Impact of Weather on Marathon-Running Performance

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ABSTRACT

ELY, M. R., S. N. CHEUVRONT, W. O. ROBERTS, and S. J. MONTAIN. Impact of Weather on Marathon-Running Performance. *Med. Sci. Sports Exerc.*, Vol. 39, No. 3, pp. 487–493, 2007. Marathon running performance slows in warm weather conditions, but the quantitative impact of weather has not been established. **Purpose:** To quantify the impact of weather on marathon performance for different populations of runners. **Methods:** Marathon results and weather data were obtained for the Boston, New York, Twin Cities, Grandma's, Richmond, Hartford, and Vancouver Marathons for 36, 29, 24, 23, 6, 12, and 10 yr, respectively. The race results were broken into quartiles based on the wet-bulb globe temperature (Q_1 5.1–10°C, Q_2 10.1–15°C, Q_3 15.1–20°C, and Q_4 20.1–25°C). Analysis of the top three male and female finishers as well as the 25th-, 50th-, 100th-, and 300th-place finishers were compared with the course record and then contrasted with weather. **Results:** Marathon performances of top males were slower than the course record by 1.7 ± 1.5, 2.5 ± 2.1, 3.3 ± 2.0, and 4.5 ± 2.3% (mean ± SD) for Q_1–Q_4, respectively. Differences between Q_4 and Q_1, Q_2, and between Q_3, and Q_1 were statistically different ($P < 0.05$). The top women followed a similar trend (Q_1 3.2 ± 4.9, Q_2 3.2 ± 2.9, Q_3 3.8 ± 3.2, and Q_4 5.4 ± 4.1% (mean ± SD)), but the differences among quartiles were not statistically significant. The 25th-, 50th-, 100th-, and 300th-place finishers slowed more than faster runners as WBGT increased. For all runners, equivalence testing around a 1% indifference threshold suggests potentially important changes among quartiles independently of statistical significance. **Conclusion:** There is a progressive slowing of marathon performance as the WBGT increases from 5 to 25°C. This seems true for men and women of wide ranging abilities, but performance is more negatively affected for slower populations of runners. **Key Words:** HEAT, COLD, WET-BULB GLOBE TEMPERATURE, ENDURANCE EXERCISE, MODELING, GENDER

A 42-km marathon footrace is among the most physiologically demanding endurance events in the world. Competitive runners typically maintain a pace corresponding to 70–90% of their maximal aerobic capacity (3,15,20) for more than 2 h. At maximal mechanical efficiency, more than 80% of the energy required for this task is transferred as heat to the body core (9). Moreover, the rate of endogenous heat production associated with a 2-h 10-min marathon estimated from ordinary heat-balance equations (9) is approximately 1400 $kcal \cdot h^{-1}$. This metabolic heat must be dissipated to the surrounding environment, or body temperature will rise to physiologically dangerous levels.

Lind (13) has demonstrated that core temperature is independent of climate over a temperature range he has termed the "prescriptive zone." It has been demonstrated that the width of the prescriptive zone progressively narrows as metabolic rate increases. Thus, climate begins to affect physiological responses to exercise at relatively cooler temperatures during activities that elicit high metabolic rate compared with those eliciting lower metabolic rates. More recently, it has been demonstrated that endurance performance is indeed impaired when exercising in warm versus more temperate laboratory conditions and that air temperatures of approximately 10°C seem optimal for endurance exercise (10). One criticism of these and other laboratory findings is that typical airflows used for indoor testing situations are well below those encountered when running or cycling outdoors over the ground. The lack of appropriate airflow substantially reduces the combined heat transfer coefficient (9) and may overestimate physiological strain (2).

Few field studies have examined the effect of weather conditions on endurance running performance (16,17,22). Although it is generally observed that race performances worsen as weather warms, there are currently no data quantifying the magnitude of performance reduction. In addition, these studies relied only on data from elite male runners; thus, the implications for slower competitors or women runners are only speculative.

The purpose of this study was to analyze marathon running performance from multiple mass participation marathons to 1) quantify the impact of weather on

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performance, and 2) determine whether the weather differentially affects performance of runners of varying abilities or between genders.

METHODS

Part I. Marathon race results were obtained from seven different races including Boston (Boston, MA), New York (NY, NY), Twin Cities (Minneapolis/St. Paul, MN), Grandma's (Duluth, MN), Richmond (Richmond, VA), Hartford (Hartford, CT), and Vancouver (Vancouver, Canada). To make race comparisons equitable from year to year, any race that underwent a significant course change was omitted from the dataset. As a result, a complete analysis of the above races included the past 36, 29, 24, 23, 6, 12, and 10 yr, respectively. These data are in the public domain, so written and informed consent was not required from individual athletes.

The effect of weather on marathon performance was studied for elite men and women (mean of the top three finishers) as well as the 25th-, 50th-, 100th-, and 300th-place finishers in each race. Although it would be of interest to quantify the effect of weather on runners slower than our 300th finishers, many marathons did not keep consistent records beyond the 300th place until the mid-1990s, and, as such, there are only limited data available. Performance was assessed by calculating the finishing time as a percentage off the course record [(finishing time − course record/course record) × 100]. To remove any bias associated with improving records over time, the course record used for reference was always the current course record for the year under study. The times for the top three men's and women's finishers were averaged, rather than using the single top men's and women's times, because top performances can fluctuate from year to year because of numerous intangible factors, such as prize money, race strategies, or overall competition.

Hourly weather data were obtained through the Air Force Combat Climatology Center for the day and time span of each race. Weather data included dry-bulb, wet-bulb, black-bulb, and dew-point temperatures, relative humidity, solar radiation, and wind speed. It is well recognized that meteorological indices are better predictors of athletic performance than single meteorological variables (8,14,19) in regression analyses (22). Therefore, wet-bulb globe temperature (WBGT: 21) was chosen as a biometeorological index because it is relatively easy to calculate and is used by multiple national and international organizations.

All marathon races evaluated were run in a WBGT range of 2.5 to 28.0°C and were sorted by 5°C increments in WBGT: (0–5, 5.1–10, 10.1–15, 15.1–20, and 20.1–25°C WBGT). The range of 0–5°C was later excluded from the analysis because of the low number of races run in this WBGT range (N = 3), and one race was excluded from analysis because of a WBGT > 25°C. A complete analysis was performed on four WBGT quartiles (Q_1 5.1–10°C, Q_2 10.1–15°C, Q_3 15.1–20°C, and Q_4 20.1–25°C WBGT). The quartiles consisted of 28, 56, 37, and 18 race years, respectively. Weather parameters were averaged for the duration of each race. Table 1 provides the average and range of the individual weather parameters for each WBGT quartile. Of the seven marathons examined, the Boston,

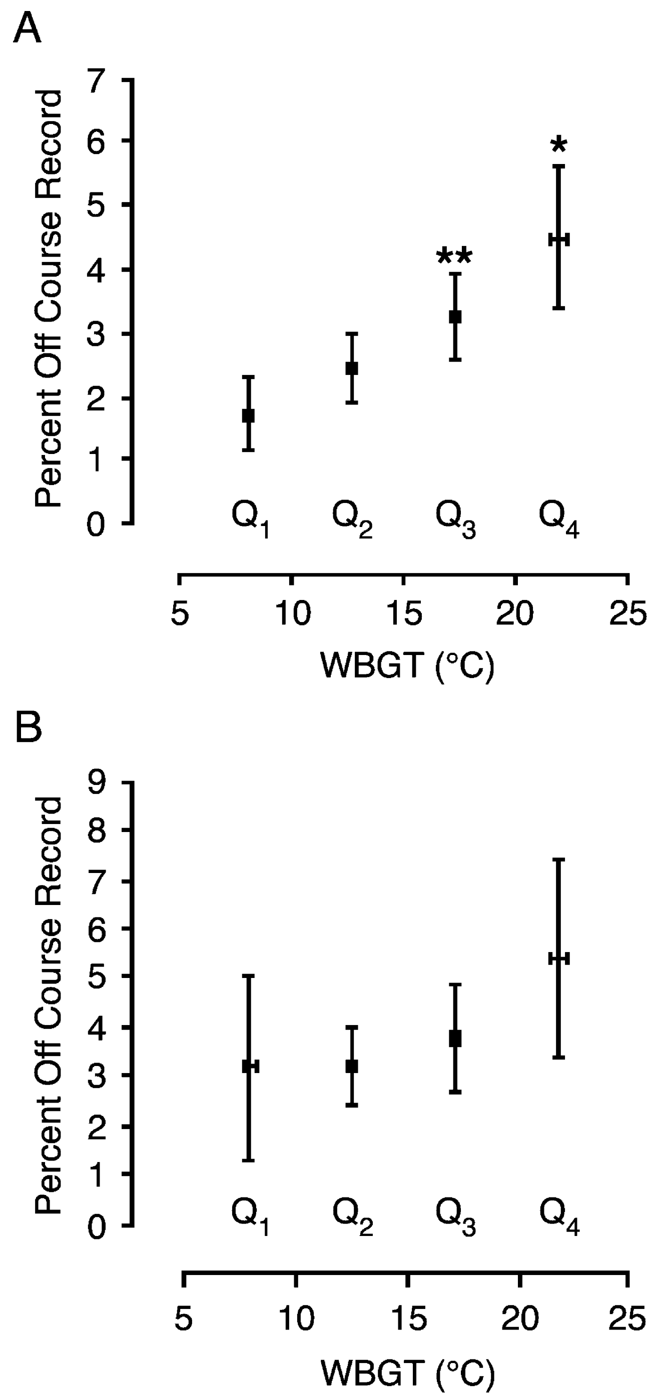

FIGURE 1—Percent off the course record plotted as mean ± inferential confidence interval (ICI) for elite men (*A*) and elite women (*B*) in response to increasing WBGT (quartile) (WBGT mean ± SE). * Denotes difference (P < 0.05) from Q_1 and Q_2. ** Denotes difference (P < 0.05) from Q_1.

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TABLE 1. Descriptive weather data separated by quartile.

Quartile	N	T_{db} (°C)	T_{wb} (°C)	T_g (°C)	RH (%)	SR (W·m^{-2})	Wind (m·s^{-1}) Speed	WBGT (°C)
Q_1	28	8.0 (5–13)	4.8 (2–10)	19.2 (6–26)	59 (17–100)	579 (192–899)	6.1 (1–13)	8.0 (6–10)
Q_2	56	12.6 (7–18)	9.0 (6–14)	25.5 (13–38)	64 (28–100)	632 (130–922)	5.3 (2–9)	12.6 (10–15)
Q_3	35	17.2 (13–24)	13.4 (9–17)	30.7 (16–41)	66 (20–100)	607 (235–930)	4.7 (2–8)	17.2 (15–19)
Q_4	17	21.9 (17–28)	17.6 (14–22)	37.6 (31–45)	64 (30–100)	732 (421–909)	5.6 (2–9)	21.9 (20–25)

Values are mean (range). T_{db}, dry-bulb temperature; T_{wb}, wet-bulb temperature; T_g, black globe temperature; RH, relative humidity; SR, solar radiation; wind (m·s^{-1}) = wind speed; WBGT, wet-bulb globe temperature.

New York, Twin Cities, and Hartford marathons were spread across all four quartiles; Grandma's and Vancouver spanned three quartiles (Q_2–Q_4; Q_1–Q_3, respectively), and Richmond spanned only Q_1 and Q_2.

Statistical analysis. The primary outcome of interest in this study was the effect of WBGT on marathon race performance. After testing the data for normality of distribution and equality of variances assumptions, a one-way ANOVA was performed for each population of runner (performance for elite men or women, 25th-, 50th-, 100th-, and 300th-place finishers) across WBGT quartiles. The Bonferroni procedure was used to maintain the family-wise α level at $P = 0.05$ for six planned *post hoc* comparisons. The actual critical t-value used in all calculations corresponded to 0.05/6, or $\alpha \approx 0.01$.

Inferential confidence intervals (ICI) were employed to investigate the statistical equivalence (18) of WBGT on marathon performance. Briefly, 95% confidence intervals are algebraically adjusted (18) so that nonoverlapping ICI are consistent with rejecting the null hypothesis. ICI that overlap are not statistically different, but they allow determination of statistical equivalence by calculating the maximum probable difference between two means (Rg). This is done by subtracting the upper limit of the greater mean from the lower limit of the lesser mean. If the maximum probable difference between means (Rg) is smaller than the *a priori* zone of indifference, then the means are also statistically equivalent. If Rg is larger, then the difference may still be of practical importance. This approach is very similar to that used for equivalence testing in the clinical sciences (7). The zone-of-indifference threshold was established narrowly as a slowing of performance by ≤ 1% on the basis that differences larger than 1%, though probably smaller than within-subject variability for marathon races (11), are important in competitive race scenarios and often represent the difference between placing in or out of the top three positions (12). In this dataset, for example, the mean difference between third and fourth place was 0.5% (47 s) for men and 1.1% (1 min 42 s) for women.

Least squares regression was used to construct lines of best fit for the percent change of the top three men, 25th, 50th, 100th, and 300th finishers across WBGT. Performance data are presented as means and adjusted 95% confidence intervals. Weather data are reported as means and standard error (SE). Analyses were conducted using SPSS (Statistical Package for the Social Sciences, Rel. 13.0.1 2004. Chicago: SPSS Inc).

Part II. The 2006 Boston Marathon (not included in part I analysis) was run in weather conditions that were distinctly different from the 2005 Boston Marathon. In an attempt to validate the nomogram created in part I, individuals who completed both the 2005 and 2006 Boston Marathon were identified ($N = 291$). Performance differences between the two races were determined for each runner by calculating a percentage difference between their 2005 and 2006 finishing times [(2005−2006/2006) × 100]. Hourly weather data for these races were obtained as in part I. Three subpopulations of the 291 individuals were extracted, on the basis of finishing times 133 ± 5 min ($N = 4$), 150 ± 4 min ($N = 9$), and 165 ± 2 min ($N = 38$), for analysis and comparison with the nomogram regression outcomes generated in part I. Time ranges were adjusted to obtain a reasonable sample size. Average percent difference between the matched pairs in 2005 and 2006 were plotted on the nomogram after estimation of the effect produced by an initial 7.3°C WBGT environment (2006 data) by interpolating between the 5 and 10°C WBGT conditions.

RESULTS

Part I. Both men and women top finishers experienced a slowing of performance (percent off course record) as WBGT increased across quartiles. The WBGT average increased from 8.0 to 12.6°C, 17.2°C, and 22.0°C across quartiles 1–4 (Table 1). The performances of the men were 1.7 ± 1.5, 2.5 ± 2.1, 3.3 ± 2.0, and 4.5 ± 2.3% (mean ± SD) slower than the course record across WBGT quartiles (Fig. 1a). *Post hoc* analysis showed that Q_1 and Q_2 were significantly different from Q_4 as well as Q_3 from Q_1

TABLE 2. Equivalence testing of Rg values (maximum probable mean difference) between quartiles against a 1% zone of indifference.

	Rg Values among Quartiles (%)					
	$Q_2 - Q_1$	$Q_3 - Q_1$	$Q_4 - Q_1$	$Q_3 - Q_2$	$Q_4 - Q_2$	$Q_4 - Q_3$
Elite men	1.7	2.5	4.3	1.8	3.5	2.7
Elite women	2.2	3.0	5.6	2.1	4.7	4.4
25th percentile	3.9	6.1	6.8	4.6	5.3	4.1
50th percentile	4.3	7.0	8.6	5.6	7.2	5.3
100th percentile	5.4	8.3	11.1	6.5	9.3	7.4
300th percentile	7.0	12.7	21.0	11.3	19.6	16.2

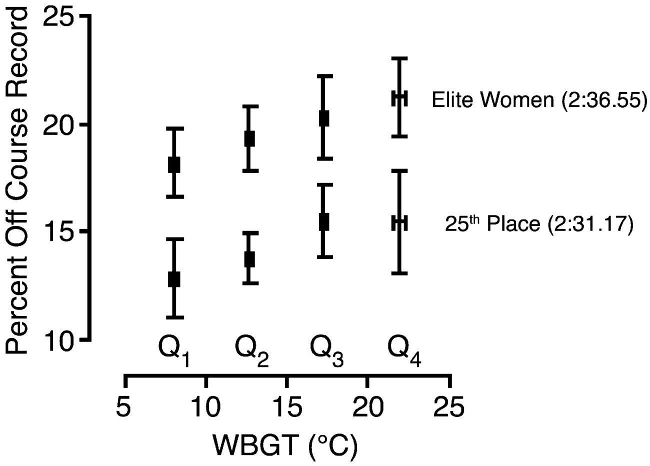

FIGURE 2—Comparison of the elite women and the 25th-place finishers plotted as the percentage off the current men's course record across quartiles. Data are mean ± ICI.

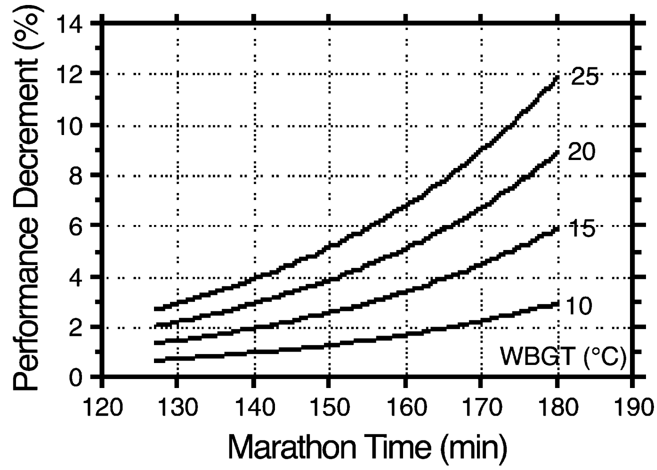

FIGURE 3—Nomogram examining the potential performance decrement (*y*-axis) based on projected marathon finishing time (*x*-axis) with increasing WBGT.

($P < 0.05$). Although differences between other quartiles were not statistically different, equivalence testing (Rg) around a 1% zone of indifference revealed statistical nonequivalence among all quartiles (Table 2). Analysis of variance revealed no differences among quartiles for elite women, but a trend toward slowing (3.2 ± 4.9, 3.2 ± 2.9, 3.8 ± 3.2, and 5.4 ± 4.1%) (Fig. 1b) with increasing WBGT, and Rg values > 1% between quartiles (Table 2), suggest a similar phenomenon to men. Moreover, when female data are compared against those from a population with similar finishing times (25th-place finisher), the pattern of change with increasing WBGT seems similar, suggesting no apparent differences between genders (Fig. 2).

WBGT seemed to have greater impact on the slower runners. The comparison of the 25th-, 50th-, 100th-, and 300th-place finishers against the current men's course record showed that their performance time declined by 2.6, 3.5, 4.9, and 7.9% between Q_1 and Q_4, respectively (Table 3), and all Rg values were well above 1% (Table 2).

TABLE 3. Mean percent off course record and upper and lower boundary of the inferential confidence interval (ICI) for each quartile separated by runner population.

	Mean	ICI Upper	ICI Lower
25th place			
Q_1	12.9	14.7	11.0
Q_2	13.8	15.0	12.6
Q_3	15.5	17.2	13.8
Q_4	15.5	17.9	13.1
50th place			
Q_1	17.9	19.9	15.8
Q_2	18.7	20.1	17.3
Q_3	21.0	22.9	19.1
Q_4	21.4	24.4	18.4
100th place			
Q_1	23.8	26.1	21.4
Q_2	25.0	26.8	23.2
Q_3	27.4	29.7	25.1
Q_4	28.7	32.5	24.8
300th place			
Q_1	34.6	38.0	31.2
Q_2	35.4	38.2	32.6
Q_3	40.0	43.9	36.0
Q_4	42.5	52.2	32.8

To quantify the slowing phenomena and to account for the large variability among the means, a nomogram (Fig. 3) was constructed from regression analysis using performance (percent off course record) and WBGT for each population of runner. The nomogram was anchored (artificial zero) against a 5°C WBGT because this quartile showed the smallest effect on performance relative to course record. The nomogram allows for a visual understanding of the effect of increasing WBGT on performance.

Part II. The 2005 Boston Marathon was run in weather conditions (13.2°C WBGT) that were 5.9°C WBGT warmer than those during the 2006 Boston Marathon (7.3°C WBGT) (Table 4). Comparison of the two marathons (Fig. 4) revealed that 251 of 292 runners

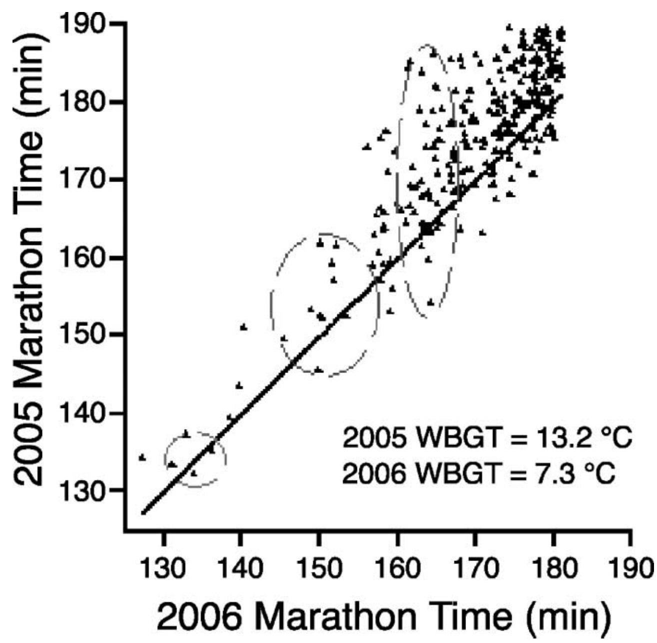

FIGURE 4—Comparison of 291 individuals who competed in the 2005 and 2006 Boston Marathons. The three population clouds represent the subpopulations extracted for comparison with the nomogram.

TABLE 4. Descriptive weather data of the 2005 and 2006 Boston Marathon.

Year	T_{db} (°C)	T_{wb} (°C)	T_g (°C)	RH (%)	SR ($W \cdot m^{-2}$)	Wind ($m \cdot s^{-1}$) Speed	WBGT (°C)
2005	15.9	7.6	31.7	28	796	5.2	13.2
2006	8.3	5.0	15.1	62	550	4.3	7.3

Values are mean (range). T_{db}, dry-bulb temperature; T_{wb}, wet-bulb temperature; T_g, black globe temperature; RH, relative humidity; SR, solar radiation; $m \cdot s^{-1}$ = wind speed; WBGT, wet-bulb globe temperature.

(86.3%) ran slower in 2005 compared with the 2006 race. Furthermore, the magnitude of slowing and the pattern relative to race pace was consistent with expected outcomes from part I cross-sectional data. To directly assess the accuracy of the nomogram, three subpopulations of the part II 2006 Boston Marathon data were compared with the nomogram (identified by the three population clouds in Fig. 4). This independent dataset using paired data produced outcomes consistent with the pattern predicted by the nomogram (Fig. 5).

DISCUSSION

The purpose of this study was to analyze running performance from multiple mass participation marathons to 1) quantify the impact of weather on performance, and 2) determine whether the weather effects are different by ability or gender. The principal finding of this study was that there is a progressive slowing of marathon performance as WBGT increases from 5 to 25°C. Our findings that modest changes in WBGT can impact marathon race performance agree with earlier studies (17,22). It seems that this phenomenon holds true for men and women and that slower runners experience larger decrements in performance. Central to the acceptance of the primary findings in this study are the measurements and analysis of weather and performance.

Implicit in the evaluation of these findings is the use of WBGT as a meteorological index. WBGT was chosen because it is a singular index that incorporates ambient temperature, humidity, and solar load, which correspond to subjective perceptions around climatic temperature (21).

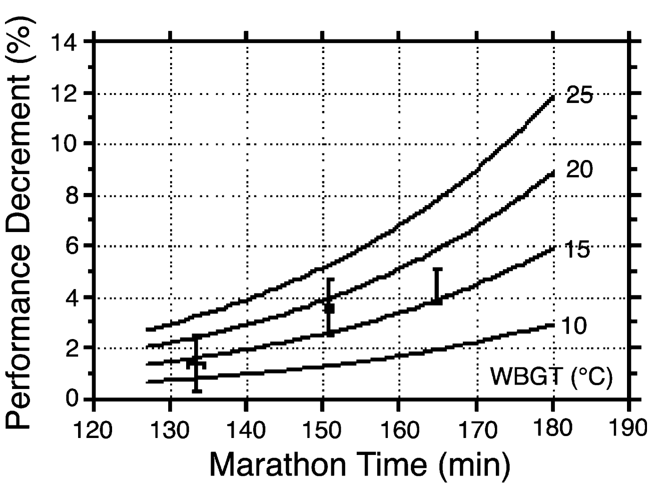

FIGURE 5—Three subpopulations of the 291 individuals' performance decrements between 2005 and 2006 marathons on the devised nomogram from Figure 3.

WBGT guidelines for distance running were developed by the National Collegiate Athletic Association. The guidelines state that distance races (> 16 km (10 miles)) should not be conducted when the WBGT exceeds 28°C (82.4°F) (1). Although domestic and international marathons do not fall under the jurisdiction of a singular governing body, none of the marathons obtained in this study had WBGT exceeding 28°C. The WBGT race data were divided into quartiles and not into smaller sets because it would have decreased the power to detect meaningful changes in performance. Additionally, no single marathon appreciably influenced the outcome of the whole analysis because four of the seven marathons spanned all four quartiles, two spanned three quartiles, and one (Richmond) spanned only the two lowest WBGT quartiles.

To quantify the impact of WBGT on performance of top finishers, the average time of the top three finishers was sorted by WBGT. This approach revealed that the elite men were 1.7 ± 1.5, 2.5 ± 2.1, 3.3 ± 2.0, and 4.5 ± 2.3% (mean ± SD) slower than the course record as WBGT increased from Q_1 to Q_4, respectively (Fig. 1a). Whereas there seemed to be progressive slowing as WBGT increased, traditional statistics revealed that Q_4 was slower than Q_1 and Q_2, and Q_3 was slower than Q_1. A common statistical confusion involves solely interpreting the importance of findings relative to rejection or acceptance of the null hypothesis. In this study, we employed both traditional analyses and nontraditional tests of statistical equivalence (7,18) as a means of better understanding the potential importance of the performance effect magnitude. Inferential confidence interval analysis (18) determined that the nonsignificant differences should not be considered equivalent and that an excess of 1% slowing between quartiles in all populations (Table 2) should be considered of potential importance (11,18).

Unlike men, the average finishing times for top women finishers did not show a progressive slowing as a function of WBGT. In women, performance seemed to be preserved until Q_3 conditions were achieved as times off course record were 3.2 ± 4.9, 3.2 ± 2.9, 3.8 ± 3.2, and 5.4 ± 4.1% for Q_1–Q_4, respectively (Fig. 1b). The lack of statistical difference between means, however, could have mainly been attributable to large variability in performance times in Q_1 and Q_4. Larger performance variability in women was also encountered by Hopkins and Hewson (11), who found that women had a higher coefficient of variation than men when examining repeat marathon performances (3.8 vs 2.5%). Another contributing factor may be the differences in depth of talent between men and women runners (5). In this dataset, the mean difference in finishing

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time between the first- and third-place male and female finishers was 3.25 and 5.20 min, respectively. The potential importance of WBGT effects on performance for women were consistent with those for men because the maximal probable population differences were outside the 1% zone of indifference (Table 2) using ICI analysis. There was a 0.7% difference between the performance decrements of elite men (2.8% between Q_1 and Q_4) and elite women (2.1%). Also, the average finishing time of elite women (2:36.55) is similar to that of the 25th-place finishers (2:31.17), and the similar magnitude of the performance decrements between the two populations suggests that gender does not measurably affect the impact of WBGT on performance (Fig. 2).

The data suggest that slower runners are affected more by a rising WBGT than faster runners. Regression analysis reveals that 25th-place runners slow approximately 1.1% between quartiles, whereas 50th-, 100th-, and 300th-place finishers slow by about 1.5, 1.8, and 3.2% with 5°C increases in WBGT (Table 3). This slowing could be attributable to the fact that each population of runners is spending more time exposed to the environmental conditions. For example, the 300th-place runners spend approximately 50 more minutes (~38% more time) exposed to the elements than the elite men. Also, slower runners tend to run in closer proximity to other runners, which has been estimated to cause more than three times the physiological heat stress compared with running solo in identical weather conditions (4,6). The increase in heat stress arises from a small net reduction of long-wave radiative heat losses (R + C), which amounts to an approximate 2°C increase in ambient temperature. More importantly, convective heat loss is reduced 50% as a result of entrainment of air (4,6). Differences in fitness relative to physiological potential could also contribute to differences in performance times and ability to cope with increasing heat stress.

Equations from the regression analysis of performance and WBGT enabled the construction of a nomogram (Fig. 3), which should allow marathon runners (2:07–3:00 h) to estimate their potential performance decrement as a function of race-day weather (WBGT 5–25°C). In an effort to validate the accuracy of the nomogram, data from 291 participants who completed the 2005 and 2006 Boston Marathon were identified. Weather conditions differed by approximately 6°C WBGT between races, similar to part I quartiles (5°C WBGT). Consistent with the curves generated from regression analysis using the original population of runners, this independent dataset shows a consistent slowing in performance as WBGT increases. Like the nomogram, the magnitude of slowing was also greater for slower runners (Fig. 4). Because no data were available from part I to produce a nomogram curve for 7.3°C WBGT, a curve was generated by interpolating between 5 and 10°C WBGT. The actual slowing of performance associated with the 5.9°C WBGT increase in 2005 (13.2°C WBGT) compared with 7.3°C WBGT in 2006 fell precisely between expected values for 10 and 15°C WBGT from the nomogram for the fastest marathoners (133 ± 5 min). The performance decrements for the next two populations (150 ± 4, 165 ± 2) were slightly higher than expected (Fig. 5), which may be attributable to factors unrelated to WBGT. One important assumption made in comparing these two marathons is that runners' performances did not improve from 1 yr to the next. It seems unlikely that 86% of the runners would have improved that much in just 1 yr, especially given the natural variability in year-to-year performances for marathon runners (11). Our interpretation is that the nomogram provides reasonably accurate estimates of changes in marathon finishing time produced by WBGT conditions. The practical application of the nomogram will allow athletes or sporting professionals to evaluate running performance and expected performance decrements as weather conditions vary from year to year.

CONCLUSION

The principal finding of this study was that there is a progressive and quantifiable slowing of marathon performance as WBGT increases from 5 to 25°C. It seems that this phenomenon holds true for men and women of wide-ranging abilities, but performance for slower runners decreases more as WBGT increases. This research is significant because 1) it adds to the idea of a threshold environmental condition (as proposed by Trapasso and Cooper (17) and Zhang et al. (22)) that leads to performance decrements, and 2) it quantifies performance decrements from genuine competitive events.

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