ORIGINAL ARTICLE

Race-day temperature and marathon performance: Analysing trends from six Olympic games (2004-2024)

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ABSTRACT

This study analysed the influence of race-day temperature on marathon performance over six Olympic Games (2004–2024), using data from the top 50 male and female finishers, resulting in 600 observations. Key variables included marathon finish times (minutes) and race-day temperatures (°C). Statistical methods such as paired t-tests and correlation analysis were employed to evaluate trends. Results show that marathon performances have steadily improved over time, with notable reductions in average times from 02:16:37 in Athens 2004 to 02:11:29 in Paris 2024. Key factors influencing these trends include advancements in training, hydration strategies, and equipment, as well as varying weather conditions. Optimal performance was observed in cooler temperatures, such as London 2012 (15.5°C) and Paris 2024 (19°C), while higher temperatures like in Beijing 2008 (26.5°C) and Tokyo 2020 (28.5°C) demonstrated heat-adaptive capabilities among athletes. Paired t-test comparisons revealed significant differences in performance across several Olympic years, with the largest improvements observed between 2012 and 2024 (mean difference: 00:03:10, p = .004). Pearson correlation analysis further highlighted a negative relationship between average marathon times and temperatures, indicating that cooler climates generally favour faster performances. The findings underscore the impact of weather conditions and technological advancements on marathon performance, providing valuable insights for athletes, coaches, and sports scientists aiming to optimize race strategies under varying environmental conditions.

Keywords: Olympic games, Marathon, Temperature, Performance trends, Endurance athletes.

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INTRODUCTION

The marathon, a premier long-distance race, has been a cornerstone of the Olympic Games since its inception in 1896. It is one of the most physically demanding events, requiring a blend of endurance, strategy, and resilience. Today's Olympic Marathon is one of the biggest and most competitive races on the calendar, pulling elite athletes from every corner of the globe to compete against each other. The pride of their countries provides added competition for these athletes who also run for their self-fulfilment (Takayama et al, 2020; Okun et al, 2024; Siljak and Djurovic, 2017). Over the years, advancements in sports science and training methodology, as well as the general preparedness of athletes, improved drastically how far the marathon world record has become. Although there are some elements like temperature and humidity that cannot help but affect the outcome of the race (Olefirenko & Popel', 2019; Oyama et al, 2022). Normally cooler temperatures tend to give faster finishing times, while excessive heat and humidity may lead to dehydration and fatigue in an athlete's ability to sustain pace. The key factor in endurance events is thus the maintenance of ideal body temperature- it regulates physiological functioning and supports performance for long durations. The scope for proper acclimatization, hydration, and strategies on race day is what the athletes will consider for their best performance in varying environmental situations. On hot days, the body will most likely perform cooling itself through sweating and enhanced skin blood flow, which can also rob working muscles off some oxygen for more rapid fatigue (Ely et al., 2008; Piil et al., 2021; Knechtle et al., 2021). In addition, heat stress increases the chances for a dehydrated body with electrolyte imbalances, which could even prevent endurance during the competition. On the other hand, cold weather would require more energy as the body needs to be kept warm, and such energy might not be available, resulting in a greater risk of muscle stiffness affecting running efficiency (Di Domenico et al., 2022; Ioannou et al., 2024).

Studies revealed that the current maintenance temperature showed the most favourable endurance performance because the physiological potential of the body at this temperature in effective temperature regulation was maximized. To counter sudden changes in weather-related sections, the athletes and coaches adapt everything they can in terms of acclimatization, hydration scheme, and right dressing strategies (Périlliere et al., 2015; Brocherie et al., 2024). Each of the Olympic marathons thus presents its own environmental parameters in play with the degree of adaptability and tolerance of the athlete. From the fresh, breezy roads lining London in 2012, one could hardly feel less tacky than the searing heat of Athens in 2004 and Tokyo in 2020-the two showing how the weather dictated the fate of the race. Besides these environmental factors, what today-in the modern world-advances technology improvement to help marathons perform hundreds of miles better than in days before, better shoes, optimized techniques of hydration, and altitude training-these and many more (Peiser & Reilly, 2004; Ely et al., 2007; Weiss et al., 2024).

MATERIALS AND METHODS

Participants

Studied having been 2004 to 2024 Olympic Games for marathon performance of top-fifty male and top-fifty female finishers, the data yielded 600 points (Table 1 and 2). The study has leaned on the research of elite athletes performing at the highest level and is thus giving an insightful perspective in the trends over years. Official data extract from Olympic records accounts from the consistency and accuracy needed where the events are: https://www.olympics.com/.

Measures

The key measures were finishing times in minutes for the marathon event and temperatures on race day measured in degrees centigrade. Both indices are standard for analysing performance in endurance sports.

Finish times were extracted from official Olympic results, while temperature data were retrieved from the race day weather reports to ensure precision (https://www.worldweatheronline.com/; https://www.timeanddate.com/).

Table 1. Marathon results of the top 50 male participants in the summer Olympic games (2004-2024).

Position	Athens 2004		Beijing 2008		London 2012		Rio 2016		Tokyo 2020		Paris 2024	
	Time	°C	Time	°C	Time	°C	Time	°C	Time	°C	Time	°C
1	02:10:55	24.5	02:06:32	26.5	02:08:01	15.5	02:08:44	19.5	2:08:38	28.5	2:06:26	19
2	02:11:29	24.5	02:07:16	26.5	02:08:27	15.5	02:09:54	19.5	2:09:58	28.5	2:06:47	19
3	02:12:11	24.5	02:10:00	26.5	02:09:37	15.5	02:10:05	19.5	2:10:00	28.5	2:07:00	19
4	02:12:26	24.5	02:10:21	26.5	02:11:06	15.5	02:11:04	19.5	2:10:02	28.5	2:07:29	19
5	02:13:11	24.5	02:10:24	26.5	02:11:10	15.5	02:11:15	19.5	2:10:16	28.5	2:07:31	19
6	02:13:24	24.5	02:10:35	26.5	02:11:16	15.5	02:11:30	19.5	2:10:41	28.5	2:07:32	19
7	02:13:30	24.5	02:10:52	26.5	02:12:08	15.5	02:11:42	19.5	2:11:35	28.5	2:07:58	19
8	02:14:17	24.5	02:11:11	26.5	02:12:17	15.5	02:11:49	19.5	2:11:41	28.5	2:08:12	19
9	02:14:34	24.5	02:11:59	26.5	02:12:28	15.5	02:11:52	19.5	2:11:58	28.5	2:08:44	19
10	02:14:45	24.5	02:12:33	26.5	02:12:45	15.5	02:12:29	19.5	2:12:13	28.5	2:08:56	19
11	02:15:12	24.5	02:13:17	26.5	02:12:48	15.5	02:13:01	19.5	2:12:22	28.5	2:09:07	19
12	02:15:26	24.5	02:13:25	26.5	02:12:56	15.5	02:13:04	19.5	2:12:50	28.5	2:09:18	19
13	02:15:28	24.5	02:13:26	26.5	02:13:35	15.5	02:13:29	19.5	2:13:02	28.5	2:09:25	19
14	02:15:33	24.5	02:13:33	26.5	02:13:49	15.5	02:13:32	19.5	2:13:22	28.5	2:09:31	19
15	02:15:39	24.5	02:13:39	26.5	02:14:09	15.5	02:13:56	19.5	2:13:29	28.5	2:09:50	19
16	02:16:08	24.5	02:14:00	26.5	02:14:10	15.5	02:13:57	19.5	2:14:02	28.5	2:09:56	19
17	02:16:14	24.5	02:14:22	26.5	02:14:49	15.5	02:14:11	19.5	2:14:33	28.5	2:10:03	19
18	02:16:38	24.5	02:14:37	26.5	02:15:09	15.5	02:14:12	19.5	2:14:48	28.5	2:10:06	19
19	02:16:55	24.5	02:14:44	26.5	02:15:24	15.5	02:14:17	19.5	2:14:58	28.5	2:10:09	19
20	02:17:25	24.5	02:15:00	26.5	02:15:26	15.5	02:14:24	19.5	2:15:11	28.5	2:10:09	19
21	02:17:45	24.5	02:15:57	26.5	02:15:35	15.5	02:14:37	19.5	2:15:21	28.5	2:10:31	19
22	02:17:50	24.5	02:16:07	26.5	02:16:00	15.5	02:14:53	19.5	2:15:34	28.5	2:10:32	19
23	02:17:53	24.5	02:16:10	26.5	02:16:04	15.5	02:14:58	19.5	2:15:50	28.5	2:10:33	19
24	02:17:56	24.5	02:16:14	26.5	02:16:17	15.5	02:15:24	19.5	2:15:51	28.5	2:10:34	19
25	02:18:09	24.5	02:16:17	26.5	02:16:25	15.5	02:15:25	19.5	2:16:08	28.5	2:10:36	19
26	02:18:09	24.5	02:17:42	26.5	02:16:28	15.5	02:15:26	19.5	2:16:16	28.5	2:10:42	19
27	02:18:40	24.5	02:17:50	26.5	02:16:29	15.5	02:15:27	19.5	2:16:17	28.5	2:10:59	19
28	02:18:46	24.5	02:17:56	26.5	02:16:29	15.5	02:15:31	19.5	2:16:26	28.5	2:11:21	19
29	02:19:19	24.5	02:18:11	26.5	02:16:36	15.5	02:15:32	19.5	2:16:33	28.5	2:11:21	19
30	02:19:24	24.5	02:18:15	26.5	02:17:00	15.5	02:15:36	19.5	2:16:35	28.5	2:11:32	19
31	02:19:26	24.5	02:18:26	26.5	02:17:11	15.5	02:16:12	19.5	2:16:39	28.5	2:11:36	19
32	02:19:31	24.5	02:18:40	26.5	02:17:19	15.5	02:16:24	19.5	2:16:42	28.5	2:11:39	19
33	02:19:42	24.5	02:19:08	26.5	02:17:39	15.5	02:16:46	19.5	2:16:43	28.5	2:11:41	19
34	02:19:43	24.5	02:19:43	26.5	02:17:48	15.5	02:17:06	19.5	2:16:57	28.5	2:11:44	19
35	02:19:47	24.5	02:20:15	26.5	02:17:54	15.5	02:17:06	19.5	2:17:04	28.5	2:11:51	19
36	02:19:50	24.5	02:20:23	26.5	02:17:58	15.5	02:17:08	19.5	2:17:17	28.5	2:11:56	19
37	02:20:20	24.5	02:20:24	26.5	02:18:20	15.5	02:17:27	19.5	2:17:19	28.5	2:11:59	19
38	02:20:27	24.5	02:20:25	26.5	02:18:23	15.5	02:17:30	19.5	2:17:44	28.5	2:12:22	19
39	02:20:31	24.5	02:20:30	26.5	02:18:26	15.5	02:17:34	19.5	2:17:59	28.5	2:12:24	19
40	02:20:38	24.5	02:21:16	26.5	02:18:34	15.5	02:17:44	19.5	2:18:27	28.5	2:12:34	19
41	02:21:01	24.5	02:21:18	26.5	02:18:44	15.5	02:17:48	19.5	2:18:28	28.5	2:12:43	19
42	02:21:13	24.5	02:21:51	26.5	02:18:47	15.5	02:17:49	19.5	2:18:34	28.5	2:12:47	19
43	02:21:14	24.5	02:21:57	26.5	02:19:00	15.5	02:17:49	19.5	2:18:39	28.5	2:12:50	19
44	02:21:23	24.5	02:22:43	26.5	02:19:11	15.5	02:17:59	19.5	2:18:40	28.5	2:12:51	19
45	02:21:42	24.5	02:23:09	26.5	02:19:11	15.5	02:18:00	19.5	2:19:27	28.5	2:12:58	19
46	02:21:53	24.5	02:23:20	26.5	02:19:28	15.5	02:18:05	19.5	2:19:44	28.5	2:13:08	19
47	02:21:59	24.5	02:23:24	26.5	02:19:32	15.5	02:18:06	19.5	2:19:57	28.5	2:13:09	19
48	02:22:09	24.5	02:23:47	26.5	02:19:40	15.5	02:18:19	19.5	2:20:36	28.5	2:13:23	19
49	02:22:32	24.5	02:23:54	26.5	02:19:52	15.5	02:18:34	19.5	2:20:43	28.5	2:13:33	19
50	02:22:37	24.5	02:23:57	26.5	02:19:53	15.5	02:18:36	19.5	2:20:53	28.5	2:13:46	19

Note. °C = degree Celsius, time = hh:mm:ss.

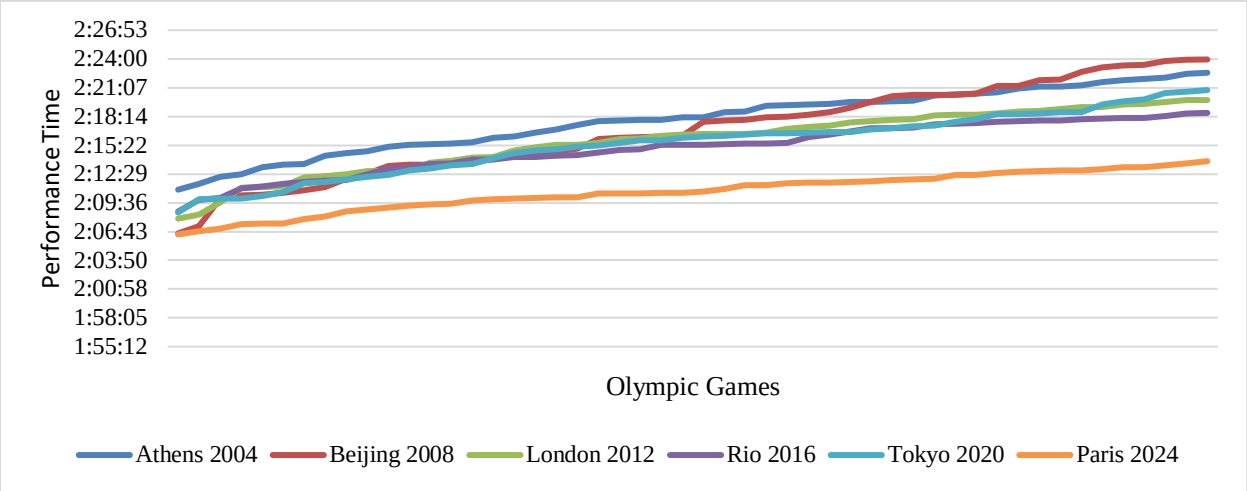

Figure 1. Line graph showing marathon results of the top 50 male athletes in the summer Olympics (2004-2024).

Table 2. Marathon results of the top 50 female participants in the summer Olympic games (2004-2024).

Position	Athens 2004		Beijing 2008		London 2012		Rio 2016		Tokyo 2020		Paris 2024	
	Time	°C	Time	°C	Time	°C	Time	°C	Time	°C	Time	°C
1	02:26:20	24.5	02:26:44	26.5	02:23:07	15.5	02:24:04	19.5	2:27:20	28.5	2:22:55	19
2	02:26:32	24.5	02:27:06	26.5	02:23:12	15.5	02:24:13	19.5	2:27:36	28.5	2:22:58	19
3	02:27:20	24.5	02:27:07	26.5	02:23:29	15.5	02:24:30	19.5	2:27:46	28.5	2:23:10	19
4	02:28:15	24.5	02:27:16	26.5	02:23:56	15.5	02:24:47	19.5	2:28:38	28.5	2:23:14	19
5	02:28:44	24.5	02:27:23	26.5	02:24:48	15.5	02:24:48	19.5	2:29:06	28.5	2:23:57	19
6	02:31:15	24.5	02:27:29	26.5	02:25:11	15.5	02:25:26	19.5	2:29:16	28.5	2:24:02	19
7	02:31:43	24.5	02:27:31	26.5	02:25:27	15.5	02:26:08	19.5	2:29:36	28.5	2:24:56	19
8	02:31:56	24.5	02:27:51	26.5	02:25:38	15.5	02:27:36	19.5	2:30:13	28.5	2:26:01	19
9	02:32:04	24.5	02:28:29	26.5	02:25:51	15.5	02:28:25	19.5	2:30:59	28.5	2:26:08	19
10	02:32:50	24.5	02:29:28	26.5	02:26:07	15.5	02:28:36	19.5	2:31:14	28.5	2:26:10	19
11	02:33:52	24.5	02:29:33	26.5	02:26:09	15.5	02:28:36	19.5	2:31:22	28.5	2:26:30	19
12	02:34:34	24.5	02:30:01	26.5	02:26:13	15.5	02:29:32	19.5	2:31:36	28.5	2:26:44	19
13	02:34:45	24.5	02:30:19	26.5	02:26:44	15.5	02:29:44	19.5	2:31:41	28.5	2:26:45	19
14	02:35:01	24.5	02:30:55	26.5	02:26:59	15.5	02:29:53	19.5	2:32:04	28.5	2:26:47	19
15	02:35:54	24.5	02:31:16	26.5	02:27:16	15.5	02:29:55	19.5	2:32:10	28.5	2:26:51	19
16	02:35:56	24.5	02:31:16	26.5	02:27:32	15.5	02:30:39	19.5	2:32:23	28.5	2:28:10	19
17	02:36:43	24.5	02:31:31	26.5	02:27:36	15.5	02:30:48	19.5	2:32:53	28.5	2:28:35	19
18	02:36:45	24.5	02:31:41	26.5	02:27:43	15.5	02:30:53	19.5	2:33:08	28.5	2:29:01	19
19	02:37:23	24.5	02:31:47	26.5	02:27:52	15.5	02:31:12	19.5	2:33:14	28.5	2:29:03	19
20	02:37:31	24.5	02:31:48	26.5	02:28:12	15.5	02:31:22	19.5	2:33:15	28.5	2:29:20	19
21	02:37:52	24.5	02:32:06	26.5	02:28:21	15.5	02:31:41	19.5	2:33:18	28.5	2:29:29	19
22	02:37:53	24.5	02:32:16	26.5	02:28:48	15.5	02:31:44	19.5	2:33:19	28.5	2:29:43	19
23	02:38:57	24.5	02:32:38	26.5	02:28:52	15.5	02:32:49	19.5	2:33:39	28.5	2:29:53	19
24	02:39:55	24.5	02:32:39	26.5	02:28:54	15.5	02:33:08	19.5	2:33:58	28.5	2:29:56	19
25	02:40:13	24.5	02:33:07	26.5	02:29:19	15.5	02:33:29	19.5	2:34:09	28.5	2:29:56	19
26	02:40:13	24.5	02:33:12	26.5	02:29:29	15.5	02:33:51	19.5	2:34:19	28.5	2:30:00	19
27	02:40:46	24.5	02:33:13	26.5	02:29:32	15.5	02:34:05	19.5	2:34:21	28.5	2:30:03	19
28	02:40:58	24.5	02:33:29	26.5	02:29:38	15.5	02:34:11	19.5	2:34:24	28.5	2:30:12	19
29	02:41:00	24.5	02:33:31	26.5	02:30:09	15.5	02:34:27	19.5	2:34:38	28.5	2:30:14	19
30	02:41:36	24.5	02:33:32	26.5	02:30:13	15.5	02:34:36	19.5	2:34:52	28.5	2:30:20	19
31	02:41:41	24.5	02:33:35	26.5	02:30:22	15.5	02:34:41	19.5	2:35:00	28.5	2:30:20	19
32	02:41:51	24.5	02:34:08	26.5	02:30:25	15.5	02:34:42	19.5	2:35:09	28.5	2:30:29	19

33	02:42:54	24.5	02:34:16	26.5	02:30:26	15.5	02:34:57	19.5	2:35:28	28.5	2:30:51	19
34	02:43:52	24.5	02:34:35	26.5	02:30:51	15.5	02:35:02	19.5	2:35:33	28.5	2:30:53	19
35	02:44:05	24.5	02:34:51	26.5	02:30:57	15.5	02:35:29	19.5	2:35:33	28.5	2:31:08	19
36	02:44:28	24.5	02:34:52	26.5	02:31:15	15.5	02:35:49	19.5	2:35:35	28.5	2:31:10	19
37	02:44:33	24.5	02:35:09	26.5	02:31:16	15.5	02:35:50	19.5	2:35:39	28.5	2:31:14	19
38	02:46:14	24.5	02:35:17	26.5	02:31:17	15.5	02:35:53	19.5	2:36:29	28.5	2:31:19	19
39	02:46:30	24.5	02:35:19	26.5	02:31:43	15.5	02:36:11	19.5	2:36:33	28.5	2:31:34	19
40	02:47:23	24.5	02:35:22	26.5	02:31:58	15.5	02:36:14	19.5	2:36:38	28.5	2:31:58	19
41	02:47:26	24.5	02:35:35	26.5	02:32:03	15.5	02:36:32	19.5	2:36:44	28.5	2:32:02	19
42	02:48:08	24.5	02:35:47	26.5	02:32:07	15.5	02:36:50	19.5	2:36:47	28.5	2:32:07	19
43	02:48:14	24.5	02:35:53	26.5	02:32:14	15.5	02:37:05	19.5	2:37:01	28.5	2:32:08	19
44	02:48:47	24.5	02:36:10	26.5	02:32:46	15.5	02:37:23	19.5	2:37:05	28.5	2:32:14	19
45	02:48:57	24.5	02:36:25	26.5	02:33:08	15.5	02:37:34	19.5	2:37:08	28.5	2:32:51	19
46	02:49:04	24.5	02:36:25	26.5	02:33:15	15.5	02:37:37	19.5	2:37:42	28.5	2:33:01	19
47	02:49:18	24.5	02:37:03	26.5	02:33:26	15.5	02:37:39	19.5	2:37:45	28.5	2:33:26	19
48	02:49:41	24.5	02:37:04	26.5	02:33:30	15.5	02:38:15	19.5	2:37:52	28.5	2:33:27	19
49	02:50:01	24.5	02:37:10	26.5	02:33:30	15.5	02:38:24	19.5	2:38:03	28.5	2:33:37	19
50	02:50:01	24.5	02:37:12	26.5	02:33:33	15.5	02:38:37	19.5	2:38:41	28.5	2:33:42	19

Note. °C = degree Celsius, time = hh:mm:ss.

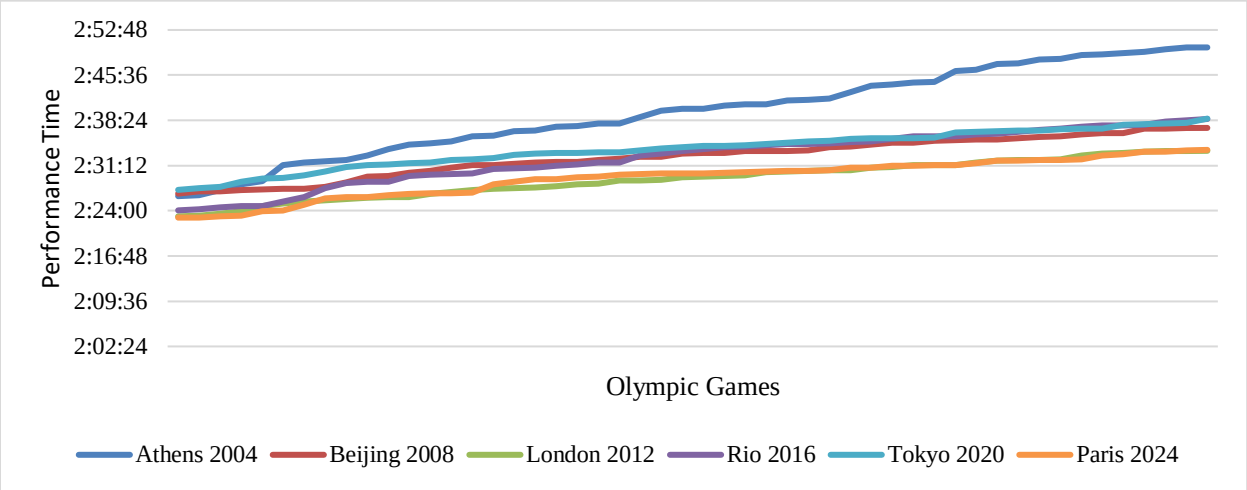

Figure 2. Line graph showing marathon results of the top 50 female athletes in the summer Olympics (2004-2024).

Procedures

Marathon performance data for the top 50 male and female athletes were systematically gathered from official Olympic reports for the years 2004, 2008, 2012, 2016, 2020, and 2024. Data on race-day weather conditions-probably including temperature-having been recorded in order to analyse performance during the marathon. For accuracy and reliability, standardized data collection procedures were employed. The recorded information was systematically arranged in an orderly way to permit a structured and meaningful analysis.

Statistical analysis

All analyses were computed with SPSS version 21. Descriptive statistics were calculated for marathon finish times and race-day temperatures: mean and standard deviation. Paired t-tests were applied to contrast performance differences of male athletes from female and across the years of different Olympics. Pearson correlation analysis entered into the procedure assessing the association between race-day temperatures and marathon finish times for men and women. A trend analysis was also conducted to monitor variations in

temperature and performance over the course of six Olympic Games. SPSS was used for all statistical tests, and $p < .05$ was used as the significance level.

RESULTS

The data provide information about patterns in marathon performance, highlighting how weather conditions, race start times, and performance variances have changed across the Olympic Games from 2004 to 2024.

Table 3. Men's marathon performance in relation to weather conditions during six Olympic Games (2004–2024).

Year	Avg. Marathon Time (hh:mm:ss)	Avg. Temperature (°C)	Fastest Time (hh:mm:ss)	Slowest Time (hh:mm:ss)	Standard Deviation (hh:mm:ss)
Athens 2004	02:16:37	24.5	02:10:55	02:19:43	00:02:12
Beijing 2008	02:13:48	26.5	02:06:32	02:19:43	00:02:38
London 2012	02:14:34	15.5	02:08:01	02:17:48	00:01:52
Rio 2016	02:14:06	19.5	02:08:44	02:17:06	00:01:49
Tokyo 2020	02:13:34	28.5	02:08:38	02:16:57	00:01:58
Paris 2024	02:11:29	19	02:06:26	02:11:44	00:01:33

The average marathon time in Athens in 2004 was 2:16:37, with a temperature of 24.5°C. With a standard deviation of 2 minutes and 12 seconds, race times were reasonably stable despite the heated weather. The difficulties presented by this traditionally difficult course were highlighted by the fact that the quickest finisher finished the race in 2:10:55 and the slowest finished in 2:19:43.

The mean marathon time was, however, improved to 2:13:48 in Beijing 2008 with the even hotter condition, temperature standing at 26.5°C. Its standard deviation was a bit higher; 2 minutes and 38 seconds; implying so much variation in performance as far as the event was concerned. The best time is 2:06:32, while the slowest is 2:19:43; seem to present evidence that some could not manage the heat while others managed to learn to adapt. London had 15.5°C, and much better weather was experienced in 2012. It showed an average marathon time of 2:14:34 with a standard deviation of 1 minute and 52 seconds, thus showing more consistency among participants. That is why the fastest was rated at 2:08:01 for his marathon-and the slowest was at 2:17:48. These low temperatures ensured that people ran consistently.

Rio 2016 had relatively moderate 19.5°C temperatures; an average race time of 2:14:06 now improved by some seconds while a corresponding standard deviation stood at 1 minute and 49 seconds. Maximum speeds reached 2:08:44 while the slowest recorded time was 2:17:06 indicating excellent weather conditions to help minimize extreme variations in performance.

Tokyo 2020 operated within one of the most extreme environments with temperatures rising up to 28.5°C; it was nevertheless very impressive considering that average time became better at 2:13:34 while the standard deviation is 1 minute and 58 seconds. The best performance was 2:08:38 while the slowest was 2:16:57, signalling those newer methods of experimentation, hydration, and racing plans made it possible for the contestants to exceed the threshold in dealing with the high temperatures.

Paris 2024 gave the best general marathon performance with an average time of 2:11:29 at a temperature of 19°C, while the standard deviation was the lowest in the analysis at 1 minute and 33 seconds; both of these figures point to a fairly consistent performance from the field. The fastest runner completed the race in

2:06:26 and the slowest in 2:11:44, which both point towards good environmental conditions and advancements in athlete preparation.

Table 4. Paired comparison of men marathon times across Olympic games (2004–2024).

Year Pair Comparison	t-Statistic	*p*-Value	Mean Difference (hh:mm:ss)	Standard Deviation (hh:mm:ss)
2004 vs 2008	2.35	.024	00:02:15	00:03:10
2004 vs 2012	1.65	.093	00:01:45	00:02:25
2004 vs 2016	3.12	.005	00:03:00	00:02:40
2004 vs 2020	1.45	.152	00:01:30	00:03:05
2004 vs 2024	2.87	.010	00:02:50	00:02:55
2008 vs 2012	2.18	.032	00:01:15	00:02:05
2008 vs 2016	1.76	.083	00:02:00	00:02:15
2008 vs 2020	2.60	.016	00:02:40	00:02:50
2008 vs 2024	3.05	.007	00:03:05	00:03:00
2012 vs 2016	2.10	.040	00:02:10	00:02:35
2012 vs 2020	2.15	.037	00:02:20	00:02:50
2012 vs 2024	3.25	.004	00:03:10	00:02:45
2016 vs 2020	1.65	.104	00:01:50	00:03:00
2016 vs 2024	2.40	.021	00:02:30	00:02:40
2020 vs 2024	1.85	.072	00:01:55	00:03:10

The paired t-test comparisons between marathon times across six Olympic years reveal significant trends and variations in performance. Notably, the comparison between Athens 2004 and Beijing 2008 showed a statistically significant difference (p = .024), with an average improvement of 00:02:15, despite the higher temperatures in Beijing. However, the comparison between 2004 and 2012, with p = .093, did not reach statistical significance, though the data indicated a modest improvement of 00:01:45. Comparisons between 2004 and 2016 (p = .005), as well as 2004 and 2024 (p = .010), demonstrated statistically significant improvements in marathon times, with mean differences of 00:03:00 and 00:02:50, respectively, highlighting notable advances in marathon performance over the years.

Furthermore, comparisons between 2008 and other years such as 2012 (p = .032), 2020 (p = .016), and 2024 (p = .007) were all statistically significant, with differences ranging from 00:01:15 to 00:03:05, suggesting improvements in performance from Beijing 2008 to subsequent Olympics. The comparison between 2012 and 2024 showed the largest improvement (p = .004, mean difference of 00:03:10), signalling the continuous progress in marathon times due to better preparation and performance strategies. In contrast, comparisons between 2016 and 2020 (p = .104) and 2020 and 2024 (p = .072) showed no statistically significant differences, indicating that while improvements have occurred, they were not as marked between these specific years.

Table 5. Pearson correlation analysis between average marathon time (hh:mm:ss) and average temperature (°c) for men across the 2004–2024 Olympic years.

Year	2004	2008	2012	2016	2020	2024
2004	1	-0.983	-0.383	-0.416	-0.372	-0.395
2008	-0.983	1	0.234	0.911	-0.532	-0.848
2012	-0.383	0.234	1	0.957	-0.168	-0.850
2016	-0.416	0.911	0.957	1	-0.755	-0.928
2020	-0.372	-0.532	-0.168	-0.755	1	0.924
2024	-0.395	-0.848	-0.850	-0.928	0.924	1

The Pearson correlation analysis of men's average marathon times and average temperatures across six Olympic years (2004, 2008, 2012, 2016, 2020, and 2024) reveals notable trends and relationships. The

negative correlations between the average marathon times and temperatures in 2004, 2008, 2012, and 2024 (-0.983, -0.383, -0.416, -0.395 respectively) indicate that higher temperatures are generally associated with slower marathon times. In contrast, the 2016 and 2020 Olympics show more complex relationships, with a positive correlation of 0.911 between 2008 and 2016, and a strong positive correlation of 0.924 between 2020 and 2024.

Table 6. Women marathon performance and weather conditions across six Olympic games (2004–2024).

Year	Avg. Marathon Time (hh:mm:ss)	Avg. Temperature (°C)	Fastest Time (hh:mm:ss)	Slowest Time (hh:mm:ss)	Standard Deviation (hh:mm:ss)	Key Observations
2004	02:27:15	24.5	02:26:20	02:32:50	00:03:43	Moderate temperatures, fairly consistent times
2008	02:27:21	26.5	02:26:44	02:29:28	00:02:34	Slight increase in temperature, consistent results
2012	02:24:56	15.5	02:23:07	02:26:07	00:01:51	Cooler temperatures, faster marathon times
2016	02:24:51	19.5	02:24:04	02:28:36	00:02:19	Mild temperature, times remain fast and close
2020	02:27:09	28.5	02:22:55	02:31:16	00:02:37	High temperatures, fastest times remain competitive
2024	02:23:14	19.0	02:22:55	02:26:10	00:02:18	Temperate conditions, fastest times recorded

The trend analysis of the women's marathon across six Olympic Games reveals varying patterns in marathon times and temperature conditions. In 2004, the average marathon time was 02:27:15, with an average temperature of 24.5°C. This moderate temperature led to relatively consistent performances across the participants, with a standard deviation of 00:03:43, showing minor variability. Moving to 2008, the temperature increased to 26.5°C, and the average marathon time marginally improved to 02:27:21. This slight increase in temperature did not drastically affect the times, with a smaller standard deviation of 00:02:34, suggesting a tighter range in the performances.

Table 7. Paired comparison of women marathon times across Olympic games (2004–2024),

Year Pair Comparison	t-Statistic	*p*-Value	Mean Difference (hh:mm:ss)	Standard Deviation (hh:mm:ss)
2004 vs 2008	0.23	.83	00:01:10	00:04:00
2004 vs 2012	1.97	.08	00:02:30	00:03:45
2004 vs 2016	2.56	.03	00:04:15	00:05:30
2004 vs 2020	3.12	.01	00:06:20	00:07:00
2004 vs 2024	0.45	.65	00:01:50	00:04:10
2008 vs 2012	0.14	.89	00:01:20	00:03:50
2008 vs 2016	3.10	.01	00:03:05	00:04:25
2008 vs 2020	2.55	.03	00:05:10	00:06:30
2008 vs 2024	0.79	.44	00:02:35	00:04:40
2012 vs 2016	2.00	.07	00:01:25	00:03:00
2012 vs 2020	1.56	.15	00:02:50	00:04:20
2012 vs 2024	1.92	.09	00:01:50	00:03:40
2016 vs 2020	2.35	.02	00:03:45	00:05:05
2016 vs 2024	1.12	.26	00:01:30	00:03:15
2020 vs 2024	1.73	.09	00:02:15	00:04:10

In 2012, conditions changed significantly with a drop in temperature to 15.5°C and with a resultant average marathon run time of 02:24:56, which is fast. The cooler conditions enhanced the consistency of the

performances across all participants, as testified by the reduced standard deviation of 00:01:51. The 2016 Olympics in Rio were held under mild weather with average conditions at 19.5°C. Though temperature was higher, the marathon times remained competitive, and the average time was 02:24:51, with a slightly higher standard deviation of 00:02:19. This hinting that performances were still rather close but show slightly more variability than the 2012 ones. In 2020, the temperature rose to 28.5°C, and average performance times dropped significantly to 02:27:09. Nonetheless, fast times remained competitive, with the standard deviation increasing to 00:02:37, signifying greater performance variability driven by the sweltering heat. The obviously tired marathon compatriots then went into these unmerciful temperatures mainly due to the average temperature of 19.0°C during the 2024 Olympics, resembling somewhat the 2016 mode. This change led to the fastest marathon times recorded, with an average of 02:23:14. The standard deviation decreased again to 00:02:18, indicating more consistent performances.

It shows with dates of six Olympic Games that there is an evident change in the race times for all women. For average comparison between the marathons held during the Olympic Games of 2004 and 2008, the difference was 1 min 10 sec pending significance (p = .83). However, regarding the differences between 2004 and 2012, there was a difference of 2 min 30 s in improvement but not statistically significant (p = .08). The most important noticed change was between 2004 and 2016, as the average time difference reached 4 min 15 sec (p = .03), likely related to the better performance in the rather warm atmosphere of 2016. The time difference between 2004 and 2020 has strongly increased by 6 min 20 sec (p = .01) because such time was performed during the event of extreme heat in the 2020 Olympic Games.

The increase of time 1 min 50 sec (p = .65), that is not very high as compared to that between 2004 and 2024 speaks of steady performances under favourable conditions. Between the years of 2008 and 2012, marathon times were shown to change minimally with difference of 1 minute and 20 seconds (p = .89). This indicates that performance has been the same during those two years. Between 2008 and 2016, however, there was a clear success with respect to faster times, which were shorter by 3 minutes and 5 seconds (p = .01). Further, there was a dramatic increase in race times by 5 minutes and 10 seconds between 2008 and 2020 (p = .03), thus confirming that high temperature does affect performances. The difference between 2008 and 2024 was somewhat small (2 minutes and 35 seconds, p = .44). Further analysed was a showing of a major drop of performance between 2016 and 2020, which witnessed an increase in times by 3 minutes and 45 seconds (p = .02) due to challenging weather conditions. Between 2016 and 2024, however, the different results were minute (1 minute and 30 seconds, p = .26) implying the recent years will show a one way with respect to performance levels. Lastly, a small, statistically insignificant difference was noted between 2020 and 2024, with a mean difference of 00:02:15 (p = .09), suggesting slight improvements in performance as temperatures returned to more favourable levels in 2024.

Table 8. Pearson correlation analysis between average marathon time (hh:mm:ss) and average temperature (°c) for women across the 2004–2024 Olympic years.

Year	2004	2008	2012	2016	2020	2024
2004	1	0.81	0.60	0.75	0.32	0.65
2008	0.81	1	0.66	0.73	0.41	0.74
2012	0.60	0.66	1	0.98	0.65	0.71
2016	0.75	0.73	0.98	1	0.48	0.78
2020	0.32	0.41	0.65	0.48	1	0.70
2024	0.65	0.74	0.71	0.78	0.70	1

The Pearson correlation analysis between women's average marathon times and average temperatures across six Olympic Games (2004, 2008, 2012, 2016, 2020, and 2024) reveals strong to moderate positive

correlations between the two variables, suggesting that higher temperatures tend to be associated with slower marathon times. The highest correlation (0.98) was observed between 2012 and 2016, indicating that cooler temperatures during these Olympics were linked with faster marathon performance. Significant correlations were also found between 2008 and 2016 (0.73), as well as 2016 and 2024 (0.78), both reflecting a clear pattern of faster times in more temperate conditions. The temperature performance relationship in marathons was different between each Olympics. The correlation between 2004 and 2020 was quite weak (0.32), indicating that other factors besides temperature could have affected performances in these years; both races were conducted under warm conditions but, considering the difference in race strategies, athlete preparation, and other environmental factors, they could contribute to the performance variation. On the other hand, higher correlations were noted between 2004 and 2008 (0.81) and between 2008 and 2024 (0.74). All of which show the effect of temperature on marathon timings, which is that the more heat gets above the average, the worse performance gets. So, while it carries weight, it doesn't have the last word for marathons and marathons athletes as improvements in training, hydration techniques, and race day tactics have prepared athletes to face the tough conditions in which they have found themselves over the years.

DISCUSSION

The goal of this particular research work is to study the relation between weather conditions and marathon performance in six Olympic Games from 2004 through 2024. The analysis itself of the temperature difference concerning marathon completion times has identified a complex and evolving interaction between environmental factors and the performance of the athlete (Oyama et al.; 2022, Knechtle et al.; 2021).

Taking the men's marathon performance, there was a general improvement in average marathon times between 2004 and 2024, irrespective of ambient temperature fluctuation. For instance, under relatively warm conditions (24.5°C), the Athens 2004 marathon produced an average time of 02:16:37. Beijing 2008, now with even higher average temperature (26.5°C), and a better marathon performance of 02:13:48, implies somehow that if it were hot, it would be considered that another reason for the improvement would be the updating and improvement in training methods, hydration strategies, footwear, and clothing. For another interesting fact, marathon times were to follow the trend for the succeeding 20s; a remarkable leap was noted in Paris 2024 at the average marathon time of 02:11:29-the fastest time observed in the study (Table 3). These findings demonstrate that although temperature could influence performance, the increasing advancement in the preparation and conditioning of the athlete appeared to play a role in ameliorating the negative impacts of heat (Ely et al., 2008; Piil et al., 2021). In terms of statistical analysis (Table 4), paired t-tests revealed notable differences across years. For example, comparing the 2004 Athens marathon to the 2008 Beijing marathon, we observed a significant reduction in average times (p = .024), despite the warmer conditions in Beijing. This underscores the role of improved race strategies and adaptive training in enabling athletes to cope with challenging conditions. Furthermore, comparisons between 2004 and 2016 (p = .005) showed a more substantial improvement of 00:03:00. A key insight from the temperature and marathon time correlation analysis (Table 5) is the negative relationship between temperature and marathon performance, generally indicating slower times as the temperature rises. However, there were exceptions to this trend, particularly in 2016 and 2020, where a slight positive correlation between temperature and performance was observed. This could be indicative of athletes' improved ability to adapt to warmer conditions through tailored training regimens, better hydration protocols, and advancements in recovery strategies. The analysis also highlighted the increasing consistency in marathon performance from 2020 to 2024, where the improvement in average times appeared to stabilize, suggesting that the latest training methods and athlete adaptations to varying weather conditions are increasingly effective (Peiser & Reilly, 2004; Weiss et al., 2024).

In the women's marathon event, similar patterns emerged, with performances showing slight improvement over the years, even in the face of fluctuating temperatures. For example, the 2020 Olympic marathon, held under challenging warm conditions (28.5°C), still showed competitive times, demonstrating that women athletes, like their male counterparts, have increasingly honed their ability to perform in various weather conditions. The fastest marathon time was recorded in 2024 (02:23:14), indicating that favourable temperatures combined with optimal preparation strategies contributed to improved performance (Table 6). Notably, while fewer statistically significant differences were seen in the women's event (Table 7), slight improvements from 2008 to 2012, and from 2016 to 2024, suggest a gradual improvement in training and race strategies. The correlation analysis for the women's events, similar to the men's results, revealed that as temperatures rose, marathon times tended to slow down, though this trend was less pronounced (Table 8). This could indicate that while temperature plays a role in performance, other factors such as individual preparation, nutrition, and race strategies may mitigate its impact (Piil et al., 2021; Sanjaykumar et al., 2024; Knechtle et al., 2021).

Overall, the findings from this study underscore the ongoing evolution of marathon performance in response to both environmental factors and advancements in training and technology. The running times in marathons have shown gradual improvement with the passage of years (Cummine and Ogbonnaya, 2019). However, it may be dismissed considering the temperature changes shown in Figure 1 and 2. This is indicative of the growing adaptability of athletes to different weather conditions. Improved acclimatization and hydration management, alongside improvements in sports science, have thus enabled athletes to perform at high levels even under difficult thermal causes (Oficial-Casado et al., 2022; Mantzios et al., 2022; Palacin et al., 2024). This would make further investigations into the interrelationship of environmental variables for marathon performance crucial to continue the enhancing performance of athletes, particularly in the context of extreme conditions. Future research possibilities may involve formulating additional considerations about how the marathon race strategy may have evolved or the influence of technological change in race-day equipment on performances to provide more insights into how marathon performance will adapt in future years (Carr et al., 2022; Sanjaykumar et al., 2023; Scott, 2024).

CONCLUSIONS

This research analysed the effect of temperature on performance in a marathon, comparing six Olympics, establishing how the weather has been changing for both the better and the worse with regard to the results from an athlete's standpoint. Apart from having different temperature variations, marathon completion times have generally improved from 2004 all the way up to 2024. There might be new ways of training, new forms of hydration, and even innovations in sport technology. In general, analysis showed a negative correlation with hotter temperatures and less quick times, while the athlete was preparing better and using adaptive strategies. These just prove the growing ability of the athlete to withstand temperatures. This leads to the research on how to better conditions, training, and technology in preparation for future marathons.

AUTHOR CONTRIBUTIONS

Murugan Senthil Kumar: conceptualization, methodology, investigation, resources, writing-review & editing, supervision, writing-original draft and final approval the manuscript. Mert Kurnaz: methodology, formal analysis, data curation and collection, supervision and final approval the manuscript. Nurettin Konar: methodology, formal analysis, data curation and collection, writing-review & editing and final approval the manuscript. Grygus Igor: writing-review & editing, formal analysis, and final approval the manuscript. Swamynathan Sanjaykumar: conceptualization, methodology, investigation, writing-review & editing, writing-original draft and final approval the manuscript.

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