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ORIGINAL PAPER

Effects of weather on the performance of marathon runners

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Abstract The effects of air temperature, relative and specific humidity, wind speed, solar shortwave radiation, thermal longwave radiation, and rain on the performance of participants in the annual Stockholm Marathon from 1980 to 2008 were analysed statistically. The objective was to validate and extend previous studies by including data on finishing times of slower male and female runners and on the percentage of non-finishers. Due to decadal trends in the finishing time not related to weather, the finishing time anomaly (FTA) was calculated as the deviation of the annual finishing time from the linear trend of the finishing time. In all categories of runners, the single weather parameter with highest correlation with the FTA was the air temperature (correlation coefficient r=0.66–0.73, with the highest values for slowest runners). Also, the solar shortwave radiation (r=0.41–0.71), air relative humidity (r=−0.57 to −0.44) and, for male runners, the occurrence of rain (r=−0.51 to −0.42) reached a statistically significant correlation with the FTA, but the effects of the relative humidity and rain only arose from their negative correlation with the air temperature. The percentage of non-finishers (PNF) was significantly affected by the air temperature and specific humidity (r=0.72 for multiple regression), which is a new result. Compared to faster runners, the results of slower runners were more affected by unfavourable weather conditions; this was previously known for runners with finishing times of 2.1–3 h, and now extended to finishing times of 4.7 h. Effects of warm weather were less evident for female than male runners, which was probably partly due to female runners' larger ratio of surface area to body mass and slower running speed.

Keywords Marathon · Heat stress · Weather · Air humidity · Gender differences

Introduction

Warm weather during a marathon race poses a problem for the competitors (Cheuvront and Haymes 2001; Ely et al. 2007a; Noakes 2007). During heavy physical effort, the metabolic production of heat is approximately ten times higher than at rest (Havenith 2001). In addition, a runner is heated by the solar radiation. To prevent the body core temperature from rising dangerously high, the excessive heat has to be transported to the skin. The methods available are the transport by the vascular system and by heat conduction through tissues. This transport can, however, be maintained only as long as the skin temperature remains lower than the body core temperature. Hence, heat must be further transported from the skin to the atmosphere. The methods available are (1) evaporation of sweat or rain water, which results in a flux of latent heat from the skin to the air, (2) flux of sensible heat from the skin by turbulent convection (in the first millimeters above the skin, however, molecular diffusion of heat dominates), and (3) thermal longwave radiation. In addition, via respiration, heat can be transported directly from the inner parts of the body to the atmosphere. Hence, to better understand the effects of weather on the performance of marathon runners, meteorological parameters that affect processes (1) to (3) need to be analysed. These are the air specific humidity (1 and 3), air temperature (2 and 3), wind speed (1 and 2), and rain (1, 2, and 3).

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Most previous studies on the impact of weather on the performance of marathon runners have focused on the fastest runners. Verdaguer-Godina et al. (1995) and Nielsen (1996) analysed the performances in the Olympic marathons in Barcelona, 1992, and Atlanta, 1996, respectively. Trapasso and Cooper (1989) studied the results of the top three finishers in the Boston marathon in 1957–1987. They found out that for the record-breaking and unusually slow performances the most important meteorological factors were the wet-bulb temperature, percent of sky cover, and presence or absence of light precipitation. Zhang et al. (1992) analysed the results of the Beijing marathon for the top 10 finishers and those with finishing times faster than 2 h 30 min. For the top 10 finishers, the finishing time and the air temperature had a high correlation coefficient of 0.89. Also, the wet-bulb temperature was found to be a good indicator for the finishing time. Ely et al. (2007a) made an extensive analysis of the results of seven U.S. or Canadian marathon races in a period of 10–36 years. They found a strong relationship between the finishing time and the wet-bulb globe temperature. Bouoncristiani and Martin (1983) and Ely et al. (2007a) also considered how the fitness of the runner is related to the sensitivity of the results on the weather conditions. The differences between male and female runners in sensitivity to weather have been addressed by Roberts (2000), Cheuvront et al. (2005), and Ely et al. (2007a, b, 2008). Besides Roberts (2000), the effects of weather on the percentage of non-finishers have received very little attention.

In this study, I analyse the results of the Stockholm Marathon with focus on the elite, intermediate and slow male and female runners with finishing times ranging from 2 h 11 min to almost 5 h. Besides finishing time, I focus on the percentage of non-finishers. I present statistical analyses between the marathon results and weather parameters, and interpret the results paying attention to physiological aspects and the inter-relationship between the weather parameters. The new aspects of this study are (1) the possibility to examine impact of weather on runners considerably slower than those which have been examined previously, (2) application of quantitative information on solar radiation and thermal longwave radiation, (3) a race run in summer afternoon conditions with large solar radiation, and (4) the possibility for extensive analyses on the percentage of non-finishers.

Materials and methods

The results of the Stockholm Marathon were selected for this study because results of all finishers throughout the history of the race were available on the internet at http://www.stockholmmarathon.se. In addition, the number of starters and finishers were available. Because of the small number of participants in the first year of the race in 1979, I excluded it from the analysis. For each year from 1980 to 2008, I computed the ratio of finishers to starters (separation between male and female was not possible) and the mean times of male runners finishing at places 1–3, 1–250, 1,001–1,250, and 4,001–4,250 (on the internet, the results were archived in groups of 250 runners). The trends, 29-year means, inter-annual standard deviations, as well as the best and worst annual means of finishing times for these four categories are presented in Table 1. The performances of female runners were analysed separately. The number of female participants was very small in 1979–1982, and I therefore started the analysis from 1983. The results of female runners who finished at places 1–3, 1–250, and 1,001–1,250 were analysed. The number of female finishers exceeded 1,250 only in 1998, yielding 11 years of data for this category of runners. In 1990, a small change was made in the marathon route, but it did not cause statistically detectable effects on the finishing times.

I included in the analyses the weather parameters that affect the human heat budget during a marathon race: air temperature, air humidity, wind speed, occurrence of rain, as well as the incoming solar shortwave and thermal longwave radiation. I analysed statistics between these parameters and the finishing times in the Stockholm Marathon. The weather data (air temperature, dew point

Table 1 Finishing times and their trends for runners placed at positions 1–3, 1–250, 1001–1250, and (male only) 4001–4250

Finishing category	29-year mean	Best annual mean	Worst annual mean	Standard deviation of annual means	Trend and its confidence level *p*
Male, 1–3	2 h 17 min	2 h 12 min	2 h 22 min	2.5 min	Increasing, $p<0.05$
Male, 1–250	2 h 45 min	2 h 33 min	2 h 58 min	6.3 min	Increasing, $p<0.01$
Male, 1,001–1,250	3 h 18 min	2 h 59 min	3 h 37 min	9.9 min	Increasing, $p<0.01$
Male, 4,001–4,250	3 h 56 min	3 h 31 min	4 h 17 min	13.1 min	Increasing, $p<0.01$
Female, 1–3	2 h 40 min	2 h 32 min	2 h 47 min	2.6 min	Insignificant
Female, 1–250	3 h 35 min	3 h 29 min	3 h 45 min	4.1 min	Decreasing, $p<0.05$
Female, 1,001–1,250	4 h 39 min	4 h 23 min	4 h 59 min	13.9 min	Decreasing, $p<0.01$

temperature, and wind speed) were based on the observations at the Swedish Meteorological and Hydrological Institute (SHMI) weather station located 5 km from the midpoint of the race course. In a town environment, the local wind speed measurement was not representative for all parts of the course. The air relative and specific humidity were calculated on the basis of the air and dew point temperature. The data were available at 3-h intervals, and I used the records from 1500 hours UTC, which in summer is local time 5 p.m. in Stockholm. The starting time of the marathon has always been in the afternoon, in 90% of the years at 2 or 3 p.m., with the mean starting time at 2.48 p.m. From 1979 to 1981, the marathon was organised in August, but from 1982 onwards between 30 May and 14 June. In addition to the direct weather observations, I utilised the fluxes of incoming solar shortwave and thermal longwave radiation at the Earth surface based on the operational analyses of the European Centre for Medium-Range Weather Forecasts (ECMWF). The data represented the mean radiative fluxes from 1200 to 1800 hours UTC.

Due to decadal trends in the finishing times not related to weather, I compared the weather parameters against the finishing time anomaly (FTA), defined as the deviation of the annual finishing time from the linear trend of the finishing time, as illustrated in Fig. 1a. Linear regression analyses were then performed between single weather parameters and the FTA. The regression equations were then applied to calculate the FTA increments when the air temperature increases from 10 to 25°C. Stepwise multiple regression analyses were made to better understand the effects of inter-relationships between the weather parameters.

To better interpret the results of the Stockholm Marathon and compare them against previous studies, I made additional calculations on the basis of data tabulated in Zhang et al. (1992) and Roberts (2000), as well as on the basis of all-time athletic statistics of Finland, obtained from Tilastopaja Ltd (www.tilastopaja.fi).

Results

The mean finishing time of the first 250 male runners had an increasing trend (Fig. 1a): the correlation coefficient (r= 0.76) was statistically significant at the 99% confidence level (p<0.01). The results were almost the same for the 1,001–1,250th and 4,001–4,250th placed finishers (p< 0.01), while the correlation was lower for the best three runners (r=0.46, p<0.05) (not shown in Fig. 1). The finishing time of female runners had a decreasing but insignificant trend. The air temperature (Fig. 1d) and other meteorological parameters did not show significant trends. Hence, the trends in the finishing time were not related to weather. The numbers of starters and finishers had increasing trends (Fig. 1b). Above all, the number of female runners had strongly increased during the history of the race. In 1983, 388 women finished the race (4.3% of finishers), while in 2008 the number was 3,030 (22.4%). The increased number of female runners probably explains

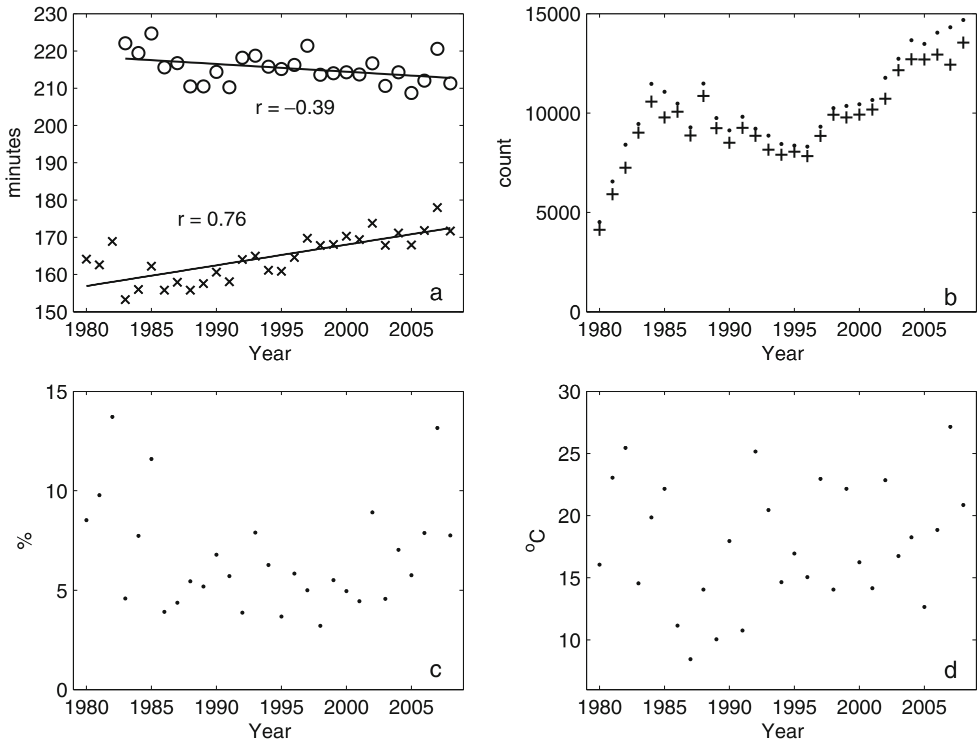


Fig. 1 Time series of **a** the mean finishing time of the first 250 male (*crosses*) and female (*circles*) competitors, **b** number of starters (*dots*) and finishers (*crosses*), **c** percentage of non-finishers, and **d** the air temperature. The correlation coefficients (r) and linear trends of the finishing times are included in (**a**). The finishing time anomaly (FTA) is defined as the difference of the annual finishing time from that according to the regression line in (**a**)

the fact that the mean finishing time of female runners placed among the first 250 (as well as in positions 1,001–1,250) has not become worse, although male runners have simultaneously become slower.

On the basis of the percentage of non-finishers (Fig. 1c), the two years with most demanding conditions in the history of the Stockholm Marathon have been 1982 and 2007. In 1982, the exceptional aspects in the weather conditions were the high air specific humidity of 11.2 g/kg and a downward longwave radiation of 380 W/m^2, which were higher than in any other year (the mean values in 1980–2008 were 6.9 g/kg and 330 W/ m^2, respectively). The air temperature was second highest in the history of the race (Fig. 1d), while the solar radiation, relative humidity, and wind speed were close to their mean values. In 2007, the air temperature was the highest in the history, 27.2°C, the specific humidity was third highest, 9.2 g/kg, and the solar radiation, 400 W/m^2, was 6th highest in the history, whereas the other weather parameters were not far from their mean values. In 1982, the FTA was the highest (worst) in all categories of male runners, while in 2007, the FTA was the second highest for the best three finishers, and among the highest five in the other categories. In 2007, the FTA of female runners was the highest in the categories of 1–250th and 1,001–1,250th placed finishers, whereas the FTA of the three best female runners was not affected (the analysis of female runners started from 1983).

The dependence of the percentage of non-finishers (PNF) on meteorological parameters is illustrated in Fig. 2. The air temperature and specific humidity were the parameters reaching the highest correlations: $r=0.64$ and $r=0.48$, respectively ($p<0.01$ for both). For no other parameter is

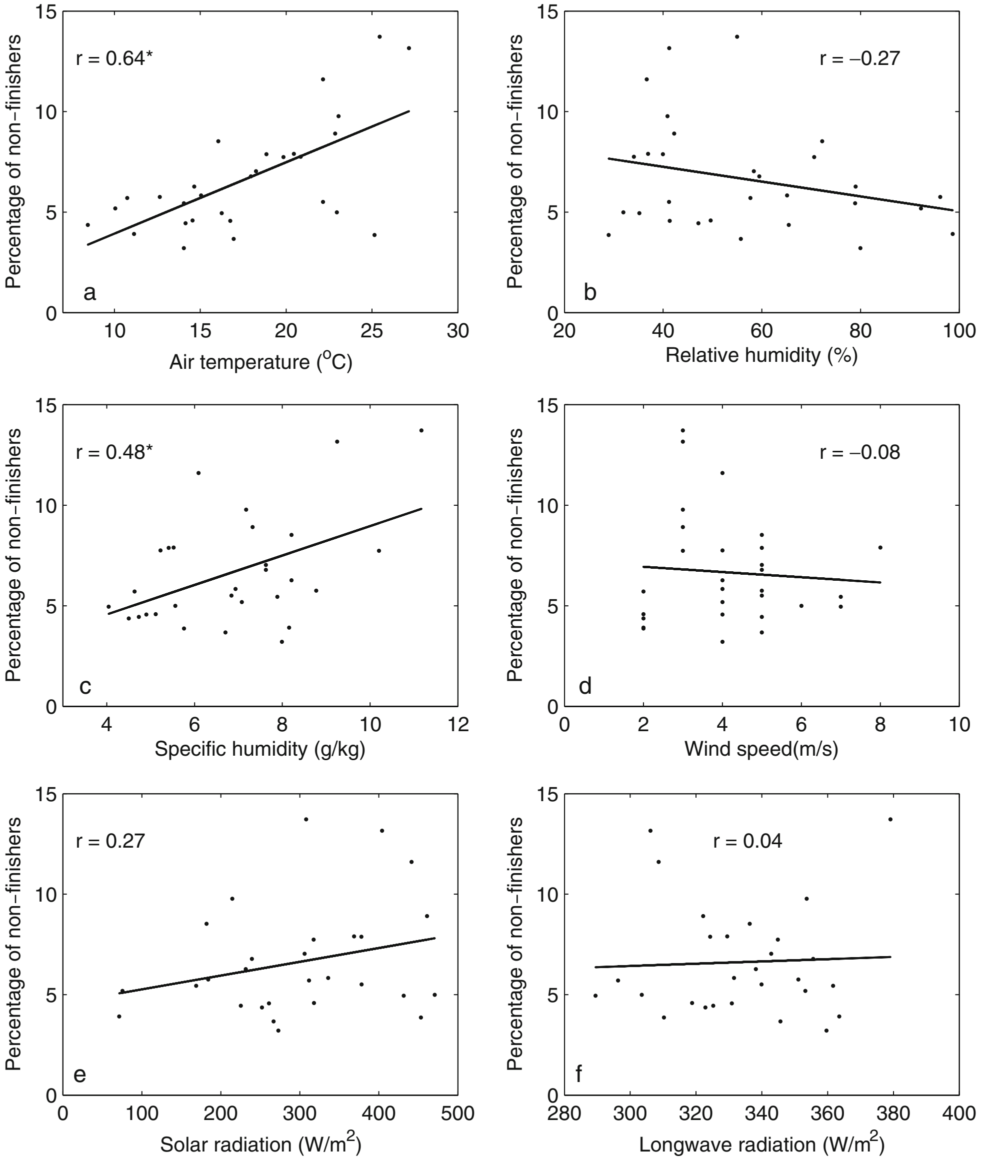


Fig. 2 Dependence of the percentage of non-finishers on the **a** air temperature, **b** relative humidity, **c** specific humidity, **d** wind speed, **e** solar radiation flux, and **f** longwave radiation flux. Correlation coefficients marked by * are significant ($p<0.01$)

$p<0.05$, but it is noteworthy that the effect of the relative humidity was opposite to that of the specific humidity. Following Trapasso and Cooper (1989), stepwise multiple regression analyses were made starting from the air temperature with $r=0.64$. Inclusion of the specific humidity increased r to 0.72, but inclusion of more variables did not improve the correlation. The multiple regression equation got the form

$$\mathrm{PNF} = 0.30\ \mathrm{T} + 0.54\ \mathrm{q} \qquad (1)$$

where T is the air temperature in °C and q is the specific humidity in g / kg.

Figure 3 shows how the FTA of male runners depended on the meteorological parameters. The FTA had a significant correlation with the air temperature ($p<0.01$ for all categories), relative humidity ($p<0.01$ for all categories except $p<0.05$ for the 1–250th placed finishers), and solar radiation ($p<0.01$ for the 4,001–4,250th placed finishers; $p<0.05$ for the other categories). The strongest relationship was found between the FTA and air temperature, but the correlation coefficient and the slope of the regression line depended on the category of runners (further analysed below). The wind speed and the longwave radiation had no statistically significant correlation with the FTA. With increasing air relative humidity the FTA decreased, whereas it (insignificantly) increased with increasing air specific humidity (further addressed in the Discussion).

Results from similar analyses for female runners are presented in Fig. 4. Correlation with the FTA was found for the air temperature ($p<0.01$ for the 1–250th and 1,001–1,250th placed finishers), relative humidity ($p<0.01$ for the 1–250th placed finishers), solar radiation ($p<0.01$ for the 1–250th placed finishers; $p<0.05$ for the 1,001–1,250th placed finishers), and longwave radiation ($p<0.01$ for the

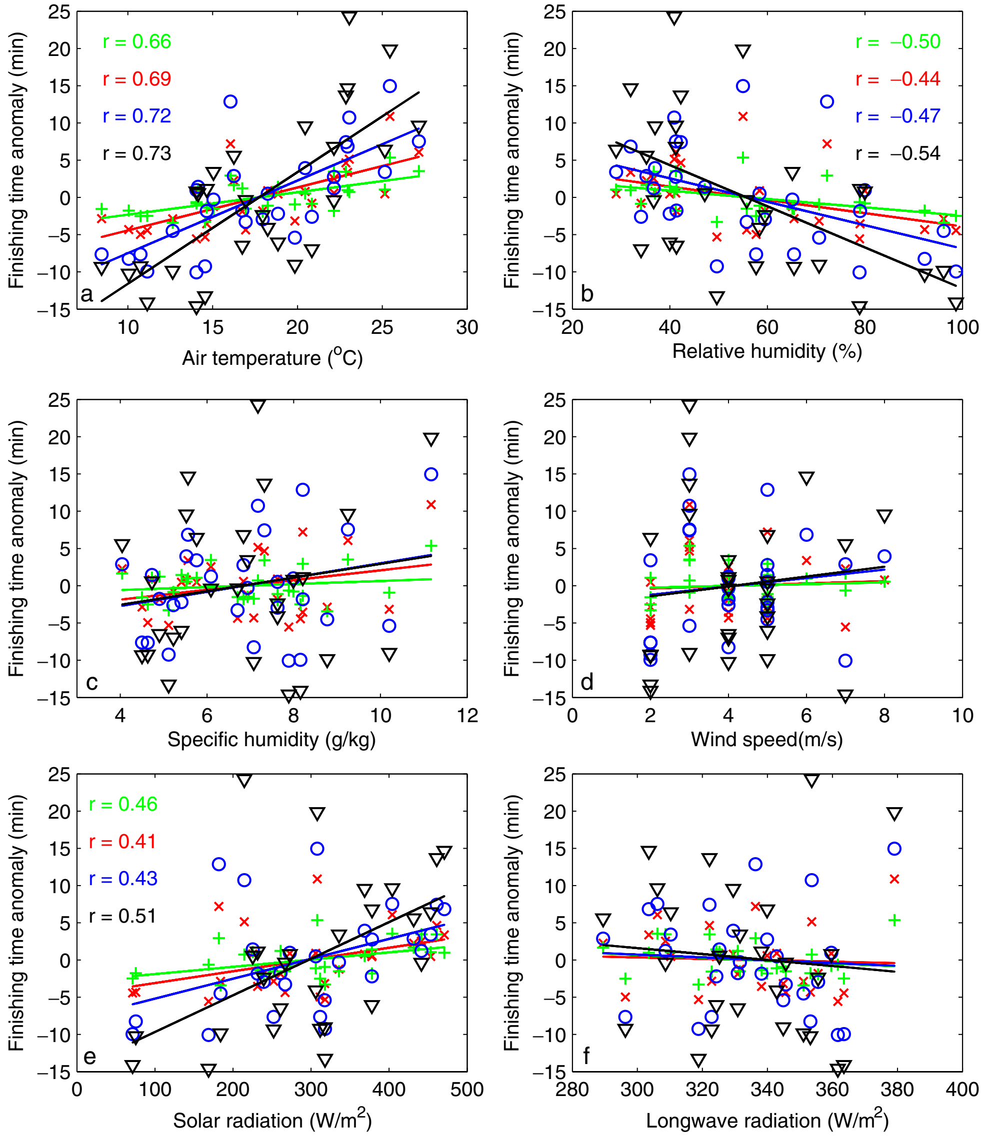
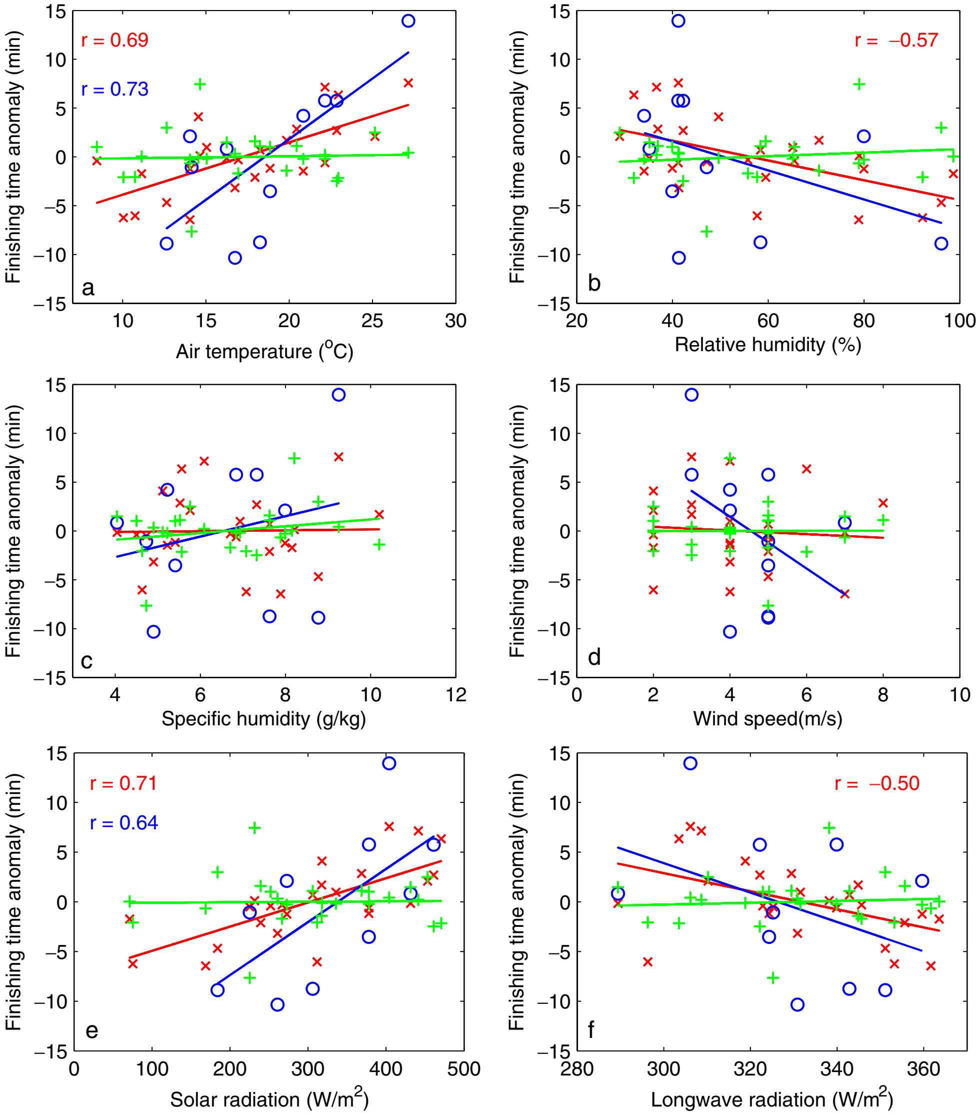


Fig. 3 Effect of the **a** air temperature, **b** relative humidity, **c** specific humidity, **d** wind speed, **e** solar radiation flux, and **f** longwave radiation flux on the finishing time anomaly of male competitors at positions 1–3 (*green* +), 1–250 (*red x*), 1,001–1,250 (*blue o*), and 4,001–4,250 (*black triangles*). The correlation coefficients with $p<0.05$ are marked

Fig. 4 As Fig. 3, but for female runners at finishing positions 1–3 (*green* +), 1–250 (*red x*), and 1,001–1,250 (*blue o*)



1–250th placed finishers). It is noteworthy that the FTA of the best three female runners was very little affected by any of the weather parameters.

To better understand the inter-related effects of the different meteorological variables on the FTA, stepwise multiple regression analyses were made starting from the air temperature. Inclusion of relative humidity did not improve the regression model for the FTA. No statistically significant correlation was found between the FTA and specific humidity. This indicates that the statistically significant dependence between the FTA and relative humidity only resulted from the fact that a high relative humidity is usually associated with a low air temperature ($r=-0.69$, $p<0.01$), the latter improving the FTA. In the three years with the relative humidity exceeding 90% (1986, 1989, and 2005), the air temperature ranged from 10.1 to 12.7°C, and the FTA was on average −4 min.

The effects of air temperature and solar radiation on the FTA were not easily distinguishable from each other. The air temperature and solar radiation were positively correlated ($r=0.67$, $p<0.01$). In all categories except the three best female runners, both air temperature and solar radiation had a statistically significant correlation with the FTA. In five of these six categories, the correlation coefficient with the air temperature was higher (Figs. 3 and 4), but the difference between the correlation coefficients was never statistically significant. Multiple regression analyses indicated that in the five categories the degree of explanation (measured as the root-mean-square error and p value) of the regression model between the FTA and air temperature was not improved by including solar radiation as the second variable, and for female runners at positions 1–250 (for which the correlation with solar radiation was higher), the degree of explanation of the regression model between the FTA and solar radiation was not improved by including air temperature as the second variable. Differences in the mean FTA between warm days with high and low solar radiation were not statistically significant, but this was the case also for differences in the mean FTA between warm and cold days under high solar radiation. Hence, I conclude that both the air temperature and solar radiation were statistically linked with the FTA, but a larger dataset is needed to quantify the relative importance of these variables.

Based on the regression lines for the dependence of the FTA on air temperature (Figs. 3a and 4a), I calculated the absolute and relative increment in the FTA for various air temperatures and finishing times. A temperature of 10°C, for which the FTA was smallest on average, was used as a reference when calculating increments of the FTA with increasing air temperature. The results demonstrated that slower runners were more strongly affected by warm weather (Fig. 5). For an elite male runner, the increase of air temperature from 10 to 25°C only yielded a time increment of 5 min, whereas for a 4-h marathon runner the effect was 23 min. For an elite female runner, the statistical analysis did not reveal an effect of the air temperature, whereas a 4.7-h female runner used 18 min more time under a temperature of 25°C compared to 10°C. The results for the relative increase in the FTA were qualitatively similar: slower runners were more strongly affected (Fig. 5 b, d). The relative FTA increments increased almost linearly with the finishing time, whereas the absolute FTA increments increased exponentially in the time range studied.

In addition to the quantitative meteorological parameters, I applied information on the occurrence of rain. At least occasional rain during the race was recorded in 9 years: 1983, 1986, 1988, 1989, 1991, 1994, 1996, 1998, and 2001. The differences in FTA between races without and with rain ranged from 1 to 4%. Giving an index 1 for the races under rain and 0 for the races without rain, the correlation coefficient between the index and FTA of male runners was −0.51 (positions 1–250 and 1,001–1,250), −0.45 (positions 1–3), and −0.42 (positions 4,001–4,250). In all years with rain, however, the air temperature was low and its range was small, from 10.1 to 15.1°C. Among all years with the air temperature in this range, 9 races were run under rain and only 1 without rain. The FTAs did not differ significantly. To include more cases without rain (six), the analysis was repeated for the temperature range from 8 to 17°C, but no effects of rain on the FTA were detected.

Discussion

The results of Stockholm Marathon showed that the air temperature was the weather parameter with the strongest effect on the FTA. Also, the solar shortwave radiation, air relative humidity, for male runners the occurrence of rain,

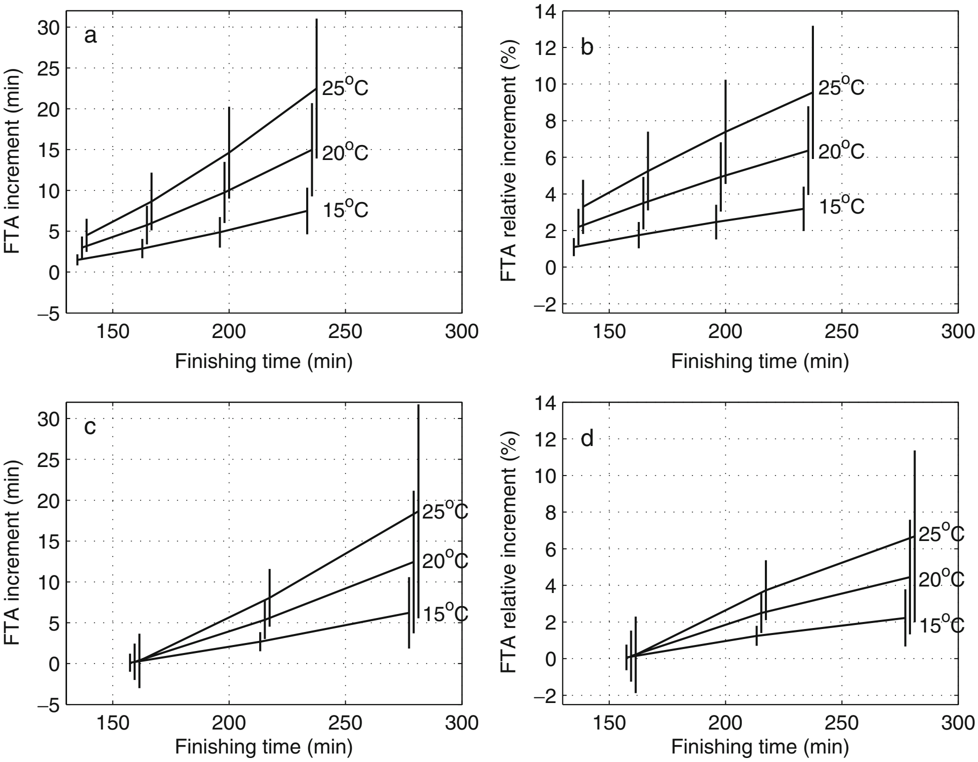


Fig. 5 Nomograms presenting the dependence of (**a** and **c**) absolute and (**b** and **d**) relative increase in the FTA on the finishing time and air temperature (**a** and **b** for male, **c** and **d** for female runners). The FTA increments are calculated with respect to a race run under +10°C temperature. The *error bars* indicate the 95% confidence limits. To avoid overlapping of the *error bars*, those for 15 and 25°C are slightly shifted along the *x-axis*

and for one category of female runners the downward longwave radiation reached a significant correlation with the FTA, but the effects of the relative humidity and rain only arose from their negative correlation with the air temperature.

During daytime, solar radiation is always a heat source for the runner, but according to Ely et al. (2007b) low solar loads are not statistically associated with fast marathon performance. Most races analysed by Ely et al. (2007b) were run in spring or autumn. In the dataset of the summertime Stockholm Marathon, solar radiation did have a statistically significant correlation with the FTA but, due to the positive correlation between solar radiation and air temperature ($r=0.67$, $p<0.01$), it was not possible to statistically separate their effects on the FTA. Further studies based on a larger dataset are needed.

Lind (1963) addressed the different effects of relative and specific humidity on sweat evaporation. Later, Trapasso and Cooper (1989) and Zhang et al. (1992) proposed that relative humidity is not a good variable in predicting marathon performances, but they did not specifically explain the reasons for that. The explanation is that relative humidity alone does not include information on the skin–air difference in specific humidity. The rate of evaporation from a wet skin depends on (1) the difference between the saturation specific humidity for the skin temperature and the air specific humidity, and (2) the effectiveness of the turbulent transfer of water vapour above the skin, controlled by the velocity difference between the air flow and the runner (the relative wind speed), aerodynamic properties of the body, and the skin–air temperature difference (de Freitas et al. 1985). Both Zhang et al. (1992) and I found that the performances improve with increasing relative humidity, but this is a statistical result only, arising from the negative correlation between the air temperature and relative humidity. Further, it is not necessarily valid in all climate zones. A high relative humidity may result from either a high specific humidity or a low air temperature (or both), and these have opposite effects on a marathon runner. From the point of view of marathon runners and race organisers, who are usually not experts in meteorology, it is unfortunate that the relative humidity is the most commonly used humidity variable in weather forecasts and information on actual weather.

In the Stockholm Marathon, the highest air temperature recorded has been 27°C. It still allows significant body heat loss via all the processes normally available: convective flux of sensible heat, evaporation, net longwave radiation, and breathing. In more extreme conditions, if the air temperature rises and finally reaches the skin temperature (which also rises with rising air temperature), heat release from the skin via the convective flux of sensible heat is no longer possible. Under such high temperatures, the air relative humidity is, however, always well below 100% (there is no fog). With the air and skin temperatures equal, this means that the air specific humidity is below the saturation specific humidity for the skin temperature, and heat release from the skin can accordingly continue via evaporation and net longwave radiation. In such conditions, the air specific humidity must be the meteorological variable controlling the running performance.

Theoretically, as long as the air specific humidity is lower than the saturation specific humidity for the skin temperature, an increasing wind speed decreases the heat stress of a marathon runner (assuming a circular race course with both headwind and tailwind conditions). Compensating effects probably explain the fact that the wind speed correlated with neither PNF nor FTA. A strong wind enhances the body heat loss via both convection and evaporation, but otherwise strong wind does not favour fast running; the disadvantage caused by headwind is larger than the advantage obtained from tailwind. This is because the drag on the body is proportional to the cube of the relative wind speed. Accordingly, the favourable effect of enhanced heat loss and the disadvantageous effect of increased drag possibly compensate for each other, yielding near-zero correlations in Figs. 3 and 4. Another factor decreasing the correlation is the spatial variability in the wind field between the measurement site and various parts of the race course.

Compensating effects may also partly explain the generally low correlation between the incoming longwave radiation and both PNF and FTA ($p<0.01$ was reached only for the FTA of one category of female runners). The incoming longwave radiation is a heat source, and therefore tends to increase the heat stress, PNF, and FTA. The incoming longwave radiation is highest during cloudy skies (thick clouds emit longwave radiation as a black body, whereas under clear skies the atmospheric emittance is low), when the incoming solar radiation is low. Hence, there is a negative correlation ($r=-0.67$, $p<0.01$) between the incoming solar and longwave radiation, which dominates over the effect of the longwave radiation itself, resulting in the low correlations with the PNF and FTA. Note that information was not available on the body heat loss via the net longwave radiation, which is the difference between the longwave radiation emitted and absorbed by the runner, the latter originating from the atmosphere (analysed here), road, other runners, buildings and other surrounding objects.

Zhang et al. (1992) found that weather conditions had a stronger impact on the finishing times of faster than slower runners. The reasons for this were partly related to the fact that Zhang et al. (1992) analysed the finishing time itself instead of the FTA. They reported the following correlations between the finishing time and air temperature: $r=$

0.51 for all participants and $r=0.89$ for the first 10 finishers. Utilizing the information from their Tables 2 and 3, I calculated the correlation coefficients for the dependency of the FTA on the air temperature, resulting in $r=0.86$ for all participants and $r=0.69$ for the best 10 participants. Accordingly, it is essential to take into account trends in the marathon results that are not related to weather.

In agreement with my results, Ely et al. (2007a) found that unfavourable weather had a larger effect on the performance of slower than faster runners. The nomograms on the dependence of the relative increment of the FTA on the air temperature and finishing time (Fig. 5 b, d) can be roughly compared against an analogous nomogram in Ely et al. (2007b); their Fig. 3). They used, however, the wet-bulb globe temperature (WBGT) instead of the conventional air temperature, and set the reference to WBGT=5°C. On the basis of Table 1 of Ely et al. (2007a), the WBGT was, however, close to the air temperature (called as dry-bulb temperature by Ely et al.). Assuming the temperatures equal and taking into account the different reference levels, the predictions of the nomograms agree well for faster runners with finishing times less than 2.5 h. For slower runners, my nomograms give smaller temperature effects, but for finishing times of 3 h (the upper limit in Ely et al. 2007b), the nomograms still agree within my error bars. Extrapolating the Ely et al. nomogram to 4–5 h would, however, show large differences. The nomogram of Ely et al. (2007b) predicts an exponential effect of the finishing time on the relative time increment, while my nomograms are close to linear.

I can identify the following reasons that may explain why the finishing times of slower runners are more strongly affected by high temperature and intense solar radiation. First, slow runners usually have a larger body mass than fast runners. Statistics from Stockholm Marathon are not available, but for Finns with the marathon record (1) better than 2 h 20 min ($n=82$), (b) from 2 h 20 min to 2 h 25 min ($n=72$), and (3) from 2 h 25 min to 2 h 30 min ($n=99$), the mean body masses are 61, 63, and 64 kg, respectively. Body mass strongly increases metabolic heat production, and therefore a heavy runner has to slow down his/her running speed more than a lighter runner (Nielsen 1996; Dennis and Noakes 1999; Wright et al. 2002). Second, in a race, the vascular system has to transport both blood for muscles and heat from the inner body to the skin. To perform both duties, the running speed has to be reduced in warm weather. An elite runner has a high-capacity vascular system, and if he uses a certain percentage of it for the heat transport, the absolute capacity for this function is larger than in the case of a less fit runner. Third, well-trained elite runners are probably better acclimatised to warm weather. Fourth, a slower runner is on average more closely surrounded by other runners. In Stockholm in 2008, in the positions of 1–250, on average 5.3 runners per minute crossed the finishing line, while in the positions of 4,001–4,250 the number was 74.6. The vicinity of other runners strongly reduces the heat loss from the skin by longwave radiation, evaporation, and convection, and in occasions causes more than three times the heat stress compared to that experienced when running solo (De Freitas et al. 1985). Another interesting aspect in the comparisons between faster and slower runners is that, probably due to the anticipatory control (Tucker et al. 2006), warmer weather causes slower runners to run slower from start to finish, rather than a greater deceleration in pace which is exhibited by faster runners (Ely et al. 2008).

Ely et al. (2007b) found that male and female runners reach their peak performance in similar conditions of a low (~12°C) air temperature. Except for the top three females, this was also the case in the Stockholm Marathon. The results indicated, however, weaker effects of heat on female runners. On average, women run approximately 10% slower and have larger body surface area-to-mass ratios than men, which may explain why female runners seem to suffer less from heat than male runners (Haymes 1984; Wright et al. 2002); exercise heat production increases with the running speed and body mass, while heat loss depends on body surface area. One cannot, however, exclude possible effects of other physiological differences related to thermoregulation and sweat rate (Cheuvront and Haymes 2001; Cheuvront et al. 2005). The statistical analysis suggested that the best three female runners in the Stockholm Marathon were practically unaffected by weather. This can be partly explained by the above-mentioned factors, but I believe that the results were also affected by factors not related to meteorology and physiology. In particular, in the early years, the number of female runners was low and there were large differences in their level of performance. The standard deviation of the finishing times of the three best runners was on average 1.1 min for men but 3.6 min for women. From 1983 to 2008, a total of 54 female and 60 male runners have been placed among the first three, demonstrating that the people involved usually changed from year to year. Hence, the mean finishing time of the three best female runners in a certain year must have been strongly affected by who were the elite-class participants that year. For males, the effect has been smaller due to less variability in the level of performance among the best runners.

I know only one previous study on the effects of weather on the PNF. Roberts (2000) analysed 13 years (1982–1994) of data from the Twin Cities Marathon in the USA, but his main focus was on medical injury and illness. He interpreted the anomalously high PNF in 1986 as result of a very low wind chill factor (−7°C). My regression analyses on the basis of data from Tables 3 and 4 of Roberts (2000) showed that the statistically most important factor related to high PNF was, surprisingly, the air relative humidity at the time of the race start (8 a.m.): $r=0.74$ for male, and 0.80 for female ($p<0.01$). Among the five years with the highest PNF, however, four had been cold with air temperature at 8 a.m. between −5 and 5°C, while one had been relatively warm with fog (+16°C, 100% relative humidity). Hence, in the Twin Cities Marathon in 1982–1994, the reasons for the variability of PNF were not primarily related to heat stress.

The above, together with the considerations on the role of specific humidity in extremely high temperatures, demonstrate that the results obtained for the Stockholm Marathon cannot be generalised to marathon races in different climate. On the other hand, the results of the Stockholm Marathon (Figs. 3 and 4) are in line with the previous findings that the effects on finishing times are already evident in air temperatures well below 20°C (de Freitas et al. 1985; Trapasso and Cooper 1989; Ely et al. 2007a), which is due to the excessive metabolic heat production by the runner. Organisers of marathon races should take this more into account: to reduce the disadvantageous effects of heat on the finishing times, attention should be paid to the dates and starting times of races.

For further statistical analyses, more data are needed to better quantify the effects of solar radiation and specific humidity. To better interpret various statistical results of this study, among others the importance of the body mass and the differences between male and female runners, further studies are needed applying physiological models, such as Havenith (2001), together with a detailed description of the heat exchange between the moving body and the atmosphere (de Freitas et al. 1985).

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