The Impact of Temperature on Major League Baseball

BRANDON LEE D. KOCH AND ANNA K. PANORSKA

Department of Mathematics and Statistics, University of Nevada, Reno, Reno, Nevada

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ABSTRACT

Major League Baseball is played from the beginning of April through the end of October each year, encompassing three of the four meteorological seasons: spring, summer, and fall. The 30 teams play in cities across the United States and Canada in many types of weather. This work studies the impact of temperature on a Major League Baseball game by examining the association between temperature and several Major League Baseball game statistics, including runs scored, batting average, slugging percentage, on-base percentage, home runs, walks, strikeouts, hit-batsmen, stolen bases, and errors. Data from 22 215 games, spanning the 2000–11 regular seasons, were studied. Temperature was categorized as ''cold,'' ''average,'' and ''warm.'' Analyses were performed on the following populations: all Major League Baseball games, games played in the National League, games played in the American League, and games played in 23 different stadiums that are currently being used by Major League Baseball teams. Home and away teams' performances were analyzed separately for each population of games. The results of this study show that runs scored, batting average, slugging percentage, on-base percentage, and home runs significantly increase while walks significantly decrease in warm weather compared to cold weather.

1. Introduction

Weather impacts our lives each and every day. For some people, weather has only a small impact on life, such as deciding what to wear on a given day. For others, though, weather can have a much larger impact, particularly on those who work outdoors, such as sportsmen in outdoor sports. One example of a weather affected sport is Major League Baseball (MLB). MLB games are played in 30 stadiums at various locations over the United States, which includes 1 stadium in Canada. Only 1 of those 30 stadiums has a permanent roof and 5 stadiums have retractable roofs, leaving the players completely exposed to the weather, and in particular, temperature. Additionally, a MLB season spans three of the four meteorological seasons: spring, summer, and fall. Thus, MLB players play in many different weather conditions.

Review of literature shows that weather has a significant impact on MLB. Recently, Kent and Sheridan (2011) examined the impact of cloud cover on many statistics of a MLB game, including batting average, home runs, walks plus hits per innings pitched, slugging percentage, earned run average, walks, strikeouts, fly ball outs, ground ball outs, errors, and winning percentage. Evidence showed that offensive production tends to decrease during clear-sky conditions as opposed to cloudy-sky or nighttime conditions. Additionally, it was found that the home teams' winning percentage increased during clear-sky conditions, which supported weather as a significant factor of home field advantage in MLB.

Several studies have investigated how home runs and fly ball distances are affected by weather. Denver's Coors Field was examined by analyzing how its micrometeorology, weather dynamics, and elevation affected fly ball distances (Chambers et al. 2003). A study by Kraft and Skeeter (1995) found that temperature has a significant impact on fly ball distances in every MLB stadium. Additionally, it was found that fly ball distances in Fenway Park (Boston, Massachusetts) were affected by humidity and wind much more than at other MLB stadiums. Home run frequencies have also been investigated and shown to be impacted by multiple meteorological conditions, including temperature, wind, and dewpoint (see, e.g., Kingsley 1980; Rohli and Faiers 2000). Although many studies investigated the relationship between various weather elements and fly ball distances or home

Corresponding author address: Anna K. Panorska, Department of Mathematics and Statistics, University of Nevada, Reno, MS 0084, Reno, NV 89557-0084.
E-mail: ania@unr.edu

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runs, with the exception of Kent and Sheridan's study, there have been very few that have examined how these weather elements impact many of the other key statistical aspects of a MLB game.

After investigating how temperature, humidity, and wind affect fly ball distances at numerous MLB stadiums, Kraft and Skeeter (1995) concluded that temperature "is the most important meteorological variable affecting fly ball distances for MLB as a whole." That study also found that batted fly balls in cool temperatures (at most 50°F) travel on average 16 ft less compared to warm temperatures (at least 90°F). Kingsley (1980) investigated the influence of temperature on home run frequencies in Atlanta, Georgia, and found evidence that higher temperatures led to an increase in the number of home runs.

Since home runs are only one measure of a MLB game, in order to learn the overall impact of temperature on baseball it is important to investigate other MLB statistics. Overall, it seems that total offensive production might be higher in warmer temperatures than in colder temperatures. A baseball's coefficient of restitution (COR), which is the ratio of speeds after and before an impact, is lower with a cold baseball compared to a warm baseball (Drane and Sherwood 2004). This means that a baseball hit in lower temperatures might be colder and leave the bat at a lower speed than in higher temperatures. Human reaction and movement time are crucial elements in hitting a pitched baseball in a fraction of a second. Rammsayer et al. (1995) found that a decrease in body core temperature results in significantly slower reaction and movement time. This may mean that cold temperatures slow a hitter's reaction and movement time, thereby decreasing his performance in cold temperatures. Thus, it appears that cold temperature could negatively impact a hitter's performance, and consequently, decrease offensive production. Another theory presented by Kingsley (1980) was: "the hitters are stressing home runs in Atlanta when the temperature is up and not stressing home runs when the temperature is down." If this was true for all stadiums when the temperature is high, then warm temperatures could have a negative impact on offensive production. If a hitter tries harder than usual to hit home runs when the temperature is up, then he might change his normal hitting mechanics and use an approach to hitting to which he was unaccustomed. Accordingly, he could earn less total base hits and walks and actually lower offensive production.

This work is a comprehensive study of how temperature impacts MLB games by analyzing its impact on numerous MLB game statistics, including runs scored, batting average, slugging percentage, on-base percentage, strikeouts, walks, hit batsmen, errors, and stolen bases. This study also analyzes the impact of temperature on home runs to determine if the results are consistent with past findings.

2. Data and methods

In this section, we discuss the data describing baseball games and temperature along with the statistical methods used in the analysis.

a. Data

This study required collection of both baseball and temperature data. Baseball data were collected from Retrosheet, a nonprofit corporation that provides MLB game data free to the public. The data we obtained from Retrosheet contained 29 150 MLB games played during the 2000–11 regular seasons. As some MLB stadiums have permanent or retractable roofs where the temperature can be controlled inside the stadium, the game data for games played in these stadiums were excluded. Temperature data, recorded in degrees Fahrenheit, were collected from the National Climatic Data Center (NCDC) from weather stations located at airports nearest to each MLB stadium. Baseball data (Retrosheet) did not specify precise start times for each game; it only designated games as a day game or a night game. For each day game we used the temperature recorded at approximately 1300 local time (LT) and for each night game we used the temperature recorded at approximately 1900 LT. We chose temperatures at 1300 and 1900 LT because MLB teams start the majority of day games and night games at 1300 and 1900 LT, respectively. We believe that the temperatures we used provide a reasonable representation of the temperatures at which each MLB game in our dataset was played. The few games for which we could not find temperatures near 1300 and 1900 LT were eliminated from the dataset. The final game dataset consisted of 22 215 games.

b. Methodology

We used Statistical Analysis Software (SAS) version 9.2 to manage and Minitab to analyze the data. Each game was categorized into one of three different groups based on the temperature at which it was played: "cold," "average," and "warm." The cold group consists of games played in temperatures less than 60°F, the average group consists of games played in temperatures between 60° and 83°F, and the warm group consists of games played in temperatures greater than 83°F. These temperature groups were chosen based on the distribution of temperatures for all MLB games played in our dataset. The average temperatures are within approximately (up to

TABLE 1. Mean values of each baseball variable studied in this research by temperature group.

Statistic	Cold	Avg	Warm
Runs scored (away team)	4.343	4.591	4.909
Runs scored (home team)	4.608	4.739	5.173
Batting avg (away batters)	0.235	0.254	0.261
Batting avg (home batters)	0.256	0.264	0.276
Slugging percentage (away batters)	0.373	0.399	0.418
Slugging percentage (home batters)	0.405	0.421	0.449
On-base percentage (away batters)	0.317	0.323	0.329
On-base percentage (home batters)	0.336	0.337	0.346
Home runs (away batters)	0.841	1.028	1.151
Home runs (home batters)	0.949	1.058	1.202
Hit batsmen (away batters)	0.349	0.342	0.388
Hit batsmen (home batters)	0.352	0.348	0.384
Walks (away batters)	3.481	3.269	3.205
Walks (home batters)	3.669	3.367	3.286
Strikeouts (away batters)	6.951	6.897	6.930
Strikeouts (home batters)	6.203	6.306	6.293
Stolen bases (away team)	0.629	0.604	0.591
Stolen bases (home team)	0.564	0.563	0.580
Errors (away team)	0.685	0.648	0.663
Errors (home team)	0.645	0.640	0.664

rounding) one standard deviation of the mean, while the cold group represents temperatures below the average group and the warm group represents temperature above the average group. Approximately 70% of all games in the dataset were played in average temperatures, 14% were played in cold temperatures, and 16% were played in warm temperatures. Next, we investigated the impact of temperature on 10 baseball statistics, listed in Table 1. For each statistic, the away batters and home batters were analyzed separately. The impact of temperature was assessed using the Wilcoxon rank-sum test (WRT) to test differences in medians between the three temperature groups. In particular, for each statistic and both the away and home batters, the WRT was used to test differences between cold and warm games, cold and average games, and average and warm games. A 5% significance level was used for the WRT. As about 90% of Major League Baseball regular season games are played within each league, the National League (NL) and the American League (AL), the leagues were analyzed separately. As night games are presumably colder than day games, the Friedman test was used to test the effects of temperature after controlling for time of game (day or night game) in each league. Additionally, understanding that all MLB ballparks differ in size and other characteristics, the WRT was also performed individually on 23 MLB stadiums, which are listed in Table 2. Examining stadiums individually also provides insight as to which stadiums are affected by temperature the most and the least. Further, to determine significance across all stadiums, the trends of each statistic from cold to warm were analyzed as well. By trend from cold to warm we understand the increase (decrease) of a given statistic from cold to warm. Using the binomial test at the 5% significance level, it was determined that the trends from cold to warm for each baseball statistic were collectively significant across all stadiums if 16 out of the 23 stadiums showed a trend in the same direction. Finally, we assumed that the pair of teams that play each game was random. That is we assumed that for each team and game, the opponent is random, thus the choice of the opponent does not influence the results. Since we analyzed over 22 000 games, we believe this assumption is reasonable.

TABLE 2. Number of games per stadium by temperature group.

Stadium	Cold	Avg	Warm
Atlanta: Turner Field	29	674	269
Baltimore: Oriole Park at Camden Yards	118	707	145
Boston: Fenway Park	254	663	55
Chicago (AL): U.S. Cellular Field	198	667	110
Chicago (NL): Wrigley Field	177	661	133
Cincinnati: Great American Ballpark	72	526	131
Cleveland: Progressive Field	194	714	58
Colorado: Coors Field	213	619	141
Detroit: Comerica Park	188	688	92
Kansas City: Kauffman Stadium	88	620	262
Los Angeles (AL): Angel Stadium of Anaheim	80	871	22
Los Angeles (NL): Dodger Stadium	114	854	4
Minnesota: Target Field	31	107	24
New York (AL): Yankee Stadium II	32	167	44
New York (NL): Citi Field	31	177	35
Oakland: O.co Coliseum	276	681	13
Pittsburgh: PNC Park	106	701	82
Philadelphia: Citizens Bank Park	65	462	123
San Diego: Petco Park	28	613	7
San Francisco: AT&T Park	315	643	15
St. Louis: Busch Stadium III	46	291	148
Texas: Rangers Ballpark in Arlington	16	376	581
Washington: Nationals Park	26	209	87

3. Results

The following sections report analysis results by baseball variable. The results for all MLB games in our study are shown in Table 1. Results by league are shown in Table 3. The statistics shown in Table 3 are those that show significant increases or decreases from cold to warm after controlling for time of game (day or night game) by either the away batters or the home batters in at least one league. All significant results by league according to the WRT remained significant when controlling for time of game with the exception of strikeouts by home batters in the National League. We assume these minimal effects of time of game among leagues are

TABLE 3. The numerical change (percent change) in baseball variables from ''cold'' to ''warm'' temperature categories by league. Bold values indicate results statistically significant (5% significance level) according to the Wilcoxon rank-sum test. ''FT P'' represents the *p* value associated with the Friedman test testing the effects of temperature (cold and warm) controlling for time of game (''day'' and ''night'').

	Away batters				Home batters			
Statistic	AL	FT P	NL	FT P	AL	FT P	NL	FT P
Runs scored	**+0.891 (21%)**	**<0.0001**	**+0.303 (7%)**	**0.049**	**+0.910 (20%)**	**<0.0001**	**+0.318 (7%)**	**0.002**
Batting avg	**+0.024 (10%)**	**<0.0001**	**+0.014 (6%)**	**<0.0001**	**+0.028 (11%)**	**<0.0001**	**+0.013 (5%)**	**<0.0001**
Home runs	**+0.380 (46%)**	**<0.0001**	**+0.250 (29%)**	**<0.0001**	**+0.346 (35%)**	**<0.0001**	**+0.192 (21%)**	**<0.0001**
Slugging percentage	**+0.059 (16%)**	**<0.0001**	**+0.034 (9%)**	**<0.0001**	**+0.061 (15%)**	**<0.0001**	**+0.076 (8%)**	**<0.0001**
Walks	−0.151 (4%)	0.143	**−0.408 (11%)**	**<0.0001**	**−0.490 (13%)**	**<0.0001**	**−0.294 (8%)**	**<0.001**
On-base percentage	**+0.019 (6%)**	**<0.0001**	+0.005 (2%)	0.170	**+0.014 (4%)**	**<0.0001**	**+0.007 (2%)**	**0.013**
Hit-batsmen	**+0.085 (26%)**	**<0.001**	−0.001 (0%)	0.756	−0.010 (3%)	0.702	**+0.075 (24%)**	**0.007**
Strikeouts	**−0.213 (3%)**	**0.004**	+0.062 (1%)	0.764	−0.097 (2%)	0.071	**+0.188 (3%)**	0.098

consistent by stadium. Accordingly, we did not consider time of game in the stadium analysis. Significant results by stadium for the home batters are shown in Table 4 and the significant results by stadium for the away batters are shown in Table 5. In these two tables, only the statistics that show a significant trend from cold to warm collectively across all stadiums are displayed. The most significant results are observed between the cold and warm temperature groups, so only those results are discussed and shown in Tables 3, 4, and 5. Only statistics that show significant results by both league and stadium are described below.

a. Runs scored

Runs scored is arguably the most important statistic in a baseball game because the team with the most runs scored wins. Thus, scoring runs and preventing the other team from scoring runs is the primary goal for all teams. In this study, the results for runs scored are very consistent among the leagues. As seen in Table 3, runs scored increase a significant amount from cold to warm for both the away batters and the home batters in both leagues. However, the American League shows much greater increases in runs scored than the National

TABLE 4. The numerical change (percent change) in baseball variables from ''cold'' to ''warm'' temperature groups for the home team at each stadium. Bold values indicate results statistically significant (5% significance level) according to the Wilcoxon rank-sum test.

Team	Runs scored	Batting avg	Slugging percentage	On-base percentage	Home runs	Walks
Anaheim	+1.002 (21%)	+0.022 (8%)	+0.046 (12%)	+0.041 (12%)	+0.081 (11%)	**+1.122 (40%)**
Atlanta	−0.073 (2%)	−0.001 (1%)	+0.029 (7%)	−0.008 (2%)	+0.255 (32%)	−0.455 (12%)
Baltimore	**+0.533 (13%)**	**+0.030 (12%)**	**+0.058 (15%)**	+0.010 (3%)	**+0.292 (32%)**	**−0.799 (22%)**
Boston	+0.395 (7%)	+0.012 (4%)	+0.043 (10%)	+0.008 (2%)	+0.228 (23%)	−0.346 (8%)
Chicago (AL)	+0.879 (19%)	**+0.035 (14%)**	**+0.077 (19%)**	+0.012 (4%)	**+0.450 (34%)**	**−0.732 (19%)**
Chicago (NL)	+0.616 (15%)	**+0.021 (8%)**	**+0.072 (19%)**	+0.005 (1%)	**+0.472 (60%)**	**−0.642 (18%)**
Cincinnati	+0.541 (12%)	**+0.031 (13%)**	+0.043 (11%)	+0.016 (5%)	+0.157 (14%)	**−0.863 (21%)**
Cleveland	+0.555 (12%)	**+0.027 (11%)**	+0.043 (11%)	+0.020 (6%)	+0.033 (3%)	−0.342 (9%)
Colorado	+0.534 (9%)	**+0.019 (7%)**	+0.037 (8%)	+0.014 (4%)	+0.151 (13%)	−0.214 (6%)
Detroit	+0.260 (6%)	+0.018 (7%)	+0.035 (9%)	+0.006 (2%)	+0.128 (14%)	−0.427 (13%)
Kansas City	+0.743 (17%)	**+0.024 (10%)**	+0.026 (7%)	+0.006 (2%)	+0.158 (22%)	**−0.755 (21%)**
Los Angeles	−2.232 (50%)	−0.034 (13%)	−0.103 (25%)	−0.036 (11%)	−0.351 (41%)	−0.031 (1%)
Minnesota	+0.078 (2%)	−0.001 (0%)	+0.041 (12%)	−0.004 (1%)	+0.312 (88%)	−0.597 (19%)
New York (NL)	−0.087 (2%)	+0.005 (2%)	+0.005 (1%)	−0.011 (3%)	−0.031 (4%)	−0.625 (16%)
New York (AL)	**+1.784 (35%)**	**+0.039 (15%)**	+0.061 (13%)	**+0.043 (12%)**	−0.042 (3%)	+0.386 (10%)
Oakland	**+3.445 (79%)**	**+0.075 (31%)**	**+0.142 (37%)**	**+0.063 (20%)**	**+0.874 (98%)**	+0.052 (1%)
Philadelphia	**+1.048 (22%)**	+0.018 (7%)	+0.050 (12%)	+0.012 (3%)	+0.273 (25%)	−0.333 (8%)
Pittsburgh	+0.711 (18%)	**+0.031 (13%)**	**+0.052 (14%)**	+0.021 (7%)	+0.192 (28%)	−0.369 (12%)
San Diego	−1.000 (29%)	−0.024 (10%)	−0.024 (7%)	−0.032 (10%)	−0.179 (24%)	−0.321 (9%)
San Francisco	**+2.362 (55%)**	**+0.045 (18%)**	+0.074 (18%)	**+0.045 (14%)**	+0.324 (37%)	+0.447 (14%)
St. Louis	+0.334 (7%)	+0.010 (4%)	+0.021 (5%)	−0.014 (4%)	+0.106 (11%)	**−1.047 (24%)**
Texas	+0.320 (6%)	−0.005 (2%)	+0.036 (8%)	−0.009 (3%)	+0.384 (34%)	−0.130 (4%)
Washington	−0.811 (17%)	+0.001 (0%)	+0.008 (2%)	−0.004 (1%)	+0.212 (29%)	−0.667 (17%)

TABLE 5. The numerical change (percent change) in baseball variables from cold to warm temperature groups for the away team at each stadium. Bold values indicate results statistically significant (5% significance level) according to the Wilcoxon rank-sum test.

Team	Runs scored	Batting avg	Slugging percentage	On-base percentage	Home runs	Walks
Anaheim	−0.492 (11%)	−0.005 (2%)	−0.017 (4%)	−0.011 (3%)	−0.003 (0%)	−0.323 (9%)
Atlanta	+.389 (10%)	+0.026 (11%)	+0.067 (21%)	+0.010 (3%)	+0.258 (37%)	−0.566 (15%)
Baltimore	**+1.049 (25%)**	**+0.028 (11%)**	**+0.093 (27%)**	**+0.017 (5%)**	**+0.403 (42%)**	−0.248 (7%)
Boston	+0.668 (16%)	**+0.022 (9%)**	**+0.054 (15%)**	+0.009 (3%)	**+0.334 (46%)**	−0.502 (16%)
Chicago (AL)	+0.461 (11%)	+0.012 (5%)	+0.034 (9%)	+0.007 (2%)	**+0.303 (30%)**	−0.163 (5%)
Chicago (NL)	**+1.421 (36%)**	**+0.033 (15%)**	**+0.104 (31%)**	**+0.020 (7%)**	**+0.818 (113%)**	−0.440 (11%)
Cincinnati	+0.556 (12%)	**+0.032 (13%)**	**+0.048 (12%)**	**+0.029 (9%)**	+0.175 (14%)	+0.007 (0%)
Cleveland	+0.142 (3%)	+0.008 (3%)	**+0.054 (15%)**	−0.003 (1%)	**+0.540 (72%)**	**−0.856 (25%)**
Colorado	+0.395 (7%)	+0.012 (4%)	+0.033 (7%)	+0.009 (2%)	**+0.292 (24%)**	−0.240 (7%)
Detroit	−0.369 (7%)	+0.002 (1%)	+0.008 (2%)	−0.006 (2%)	+0.036 (4%)	**−0.611 (17%)**
Kansas City	**+1.755 (45%)**	**+0.040 (16%)**	**+0.098 (28%)**	**+0.033 (10%)**	**+0.596 (101%)**	−0.137 (4%)
Los Angeles	+0.395 (11%)	+0.033 (14%)	+0.045 (13%)	+0.038 (13%)	+0.202 (25%)	+0.886 (28%)
Minnesota	−0.760 (16%)	−0.009 (4%)	−0.033 (8%)	−0.009 (3%)	−0.172 (21%)	−0.256 (9%)
New York (NL)	+0.397 (11%)	+0.014 (6%)	+0.023 (7%)	−0.023 (7%)	+0.258 (35%)	**−1.788 (38%)**
New York (AL)	−0.341 (8%)	−0.008 (3%)	+0.025 (7%)	−0.013 (4%)	+0.383 (45%)	−0.701 (19%)
Oakland	+0.900 (23%)	+0.018 (8%)	+0.071 (20%)	+0.010 (3%)	**+1.071 (138%)**	−0.119 (4%)
Philadelphia	−0.355 (8%)	−0.018 (7%)	−0.006 (2%)	−0.024 (7%)	+0.071 (6%)	−0.333 (11%)
Pittsburgh	+0.958 (21%)	**+0.023 (9%)**	+0.040 (11%)	+0.018 (6%)	+0.174 (22%)	−0.177 (5%)
San Diego	+0.929 (27%)	+0.013 (6%)	+0.060 (18%)	+0.043 (15%)	+0.607 (89%)	+2.607 (88%)
San Francisco	+0.968 (24%)	**+0.050 (21%)**	**+0.115 (33%)**	+0.036 (12%)	**+0.740 (112%)**	−0.276 (8%)
St. Louis	+0.873 (22%)	**+0.038 (17%)**	**+0.071 (21%)**	+0.025 (8%)	+0.322 (44%)	**−0.578 (17%)**
Texas	+1.543 (40%)	+0.014 (6%)	+0.061 (16%)	+0.013 (4%)	+0.524 (76%)	+0.192 (6%)
Washington	−0.685 (14%)	+0.010 (4%)	+0.003 (1%)	−0.007 (2%)	+0.069 (8%)	**−0.818 (24%)**

League. Away batters in the American League show a 21% increase in runs scored from cold to warm while the away batters in the National League show only a 7% increase in runs scored from cold to warm. Similar results hold for the home batters.

An increase in runs scored from cold to warm is seen in 18 out of 23 stadiums (78.2%) for both the home team and the away team. The largest stadium increases in runs scored for the home teams are seen in Northern California at the homes of the San Francisco Giants and the Oakland Athletics. The Athletics scored an average of 4.351 runs in cold temperatures and an astounding average of 7.769 runs in warm temperatures, an increase of 79%. The Giants showed similar results, scoring an average of 4.305 runs in cold temperatures and an average of 6.667 runs in warm temperatures, representing a 55% increase. However, these results may be affected by the relatively small number of games played in warm temperatures for both teams: 13 for the Athletics and 15 for the Giants. Along with the Athletics and the Giants, the Baltimore Orioles, New York Yankees, and Philadelphia Phillies showed a significant increase in runs scored from cold to warm at their home stadiums. Significant stadium increases in runs scored by the away teams (or runs allowed by the home teams) are seen at Kauffman Stadium, Wrigley Field, and Orioles Park at Camden Yards, homes of the Kansas City Royals, Chicago Cubs, and Baltimore Orioles, respectively.

b. *Batting average*

One of the most popular statistics in measuring offensive production in baseball is batting average. In both leagues, batting average shows significant increases from cold to warm for both the away and home batters. Similar to runs scored, the American League shows greater increases in batting average from cold to warm than the National League for both the away hitters (10% for the American League compared to 6% for the National League) and the home hitters (11% for the American League compared to 5% for the National League).

An increase in batting average is seen in 19 out of 23 stadiums (82.6%) for the home batters and in 20 out of 23 stadiums (87.0%) for the away batters. Eleven teams show significant increases in batting average from cold to warm at games played in their home stadiums. Eight ballparks show significant increases in batting average from cold to warm for the opposing batters. The stadiums that are the homes to the Baltimore Orioles, Chicago Cubs, Cincinnati Reds, Kansas City Royals, Pittsburgh Pirates, and San Francisco Giants show significant increases in batting average from cold to warm for both the home and away batters.

c. *Home runs*

Another popular offensive statistic in Major League Baseball is the home run. As expected, home runs were strongly affected by temperature in this study. Both leagues showed significant increases in home runs from cold to warm for both the home and away batters. Again, the American League shows much larger increases in home runs from cold to warm than the National League. Away batters in the American League hit an average of 46% more home runs in warm temperatures compared to cold temperatures while away batters in the National League hit an average of 29% more home runs in warm temperatures. Similar results hold for the home batters.

A positive trend in home runs from cold to warm was noted in 22 out of 23 (95.7%) stadiums for the away batters and in 19 out of 23 stadiums (82.6%) for the home batters. The only stadium that showed a decrease in the number of home runs from cold to warm for the away batters was Angel Stadium of Anaheim, which showed a 0.003 decrease in home runs. This could be due to the small number of games played in warm temperatures at Angel Stadium (i.e., 22). Four stadiums showed significant increases in home runs for the home batters while nine stadiums showed significant increases in home runs for the away batters. Away batters in the Oakland Athletics stadium are hitting an average of 1.071 more home runs in games played in warm temperatures compared to cold temperatures, an increase of 138%. This could be due to the small number of games played in warm temperatures at Oakland's stadium.

d. Slugging percentage

Slugging percentage is similar to batting average, but with more weight put on extra base hits, such as doubles, triples, and home runs. Hence, slugging percentage is often considered a more efficient measure of offensive production than batting average as extra base hits often produce more runs than singles. In both leagues, slugging percentage shows a significant increase from cold to warm for the away and home batters. Additionally, the increases in the American League are larger than those in the National League. Overall, 21 out of 23 stadiums (91.3%) show increases in slugging percentage from cold to warm for both the away batters and the home hitters. For the home hitters, five of these increases are significant, and for the away hitters, eight of the increases are significant.

e. Walks

In both leagues, walks show a decrease from cold to warm. Away batters show a significant decrease in walks in the National League from cold to warm, whereas American League away batters do not show a significant decrease in walks from cold to warm. Home batters show significant decreases in walks from cold to warm in both the American League and the National League, with the American League showing a larger average decrease. Overall, 19 out of 23 stadiums show a decrease in walks for both the home batters and the away batters. Six of those decreases are significant for the home batters while five are significant for the away batters. Home batters that show the most significant decrease in walks from cold to warm are those that play in Busch Stadium III, home of the St. Louis Cardinals, where walks decrease by 1.047 on average, a 24% decrease. The away batters that show the most significant decrease in walks from cold to warm are those that play at Citi Field, home of the New York Mets, where walks decrease by 1.788 on average, a 38% decrease.

4. Discussion

It appears that temperature has a formidable impact on the offense in a MLB game. Overall, offensive production tends to increase in warm weather as runs scored, batting average, slugging percentage, and home runs all show significant increases in games played in warm temperatures compared to cold temperatures. Our findings can be explained by the possible impact of temperature on a baseball's COR, human reaction time and movement, and a baseball's flight distance (see Drane and Sherwood 2004; Rammsayer et al. 1995; Kraft and Skeeter 1995).

The American League shows a much stronger association between temperature and many offensive statistics—runs, home runs, batting average, and slugging percentage—than the National League, which might also suggest that the offense is impacted by temperature more than pitching and defense. In games played under National League rules, the pitcher must bat, which is a disadvantage offensively because most pitchers do not hit as well as position players. However, in the American League, teams use a designated hitter to bat for the pitcher. Consequently, American League lineups contain better hitters as a whole than the National League. Additionally, the two leagues differ in how managers typically attempt to manufacture runs. Sacrifice bunts are more widely used to manufacture runs in the National League than in the American League. For example, National League teams averaged 71.1 sacrifice bunts in the 2011 regular season, whereas American League teams only averaged 37.9 sacrifice bunts in the same season. Further, a National League team that needs to sacrifice their pitcher (or another batter) to score a run may not score as many runs in an inning as an American League team that allows the ninth hitter in the lineup (or another batter) to try to reach base without giving up an out. These reasons may explain why games played in the American League

TABLE 6. Per game mean values for runs scored, home runs, batting average, and slugging percentage for games played in the American and National Leagues. The p value is associated with the Wilcoxon rank-sum test.

Statistic	American League	National League	p value
Runs scored	9.80	9.07	<0.0001
Home runs	2.18	2.01	<0.0001
Batting avg	0.266	0.258	<0.0001
Slugging percentage	0.422	0.407	<0.0001

produced significantly more runs and home runs and had higher batting averages and slugging percentages per game than games played in the National League (Table 6). Consequently, runs scored, home runs, batting average, and slugging percentage show a stronger dependence on temperature in the American League.

Walks, which tend to decrease as temperatures increase, is the only statistic that shows a significant negative effect for the offense in warm temperatures compared to cold temperatures. We believe that this is due to the effect of cold weather on the pitcher. Our hands typically get dry in cold weather (Uter et al. 1998). A pitcher with dry hands may not be able to get as good a grip on the baseball as a pitcher with nondry hands, which may result in reduced control and more walks. Even though pitchers use rosin bags to dry their hands in warm weather to help them grip the baseball, they also frequently blow into their hands and lick their fingers during cold weather, presumably to help them grip the ball. Since these acts provide moisture to the hand, it seems that dryness caused by cold weather negatively impacts a pitcher's grip. Diminished pitching control in cold weather could also be caused by the effect of temperature on strength. Low muscle temperature reduces maximal strength in short-term exercises, like pitching (Bergh and Ekblom 1979). Consequently, cold temperature might decrease a pitcher's ability to grip a baseball. However, pitchers try to keep warm between innings during cold weather by wearing jackets or other warming devices on their pitching arms, so the effect of cold weather on a pitcher's muscular temperature is uncertain.

Given the results of this study, it may be beneficial for managers of MLB teams to take game-day temperature into account when setting their lineups. For instance, if a manager is having difficulty choosing between two players for his starting lineup, and one player is a more patient hitter and tends to draw more walks than the other player, the manager might benefit from starting the patient hitter in cold temperatures. Since batting average, slugging percentage, and home runs occur less frequently while walks occur more frequently in colder temperatures, a hitter may be more likely to reach base via a walk rather than with a hit on these days, possibly making a patient hitter more offensively efficient in cold temperatures. Knowing that runs are less likely in cold temperatures, managers could use this knowledge to gain an advantage when making in-game decisions as well. For example, managers are often faced with a difficult decision of whether or not to sacrifice bunt in certain situations. Since a sacrifice bunt allows a player to move into scoring position while giving up an out, it is usually used to manufacture one run in an inning as a base hit after the sacrifice should score a run. The decision to not sacrifice bunt is usually made in hopes of earning a few hits in an inning and possibly scoring more than one run in the inning. Consequently, a manager may benefit from a sacrifice bunt during times when hits are less likely, as in cold temperatures, compared to times when hits are more likely, as in warm temperatures.

Our study has several limitations. One of them is the small sample size of games seen in the cold or warm temperature categories at certain stadiums. The stadiums in San Diego, San Francisco, Oakland, Los Angeles (NL), Los Angeles (AL), Atlanta, Texas, Minnesota, and Washington all had less than 30 games played in either the cold or warm temperature category. As a result, some of these stadiums showed results that were not consistent with the results found in other stadiums. For example, Atlanta, Los Angeles (NL), San Diego, and Washington all showed a decrease in runs scored from cold games to warm games. On the other hand, some of these stadiums showed much stronger results than others, such as the stadiums in Oakland and San Francisco.

Another limitation of this study is control for other weather variables that could impact player performance. For example, adding humidity, cloud cover, and wind to this analysis may show the combined effect of weather on a MLB game.

Despite numerous significant results that have been found in this study, there may be a more complex dependence between temperature and baseball that has yet to be discovered. The impact of temperature on winning percentage, which could be used to measure a team's quality, was not explored in this research. However, based on our results, temperature could have a significant impact on winning percentage. For example, the Philadelphia Phillies and the New York Yankees both showed a significant increase in runs scored for home games in warm temperatures compared to cold temperatures while both teams also allowed less runs in warm temperatures compared to cold temperatures. This suggests that these two teams may win a higher percentage of games in warm temperatures, but a more thorough analysis should be used to account for other factors, such as the opposition. Temperature categories that are more team specific, rather than the categories that were used for all teams in this research, could also be used to analyze the impact of temperature on winning percentage and other baseball statistics. Finally, future research might examine why some stadiums appear to be more affected by temperature than others, which is beyond the scope of this study.

5. Conclusions

The results show that, overall, offensive production is higher in warm temperatures compared to cold temperatures. Across all populations, runs scored, batting average, slugging percentage, and home runs show significant increases while walks show significant decreases in warm temperatures compared to cold temperatures. Additionally, the American League shows a much stronger impact of temperature on the statistics than the National League.

Consistent with past findings, home runs were most affected by temperature, increasing from 1.79 per game in cold temperatures to 2.35 per game in warm temperatures for away and home batters combined. Runs scored, which is arguably the most important statistic of a MLB game, showed the second strongest response to temperature in this study, increasing from an average of 8.95 per game in cold temperatures to 10.08 per game in warm temperatures overall. Home batters playing for the Oakland Athletics benefit the most from warm weather, where runs scored, batting average, slugging percentage, on-base percentage, and home runs all show significant increases in warm temperatures compared to cold temperatures. Away batters playing in Baltimore, Chicago's Wrigley Field, and Kansas City should expect greater offensive production in warm weather as runs scored, batting average, slugging percentage, on-base percentage, and home runs increase significantly in warm temperatures at those stadiums compared to cold temperatures.

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