Earlier Boston Marathon Start Time Mitigates Environmental Heat Stress

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ABSTRACT

CHEUVRONT, S. N., A. R. CALDWELL, P. J. CHEUVRONT, R. W. KENEFICK, and C. TROYANOS. Earlier Boston Marathon Start Time Mitigates Environmental Heat Stress. *Med. Sci. Sports Exerc.*, Vol. 53, No. 9, pp. 1999–2005, 2021. Historical environmental data from the Boston Marathon afford a pragmatic opportunity to retrospectively quantify how the 2007 earlier start time altered the odds of runner exposures to environmental conditions associated with exertional heat illness. **Purpose:** This study aimed to compare the wet bulb globe temperature (WBGT) index and other environmental parameters between early and late Boston Marathon race start times from 1995 to 2016. **Methods:** Environmental data from 1995 to 2016 (excluding 1996) were used to compare two identical time frames using the 0900–1300 h start versus the 1100–1500 h start. This included the WBGT, dry bulb (Tdb), black globe (Tbg), wet bulb (Twb), solar radiation, relative humidity, and air water vapor pressure. To make comparisons between start times, the difference in the area under the curve (AUC) for each environmental variable was compared within each year with a Wilcoxon signed rank test with a Holm–Bonferroni correction. **Results:** AUC exposures for WBGT ($P = 0.027$), Twb ($P = 0.031$), Tdb ($P = 0.027$), Tbg ($P = 0.055$), and solar radiation ($P = 0.004$) were reduced with an earlier start, whereas those for relative humidity and air water vapor pressure were not. Overall, an earlier race start time by 2 h (0900 vs 1100 h) reduced the odds of experiencing a higher flag category 1.42 times ($\beta = 0.1744$, $P = 0.032$). **Conclusions:** The 2007 decision to make the Boston Marathon start time earlier by 2 h has reduced by ~1.4 times the odds that runners will be exposed to environmental conditions associated with exertional heat illness. **Key Words:** WET BULB GLOBE TEMPERATURE INDEX, DISTANCE RUNNING, EXERTIONAL HEAT ILLNESS, PERFORMANCE

The Boston Marathon is traditionally run through several host cities in Massachusetts on the third Monday in April (Patriot's Day). The start of the race in Hopkinton occurred at 1200 h (wheelchair and elite women competitors at 1130 h) until 2006, after which it was moved to an earlier 1000 h start (wheelchair and elite competitors at 0900 and 0930 h). After more than 100 yr of racing tradition, the Boston Athletic Association (BAA) had multiple reasons to consider the change to an earlier start time, chief among them was a desire to reduce mass casualty events related to environmental heat stress (1,2). Although the impact of an earlier start time on the reduction of runner heat stress seems intuitive (3,4), the historic change at Boston affords a pragmatic opportunity to retrospectively study and quantify how the time change affected each wet bulb globe temperature (WBGT) index parameter, flag category classification, and overall runner risk of exertional heat illness.

The WBGT index is sometimes used to study the combined effects of environmental heat stressors on endurance performance (5–7), but it is best known for its use in monitoring and mitigating the risk of exertional heat illnesses (1–3,8–10). For more than 30 yr, the American College of Sports Medicine has urged the educational use of easy-to-understand WBGT color-coded heat stress flag categories for balancing the desire for competitive performances against managing the risk of exertional heat illness (3,9). Although the WBGT index and its associated flag categories are not without criticisms (11,12), when used properly and thoughtfully (8,13) they can help shape road racing safety (2,10,14) and fundamentally improve the health and enjoyment of runners.

One of the simplest recommended strategies for reducing the WBGT index and mitigating heat stress during mass participation running events is to schedule races for the coolest time of day and during cooler seasons of the year (3,4). In the northern hemisphere, early start times in conjunction with meteorological spring or autumn race seasons reduce the likelihood of high air temperatures and high solar loads, thus

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minimizing two of three WBGT parameters; the same is true for winter races held in the southern hemisphere (2,4). However, this seemingly sound and simple recommendation is easily complicated. Many annual races run in cool seasons experience unseasonably warm race day temperatures (2,14). For larger and more popular races, factors such as TV network coverage, local lodging capacities, the logistics of city traffic, and the need for runner shuttles can also influence precisely what time of day a race is run (4).

The purpose of this study was to compare the WBGT index, its three components, and other environmental parameters between late start (1995 to 2006) and early start (2007 to 2016) times at the Boston Marathon. A proportional odds model of WBGT index flag categories was also generated at every hour for a total of 7 h (0900 to 1500 h) to help assess the effect of time on heat stress risk mitigation. Our hypothesis was that earlier start times would result in lower environmental heat stress via reductions in all three WBGT index parameters, and this would also translate to lower odds of high-risk heat stress flag categories.

METHODS

Hourly Boston Marathon weather data (0900 to 1500 h) were obtained for Patriot's Day from 1995 to 2016 (data not available for 1996), courtesy of the Air Force Combat Climatology Center, as previously described (7). The data included dry bulb temperature (Tdb, °C), wet bulb temperature (Twb, °C), black globe temperature (Tbg, °C), relative humidity (%), air water vapor pressure (VP) (mm Hg), and solar radiation ($\mathrm{W \cdot m^{-2}}$). The outdoor WBGT index was calculated conventionally (12,13) as follows:

$$\mathrm{WBGT} = 0.7T_{\mathrm{wb}} + 0.2T_{\mathrm{bg}} + 0.1T_{\mathrm{db}}$$

To compare the differences in thermal stress for different start times at the Boston Marathon, the data were split into 4-h observation blocks representing an early start time (early start: 0900–1300 h) and late start time (late start: 1100–1500 h). Figure 1 illustrates how the data were split for analysis using the WBGT index. Although the majority of competitors began the race at 1200 h before 2007 and begin today between ~1000 h (wave 1) and ~1100 h (wave 4), we elected to fairly include all competitors, including those in the wheelchair, and elite women and men's divisions who begin the race ~1 h earlier. Four hours was used as it represents the approximate mean runner finishing time at Boston (5). From these separate data frames, the area under the curve (AUC) in each year for each environmental variable was then calculated (15). The AUC is commonly used in pharmacokinetics studies to quantify and compare the exposure, or bioavailability, of

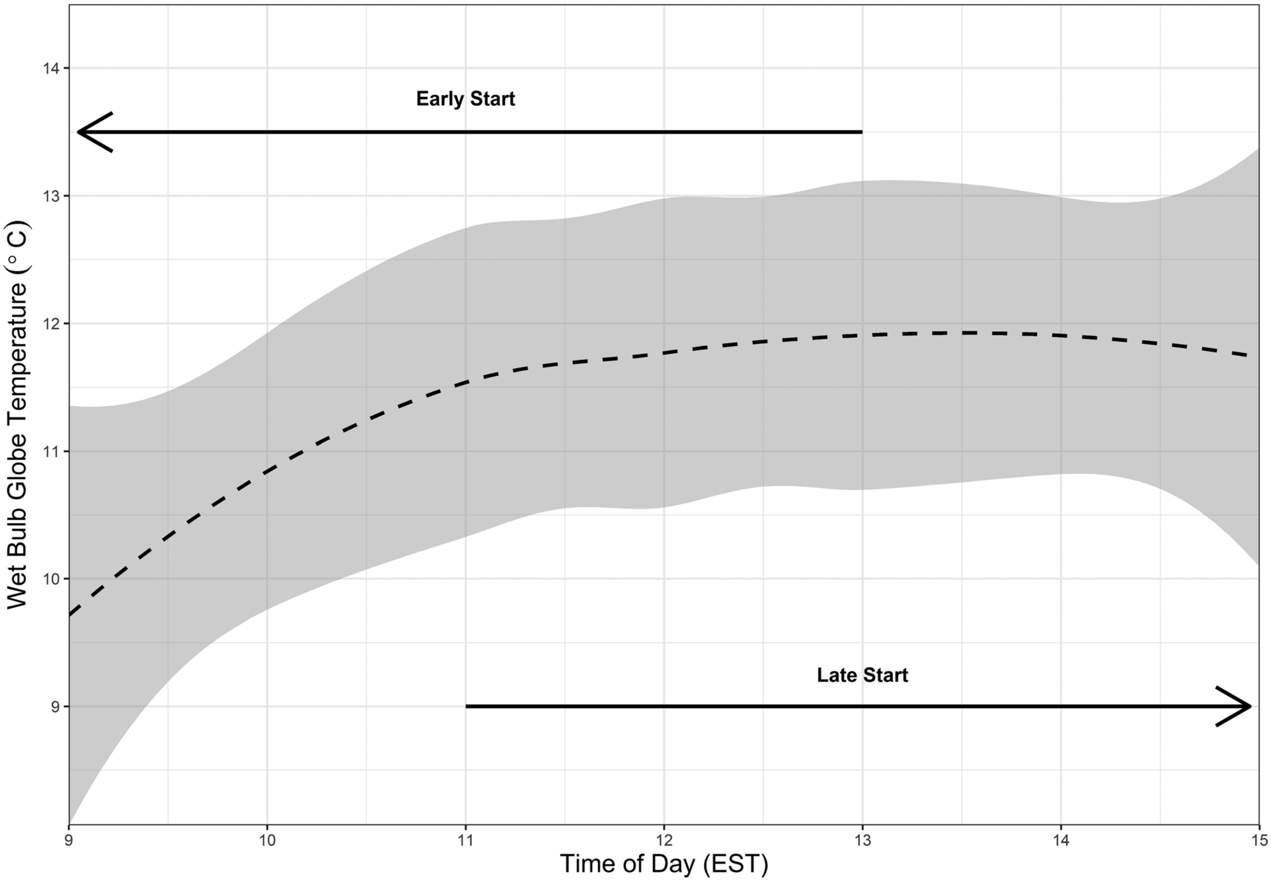

FIGURE 1—Hourly wet bulb globe temperature (WBGT) represented with locally weighted smoothing curve (loess). Black horizontal lines represent the data included in the "late" and "early" start AUC calculations. Gray band indicates the 95% confidence interval of the smoothed conditional mean.

different drugs (15). The AUC was used similarly herein to compare the integrated cumulative (total) exposure to each environmental variable across the entirety of the marathon event (4-h block), between early and late start times. Considering that there are two AUC calculations, one for the early start time and one for the late start time, within each year's environmental data, we have paired observations that can be compared by calculating the paired difference AUC (ΔAUC).

$$\Delta \mathrm{AUC} = \mathrm{AUC}_{\text{late start}} - \mathrm{AUC}_{\text{early start}}$$

Lastly, the WBGT index flag categories (14) were designated for each WBGT measurement to calculate the designated risk categories on an hour-to-hour basis. Additional method details are provided in the Appendix (see Document, Supplemental Digital Content 1, Appendix, http://links.lww.com/MSS/C290).

Statistical analyses. Overall, we hypothesized that an earlier start time (i.e., 0900 vs 1100 h) would provide environmental conditions that lowered the risk for exertional heat illness. Therefore, we compared the ΔAUC scores for each environmental variable with one-tailed Wilcoxon signed ranked test (H_0 : median ≤ 0, H_1 : median > 1). With regard to statistical power, with a sample size of 21 observations ($N = 21$), we would have 80% power ($\beta = 0.2$) to detect an effect size approximately equivalent to Cohen's $d = 0.57$ (calculated with Gpower version 3.1). Because there were multiple outcomes, we corrected for multiple comparisons by adjusting the P values with a Holm–Bonferroni correction (16). The size of the effect is expressed by a common language effect size (CLES) (17), otherwise known as the probability of superiority, with bootstrap (percentile method; 2000 replicates) 95% confidence intervals (18) reported with brackets after the point estimate. The CLES can be interpreted as the percent chance, in any random year, that a later start will have a higher AUC. Lastly, to quantify the effect of time of day on the WBGT-based flag categories, we used a proportional odds model wherein the outcome was WBGT index flag category and time of day was a linear predictor using the "rms" R package (19). All statistical analyses were completed in the R programming language, and data visualizations were created with the ggplot2 R package (20).

RESULTS

Descriptive statistics for all of the environmental parameters examined are provided in Table 1, grouped according to early (0900–1300 h) or late (1100–1500 h) start times. The early start period (0900–1300 h) resulted in lower values for all environmental variables examined compared with the late start period (1100–1500 h). Most measures of temperature were increased with a late start with WBGT (Fig. 2D), $P = 0.022$, CLES = 68.53% [54.32, 84.09]; Twb (Fig. 2C), $P = 0.031$, CLES = 72.39% [57.48, 88.51]; and Tdb (Fig. 2A), $P = 0.027$, CLES = 72.63% [57.51, 88.11], all significantly greater with the late start. The effect of start time on Tbg (Fig. 2B) was directionally consistent, but smaller, $P = 0.055$, CLES = 67.70% [50.99, 87.52].

TABLE 1. Descriptive environmental variables for early and late Boston Marathon start times.

	Early			Late		
	Median	Minimum	Maximum	Median	Minimum	Maximum
WBGT (°C)	10.2	5.3	23.6	11.2	5.8	24.5
Tdb (°C)	9.0	5.0	26.0	11.0	5.0	30.0
Tbg (°C)	24.0	11.0	43.5	25.1	13.5	45.1
Twb (°C)	6.5	1.6	18.0	6.9	2.1	18.4
Solar ($\mathrm{W{\cdot}m^{-2}}$)	639	125	937	712	217	937
RH (%)	57	18	100	60	18	93
VP (mm Hg)	5.2	3.0	11.9	5.2	3.1	11.9

Early = 0900–1300 h; late = 1100–1500 h; all abbreviations defined in text.

In the other environmental variables, the greatest difference was in solar radiation (Fig. 3A) with the late start associated with much higher, CLES = 82.13% [68.27, 95.40], solar radiation exposure ($P = 0.004$). Environmental variables such as relative and absolute humidity were not affected by start time. Both air water vapor pressure (Fig. 3B), $P = 0.13$, CLES = 54.21% [37.72, 73.72], and relative humidity (Fig. 3C), $P = 0.87$, CLES = 38.88% [23.10, 56.24], were compatible with no increase in the AUC with a late start.

Figure 4A shows the stacked proportion of flag categories with respect to the time of day for all years combined. Figure 4B shows the flag categories in time series according to each year. The majority of WBGT flag categories collected during the Boston Marathon from 1995 to 2016 were very low to low risk (Fig. 4A and B). In fact, the first "red" flag observations did not occur until at least 1200 h. An ordinal regression analysis indicates that the odds for an increase in the WBGT by one full flag category is ~1.2 times higher with every passing hour ($e^{0.1774 \times \text{hours}}$) (see Document, Supplemental Digital Content 1, Appendix, http://links.lww.com/MSS/C290). An earlier race start time by 2 h (0900 vs 1100 h) reduced the odds of experiencing a higher flag category 1.42 times ($\beta = 0.1744$, $P = 0.032$). To put it another way, the relative risk of a "yellow" or "red" flag at race start is reduced by ~28% with the start time moved 2 h earlier. Additional results are provided in the Appendix (see Document, Supplemental Digital Content 1, Appendix, http://links.lww.com/MSS/C290).

DISCUSSION

The principal finding of this study is that the decision by the BAA to adopt an earlier start time for the Boston Marathon empirically reduced the odds of exposing runners to higher WBGT index categories when compared with a start time 2 h later (Fig. 4). This finding is particularly impressive given that both early and late start times shared 2 h of overlapping data in common (Fig. 1) and the bandwidths within a sports medicine flag category are as large as 8°C WBGT (14,21). Because half of all Boston Marathon finishers complete the course within the time duration examined in this study (5), by extension the decision reduces the odds of exertional heat illness (2,3,8–10) for ~15,000 runners each year. Importantly,

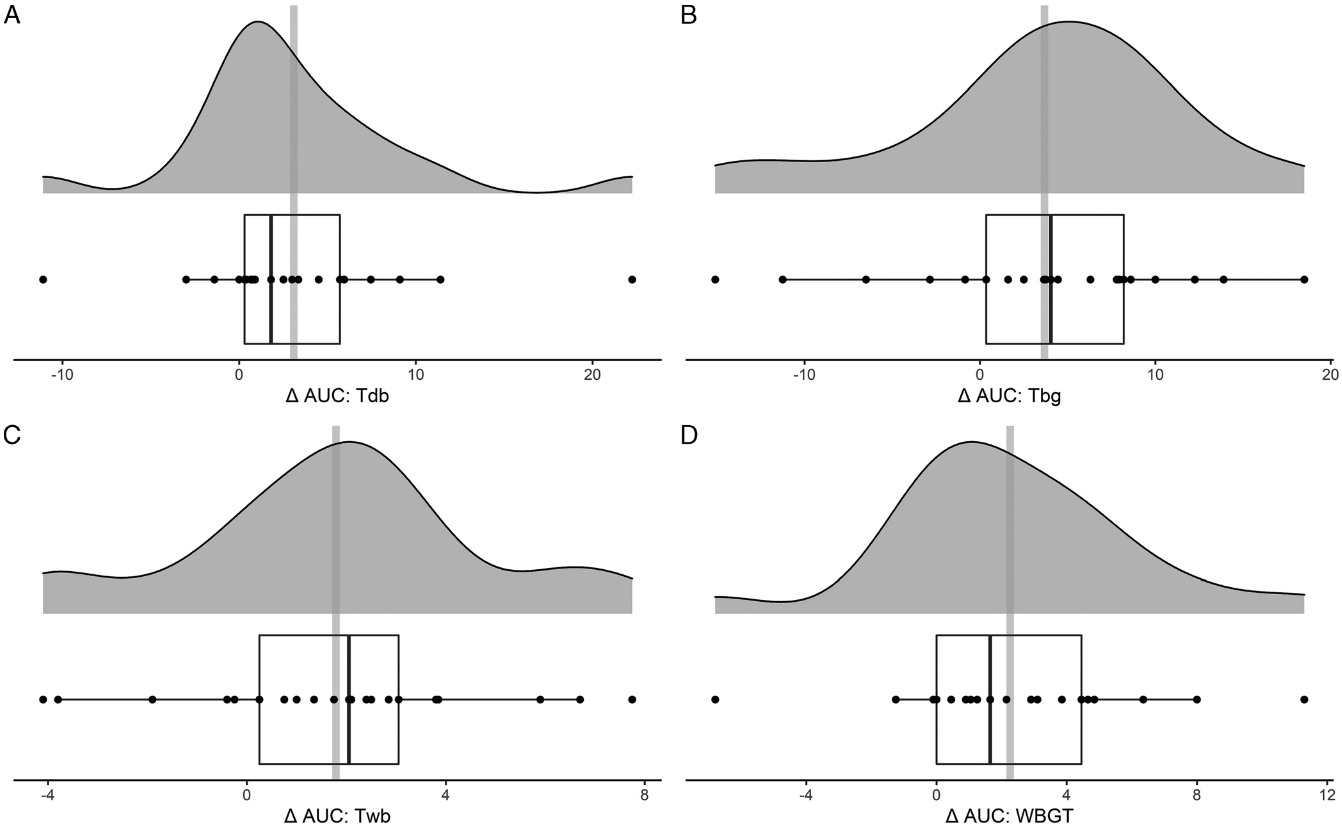

FIGURE 2—Differences (late start − early start) in AUC for each temperature variable: dry bulb temperature (Tdb, °C) (A), black globe temperature (Tbg, °C) (B), wet bulb temperature (Twb, °C) (C), and wet bulb globe temperature index (WBGT, °C) (D). In addition to the individual data points, the visualization includes summary statistics with a box plot depicting the median and interquartile range (whiskers = 1.5 IQR), a *gray vertical bar* indicating the mean, and a kernel density estimate that depicts a smoothed version of the histogram.

the overall exposure during the entirety of the event (AUC), not just the peak values, will determine risk during an outdoor event. The conventional data outputs for early and late starts (Table 1) seem less remarkable, and their skewness does not capture the full brunt of exposure to the environmental conditions during the marathon (Figs. 2 and 3). The AUC reveals that all three components of the WBGT index were decreased during the earlier start time (Fig. 2).

The 10% composite contribution of dry bulb temperature to the WBGT index is comparatively small because it was developed for use in hot weather, whereby air temperature ranges are presumed more narrow (22) than those observed for Boston (Table 1). Dry bulb temperatures have important functional consequences as they determine the potential for dry heat exchange (23,24) and are an integral influence on both black globe and wet bulb temperatures, which are

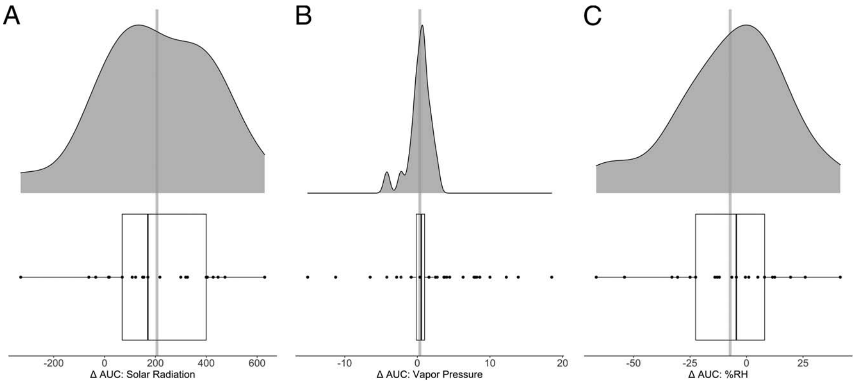

FIGURE 3—Differences (late start − early start) in AUC for other environmental variables: solar load ($W \cdot m^{-2}$) (A), air water vapor pressure (mm Hg) (B), and relative humidity (%RH) (C). In addition to the individual data points, the visualization includes summary statistics with a box plot depicting the median and interquartile range (whiskers = 1.5 IQR), a *gray vertical bar* indicating the mean, and a kernel density estimate that depicts a smoothed version of the histogram.

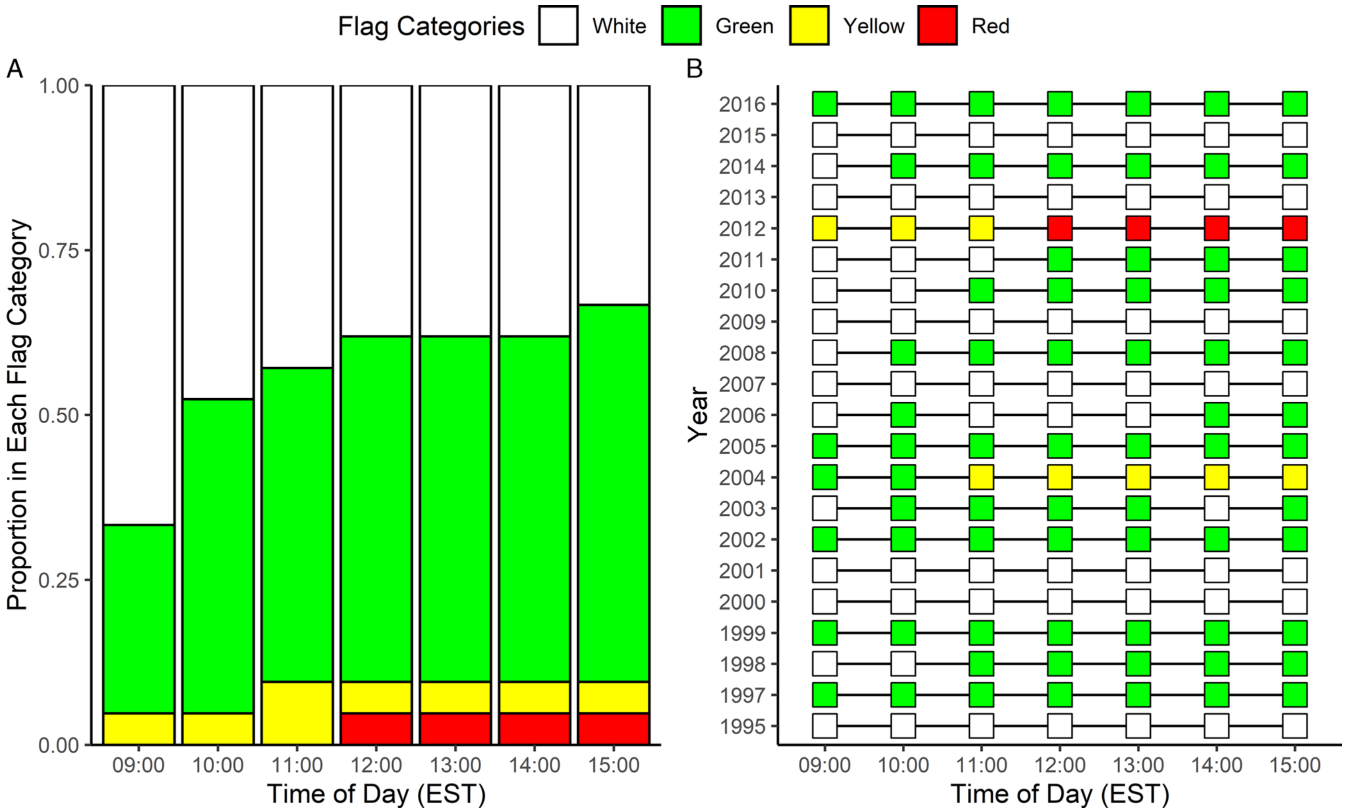

FIGURE 4—Proportions of WBGT measurements in each WBGT flag category stacked by time of day for all years examined (A) and displayed in time series by individual year (B).

measured with combination instruments (25). Therefore, the lower AUC for air temperature observed with an earlier start time is key to a lower WBGT although its mathematical contribution to the index is comparatively small.

The AUC for globe temperature was also lower when the start time was earlier, but the difference was nonsignificant ($P = 0.055$). Despite this fact, the upper range of measured solar load ($W \cdot m^{-2}$) at the Boston Marathon (Table 1) was higher than those reported to impair performance in combination with warm air temperatures (26). The measured AUC for solar load was significantly lower for an earlier start. Absolute median values for an early start were 73 $W \cdot m^{-2}$ less than for a later start (Table 1). This is entirely consistent with the known behavior of daily air temperature and solar radiation rhythms, which covary at the earth's surface (25). If we assume that clothing provides 25% absorptive power (27), 73 $W \cdot m^{-2}$ can be equated to ~10% (~ 1 MET) of the metabolic heat load experienced by a 4-h marathon finisher, or similarly equated to the added heat load that would occur for said runner completing the marathon distance ~15 min faster (14). An explanation for the discrepancy between black globe and solar load outcomes is that they are not the same; the former is a derivative of the latter and can be greatly affected by air velocity and air temperature (11,25,28), whereas pyronometers and radiometers are generally insensitive to each by design. When combined, the black globe and solar load measurements reflect an important contribution by the sun to runner heat balance and the WBGT flag category classification.

The AUC for wet bulb temperature was significantly lower for an earlier start time. Relative humidity, a more common but less useful measure (25), declined as air temperature rose because the absolute humidity (air water vapor pressure, mm Hg) remained modest and unchanging during both the early and the late start periods as the dry bulb temperature rose (see Document, Supplemental Digital Content 1, Appendix, http://links.lww.com/MSS/C290). A rational analysis (23) might conclude that the rising wet bulb temperature over time and its majority formula weighting (70%) could exaggerate the heat stress flag category for late starts in cool weather because the low absolute humidity, significant airflow (≥ movement velocity), and presumably large evaporation gradients between skin and air would strain runner evaporative efficiency little. Like the black globe, the wet bulb temperature is influenced by airflow and dry bulb temperatures (25). Therefore, when the lower AUC for wet bulb temperature is combined with lower AUC for dry bulb and black globe temperatures during early start times, the lower WBGT index and heat stress flag category empirically provides runners, in whom high metabolic rates are presumed, room to increase their prescriptive zone (24) for competitive, safe, and enjoyable exercise.

The 2007 decision to make the Boston Marathon start time earlier by 2 h has reduced by ~1.4 times the odds that runners will be exposed to environmental conditions associated with exertional heat illness (Fig. 4). The association between WBGT and exertional heat illnesses is appreciated for both shorter (8,10) and longer road races (2,8). Roberts (2) demonstrated that both the number of unsuccessful marathon starters, defined as medical encounters or nonfinishers, and the mass casualty events increased when the flag category was ≥yellow. Similarly, Hosokawa et al. (10) reported that WBGT explained between 48% and 69% of the variance in combined exertional heat illness incidence rates. Like Roberts (2), exertional heat illnesses became more common when the flag category was ≥yellow (10). Although the absolute odds of a WBGT flag category ≥yellow was generally low for the years examined in this study (Fig. 4), empirical associations between exertional heat illnesses and WBGT support that an earlier Boston Marathon start time should indeed reduce the odds of exertional heat illnesses (2,10).

One limitation to the analyses and interpretations of the data presented is that the overall occurrence of yellow and red flag categories is less frequent than green or white, but this is consistent with overall weather patterns for the time of year and global location. Unusually warm weather does occur in the typically cool seasons of northern climates (2) (Table 1), however, and the proportional odds model indicates that red flag conditions can be all but avoided by an earlier start time. A second limitation relates to the meteorological station location of the measured environmental variables, which were made at the Logan International Airport rather than on the course itself. Measurements on location are always preferred, but nearby meteorological station measurements at Boston tend to underestimate within one flag category of course measures (21). Importantly, all early and late start comparisons were made using the same meteorological station, thus making AUC difference calculations valid. A third limitation involves the implementation of a staggered "wave start" at Boston beginning in 2006, which creates an approximate 2-h difference between the first and the last (slowest runners) starters. A wave start blunts the potential benefit of the earlier start time, but it is still an improvement over a later start time policy given that the wait time exposure duration is fixed. Finally, complete exertional heat illness data at the Boston Marathon before and after the change in start time are not available (personal communication with Chris Troyanos, Medical Coordinator, Boston Marathon, 1996 to present); thus, the reduced exertional heat illness risk of a lower WBGT with an earlier start time cannot be empirically validated across the same years. However, as indicated above, the association between WBGT and exertional heat illnesses, independent of time of day, is well documented (2,8,10). The measurement of time of day changes on WBGT could be used in future research to model the potential influence on exertional heat illness risk (21,23,24,29,30).

CONCLUSIONS

We conclude that an earlier start time for the Boston Marathon can empirically reduce the odds of total exposure (AUC) of runners to higher WBGT index categories when compared with a start time just 2 h later. All three WBGT index components were reduced by an earlier start time and contributed to this outcome. Because half of all Boston Marathon finishers complete the course within the exposure duration examined in this study (5), an earlier start time should reduce the odds of exertional heat illness (2,3,8–10) for at least half of all Boston Marathon runners. To this end, mean finishing times for marathons requires that early and late start times overlap to some degree when considering AUC exposures. For shorter races (e.g., 10 km and 21 km) or events, differences in AUC for WBGT may not overlap at all (e.g., 0800–1000 vs 1000–1200 h), and the differences are likely to be larger based on fundamental environment principles and assumptions (25). Therefore, earlier start times of road races (and other outdoor sports) can mitigate exertional heat illness risk and fundamentally improve the performance, health, safety, and enjoyment of sport.

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