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Study of the relationships between weather conditions and the marathon race, and of meteorotropic effects on distance runners

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Abstract. The relationships between the results of Beijing International Marathon Races and the corresponding weather conditions are analysed quantitatively. There are obvious interrelationships between the marathon results and weather factors such as air temperature, wet bulb temperature and human biometeorological indices. For example, the correlation coefficient between the average times of the top ten finishers and temperature is $r = 0.8910$. The meteorological conditions are classified into three categories, suitable, moderate and unsuitable for running a marathon race, and the optimum meteorological index is given. Also the concept of a meteorological result, i.e. the part of the actual performances fluctuating with the changes in weather conditions, is presented. This plays an important role in some kinds of sports such as marathon racing. Finally, the results of physiological tests are given, which illustrate the physiological reactions of long- and middle-distance runners to the surrounding temperature.

Key words: Marathon – Weather conditions – Correlation analysis – Exercise physiology

Introduction

The performances of marathon runners are closely related to weather conditions. Some marathon experts suggest that the range of most suitable air temperatures for the race is 8–15° C, and above this threshold the results will worsen by 1 min for each degree of temperature rise. The American Sports Medicine Society proposes that the highest temperature limit for long-distance running is 82.4° F (28° C; Pugh et al. 1967). Weather factors other than air temperature are also associated with the marathon results. This study sets out to investigate the effect and extent of these factors on the marathon results, whether athletes with a certain exercise load are more sensitive to air temperature, and also their physiological reactions to air temperature.

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Materials and methods

Definition of meteorological result. The results of sporting competitions are affected by many elements and the mechanism of their interrelationships is complex. Through the history of the development of athletic sports, it can be seen that results increase gradually with the improvement of athletes' quality, training level, and the training and contesting conditions. This aspect of the results is referred to as the technical or tendency result. On the whole, the technical result is stable, increases regularly with time and occupies a large proportion of the actual result. Some random factors, such as unhealed wounds, and unsuitable adjustment before competition, also affect the results but are not considered here. The remaining part of the actual result is assumed in this paper to be completely influenced by weather conditions and is referred to as the meteorological result. Although the meteorological result comprises only a small part of the whole race result, it is unstable, varies considera-

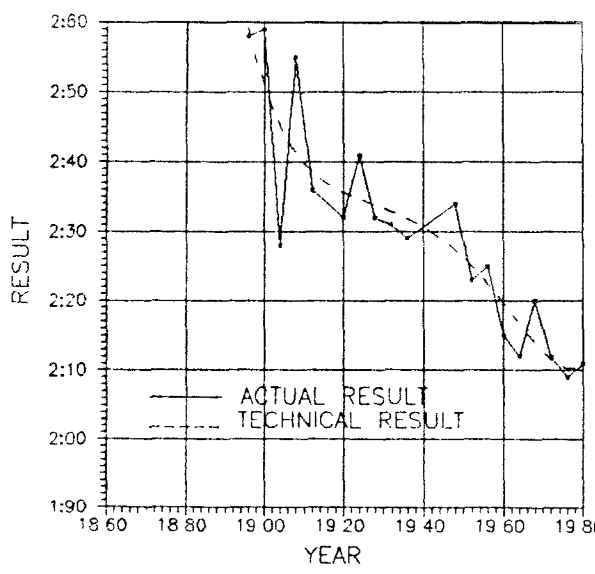

Fig. 1. The performances of marathon champions in Olympic Marathons from 1896 to 1980 (from Humphreys and Holman 1983)

Table 1a. Regions of origin for the top 30 finishers of the Beijing International Marathon

	1981	1982	1983	1984	1985	1986	1987	1988	1989
East Asia	19	11	21	21	18	15	18	17	18
Australia/New Zealand	0	0	1	1	1	1	2	1	1
East Africa	1	0	0	1	3	4	5	4	4
Europe	6	16	7	5	8	10	5	8	6
North America	4	3	1	2	0	0	0	0	0
South America	0	0	0	0	0	0	0	0	1

Table 1b. Statistics of the participating countries[a]

JPN	TAN	PRK	USA	POL	DEN	GBR	SWE	ETH	NZL	BEL	KEN	ITA
9,55	9,19	8,29	8,21	7,17	6,16	6,15	6,6	5,12	5,11	5,10	5,8	4,12
HUN	HKG	AUS	FRG	SUI	IRE	URS	FRA	HOL	ESP	CAN	FIN	MEX
4,10	4,9	4,5	4,5	4,4	4,4	3,9	3,8	3,5	3,5	3,4	3,3	2,2
COL	NOR	LES	KOR	ECU	NEP	SIN	GRE	PHI	POR	CHN		
2,2	1,1	1,1	1,1	1,1	1,1	1,1	1,1	1,1	1,1	9,2001		

[a] The first figure indicates the number of times each country has participated, followed by the number of individuals participating

JPN, Japan; TAN, Tanzania; PRK, D.P.R. Korea; USA, United States; POL, Poland; DEN, Denmark, GBR, Great Britain; SWE, Sweden; ETH, Ethiopia; NZL, New Zealand; BEL, Belgium; KEN, Kenya; ITA, Italy; HUN, Hungary; HKG, Hongkong; AUS, Australia; FRG, F.R. Germany; SUI, Switzerland; IRE, Ireland; URS, Soviet Union; FRA, France; HOL, the Netherlands; ESP, Spain; CAN, Canada; FIN, Finland; MEX, Mexico; COL, Colombia; NOR, Norway; LES, Lesotho; KOR, Korea; ECU, Ecuador; NEP, Nepal; SIN, Singapore; GRE, Greece; PHI, the Philippines; POR, Portugal; CHN, China

bly with the weather conditions, and under certain circumstances plays an important role in the competitions.

Thus the actual result can be divided into three parts, the technical result, the meteorological result and random error expressed as

$$Y = Yt + Ym + \Delta Y$$

where Y = actual result, Yt = technical result, Ym = meteorological result and ΔY = random error. Figure 1 shows the actual performances gained by the winners in each Olympic Marathon from 1896 to 1980, compared to the corresponding tendency or technical results obtained by the polynomial method. The former varies considerably from one race to the next, while the latter varies according to the performances achieved by the runners finishing first in each race, and has fallen gradually with time since 1896. The difference between the two results is the meteorological result.

Source of the data. The Beijing International Marathon has been run continuously since 1981 and on the same course of 42.195 km (26.2 miles). Held always in the autumn, the finest season of the year in Beijing, it draws more and more marathon runners from the rest of the world. The statistics of the regions and countries involved in the last nine Beijing International Marathons are listed in Table 1a and b. The data used in the analyses are mainly obtained from the lists and programmes of the Beijing International Marathon Races held from 1981 to 1989. Other information was supplied by China's State Sport Committee and the Beijing Weather Service. In order to obtain the value of Ym, an orthogonal polynomial simulation was used to approximate the actual performance variation curve. The curve obtained represents the technical result which, is then subtracted from the actual times; thus the meteorological result can be written as:

$$Ym = Y - Yt.$$

Our research focuses on the relationships between the meteorological result and the weather conditions. Three-hour urinary samples of distance runners were tested before and after training. The amount and intensity of training by the subjects and their fluid consumption were kept constant.

Correlation analysis. Weather factors considered were: air temperature (ta), relative humidity (RH), wet bulb temperature (tw), and

Table 2. Values of weather factors

Year	ta (°C)	RH (%)	v (m/s)	tw (°C)	DI (°C)	Ko (kcal/m^2 per h)	ET (°C)	ETv (°C)	Hw (mcal/cm^2 per s)
1981	13	51	4	10	57	529	14	7	43
1982	15	27	7	7	56	538	14	5	62
1983	29	24	2	16	73	88	23	22	23
1984	18	57	2	13	63	318	17	13	24
1985	21	35	1	12	65	223	18	17	20
1986	8	84	1	7	51	482	8	4	26
1987	15	44	4	9	58	487	14	7	45
1988	19	56	1	14	64	272	17	15	20
1989	13	29	5	6	55	545	12	5	41

ta, Air temperature; RH, relative humidity; v, wind velocity; tw wet bulb temperature; DI, Discomfort Index; Ko, Windchill Index, ET, Effective Temperature; Hw, Wet Cooling Power

Table 3. Actual times of Beijing International Marathon Races from 1981 to 1989

Year	$\overline{Y}$t	$\overline{Y}$10	2:20 (n)	2:30 (n)	2:20 (%)	2:30 (%)
1981	2:35′39″	2:17′21″	9	20	14.75	23.81
1982	2:36′30″	2:17′07″	14	44	10.22	22.56
1983	2:41′04″	2:23′47″	1	11	1.67	6.21
1984	2:40′31″	2:16′06″	14	43	7.41	17.20
1985	2:39′19″	2:13′53″	19	44	10.05	18.80
1986	2:36′32″	2:10′54″	46	86	16.61	19.48
1987	2:40′04″	2:13′31″	26	53	10.24	16.16
1988	2:41′12″	2:12′21″	18	45	6.84	15.00
1989	2:41′39″	2:15′40″	14	28	7.25	14.51

$\overline{Y}$t, total average times (in hours, min and s);
$\overline{Y}$10, average times of the 10 frontrunners (in h, min and s);
2:20 (n), number of finishers arriving within 2 h 20 min;
2:30 (n), number of finishers arriving within 2 h 30 min;
2:20 (%), percentage of 2:20 (n);
2:30 (%), percentage of 2:30 (n)

Table 4. Correlation coefficients (R) between meteorological factors and the meteorological results of Beijing International Marathon Races from 1981 to 1989[a]

	ta	RH	tw	v	DI	Ko	Hw	ET	ETv
$\bar{Y}$t[b]	0.51	−0.12	0.73	−0.50	0.60	−0.59	−0.55	0.61	0.61
$\bar{Y}$10	0.89	−0.56	0.76	−0.22	0.87	−0.76	−0.35	0.83	0.80
2:20 (%)	−0.93	0.67	−0.88	0.19	−0.94	0.77	0.34	−0.95	−0.87
2:30 (%)	−0.83	0.37	−0.78	0.39	−0.79	0.80	0.49	−0.77	−0.79

[a] $R_{0.05}=0.71$, $R_{0.001}=0.92$
[b] $\bar{Y}$t, $\bar{Y}$10, 2:20 (%) and 2:30 (%) are as defined in the footnote to Table 3

wind velocity (v). Man's actual thermal sensations depend not only on single weather factors, but also on combinations of factors. For instance, people feel colder on a windy, wet day than on a calm, dry day even if the air temperature remains the same. Therefore biometeorological indices are used, such as the Discomfort Index, DI (Thom 1957), Windchill Index, Ko (Siple and Passel 1945), Effective Temperature, ET and ETv taking wind velocity into account for the calculation of ET (Missenard 1937) and Wet Cooling Power, Hw (Lehmann 1936). The corresponding formulae are:

$$\mathrm{DI}=0.72\,(ta+tw)+40.6$$
$$\mathrm{Ko}=((100v)^{1/2}+10.45-v)(33-ta)$$
$$\mathrm{ET}=ta-0.4(ta-10)(1-RH/100)$$
$$\mathrm{ET}v=37-(37-ta)/[0.68-0.0014RH+1/(1.76+1.4v^{0.75})]$$
$$-0.29ta(1-RH/100)$$
$$\mathrm{Hw}=(0.37+0.51v^{0.63})(36.5-tw)$$

where ta, tw, DI, ET, ETv are in °C, RH in %, v in m/s, Ko in kcal/m^2 per h and Hw in mcal/cm^2 per s. DI is defined for warm conditions. Ko shows that the velocity of air movement affects the rate of heat exchange between the skin surface and the ambient air. The values of those weather factors for 1981–1989 are presented in Table 2.

The actual performances are classified into six groups as shown in Table 3. The corresponding meteorological result was obtained as the orthogonal polynomial analogue. The correlation coefficients between the meteorological results and weather factors are presented in Table 4.

Results

Air temperature

The correlation between the air temperature and the average marathon results was statistically significant (Table 4). It appears that the correlation is more significant at better finishing times, e.g. $|R2{:}20(\%)|>|R2{:}30(\%)|>|R\bar{Y}t|$. This reveals that the more intensive is the performance, the more sensitive is the runner to changes of air temperature. The anti-correlation, e.g. $R2{:}20(\%)<0$ means that fewer athletes reach the finishing line within 2 h 20 min in higher air temperature. Such effect can be seen more clearly in Table 5: in 1983 the average time of the first ten finishers was worse than their registered result, whereas in 1986 it was much better.

Table 5. Comparison between 1983 and 1986

	Registered time	Actual race time	Difference	Temperature (°C)
$\bar{Y}$10 in 1983	2:13′57″	2:23′47″	−9′50″	29.0
$\bar{Y}$10 in 1986	2:12′02″	2:10′53″	1′09″	8.2
Difference	1′55″	12′54″	10′59″	20.8

$\bar{Y}$10, Average time of the first 10 runners (in h, min and s)

Humidity

As we can see from Table 4, tw is more closely related to the meteorological result compared with RH. Similar to the correlations to air temperature, the ranking of correlation coefficients for tw is $|R2{:}20(\%)|>|R2{:}30(\%)|>|R\bar{Y}t|, R\bar{Y}t>0$ and $R2{:}20(\%)<0$. It is also noted that the interrelation between $\bar{Y}$t and tw is most closely correlated with success for all of the participants ($R=0.73$). Trapasso and Cooper (1989) proposed that dry bulb temperature and relative humidity are not the best variables for explaining extremes in marathon performances. However, our research shows a similar result only for relative humidity. The correlation coefficients between the results of the marathon and relative humidity are relatively small. It is suggested that the correlation with the marathon results is similar for both air temperature and wet bulb temperature (Table 4); only in extreme conditions of air temperature conditions does man's reaction to the changes in humidity become remarkable. This aspect will be further discussed in the following paragraph.

Evaporation of perspiration becomes difficult in wet conditions. Actually, only when air temperature is rather high or low does the effect of humidity on man's heat

Table 6. Variation of effective temperature, ET, in different ta and RH[a]

ta (°C)	ET at RH in %		
	80	50	20
−20	−17.6	−14.0	−10.4
−10	− 8.4	− 6.0	− 3.6
0	0.8	2.0	3.2
10	10.0	10.0	10.0
20	19.2	18.0	16.8
30	28.4	26.0	23.6
40	37.6	34.0	30.4
50	46.8	42.0	37.2

[a] From Hentschel (1986)
ta, Air temperature; RH, relative humidity

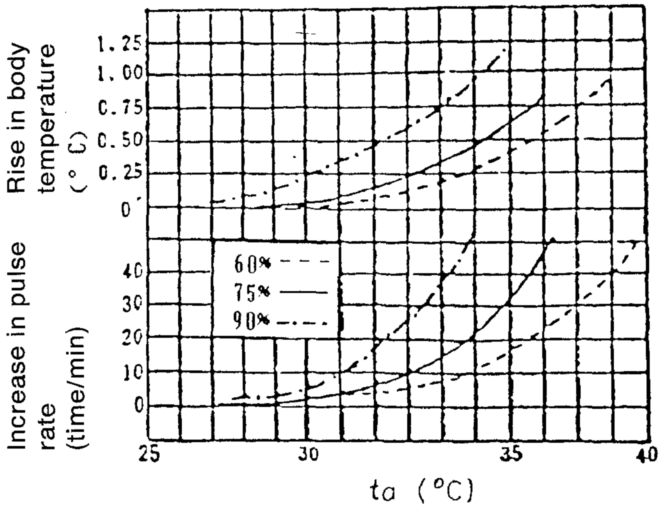

Fig. 2. Influence of relative humidity on body temperature and pulse rate (from Shanghai First Medical College 1981)

balance become important. It can be seen from Table 6 that at relative humidities of 20%–80%, effective temperature, ET, remains the same when the air temperature is 10° C. When air temperature is in either of the extremes (hot and cold), the variation of ET with humidity is as large as the difference between the values at air temperatures differing by several degrees, even if air temperature remains the same. Figure 2 illustrates the combined effect of air temperature and humidity on the human body. When the air temperature is not very high, e.g. $<28°$ C, the impact of relative humidity on body temperature and pulse rate is small. Considering the intensive exercise of marathon performers, the reaction of the human body to the environment will be much stronger and the threshold values of air temperature should decrease. With a rise in air temperature, one's body temperature increases and one's pulse rate quickens, effects that become more significant under conditions of high humidity. According to the laws of exercise physiology, long and intensive activity is likely to cause an ascent of body temperature and a loss of body fluids. After a marathon, body temperature may rise as high as 39° C; the loss of body fluid can be as high as 5% of the body weight (Humphreys and Holman 1983). However a 5.2% loss of body weight caused by dehydration may lead to a 25% decrease in plasma volume under hot conditions (Astrand and Saltin 1964), thus leading to the exhaustion of the whole system. If a marathon race is held under such circumstances, the results are seriously affected due to the rapid fall of muscular endurance and illness, such as heat stroke, is likely to occur.

Wind

Winds can produce favourable or unfavourable effects: moderate wind improves evaporation and convection. Usually the marathon race takes a circular route and wind resistance can be ignored, except in circumstances where there is a strong wind. Furthermore, a light breeze stimulates the nervous system so that runners get excited and are likely to be in good form. Since there were generally no strong winds during the Beijing International Marathon Races between 1981 and 1989, the coefficients show that the effect of wind is conducive to better performances, e.g. $R\bar{Y}t<0$ (Table 4). It is possible for the athlete to compete better if wind effects are taken into account when tactics and techniques are designed.

Biometeorological index

Five human biometeorological indices are used here (see Table 2 and foregoing text). Larger absolute values of correlation coefficients between the marathon results and the biometeorological indices (Table 4) illustrate that the indices are in general better indicators of marathon performances than single meteorological elements. This suggests that using biometeorological indices is a more effective predictor of meteorotropic effects on human beings. From Table 4, the effect of wind is seen to be relatively small, but when combined with other meteorological elements the effect becomes greater, e.g. Ko.

Classification

As discussed above, the marathon results are closely related with weather conditions, but little indication is gained of the kind of environment that provides the most suitable conditions for the marathon. A classification for outdoor conditions was made by Hentschel (1986), who found that ET is the most suitable indicator taking

Table 7. Comprehensive classification by 12° to 6°-ET-steps

ET (°C)	Description of man's sensation	
	Heavy	
30° C		hot
	Moderate	
24° C		
	Warm	
		pleasant
	Mild	
12° C		
	Cool	
6° C		cool
	Very cool	
0° C		
− 6° C		cold
−12° C		
−18° C		very cold
−24° C		
	Beginning	
−30° C		danger of frostbite
	Increasing	

[a] From Hentschel (1986)

Table 8. Classification

	Classification according to weather parameters						Classification according to 2:20 (%)	
	ta	*tw*	DI	Ko	ET	ET*v*		
Suitable							the first class	
1981	13.0	9.5	57	529	14	7	1981	14.75
1982	15.0	7.0	56	538	13	5	1982	10.22
1986	8.2	6.9	52	482	8	4	1986	16.61
1987	14.8	8.9	58	488	14	7	1987	10.24
1989	13.4	6.0	55	545	12	5	1985	10.05
Moderate							the second class	
1984	18.0	12.9	63	318	17	13	1984	7.41
1985	21.0	12.4	65	223	18	17	1989	7.25
1988	19.0	13.8	64	272	17	15	1988	6.84
Unsuitable							the third class	
1983	29.0	16.0	73	88	23	28	1983	1.67

For explanation of abbreviations used see the footnote to Table 2

into account the heat and sultriness load under hot conditions and the wind-chill under cold conditions. The range of effective temperatures between $ET \geq 12$ and 24° C provides "pleasant" outdoor conditions for recreation, tourism and human life in general (Table 7). Whether or not such conditions are effective for marathon races is evaluated from the results presented in Table 8.

Compared with Table 7, Table 8 illustrates a different classification. At first appraisal, the classification of weather conditions seems to be in accordance with the marathon results except for 1985 and 1989. Secondly, it seems quite reasonable to suggest that the range between $ET > 8$ and 15 may be classified as "suitable" for a marathon race, the best performances are achieved in this range. A limit between "moderate" and "unsuitable" classification of weather parameters exists at about an ET of 20. At higher ET values there is an increasing danger of heat stroke or dehydration may occur and the results will surely not be as good as might be expected in advance. For example in 1983 about 100 participants failed and had to withdraw from the competition about half-way through the course.

Studies by Hentschel (1961) show that below ET 12 the prevailing sensation is "cool". Baibakova et al. (1964) suggest that the sensation of "cold" is already observed at $ET \leq 8°$ C, as experienced by the naked human body. From Table 8, this value ($ET = 8$) seems to be the optimum weather condition under which marathon runners have set the record of the Beijing International Marathon Races. In 1986 a Japanese marathon runner, Kodama Talsuke, set a record of 2:07′35″ which was the best time for the marathon race in that year and the second best time ever in the world. So man's thermal sensations given in Table 7 are not effective for marathon runners who tend to prefer much cooler conditions as in their performances. It should be pointed out that light drizzle was recorded on that day, but there was no light precipitation during any of the other races. This result is in accordance with the suggestion of Trapasso and Cooper (1989) that a light drizzle is conducive to a better performance.

Physiological reactions to air temperature

The foregoing considerations are mainly based on the relations between weather factors and the results of marathon races. It is more difficult to collect convincing results that indicate athletes' physiological reactions to changes of air temperature. A slight fall of temperature is accompanied by an increased urinary output, increased excretion of 17-ketosteroids, and a rise in pH

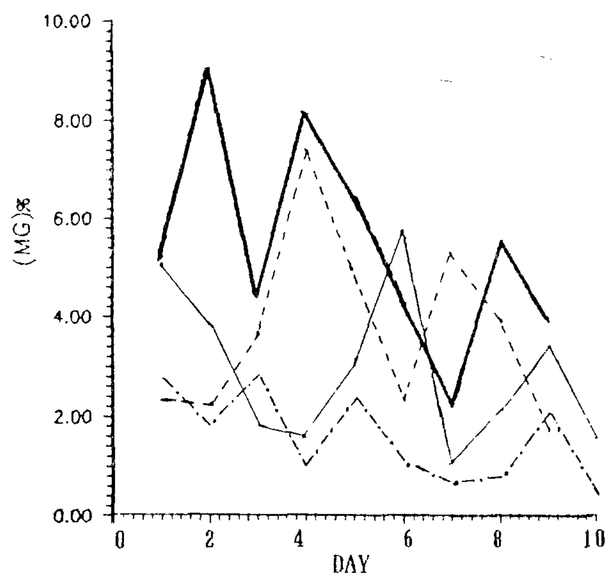

Fig. 3. Variation of 17-hydroxy-corticosterone content in urine of long- and middle-distance runners. -·- After training in summer; — before training in summer; — after training in winter; --- before training in winter

(Tromp 1980). However, these parameters refer only to healthy persons involved in everyday activities.

In this study, 3-h urinary samples from long- and middle-distance runners were tested for meteorotropic effects on well-drilled athletes. Since distance running is an aerobic endurance sport, the excretion of 17-hydroxy-corticosterone in urinary samples was measured because of its relationship to aerobic metabolism (Fig. 3). It is interesting to compare the experimental results between winter and summer, both after and before training. On the one hand, in winter the excretion of 17-hydroxy-corticosterone increases after training, whereas in summer training causes a reverse effect although the amount and intensity of training was the same. Statistical testing of the hypothesis indicated that both of the trends are significant. On the other hand before training, few changes are observed in the quantity of excretion even though large differences of air temperature exist between winter and summer. After training, the excretion of 17-hydroxy-corticosterone is much greater in winter than in summer. It seems reasonable to suggest that the subjects have adapted themselves to the surrounding environment during a gradual seasonal change, but such a suggestion does not explain the considerable differences of 17-hydroxy-corticosteroid excretion occurring after training.

According to physiological concepts, the amount and intensity of exercise influences the excretion of corticosteroids: relatively heavy work loads can stimulate the excretion (Bunyatyan and Erez 1972), while slight or moderate work loads will not (Korenskaya 1967). In our research, the changes in the excretion of hormones in relation to energy supplementation are connected with both training load and ambient temperature. Thus, the athletes are more sensitive to the surrounding environment when they are giving a performance. The measurement of the urinary hormone level also gives a physiological explanation why more significant correlation coefficients are found for the best ten results of marathon races.

Conclusions

a. Marathon performances are easily influenced by weather conditions and, therefore, the concept of a meteorological result is proposed in this research. Other sports such as long- and middle-distance running, cycling etc., which are also closely related to outside weather conditions, can also be studied in this way.

b. Both wet bulb temperature and air temperature are good indicators of marathon performances. However using human biometeorological indices to analyse the effect of the weather on athletic performance is a more effective predictor.

c. Marathon performances are affected by many weather elements. Selecting the appropriate weather parameters is necessary for a correct evaluation of an athlete's performance level and for health protection, recovery and adjustment after competition, adaptive training, and the application of techniques and tactics.

d. Our physiological experiment shows that changes in the urinary excretion of 17-hydroxy-corticosteroid are related to air temperature and training load. It should be pointed that the excretion of corticosteroids is influenced by many elements, such as age, sex, emotion, and health conditions. In this study the subjects were all male distance runners, in good health and about 20 years old; however, only air temperature was taken into consideration as affecting hormone secretion levels.

e. The results of this study should be viewed with caution due to the limited size of the data set.

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