Temperature and barometric pressure are related to running speed and pacing of the fastest runners in the 'Berlin Marathon'

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Abstract. – OBJECTIVE: The influence of environmental conditions, such as temperature, barometric pressure, humidity, precipitation, sunshine and cloud cover on marathon running has been widely investigated. However, the influence of such conditions on the pacing of elite marathoners has not been considered yet. The present study aimed to investigate whether environmental conditions are related to the running speed and pacing of the fastest marathoners competing in the fastest racecourse in the world, the 'Berlin Marathon'.

SUBJECTS AND METHODS: A total of 668,735 finishers (520,715 men and 148,020 women) competing between 1999 and 2019 in the 'Berlin Marathon' were analyzed by comparing elite and recreational runners. The associations between time-adjusted averages of the environmental conditions, the race times and running speeds were investigated. The runners were divided into performance groups consisting of recreational (all runners) and elite runners (the top 100, the top 10 and the top 3) which were separately analyzed for male and female participants.

RESULTS: During race days, the temperature increased while humidity decreased showing a strong negative correlation between the two variables. For all runners, the average running speed through the race showed a strong negative correlation with temperature and a strong positive correlation with the level of humidity. Faster runners experienced lower temperatures and higher humidity levels than slower runners. When the performance groups were analyzed, temperature and humidity remained correlated to a similar extent for the top 100 but dropped dramatically for the top 10 and top 3, suggesting a weaker influence. In addition, barometric pressure showed a positive correlation with running speed in the top 100 and top 3 groups.

CONCLUSIONS: Temperatures increased during race days while humidity decreased and both variables were negatively and significantly correlated. Faster runners experienced lower temperatures and higher humidity levels, while slower runners experienced higher temperatures and lower humidity levels which had a stronger negative impact on running speeds. Running speed was also significantly and positively correlated with barometric pressure in elite runners.

Key Words:
Marathon, Running, Temperature, Weather, Sunshine, Rain.

Introduction

Elite marathon running has been of the outmost scientific and public interest since it was assumed that the barrier of 02:00 h:min could be broken[1,2]. On October 12, 2019, the Kenyan marathoner Eliud Kipchoge became the first person in history to achieve the barrier-breaking sub-two-hour marathon in a time of 01:59:40.2 h:min:s (www.ineos159challenge.com). To break it down, he ran each mile in ~4:34 min/mile (running speed of ~2:50 min/km). However, this record was not certified as an official record, because a plethora of variables were strongly controlled. A rather flat course was chosen, the pace was set electronically (*via* car and lasers) and other runners provided draft conditions for the runner throughout the entire race (www.ineos159challenge.com/education).

The weather conditions were very important for his project and were detrimental in the course

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selection because temperature interacts with humidity and high humidity impairs sweating and cooling down. Vienna was chosen as the venue for the challenge because it offered the best chance of getting the right environmental conditions (www.ineos159challenge.com/performance/weather). A minimum temperature of 6.4°C, a maximum temperature of 14.3°C, average humidity of 79% and an average wind speed of 9.1 km was measured on the planned date. At the start at 08:15, the temperature was 9°C which rose to 11°C at the finish while the humidity stayed low throughout the entire challenge (www.redbull.com/za-en/eliud-kipchoge-sub-two-marathon-in-numbers).

Existing studies report that air temperatures must be rather low for elite marathoners to achieve top performance[3-6]. The optimal temperature for a fast marathon race time is generally in the range of 10 to 12°C[3,5]. However, lower temperatures might be even better for fast race times. An analysis from the 'Boston Marathon' with data from 1897 to 2017 showed that air temperature ≤8°C significantly improved race times compared to air temperature >8°C[4]. Record-breaking performances at the 'Boston Marathon' were marked by a wet-bulb temperature of less than 7.8°C and 100% sky cover[6]. However, in the 'Berlin Marathon' which is the fastest racecourse in the world and where most marathon world records were achieved (i.e., five of the last ten records were achieved in the 'Berlin Marathon'), the ideal environmental conditions for a male world record were temperatures of 18.6°C, sunny, mostly dry days, with higher atmospheric pressure and little cloud cover. For women, ideal conditions for a world record were temperatures of 13.07°C, with low atmospheric pressure, but more rain, and with no sunshine and cloud cover[7].

We considered that the pacing strategy is pre-determined but is still directly influenced by the constraint during the race event, which can be related to natural (i.e., windy, rain, altimetry) or environmental (e.g., competitors, perception effort) factors and that the ambient temperature impairs the physiological answers to physical activity. With those considerations in mind, the purpose of this study was to identify the influence of environmental conditions such as temperature, humidity, barometric pressure, sunshine duration, cloud cover and precipitation on pacing in elite marathoners competing in the 'Berlin Marathon'. Based upon the recent findings for the 'Berlin Marathon' for world record performances, we hypothesized that the running speed of elite marathoners would correlate with temperature during the race.

Subjects and Methods

Ethical Approval

This study was approved by the Institutional Review Board of Kanton St. Gallen, Switzerland, with a waiver of the requirement for informed consent of the participants as the study involved the analysis of publicly available data (EKSG 01-06-2010).

Subject Data

Data (i.e., first and last name, sex, age, calendar year, split times for each 5 km, and overall race time) from all successful female and male finishers in the 'Berlin-Marathon' between 1999 and 2019 was obtained from the official race website (www.bmw-berlin-marathon.com). Before 1999, no split times were recorded in the race records. In 2020, no race was held due to the COVID-19 pandemic (www.bmw-berlin-marathon.com/en/news-center/news-archive/).

The Race

The 'Berlin Marathon' is one of the largest marathons in the world and is considered the fastest city marathont[7]. The race takes place between mid to end of September (www.bmw-berlin-marathon.com/en/your-race/course/). The racecourse is a large loop through the historic city of Berlin, with the finish line under the 'Brandenburger Tor'. The total elevation of the course is 50 m (www.bmw-berlin-marathon.com/en/your-race/course/). The race starts in blocks between 09:15 and 10:30, determined by the personal best time stated when registering for the race (www.bmw-berlin-marathon.com/en/your-race/start/).

Weather Data

Berlin lies 34 meters above sea level, the average temperature in September is ~15°C and the average humidity is ~75% (www.weather-atlas.com/en/germany/berlin-weather-september).

Weather data on race day was obtained from the website of 'Deutscher Wetterdienst' (https://opendata.dwd.de/climate_environment/CDC/observations_germany/climate/hourly/). We chose the data from the weather station 'Berlin Dahlem' because of its proximity to the Berlin Marathon route and obtained hourly data between 09:00 and 16:00 of temperature (maximum, minimum and average in

°C), sunshine (duration in hours), precipitation (in mm), cloud cover (duration in hours) and atmospheric pressure (in mbar).

Data Processing

The processing of the data files involved several steps. First, the data was cleaned up and its integrity verified. Then, each race record had the time-adjusted average values of the weather magnitudes assigned. We compared elite and recreational runners. Since the duration of each runner's race is different, from just over 2 hours for elite runners to 6 or 8 hours and more for recreational runners, the average values of the temperature, pressure and other weather factors they experience during the race varied. Considering these differences when calculating and imputing the weather values to each record, we were able to better represent the actual average values during their running time. Performance groups were created by sampling down from the full sample of 668,735 records to the top 3, top 10, top 100 males and females' sub-groups. The 'top 3' group was created by extracting the best (fastest) 3 male and 3 female finishers from each year's race. The 'top 10' was created by extracting the best (fastest) 10 male and 10 female finishers from each year's race. The 'top 100' was created by extracting the best (fastest) 100 male and 100 female finishers from each year's race. These groups are not exclusive, so one record in the top 3 will also appear in the subsequent groups (top 10, top 100 and all runners). Because of this, the groups are nested (so the top 100 includes the top 10 which includes the top 3). The downsampling process significantly reduces the sample size, especially in the top 3 groups, wherewith 21 years in the data set, the sample size will be only 63 male and 63 female records. This was considered when selecting the statistical methods. After the downsampling processing was complete, descriptive statistical methods were used to make comparisons between groups and draw insights and conclusions. All data processing was carried out with Python in a Google Colab notebook.

Statistical Analysis

Descriptive statistical analysis was carried out, including Pearson and Spearman correlation analysis and the calculation of statistical parameters of the full and partial running speeds, and the environmental conditions of each performance group (i.e., all runners, top 100, top 10 and top 3). The resulting values were presented in tables in terms of their average value (mean) and standard deviation (SD), along with maximum (max) and minimum (min) values, with box plot charts showing the median, 20% and 75% percentiles and the max and min values (plus any outlier points). Gaussian (normal) distribution of race times and paces was verified by plotting histograms, and statistical significance tests and calculation of *p*-values were also done when needed. To account for the different sample sizes of each performance group, and for the non-random sampling used to create the groups, the robust Kolmogorov-Smirnov two-sample test was used. All analyses were carried out using the Python programming language (Python Software Foundation, www.python.org/), in a Google Colab notebook (https://colab.research.google.com/). Significance was set at $p<0.05$

Results

A total of 668,735 finishers (520,715 men and 148,020 women) competing between 1999 and 2019 in the 'Berlin Marathon' were analyzed.

Figure 1 presents the running speed by performance groups (i.e., all runners, top 100, top 10 and top 3) for both women and men with a set of boxplot charts. Differences in running speed between the four performance groups (i.e., all runners, top 100, top 10 and top 3) are statistically significant ($p<0.05$) for both men and women.

Table I summarizes the environmental conditions. The temperature was at ~16°C and there was practically no rain in all these editions. Figure 2 presents the trends of temperature, barometric pressure and humidity during the race hours. The correlation matrixes show that, within the 8 hours of observation, the temperature increases with the time of the day (r=0.51) whilst humidity decreases with it (r=-0.4) (Figure 3). The rest of the weather variables show a negligible correlation coefficient with the time of the day.

Figure 4 shows the weather conditions by performance groups (i.e., all runners, top 100, top 10 and top 3) for both women and men. Elite groups experienced colder temperatures and higher levels of humidity as they ran in less than three hours from 09:00 when the temperature was low and humidity high. Recreational runners completed the race throughout the afternoon during which the temperature increased, and the humidity dropped. The correlation analysis for each performance group (with time-adjusted weather averages) is shown in Figures 5, 6, 7 and 8.

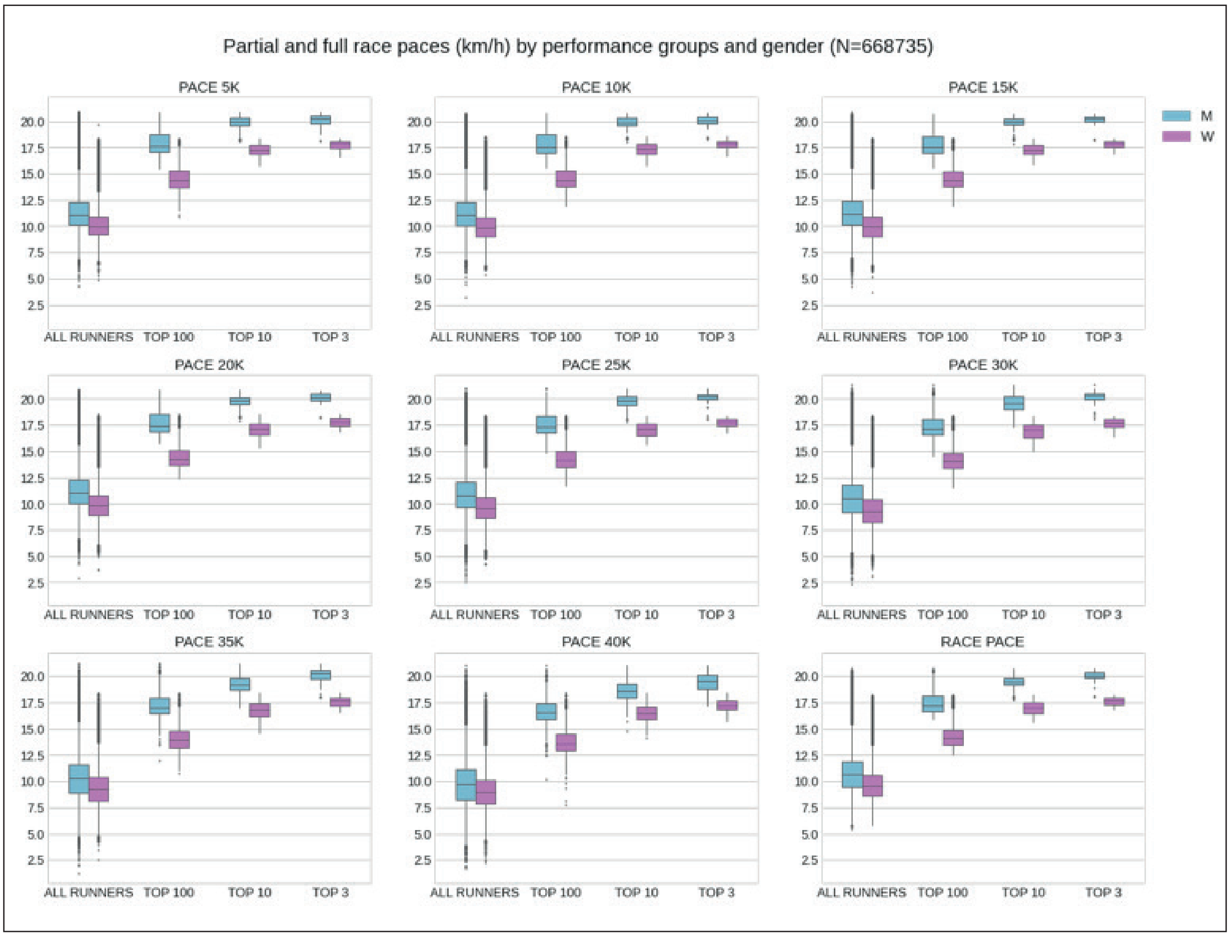

Figure 1. 'Berlin Marathon' performance differences between the top 100, top 10 and top 3 athletes, for both sexes.

Discussion

This study intended to investigate the relationships between environmental conditions, such as temperature or humidity and the pacing of elite marathoners competing in the 'Berlin Marathon'. We have hypothesized that the running speed of elite marathoners would correlate with temperature during the race. The most important findings were (*i*) temperatures increased during race days while humidity decreased and both variables were negatively and significantly correlated, (*ii*) faster runners experienced lower temperatures and higher humidity levels than slower runners, (*iii*) the association of temperature and humidity with running speed is weaker in the elite groups than for the full population and (*iv*) a weak but noticeable positive correlation was observed between running speed of the top 100 and top 3 groups and barometric pressure.

Faster Runners Experienced Lower Temperatures and Higher Humidity Levels

The first important finding was that the faster runners were competing at lower temperatures and

Table I. Descriptive statistics for environmental characteristics during Berlin marathons (1999-2019).

mean	16.19	1014.75	69.33	0.06	33.01	61.44
SD	4.09	9.26	17.78	0.28	27.09	37.24
min	7.00	995.00	35.00	0.00	0.00	0.00
25%	13.00	1006.00	54.75	0.00	0.00	25.00
50%	16.00	1018.00	70.50	0.00	40.50	75.00
75%	18.25	1022.00	86.00	0.00	60.00	100.00
max	27.00	1032.00	97.00	2.00	60.00	100.00

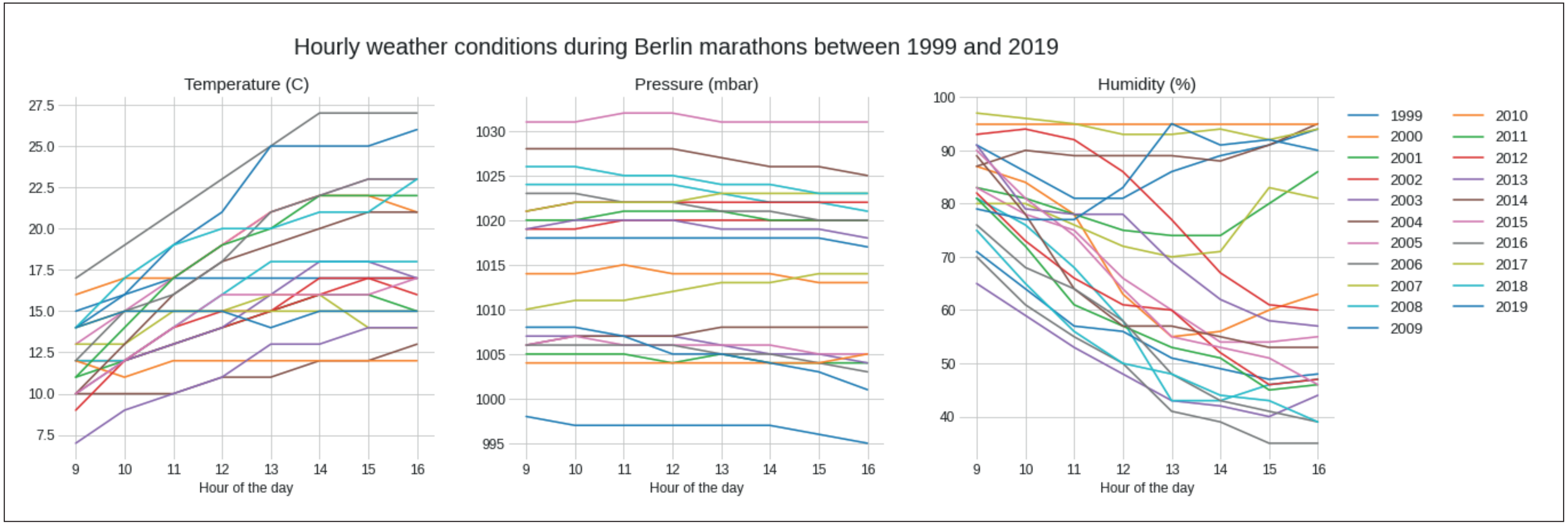

Figure 2. Hourly data line plot, for temperature, barometric pressure and humidity from 09:00 AM to 04:00 PM from 1999 to 2019.

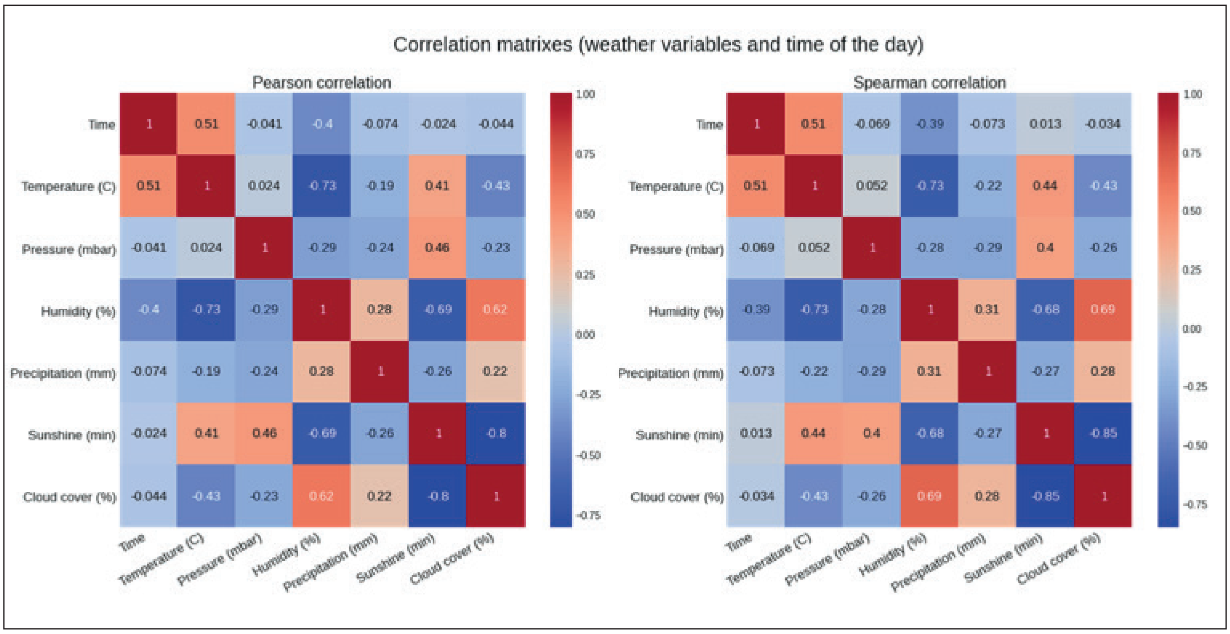

Figure 3. Correlation matrixes for weather variables and time of day in marathoners in 'Berlin Marathon'.

higher humidity levels than the slower runners. This finding is most likely explained by the specific local conditions that faster runners start early in the morning but finish faster than the slower runners when temperatures are still rather low.

The second important finding was that the humidity decreased during the race and running speed was significantly and positively correlated with humidity. In other words, runners become slower during the day when humidity decreased. Interestingly, high humidity had no negative influence on the running performance of elite marathoners. The positive correlation of running speed with humidity in the lower performance groups (i.e., top 100 and all runners) is difficult to explain although humidity and temperature have a strong and negative correlation.

Humidity corresponds to the amount of water vapor in the air and is high when a lot of water vapor is in the air. Air temperature has also an effect on the humidity where a decrease in air temperature increases relative humidity and an increase in air temperature decreases relative humidity. Based on past studies we might assume that high humidity impairs performance[8,9]. A laboratory study[10] reported that maximal aerobic capacity was impaired at high temperatures and under different humidity conditions. Another laboratory study[11] showed that exercise capacity at a moderate intensity in a warm environment was progressively impaired with an increase in relative humidity. However, runners become slower during the day when humidity decreased.

Little is known regarding the influence of humidity on marathon running performance[12,13]. However, we could confirm recent findings that a decrease in humidity was associated with a decrease in running performance. A study[13] investigating the influence of weather conditions on running performance in 1 280 557 age group runners competing in the 'New York City Marathon' between 1970 and 2019 showed that performance degraded with low humidity. In other words, running performance was improved on race days with high humidity. The effect of high humidity on performance was dependent upon age and sex and significantly increased in 40-59 years old men and 25-65 years old women[13]. In a study[12] investigating the effects of weather on marathon running performance in the 'Stockholm Marathon', relative air humidity was significantly and negatively related to marathon finishing time anomaly. The author explained that the effects of relative humidity depended on the negative correlation with air temperature[12]. The increase of air temperature and the duration of the race was most probably a more important factor in the performance decline than the decrease of humidity.

The Negative Correlation of Temperature with Running Speed Decreasing in Strength with Performance

Another important finding was that the temperature was significantly and negatively related

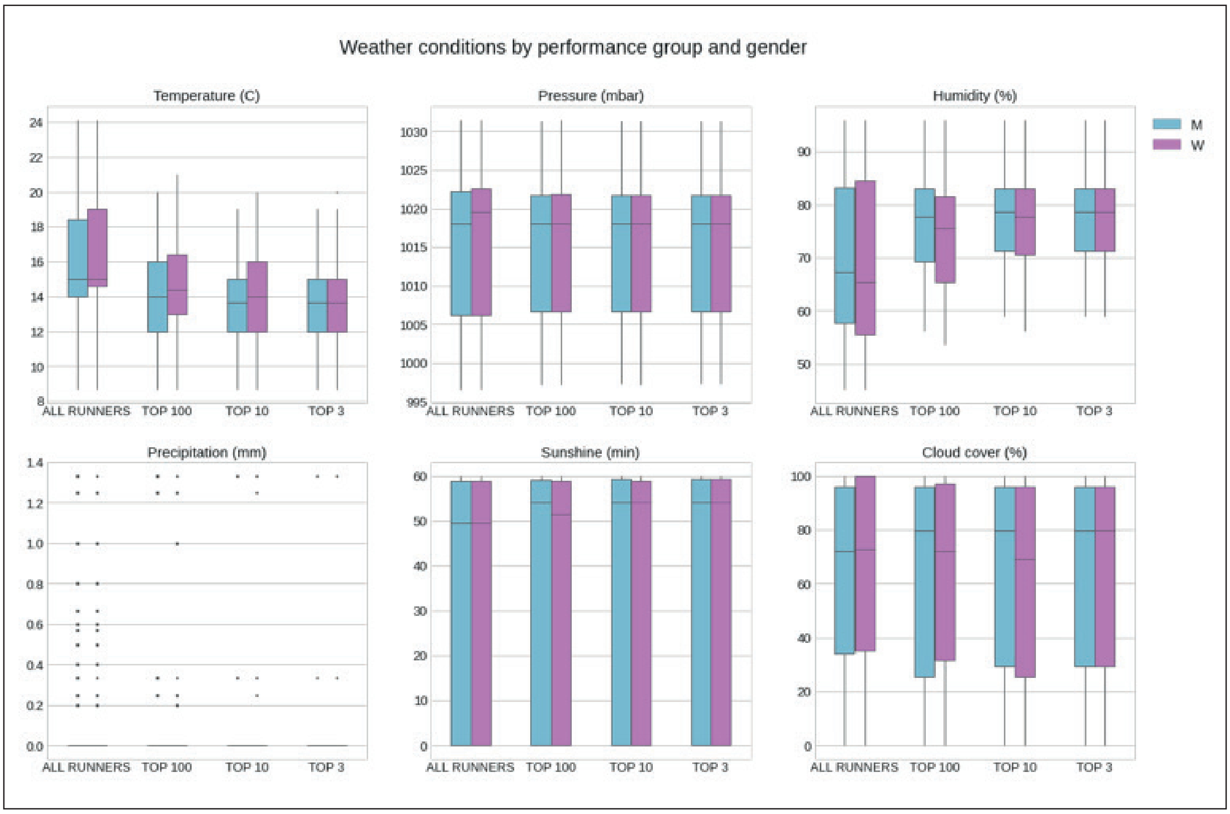

Figure 4. Box plot for weather characteristics according to performance level and sex.

to the running speed for all performance groups. However, its significance decreased in the 'top 3' where runners exhibited the smallest correlation and less than half the correlation coefficient compared to all runners. The negative correlation between running speed and temperature may feel intuitive (lower running speeds with higher temperatures, especially when the temperatures are too high), but the result we are observing here are mostly because faster runners run only 2 or 3 hours from 09:00 when the temperature is still low. Lower pace runners – those over 4 hours – will likely experience the warmer temperatures of the afternoon and therefore experience a decrease in running speeds. Nonetheless, runners used to warmer temperatures were, mainly East African runners, less affected by the temperature increase[14]. The high relationship between the temperature and low performance was shown among non-professional runners, possibly due to the absence of acclimatization of these runners to the running events. Furthermore, the body temperature responses to a given heat load are strongly influenced by body mass, which serves as an internal "heat sink". In this sense, non-professional runners tend to present higher values for body fat and body mass index[15], in comparison to elite athletes.

Positive Correlation of Barometric Pressure with Running Speed for the Top 3 and Top 100 Performance Groups

The last finding was that barometric pressure was significantly and negatively related to running speed in the fastest runners (top 3) and the sub-elite top 100 group, but not in the other groups. In other words, the higher the barometric pressure, the faster the athlete. While we found a significant and negative correlation between temperature and humidity, we found no correlation between temperature and barometric pressure and barometric pressure remained relatively unchanged during the duration of the races whilst temperature increased, and humidity decreased. Only a few studies[7,16,17] investigated the aspect of barometric pressure and marathon running performance. A study[16] investigating the relationship of weather conditions with running performance in the Boston Marathon from 1972 to 2018 in a total of 580 990 observations showed that both increasing temperature and in-

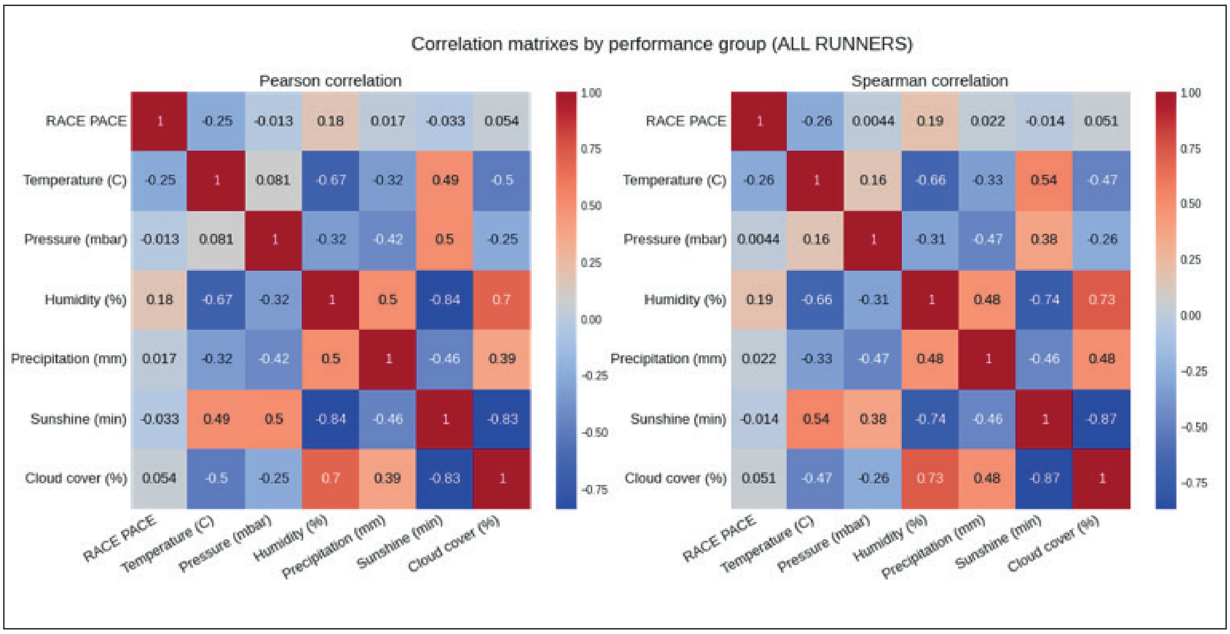

Figure 5. Matrix correlation results for environmental characteristics and performance.

creasing barometric pressure were related to slower race times. A study analyzing the influence of environmental conditions on marathon running times in 869474 age group marathoners competing in the 'Berlin Marathon' from 1974 to 2019 showed an influence of temperature and precipitation on performance. Higher daily maximum temperatures (i.e., >15°C) and higher precipitation levels impaired the performance of master marathoners (i.e., 35-40 years and older) but barometric pressure was not related to marathon race times[17]. In all editions in the 'Berlin Marathon' with world record performances, the ideal weather conditions were different between female and male world records. For men, the ideal environmental conditions were an average temperature of 18.61°C, sunny, mostly dry

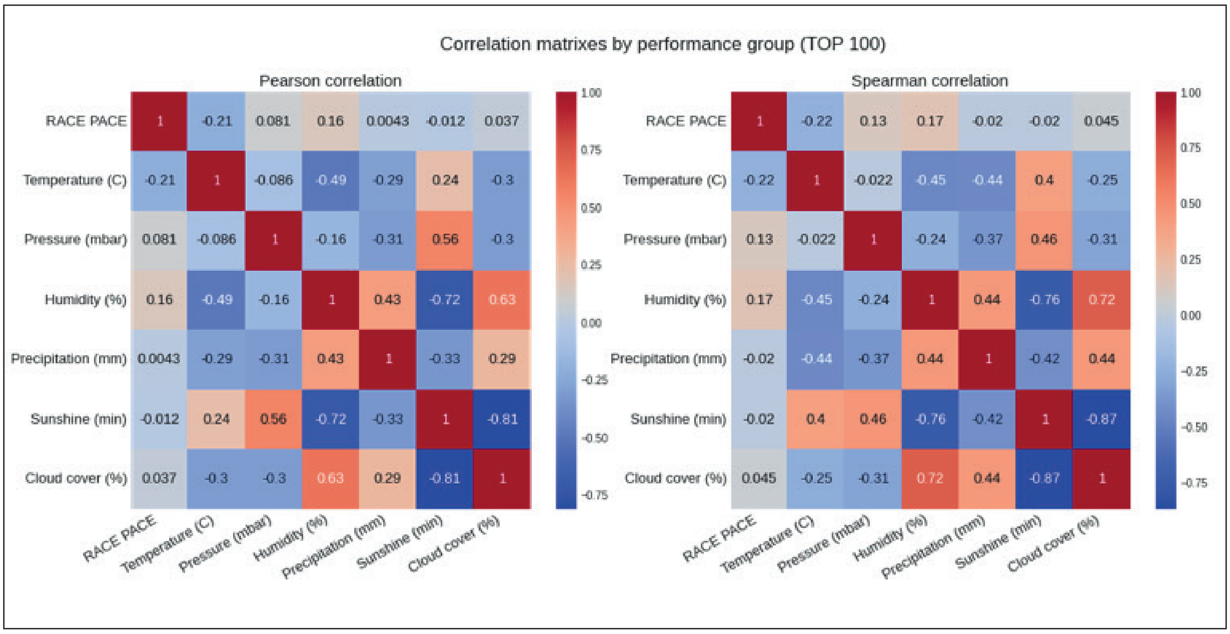

Figure 6. Matrix correlation results for environmental characteristics and performance in top 100 runners.

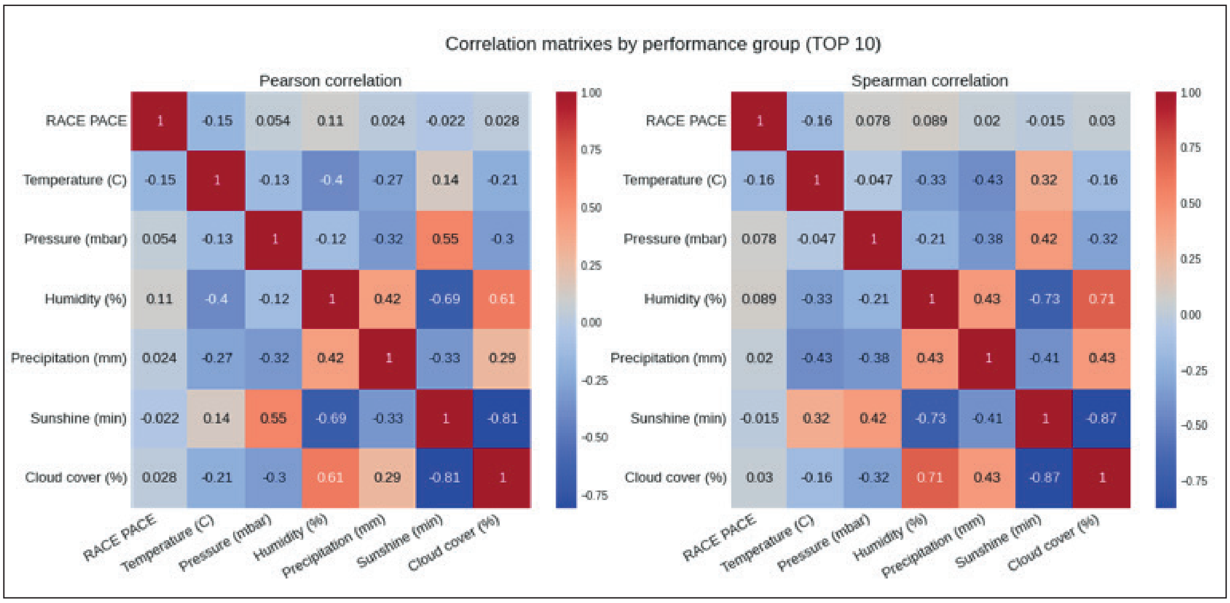

Figure 7. Matrix correlation results for environmental characteristics and performance in top 10 runners.

days, with higher atmospheric pressure and little cloud cover. For women, ideal conditions were an average temperature of 13.07°C, low atmospheric pressure, significantly more rain and heavy cloud cover[7]. It seems that barometric pressure influences the performance level of athletes. Whereas elite athletes seemed to be faster on race days with higher barometric pressure, recreational runners did not show any changes related to barometric pressure. Future studies need to investigate this association more deeply in other marathon running races.

Limitations

The limitation of this study is that we did not control for runners' age, training, and pre-race strategy. Secondly, we have not performed the altime-

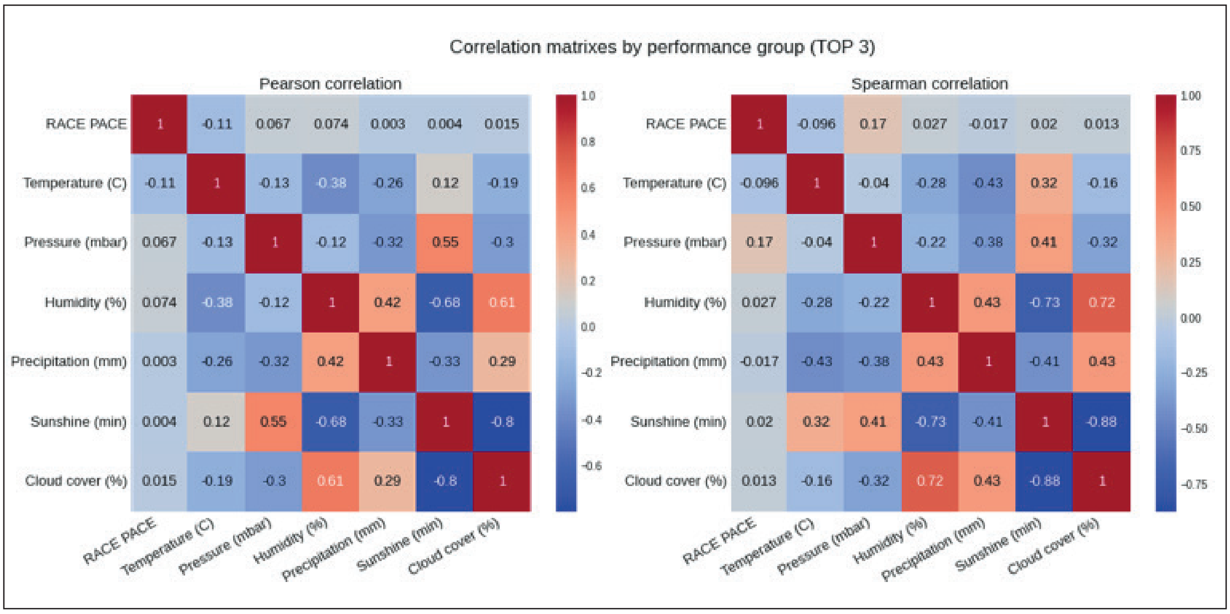

Figure 8. Matrix correlation results for environmental characteristics and performance in top 3 runners.

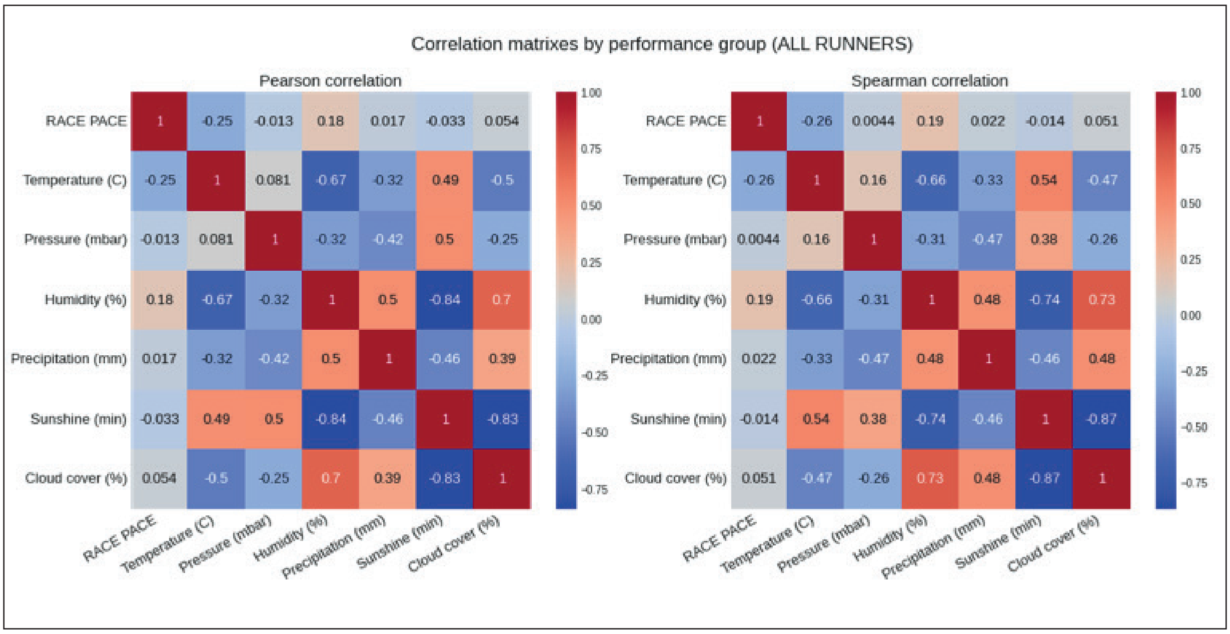

Figure 5. Matrix correlation results for environmental characteristics and performance.

try control, which can bias the race event duration time. On the other hand, this information can be used to reinforce the importance of acclimatization, especially in non-professional runners.

Conclusions

In summary, temperatures increased during race days while humidity decreased and both variables were negatively and significantly correlated. Faster runners experienced lower temperatures and higher humidity levels than slower runners, and the association between running speed and these environmental conditions seemed to be stronger in slower runners. Running speed was also significantly and positively correlated with barometric pressure in elite runners. Future studies can provide more insights to understand the magnitude of changes in the running pace resulting from these conditions.

Ethics Approval and Consent for Publication

The institutional review board of St. Gallen, Switzerland, approved this study (EKSG 01/06/2010). Since the study involved the analysis of publicly available data, the requirement for informed consent was waived.

Consent for Publication

Not applicable.

Conflict of Interest

The authors have no conflicts of interest to report. The authors confirm that the research presented in this article complies with ethical guidelines, including compliance with legal requirements.

Availability of Data and Materials

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Acknowledgments

Not applicable.

Authors' Contributions

KW drafted the manuscript, DV performed the data processing and statistical analyses, EV collected the data, VS, MT, and BK helped in drafting the manuscript. All authors approved the final version.

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