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# Warming climate is helping human beings run faster, jump higher and throw farther through less dense air

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Understanding both positive and negative impacts of climate change is essential for comprehensively assessing and well adapting to the impacts of changing climate. Conventionally, climate warming is revealed to negatively impact human activities. Here, we reveal that human beings' performance in anaerobic sports may benefit from climate warming. Using global weather observation and athletes' performance datasets, we show that world-top athletes' performances in nearly all athletics anaerobic events (i.e., sprints, jumps and throws) substantially improve as ambient temperature rises. For example, 100 m performance monotonically improves by 0.26 s as ambient temperature rises from 11.8° to 36.4 °C. Using Coupled Model Intercomparison Project Phase 6 datasets, we further show that global warming can substantially improve world-top athletes' performance in eleven of the thirteen Olympics athletics anaerobic events by 0.27%–0.88% and 0.14–0.48% under high-emission and medium-emission scenarios, respectively, during 1979–2100. Among them, the improvements for 100 m are 0.59% (0.063 s) and 0.32% (0.034 s), respectively. Mechanism analysis shows that the warmed ambient atmosphere can improve competitors' performance through expanding the air and thus reducing the air resistance to the competitors and throwing implements for hammer throw and all the sprints, hurdling and jumps. Quantitative analysis estimates that this thermodynamic process is essential for the impacts of warmed ambient atmosphere on the performances in these events as physiological processes are.

The warming climate and hot weathers are widely revealed to negatively impact human activities and wellbeings<sup>1–7</sup>. They can increase thermal discomfort<sup>4</sup>, reduce labor capacity<sup>5</sup> and increase mortality<sup>3,6,8</sup>. Sport competitions and physical exercises are among essential parts of public health and human activities. The impacts of weather variations and climate changes on the game organization and competitors' performances have draw much attention in existing studies. Extensive studies indicated that increased air temperature can worsen the performance of endurance sports

such as marathon<sup>9–15</sup>, and the impact of warming climate on human's sports performance also seems to be negative. Other studies indicate that the increased ambient temperature and the warming climate may threaten the health of the competitors and even the holding of the games including the Olympic games<sup>16,17</sup>.

The effects of weather conditions, especially surface air temperature, and climate changes on the performance of anaerobic sports (duration <90 s, e.g., 100 m sprint) have drawn limited attention. In fact, athletics

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anaerobic sports are very popular throughout the world. In recent Olympic Games, 30 of the 47 athletics events are anaerobic sports (sprints, jumps, throws and relay races). Especially, 100-meters dash is among the most popular and prestigious sport events of all existing sports and its reigning world champion such as Usain Bolt was often named “the fastest man in the world”. Among all meteorological elements, tailwind<sup>18–22</sup> and altitude increase<sup>23–25</sup> are acknowledged to improve the performance of sprints and jumps. Besides, several studies also investigated effects of temperature and humidity on these sports performances<sup>26–28</sup>.

However, they conventionally investigated the changes in the average performances of all or certain parts of the competitors in each game with the changes in ambient weather conditions across a series of relevant games. This method may bring large uncertainties caused by the large difference in the participants among different games. There are also no systematic and large-scale investigations quantifying the impacts of weather conditions, especially temperature, on the competitors’ performances in anaerobic athletics events. We conduct this analysis via looking at certain individual competitors instead of many games with different participants to eliminate the relevant uncertainties. The mechanism of the impacts will be investigated both qualitatively and quantitatively and we will reveal that the thermodynamic processes in the atmosphere are almost as essential as the physiological processes for the impacts of ambient temperature. Based on the above analyses, we further assess the changes of the world top competitors’ performance in anaerobic athletics events in the past and future attributable to the global warming climate. We pay more attention to the 100 m sprint in the analyses since it usually attracts the most attention among all the anaerobic athletics events. Our results reveal a positive impact of hot weathers and warming climate on the competitors’ performances. This result is quite distinctive from the widely-recognized negative impacts of the warming climate on human activities and the public health. Such an analysis is of great significance for more comprehensively understanding the balance of the positive and negative impacts of climate change, especially regarding sports, and thus to more comprehensively assess and better adapt to the warming climate.

The rest of the paper is organized as follows. Section “Results” briefly describes the data and the relevant methods used in this study. Section “Discussions” and “Methods” investigate the effects of weather conditions on the competitors’ performances in the athletics anaerobic events and explore for the possible mechanism for the impacts. Based on these effects, Section 5 estimates the world top athletes’ performance attributable to the climate changes under different emission scenarios, followed by a brief conclusion and further discussion in Section 6.

## Results

### Effects of weather conditions on the performance changes

In order to reveal the relation of competitors’ performance in each athletics anaerobic event with the possible controlling factors, multiple linear regression of the performance upon the controlling factors is conducted (Table 1). Multivariate regression analysis is an attempt to account for the contribution of the independent variables to the dependent variable synchronically and its model is formulated as in the following:

$$y = b_0 + b_1x_1 + b_2x_2 + \dots + b_nx_n + e \quad (1)$$

Where  $y$  is the dependent variables,  $x_i$  is the independent variables,  $b_i$  is the regression coefficient for  $x_i$ ,  $b_0$  is the intercept,  $e$  is the error. See more details for the model in<sup>29</sup>.

The involved factors include meteorological elements (ambient temperature, tail wind speed, atmospheric pressure and relative humidity anomalies), age, the climatological-mean temperature at the capital of each athlete’s country (TC), the round of competition, each competitors’ annual mean performance and the sex. The results show that the ambient temperature has significant relationship with the competitors’ performance in 11 of the 13 athletics anaerobic events ( $P < 0.05$ ). The performance tends to be improved with the ambient temperature rise. Note that the shorter

finishing time or the longer height/distance denotes the better performance. The two exceptions are the javelin throw and discus throw, whose performance has no significant relationship with any of the four meteorological variables ( $P > 0.1$ ). For all the 5 events with wind speed records, the competitors’ performance improves significantly with increasing tail wind ( $P < 0.01$ ). Athletes’ performance worsens with rising ambient pressure (i.e., altitude reduction) for 10 of the 13 events but not for shot put, javelin throw and discus throw. The relationship is significant for 100 m, 200 m, 100/110 m hurdles, 400 m and 400 m hurdles, high jump and hammer throw ( $P < 0.1$ ). The relationship with relative humidity is not stable and statistically significant only for 400 m hurdles and triple jump ( $P < 0.05$ ). The performance improves significantly with increasing competition round for 12 of the 13 events ( $P < 0.01$ ) except javelin throw. The sex, age, annual-mean performance (competitive level) and TC (nationality) have no significant relationship with the performance in any of the 13 events ( $P > 0.1$ ).

Figure 1a, d–f shows the more detailed 100 m performance changes with ambient weather conditions. The multivariable restricted cubic spline generalized linear model (rcs-GLM) is used to illustrate these changes. When the relationship between air temperature and 100 m performance is predicted, other three meteorological variables (i.e., the relative humidity, atmospheric pressure and tail wind speed) and the competition round are selected as covariates in the model, and so on for the relationship of other weather variables with the performance. The age, the climatological-mean temperature at the capital of competitor’s country and the annual mean performance are not considered since they have no significant relationship with competitors’ performance for all the 13 events based on the multiple linear regression. The 100 m performance improves monotonically by 0.26 second as ambient temperature anomaly increases from  $-12.9^\circ$  to  $11.7^\circ\text{C}$  (equivalent to ambient temperature increasing from  $11.8^\circ$  to  $36.4^\circ\text{C}$ , Fig. 1a), and the relationship is nearly linear. 0.26 s is quite marked for 100 m competitors since the average performance of the currently world place 20th competitor is only 0.15 s and 0.36 s slower than the place 1st competitor for men and women, respectively. If men and women are analyzed separately, the performances monotonically improve with ambient temperature for both sexes (Fig. 1b and c). The improvement for women is  $0.0115\text{ s }^\circ\text{C}^{-1}$  (Fig. 1c), slightly greater than that for men ( $0.0080\text{ s }^\circ\text{C}^{-1}$ ) and mixed-sex competitors ( $0.0101\text{ s }^\circ\text{C}^{-1}$ ). This performance-temperature relationship is interesting. It counters the intuition that high temperature makes human feel uncomfortable. It is also quite distinct from the endurance sports performances<sup>9,11,12,30</sup> as well as public health burdens, wellbeings and other human activities, which usually worsen as ambient temperature rises at least when ambient temperature is high<sup>5,6,8</sup>.

Figure 1d shows that 100 m performance improves by 0.50 s as tailwind speed anomaly increases from  $-3.6\text{ m s}^{-1}$  to  $+2.9\text{ m s}^{-1}$ . This relation is overall consistent with existing studies and the decreased wind resistance as tail wind increases is revealed to cause the performance improvement<sup>18–22</sup>. 100 m performance also improves as atmospheric pressure decreases (Fig. 1e), which is basically equivalent to altitude increasing according to static equilibrium<sup>31</sup>. 2000m increase in altitude (equivalent to 240 hPa decrease in atmospheric pressure) is associated with about 0.13 s improvement in 100 m performance. The decreased atmosphere pressure can reduce the atmosphere density. The decrease in ambient temperature as altitude rises can partly offset the atmosphere density decrease directly caused by the pressure reduction based on the equation of state for dry air. However, the proportion offset by the atmosphere cooling is small (see Section “Methods” for detail). The reduced atmosphere density decreases the air resistance as the tail wind does and thus improves competitors’ performance<sup>24</sup>. 100 m performance tends to slightly improve as relative humidity rises, however, the relationship of relative humidity with finishing time anomalies is overall nonlinear and not statistically significant (Fig. 1f). Repeating these analyses for men and women competitors separately shows similar results to the above mixed-sex results (Fig. 2). Overall, tailwind speed and ambient temperature variations are related to much larger changes in 100 m performance than relative humidity and atmospheric pressure variations.

**Table 1 | Multiple linear regression of competitors' performance (anomalous finishing time for sprints and hurdles, distance/height for jumps/throws) upon meteorological variables (i.e., anomalies of ambient temperature, tail wind speed, atmospheric pressure and relative humidity), age, the climatological-mean temperature at the capital of each athlete's country (TC), the round of competition, each competitors' annual mean performance (AMP) and the sex for each athletics anaerobic event**

Variable	100 m	200 m	100/110 mH	Long Jump	Triple Jump	Hammer Throw	
AMP	0.000	-0.008	0.009	0.013	-0.005	0.007	
Temperature	-0.010***	-0.010***	-0.011***	0.007***	0.018***	0.056***	
Pressure	0.055***	0.137*	0.098***	-0.034	-0.031	-0.593*	
Humidity	-0.057*	0.002	-0.030	-0.013	0.259***	0.415	
Tail Wind	-0.067***	-0.051***	-0.057***	0.046***	0.071***	/	
TC	0.000	-0.001	0.000	0.000	0.000	0.004	
age	0.000	0.002	0.001	-0.001	0.000	-0.002	
Round	-0.028***	-0.084***	-0.040***	0.044***	0.111***	0.532***	
Sex	0.004	0.013	0.005	0.017	-0.016	0.049	
R Squared	0.41***	0.11***	0.20***	0.12***	0.15***	0.05***	
Standard Deviation	0.117	0.27	0.17	0.16	0.26	1.73	
Sample Size	988	614	1122	787	706	997	
Variable	400 m	400 mH	Pole Vault	High Jump	Shot Put	Discus Throw	Javelin Throw
AMP	0.011	0.006	0.002	0.023	0.002	-0.001	0.000
Temperature	-0.037***	-0.061***	0.006***	0.003***	0.009***	0.000	0.008
Pressure	0.278**	0.301**	-0.033	-0.013	0.066	0.411	0.156
Humidity	-0.133	-0.580***	0.012	0.003	-0.048	0.082	-1.217*
TC	-0.001	-0.001	0.000	0.000	0.000	0.000	0.001
age	0.003	0.006	0.000	0.000	0.000	-0.003	0.000
Round	-0.208***	-0.305***	0.049***	0.018***	0.099***	0.343***	0.312*
sex	-0.044	-0.022	0.004	0.007	-0.007	0.024	-0.012
R Squared	0.12***	0.18***	0.08***	0.13***	0.02**	0.01	0.01
Standard Deviation	0.60	0.67	0.13	0.039	0.49	1.83	2.58
Sample Size	762	831	917	780	1012	924	910

The number for each variable indicates the regression coefficient and \*, \*\* and \*\*\* denote the ones significant at 90%, 95% and 99% confidence level, respectively.

One may argue that the annual important games (e.g., Olympic Games) are mostly held in boreal summer and thus the competitors may be in better form in summer than in other seasons. To eliminate interference of this seasonal cycle in the performance-weather relationship, we repeat the analysis shown in Fig. 1 using the competition results obtained in June, July and August only. The result also shows that 100 m performance increases monotonically as ambient temperature rises and tailwind speed rises (Fig. 3a, b). The improving slope of the performance with ambient temperature is 0.0101 s °C<sup>-1</sup>, almost equal to that using the 12-months data (i.e., 0.0098 s °C<sup>-1</sup>). 100 m performance changes with ambient pressure and relative humidity are very weaker based on the summer-month data (Fig. 3c, d). Overall, the above results indicate the robustness of the interesting monotonic relationship between ambient temperature and 100 m performance.

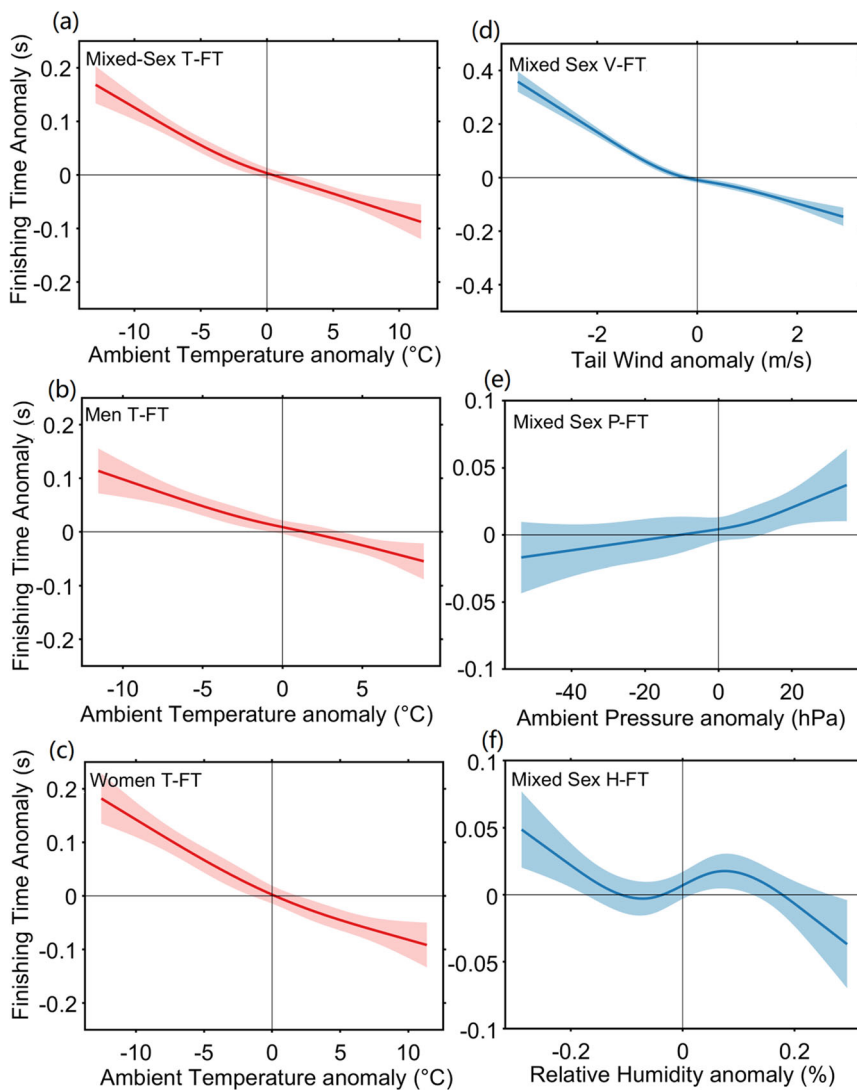
Random Forest is a machine learning technique using an ensemble learning approach and it has prestigious advantage in tackling the nonlinear and hierarchical relationships between predictor variables and the response<sup>32</sup>. Here we use random forest regression method to further assess the contributions of weather variables to 100 m performance changes (Table 2). We randomly select 2/3 of all the 100 m results during 2019–2021 as training data to train the random forest regression model. The rest 1/3 results are used as testing data to evaluate the model prediction capacity, which is characterized with the correlation coefficient (CC) between the predicted and actual finishing time anomalies. We focus on the effects of the meteorological elements (ambient temperature, tail wind speed, atmospheric pressure and relative humidity anomalies). The other elements such as annual-mean

performance, competition round, TC, age and the sex are used as covariates.

If one single variable is used to train and evaluate the model, the CC is the largest using tailwind speed (V, CC = 0.51), followed by ambient temperature (T, CC = 0.28). The CCs using relative humidity (H, CC = 0.13) and atmospheric pressure (P, CC = 0.15) are smaller. If two weather variables are used, the CC using V + T (0.62) is higher than those using V + P (0.53) and V + H (0.57). When using three variables, the CC using V + H + P (0.57) is smaller than that using V + H + T (0.64) and V + P + T (0.61). All these results suggest that tailwind speed and ambient temperature are the two most important weather variables affecting 100 m performance, consistent with that illustrated by multiple linear regression analysis and rcs-GLM (Figs. 1, 2 and Table 1). Overall similar results are obtained if men and women are analyzed separately. The CCs using V + H + T + P are 0.64, 0.55 and 0.64 for mixed-sex, men and women competitors, respectively, indicating that a considerable part of 100 m performance changes is attributable to weather conditions. If training and evaluating the model based on only the covariates (i.e., annual-mean performance, TC, competition round, age and sex), the derived CCs become -0.07, -0.16, -0.09 for mixed-sex, men and women competitors, respectively. These results justify the significance of the present study.

Figure 4 shows the weather-performance relationship for the rest 12 athletics events. The finishing time of the sprints/hurdles (i.e., 100 m, 200 m, 100/110 m hurdles and 400 m hurdles) monotonically decreases as ambient temperature rises, indicating the performance monotonically improves, and the associated finishing time anomalies are mostly significant (Fig. 4a, b). The distance/height of the four jumps shows monotonic increasing as

**Fig. 1 | 100 m performance changes with ambient weather conditions.** Relation of 100 m finishing time anomaly (unit: second) with (a) the ambient temperature anomaly, (d) tail wind speed anomaly, (e) atmospheric pressure anomaly and (f) relative humidity anomaly using rcs-GLM. 988 competition results of the current world-top 20 men and 20 women competitors with valid values of meteorological variables are used for obtaining the relation. The shadings denote the 95% confidence interval. **b, c** As in (a), but for the 499 results of world-top men and 489 results of world-top women competitors, respectively.



ambient temperature rises, also indicating performance monotonically improves (Fig. 4c, d). Among the four throws, the performances of shot put and hammer throw monotonically improve as ambient temperature rises, although the changes are not so significant, while the changes in javelin throw and discus throw performances are rather weak (Fig. 4e, f). Overall, performance of overwhelming majority of athletics anaerobic events beyond 100 m monotonically improves as ambient temperature rises despite of the wide variation in the form of these events, indicating that the increasing ambient temperature may be related to the improvement of human being's anaerobic capacity. In fact, javelin and discus are more aerodynamic than other throwing implements<sup>33,34</sup>, which may cause the weak temperature-performance relationship as discussed later.

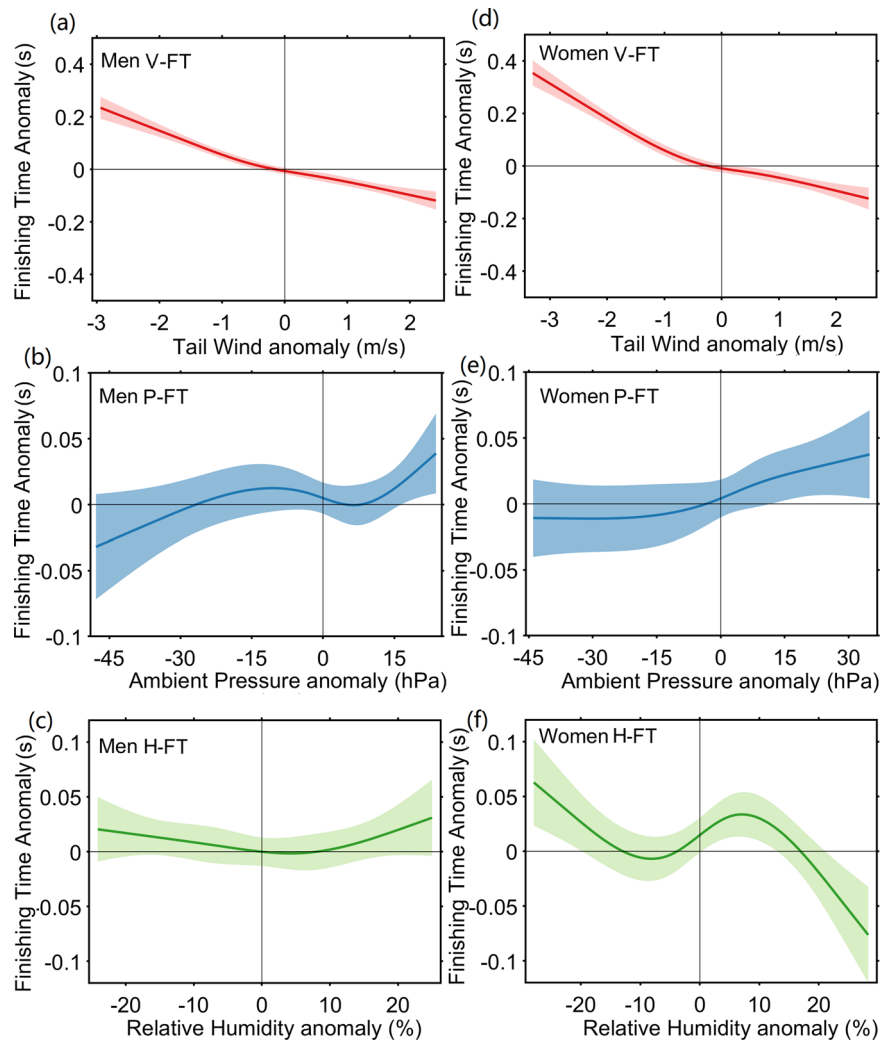
Wet-Bulb Globe Temperature (WBGT) and Universal Thermal Climate Index (UTCI) provide comprehensive information of the thermal environment<sup>5,35</sup>. We repeat the above analyses by replacing the ambient temperature with WBGT and UTCI, respectively, for the 11 events (five sprints/hurdles, 4 jumps and 2 throws, not including javelin throw and discus throw). The result shows that the performance monotonically improves with the rise of both WBGT and UTCI (Supplementary Figs. 2, 3), which is similar to the relation with increasing ambient temperature (Fig. 4).

Among these 12 athletics events, tailwind speed is reported only in 200 m, 110 m/100 m hurdles, long jump and triple jump competitions. Competitor's performance in all the four events monotonically improves (worsens) as tailwind (headwind) strengthens (Fig. 5). The increasing

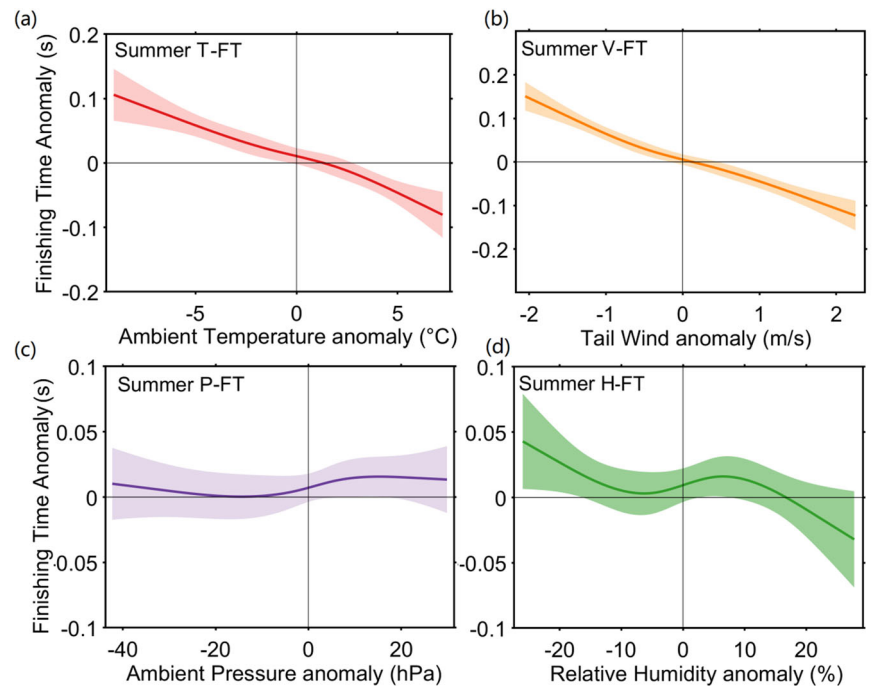
percentages are around 3% associated with  $4 \text{ m s}^{-1}$  increase in the tail wind, which is similar to that of 100 m sprint. As indicated in existing studies, the decreased air resistance associated with increased tail wind is the possible reason for the performance improvement in these events<sup>20,24</sup>. As relative humidity rises, however, the performance changes of all the 12 events are much weaker than those associated with tail wind and ambient temperature changes (Supplementary Fig. 4).

As ambient atmospheric pressure decreases, competitors' performances in 9 of the 12 events tend to improve (Fig. 6). The mean improving rate of the 9 events is 0.58% per 100-hPa reduction in atmospheric pressure and it ranges from the 0.20% of the triple jump to the 0.82% of the 100/110 m hurdling (Fig. 7). The decreased air resistance to the competitor or the throwing implement when ambient pressure decreases is the possible cause of the performance improvement<sup>25</sup>. The three exceptions are shot put, javelin throw and discus throw. Competitor's performance in javelin throw and discus throw does not improve or even deteriorates as ambient pressure decreases (Fig. 6e, f). In fact, javelin and discus throwing are affected by aerodynamic lift<sup>25,34</sup>. The performance in shot put tends to improve as ambient pressure decreases, but the rate is small since both the implement size and throwing speed of shot put are small and thus the air resistance to the implement is weak. These are the possible reasons for the weaker relationship between ambient pressure and competitors' performance in these three events. The above results are overall consistent with those obtained by multiple linear regression analyses (Table 1). It is noticeable that the

**Fig. 2 | 100 m performance changes with ambient weather conditions for men and women, respectively.** Same as Fig. 1d–f, but for the results of (left column, a–c) men and (right column, d–f) women competitors, respectively.



**Fig. 3 | 100 m performance changes with ambient weather conditions for boreal summer.** a–d Same as Fig. 1a, d–f, respectively, but only using the results obtained in boreal summer (June, July and August).



**Table 2 | Correlation between actual 100 m finishing time anomalies and the predicted ones with various weather variables by random forest method (regression)**

Predictor variables	Mixed-Sex (329)	Men (166)	Women (163)
<i>V</i>	0.51*	0.45*	0.52*
<i>T</i>	0.28*	0.16*	0.33*
<i>H</i>	0.13	-0.01	0.17*
<i>P</i>	0.15	-0.03	0.11
NAN	-0.07	-0.16	-0.09
<i>V + T</i>	0.62*	0.56*	0.64*
<i>V + H</i>	0.57*	0.48*	0.61*
<i>V + P</i>	0.53*	0.47*	0.55*
<i>V + T + H</i>	0.64*	0.55*	0.66*
<i>V + T + P</i>	0.61*	0.55*	0.62*
<i>V + P + H</i>	0.57*	0.49*	0.59*
<i>V + T + H + P</i>	0.64*	0.55*	0.64*

*V*, *T*, *H* and *P* denote tail wind speed, ambient temperature, relative humidity and atmospheric pressure anomalies, respectively. *V + T* denotes that *V* and *T* are used as predictors in the model for predicting the finishing time anomalies, and so on for the others. In all the experiments, annual-mean performance, competition round, TC, age and the sex are used as covariates. NAN denotes the experiments with only covariates. Star (\*) denotes correlation statistically significant at 5% level (two-tailed test).

relationships obtained here have large uncertainties due to the too few competitions held at moderate and high altitude (i.e., low ambient pressure conditions). For example, only 17 and 117 of the total 988 competitions of 100 m sprint were held when the ambient pressure was lower than 950 and 980 hPa, respectively. Therefore, the performance changes with ambient pressure have large confidence intervals (Fig. 6). The too few high-altitude competitions may also cause the underestimation of the performance changes associate with ambient pressure. The reason is that the most prominent impacts of altitude on the performance in athletics anaerobic events such as 100 m sprinting often occur when the altitude is higher than 1500 m (~850hPa)<sup>25</sup>.

The above results are obtained for the mixed sex. We also repeat the analysis for men and women competitors, respectively (Supplementary Figs. 5, 6). Both men and women competitors' performance monotonically increase with the rise of temperature in nearly all the 26 events except men/women's discus throw, men's javelin throw and women's long-jump. The performance improvement is obvious but not strictly monotonic for women's long jump and women's discus throw, and no obvious improvement with ambient temperature anomaly is observed for men's discus throw and men's javelin throw. These results are overall consistent with those for mixed sex competitors revealed above. Although the performance changes with ambient temperature are similar between men and women events, some differences still exist between them. For example, the performance of women's javelin throw monotonically improves with the ambient temperature rise, but that of men's javelin throw does not (Figs. 4f, 5f).

The performance-temperature relationship at the individual runner level is investigated based on multiple linear regression of competitors' performance upon meteorological elements and the round of competition for each athlete (Supplementary Table 1). Here the discus throw and javelin throw are not analyzed since their performance-temperature relationship is weak and not statistically significant based on both the multiple linear regression analysis (Table 1) and rcs-GLM (Fig. 4) at event level. The results indicate that the performance of a vast majority of the 440 athletes (80.4%) for the 11 athletics anaerobic events improves with the rise in ambient temperature. The rest 19.6% athletes have an opposite temperature-performance relationship, possibly due to the too small sample size of competitions for each athlete as well as individual differences. The average sample size of the 440 athletes is only 21.6. In order to further investigate the athletes' individual difference and its possible dependencies, the correlation

between each competitor's regression coefficient on ambient temperature and possible controlling variables is analyzed (Supplementary Table 1). The three variables include each competitor's annual mean performance, climatological-mean temperature at the capital of the competitor's country and age. The correlations are mostly not stable and statistically insignificant for each of the three variables. For example, two of the five significant correlations with annual-mean performance are negative, while the other three are positive. Therefore, these variables are not among the significant controlling factors for the individual difference; further exploration is warranted.

**Thermodynamic mechanisms**

Here we explore for the mechanism for the relation of competitors' performance with ambient temperature in the anaerobic events. The equation of state for dry air is  $P = \rho RT$ , where *P* is the atmosphere pressure, *R* is the gas constant for dry air ( $R = 287 \text{ J kg}^{-1} \text{ K}^{-1}$ ),  $\rho$  is the air density and *T* is the atmosphere temperature<sup>36</sup>. In the moist air, *T* is replaced with virtual temperature ( $T_v = T(1 + 0.378e/P)$ ). Since the difference between *T<sub>v</sub>* and *T* is very small, the moist air is usually regarded as the dry air when using the equation of state. This equation suggests that both the decrease in atmosphere pressure and the increase in air temperature can reduce the air density.

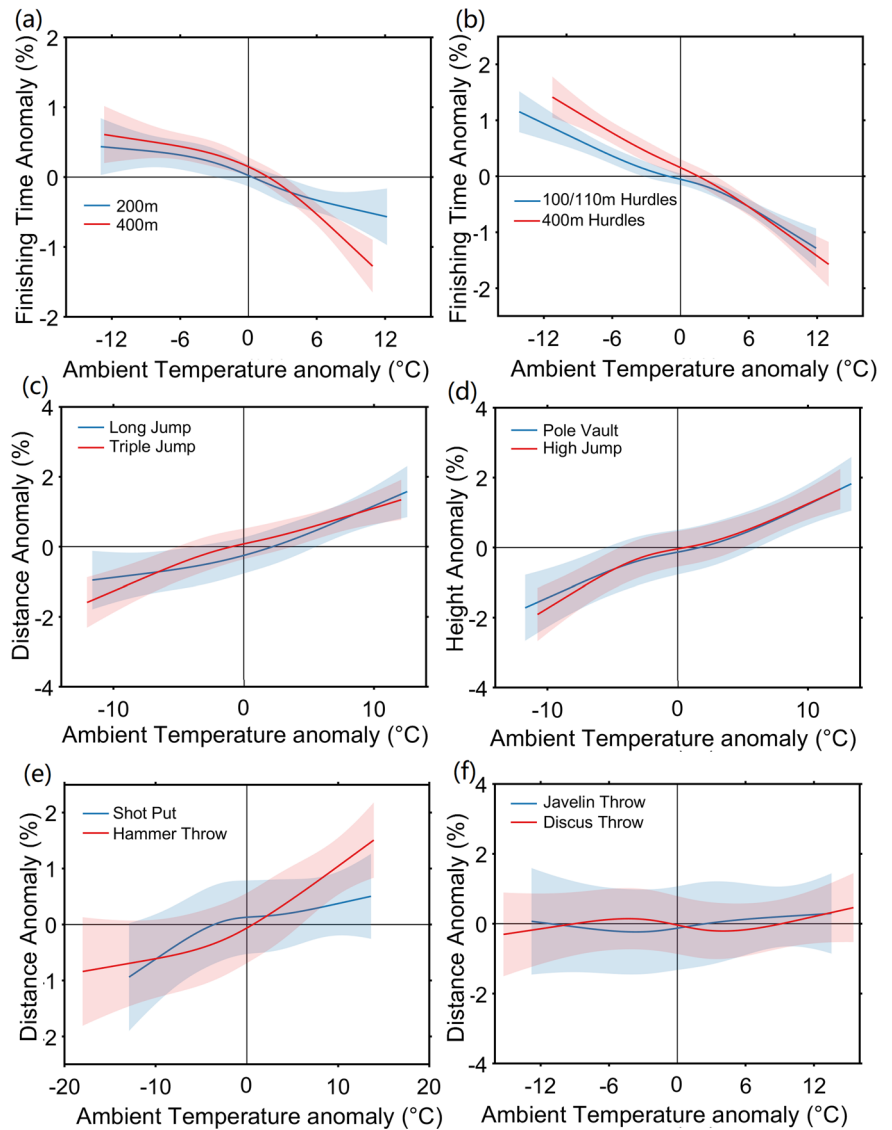
As revealed in Section "Methods", competitors' performance in 10 of the 13 athletics anaerobic events improves with the ambient pressure decreasing. The decreased atmospheric pressure reduces the air density and thus weakens the air resistance to the competitors or throwing implements, which assists the competitors to perform better in these events. The rise in air temperature also results in the decreased air density through expanding the air and thus reduces the air resistance as the decreasing in ambient pressure does, which assists the competitors to perform better in these events. The exception is the shot put, javelin throw and discus throw<sup>25</sup>. Competitors' performance in javelin throw and discus throw does not increase or even deteriorates with the decreasing in ambient pressure, while the improving rate for shot put is small. Thus, the rise in ambient temperature can not improve or even harm the competitors' performance in these events through expanding the air. This is consistent with the much weaker changes in competitor's performance with ambient temperature rise in these three events than in the rest events (Fig. 4).

This mechanism is further quantitatively investigated as follows. In relative to the International Standard Atmosphere, 1 °C increase in air temperature can cause 0.37% decrease in air density based on the equation of state for dry air. This change will further reduce the air resistance by 0.37%<sup>24</sup>.

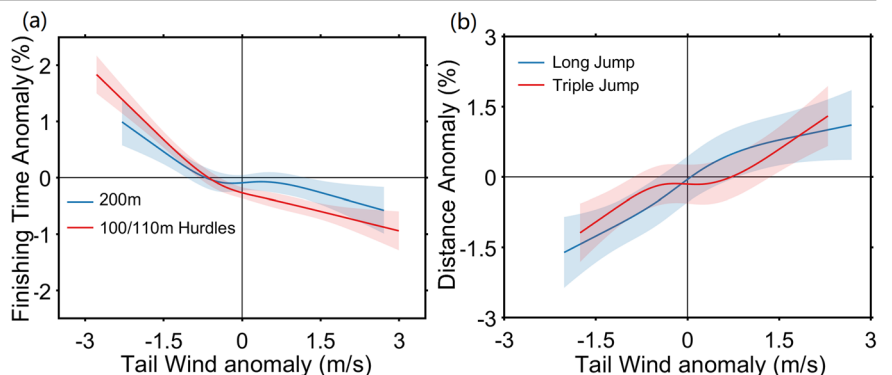
The changes in competitors' performance caused by the 0.37% reduction in air resistance can be estimated with three methods. We take the 100 m sprinting for instance. The first method is based on the relationship of competitors' performance with the tail/heading wind speed. When the tail/heading wind speed increases by 1 m/s, the air resistance to a 100 m competitor at 9.39 m/s (the mean speed of all the 988 competition results) is reduced by about 21.3% based on the quadratic relationship between wind speed and air resistance. Figure 1d shows that the 1 m/s increase in tail/heading wind speed can result in 0.074 s improvement in the 100 m sprint performance in average. Based on these results, we can infer that 0.37% decrease in air resistance associated with 1 °C increase in air temperature can cause about 0.0013 s improvement in 100 m sprint performance, accounting for about 13% of total 0.0101 s. This proportion may be underestimated because the runners tend to alter their posture to reduce the air resistance if the heading wind speed is large<sup>37</sup>.

The second method is based on the extra energy cost due to the air resistance and relationship between the total energy cost and running speed reported in the literature. The relationship between the total energy coast and running speed is approximately linear, as proposed by<sup>38</sup>. The air resistance coasts about 7.8% of the total energy when sprinting at 10 m/s<sup>37</sup>. The 0.37% decrease in air resistance associated with 1 °C increase in air temperature can thus save the 0.029% of the total energy cost for running.

**Fig. 4 | Weather–performance relationship for the rest 12 athletics events.** a–f Relation of finishing time, height or distance anomaly (%) with ambient temperature anomaly for the rest 12 athletics events. The curves in each panel show the relationships obtained using rcs-GLM. The shadings denote the 95% confidence intervals for the relationships shown with the curves of the same color.



**Fig. 5 | Relation of competitors’ performances with tail wind anomaly for the 4 athletics events.** a, b Same as Fig. 4 but for the relation of finishing time or distance anomalies with tail wind speed anomaly.

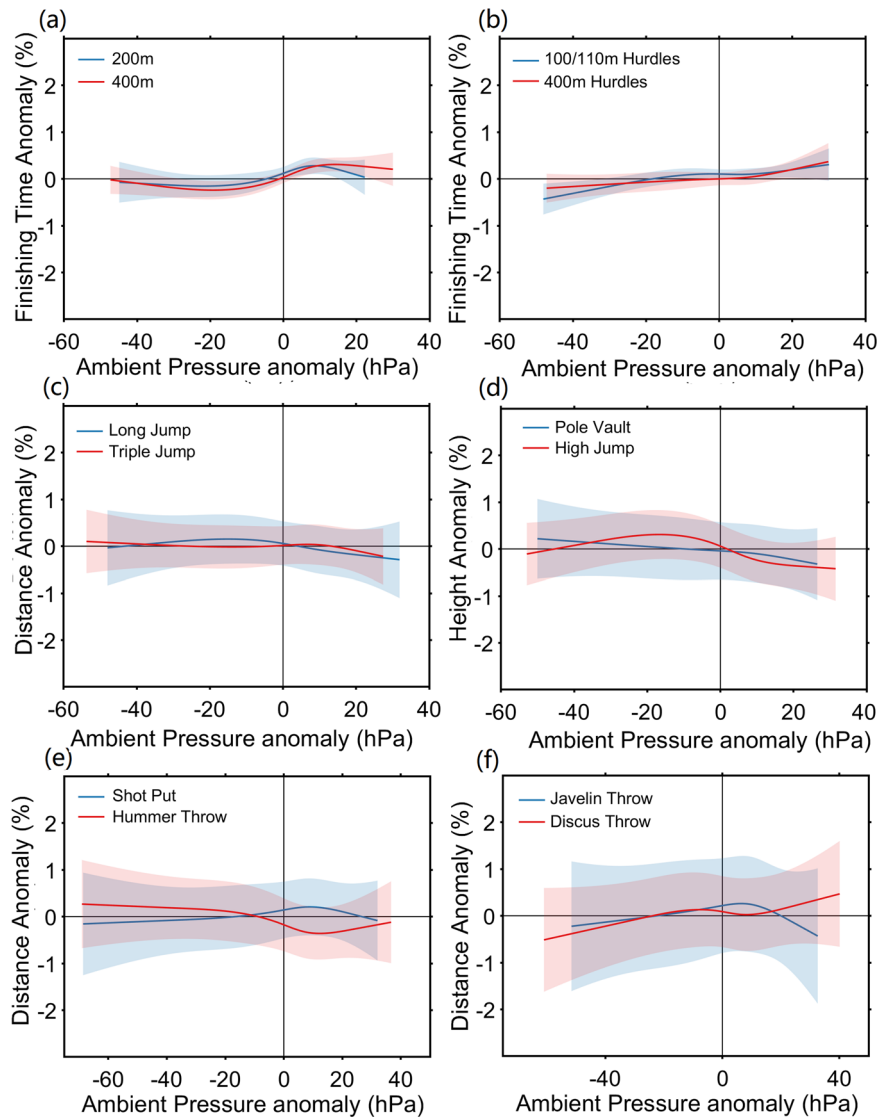


The saved energy can be used for increasing the running speed by about 0.029% or 0.0031 s during the 100 m sprinting, accounting for about 31% of the total 0.0101 s improvement of 100 m sprint performance.

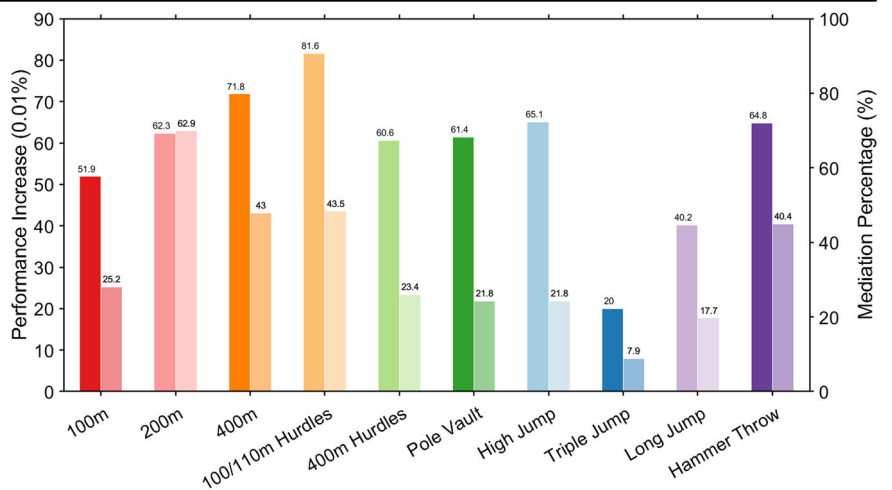
The third is based on the impact of ambient atmosphere pressure on sprinting speed. As proposed by Peronnet et al. (1990) theoretically, 100 m performance improves by 0.096 s as altitude rises by 1000 m. According to

the International Standard Atmosphere, 1000 m rise in altitude is associated with 114.2 hPa decrease in pressure, which reduces air density by 11.9% according to the equation of state for dry air. However, air temperature decreases by 6.5 K as altitude rises by 1000 m, which is associated with 2.3% increase in air density. Thus, 19.1% of the air density reduction associated with pressure decrease is offset by the air shrink due to the atmospheric cooling

**Fig. 6 | Relation of competitors' performances with ambient pressure anomaly for the 12 athletics events. a–f** Same as Fig. 4 but for the relation of finishing time, height or distance anomalies with ambient atmospheric pressure anomaly.



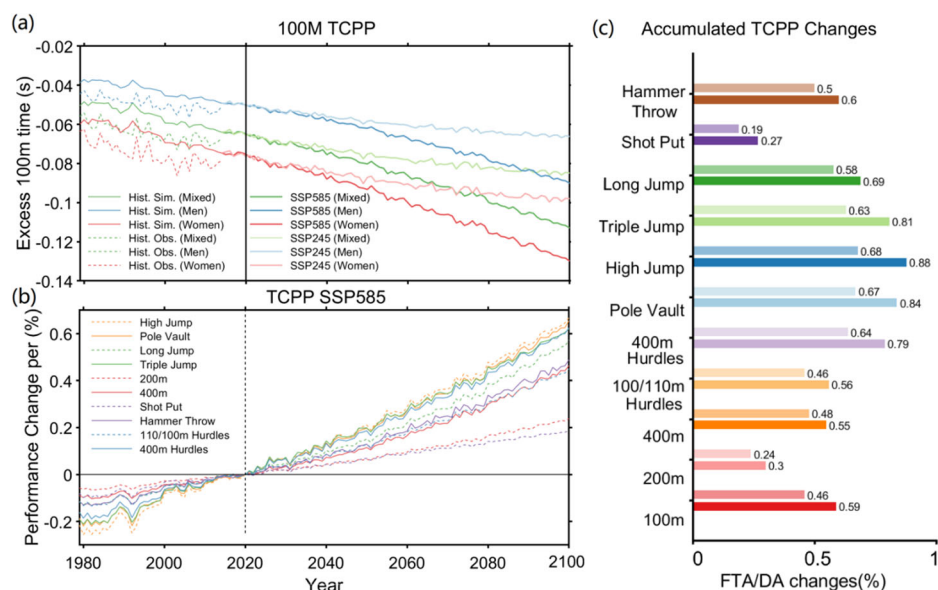
**Fig. 7 | Left bar for each event: percentage of performance improvement associated with 100 hPa decrease in ambient atmosphere pressure (unit: 0.01%). Right bar for each event: the proportion of the impacts of the ambient temperature rise on competitors' performance improvement that is taking effect through expanding the air and reducing air resistance to competitors or throwing implements (unit: 1.0%).**



with the altitude rise. The net air density decrease associated with 1000 m rise in altitude (equivalent to 114.2 hPa decrease in pressure) is 9.7%, causing 9.7% reduction in the air resistance to the 100 m runner. Based on these results, we can infer that the 0.37% decrease in air resistance associated with 1 °C increase

in ambient temperature can improve the 100 m performance by 0.0037 s. This improvement accounts for about 36% of the total 0.0101 s °C<sup>-1</sup>. If using the performance change with ambient pressure obtained in the present study (about 0.055 s per 100hPa, Fig. 1e), the proportion is estimated to be 24%. This





**Fig. 8 | Global TCPP changes of athletics anaerobic events due to warming climate.** **a** TCPP of 100 m sprinting calculated game by game before averaging over all the games throughout the world. Here TCPP is shown in relative to that at 15 °C for visual purpose. We assume that all the games over 2019–2021 will be held in each year over 1979–2100 with no change in positions, dates and events. The Hist. Sim. and Hist. Obs. denote the TCPP over 1979–2014 calculated based on the bias-corrected CMIP6 historical climate simulations and the GHCN CAMS monthly observations, respectively. The future projections are based on the CMIP6 projections under two future scenarios (SSP245 and SSP585)<sup>40</sup> for 2015–2100. **b** Global

mixed-sex TCPP changes of the other 10 athletics events based on CMIP6 historical (1979–2014) climate simulations and future (2015–2100) projections under the scenario of SSP585. The TCPP changes are shown as the anomaly percentage to those during 2019–2021 and the results for 200 m, 400 m, 400 m hurdles and 110/100 m hurdles are reversed for visual purpose. **c** TCPP improvements (percentage) over 2014–2100 and 1979–2100 under SSP585 for the 11 events shown in Panel (a) and (b). The upper and lower bars for each event denote the improvement during 2014–2100 and 1979–2100, respectively. The TCPP changes during 1979–2014 are based on CMIP6 historical climate simulations.

is smaller than the 36% based on the theoretical relationship, which may be due to the underestimation of the performance changes with ambient pressure due to too few high-altitude results.

The results of the three methods all indicate that a substantial proportion of the performance improvement of 100 m sprinting associated with ambient temperature rise is through the warming-induced air expanding and the resultant air resistance reduction.

The mechanisms are also investigated quantitatively for the rest 9 events based on the competitors’ performance changes with ambient pressure (Fig. 6) using the third method introduced above. The results also show that a substantial proportion of the performance improvement associated with the rise in ambient temperature takes effect through expanding air and thus reducing air resistance for these events (Fig. 7), which is similar to the mechanism for the 100 m sprinting. The proportion is estimated to be 31% based on the mean of the 9 events and ranges from 7.9% (triple jump) to 62.9% (200 m sprinting). The rest portion of the impact may be through other processes including physiological processes. For example, the rise in ambient temperature may increase the muscle, core or brain temperature and thus improve competitors’ performance in the athletics anaerobic events. It is noticeable that the proportion mediated by the air expanding is probably underestimated for these events due to too few high-altitude results as that for 100 m. Therefore, this thermodynamic process is almost as essential as other factors including physiological processes for inducing the relation of the competitors’ performance changes with ambient temperature in these events.

### Future projections under the warming climate

Considering the considerable impacts of weather conditions on the athletics performance, we further investigate competitors’ performance changes in these athletics events attributable to climate change. Among the four analyzed meteorological variables, wind speed plays the most important role in modulating competitors’ performances in 100 m, 110/100 m hurdles, 200 m, long jump and triple jump. However, the angle between ambient wind and running/jumping direction is highly random and the global-scale

net effect of wind is near-zero. Temperature plays the second and the first most important role in these five and the rest six events, respectively. The climate change in global-scale relative humidity is very small in both the past and the future<sup>4,39</sup>, and global-scale atmospheric pressure keeps constant since the global-total atmosphere mass is almost constant. Moreover, relative humidity and atmospheric pressure play less important role in modulating the performance compared to ambient temperature. Thus, air temperature dominates the changes in top competitors’ potential performance (TCPP) in athletics anaerobic events attributable to climate change. Temperature in bias-corrected CMIP6 global datasets provided from the Earth’s historical and future climate (1979–2100)<sup>40</sup> simulations and GHCN CAMS monthly 2-m land surface air temperature datasets are used to evaluate TCPP changes. We interpolate the gridded temperature into the positions of the analyzed games before calculating TCPP. The temperature-performance relationships of each event shown in Figs. 1 and 4 are used for calculating TCPP.

Figure 8a shows the global-mean TCPP for 100 m sprinting during 1979–2100 that is estimated by assuming that all the games and their holding dates during 2019–2021 keep unchanged in each year of 1979–2100. We also assume that human physiology and thus the performance-weather relationship keep unchanged during 1979–2100. These assumptions are following the conventions of existing studies, in which measures to adapt to the warming climate and the relationships for the impacts of ambient weather conditions will keep unchanged. During 1979–2014, men, women and mixed-sex TCPPs based on CMIP6 historical simulations all show long-term improvements that are in good agreement with those based on the observations (i.e., CAMS data), although the former is slightly greater. This confirms the reliability of the CMIP6 datasets in estimating long-term TCPP changes. The warming climate improved mixed-sex, men and women TCPP in 100 m sprinting by 0.014 s, 0.11 s and 0.15 s, respectively, during 1979–2014 (CMIP6 dataset). The future TCPPs all show continuous improvement for men, women and mixed-sex competitors over the whole period of 2014–2100 under both the medium (SSP245) and high (SSP585) emission scenarios. Under the SSP585, the

TCPP will improve by 0.049 s, 0.041 s and 0.055 s during 2014–2100 for mixed-sex, men and women competitors, respectively.

These improvements are non-ignorable given that the gold-medal winner was often only <0.049 s faster than the silver-medal winner in the 100 m sprinting of Olympic games and World Athletics Championships (e.g. the 2021 Summer Olympics and the 2022 World Athletics Championships). In fact, most of the new world record settings in recent decades only improved the 100 m world record by <0.049 s. The mixed-sex, men and women TCPPs will improve by 0.021 s, 0.17 s and 0.23 s, respectively, during 2014–2100 under SSP245, which is smaller but still non-ignorable. These results indicate that human beings can substantially benefit from the warming climate to run faster, though the warming climate has almost always been blamed to negatively impact human beings.

Figure 8b shows impacts of the warming climate on global-mean TCPP of the other 10 athletics events calculated with the same procedures as that of 100 m sprinting under SSP585. Here TCPP changes in javelin throw and discus throw are not analyzed due to their weak temperature-performance relationship (Fig. 4). The warming climate continuously improves the TCPP of all the 10 events over 1979–2100, although the improving rate shows a wide spread among these events. The TCPP improvement during 2014–2100 ranges from 0.19% (shot put) to 0.68% (high jump), while that of 100 m sprinting is 0.46%, ranking ninth among the 11 events (Fig. 8c). If considering the whole period of 1979–2100, the TCPP improvement ranges from 0.27% (shot put) to 0.88% (high jump), while the TCPP of 100 m sprinting improves by 0.59%, ranking 7th among the 11 events. Similar TCPP improvements can be found under the SSP245 scenario (Supplementary Fig. 7), although the improving rate is overall smaller than that under SSP585. Therefore, the warming climate can potentially improve competitors' performances in overwhelming majority (11 of 13) of athletics anaerobic events despite of the various forms of these events. In other words, the warming climate will assist human beings not only to run faster, but also to jump further/higher and throw farther through expanding air and reducing the air resistance to the competitors or the implements.

In fact, these athletics anaerobic events share the same aerodynamic processes (air resistance) and muscle metabolism processes (e.g. anaerobic processes) with a large quantity of non-athletics sports (e.g., rock climbing and cycling track) and even some non-sport human activities (e.g., weight carrying and step climbing). Thus, the revelation of the present study implies that the changing climate will possibly also assist human beings to perform better in various other sports and even certain daily life and labor activities, assuming that human physiology keeps unchanged.

## Discussions

Via looking at world-top competitors instead of certain games, the present study reveals that the performance of nearly all athletics anaerobic events monotonically improves as ambient temperature rises. This change counters our intuition and is quite distinctive from other human activities and public health burdens, which were conventionally recognized to be harmed by the increasing temperature at least when temperature is high. Mechanism analysis shows that the rise in ambient temperature can improve the competitors' performance through expanding the air and thus reducing the air resistance to the competitors or the throwing implements in these events. Quantitative analysis estimates that a substantial proportion (about 31%) of the total competitors' performance improvement associated with ambient temperature rise is through this mechanism. Further analysis shows that the warming climate helps improve competitors' performance in athletics anaerobic events, which is distinct from the widely-revealed harm that the warming climate has done and will continue to do on human beings. This means that human beings can run faster, jump further/higher and even throw farther with the assist of global warming. Similar positive impacts of increased temperature and the warming climate may also exist extensively in many non-athletics sports and even non-sport human activities since the aerodynamic processes and anaerobic capacity involve a variety of sports and other human activities. However, this does not indicate that it is unnecessary to commit to the active mitigation of greenhouse gas emission.

In fact, this kind of benefit brought by global warming is rare and it can far from offset the extensive harm done by the climate change to other sports, public health burdens and human activities. Thus, global community should still insist on controlling greenhouse gas emission, while a more comprehensive assessment of both the positive and negative impacts of anthropogenic climate change on human beings is urgent to better adapt to the changing climate.

## Methods

### Data of competition results

In the Olympic Games and World Athletics Championships, 43 individual athletics events are held currently (excluding 4 relay events); 26 of them are anaerobic. They are six sprints (men/women 100 m, 200 m and 400 m), four hurdles (women 100 m hurdles, men 110 m hurdles and men/women 400 m hurdles), eight throws (men/women javelin throw, shot put, discus throw and hammer throw) and 8 jumps (men/women long jump, triple jump, pole vault and high jump). The competition results of all the current world-top 20 competitors for each of the 26 events over 2019–2021 are used in the present study. The original competition results (finishing time for sprints and hurdles, height for high jumps and pole vault and distance for long jump and high jump) are obtained from the world athletics official website (<https://worldathletics.org>). For 100 m, 200 m, 100 m hurdles, 110 m hurdles, long jump and triple jump, wind speeds were observed in the Track-and-Field stadium when competition was going on, which are obtained along with the competition results from the world athletics official website. In these events, only competition results with valid wind observations are extracted. The rounds of competitions, the nationalities and the ages of athletes are also acquired along with the competition results. In order to reduce uncertainties caused by incidents (e.g., getting injury in competition), the poorest 1% performance results are removed for each of the 26 events, respectively.

### Weather observations

Temperature, relative humidity and atmospheric pressure for each result are derived from the observations at adjacent weather stations based on the Integrated Surface Data (ISD). Summary of the events, the athletes and meteorological variables for each event that will be analyzed in the present study is shown in Supplementary Table 2. The averages of weather variables (temperature, dew point, atmospheric pressure) during 9:00–22:00 at the nearest adjacent weather stations (ISD datasets) on the day when each competition result was obtained are used to represent the weather condition of this result. If any of the three weather variables on the day is invalid (with <2 valid values), data at the second nearest station was used instead. If they are still invalid, this competition result is dismissed. The period of 9:00–22:00 is selected because athletics anaerobic events are usually held in this time range. In fact, exact times of these results are mostly not publicly available since a competition usually has many rounds and trials. Moreover, the averaged hour-to-hour variances of weather conditions over 9:00–22:00 are much smaller (e.g., ~8.7–12.9% for temperatures of the 13 events) than the average variances among different competitions held in different days and places (Supplementary Fig. 1). Hence errors caused by ignoring hour-to-hour variances of the weather conditions are acceptable. Relative humidity  $f$  (%) is calculated as follows:

$$f = \frac{e_a}{E} \times 100\%, \quad (2)$$

where saturated vapor pressure  $E$  (hPa) and actual vapor pressure  $e_a$  (hPa) are derived from observed air temperature  $t$  (°C) and dew point  $t_0$  (°C), respectively, via the Magnus formula with respect to water as follows<sup>41</sup>:

$$E = 6.1094e^{\frac{17.625t}{t+243.04}}, \quad (3)$$

$$e_a = 6.1094e^{\frac{17.625t_0}{t_0+243.04}}. \quad (4)$$

The land surface atmospheric pressure ( $p_{ls}$ , hPa) is calculated from sea level pressure ( $p_{sl}$ , hPa), land surface altitude ( $H$ , m) and air temperature derived from the original data in the ISD datasets as follows:

$$p_{ls} = p_{sl} \left( 1 + \frac{\gamma H}{t + 273.15} \right)^{-\frac{g}{\gamma R}}, \quad (5)$$

where  $g$  is the gravitational acceleration ( $9.8 \text{ m s}^{-2}$ ),  $R$  is the gas constant for dry air ( $287.053 \text{ J K}^{-1} \text{ kg}^{-1}$ ),  $\gamma$  is the environmental lapse rate. Here  $\gamma$  is set as  $6.5 \text{ }^\circ\text{C km}^{-1}$ , i.e., the global average value of  $\gamma$ . This formula is deduced based on an ideal model atmosphere in hydrostatic balance that has the constant  $\gamma$  as given in the following equations:

$$\begin{cases} \frac{dp}{dz} = -\frac{gp}{RT} = -\frac{gp}{R(T_0 - \gamma z)} \\ p|_{z=0} = p_{sl} \\ t = T|_{z=H} = T_0 - \gamma H \end{cases}, \quad (6)$$

where  $p$  is the atmospheric pressure,  $z$  is the altitude,  $T_0$  is the atmosphere temperature at sea level, and  $T$  is the atmospheric temperature in the ideal model atmosphere.

### Other covariates

Nationality can play a role in the competitors' performance due to athletes' acclimatization to different climates. For example, an athlete accustomed to high temperature might perform better in a hot weather condition than the one accustomed to low temperature. In order to investigate this effect, the climatology of annual-mean temperature in the capital of each competitor's country is obtained from GHCN CAMS monthly 2-m land surface air temperature datasets.

Different rounds of a competition might influence the performance of athletes. For instance, 100 m runners in the final round may perform better compared to the preliminary round. We set the preliminary, semi-final/qualifying-final and final round as round 1, 2 and 3, respectively, to quantitatively analyze the effect of the competition round on competitors' performance.

The level of individual athletes may also influence the relationship between weather conditions and their performance since top runners may have different performance patterns compared to non-world class runners. In order to characterize the level of an athlete of an event, the athlete's annual-mean performance (finishing time or distance) in this event is used.

### Anomalies of athletes' performance and other variables

To remove the competition level differences among competitors and among years, we subtract annual-average height, distance or finishing time of each competitor from original results of this competitor year by year to obtain distance/height anomalies or finishing time anomalies. If only one valid competition result exists in a year for a competitor, this result will be removed. Correspondingly, ambient temperature, tail wind speed, atmospheric pressure and relative humidity anomalies are calculated to keep consistency. After these processes, the sample size of competition results with valid meteorological variables for each event is summarized in Supplementary Table 2.

### Data availability

The athletes' performance data are obtained from the world athletics official website <https://worldathletics.org>. The near surface weather observations are provided by ISD datasets at <https://www.ncei.noaa.gov/data/global-hourly/access>. The climate change projection data under SSP245 and SSP585 emission scenarios are available at <https://www.scidb.cn/en/detail?dataSetId=791587189614968832&dataSetType=personal>.

### Code availability

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

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### References

- Harvell, C. D. et al. Climate warming and disease risks for terrestrial and marine biota. *Science* **296**, 2158–2162 (2002).
- Rocklöv, J. & Dubrow, R. Climate change: An enduring challenge for vector-borne disease prevention and control. *Nat. Immunol.* **21**, 479–483 (2020).
- Yang, J. et al. Projecting heat-related excess mortality under climate change scenarios in China. *Nat. Commun.* **12**, 1–11 (2021).
- Li, J. et al. Elevated increases in human-perceived temperature under climate warming. *Nat. Clim. Change* **8**, 43–47 (2018).
- 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).
- Vicedo-Cabrera, A. M. et al. The burden of heat-related mortality attributable to recent human-induced climate change. *Nat. Clim. Change* **11**, 492–500 (2021).
- Cissé, G. et al. Health, wellbeing, and the changing structure of communities. *Clim. Chang.* **2022**, 1041–1170 (2022).
- Staddon, P. L., Montgomery, H. E. & Depledge, M. H. Climate warming will not decrease winter mortality. *Nat. Clim. Change* **4**, 190–194 (2014).
- Nikolaïdis, 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. Env. Res. Public Health* **16**, 614 (2019).
- Ely, M. R. et al. Impact of weather on marathon-running performance. *Med. Sci. Sports Exerc.* **39**, 487–493 (2007).
- Ely, M. R. et al. Effect of ambient temperature on marathon pacing is dependent on runner ability. *Med Sci. Sports Exerc* **40**, 1675–80 (2008).
- Vihma, T. Effects of weather on the performance of marathon runners. *Int. J. Biometeorol.* **54**, 297–306 (2010).
- Montain, S. J., Ely, M. R. & Chevront, S. N. Marathon performance in thermally stressing conditions. *Sports Med.* **37**, 320–323 (2007).
- Gasparetto, T. & Nessler, C. Diverse effects of thermal conditions on performance of marathon runners. *Front. Psychol.* **11**, 1438 (2020).
- 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).
- Nybo, L. et al. Football facing a future with global warming: perspectives for players health and performance. *Br J Sports Med.* **55**, 297–298 (2021).
- Smith, K. R. et al. The last Summer Olympics? Climate change, health, and work outdoors. *Lancet* **388**, 642–644 (2016).
- Ward-Smith, A. J. A mathematical analysis of the influence of adverse and favourable winds on sprinting. *J. Biomech.* **18**, 351–357 (1985).
- Ward-Smith, A. J. New insights into the effect of wind assistance on sprinting performance. *J. Sports Sci.* **17**, 325–334 (1999).
- Egoyan, A. & Khipashvili, I. On the influence of air resistance and wind during long jump. *Gen. Sci. J.* <https://www.gsjournal.net/Science-Journals/Research%20Papers/View/4541> (2013).
- Haugen, T. & Buchheit, M. Sprint running performance monitoring: Methodological and practical consideration. *Sports Med.* **46**, 641–656 (2016).
- Moinat, M., Fabius, O. & Emanuel, K. Data-driven quantification of the effect of wind on athletics performance. *Eur. J. Sport Sci.* **18**, 1185–1190 (2018).
- Dapena, J. & Feltner, M. E. Effects of wind and altitude on the times of 100-meter sprint races. *J. Appl. Biomech.* **3**, 6–39 (1987).

24. Peronnet, F., Thibault, G. & Cousineau, D. A theoretical analysis of the effect of altitude on running performance. *J. Appl. Physiol.* **70**, 399–404 (1991).
25. Hamlin, M. J., Hopkins, W. G. & Hollings, S. C. Effects of altitude on performance of elite track-and-field athletes. *Int. J. Sports Physiol. Perform.* **10**, 881–887 (2015).
26. Guy, J. H. et al. Adaptation to hot environmental conditions: an exploration of the performance basis, procedures and future directions to optimise opportunities for elite athletes. *Sports Med.* **45**, 303–311 (2015).
27. Girard, O., Brocherie, F. & Bishop, D. Sprint performance under heat stress: A review. *Scand. J. Med. Sci. Sports* **25**, 79–89 (2015).
28. Shi, Y. et al. Effects of multiple indoor environmental factors on anaerobic exercise performance. *J. Therm. Biol.* **108**, 103280 (2022).
29. Uyanik, G. K. & Güler, N. A study on multiple linear regression analysis. *Proc. Soc. Behav. Sci.* **106**, 234–240 (2013).
30. Ely, M. R., Cheuvront, 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).
31. Lv, M., Hou Z. & Zhou, Y., *Dynamic Meteorology*. China Meteorological Press (2004).
32. Everingham, Y. et al. Accurate prediction of sugarcane yield using a random forest algorithm. *Agron. Sustain. Dev.* **36**, 1–9 (2016).
33. Morriss, C. & Bartlett, R. Biomechanical factors critical for performance in the men's javelin throw. *Sports Med.* **21**, 438–446 (1996).
34. Bartlett, R. M. The biomechanics of the discus throw: A review. *J. Sports Sci.* **10**, 467–510 (1992).
35. Di Napoli, C. et al. ERA5-HEAT: A global gridded historical dataset of human thermal comfort indices from climate reanalysis. *Geosci. Data J.* **8**, 2–10 (2021).
36. Holton, J. R. An introduction to dynamic meteorology. *Am. J. Phys.* **41**, 752–754 (1973).
37. Davies, C. Effects of wind assistance and resistance on the forward motion of a runner. *J. Appl. Physiol.* **48**, 702–709 (1980).
38. Pugh, L. G. C. E. Oxygen intake in track and treadmill running with observations on the effect of air resistance. *J. Physiol.* **207**, 823–835 (1970).
39. Willett, K. M. et al. Attribution of observed surface humidity changes to human influence. *Nature* **449**, 710–712 (2007).
40. Xu, Z. et al. A bias-corrected CMIP6 global dataset for dynamical downscaling of future climate, 1979–2100. *Sci. Data.* **8**, 293 (2021).
41. Huang, J. A simple accurate formula for calculating saturation vapor pressure of water and ice. *J. Appl. Meteorol. Clim.* **57**, 1265–1272 (2018).

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## Author contributions

Shixin Wang designed the research, performed the analysis and wrote the draft. Jingjia Luo supervised the project and revised the manuscript. Chaoxia Yuan and Toshio Yamagata revised the manuscript. All authors contributed to the interpretation of the results and the writing of the paper.

## Competing interests

All authors declare no competing interests.

## Additional information

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