

<https://doi.org/10.1038/s41612-024-00637-x>

Wasted efforts of elite Marathon runners under a warming climate primarily due to atmospheric oxygen reduction

Check for updates

Shixin Wang^{1,2,3}, Meng Gao¹✉, Xiang Xiao¹, Xiaodong Jiang⁴ & Jingjia Luo³

Meteorological conditions exert influences on sport performances via complex processes. Previous studies conventionally investigate the effects of weather conditions on marathon performance by following events held at the same places, which brings large uncertainties due to the changed participants. Via following each athlete to eliminate these uncertainties, we show that elite athletes' marathon-running performance tends to monotonically worsen as ambient temperature rises except when it is extremely cold based on the best 16 athletes from each of the sex continents. It worsens by 0.56 (0.39 for men and 0.71 for women) min/°C when it rises beyond 15 °C. Theoretical analysis based on global marathon performance and weather observation datasets shows that more than half of this effect is mediated by reduced oxygen partial density as warmer temperature expands air and increases vapor pressure for both the men and women athletes, which is confirmed by the methods of Baron–Kenny. This atmospheric thermodynamic mechanism has not been emphasized previously. We also show that world-top athletes' marathon performance approximately linearly worsens as ambient pressure decreases and slightly worsens as relative humidity rises if not extremely wet. These results substantially differ from the previous ones following the events instead of each athlete. Multi-variable changes in climate system are projected to slow Olympic marathon athletes by 2.51 and 1.06 min by the end of the 21st century in relative to 2020 under the high and intermediate emission scenario, respectively. Therefore, future progression of marathon performance is likely to be substantially slowed or even halted by climate changes without efficient greenhouse gas mitigation.

On May 22, 2021, a hailstorm with extreme cold temperature and heavy rain struck Baiyin City, Northwest China, and 21 ultramarathon runners died from it during an ultramarathon event (a 100 km long-distance footrace), including Liang Jing, one of the world's top ultramarathon runners¹. Similar catastrophic extreme weather events, including devastating droughts and raging heatwaves, are claiming lives, and these events are anticipated to occur more intensely and frequently under a warming climate^{2–4}. Marathon, a 42.195 km long-distance footrace, has been a central part of the modern Olympics since 1896. It also takes places in numerous cities around the world every year. Nearly 18 million people registered for marathon and

other long-distance race events in the US in 2019 (<https://www.runninginsight.com/running-usa-releases-u-s-running-trends-report>).

Resembling other outdoor activities, performances of marathon running are susceptible to environmental factors, including weather conditions⁵. Warmer temperature tends to slow both elite and non-elite marathon runners^{6–11} although some discrepancies in the weather-performance relationship exist among the athletes of different levels^{12–15}. No consensus has been reached on the influence of rise in altitude (equivalent to reduction in air pressure)^{6–11}. The roles of other weather parameters, including solar radiation, relative humidity, wind speed and rainfall, have also been explored previously^{7,16,17}.

¹Qinghai Provincial Key Laboratory of Plateau Climate Change and Corresponding Ecological and Environmental Effects, Qinghai University of Science and Technology, Xining 810016, China. ²Department of Geography, Hong Kong Baptist University, Hong Kong, Hong Kong SAR 999077, China. ³Institute for Climate and Application Research, Key Laboratory of Meteorological Disaster, Ministry of Education/Joint International Research Laboratory of Climate and Environment Change/Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Nanjing University of Information Science and Technology, Nanjing 210044, China. ⁴School of Applied Meteorology, Nanjing University of Information Science and Technology, Nanjing, China.

✉ e-mail: mmgao2@hkbu.edu.hk

Commonly, elite marathon runners' competition results were obtained at different marathon races with different meteorological conditions, which are characterized by variables such as ambient temperature, atmospheric pressure, relative humidity and solar radiation^{6–11,15–18}. Approaches used in existing studies conventionally focus on the results and weather conditions of the marathon events at certain locations (analogous to Eulerian representation of fluid dynamics), yet runners participated in these events that held at the same places usually differ greatly across time^{9,17,18}, leading to substantially uncertain conclusions. Moreover, only general associations of marathon performance with meteorological conditions were previously reported, while studies involving underlying mechanisms remain limited^{9,11}. A theoretical analyses¹⁹ emphasized the role of atmospheric oxygen loss associated with rise in altitude and the resultant reduction in pressure in degraded marathon performance. Dehydration and body-skin temperature increase were also regarded as the reason for worse performance under higher temperature conditions²⁰.

Global warming is anticipated to continue in coming decades, and the associated increase in occurrences of extreme weather may thus pose greater influences on performances of marathon running^{21,22}. Projections suggested that number of cities with appropriate weather conditions for hosting Olympic marathon would decline significantly by the end of this century under RCP8.5 emission scenario²¹. The marathon race at 2019 Doha World Athletics Championships was held when air temperature was above 30 °C^{23,24}. Given these circumstances, we believe that Olympic marathon events are very likely to be held still under a warming climate. Here we aim to understand how weather conditions affect the performances of elite marathon runners through a systematic investigation based on the global datasets of marathon performance and weather observations. In the investigation we track the performances of each runner across different events (analogous to Lagrangian representation of fluid dynamics) to eliminate the large uncertainties caused by the different runners participating the events held at the same place in different time in existing studies. We will further investigate the underlying mechanism from the perspective of the thermodynamic processes in the atmosphere, which will be revealed to be essential for the effects. This mechanism has not been emphasized previously. We hypothesize that the rise in temperature, altitude or humidity can worsen the marathon performance since they can reduce the oxygen partial density (Eq. (3)). We also hypothesize that the future progression of marathon performance is likely to be substantially slowed or even halted by the changed climate without powerful greenhouse gas mitigation, which will be investigated with model projections of future climate.

The rest of the paper is organized as follows. Section “Effects of weather conditions on marathon-running performance” quantitatively analyzes the

effects of the ambient weather conditions on the marathon performance of elite athletes via tracking the performances of each runner across different events. Section “Essential role of atmospheric thermodynamic processes in the effects” explores for the underlying mechanism for the effects focusing on the thermodynamic processes in the atmosphere. Section “Projected changes in future marathon-running performances of top athletes” projects the long-term changes in the elite marathon athletes' performance in the past and in the future under the different emission scenarios, followed by a brief conclusion and further discussion in Section “Discussion”. Section “Methods” brief the data and methods used in the present study

Results

Effects of weather conditions on marathon-running performance

Multiple linear regression analysis of marathon finishing time upon the possible influencing variables is conducted and the regression coefficients are shown in Table 1. Here the increase in marathon finishing time denotes the worsening in performance. For the top-96 athletes, the marathon performance tends to worsen significantly with the rise in ambient temperature by 0.31 min °C⁻¹. The performance tends to significantly improve by 0.025 min hPa⁻¹ as the ambient pressure rises, which is equivalent to the reduction in the altitude based on Eq. (1). The increase in relative humidity tends to worsen the marathon performance. Among the four influencing variables related to athlete individuals, the age significantly and positively affects athlete's performance, while home advantage does not have significant relationship with the marathon performance. The athlete's sex also has no significant relationship with the marathon performance since most of its effects have been included in the effects of the athlete's average performance. In fact, if not including the average performance in the model, the regression coefficient of marathon performance upon the sex is 19.1 min, which is significant at 0.999 confidence level.

Similar analysis is also conducted for athletes in the six areas of the world, respectively. The marathon performance tends to significantly worsen with the rise in ambient temperature in all the six areas except the North America, where the worsening is not statistically significant. The relationships with atmospheric pressure and relative humidity for 5 of the 6 areas have the same sign with those for the world, but are statistically significant for only 1 of the 6 areas. The lower statistical significance and the differences among areas may be associated with both ethnic difference as well as small sample sizes for each area (Table 2). In fact, the sample size is the smallest in the North America, the Asia and the Oceania among the 6 areas. In the Asia (Oceania), the relationship of marathon performance with air pressure (relative humidity) has the opposite sign to that for the world. In the North America, the relationship with ambient temperature is not significant.

Table 1 | Regression model results

Factors	World	Europe	North America	South America	Africa	Asia	Oceania
Temperature	0.31***	0.38***	0.14*	0.51***	0.23***	0.29***	0.39***
Pressure	-0.025***	-0.034	-0.0096	-0.014	-0.036***	0.017	-0.068
Relative humidity	0.031***	0.039	0.036	0.094***	0.0035	0.026	-0.0024
Average performance	0.97***	0.75***	1.0***	0.62***	0.79***	0.91***	0.91***
sex	0.057	0.46	-0.029	0.73**	0.24	0.21	0.29
Home advantage	0.056	0.037	0.27**	0.016	0.31	-0.19*	0.021
age	-0.13***	-0.38**	-0.14	-0.31**	-0.32***	-0.25	-0.21
Sample size	678	124	90	112	159	99	94
Standard errors	4.8	4.8	3.9	5.1	4.2	5.1	5.6
Adjusted R squared	0.84***	0.80***	0.80***	0.82***	0.83***	0.79***	0.82***

Regression coefficients of marathon finishing time upon influencing factors using multiple linear regression analysis for all the top-96 athletes over the world and for the 16 athletes in each of the six areas over the world, respectively. The *, ** and *** denotes the regression coefficients significant at 0.90, 0.95 and 0.99 confidence level, respectively. The unit are °C, hPa, %, minutes and years for the temperature, pressure, average performance and age, respectively. If an athlete has home advantage in a race, the variable characterizing home advantage is set as 10, and otherwise set as 0. The variable sex is set as 0 and 10 for men and women, respectively.

Table 2 | Marathon participants and the years of their competitions

Area	Place	Athlete name (Men)	Birth year	Years of competition	Athlete name (Women)	Birth year	Years of competition
Europe	1	Kaan Kigen ÖZBILEN	1986	2013–2020	Lonah Chemtai SALPETER	1988	2016–2021
	2	Bashir ABDI	1989	2018–2020	Volha MAZURONAK	1989	2013–2020
	3	Tadesse ABRAHAM	1982	2013–2019	Eva VRABCOVÁ NYVLTOVÁ	1986	2016–2021
	4	Abdi NAGEEYE	1989	2014–2020	Melat Yisak KEJETA	1992	2019–2019
	5	Koen NAERT	1989	2015–2019	Sara DOSSENA	1984	2017–2019
	6	Callum HAWKINS	1992	2015–2019	Fabienne SCHLUMPF	1990	2021–2021
	7	Mo FARAH	1983	2014–2019	Sardana TROFIMOVA	1988	2013–2021
	8	Maru TEFERI	1992	2015–2021	Charlotte PURDUE	1991	2016–2019
North America	1	Leonard KORIR	1986	2019–2020	Sara HALL	1983	2015–2020
	2	Jared WARD	1988	2013–2020	Betsy SAINA	1988	2018–2019
	3	Jacob RILEY	1988	2014–2020	Emily SISSON	1991	2019–2019
	4	Scott FAUBLE	1991	2017–2020	Aliphine Chepkerker TULIAMUK	1989	2015–2020
	5	Abdi ABDIRAHMAN	1978	2014–2020	Kellyn TAYLOR	1986	2016–2020
	6	Juan PACHECO	1990	2018–2020	Emma BATES	1992	2018–2020
	7	Martin HEHIR	1992	2018–2020	Desiree LINDEN	1983	2013–2020
	8	Augustus MAIYO	1983	2016–2020	Malindi ELMORE	1980	/
South America	1	Derlys AYALA	1990	2015–2020	Gladys TEJEDA	1985	2013–2020
	2	Eulalio MUNOZ	1995	2019–2020	Marcela Cristina GOMEZ	1984	2018–2020
	3	Joaquin ARBE	1990	2014–2019	Daiana OCAMPO	1991	2019–2021
	4	Ulise MARTIN	1996	2019–2021	Angie ORJUELA	1989	2014–2020
	5	Paulo Roberto DE ALMEIDA PAULA	1979	2013–2020	Rosa CHACHA	1982	2012–2021
	6	Segundo JAMI	1986	2014–2020	Jovana De La Cruz Capani	1992	2015–2021
	7	Daniel Chaves DA SILVA	1988	2018–2019	Andrea Paola BONILLA	1986	2019–2020
	8	Nicolás CUESTAS	1986	2016–2020	Kellys Yesenia ARIAS FIGUEROA	1989	2015–2021
Africa	1	Birhanu LEGESE	1994	2018–2020	Brigid KOSGEI	1994	2015–2020
	2	Evans CHEBET	1988	2014–2020	Ruth CHEPNGETICH	1994	2017–2020
	3	Lawrence CHERONO	1988	2015–2020	Worknesh DEGEFA	1990	2017–2020
	4	Mosinet GEREMEW	1992	2017–2020	Ashete BEKERE	1988	2013–2020
	5	Vincent KIPCHUMBA	1990	2014–2020	Joyciline JEPKOSGEI	1993	2019–2020
	6	Sisay LEMMA	1990	2013–2020	Birhane DIBABA	1993	2013–2020
	7	Amos KIPRUTO	1992	2016–2020	Roza DEREJE	1997	2016–2019
	8	Eliud KIPCHOGE	1984	2013–2021	Degitu AZIMERAW	1999	2019–2020
Asia	1	El Hassan EL ABBASSI	1984	2017–2020	Mizuki MATSUDA	1995	2018–2021
	2	Marius KIMUTAI	1992	2013–2019	Mao ICHIYAMA	1997	2019–2021
	3	Yuta SHITARA	1991	2017–2020	Shitaye ESHETE	1990	2016–2020
	4	Yuya YOSHIDA	1997	2020–2020	Sayaka SATO	1994	2020–2021
	5	Alemu BEKELE	1990	2015–2019	Mimi BELETE	1988	2018–2020
	6	Yuma HATTORI	1993	2016–2019	Zhixuan LI	1994	2017–2021
	7	Suguru OSAKO	1991	2017–2020	Yuka ANDO	1994	2017–2020
	8	Natsuki TERADA	1991	2017–2020	Desi Jisa MOKONIN	1997	2018–2019
Oceania	1	Liam ADAMS	1986	2014–2020	Sinead DIVER	1977	2014–2020
	2	Brett ROBINSON	1991	2019–2019	Lisa WEIGHTMAN	1979	2013–2020
	3	Jack RAYNER	1995	2019–2019	Milly CLARK	1989	2015–2021
	4	Malcolm HICKS	1987	2018–2020	Ellie PASHLEY	1988	2016–2020
	5	Ben ST. LAWRENCE	1981	2017–2020	Nera JAREB	1982	2014–2019
	6	Caden SHIELDS	1988	2019–2021	Alice MASON	1987	2015–2021
	7	Reece EDWARDS	1990	2018–2021	Tennile ELLIS	1985	2019–2019
	8	Daniel JONES	1990	2018–2021	Rochelle RODGERS	1987	2015–2020

List of marathon participants selected from the official website of world athletes and the years of their competition results that are included in the statistics of the present study.

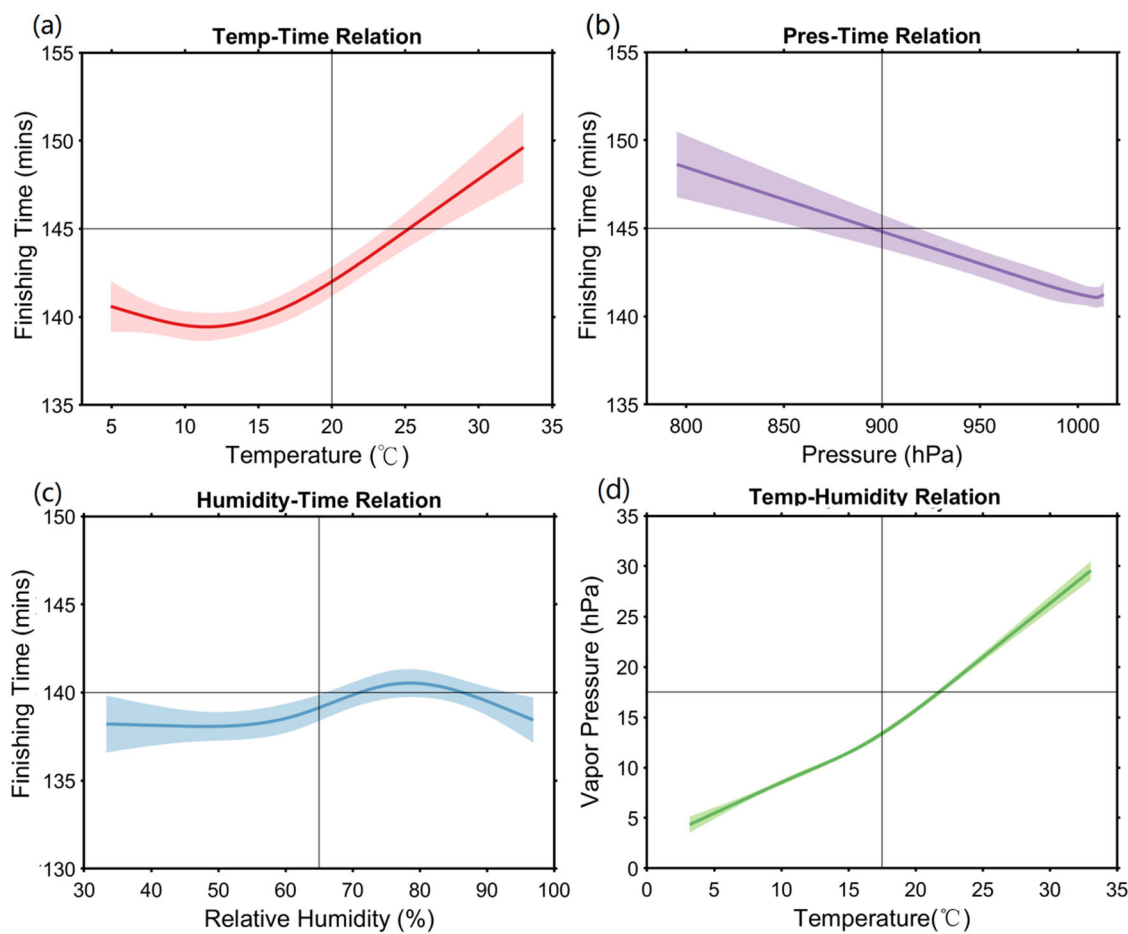


Fig. 1 | Relationship between ambient weather conditions and marathon-running performance. Relationship of MFT with ambient air temperature (a), atmosphere pressure (b) and relative humidity (c) obtained with GLM. **d** Relationship between ambient temperature and vapor pressure obtained with

GLM. The shadings denote the 95% confidence intervals for the relationships and the solid curve denotes the fitting line. **a**, **c** and **d** are obtained based on the competition results of top 96 athletes over the world, and **b** is based on those of top-160 athletes.

The relationship between influencing variables and the performances is also further investigated with GLM for the results obtained by the world top-96 marathon athletes. Among the four influencing variables related to athlete individuals, here only athlete's average performance and age are used in the model since the relationship of the other two variables with marathon performance is weak as revealed in Table 2. In fact, adding the home advantage and sex to the model only increases the confidence interval of the relationship (Supplementary Fig. 1a–c vs. Supplementary Fig. 1d–f) and thus reduces the statistical significance and increases the uncertainty. When analyzing the relationship between ambient temperature and marathon performance, the performance is predicted using only ambient temperature and other influencing variables are used as covariates, and so on for other meteorological variables.

As the ambient temperature rises, marathon finishing time (MFT) slightly decreases (Fig. 1a) when the ambient temperature is extremely low (<12 °C), indicating the slight improving of the runners' performance. When the ambient temperature is above 12 °C, MFT increases monotonously with ambient temperature, indicating the marathon performance worsening. The MFT increases by 0.56 min/°C in average as the ambient temperature rises when it is above 15 °C. Since men and women athletes may have different responses to heat stress and other weather condition changes^{25,26}, analysis is also conducted for men and women athletes, respectively. Similar shapes of curves are also found for men and women athletes, separately (Fig. 2a, b). The MFT of both men and women athletes slightly decreases and monotonously increases with ambient temperature when it is below and above 12 °C, respectively. When it rises beyond 15 °C,

MFT sharply increases by 0.39 and 0.71 min °C⁻¹ in average with ambient temperature for men and women athletes, respectively. Such a nonlinear relationship is different from those reported previously using Eulerian representation^{6,20}, which show that the MFT increases monotonously as ambient temperature rises for all temperatures and for both men and women athletes. Moreover, these previous reports show that the MFT increases by ~0.2 and 0.3 min °C⁻¹ in average when ambient temperature rises from 15 to 25 °C for men and women^{6,20}, respectively, substantially smaller than the current 0.38 and 0.70 min °C⁻¹.

For both men and women athletes and for mixed-sex athletes, MFT increases approximately linearly as ambient atmospheric pressure decreases (Figs. 1b and 2c, d), indicating the worsening of marathon performance. A 100 hPa decrease in ambient atmospheric pressure (equivalent to an increase of ~1000 m in altitude) is associated with an increase of 1.8, 4.5 and 3.6 min in MFT for men, women and mixed-sexed competitors, respectively. The difference in MFT change rate with ambient atmospheric pressure between men and women athletes might be due to the physiological differences in adapting to environmental changes. These results are overall similar to those by Peronnet et al.¹⁹ obtained through theoretical analyses, which shows that MFT monotonously increases with altitude by 4.1 min per 1000 m for men and 4.5 min/1000 m for women. However, the changing rates revealed here are substantially smaller than those concluded by Lara et al.¹⁸ (10.8–12.3%, ~15 min per 1000 m) based on conventionally-used Eulerian method. The consistence with the previous theoretical results and difference from the conventionally-used Eulerian-representation-based results confirm the

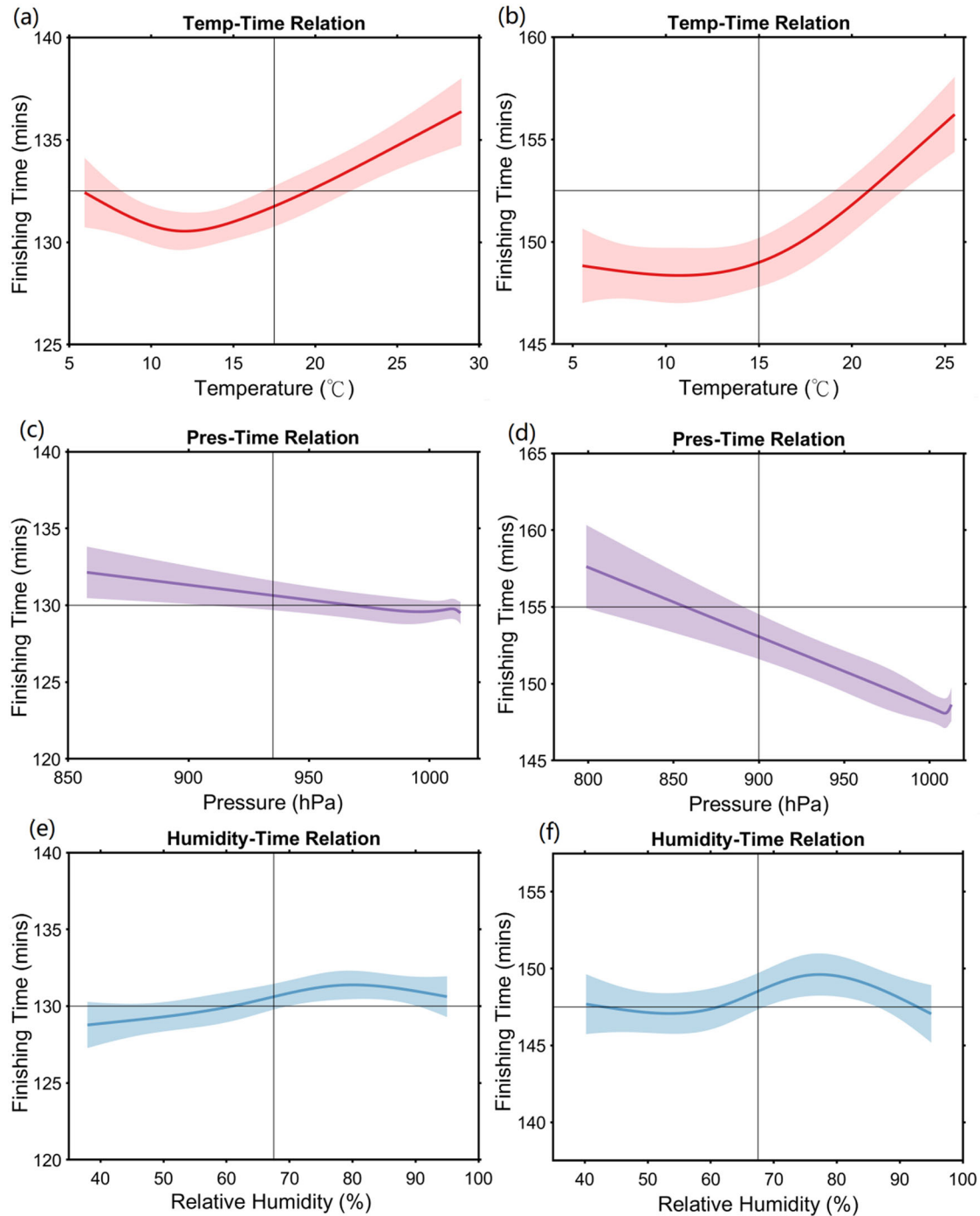


Fig. 2 | Relationship between ambient weather conditions and marathon-running performance for men and women. Same as Fig. 1a–c but for men athletes (a, c, e) and women athletes (b, d, f), respectively.

robustness of the previous theoretical results as well as the advantage of the present methods based on Lagrangian representation.

When relative humidity is below 80%, marathon performance worsens as relative humidity rises (Fig. 1c). While relative humidity rises beyond 80%, marathon performance exhibits an improving trend. Similar shapes of curves are also obtained for men and women athletes, separately (Fig. 2e, f). Overall, MFT changes associated with relative humidity (max ~2 min, Figs. 1c and 2e, f) are much smaller than those associated with ambient temperature (max ~10 min, Figs. 1a and 2a, b) and atmospheric pressure (max ~7 min, Figs. 1b and 2c, d).

The scatter plots of marathon finishing time versus meteorological variables are shown in Supplementary Fig. 2. It shows obvious performance

worsening with ambient temperature, especially when the ambient temperature is above 15 °C (Supplementary Fig. 2a). Correlation between ambient temperature and the marathon finishing time for the 678 results is 0.17, significant at 0.95 confidence level. The scatter plot also shows obvious performance worsening with the reduction of the ambient pressure (~altitude rise) and the correlation between ambient pressure and the marathon finishing time is -0.17 ($P < 0.05$) (Supplementary Fig. 2b). The marathon finishing time change with relative humidity is positive but weak (Supplementary Fig. 2c) and the correlation is 0.03 ($P > 0.05$). These results are overall consistent with those based on GLM and multiple linear regression analysis (Fig. 1a–c, Table 2), confirming the robustness of the results based on these two methods.

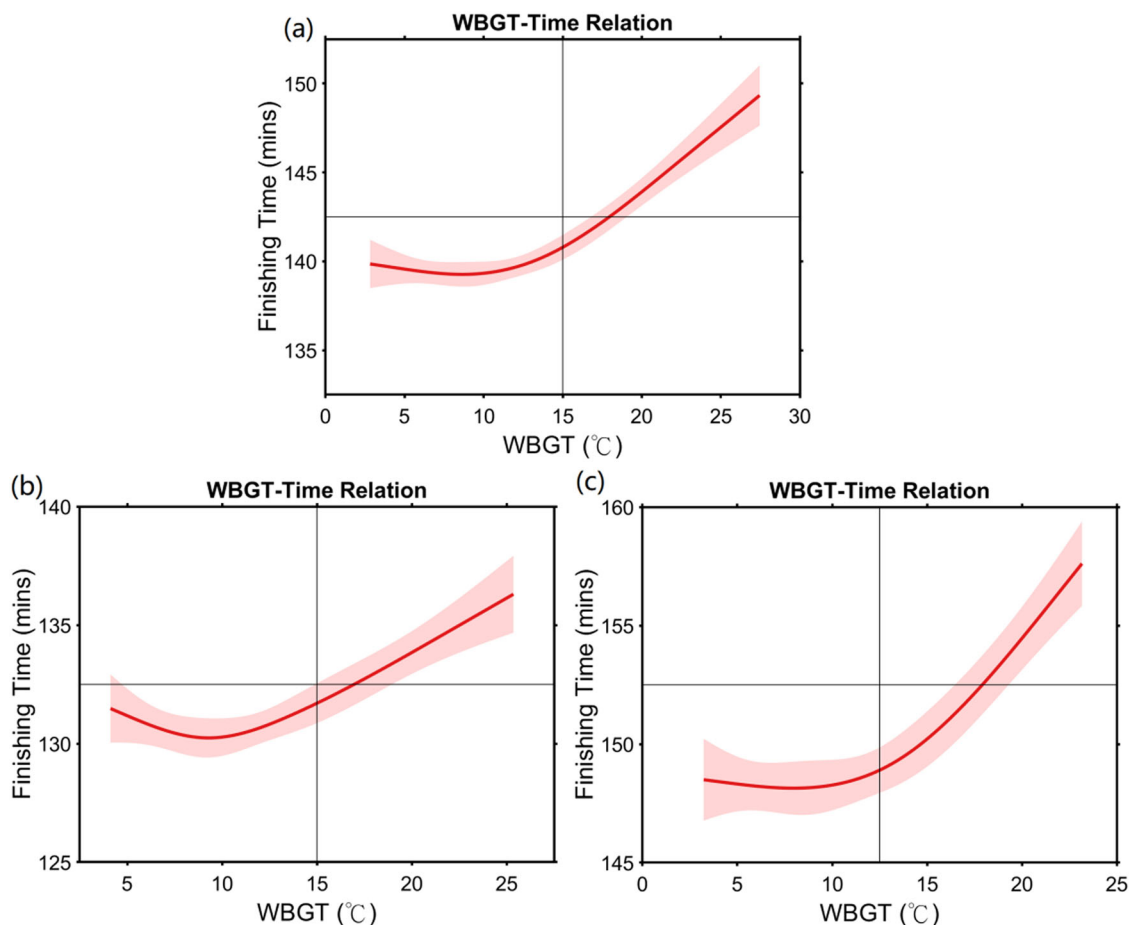


Fig. 3 | Relationship between WBGT and marathon-running performance. Panel a–c: Same as Figs. 1a and 2a, b, respectively, but for WBGT. Here the WBGT is calculated using the method introduced in ref. 27.

We repeat these analyses using the competition results obtained by the 100 best athletes throughout the world (Supplementary Fig. 3). The results are overall similar to those based on the top-96 and top-160 athletes (Figs. 1 and 2), confirming the robustness of the above results. Some differences are found in the magnitude of athletes' performance changes with weather conditions. For example, the performance worsens with ambient temperature by $0.20 \text{ min } ^\circ\text{C}^{-1}$ based on the top-100 athletes (Supplementary Fig. 3a), which is smaller than that based on the top-96 athletes ($0.37 \text{ min } ^\circ\text{C}^{-1}$, Fig. 1a). This discrepancy may be associated with the many more athletes from Africa than from other areas of the world. In fact, there are only 12 athletes (5 men and 7 women) from areas outside Africa among the top 100 athletes. The performance improvement with ambient temperature for athletes in Africa is only $0.23 \text{ min } ^\circ\text{C}^{-1}$, which is among the smallest over the six areas of the world (Table 2). The dataset of competition results for top-100 athletes is too biased toward the African athletes, while the top-96 athletes are equally distributed over the six areas of the world. Therefore, we conduct the analysis primarily based on the top-96 athletes in the present study.

Wet-bulb globe temperature index (WBGT) is a widely used index to describe the effect of heat stress on the human beings²². We repeat the above analysis with WBGT and found that the performance improves with the rise of WBGT if WBGT is not very low (Fig. 3). These results are similar to those with ambient temperature (Figs. 1a and 2a, b).

Essential role of atmospheric thermodynamic processes in the effects

The above results indicate that the marathon runners' performance tends to worsen with the rise in ambient temperature, although slight improvement

is observed when the ambient temperature is extremely low. Here we will explore for the underlying mechanism theoretically and quantitatively based on the principles of atmospheric physics and observational data. Partial density of oxygen (ρ_{O_2}) decreases as altitude rises primarily due to air pressure reduction and the resultant total air density loss, which substantially worsens endurance performance in sport. Besides, rise in air temperature and water vapor pressure can also reduce ρ_{O_2} through expanding air parcels and reducing dry air partial pressure, respectively (Eq. (3) in Data and Methods). The water vapor pressure is closely and positively correlated with air temperature (Fig. 1d) since the rise in air temperature can elevate the saturate vapor pressure and thus the water vapor capacity (Eq. (2)). Thus, the rise in ambient temperature can reduce ρ_{O_2} both through directly expanding air parcels and through increasing water vapor pressure and thus result in the worsening of the runners' marathon performance, as the rise in altitude does.

Here we quantitatively explore for the mediating role of ρ_{O_2} reduction in the effects of ambient temperature rising on marathon performance worsening based on Eq. (3) and the data of marathon performance and weather observations. We observe an approximately linear relationship of MFT with ρ_{O_2} and MFT increases by 0.14 min in average associated with 1 g m^{-3} decrease in ρ_{O_2} (Fig. 4a). When air temperature increases by 1°C , water vapor pressure would increase by 0.87 hPa in average (Fig. 1d), leading to a decrease of 0.24 g m^{-3} in ρ_{O_2} according to Eq. (3) (setting air temperature and pressure as 14.20°C and 998.9 hPa , respectively, the averages for all the competition results obtained by the 160 athletes). Yet 1°C rise of air temperature itself causes a decrease of 0.96 g m^{-3} in ρ_{O_2} via expanding air parcels according to Eq. (3) (setting vapor pressure as 11.51 hPa , the average over all the results of 160 athletes). Thus, the total decrease of

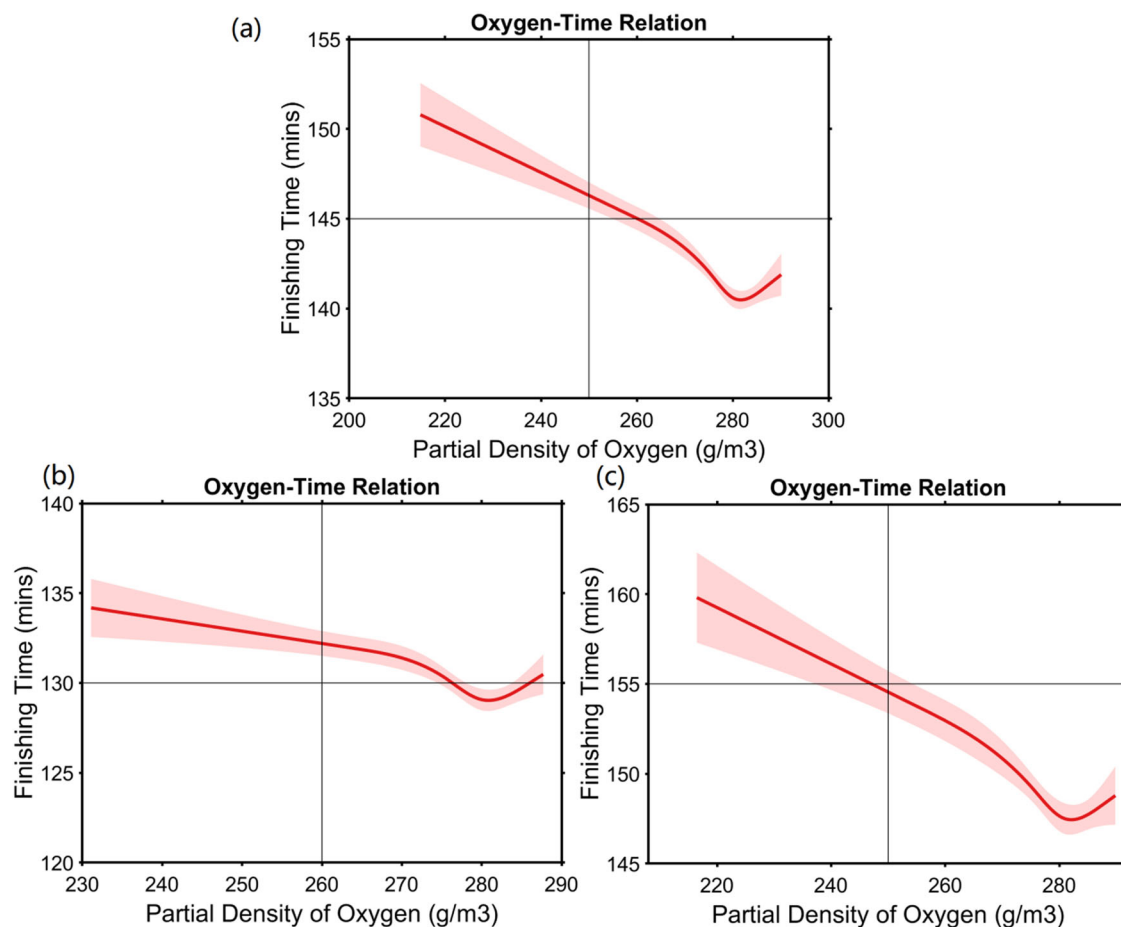


Fig. 4 | Relation of partial density of oxygen with Marathon Running performance. Relationship of the MFT with the partial density of Oxygen obtained with rcs-GLM for men athletes (a), women athletes (b) and all athletes (c). The shadings denote the 95% confidence intervals for the relationships.

1.21 g m^{-3} in ρO_2 results in additional 0.17 min of MFT based on the 0.14 min increase in MFT per 1 g m^{-3} decrease in ρO_2 estimated above (Fig. 4a). The 0.17 min account for ~58% of the total average extension of MFT associated with 1°C rise in ambient temperature (0.30 min in average for all the performance results of 160 athletes). We thus conclude here that 58% of the negative effect of air temperature on marathon performance is mediated by the role of ρO_2 changes induced by air temperature changes. We also find that the proportions for men and women athletes are 48% and 69%, respectively, using the same procedures.

Besides, we quantitatively explore the casual mediation effect of ρO_2 between air temperature and MFT following the methods of Baron–Kenny^{27,28}, and yield general consistent results with the above ones estimated based on the principles of atmospheric physics and observational data. The Baron–Kenny method suggests that 59% of the effect of air temperature on marathon performance is mediated by ρO_2 ($P < 0.001$) and the proportions for men and women are 40% and 61%, respectively. These results confirm that most of the marathon runners' performance worsening associated with the rise of ambient temperature is caused via expanding air parcels and increasing water vapor pressure and thus reducing ρO_2 .

As suggested in extensive existing studies on mortality changes^{29,30}, the negative impact of ambient temperature on human body reaches the minimum when the temperature is moderate. It sharply decreases and increases with the rise of ambient temperature when the ambient temperature is lower and higher than the moderate one, respectively. The marathon competitors' performance, however, only slightly improves with ambient temperature when it is extremely low and tends to monotonously worsen for other temperatures (Figs. 1a and 2a, b). The possible cause of the

paradox is as follows. As shown in Fig. 4, competitors' performance almost monotonously worsens with the reduction of ρO_2 . The rise in ambient temperature can monotonously reduce ρO_2 as revealed above (also see Eq. (3) and Fig. 1d). Thus, the rise in ambient temperature can monotonously worsen the marathon competitors' performance through reducing ρO_2 for nearly all temperatures. When the ambient temperature is low than the moderate one but not extremely low, the oxygen reduction with the rise of ambient temperature may exceed the reduction of cold stress in affecting marathon performance. Thus, the competitors' performance still worsens with ambient temperature.

Projected changes in future marathon-running performances of top athletes

We consider here cities with population greater than 1 million (579 cities) as potential host of Olympic Games in the period of 2024–2100 (locations are marked in Fig. 5a), as all the cities hosted Olympic Games after World War II have a minimum population of 1.3 million. Here the population data was obtained from the Department of Economic and Social Affairs, United Nations (<https://population.un.org/wpp/Download/Standard/Population/>). Figure 5b displays projected elite athletes' MFT changes averaged over the 579 selected cities under changing climate. At each city, projected MFT is calculated from the projected surface air temperature, pressure and relative humidity at this city using the relationship of all the top-96 competitors' MFTs since 2013 with the corresponding weather conditions obtained using GLM.

Over 1979–2014, the MFT derived from the biased corrected global dataset exhibits the same multi-decadal changes as the historical MFT derived from the NCEP dataset, although the NCEP-derived one

Fig. 5 | Potential host cities of future Olympic Games and averaged MFT changes due to climate change. **a** Locations of all the potential host cities of future Olympic Games (red dots, 579 cities with current population greater than 1 million, population data was obtained from the Department of Economic and Social Affairs, United Nations⁴⁹). **b** Historical and future projected elite athletes' MFT changes averaged over the 579 selected cities under the changing climate. At each city, projected MFT is calculated from projected surface air temperature, pressure and relative humidity at this city using the relationship of all the top-96 competitors' MFTs since 2013 with the corresponding observed weather conditions obtained using the rcs-GLM. Red, green and brown curves denote the projected MFT changes obtained using future climate conditions under two emission scenarios (SSP585 and SSP245) and historical climate conditions derived from the biased corrected global historical and future climate dataset⁴⁸, respectively. The black curves denote the MFT changes obtained using historical weather conditions derived from the NCEP dataset. The projected MFT is shown as the anomaly in reference to the MFT in 1979 (simulations) for visual purpose.

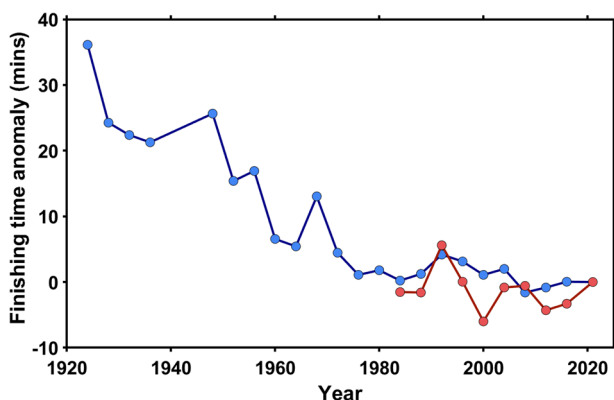
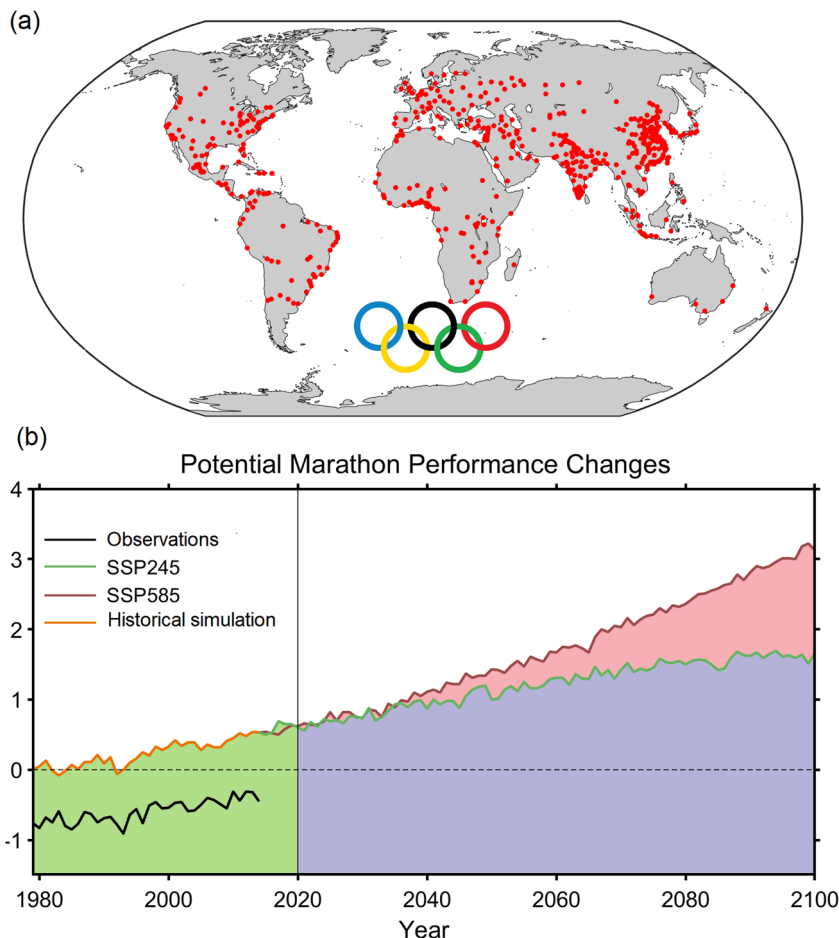


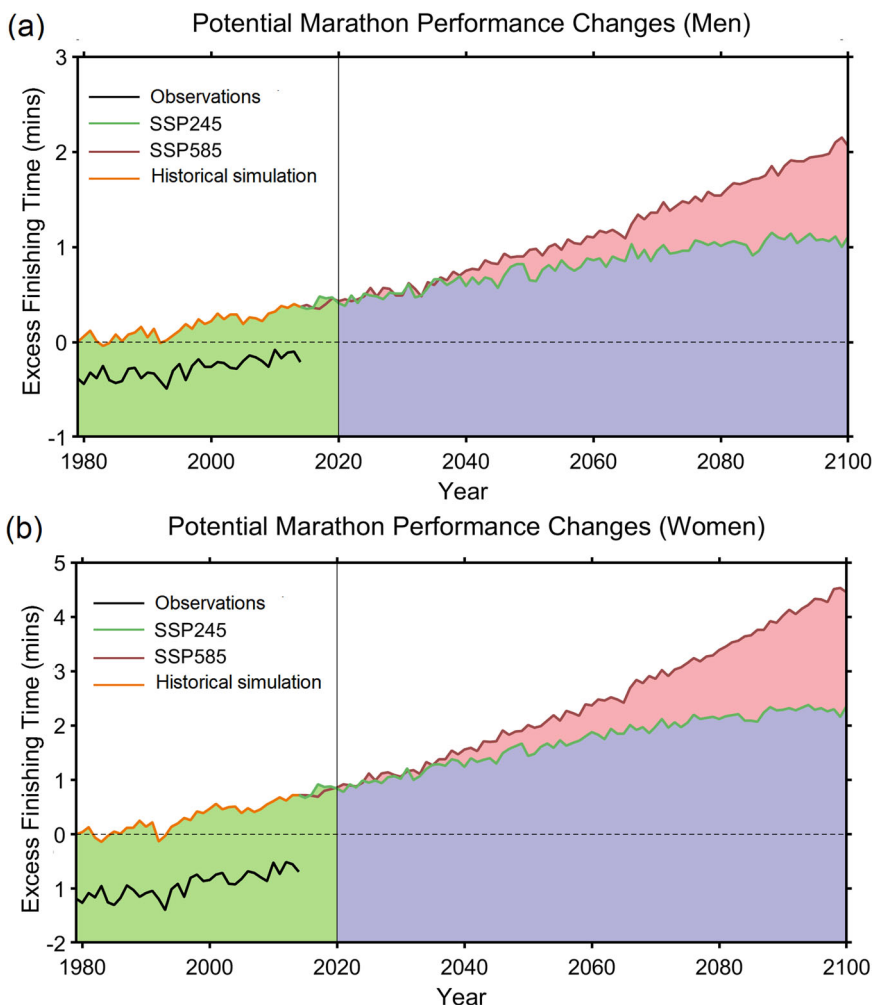
Fig. 6 | Historical progression of Olympic marathon athletic level. Historical mean finishing times of the three medal winners of Olympic marathon for men (blue) and women (red) athletes. The mean finishing times were subtracted by the ones of 2021 Tokyo Olympic Games (129.5 min for men and 147.6 min for women athletes) for better comparison between men and women athletes.

is overall ~0.8 min smaller. The consistency confirms that the projected MFT derived from the biased corrected global dataset is able to capture the long-term changes of MFT caused by climate change. During this period, MFT derived from the biased corrected global dataset increases by 0.54 min. Under both the intermediate emission scenario (SSP245) and the high emission scenario (SSP585)³¹, MFT is projected to almost continuously increase during 2020–2100 based the biased corrected global dataset, although some short-time withdrawals still exist

(Fig. 5, red and green curves). This indicating the continuous worsening of elite marathon athletes' performance in the future. The MFT increases by 1.06 min during 2020–2100 (green curves in Fig. 5) under the SSP245 scenario. This trend slows down after 2060 due to the achievement of sustainable development. Under the SSP585 scenario, however, the projected MFT rapidly increases by 2.51 min during this period. These changes are terrifying for the world top marathon athletes, as the average performance of the three medal winners of the Olympic marathon has been improved by only 2.25 min for men athletes over 1976–2021 and 2.39 min for women athletes over 1984–2021, estimated based on the linear trend.

In fact, the progression pace of the average performance of the three Olympic marathon medal winners has gradually slowed down as the marathon performance gradually approached the human physiological limits. For example, the average progression pace for men competitors was 0.51 min yr⁻¹ during 1924–1972 (twelve Olympic Games, Fig. 6, blue curves), while the pace slowed to 0.05 min yr⁻¹ over 1976–2021 (twelve Olympic Games). For women competitors, the average progression pace was 0.06 min yr⁻¹ since 1984 (ten Olympic Games), the year that the women marathon was introduced into the Olympic Games. Thus, it is very likely that the progression pace will be further reduced to <0.05 or even 0.03 min yr⁻¹ in the coming 2020–2100 period. In fact, this progression pace will be mostly offset by the projected MFT increase caused by climate change over 2020–2100 under the SSP585 scenario (2.51 min, or 0.031 min yr⁻¹). Therefore, the world-top marathon runners' efforts in improving marathon performance will be mostly wasted without powerful climate change mitigation, at least regarding the marathon event in the Olympic Games, the currently most important marathon event over the world.

Fig. 7 | Projected changes in MFT for men and women athletes under warming climate. Same as Fig. 5b, but for men (a) and women (b) athletes.



Projected changes in MFT in the past and future under the changing climate are also calculated for the men and women athletes, respectively, using the same procedures and datasets as the above ones for mixed-sex athletes. The MFT over the whole 1979–2100 period tends to continuously increase for both the men (Fig. 7a) and women athletes (Fig. 7b) under both the SSP245 (green and brown curves) and SSP585 emission scenarios (brown and red curves). These long-term MFT changes are overall similar to those for the mixed-sex athletes (Fig. 5b), although the rise speed shows obvious difference between the men and women athletes. The MFT rise for women athletes is greater than that for men athletes. Over the 2020–2100 period, the MFT increases by 0.70 and 1.63 min for men athletes under the SSP245 and SSP585 emission scenarios, respectively, but increases by 1.63 and 3.59 min for women athletes under these two scenarios, respectively.

Discussion

We conduct a large-scale investigation based on global marathon-running performance and weather observation data via looking at each competitor. The results show that the rise in ambient temperature tends to extend the finishing time of marathon competitors except when it is extremely cold. Reduction in ambient air pressure and rise in relative humidity are also likely to extend MFT, although the effects of the humidity on the MFT are much smaller than those of ambient temperature and pressure. We further reveal that more than half of the MFT extension associated with the rise in ambient temperature takes effect through expanding the air and increasing the vapor pressure and thus reducing the oxygen partial density. Based on the joint effects of the changes in these meteorological variables on the MFT, we thus

project that the progression of athletic level of Olympic marathon is likely slowed substantially by the changing climate. These results confirm our hypotheses proposed in the introduction.

Recently, the introduction of high-technology shoes substantially improved performance of elite marathon athletes by ~2–3 min^{32,33}. Similar improvements were also found for 5000 m, 10,000 m and half marathon running. The greatest improvement of men marathon world record/world best since 1967 was made in 2018. New technologies emerge promising to offset potential negative influence of the warming climate. However, improving performance via new non-physiological technology is controversial due to morality issue³⁴. Similar controversy eventually led to the banning of high-technology swimsuits in 2010. It is likely that high-technology shoes will be strictly restricted or even banned in the future as debate continues and spreads.

We acknowledge here some limitations and uncertainties of this study. The quantitative relationship between marathon finishing time and weather conditions was established primarily based on the 678 events joined by top-96 athletes. The sampling size is still relatively small, and it can raise uncertainties in the estimation, especially for each of two sexes. One possible solution is to include more athletes into our analysis. However, the chance that other athletes outside the top-96 list win an Olympic medal is relatively low. All the six medals of the marathon at the 2021 Tokyo Olympic Games were won by athletes in the top-96 list. Moreover, including slower athletes into the list may bring excess uncertainties, since the effects of weather conditions on marathon-running performance can be different among athletes of different levels^{7,8}. Uncertainties remain also in projection of future Olympic marathon

MFT³⁵ with statistical method as it cannot include factors like technical breakthroughs or social events such as global war.

The present study emphasizes the substantial negative impact of high temperature and high altitude on the marathon performance. Therefore, a marathon athlete or race organizer can improve the performance, especially when hoping to break records, through choosing a city with low altitude and low temperature (not extremely low). The present study also reveals that high temperature worsens marathon performance by reducing atmospheric oxygen as high altitude does. This implies that an athlete with no condition of altitude training may achieve the similar effects when training for a marathon by breathing warm air and cooling the body. This effect and its mechanism may also be relevant to various other endurance sports or even non-sport human activities and public health issues. For example, existing studies show that living in high altitudes may result in changes in the mortality of certain diseases through hypoxia^{36,37}. These effect and mechanism may also exist when living in the tropics since the high temperature can also cause hypoxia through expanding air parcels, which merits further study. Besides, this study suggests that the harm of climate warming may reach the area of sports (especially endurance sports) and efficient greenhouse gas mitigation may substantially reduce the harm in the future (scenario SSP245 v.s SSP585). This supports the urgency of more efficient measures to mitigate greenhouse gas emission.

Methods

Selection of marathon athletes and their race results

Top 8 marathon athletes from each of the 6 major regions of the world, namely Africa, Asia, North & Central America, South America, Europe and Oceania, are selected as potential medal-winning athletes for marathon race at Olympics. Eventually, top 96 athletes, including 48 men and 48 women, are considered, and their marathon results obtained after 2013 are used in this study. The list of these athletes and their information (name, world rankings, birth year and area) are shown in Table 2. The list of these athletes and their marathon results are obtained from the official website of world athletes (<https://worldathletics.org/world-rankings/marathon/men>) and the rankings in July 2021 are used here³⁸. Here we focus on the full marathon (i.e., 42.195 km long distance race). To explore the effects of ambient atmospheric pressure and altitude on performances, we extend the list to include 160 elite marathon athletes to cover enough events held at high-altitude cities (top 160 athletes). This list contains 10 men and 10 women from each of the above 6 major regions, additional 20 men and 20 women from Africa. Additional athletes in Africa are considered given the fact that there are more elite marathon runners in Africa than in other regions (8 of 10 world top marathon athletes are from Africa³⁸). In order to confirm the robustness of the results based on the above athletes, we also select the 100 best athletes (i.e., top-100 athletes for short) from the official website of world athletes, which include 50 men ranking 1–50th and 50 women ranking 1–50th over the world.

Observations, reanalysis, climate model outputs and data processing

Hourly observations of meteorological variables, including air temperature, sea level pressure and dew point, are obtained from the Integrated Surface Data dataset (ISD, <https://www.ncei.noaa.gov/data/global-hourly/archive/isd/>)³⁹. This dataset is supplied at stations and contains observation records at time interval ranging in different stations from several minutes to several hours. As of 2020, observations from ~13,000 stations have been included in this dataset. Weather data at the station nearest to route of each marathon race is extracted and daily mean of all the records of meteorological observations on the day of the marathon race is calculated to represent the weather conditions of the race. When less than two valid records exist at the nearest station on the day of an event, records at the second nearest station are used. If this criterion fails again at the second nearest station, the associated event will be ignored in the analysis.

We derive altitudes of route of each event using the high Terrain Elevation Above Sea Level (ELE) Data (at 30 × 30 arc-sec) developed by

SolarGIS and provided by the Global Solar Atlas (GSA) (<https://datacatalog.worldbank.org/search/dataset/0037910>)⁴⁰. We also use the monthly-mean near surface air temperature, pressure and relative humidity derived from the NCEP/NCAR Reanalysis 1 dataset that are offered on 2.5° × 2.5° grids and over 1948–2020⁴¹.

As the ISD dataset does not provide land surface atmospheric pressure, we use the equation below to infer it:

$$p_{sl} = p_{sl} \left(1 + \frac{\gamma H}{T + 273.15} \right)^{-\frac{g}{\gamma R}} \quad (1)$$

where p_{sl} denotes sea level pressure (hPa), g represents the gravitational acceleration (9.8 m s^{-2}), R is the gas constant for dry air ($287.053 \text{ J K}^{-1} \text{ kg}^{-1}$), γ stands for the environmental lapse rate, H denotes the altitude of the marathon route and T is near surface air temperature. This formula is deduced based on ideal atmosphere that is in hydrostatic balance and has constant γ ($6.5 \text{ }^\circ\text{C km}^{-1}$). As observed p_{sl} values are commonly missing in the ISD, we set p_{sl} as a constant of 1013 hPa here. According to scale analysis⁴², the order of the variation of p_{sl} is $\sim 10^1$ hPa, while the altitudes of the marathon events range from 0 to 2300 m, leading to pressure changes greater than 200 hPa. Thus, the errors of setting p_{sl} as a constant are acceptable here.

Relative humidity is calculated using observed dew point, air temperature and derived actual and saturated vapor pressure. Actual and saturated vapor pressure are calculated from observed dew point and air temperature, respectively, with the Magnus formula⁴³ as follows:

$$E = 6.1094 e^{\frac{17.625t}{t+243.04}} \quad (2)$$

where E denotes saturated vapor pressure (hPa), and t stands for air temperature ($^\circ\text{C}$).

In this study we consider the influence of atmospheric oxygen on elite marathon runners' performance, and use the following equation⁴⁴ to calculate oxygen partial density (ρO_2):

$$\rho\text{O}_2 = \frac{0.232(p - e)}{R_d T} \quad (3)$$

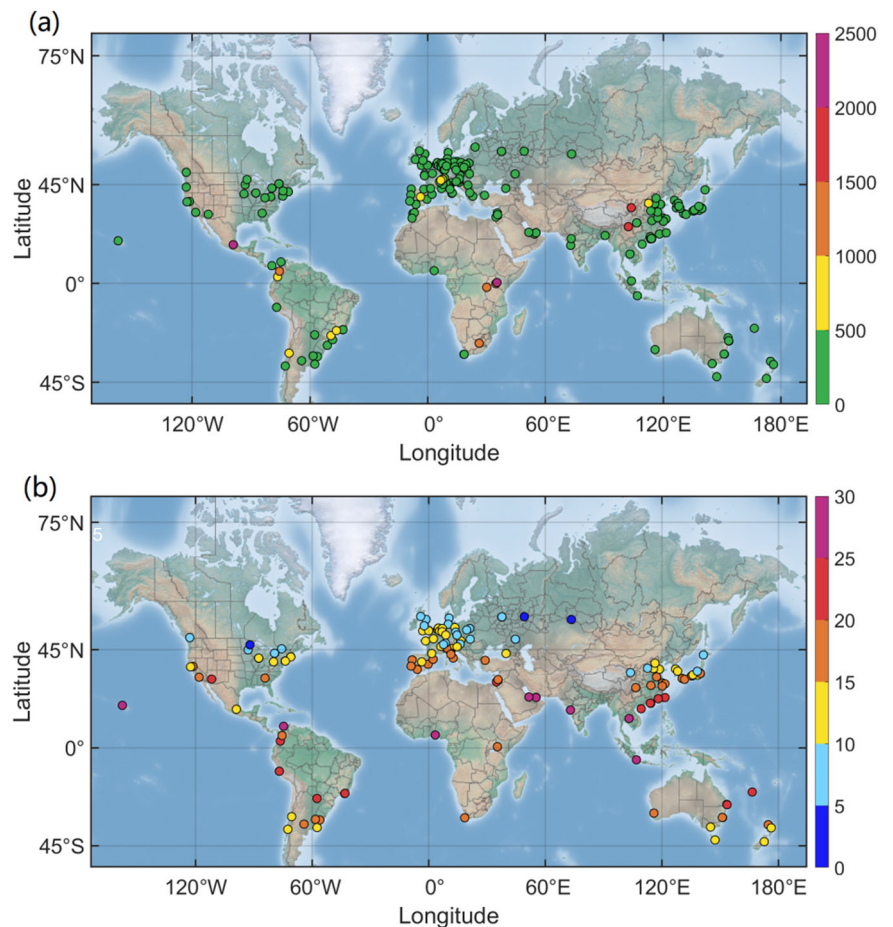
where p represents air pressure (hPa), e is vapor pressure (hPa), R_d denotes the gas constant for dry air ($287.053 \text{ J K}^{-1} \text{ kg}^{-1}$), and T is air temperature (K).

After these processes, 678 competition results with valid weather data (including air temperature, dew point, altitude and the derived atmospheric pressure, ρO_2 and relative humidity) are selected. The years of these competition results for each athlete are shown in Table 1. The geographical position, altitude and historical average temperature of the races for these results are shown in Fig. 8 and Supplementary Table 1.

The country of the competition venue and the nationalities of each athlete are also obtained from the official website of world athletes to analyze the effect of home advantage on the competition performance. If an athlete finishes a marathon in his/her country, we think that home advantage exists for the competition result, and otherwise does not exist. If an athlete has home advantage in a competition, the variable characterizing the home advantage is set as 10, and otherwise set as 0. The variable sex is set as 0 and 10 for men and women, respectively. The average marathon finishing time of all the competition results obtained by an athlete after 2013 is used to characterize his/her competition level.

Generalized linear model (GLM) is used to analyze the relationships between marathon results and influencing factors^{45,46}. In the model, three meteorological variables (ambient temperature, relative humidity and ambient pressure) and four variables related to the athletes (average finishing time, gender, age and the home advantage) are considered as the possible influencing factors. Restricted cubic spline function with four knots is applied to each influencing variable in the GLM⁴⁷ to analyze the possible nonlinear relationship (if any) of the marathon performance with the influencing factors except for average finishing time. The four knots are set

Fig. 8 | Location, altitude and historical average temperature for each of the 676 races. Each point in **a** and **b** shows the position where each marathon race was held. The color of point denotes altitude and the climatology of air temperature over 1979–2014 at the holding position of each race in **a** and **b**, respectively. The temperature is derived from GHCN CAMS monthly 2-m land surface air temperature dataset. The altitude is derived from the high Terrain Elevation Above Sea Level (ELE) Data (at 30 × 30 arc-sec) developed by Solargis. Since many marathon races are held at the same city, 148 different points are shown in the map.



at the quantiles of 5%, 35th, 65% and 95%. The confidence intervals are obtained along with the fitting lines using R language, which calculates confidence interval by making an interval on the scale of the linear predictor, then applying the inverse link function from the model fit to transform the linear level confidence intervals to the response level (https://search.r-project.org/CRAN/refmans/ciTools/html/add_ci_glm.html). Besides, multiple linear regression analysis is also used to analyze the relationships between marathon results and influencing factors.

To explore the impacts of climate change on the marathon-running performance, we use the bias-corrected global dataset based on 18 models of the Coupled Model Intercomparison Project Phase 6 (CMIP6) and the European Centre for Medium-Range Weather Forecasts Reanalysis 5 (ERA5)⁴⁸. This dataset covers the period of 1979–2100 and data is provided at a horizontal resolution of 1.25° × 1.25°. We used the monthly-mean near surface temperature, relative humidity and air pressure for historical period (1979–2014), and two future shared socio-economic pathway scenarios (SSP585 and SSP245) over 2015–2100. The monthly-mean near surface temperature is directly derived from the datasets. The relative humidity and air pressure are averaged over each month from the daily data reported on pressure levels and then interloped onto land surface. The SSP245 is called the “middle of the road” scenario with an approximately 4.5 W m⁻² radiative forcing level by 2100, while SSP585 is a high fossil fuel development scenario.

Data availability

All the data used in the present study are obtained from publicly available datasets. The ISD meteorological observations at weather stations are available at <https://www.ncdc.noaa.gov/data/global-hourly/archive/isd/>. The marathon competition data are available at <https://worldathletics.org/world-rankings/marathon/men>. The CMIP6 global dataset for the Earth’s

historical and future climate (1979–2100) is from <https://www.scidb.cn/en/detail?dataSetId=791587189614968832&dataSetType=personal>. The ELE data for calculating the altitude of marathon races are derived from (<https://datacatalog.worldbank.org/search/dataset/0037910>).

Code availability

All the key methods (e.g. multiple linear regression analysis, GLM) used in the present study are standard and are publicly available in the EXCEL and R studio software.

Received: 1 November 2023; Accepted: 31 March 2024;

Published online: 29 April 2024

References

1. Cui, F. & Lu, Y. 21 died in ultramarathon tragedy in NW China due to extreme weather, lack of emergency preparation, <https://www.globaltimes.cn/page/202105/1224262.shtml> (2021).
2. Mann, M. E. & Gleick, P. H. Climate change and California drought in the 21st century. *Proc. Natl Acad. Sci.* **112**, 3858–3859 (2015).
3. Kelley, C. P., Mohtadi, S., Cane, M. A., Seager, R. & Kushnir, Y. Climate change in the Fertile Crescent and implications of the recent Syrian drought. *Proc. Natl Acad. Sci.* **112**, 3241–3246 (2015).
4. Im, E.-S., Pal, J. S. & Eltahir, E. A. Deadly heat waves projected in the densely populated agricultural regions of South Asia. *Sci. Adv.* **3**, e1603322 (2017).
5. Stott, P. How climate change affects extreme weather events. *Science* **352**, 1517–1518 (2016).
6. Ely, M. R., Chevront, S. N., Roberts, W. O. & Montain, S. J. Impact of weather on marathon-running performance. *Med. Sci. Sports Exerc.* **39**, 487–493 (2007).

7. Vihma, T. Effects of weather on the performance of marathon runners. *Int. J. Biometeorol.* **54**, 297–306 (2010).
8. Ely, M. R., Martin, D. E., Chevront, S. N. & Montain, S. J. Effect of ambient temperature on marathon pacing is dependent on runner ability. *Med Sci. Sports Exerc.* **40**, 1675–1680 (2008).
9. Gasparetto, T. & Nessler, C. Diverse effects of thermal conditions on performance of marathon runners. *Front. Psychol.* **11**, 1438 (2020).
10. Thorsson, S. et al. Is Physiological Equivalent Temperature (PET) a superior screening tool for heat stress risk than Wet-Bulb Globe Temperature (WBGT) index? Eight years of data from the Gothenburg half marathon. *Br. J. Sports Med.* **55**, 825–830 (2021).
11. Montain, S. J., Ely, M. R. & Chevront, S. N. Marathon performance in thermally stressing conditions. *Sports Med.* **37**, 320–323 (2007).
12. Knechtle, B. et al. Elite marathoners run faster with increasing temperatures in Berlin marathon. *Front. Physiol.* **12**, 649898 (2021).
13. Weiss, K. et al. Temperature and barometric pressure are related to running speed and pacing of the fastest runners in the 'Berlin Marathon'. *Eur. Rev. Med. Pharmacol. Sci.* **26**, 4177–4287 (2022).
14. Weiss, K. et al. Relationship between running performance and weather in elite marathoners competing in the New York City Marathon. *Sci. Rep.* **12**, 21264 (2022).
15. Scheer, V. et al. The optimal ambient conditions for world record and world class performances at the Berlin Marathon. *Front. Physiol.* **12**, 654860 (2021).
16. Nikolaidis, P. T. et al. The role of environmental conditions on marathon running performance in men competing in Boston marathon from 1897 to 2018. *Int. J. Environ. Res. Public Health* **16**, 614 (2019).
17. Ely, M. R., Chevront, S. N. & Montain, S. J. Neither cloud cover nor low solar loads are associated with fast marathon performance. *Med. Sci. Sports Exerc.* **39**, 2029–2035 (2007).
18. Lara, B., Salinero, J. J. & Del Coso, J. Altitude is positively correlated to race time during the marathon. *High. Alt. Med. Biol.* **15**, 64–69 (2014).
19. Peronnet, F., Thibault, G. & Cousineau, D. A theoretical analysis of the effect of altitude on running performance. *J. Appl. Physiol.* **70**, 399–404 (1991).
20. Chevront, S. N., Kenefick, R. W., Montain, S. J. & Sawka, M. N. Mechanisms of aerobic performance impairment with heat stress and dehydration. *J. Appl. Physiol.* **109**, 1989–1995 (2010).
21. Smith, K. R. et al. The last Summer Olympics? Climate change, health, and work outdoors. *Lancet* **388**, 642–644 (2016).
22. Dunne, J. P., Stouffer, R. J. & John, J. G. Reductions in labour capacity from heat stress under climate warming. *Nat. Clim. Change* **3**, 563–566 (2013).
23. Beal, H., Corbett, J., Davis, D. & Barwood, M. J. Marathon Performance and Pacing in the Doha 2019 Women's IAAF World Championships: Extreme Heat, Suboptimal Pacing, and High Failure Rates. *Int. J. Sports Physiol. Perform.* **17**, 1119–1125 (2022).
24. Racinais, S. et al. Association between thermal responses, medical events, performance, heat acclimation and health status in male and female elite athletes during the 2019 Doha World Athletics Championships. *Br. J. Sports Med.* **56**, 439–44 (2022).
25. Kenney, W. L. A review of comparative responses of men and women to heat stress. *Environ. Res.* **37**, 1–11 (1985).
26. Gargaglioni, L. H., Marques, D. A. & Patrone, L. G. A. Sex differences in breathing. *Comp. Biochem. Physiol. Part A Mol. Integr. Physiol.* **238**, 110543 (2019).
27. Xiao, X. et al. Greenness around schools associated with lower risk of hypertension among children: Findings from the Seven Northeastern Cities Study in China. *Environ. Pollut.* **256**, 113422 (2020).
28. Baron, R. M. & Kenny, D. A. The moderator–mediator variable distinction in social psychological research: Conceptual, strategic, and statistical considerations. *J. Pers. Soc. Psychol.* **51**, 1173 (1986).
29. Curriero, F. C. et al. Temperature and mortality in 11 cities of the eastern United States. *Am. J. Epidemiol.* **155**, 80–87 (2002).
30. Guo, Y. et al. Global variation in the effects of ambient temperature on mortality: a systematic evaluation. *Epidemiology* **25**, 781 (2014).
31. Zhongming, Z., Linong, L., Wangqiang, Z. & Wei, L. *AR6 Climate Change 2021: The Physical Science Basis* <https://www.ipcc.ch/report/ar6/wg1/> (2021).
32. Muniz-Pardos, B. et al. Recent improvements in marathon run times are likely technological, not physiological. *Sports Med.* **51**, 371–378 (2021).
33. Hoogkamer, W. et al. A comparison of the energetic cost of running in marathon racing shoes. *Sports Med.* **48**, 1009–1019 (2018).
34. Crouse, K. Swimming Bans High-Tech Suits, Ending an Era, <https://www.nytimes.com/2009/07/25/sports/25swim.html> (2009).
35. Smith, K. J. P. Are We Reaching the End of World Records, <https://www.scientificamerican.com/article/are-we-reaching-the-end-of-world-records/> (2016).
36. Burtcher, M. Effects of living at higher altitudes on mortality: a narrative review. *Aging Dis.* **5**, 274 (2014).
37. Thiersch, M. & Swenson, E. R. High altitude and cancer mortality. *High. Alt. Med. Biol.* **19**, 116–123 (2018).
38. World Rankings: Men's Marathon (Half Marathon-25km-30km), <https://www.worldathletics.org/world-rankings/marathon/men> (2024).
39. Integrated Surface Data, <https://www.ncei.noaa.gov/data/global-hourly/archive/isd/> (2024).
40. World - Terrain Elevation Above Sea Level (ELE) GIS Data, (Global Solar Atlas), <https://datacatalog.worldbank.org/search/dataset/0037910> (2023).
41. Kalnay, E. et al. The NCEP/NCAR 40-year reanalysis project. *Bull. Am. Meteorol. Soc.* **77**, 437–472 (1996).
42. Lv, M., Hou, Z. & Zhou, Y. *Dynamic Meteorology* (China Meteorological Press, 2004).
43. Huang, J. A simple accurate formula for calculating saturation vapor pressure of water and ice. *J. Appl. Meteorol. Climatol.* **57**, 1265–1272 (2018).
44. Kuzmenko, N. Seasonal Variations in Atmospheric Pressure, Partial Oxygen Density, and Geomagnetic Activity as Additional Synchronizers of Circannual Rhythms. *Biophysics* **64**, 599–609 (2019).
45. Blough, D. K., Madden, C. W. & Hornbrook, M. C. Modeling risk using generalized linear models. *J. Health Econ.* **18**, 153–171 (1999).
46. Moran, J. L., Solomon, P. J., Peisach, A. R. & Martin, J. New models for old questions: generalized linear models for cost prediction. *J. Eval. Clin. Pract.* **13**, 381–389 (2007).
47. Desquilbet, L. & Mariotti, F. Dose-response analyses using restricted cubic spline functions in public health research. *Stat. Med.* **29**, 1037–1057 (2010).
48. Xu, Z., Han, Y., Tam, C.-Y., Yang, Z.-L. & Fu, C. Bias-corrected CMIP6 global dataset for dynamical downscaling of the historical and future climate (1979–2100). *Sci. Data* **8**, 1–11 (2021).
49. Department of Economic and Social Affairs. 2022 Revision of World Population Prospects. <https://population.un.org/wpp/Download/Standard/Population/> (2022).

Acknowledgements

We acknowledge the funding support from Research Grants Council of the Hong Kong Special Administrative Region, China (project no. C2002-22Y and HKBU12202021), the Center for Ocean Research in Hong Kong and Macau (CORE), National Natural Science Foundation of China (Grant No. 42088101 and 42030605), the Research start-up funding project of Qinghai University of Science and Technology (2023021wys001) and “Kunlun Talents” talent introduction scientific research project of Qinghai University of Science and Technology (2023-QLGKLYCZX-003).

Author contributions

M.G. and S.W. designed research; S.W. performed research and analyzed data; and S.W. and M.G. wrote the paper with inputs from X.X., X. J. and J. L.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at

<https://doi.org/10.1038/s41612-024-00637-x>.

Correspondence and requests for materials should be addressed to Meng Gao.

Reprints and permissions information is available at <http://www.nature.com/reprints>

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

© The Author(s) 2024