Journal of High School Science

Analyzing the impact of rising temperatures on tennis performance and athlete health

Nadgir N

Submitted: May 19, 2024, Revised: version 1, July 3, 2024, version 2, July 7, 2024, version 3, July 16, 2024
Accepted: July 17, 2024

Abstract
This study investigated the effects of rising temperatures spurred by climate change on tennis performance metrics during major tournaments, such as the Australian Open and the US Open. Analyzing data on serve performance metrics—percentage of aces, percentage of double faults, and percentage of first serves won—the research identified how higher temperatures correlate with both enhanced serve power and increased error rates. Gender-specific analyses were also conducted to investigate how temperature impacted tennis performance metrics differently among male and female players. While warmer conditions were found to boost certain aspects of serve performance, they also exacerbated fatigue and increased the probability of errors during match play. Additionally, this study analyzed exhaustion in relation to temperature to assess which factor more significantly influenced performance metrics; finding that temperature was generally the more effectual factor, with some exceptions such as double faults under high exhaustion. This study highlights the trade-offs between improved serve metrics and the key impact on player performance, emphasizing the need for strategic adaptations in tournament planning and player preparation to mitigate the challenges posed by increasing global temperatures.

Keywords
Tennis performance, Global warming, Temperature, Serves, Aces, Double faults, Athlete health risks, Exhaustion, Gender-specific analysis, Tennis tournament

---

Nidhi Nadgir, Prospect High School, 18900 Prospect Rd, Saratoga, CA 95070, USA.
nidhisnadgir@gmail.com

Introduction

Climate change has escalated global concerns across various sectors, significantly impacting environmental, economic, and social structures. Among the most palpable effects is the rise in global temperature, which poses unique challenges, particularly in the realm of sports (1). Athletes competing in outdoor environments are increasingly vulnerable to the adverse effects of heat, which can impair performance and elevate health risks. The sport of tennis provides an especially relevant case study for these impacts due to its global popularity and the duration of matches, which can extend for several hours in diverse climatic conditions. Major tournaments often take place in regions known for extreme heat, including Australia and the United States, where recent tournaments have seen extreme heat conditions that challenge even the most elite athletes (2). Former world No. 1 Andre Agassi described playing in the Australian Open as akin to "playing in a giant kiln," highlighting the extreme conditions that have led to an increasing number of match suspensions and shortened games at venues like Moorabbin and Essendon in Melbourne (3). Similar challenging conditions have plagued other major tournaments; for instance, during the 2023 US Open, extreme heat and humidity forced organizers to partially close arena roofs to alleviate the oppressive conditions, with temperatures consistently soaring above 90°F and humidity exceeding 50% (4). Players like Novak Djokovic voiced their struggles, noting the intense humidity, while spectators at Wimbledon required medical attention due to unusual highs of over 89°F, illustrating the widespread impact of rising temperatures on players and fans alike across various major tennis events (5). An analysis by the Associated Press found that the average high temperatures experienced during the U.S. Open and the other three tennis grand slams have steadily risen, becoming increasingly dangerous over the decades (6). This trend mirrors the global climate changes that have led to record-breaking heat waves over the past several summers (7). The sport's major tournaments also frequently coincide with peak summer months, exposing players to intense heat and humidity.

Understanding the effects of climate change on athletic performance, particularly in high-stress sports like tennis, is crucial due to athletes being directly exposed to outdoor conditions that can vary wildly and unpredictably. The physiological demands of tennis, which require quick bursts of intense activity, prolonged endurance, and high levels of concentration, make players especially susceptible to the detrimental effects of heat (8). Studies have shown that elevated temperatures can affect a player's reaction time, reduce their muscle strength, and increase fatigue, which in turn compromises competitive performance and increases the risk of injury (9). Moreover, as global temperatures continue to rise, the frequency and intensity of extreme weather conditions are likely to increase, thereby making the need for comprehensive research into heat mitigation strategies more urgent.

The literature on the impact of climate change on sports performance, particularly in tennis, is growing but remains fragmented. Existing research, including a study by Périard et al. (2014), highlighted the acute increases in thermal, physiological, and perceptual strain that tennis players endured in hot conditions compared to cooler climates (10). Such heat stress not only causes discomfort but can also escalate to serious athletic health risks like heat cramps, exhaustion, and heat stroke (11). However, these studies frequently do not connect temperature fluctuations to precise performance metrics such as serve accuracy and match outcomes. Instead, studies primarily focus on the impact of temperature on broader athlete well-being or the impact of exhaustion on performance metrics, not directly analyzing the effect of temperature on gameplay. For instance, Smith et al. (2018) analyzed the effect of temperature on the duration of matches and injury rates but largely overlooked crucial performance metrics such as the accuracy of serves and the frequency of aces (12).

While numerous studies have investigated the impact of fatigue and exhaustion on performance metrics in tennis, they have predominantly focussed on these factors in isolation without directly comparing them to the effect of temperature. A study by Kuroda et al. (found that an increase in perceived exertion in executive functions due to exercise intensity had an inversely proportional relationship with post-exercise serve accuracy, suggesting that the fatigue associated with intense exercise could directly influence the precision required in competitive play (13). Similarly, research by Davey et al. indicated a decline in serve accuracy by 30% from the start to the testing period due to fatigue (14). However, this study's focus on players over the age of 40 rendered it non-applicable to the younger athletes typically seen in major tennis competitions. Another study by Gescheit et al. analyzed the perceptual impacts of playing multiple, consecutive tennis matches, focusing on changes in performance, recovery metrics, and player strategies to manage fatigue (15). It was found that players often altered their playing style and exertion levels to conserve energy for critical points, meaning that changes in tennis metrics could be directly related to exhaustion rather than changes in temperature. In order to fill this gap in research, it is necessary to differentiate the direct effects of temperature from the physiological responses caused by environmental temperature-independent exhaustion.

This study’s objective was to bridge this gap by conducting a comprehensive analysis of how rising temperatures influenced key performance metrics in tennis players, such as the percentage of aces, double faults, and first serves won. By examining data from major tennis tournaments under varying temperature conditions, this research sought to quantify the direct effects of heat on game playability and player endurance. This paper also aimed to extend the analysis by differentiating the direct effect of environmental temperature from the indirect effects of environmental-temperature independent exhaustion. Specifically, the study investigated whether changes in performance metrics were predominantly driven by the thermal environment itself or were a secondary consequence of player exhaustion. The methodology involved an analysis of publicly available temperature data from several renowned tennis tournaments to assess the correlation between rising temperatures and their effect on tennis gameplay. The findings from this study were visualized through advanced data representations, providing a clear depiction of the relationship between environmental conditions and tennis performance metrics.

Methods

To analyze the effect of extreme heat conditions on tennis performance and athlete health, the usage of several data visualizations was needed. Since public data was available but not previously compiled into visualizations showing these relationships, it was needed to analyze whether/how temperatures at these major tournaments were increasing, and the effect that temperature had on athletes at major tennis tournaments as a whole. Gathering this data proved challenging due to the disparate nature of sources. A significant effort was required to obtain data from an online GitHub database containing ATP/WTA records created by Jeff Sackmann, a prolific tennis analyst who authored several GMAT textbooks and contributed to media outlets including The Economist and ESPN (16, 17). After this data was compiled, it was merged and cross-validated with records from TennisExplorer to create one comprehensive dataset (18). This extensive comparison was necessary to ensure the accuracy of the results, as the data was mostly raw and required significant processing to be properly analyzed. The use of correlational methods was necessary as causation was difficult to determine, especially while maintaining external validity to the more generalized population of professional tennis players.

For analyzing the trend of temperatures at major tennis tournaments over the past few decades, extensive data from the weather website Wunderground was utilized, including records for tournaments such as the Australian Open, Wimbledon, the US Open, the Doha Open, the Dubai Open, Indian Wells, the Miami Open, the Sydney Open, the Tokyo Open, and the Washington Open (19). The selected data spanned across various locations that hosted these tournaments, specifically focusing on Melbourne, Australia, and LaGuardia, New York, due to their long historical records availability and the effect of their climatic conditions on player fatigue during the Australian and US Opens. Data was also collected for other tournament locations to provide a comprehensive overview of the global effect of heat on tennis performance.

Locations closest to the tournament venues and with the longest stretch of available data were selected. To access the data on the website, the history tab was navigated to, and the month and year of data needed were chosen. Using the temperature average column from the "Daily Observations" table at the bottom of the page, temperature data collections for each region was extracted. The data was collected for each year starting from 2000 through 2023, specifically examining the periods corresponding to each tournament, typically lasting about two weeks.

For the Australian Open, which begins in mid-January, and the US Open, which starts in early September, temperature data was utilized to develop two key metrics for each year of the tournaments: the average daily temperatures during the event and the number of days exceeding designated heat thresholds—100°F for the Australian Open and 85°F for the US Open. The difference in heat cutoff metrics between the Australian Open and U.S. Open reflected the varying climatic conditions and heat tolerance levels typical of each tournament's location, as the Australian Open is held in the hotter, more intense summer conditions of Melbourne, requiring a higher threshold for extreme heat.

Tableau was subsequently utilized to create data visualizations measuring the average temperature during the aforementioned periods for both the Australian Open and US Open tournaments. To create the normalized visualization (Figure 5) and mitigate the effect of the differences in tournament start dates relative to the start of summer in the Northern and Southern hemispheres, it was assumed that the US Open also starts in mid-July (i.e., the month following the start of summer) similar to the Australian Open. Accordingly, temperature data from Wunderground was obtained for the second half of July. This approach allowed for a more direct comparison of temperature trends between the two tournaments, as they were now aligned to the same relative time period within the summer season, helping to account for the disparities in tournament start dates and providing a more accurate representation of the temperature conditions experienced by athletes at these major events.

To analyze match-play performance in relation to temperature, data was obtained from the TennisExplorer website and the GitHub repository maintained by Jeff Sackmann, which contains detailed datasets for men's (ATP) and women's (WTA) tennis matches. The Sackmann datasets provided key elements of each match, including the winning player, losing player, tournament, city, number of aces, number of double faults, and other performance metrics that could indicate how temperature affected gameplay. However, the Sackmann datasets only included the starting date of each tournament, rather than the exact date each individual match was played. To accurately combine this data with the daily temperature information from Wunderground obtained in the prior section, the TennisExplorer website was utilized to cross-reference and identify the precise date for each match.

By comparing the fields of winning player, losing player, tournament, and city from the Sackmann datasets with the corresponding information on TennisExplorer, along with the match date, the specific game being analyzed could be accurately matched between the two data sources. This allowed for the correct date of each match to be identified and combined with the temperature data, enabling a thorough analysis of the effect of temperature on match-play performance.

Utilizing the three data sets mentioned, a comprehensive dataset was created in Python's Pandas library, providing a detailed picture of each tennis match played, the temperature conditions, and the performance metrics of the players (20). The main fields used to create the data visualizations were from Jeff Sackmann’s database, such as the tournament name, the athlete’s gender, the number of aces, the number of double faults, the number of serve points, and the number of first serves won. These were then cross-referenced with the average temperature values obtained from Wunderground for the corresponding dates and locations. From this integrated dataset, several derivative metrics such as percentage of aces, percentage of double faults, and percentage of first serves won were calculated, as well as different combinations of tournament and gender. This allowed for a thorough analysis of the relationships between environmental conditions and player performance across the major tennis events.

Data visualizations were then created using Tableau to compare temperature data across several major tennis tournaments with various derivative performance metrics, incorporating a linear best-fit line to enhance the analysis (21). The analysis for performance metrics was constrained to only those temperatures where at least two games were available for analysis. The goal was to identify the strongest relationships, as measured by the coefficient of determination (R-squared value). The process involved integrating temperature data from Wunderground with match-level statistics obtained from Jeff Sackmann's GitHub repositories for both the ATP (men's) and WTA (women's) tours. The data visualizations were then organized based on the R-squared values, indicating how much of the variance in the performance metrics could be explained by temperature conditions. The greater the R-squared, the stronger the relationship between the environmental factor and on-court outcomes.

Tableau was utilized to analyze the effect of exhaustion on gameplay and its relationship with performance metrics in comparison to temperature. Initially, data from all referenced tournaments in the database was compiled, correlating the minutes played in each match with the number of games played for each tournament. This analysis confirmed a directly proportional relationship between match duration and the number of games played. Subsequently, the match duration data from 2000-2023 was segmented into thirds by gender, and these terciles were used to categorize levels of exhaustion—low, medium, and high—based on the minutes played. These categories reflect varying degrees of physical demand for male and female athletes, with longer durations indicating greater exhaustion, as presented in the study by Reid et al. (23). This study found that matches consisting of multiple hours of gameplay, such as the 2012 Australian Open final between Djokovic and Nadal, imposed substantial physical burdens and had the potential to decrease the accuracy of gameplay.

To further refine the analysis, the exhaustion level terciles were examined to determine how they interacted with temperature and affected performance metrics such as double faults percentage, first serve win percentage, and aces percentage. Data from both male and female players across all the aforementioned tournaments were included. Each exhaustion category was analyzed to determine the trend lines for how temperature affected these key performance metrics. This approach allowed for an assessment of how exhaustion influenced the relationship between performance metrics and temperature.

For each data visualization, R-squared values and p-values were derived from lines of best fit using linear regression analysis. To reaffirm the significance of these results, Table 2 was created, and single-factor ANOVA tests were performed using Excel for each figure that showed a relationship between performance metrics and temperature, using actual point data rather than the lines of best fit (22). For every figure, temperature data values across all metrics (e.g. percentage of double faults) analyzed were divided into three comparator groups: low, medium, and high, aiming for equal counts to ensure consistency. Within each figure, an ANOVA single-factor test was performed with the three comparator groups on each metric, and temperature ranges that defined the three comparator groups remained the same for all performance metric trends. However, from figure to figure the temperature ranges that defined the comparator groups sometimes differed to ensure equal counts due to data variance. The p-values obtained from the ANOVA tests and the linear regression were then compared at a significance level of 0.05 to determine the statistical significance of the results. The separate R-squared values, p-values, and F-statistic values from the Excel linear regression analysis were compiled in the table. This approach allowed the confirmation of the robustness of the observed relationships and accounted for any potential inconsistencies in the data.

Results

As mentioned in the methodology, finding the trends between temperature and tennis performance involved an extensive data visualization approach using Tableau to analyze the effect of extreme heat conditions on tennis performance and athlete health. This method was critical due to the complexity and scale of the available data, which was compiled from various sources including the Jeff Sackmann GitHub database and TennisExplorer. Temperature data was also acquired from Wunderground for a wide array of major tennis tournaments.

To measure the influence of temperature on tennis performance, several derivative metrics were utilized, calculated from the performance data of major tennis tournaments. These metrics included, a] Percentage of aces, calculated as the number of aces divided by the total number of serve points, b] Percentage of double faults, calculated as the number of double faults divided by the total number of serve points, c] Percentage of first serves won, calculated as the number of first serves won divided by the total number of first serves made.

To obtain a broad understanding of how rising temperatures effect tennis performance across various competitive settings, it was crucial to analyze performance metrics over an extended period and across a wide array of tournaments (from 2000 to 2023). This approach allowed for the observation of general trends to gauge how temperature influenced key aspects of tennis gameplay.

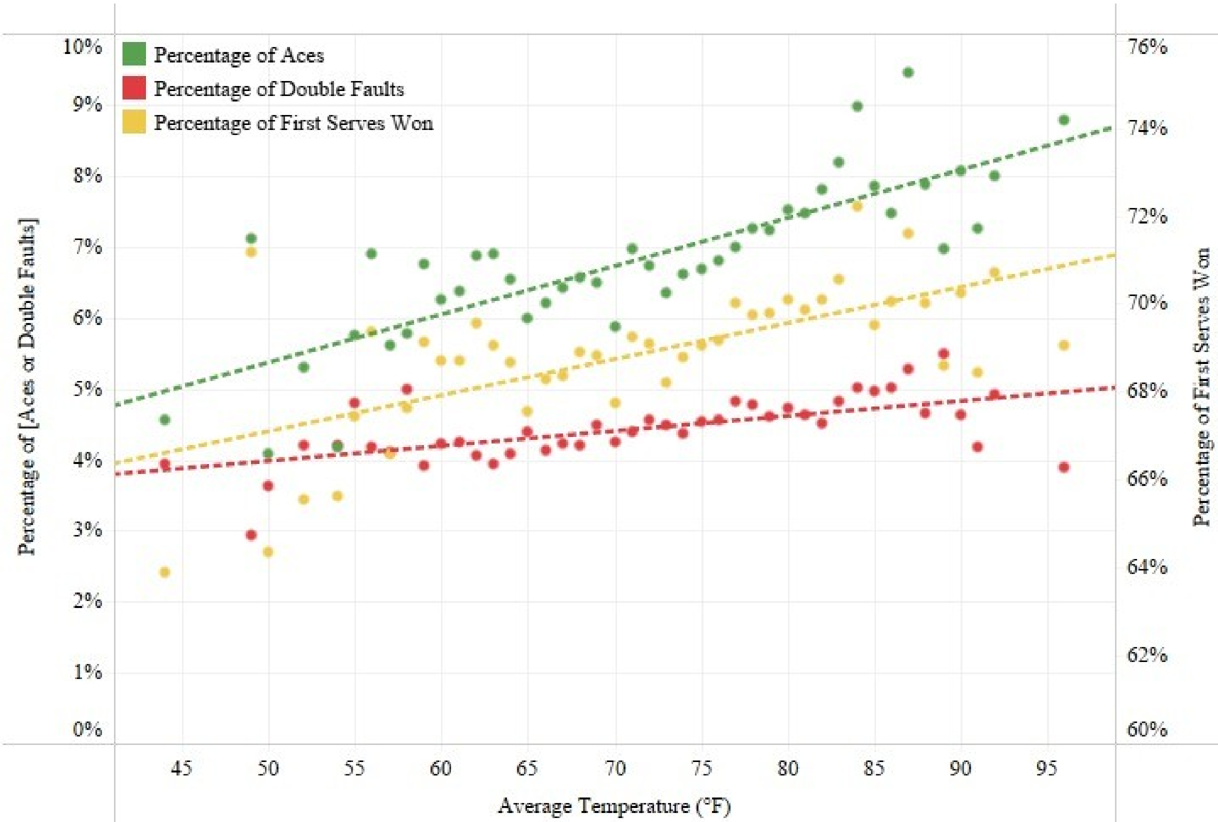

Figure 1. Serve performance metrics *vs.* average temperature in major tennis tournaments (2000-2023)

Figure 1 presents a comprehensive analysis of the relationship between average temperature and various serve performance metrics in tennis, with data spanning from 2000 to 2023 for various tournaments; the Australian Open, Wimbledon, the US Open, the Doha Open, the Dubai Open, Indian Wells, the Miami Open, the Sydney Open, the Tokyo Open, and the Washington Open. The data highlights three key metrics: the percentage of aces, which showed a strong positive trend with rising temperatures ($R^2 = 0.65$, p-value <0.0001), indicating that as temperatures increased, players tended to serve more aces; the percentage of double Faults, which also exhibited a positive trend ($R^2 = 0.38$, p-value <0.0001), suggesting that higher temperatures may lead to an increase in errors, such as double faults; and the percentage of first serves won, showing a moderate positive correlation with temperature ($R^2 = 0.42$, p-value <0.0001), implying that the effectiveness of first serves improved with temperature. Collectively, these trends underscored that while warmer temperatures enhanced certain aspects of serve performance, such as aces and first serves won, they hindered performance by increasing the rate of double faults.

Figure 2. Gender-specific analysis of serve performance *vs.* average temperature in major tennis tournaments (2000-2023)

Building on the insights from Figure 1, Figure 2 presents the gender-specific effect of temperature on serve performance in tennis, highlighting how male and female players responded differently to increasing temperature. This figure used the data from the aforementioned major tournaments from 2000 through 2023. For female players, the analysis found a strong positive correlation between temperature and the percentage of aces (R^2 = 0.62, p-value < 0.0001) and a moderate yet significant correlation with the effectiveness of first serves (R^2 = 0.31, p-value < 0.0001), suggesting that as temperatures rise, female players tended to serve more effectively. However, the relationship between temperature and the percentage of double faults for female players was found to be statistically insignificant (R^2 = 0.07, p-value = 0.0745). Conversely, male players exhibited a strong positive correlation in both the percentage of double faults (R^2 = 0.60, p-value < 0.0001) and aces (R^2 = 0.69, p-value < 0.0001), as well as a strong improvement in first serves won (R^2 = 0.59, p-value < 0.0001) with increasing temperatures. This data indicated that temperature significantly affected serve performances for both genders, but the strength of these correlations varied, with male players showing a more pronounced increase in the percentage of first serves won as temperature increased. Notably, while both genders experienced increases in aces and double faults with higher temperatures, the rate of increase in double faults was more pronounced in male players, underlining a gender-specific impact of heat on serve reliability and power.

Figure 3. Serve performance of female players at the Australian Open and US Open relative to average temperature (2000-2023)

Building on the gender-specific analysis presented in Figure 2, Figure 3 compared serve performance at the Australian Open and the US Open, focusing on female players. Distinct trends in serve performance were found, influenced by the climatic conditions characteristic of each tournament location. At the Australian Open, there was a slight positive correlation between temperature and the rate of double faults for female players ($R^2 = 0.17$, p-value = 0.013), suggesting an increase in double faults as temperatures increased. In contrast, at the US Open, the effect of temperature was more pronounced. Here, aces showed a moderate positive correlation with temperature ($R^2 = 0.34$, p-value = 0.0012), indicating an improvement in serve effectiveness as temperatures increased. However, there was also a strong positive correlation for double faults ($R^2 = 0.57$, p-value < 0.0001), highlighting a substantial increase in serve errors at the higher temperatures. These observations suggested that while there was an increase in aces and first serves won with rising temperatures in both tournaments, the increase was more pronounced at the US Open. This could be attributed (speculatively) to the higher humidity levels at the US Open, which might affect the ball's behavior and the physiological responses of the players more intensely than it would at the Australian Open. Consequently, while serving effectiveness, in terms of percentage of aces, generally improved with higher temperatures, the risk of errors, such as double faults, also increased, particularly at the US Open.

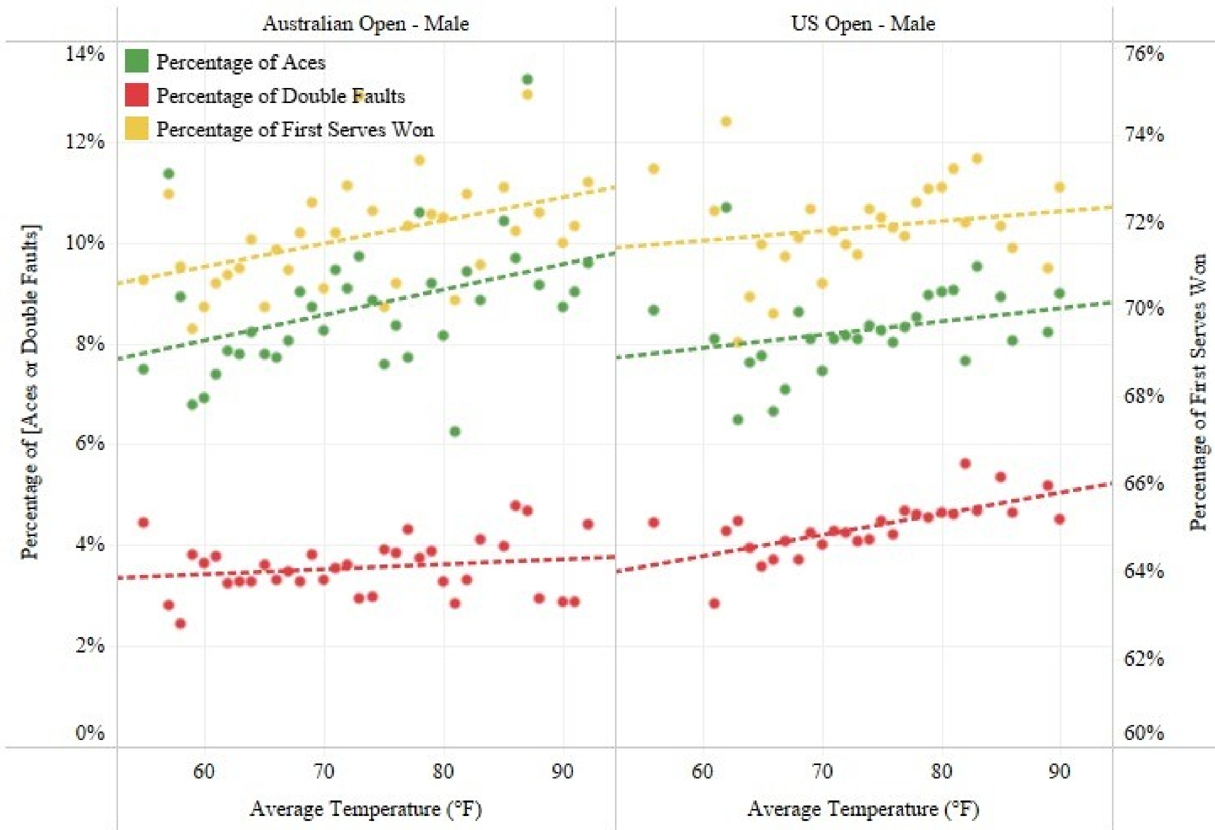

Figure 4. Serve performance of male players at the Australian Open and US Open relative to average temperature (2000-2023)

Transitioning from the analysis in Figure 3, which focused on female players, Figure 4 presents a detailed examination of how temperature affected serve performance among male players at the Australian Open and US Open. This comparison highlighted the gender-specific responses and differences between the two major tournaments. For the Australian Open, the data for male players showed a slight positive correlation between temperature and the percentage of aces ($R^2 = 0.16$, p-value = 0.016), suggesting a slight increase in the percentage of aces as temperature increased. The correlation with the percentage of first serves won was slightly stronger ($R^2 = 0.20$, p-value = 0.0064), indicating a moderate improvement in first-serve effectiveness with increasing temperature. At the US Open, the trend was more pronounced in the percentage of double faults, which exhibited a positive correlation with temperature ($R^2 = 0.47$, p-value < 0.0001). This suggested that as temperatures increased, male players at the US Open were more likely to commit double faults, highlighting the effect of heat on serve reliability. Comparing these findings with those from Figure 3 for female players, it is evident that both genders exhibited increases in serve performance metrics such as aces and first serves won with rising temperatures. However, the effect of temperature on double faults was more pronounced in male players at the US Open, contrasting with the more moderate correlations observed for female players; the most consistent and influential effect was observed in the increase of double faults at the US Open for male players.

Figure 5 shows the temperature fluctuations and extreme heat days at the Australian and US Opens from 2000 to 2022. It includes a comparison of actual temperatures and days with extreme heat, along with a normalized view that adjusts US Open data to the seasonal timing of the Australian Open, providing a unique perspective on how these events might compare under similar seasonal conditions. The analysis of temperature trends at both the Australian and US Opens showed a complex pattern. For the Australian Open, temperatures fluctuated with a slight long-term trend, as reflected by an R^2 of 0.16 and a p-value of 0.5. Due to the correlation observed above, it was fair to conclude that Australian Open temperatures are rising by around 3 degrees Fahrenheit every 10 years. By adjusting the US Open dates to align with the Australian Open's summer schedule (typically January, corresponding to July in the U.S.), the second graph offered a direct comparison of temperature trends between the two tournaments. The US Open exhibited more pronounced changes with a moderate R^2 of 0.25 for temperature trends and a p-value of 0.13, suggesting varied annual temperatures with an increasing directional trend. The number of extreme heat days during the US Open has increased, indicated by an R^2 of 0.20 and a p-value of 0.03, pointing to a stronger effect of rising temperatures at this location.

The bottom panel of Figure 5 compares average temperatures at the Australian Open and the US Open from 2000 to 2022, showcasing trends under different scheduling scenarios. The Australian Open temperatures during its regular January dates showed a minor upward trend ($R^2 = 0.09$, p-value = 0.14). For the US Open, when dates are normalized to match the Australian summer timing, essentially hypothesizing that the tournament is held in July, there was a pronounced rise in temperatures ($R^2 = 0.25$, p-value = 0.013). This contrasts with the temperatures recorded during the US Open's actual late August to September dates, which also showed an upward trend but were less pronounced ($R^2 = 0.16$, p-value = 0.05). This analysis highlighted the effect of seasonal timing and potentially higher temperatures that could be faced if the US Open were held during the early summer months.

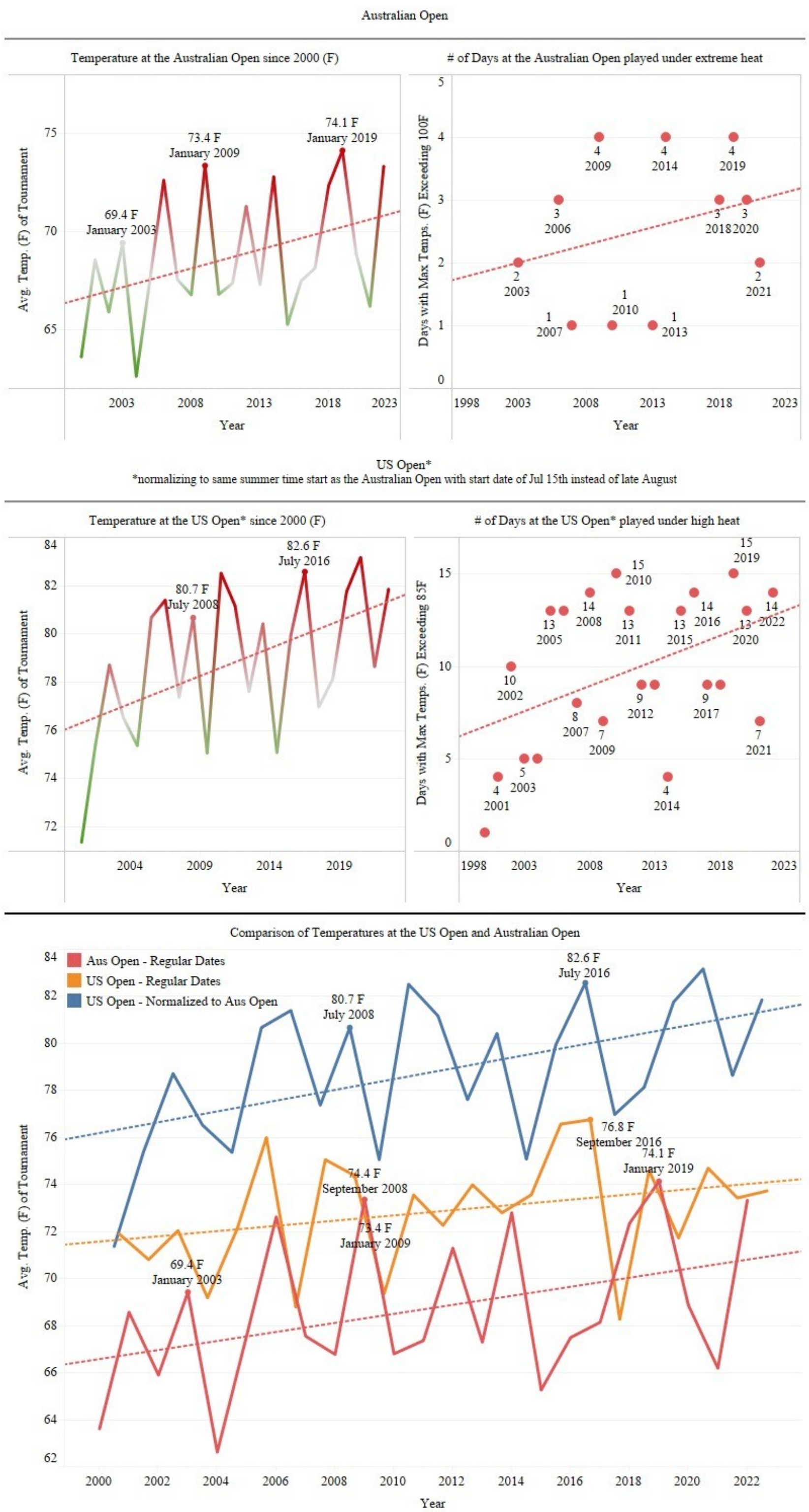

Figure 5. Comparative analysis of temperature fluctuations and extreme heat days at the Australian and US Opens (2000-2022) with normalized US Open data

Table 1: Categorization of exhaustion levels by match duration for male and female tennis players (2000-2023)

	Low Exhaustion	Medium Exhaustion	High Exhaustion
Female	< 79 minutes	79-108 minutes	> 108 minutes
Male	< 97 minutes	97-138 minutes	> 138 minutes

Table 1 categorizes exhaustion levels for male and female tennis players based on the duration of their matches in minutes. The match duration data from 2000 to 2023 were segmented into thirds by gender, using the 33rd and 66th percentiles to define the thresholds. For female players, low exhaustion corresponds to matches lasting less than 79 minutes, medium exhaustion to matches lasting between 79 and 108 minutes, and high exhaustion to matches lasting more than 108 minutes. For male players, low exhaustion corresponds to matches lasting less than 97 minutes, medium exhaustion to matches lasting between 97 and 138 minutes, and high exhaustion to matches lasting more than 138 minutes. This categorization facilitated a gender-specific analysis of how match duration may affect performance metrics and was applied in Figure 6 to categorize the different levels of exhaustion.

The graph presented in Figure 6 provides an analysis of the effect of physical exhaustion on serve performance metrics across major tennis tournaments from 2000 to 2023, incorporating data from both female and male players. This analysis addressed a gap in understanding whether it is temperature or exhaustion (framed by minutes played) that independently affects performance metrics. The graph is organized into three panels representing low, medium, and high levels of exhaustion, defined by the duration of match play, segmented into terciles

(33^{rd} percentile, 66^{th} percentile) which vary for each gender (as presented in Table 5). These exhaustion terciles served as proxies for the degree of fatigue experienced by players during matches. All points shown in the graph have corresponding points on each line for each exhaustion category that were obtained at the same temperature. Each panel in the graph plotted the relationship between average temperature and three critical serve performance metrics: percentage of aces, percentage of first serves won, and percentage of double faults.

The analysis of the relationships between temperature and tennis performance metrics found that the R-squared values were consistent across different levels of exhaustion, with one notable exception. For the percentage of aces, the relationships were strong and significant across all exhaustion levels (Low: 0.54, Medium: 0.57, High: 0.47), indicating a reliable increase in aces with rising temperatures despite the influence of exhaustion. Similarly, for the percentage of first serves won, the relationships were significant across all levels of exhaustion (Low: 0.40, Medium: 0.45, High: 0.30), with temperature possibly affecting performance more than exhaustion. The percentage of double faults showed a different temperature dependence; while the relationships were significant for low (R^2 = 0.51) and medium exhaustion (R^2 = 0.49), the relationship was weak under high exhaustion (R^2 = 0.07, p-value: 0.08). This indicated that temperature did not have a significant effect on double faults under high exhaustion. The strongest relationships were observed under low and medium exhaustion, indicating consistent performance improvements in warmer conditions.

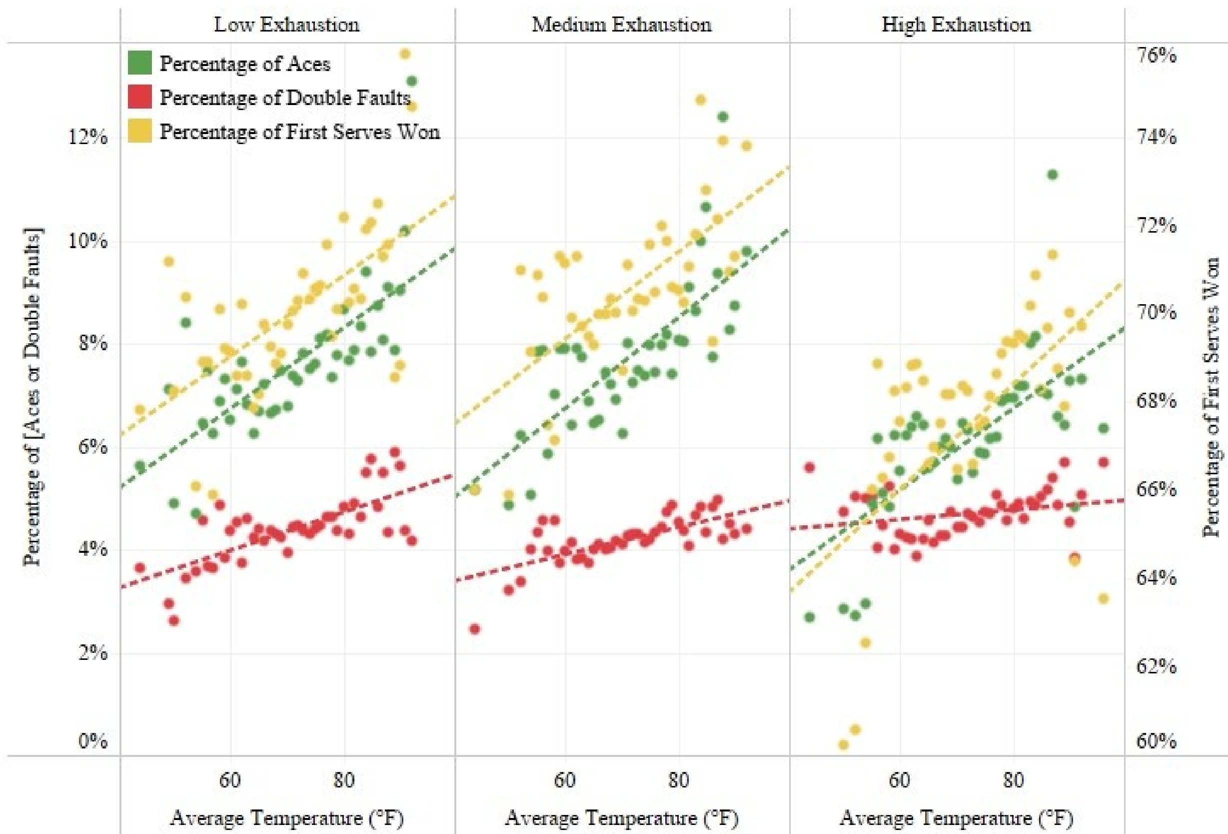

Figure 6. Impact of exhaustion on serve performance metrics relative to temperature across major tournaments (2000-2023)

Despite the differences in exhaustion levels, the trend lines across all categories demonstrated consistent patterns, indicating a generally positive correlation between higher temperatures and improved serve performance. The major exception to this generalization was the percentage of double faults; for low and medium exhaustion levels, the relationships were significant, showing a consistent increase in double faults with rising temperatures. However, the relationship was not significant under high exhaustion, suggesting that temperature was not a consistent factor in influencing double faults when players were highly exhausted. Overall, the examination of exhaustion levels showed that the trends between performance metrics and temperature remained strong across different levels regardless of the degree of fatigue. This suggested that temperature played a more influential role in affecting performance metrics than did the level of exhaustion, with the exception of double faults, which were not reliably affected by temperature under high exhaustion.

Table 2: Statistical significance of trends in performance metrics and temperature across the various Figures using linear regression and ANOVA

Figure number	Trend analyzed in relation to temperature		R-squared value from linear regression	F-statistic from linear regression	P-value from linear regression	P-value from single factor ANOVA test	Is the P-value from ANOVA < 0.05 (significance level)?	Are both ANOVA and linear regression P-values significant?
1	%Aces		0.65	79.4	3.07×10^{-11}	2.06×10^{-8}	True	True
	%Double Faults		0.38	25.6	8.55×10^{-6}	1.08×10^{-4}	True	True
	%First Serves Won		0.42	30.6	1.81×10^{-6}	2.46×10^{-4}	True	True
2	Males	%Aces	0.69	94.4	3.35×10^{-12}	3.62×10^{-8}	True	True
		%Double Faults	0.60	62.3	9.21×10^{-10}	5.79×10^{-7}	True	True
		%First Serves Won	0.59	59.6	1.58×10^{-9}	7.99×10^{-6}	True	True
	Females	%Aces	0.62	68.1	2.96×10^{-10}	9.04×10^{-6}	True	True
		%Double Faults	0.07	3.3	7.45×10^{-2}	2.39×10^{-2}	True	False
		%First Serves Won	0.31	18.8	8.96×10^{-5}	1.50×10^{-2}	True	True
3	Australian Open (Females)	%Aces	0.09	3.5	6.95×10^{-2}	1.52×10^{-1}	False	False
		%Double Faults	0.17	6.8	1.31×10^{-2}	7.56×10^{-2}	False	False
		%First Serves Won	0.05	2.0	1.65×10^{-1}	1.74×10^{-1}	False	False
	U.S. Open (Females)	%Aces	0.34	13.2	1.25×10^{-3}	4.31×10^{-3}	True	True
		%Double Faults	0.57	33.7	4.68×10^{-6}	3.42×10^{-3}	True	True
		%First Serves Won	0.09	2.6	1.13×10^{-1}	3.66×10^{-1}	False	False
4	Australian Open	%Aces	0.16	6.3	1.65×10^{-2}	5.5×10^{-2}	False	False
		%Double Faults	0.03	1.2	2.75×10^{-1}	6.43×10^{-1}	False	False

	(Males)	%First Serves Won	0.20	8.4	6.40×10^{-3}	1.29×10^{-2}	True	True
	U.S. Open (Males)	%Aces	0.07	2.1	1.52×10^{-1}	1.32×10^{-1}	False	False
		%Double Faults	0.47	23.1	5.58×10^{-5}	7.25×10^{-5}	True	True
		%First Serves Won	0.03	0.8	3.54×10^{-1}	2.01×10^{-1}	False	False
6	Low Exhaustion	%Aces	0.54	49.3	1.52×10^{-8}	5.44×10^{-6}	True	True
		%Double Faults	0.51	44.2	5.16×10^{-8}	1.86×10^{-5}	True	True
		%First Serves Won	0.40	27.6	4.88×10^{-6}	1.04×10^{-4}	True	True
	Medium Exhaustion	%Aces	0.57	51.8	1.13×10^{-8}	5.93×10^{-6}	True	True
		%Double Faults	0.49	37.5	3.42×10^{-7}	1.31×10^{-4}	True	True
		%First Serves Won	0.45	32.6	1.29×10^{-6}	9.12×10^{-4}	True	True
	High Exhaustion	%Aces	0.47	36.7	3.54×10^{-7}	6.43×10^{-5}	True	True
		%Double Faults	0.07	3.2	8.04×10^{-2}	3.17×10^{-2}	True	False
		%First Serves Won	0.30	18.0	1.21×10^{-4}	8.03×10^{-3}	True	True

The major findings from Table 2 — the statistical analysis of trends in performance metrics and temperature across figures — indicated several key points. Despite some R^2 values from the linear regression analysis appearing low, the p-values obtained from the single-factor ANOVA tests provided stronger confirmation of statistical significance. This was because the ANOVA tests were performed using the actual data points, rather than relying on the fit of a linear model. Ensuring that both the ANOVA p-value and the linear regression p-value are significant provided a stronger confirmation of the statistical significance of the observed relationships. Figure 5 was skipped in this analysis because it focused on temperature increase over time rather than directly comparing temperature to performance metrics.

The generally low p-values from these ANOVA tests indicated that the observed relationships between temperature and the performance metrics were statistically significant, reaffirming the validity of the findings despite some relatively low R^2 values. For instance, in Figure 1, the R^2 values for the percentage of aces, double faults, and first serves won were 0.65, 0.38, and 0.42, respectively, with corresponding p-values from the ANOVA test being highly significant (all p-values < 0.0001). Similar trends were observed across other figures, where statistically significant p-values were obtained for various performance metrics despite some lower R^2 values. The table also shows that when the $R^2 > 0.17$, or when the linear model explained more than 17% of the variation in the data, the difference between comparators from the ANOVA results was significant.

In particular, Figures 2 and 6 demonstrated strong relationships between temperature and performance metrics such as the percentage of aces and first serves won, with consistently low p-values indicating significance. The ANOVA tests confirmed these relationships, ensuring that the observed trends were not due to random chance but reflected real underlying patterns in the data. This combination of regression analysis and ANOVA testing provided a more comprehensive approach to understanding the effect of temperature on tennis performance metrics. However, double faults seemed to be an exception in some cases, with non-significant results depicted in linear regression for females (as shown in Figure 2) and under high exhaustion (as shown in Figure 6). These findings aligned with the trend that temperature did impact double faults, but the relationship was not consistently strong or reliable due to exhaustion.

There were notable shortcomings in some figures where the p-values from the ANOVA tests and linear regression did not indicate statistical significance. For example, in Figure 3, the trends for the percentage of aces, double faults, and first serves won at the Australian Open (Females) were not significant, with p-values of 0.152, 0.076, and 0.174, respectively. Similarly, in Figure 4, the trends for the percentage of aces and double faults at the Australian Open (Males) were not significant, with p-values of 0.550 and 0.643, respectively. The U.S. Open (Males) also showed non-significant trends for the percentage of aces and first serves won, with p-values of 0.132 and 0.201, respectively. These non-significant results suggested that, in certain contexts and tournaments, temperature may not be the dominant factor influencing these performance metrics. This variability highlighted the complexity of isolating the impact of temperature on performance, but despite these shortcomings, the overall findings indicated that temperature tended to affect performance metrics.

Discussion

The analysis conducted across various figures in this research paints a portrait of how temperature influences tennis performance metrics, shedding light on significant implications for both player performance and tournament planning. The findings demonstrated a complex interaction between temperature and tennis gameplay, where higher temperatures correlated positively with an increase in the percentage of aces and first serves won. This suggested that warmer conditions might facilitate more powerful and effective serves, potentially due to decreased air density allowing the ball to travel faster and with less drag (24). Similar trends have been observed in the Australian Open and US Open, where players committed more double faults and returned unforced errors while simultaneoulsy achieving more first-serve wins. This supports the notion that female players, in particular, might adopt a "strong-strong" serve strategy in hotter conditions, aiming to maximize serve power and effectiveness but at the cost of increased error rates (25).

However, this advantage appeared to come with a caveat; the findings also revealed a consistent rise in double faults as temperatures increased. In the analysis shown in Figure 6, it appeared that for matches with high exhaustion, temperature did not significantly affect double faults, suggesting that exhaustion may be a more influential factor in these scenarios. This visualization found that although rising temperatures did impact these performance metrics regardless of the exhaustion level, there were some exceptions, such as double faults under extreme exhaustion. This observation was consistent with previous literature, which found similar trends in the trade-off between power and precision due to heat-induced fatigue (26).

The gender-specific analysis of Figure 2 increased the understanding of how temperature affected serve performance differently among male and female players across various tournaments. Broadly, it was observed that male players exhibited a more pronounced increase in serve effectiveness with rising temperatures than female players, which might be linked to physiological differences such as muscle composition, thermoregulation, and sweat rates (27). These factors could enable male players to benefit more from warmer conditions.

However, Table 2 revealed that many of the trends observed in Figures 3 and 4 were not statistically significant, highlighting shortcomings where the p-values from the ANOVA tests did not indicate statistical significance for the trends analyzed. This suggested that the observed effects in these figures might not be as reliable. In contrast, other figures such as Figures 1, 2, and 6 showed generally statistically significant relationships between temperature and performance metrics across different tournaments. This indicated that while there was a general trend suggesting the impact of temperature on performance metrics, there were exceptions that questioned the validity of this relationship under certain conditions and for specific metrics, such as double faults under high exhaustion which were not statistically significant. These non-significant results suggested that temperature may not be the dominant factor influencing these performance metrics in every context, emphasizing the need for further research to identify other contributing variables such as player-specific factors, match conditions, and court surface types.

The historical temperature trends observed in the data visualizations indicate a troubling increase in average temperatures and extreme heat days, particularly at the locations of these major tournaments. This upward trend in temperature aligns with global warming predictions and is corroborated by the changes observed in serve performance metrics. These findings signal a pressing need for players and coaching staff to adapt their strategies and training regimens to accommodate hotter playing conditions, which are becoming increasingly common.

Furthermore, the implications of these findings are significant for tournament organizers. As extreme heat becomes more frequent, reevaluating tournament scheduling, improving infrastructural features like retractable roofs and advanced cooling systems, and adopting more flexible match scheduling could become vital to ensure player safety and maintain high levels of competition (28). The need for this re-evaluation is affirmed by the trend observed with the normalization of US Open temperatures to match Australian Open dates, which suggests that if the US Open were held during a period typical of the Australian summer, players might encounter even more challenging conditions, emphasizing the need for rigorous heat management strategies. Implementing adaptive measures that accommodate rising temperatures will be crucial for the sustainability of outdoor sports like tennis in the face of global climate change.

Limitations

While this research provides significant insights into the effect of temperature on tennis performance, it is not without limitations. The reliance on publicly available datasets from websites like Wunderground and TennisExplorer may introduce biases due to data completeness and accuracy, and weather data may not precisely reflect microclimatic conditions at tournament venues. One limitation of this study is the reliance on correlational methods, which can introduce biases as these methods do not account for potential confounding variables that might actually drive the observed trends in temperature and tennis performance. In this context, it may be that; with increased technological advances in physiotherapy, sports science and endurance training, among others; the natural ability of players has progressively increased over time. Part of the increase in metrics over time may hence be attributable to these technological advances squeezing out every ounce of physiological efficiency.

Additionally, focusing primarily on ATP and WTA events may not fully represent conditions at lower-tier or indoor tournaments. Moreover, performance data at a point or game level within a match can allow for a more granular analysis of the impact of temperature. However, the unavailability of such granular tracking data and the sole reliance on the duration of a match as a metric to estimate exhaustion introduces some assumptions and uncertainties regarding perceived exhaustion.

Despite these limitations, the findings underscore the need for more detailed studies that include finer-grained analysis of local weather conditions, comprehensive physiological monitoring during matches, and the development of adaptive strategies to manage the evolving challenges of competitive tennis and sports in a warming climate. Additionally, more set-level and granular data should be tracked and made available to enable thorough analysis and improved tracking of exhaustion levels and performance throughout matches.

Conclusion

The significant effect of rising temperatures on tennis performance, particularly during major tournaments such as the Australian and US Opens, highlights the complex relationship between climate and athletic performance. While warmer conditions might enhance certain performance metrics like serve power, they also lead to increased error rates and elevate health risks, presenting a significant trade-off. The apparent benefits, such as more aces or first serves, come at a cost. These metrics typically increase not just due to enhanced performance, but also from players aiming to shorten points to cope with the heat, leading to quicker energy loss. This strategy, while initially effective, can ultimately compromise player safety and overall performance, as both the server and receiver are likely to experience accelerated weariness and physical drain. In comparison to exhaustion, temperature was found to be the strongest factor influencing serve performance metrics. However, at high levels of exhaustion, the relationship between temperature and the percentage of double faults was not significant. While some conditions showed statistically non-significant results, the overall findings indicated a relatively strong impact of temperature on performance metrics. The effects of temperature can vary based on the tournament and other conditions, suggesting that while there was a general trend, it was subject to variability. Findings, especially regarding gender-specific impact and the simulated adjustment of tournament dates, pointed to the inadequacy of current conditions in accommodating the challenges posed by global climate change. This research calls for ongoing study and proactive adjustments in the sports industry, emphasizing a broader implementation of strategies to mitigate the detrimental effects of climate change on sports performance and to ensure athlete safety and competitive integrity in increasingly warmer climates.

References

1. Taylor L. Cancelled races, fainting players: How climate change affects sports. *World Economic Forum.* (2019). https://www.weforum.org/agenda/2019/08/climate-change-effects-turns-up-heat-on-sports/

2. Dragović B. The Influence of the Sports Industry on Climate Change and How it Can Be Part of the Solution. *Earth.org*. (2022). https://earth.org/sports-climate-change/

3. Australian Open should be moved because of extreme heat: researchers. *Australian Financial Review*. (2020). https://www.afr.com/companies/sport/australian-open-should-be-moved-because-of-extreme-heat-researchers-20200120-p53sxz

4. It's So Hot That the US Open Adopted a New Policy to Partially Close Arena Roofs. *U.S. News & World Report*. (2023). https://www.usnews.com/news/sports/articles/2023-09-05/its-so-hot-that-the-us-open-adopted-a-new-policy-to-partially-close-arena-roofs

5. Iddenden G. The heat is on! Sweaty tennis fans collapse as temperatures hit 30C at Wimbledon while thousands flock to beaches and parks to enjoy start of a scorching weekend. *Daily Mail Online*. (2023). https://www.dailymail.co.uk/news/article-12275351/Its-heating-Wimbledon-Sweaty-tennis-fans-collapse-heat-temperatures-hit-30C.html

6. Fendrich H. Grand Slam tournaments are getting hotter. US Open players and fans are feeling that this week. *Associated Press*. (2023). https://apnews.com/article/us-open-heat-humidity-climate-change-tennis-5412fac6f440c9a9191e7a501db870d1

7. NASA Announces Summer 2023 Hottest on Record. *NASA*. (2023). https://www.nasa.gov/news-release/nasa-announces-summer-2023-hottest-on-record/

8. Kovacs MS. Applied physiology of tennis performance. *Br J Sports Med*, 40(5): 381-386, (2006). https://doi.org/10.1136%2Fbjsm.2005.023309.

9. Périard JD, Eijsvogels TM, Daanen HA. Exercise under heat stress: thermoregulation, hydration, performance implications, and mitigation strategies. *Physiol. Rev*, 101(4): 1873-1979, (2021). https://doi.org/10.1152/physrev.00038.2020.

10. Périard JD, Racinais S, Knez WL, Herrera CP, Christian RJ, Girard O. Thermal, physiological and perceptual strain mediate alterations in match-play tennis under heat stress. *Br J Sports Med*, 48: 32-38, (2014). https://doi.org/10.1136/bjsports-2013-093063

11. Heat Stress. *Centers for Disease Control and Prevention.* (2020). https://www.cdc.gov/niosh/topics/heatstress/

12. Smith MT, Reid M, Kovalchik S, Woods TO, Duffield R. Heat stress incident prevalence and tennis matchplay performance at the Australian Open. *J Sci Med Sport*, 21(5): 467-472, (2018). https://doi.org/10.1016/j.jsams.2017.08.019

13. Kuroda Y, Ishihara T, Mizuno M. Association between perceived exertion and executive functions with serve accuracy among male university tennis players: A pilot study. *Front Psychol*, 14(1), (2023). https://doi.org/10.3389/fpsyg.2023.1007928

14. Davey P, Thorpe R, Williams C. Fatigue decreases skilled tennis performance. *J Sports Sci*, 20(4): 311-318, (2002). https://doi.org/10.1080/026404102753576080

15. Gescheit D, Cormack S, Reid M. Consecutive days of prolonged tennis match play: performance, physical, and perceptual responses in trained players. *Int J Sports Physiol Perform*, 10(7): 913-920, (2015). https://doi.org/10.1123/ijspp.2014-0329

16. Sackmann J. ATP Tennis Database. *GitHub*. (2024). https://github.com/JeffSackmann/tennis_atp

17. Sackmann J. WTA Tennis Database. *GitHub*. (2024). https://github.com/JeffSackmann/tennis_wta

18. Tennis Explorer. *TennisExplorer*. (2024). https://www.tennisexplorer.com/

19. Wunderground. *Wunderground*. (2024). https://www.wunderground.com/

20. pandas. *pandas - Python Data Analysis Library*. https://pandas.pydata.org/

21. Tableau Desktop. *Tableau Software*. https://www.tableau.com/

22. Microsoft Excel Analysis ToolPak. *Microsoft Excel*. https://www.microsoft.com/en-us/microsoft-365/excel

23. Reid M, Duffield R. The development of fatigue during match-play tennis. *Br J Sports Med*, 48(1), (2014). https://doi.org/10.1136/bjsports-2013-093196

24. Dinneen J. Higher temperatures are leading to more home runs in baseball. *New Scientist.* (2023). https://www.newscientist.com/article/2367894-higher-temperatures-are-leading-to-more-home-runs-in-baseball/

25. Cui Y, Gómez MA, Gonçalves B, Sampaio J. Performance profiles of professional female tennis players in grand slams. *PLoS ONE,* 13(7), (2018). https://doi.org/10.1371/journal.pone.0200591

26. Bilić Z, Sinković F, Barbaros P, Novak D, Zemkova E. Exercise-Induced Fatigue Impairs Change of Direction Performance and Serve Precision among Young Male Tennis Players. *Sports (Basel)*, 11(6), (2023). https://doi.org/10.3390/sports11060111

27. Kenney WL. A review of comparative responses of men and women to heat stress. *Environ Res*, 37(1): 1-11, (1985). https://doi.org/10.1016/0013-9351(85)90044-1

28. Hart B. Maybe They Should Move the U.S. Open Back a Week. *Intelligencer*. (2023). https://nymag.com/intelligencer/2023/09/maybe-they-should-move-the-u-s-open-back-a-week.html