data.** Results for the marathon, 50-km racewalking, 20-km racewalking, and 10,000-, 5000-, and 3000-m steeplechase were obtained from the official Web sites of the largest competitions in the world (see Table S1, Supplemental Digital Content, Appendix, <http://links.lww.com/MSS/C408>): Commonwealth Games, Diamond Leagues, World Athletics Continental Cup, World Athletics Gold Label Races, Olympic Games, World Athletics Race Walking Team Championships, and World Championships. Finish times for all races were collected from the first year of each competition for which data were available online until the end of 2019. The collection of these data was completed between February 2016 and September 2020. For each one of the World Athletics Gold Label Races (marathons), we screened out the earlier one-third (the initial  $12 \pm 5$  yr of each race), which were typically not established within the running community (17) and showed large performance fluctuations year on year that were unrelated to weather conditions. In the remaining two-thirds of the races, we followed previous methodology (8) and retrieved data for the top 3 (reflecting elite athletes) as well as the 25th, 50th, 100th, and 300th place finishers (reflecting well-trained runners). In all other competitions, we retrieved data for all athletes competing in the finals.

For each race, we defined performance as the percent difference between an athlete's finish time and the competition's standing record at that time (8). For instance, Hicham El Guerrouj won the Olympic 5000-m event in 2004 in a time of 13:14.39, while the standing Olympic record was 13:05.59, resulting in a 1.12% decrement in performance. Likewise, Eliud Kipchoge won the 2018 Berlin Marathon in 2:01:39, while the standing Berlin Marathon record was 2:02:57, resulting in a 1.05% improvement in performance. Expressing performance against the standing event record considers important race-specific factors, particularly in events held outside the track

and field stadium. To gauge our results against the best possible finishing time, we repeated all our analyses by expressing performance as a percent difference between an athlete's finish time and the standing world record at that time (i.e., the standing world record in 2018 for the above example). We present these results in the Online Supplement (see Figs. S1 and S2, Supplemental Digital Content, Appendix, <http://links.lww.com/MSS/C408>) because they were similar to those seen for the standing event record.

**Weather data.** Our weather analysis builds on recently introduced methods to assess environmental conditions during sporting events at a large and global scale (18). During September 2020, we obtained the date, time, and location for each race from its official Web site (detailed list provided in Table S1, <http://links.lww.com/MSS/C408>), but the relevant longitude and latitude were obtained from [www.locationiq.com](http://www.locationiq.com). Weather data (air temperature, dew point, wind speed, and cloud coverage) corresponding to the time at halfway of the first finisher in each race were obtained from the closest meteorological station using the official data set of the National Oceanic and Atmospheric Administration ([www.noaa.gov/data/global-hourly](http://www.noaa.gov/data/global-hourly)). In cases where these data were not available (232 out of 1258 races), we retrieved the information from widely used meteorology Web sites ([www.wunderground.com](http://www.wunderground.com) and [www.weatherspark.com](http://www.weatherspark.com)). Wind speed was adjusted for height above the ground and air friction coefficient (i.e., large city with tall buildings) using previous methodology (19,20). Dew point data were converted to relative humidity (21). For cases where cloud coverage was not available in the National Oceanic and Atmospheric Administration data sets, the cloud coverage (in okta) was computed using relative humidity data based on previous methodology and applying coefficients of 0.25 for low and high as well as 0.5 for middle clouds, as previously suggested (22). Solar radiation was calculated using the date, time, and coordinates of each race (23), while accounting for cloud coverage (24). Thereafter, the heat index ([www.wpc.ncep.noaa.gov/html/heatindex.shtml](http://www.wpc.ncep.noaa.gov/html/heatindex.shtml)), simplified WBGT (25), and WBGT (26), were calculated using previous methodology. To validate our approach for assessing weather conditions during the races, we compared our meteorological data against those reported by the race organizers on the official webpage of each race, for a total of 140 races (11% of total races; 2% of marathons, 33% of 50-km racewalking, 39% of 20-km racewalking, and 21% of 10,000-m, 20% of 5000-m, and 30% of 3000-m steeplechase races).

**Data management and statistical analysis.** For the cross-validity assessment of our weather data, we used Spearman's correlation coefficient, Wilcoxon signed-rank test, and root-mean-square error to compare the weather data from the closest meteorological station against those reported by the race organizers. In the remaining analyses, data for each of the studied events (marathon, 50-km racewalking, 20-km racewalking, and 10,000-, 5000-, and 3000-m steeplechase) were analyzed separately. To address our first objective in terms of identifying the weather conditions in which previous endurance events were held, we categorized the WBGT of each

race based on the World Athletics competition medical guidelines:  $\leq 10.0^{\circ}\text{C}$  = cold/cool,  $10.1^{\circ}\text{C}$ – $18.0^{\circ}\text{C}$  = neutral,  $18.1^{\circ}\text{C}$ – $23^{\circ}\text{C}$  = moderate heat,  $23.1^{\circ}\text{C}$ – $28.0^{\circ}\text{C}$  = high heat, and  $>28.0^{\circ}\text{C}$  = extreme heat (27). These criteria may seem rather conservative for the general population, but they are suited for well-trained and elite athletes who exercise at a high intensity (i.e., elevated rate of metabolic heat production) for a prolonged period.

To address our second objective of identifying the weather parameters associated with peak performance in each event, we used the decision tree regressor algorithm (28) to develop classification rules linking weather parameters (i.e., air temperature, relative humidity, wind speed, and solar radiation) and performance. The decision tree regressor is a machine learning method creating a decision tree that divides data points based on the feature that caused the highest disparity in the output (28). Hyperparameter selection was implemented to optimize the performance of the decision trees for each of the running events. Each decision tree was optimized with respect to several preselected hyperparameters described in Table S2 (see Table, Supplemental Digital Content, Appendix, <http://links.lww.com/MSS/C408>). More specifically, we tested the criterion: [“mse,” “mae”], max\_depth: [sample-size\*0.01, sample-size\*0.02, sample-size\*0.05, sample-size\*0.1], max\_leaf\_nodes: [2,4,6,8,10,15,20], min\_samples\_leaf: [10, 20, 30, 40, 50, 60, 70, 80, 100], and min\_samples\_split: [5, 10, 20, 30, 50, 70, 100, 150, 200]. We separated the data set for each event using 70%–30% random data split to generate the training and testing subsets, respectively. The “learning” component of the decision tree regressor model was performed on training sets (70%), and the final  $R^2$  and the root-mean-square error were estimated on the testing sets (30%). The feature importance score was used as an indicator of the usefulness of each weather parameter at predicting peak performance in each event. In addition to the machine learning approach, we used linear and nonlinear regression analyses (29) (least squares method; Origin Lab 2019, Origin Lab Corporation, Northampton, MA) with accompanying ANOVA tests to calculate the change in performance for every degree Celsius in air temperature, WBGT, heat index, and simplified WBGT.

The above-mentioned least squares regression models were also used to address our third objective of identifying the events most vulnerable to varying weather conditions by estimating the performance decline for every degree Celsius in air temperature, heat index, simplified WBGT, and WBGT. To confirm that our regression models were not affected by the number of races held in different weather conditions, we repeated the analysis using multiple nonlinear regression with the number of races for each degree WBGT and air temperature inserted in each model as a covariate. For all regression analyses, we deemed as acceptable those models achieving a least squares fit criterion of  $P < 0.005$ . Results across all analyses are shown as mean  $\pm$  SD, unless otherwise stated.

## RESULTS

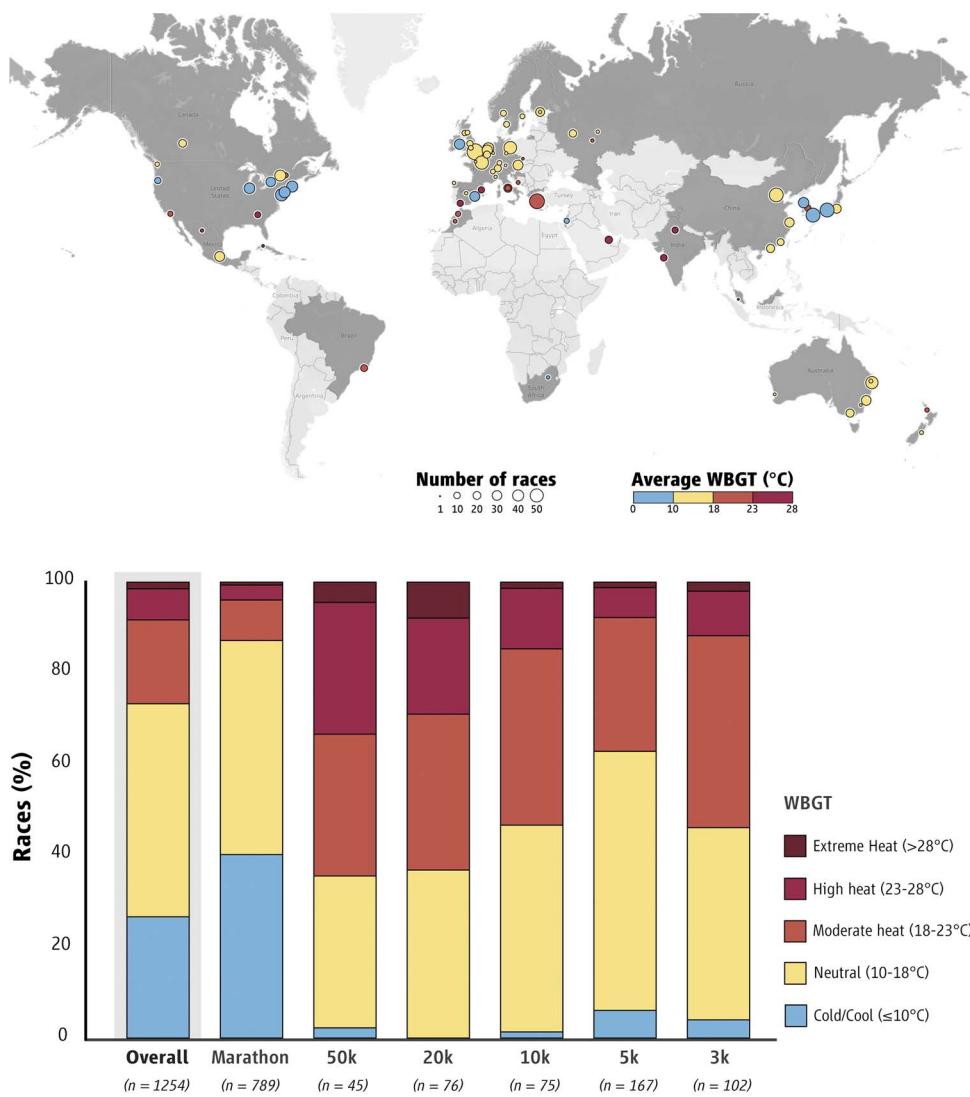
**Weather data and cross-validity.** We found date and location information for 1316 races. Of these, we were able

to identify meteorological data for 1258 races held between 1936 and 2019 across 84 locations and 42 countries (Fig. 1). The majority (69%) of these races were held in the period between 2000 and 2019, 19% were held during the 1990s, and the remaining 12% in the period between 1936 and 1989 (see Fig. S3, Supplemental Digital Content, Appendix, <http://links.lww.com/MSS/C408>). These data were collected from meteorological stations located in proximity ( $8.9 \pm 9.3$  km) to the race location (note that this figure is based on the 1026 events where NOAA data were used). The air temperature ( $\rho = 0.82$ ,  $P < 0.001$ ), the simplified WBGT ( $\rho = 0.92$ ,  $P < 0.001$ ), and the heat index ( $\rho = 0.85$ ,  $P < 0.001$ ) from the meteorological stations were strongly associated with the values reported by the organizers during the events. The values reported by the organizers were on average  $0.7^{\circ}\text{C}$  to  $1.5^{\circ}\text{C}$  higher (depending on the heat index) than those collected from the meteorological stations ( $P < 0.05$ ), with a root-mean-square error ranging between  $1.6^{\circ}\text{C}$  and  $2.8^{\circ}\text{C}$ , whereas Cohen’s  $d$  demonstrated no effect size of the differences ( $d < 0.2$ ) between the two sets of data (see Table S3, Supplemental Digital Content, Appendix, <http://links.lww.com/MSS/C408>).

**Weather conditions in endurance events.** The races were held in a wide range of weather conditions: air temperature from  $-5^{\circ}\text{C}$  to  $35^{\circ}\text{C}$  (very cold to very hot), relative humidity from 14% to 100% (dry to extremely humid), wind speed from 0 to  $25\text{ km}\cdot\text{h}^{-1}$  (none to strong wind), and solar radiation from 0 to  $1234\text{ W}\cdot\text{m}^{-2}$  (dark/night to extreme sun). Mean  $\pm$  SD values for different competitions and events are provided in Table S4 (<http://links.lww.com/MSS/C408>). The WBGT across races ranged from  $-7^{\circ}\text{C}$  to  $33^{\circ}\text{C}$ , with 27% of all races taking place in cold/cool, 47% in neutral, 18% in moderate heat, 7% in high heat, and 1% in extreme heat conditions according WBGT classifications of World Athletics competition medical guidelines (Fig. 1).

The 1258 races enabled a performance analysis of 7867 athletes (6567 elite endurance athletes and 1300 well-trained marathon runners). The mean performance decrement from the standing record was  $3.1\% \pm 3.1\%$  for the elite endurance athletes (finalist athletes in each race) across all events. The well-trained marathon runners (25th, 50th, 100th, and 300th place finishers; see Methods) showed a mean performance decrement of  $24.2\% \pm 11.1\%$  in relation to the standing record and a range of finishing times between 2:14 and 3:40 (h:min). All these data have been placed in an online data repository and are made freely available (<https://doi.org/10.6084/m9.figshare.14753565.v1>). The number of athletes as well as the air temperature, WBGT, and performance (mean  $\pm$  SD [min–max]) across each competition and event are provided in Tables S4 and S5 (see Supplemental Digital Content, Appendix, <http://links.lww.com/MSS/C408>).

**Performance effects of weather parameters.** Decision trees linking weather conditions and performance for the marathon (Fig. 2), 50-km racewalking, 20-km racewalking, and 10,000-, 5000-, and 3000-m steeplechase (see Figs. S4–S8, Supplemental Digital Content, Appendix, <http://links.lww.com/MSS/C408>).

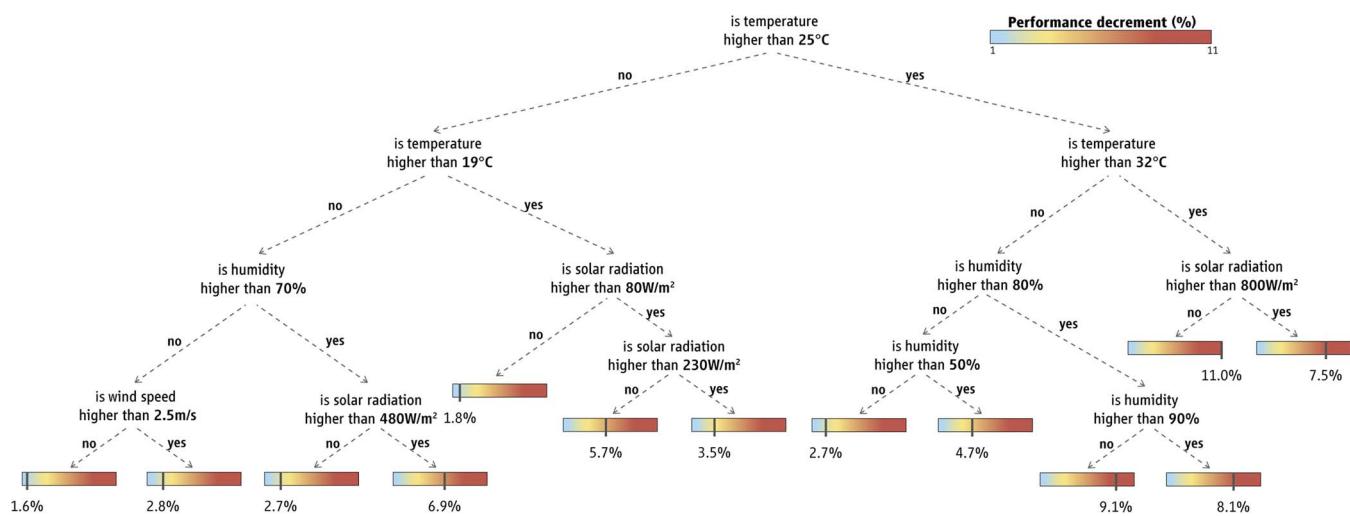


**FIGURE 1—Distribution of the 1258 races and location-average WBGT across the 84 locations that hosted endurance events between 1936 and 2019, for which complete race and weather data are available (top), as well as the heat stress level across events based on the World Athletics competition medical guidelines (bottom).**

lww.com/MSS/C408), considering the best hyperparameters in each model (Table S2, <http://links.lww.com/MSS/C408>), indicated  $R^2$  values between 0.21 and 0.58. When all endurance events were considered together, the  $R^2$  was 0.33 and the feature with the highest importance was air temperature (feature importance score = 40%) followed by relative humidity (feature importance score = 26%), solar radiation (feature importance score = 18%), and wind speed (feature importance score = 16%; Fig. 3). This shows that air temperature is the most important weather parameter influencing endurance performance in elite athletes. However, decision trees predicting the effect on performance based only on air temperature showed  $R^2$  values between 0.04 and 0.34, whereas similar decision trees based only on WBGT showed  $R^2$  values between 0.11 and 0.47 (see Table S6, Supplemental Digital Content, Appendix, <http://links.lww.com/MSS/C408>).

Across all studied events, we found that races with a WBGT  $>15^\circ\text{C}$  (or air temperature  $>17.5^\circ\text{C}$ ) and  $<7.5^\circ\text{C}$  (or air

temperature  $<10^\circ\text{C}$ ) were associated with impaired performance (Fig. 4 and Figs. S1–S2, <http://links.lww.com/MSS/C408>). Regression analyses statistically confirmed this association for the marathon, the 50-km racewalking, the 20-km racewalking, the 10,000-m race, and the 5000-m race ( $R^2 = 0.23\text{--}0.96$ ,  $P < 0.05$ , least squares fit criterion satisfied at  $P < 0.005$ ; Figs. S1–S2 and Table S7, Supplemental Digital Content, Appendix, <http://links.lww.com/MSS/C408>). For some of the weather parameters, the regression models showed  $R^2$  ranging between 0.23 and 0.51 as well as nonsignificant ANOVA tests ( $P > 0.05$ ). These models were deemed acceptable because they satisfied the least squares fit criterion of  $P < 0.005$ . This criterion was not satisfied for the models linking weather parameters and performance in the 3000-m steeplechase ( $P > 0.005$ ); therefore, no modeling results are available for this event. For all other events, the regression equation and the indicators of each model are provided in Table S7 (<http://links.lww.com/MSS/C408>).



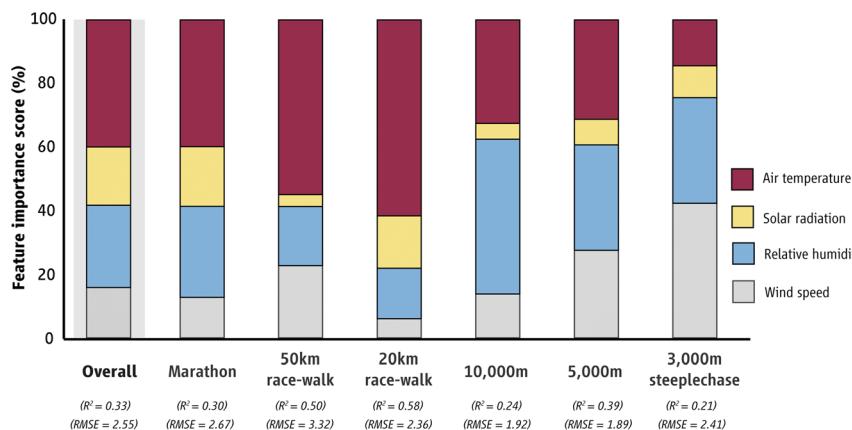
**FIGURE 2—Decision tree linking weather parameters and performance in the marathon.** The algorithm is organized in a binary tree: each node asks questions about a weather parameter and ultimately providing, an estimate of the performance decrement (because, on average, the percent difference from the standing record was negative, indicating impaired average performance). The values are rounded on the nearest integer and the decision tree is presented at a maximum depth of four.

The anticipated effect of air temperature, heat index, simplified WBGT, and WBGT on the performance against the standing record of each event is illustrated in Figure 5 and Figures S9–S12 across a wide range of finishing times (see Supplemental Digital Content, Appendix, <http://links.lww.com/MSS/C408>). We observed the highest performance at 7.5°C WBGT for the marathon (Fig. 5), at 15°C WBGT for the 50-km racewalking (Fig. S9), at 12.5°C WBGT for the 20-km racewalking (Fig. S10), at 10°C WBGT for the 10,000-m run (Fig. S11), and at 15°C WBGT for the 5000-m run (Fig. S12). Outside these optimum conditions, performance across all events declined by  $0.3\% \pm 0.2\%$  per 1°C WBGT decrease, and by  $0.4\% \pm 0.4\%$  per 1°C WBGT increase (Fig. 4 and Table S7, <http://links.lww.com/MSS/C408>): marathon (heat, 0.2%; cold, 0.1%), 50-km racewalking (heat, 1.1%; cold, 0.5%), 20-km racewalking (heat, 0.4%), 10,000-m race (heat, 0.04%), and 5000-m race (heat, 0.3%; cold, 0.2%). Based on these results, the 50- and 20-km racewalking events appear to be the most vulnerable endurance events to heat stress, followed by the marathon, the 5000-m race, and the 10,000-m race. At

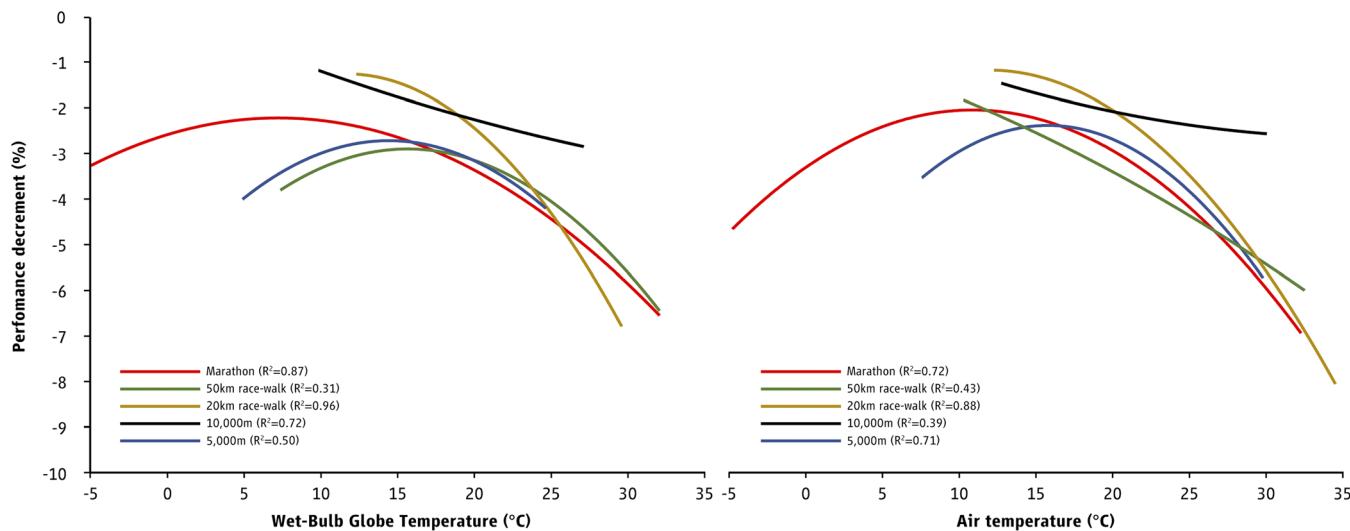
suboptimal colder conditions, the performance decline is the steepest in the 50-km racewalking, followed by the 5000-m run and the marathon. Multiple nonlinear regression analyses confirmed that these results were not affected by the number of races held at different weather conditions. Specifically, multivariate nonlinear models with the number of races per 1°C WBGT inserted in each model as a covariate showed larger  $P$  values as well as higher Akaike information criterion and Bayesian information criterion, indicating lower predictive capacity (Table S7, <http://links.lww.com/MSS/C408>).

## DISCUSSION

This large-scale analysis of the effect of weather parameters on performance showed that 27% of races across endurance events included in the list of Olympic sports were held in moderate, high, or extreme heat. Importantly, a small proportion of marathons (13%) were held in such conditions, but this was much higher (49%) for the other events studied. We found that



**FIGURE 3—Feature importance scores of the input weather variables and  $R^2$  and root-mean-square error (RMSE) of the testing data sets.**

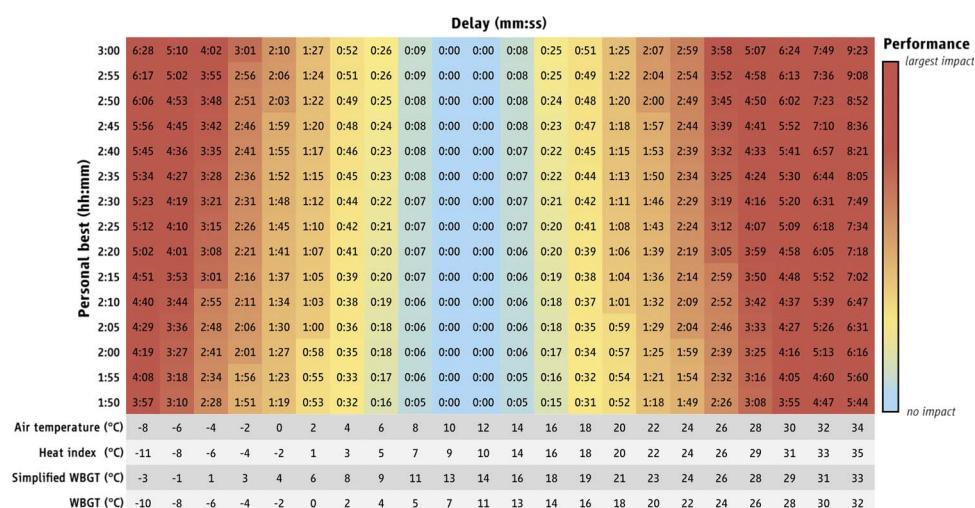


**FIGURE 4**—Performance decrement (percent difference between an athlete's finish time and the event's standing record) for every degree WBGT (*left*) and air temperature (*right*) across the studied events based on linear and nonlinear regression analyses using the least squares method. Performance is always negative (indicating impaired average performance) because, on average, the percent difference from the standing record was negative. The models for marathon do not include well-trained athletes. No curves are shown for the 3000-m steeplechase as the associated models did not satisfy the least squares fit criterion of  $P < 0.005$ .

the 50- and 20-km racewalking events were the most vulnerable endurance events to heat stress, with the 50-km racewalking and the 5000-m race being the most vulnerable endurance events to cold stress. Our analysis demonstrated that WBGT between 7.5°C and 15°C (10°C–17.5°C air temperature) is associated with peak performance in well-trained and elite athletes across the endurance events studied.

A large body of literature has established that environmental heat stress can reduce performance and increase the risk for unfavorable health outcomes (12,30–35). For instance, a heat exhaustion incidence of 3.3 per 1000 registered athletes has been reported in the World Athletics Championships (36). Additionally, injury analyses during the Berlin 2009 and Daegu 2011 World Athletics Championships revealed that heat

illness due to environmental or exercise factors was the second and third most common clinical condition (36–38). Interestingly, most heat illnesses in World Athletics Championships have occurred during racewalking events (38), which supports our finding that racewalking is the most vulnerable endurance events to heat stress. Future work using a similar methodology could be used to uncover specific weather conditions that promote a higher risk for heat-related illness. Overall, our findings that 27% of endurance races have been held in moderate, high, or extreme heat emphasize the importance of heat mitigation strategies and upper limits to heat stress when events should be canceled. These are vital to protect the health and performance of the athletes, particularly when considering the globalization of sports amid an escalating climate change (1–3) as



**FIGURE 5**—The effect of heat stress on marathon performance, across a wide range of finishing times. Numbers indicate minutes:seconds of added time to performance based on the air temperature, heat index, simplified WBGT, and WBGT. Colors illustrate the level heat-induced effect on performance. Performance is either unaffected or impaired because, on average, the percent difference from the standing record was negative.

well as the desire to go beyond existing levels of human performance (4,5).

Previous studies focusing on marathon performance reported that the optimum WBGT for this event is between 5°C and 10°C (6,8,39). Our analysis comparing performance against the standing record of an event and the standing world record confirms this, demonstrating that the marathon performance is optimized at a WBGT 7.5°C. Moreover, we extend knowledge in this field by demonstrating that the WBGT for optimum performance across a range of endurance events is between 7.5°C and 15°C (10°C–17.5°C air temperature). For every degree increase in WBGT beyond 15°C, performance decreases by ~0.2% in the marathon, ~1.1% in the 50-km racewalking, ~0.4% in the 20-km racewalking, ~0.04% in the 10,000-m race, and ~0.3% in the 5000-m race. A previous study analyzing marathon races reported similar performance decrements of ~0.1%, ~0.3%, and ~0.6% for every degree increase in WBGT for elite men, elite women, and well-trained runners, respectively (8). It is worth noting, however, that most of the marathons analyzed in our study included information only for the top 3 three finishers. Although this is based on previous methodology (8), the reported performance decrements may have been higher if more subelite athletes were included.

The machine learning analysis that we used to examine the association between weather parameters and performance in major competitions demonstrated that air temperature is the most important parameter influencing performance in elite athletes. However, our results show that coaches, athletes, and organizers should evaluate all four weather parameters because decision trees based only on air temperature explained a relatively low percent of variability in performance. Through our analysis, we provide exercise scientists, coaches, athletes, and organizers with two tools to estimate the anticipated effect on performance during a future endurance event: 1) the percent decrement in performance using decision trees (Fig. 2 and Figs. S4–S8, <http://links.lww.com/MSS/C408>) based on weather data from all four parameters and 2) the added time to performance based on athlete's personal best using the heat maps (Fig. 5 and Figs. S9–S12, <http://links.lww.com/MSS/C408>) based on air temperature, heat index, simplified WBGT, or WBGT. The overarching message is similar across these tools, yet their different designs, structures, and functions may be more relevant to specific audiences. For example, the decision trees are likely to be more relevant for event organizers, whereas the heat maps are probably more useful for exercise scientists, coaches, and athletes. It must be acknowledged that these two tools provide an estimation of performance decrement and that varying combinations of environmental parameters may influence performance differently based on fitness, hydration status, heat acclimation status, and the use of heat mitigation strategies (8,40–44). A recently developed software to predict heat strain can also be used by exercise scientists, coaches, and athletes who wish to estimate more accurately the anticipated effect of weather parameters on physiology and performance (45).

We found that the 50- and 20-km racewalking events were the most vulnerable to heat stress. Compared with running, racewalking has substantially lower mechanical efficiency, which means that more of the energy used to produce work ends up being lost as heat (45). This is because racewalking requires constant contact with the ground, producing a larger pelvis displacement than running (46). As a consequence, racewalkers reach higher core temperatures for the same movement speed compared with runners (47,48), which may explain why most heat illnesses in World Athletics Championships have occurred during racewalking events (38).

**Methodological considerations.** In the analyses presented within the main article, performance is expressed against the standing event record to reflect race-specific factors, which are important to consider particularly in events held outside the track and field stadium. For instance, the course remains unchanged across time for most marathon races, but there is wide course variation among races. This approach also accounts for other environmental factors such as in events always taking place in cities at higher elevations where performance is bound to be affected as compared with the standing world record. Yet, comparing against the standing record does not account for variability in performance for some cases where major course changes have been introduced (e.g., more uphill) or competitions took place in higher elevations (e.g., Olympic games in Mexico City in 1968), which would affect race performance. Also, this approach reduces the effect of weather factors as a given race is typically held in similar conditions every year. For example, the Mumbai marathon held on the third Sunday of January every year in similarly hot conditions (26.8°C ± 1.6°C air temperature) will have its standing record always set in the heat. Another limitation of this approach is that it assumes that the competition was equally strong each year. Our analysis was designed to address these limitations by including a large number of races held across a wide range of locations and weather conditions (Fig. 1). Although standing records were specific for each particular race, this effect was diluted when all data were merged together, reflecting the true weather conditions that increase the likelihood for peak performance. Moreover, to address any potential limitations of using the standing record, we expanded our analysis to evaluate performance against the standing world record. This process is presented in the annex (<http://links.lww.com/MSS/C408>) and revealed similar results, confirming the validity of the main analysis.

It is important to note that the weather data for the evaluated endurance races were not measured at the racing grounds but at the closest meteorological station, on average 9 km away. Therefore, the true conditions during the races may have been different. Our cross-validity analysis performed in 11% of the races showed that the weather parameters from the meteorological stations were highly associated with the values reported by the organizers during the events with no effect size of the differences between the two data sets. These results are in line with a previous cross-validation study of this method

(18), which showed that using WBGT values from the closest weather station (situated 33 km away in that study) generally reflected the WBGT values recorded at the racing grounds. This previous cross-validity exercise showed that the meteorological station WBGT values were  $1.2^{\circ}\text{C} \pm 2.1^{\circ}\text{C}$  lower. This was also the case for the present analysis, which showed that the values reported by the organizers were on average  $0.7^{\circ}\text{C}$  to  $1.5^{\circ}\text{C}$  higher (depending on the heat index) than those collected from the meteorological stations. Although a difference of about  $1^{\circ}\text{C}$  is unlikely to have a strong physiological effect for the present study, it may suggest that a larger percent of races took place in hot conditions. It is logical to anticipate some degree of variability because meteorological stations are located in areas so as to be as unaffected by microclimate and the natural surroundings (49). A recent study in Brazil using meteorological station data to calculate WBGT using methods similar to those followed in our study showed no significant deviation for distances as large as 80 km (50). On the whole, our cross-validity analysis, the large number of competitions covered across 42 countries, and the limited distance between the meteorological stations and the racing grounds in most cases supports the robustness of the approach used, suggesting that the findings reflect the true conditions.

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## CONCLUSION

This large-scale analysis of 1258 races held between 1936 and 2019 across 84 locations and 42 countries demonstrates that more than one-quarter of endurance running events held since the beginning of sports record keeping and weather data recording were held in moderate, high, or extreme heat, and this number reaches one-half for events other than the marathon (i.e., 50-km racewalking, 20-km racewalking, and 10,000-, 5000-, and 3000-m steeplechase). The high number of races held in moderate, high, or extreme heat confirms previous suggestions that athletes, coaches, organizers, and officials must be very aware of the health and performance implications of exercising at maximal intensities in a hot environment (1,2,6,32,33). Organizers of endurance running events included in the list of Olympic sports must evaluate all four weather parameters and adopt measures that mitigate risks to the health and performance of athletes. At the same time, athletes, coaches, and officials must be educated about these risks and prepare for the heat by using heat mitigation strategies where possible.

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