The Effect of Ambient Temperature on the Movement of a Baseball Pitch

Christopher Youngdahl (1), LaNell A. Williams (2)

(1) San Marcos High School, Santa Barbara CA, 93110

(2) Princeton University, Department of Physics, Princeton NJ, 08544

Abstract - **While prior studies acknowledge environmental effects on the movement of a baseball pitch, most rely on observational in-game data with uncontrolled variables, leaving a gap in experimental research that isolates the role of ambient temperature. To address this, we investigated the effect of ambient temperature on the vertical and horizontal movement of fastballs, curveballs, and sliders across three controlled conditions: cold (55°F), average (70°F), and hot (85°F). We hypothesized that pitch movement across all three pitch types would decrease as ambient temperature increased due to reduced air density and aerodynamic forces. Pitches were delivered using a calibrated three-wheel pitching machine at 54.2 feet and recorded using video-tracking software. Relevant external variables were controlled to isolate the impact of temperature. Results demonstrate an inverse relationship between temperature and pitch movement, with colder conditions producing increased movement. Curveballs and sliders exhibited the greatest sensitivity to temperature changes, with increases in vertical and horizontal movement in colder air, while fastballs showed more subtle variations. To support these findings under controlled conditions, a Python-based simulation was constructed using drag models, isolating temperature-dependent air densities and horizontal/vertical wind vectors. The computational model further demonstrated that the reduced velocity decay and trajectory deflection observed in warmer air are driven by density-induced reductions in drag force, establishing a theoretical baseline that bridges physical field data with fluid dynamic principles. These findings highlight the role of environmental conditions on pitch behavior, offering insights for players and coaches to account for weather conditions when evaluating pitch movement.**

Index Terms - Ambient temperature, Pitch movement, Aerodynamic drag, Baseball physics

I. INTRODUCTION

Pitch movement—the deviation of a baseball from its predicted, spinless trajectory—is a fundamental aspect of baseball pitching that significantly affects a pitcher's ability to get hitters out (1). A pitched baseball experiences forces such as drag and lift, generated primarily by the ball's spin and the orientation of its seams (2). These aerodynamic forces alter the ball's flight path, creating what players and analysts refer to as "break" or "movement." The magnitude and direction of this movement directly influence how difficult a pitch is to hit, making movement a vital component of pitching performance (1).

Ambient environmental factors, including temperature, humidity, wind, and air pressure, impact drag and lift by altering the properties of the air through which the ball travels (3). Among these factors, ambient temperature may play a particularly important role because it changes air density—a key determinant of the drag and lift forces acting on the baseball (3). Increased air density alters aerodynamic forces, which can enhance the ball's movement by increasing drag (slowing the ball) and lift (changing its vertical and horizontal trajectory) (3). Conversely, warmer air is less dense, reducing these forces and potentially decreasing pitch movement (3).

Understanding the relationship between ambient temperature and pitch movement is not only scientifically significant but also practically valuable for players, coaches, and teams. If temperature has a significant impact on how much a pitch moves, pitchers may need to adjust their technique or pitch selection depending on the weather. For example, breaking pitches like curveballs and sliders, which rely heavily on spin-induced Magnus lift forces (4), may become less effective when air density is altered. Coaches could consider this while arranging pitching strategies and game plans to maximize performance in different temperature environments. For example, a coach might choose a pitcher who throws mostly breaking pitches on one day over a pitcher who throws mostly fastballs. On another day with a different temperature, a coach might use a pitcher who throws mostly fastballs because breaking pitches will be less effective.

The central question this research addresses is: How does ambient temperature affect the movement of baseball pitches? This study focuses specifically on three common pitch types: the four-seam fastball, the curveball, and the slider. These three pitches were chosen because they are among the most popular and widely used in baseball. As a group, they are ideal for studying how temperature affects pitch behavior because each pitch type has unique movement characteristics (5, 6).

The fastball is the most common pitch and is typically characterized by its high velocity and relatively straight trajectory (6). The curveball is known for its significant vertical drop and its sometimes pronounced horizontal break (6). It relies heavily on spin-induced lift forces (5), making it highly sensitive to changes in environmental conditions like air density. The slider combines both horizontal and vertical movement, offering a sharp, late break that differs from the curveball's more looping motion (6). It typically has a velocity between that of a curveball and a fastball and is one of the most effective pitches in baseball. Together, these pitches cover a broad spectrum of movement types, allowing for a comprehensive investigation into how temperature influences pitch behavior.

This investigation compares pitch movement—both vertical and horizontal—across three temperature conditions: cold (approximately 55°F), average (around 70°F), and hot (near 85°F). By isolating temperature as the independent variable, while controlling for other variables such as spin rate, velocity, humidity, and wind, this study aims to provide insight on temperature's effect on pitch movement. Furthermore, this investigation pairs physical pitching machine experiments with a computational Python simulation of drag. The computational model evaluates pitch dynamics across 45 distinct conditions, mimicking the same pitch types and environmental factors as the physical experiment. In addition, the model incorporates horizontal and vertical wind vectors to suggest a possible effect of wind on pitch movement.

This research is significant because, while prior studies have broadly acknowledged that environmental conditions influence baseball performance, there is limited experimental work isolating temperature's specific role in pitch movement. Many existing analyses derive from observational data during games, where multiple variables fluctuate simultaneously, making it difficult to pinpoint the isolated effect of temperature (7). This study aims to fill that gap by utilizing controlled experimental conditions, thereby providing deeper insight of how temperature affects pitch behavior. Furthermore, by pairing empirical field data with a computational simulation, this framework provides a theoretical baseline that reduces physical noise (e.g. human error, wind, equipment error).

We hypothesized that colder temperatures would increase pitch movement due to higher air density and aerodynamic forces. In alignment with our hypothesis, our results revealed that horizontal and vertical pitch movement increased as temperature dropped from 85 °F to 70 °F to 55 °F, with sliders and curveballs demonstrating greater temperature sensitivity than fastballs.

II. METHODOLOGY

This study employs a controlled experimental design to examine and quantify the effect of ambient temperature on the movement of baseball pitches. The experiment was conducted using a Hack Attack three-wheel pitching machine, selected for its ability to deliver consistent pitch speeds, spin rates, and spin axes. Consistency was critical to ensure that ambient temperature was the primary varying factor influencing pitch movement. The pitching machine was positioned at a distance of 54.2 feet, measured from the machine's release point to the front edge of home plate using a tape measure. This distance was less than the official MLB pitching distance of 60 feet and 6 inches to account for realistic pitcher release extension (8). The average pitcher strides and extends the ball 6.3 feet in front of their body before releasing, which decreases the actual distance the ball stays in the air to 54.2 feet (8). The machine released the ball 52 inches off the ground and was calibrated to throw each pitch across the middle of the plate. To create a stable and consistent visual background for pitch tracking, a protective screen was placed one foot behind home plate. This screen helped minimize visual distractions and improved the accuracy of video-based tracking software. It also provided a spot to film behind for alternative camera angles.

The baseballs used in this study were new National Federation of State High School Associations (NFHS)-certified balls, identical in brand and manufacture, inspected prior to use to confirm the absence of any significant scuffs, dirt, or surface imperfections that could affect aerodynamics. Six baseballs were rotated across each pitch to limit the effects of built up surface wear on pitch movement. One baseball in every rotation was marked on one hemisphere with black Sharpie ink. This marking enhanced visibility of the ball's rotation and spin axis during video capture, aiding in precise spin rate calculation.

Three pitch types were selected for testing—fastballs, curveballs, and sliders—due to their prevalence in baseball and distinct movement characteristics (6). Fastballs are high-velocity, direct pitches that use heavy backspin to generate lift that resists gravity (5). Curveballs are slower, high-movement pitches defined by heavy topspin that creates a sharp downward drop and often horizontal sweep (5). Sliders travel at speeds between a fastball and curveball and rely primarily on sidespin to generate horizontal sweep (5). Target pitch velocities were set at 85 miles per hour for fastballs, 80 miles per hour for sliders, and 75 miles per hour for curveballs, reflecting realistic velocity profiles typical of high school, collegiate, and low-level professional competition (9, 10).

To achieve these velocities with consistent spin rates and axes, the pitching machine's wheel speeds, angles, and release points were calibrated for each pitch type. A Pocket Radar, a reliable and professional grade speed radar, was used to maintain consistent speed within each pitch type. All of the pitches recorded traveled at their previously designated velocities within a tolerance of 1 mile per hour. These experimental pitch velocities were directly parameterized into the computational model. In addition, a launch angle of -2° was assigned to fastballs, 0° for sliders, and +2° for curveballs. These launch angles reflect real world launch angles of the three pitches (11).

Environmental conditions were monitored to limit temperature as the primary independent variable affecting pitch movement. The study took place over three test sessions conducted on different days with substantially different ambient temperatures. There was a baseline session at 70°F and two more comparison sessions at 55°F and 85°F. To reduce confounding influences, humidity was maintained within a tolerance of ±5% among the three sessions. Barometric pressure was controlled to remain within ±0.5 inches of mercury (inHg), and wind speeds were limited to below 2 mph, consistently blowing in the same direction for the duration of each session. Environmental parameters were obtained using localized meteorological data, and temperature was verified using an onsite thermometer. No pitches were recorded when environmental variables exceeded these limits. The calculated air density values across these three temperatures served as key density inputs in the computational drag model.

Pitch trajectories were recorded using a high-speed digital camera (iPhone 16) capturing video at 240 frames per second. The phone recorded pitches from multiple angles including directly behind the pitching machine, directly in front, and behind home plate. This camera placement maximized visibility of both the horizontal and vertical components of pitch movement while minimizing distortion and error. To prevent lens distortion from skewing measurements, software tracking was centered within the middle of the frame rather than near the edges. Lighting conditions were kept constant to ensure video clarity for post testing analysis.

Recorded video files were imported into Kinovea, a professional-grade sports science image analysis software, for frame-by-frame pitch tracking. Kinovea was used to track each pitch's spin rate and movement. Spin rate was calculated manually by measuring revolutions and time, then converting to revolutions per minute (RPM). Kinovea’s calibration features were employed to convert pixel distances into real-world units of inches, using known reference lengths in the video frame. Real-world distance scale was set in Kinovea using physical reference objects directly in the flight path: the 17.0-inch width of home plate and a 12.0-inch reference line marked on the screen behind the plate. This ensured consistent and precise dimensional accuracy across all tracked pitches. To measure movement, the ball’s center was manually marked on every frame throughout its flight path, capturing precise horizontal and vertical positional data points. These values for movement were then translated into horizontal movement and induced vertical break. Induced vertical break—often referred to simply as vertical break or vertical movement—is the vertical deviation of the ball relative to a hypothetical, gravity-only trajectory. This gravity-only baseline was calculated using standard kinematic equations in a vacuum:

$$x_{ref}(t) = x_0 + v_{x0}t$$

$$y_{ref}(t) = y_0 + v_{y0}t - \frac{1}{2}gt^2$$

where g = 9.81 m/s^2. Because gravity acts exclusively in the vertical direction, horizontal movement is already generated entirely by aerodynamic forces and remains unchanged. Conversely, vertical displacement includes the constant acceleration of gravity, requiring vertical data to be converted into induced vertical break by subtracting the displacement due to gravity. For every pitch, data relied on the ball's actual initial position (x_0, y_0) and release velocity (v_{x0}, v_{y0}) extracted from the first frame and the speed radar. Total movement and vertical break were measured from the instant the ball left the wheels of the machine to the instant it crossed the front edge of home plate. Human tracking error was evaluated by tracking each pitch three separate times, yielding a maximum manual tracking variance of ± 0.8 inches. Outlying data, such as movement for pitches that landed significantly outside of the strike zone, or pitches where the spin rate was outside of a 50 RPM tolerance, were excluded. For each pitch type, the first twelve trials meeting these consistency criteria were recorded and included in the final dataset.

Following data extraction, pitch data—including velocity, environmental conditions, and values for movement—were organized into datasets and imported into Anaconda. Statistics, including means and standard deviations, were calculated to summarize movement and consistency across conditions. To test for differences across temperature groups, one-way Analysis of Variance (ANOVA) tests were conducted, yielding F-statistics, p-values, and effect sizes (η^2).

To establish a baseline model to confirm and compare our field experiment to, a Python simulation was executed in Anaconda using standard numerical integration libraries (NumPy and Matplotlib). The simulation modeled a non-spinning hard sphere, the size and mass of a baseball, moving through air. It modeled a gravity plus quadratic drag trajectory governed by state derivatives:

$$\frac{dx}{dt} = v_x, \frac{dy}{dt} = v_y$$

$$a_x = \frac{F_{D,x}}{m}, a_y = -g + \frac{F_{D,y}}{m}$$

where instantaneous quadratic drag was calculated using ball velocity relative to surrounding air.

$$F_D = -\frac{1}{2}\rho_{air} C_D A|v_{rel}|v_{rel}$$

Equations of motion were integrated numerically using a fourth-order Runge-Kutta (RK4) algorithm with a discrete time step of 0.001 s. Output plots included total time to target, arrival speed, horizontal speed loss, instantaneous drag force magnitude, and drag acceleration. Results were exported to CSV tables and high-resolution PNG plots.

Multiple measures were taken throughout the study to maximize accuracy, reliability, and repeatability. The pitching machine's settings, positions, and release angles were kept the same for each of the three testing days. The same six near-identical balls were each used three times for each type of pitch on each day. Environmental parameters were logged and continuously cross-checked against external weather reports to ensure consistent environmental factors during pitch collection. Each pitch's trajectory was tracked multiple times in Kinovea, and discrepancies were resolved through comparison and remeasurement to minimize human error.

By combining mechanical pitch delivery, environmental monitoring, detailed manual tracking, numerical computational modeling, and rigorous data analysis, this methodology established a robust framework to quantify the relationship between ambient temperature and baseball pitch movement while minimizing confounding variables. This methodology directly tests the hypothesis that ambient temperature influences the movement of baseball pitches and provides a replicable framework for future studies investigating environmental effects on ball flight dynamics.

III. RESULTS

We used experimental and computational approaches to measure how temperature alters pitch movement across distinct pitch types.

SECTION 1: OVERVIEW OF EXPERIMENTAL SETUP AND FINDINGS

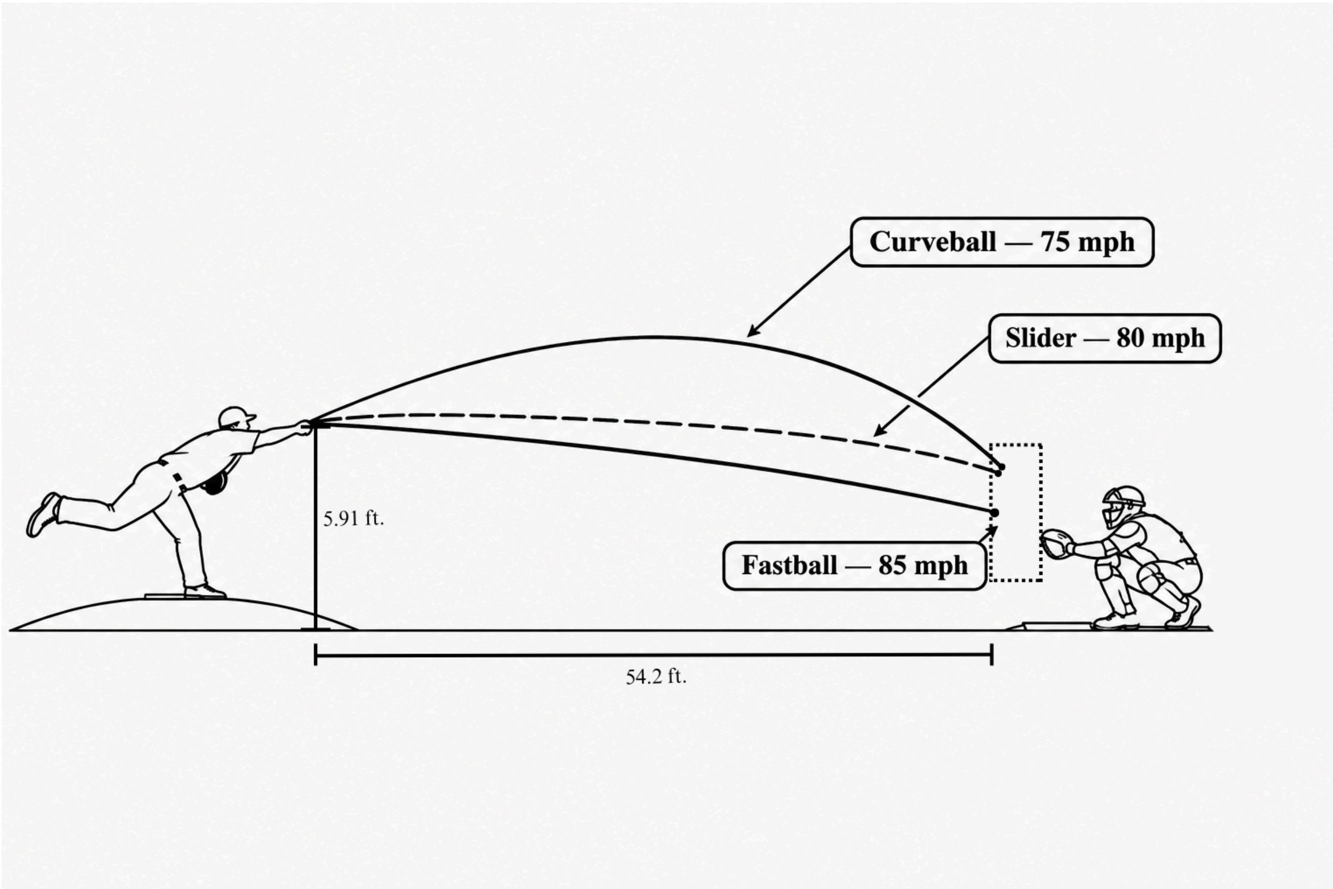

Figure 1: Diagram of pitch types. The trajectory of a fastball, curveball, and slider are illustrated from release (54.2 ft) to home plate. Fastballs are high velocity with minimal movement, curveballs are low velocity with vertical drop, and sliders are moderate velocity with lateral sweep and drop. Speed for each pitch type, release height, and distance are labeled.

Pitch movement was measured for fastballs, curveballs, and sliders across cold (55°F), average (70°F), and hot (85°F) temperature conditions over a distance of 54.2 feet (Figure 1). High-speed video analysis and Python modeling for all three temperature conditions were used to compare changes in movement. Horizontal, vertical, and total movement were compared to determine how temperature affected each pitch type. We found that pitches exhibited increased movement in colder temperature environments compared to warmer conditions, although the size of this change differed among the three pitch types. We conclude that lower ambient temperatures enhance overall pitch movement by increasing air density and total aerodynamic forces. To examine these temperature-related changes more closely, horizontal movement and vertical movement were first analyzed separately.

Section 2: Horizontal Movement

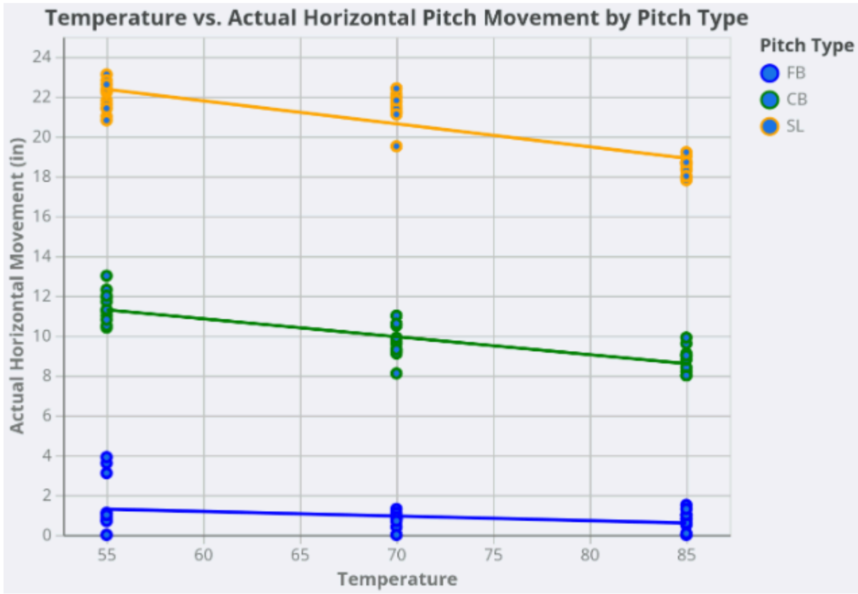

Figure 2: Horizontal pitch movement across ambient temperatures. Magnitude of horizontal displacement (inches) plotted against temperature (55 °F, 70 °F, and 85 °F) over a 54.2 ft flight distance for fastballs (FB), curveballs (CB), and sliders (SL). Movement was tracked via Kinovea high-speed video analysis, with solid lines representing linear best-fit trends (n = 12 pitches per temperature per pitch type; total N = 36 per group). Sliders exhibited the greatest lateral decay (-0.115 in/°F, $p < 0.001$), followed by curveballs (-0.090 in/°F, $p < 0.001$) and fastballs (-0.023 in/°F, $p = 0.086$).

Horizontal movement generally decreased as temperature increased from 55°F to 85°F. To find horizontal movement across pitches, we used Kinovea to track the magnitude of horizontal displacement for all three pitch types across 55°F, 70°F, and 85°F. A linear best-fit line was used to summarize the observed trend across the three temperatures (Figure 2). The slider showed the largest change in horizontal movement, decreasing from 22.0 inches at 55°F to 21.4 inches at 70°F, and finally to 18.5 inches at 85°F (-0.115 in/°F) [$F(2, 33) = 100.26, p < .001, \eta^2 = 0.86$]. The curveball changed from 11.5 inches at 55°F to 9.6 inches at 70°F, and finally to 8.8 inches at 85°F (-0.090 in/°F) [$F(2, 33) = 42.31, p < .001$, $\eta^2 = 0.72$]. Finally, the fastball had the least change in horizontal movement, decreasing from 1.4 inches at 55°F to 0.7 inches at both 70°F and 85°F (-0.023 in/°F) [$F(2, 33) = 2.64, p = .086, \eta^2 = 0.14$]. We conclude that lateral pitch movement decays as temperature rises, with sliders exhibiting the greatest lateral sensitivity. After examining side-to-side movement, vertical movement was analyzed to determine whether temperature produced a similar pattern.

SECTION 3: VERTICAL MOVEMENT (INDUCED VERTICAL BREAK)

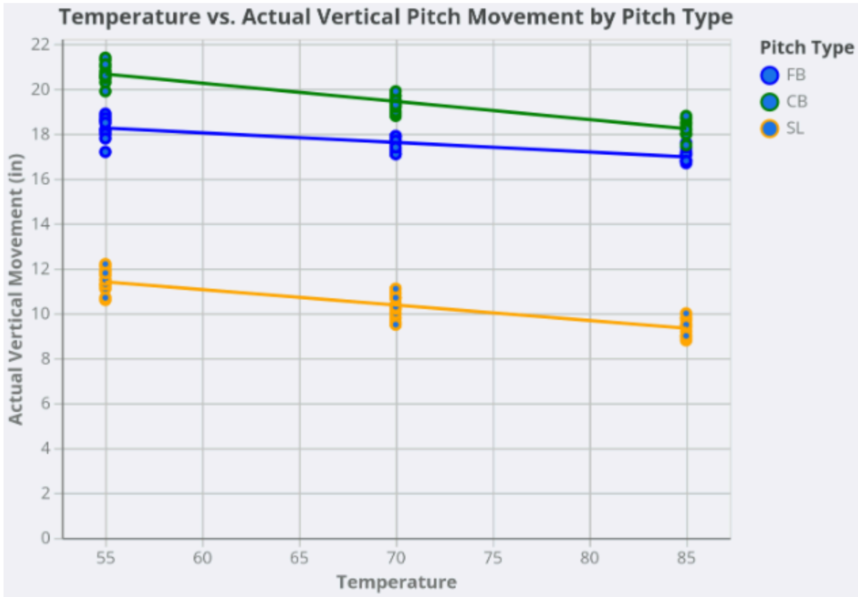

Figure 3: Vertical pitch movement across ambient temperatures. Magnitude of induced vertical break (inches) plotted against temperature (55 °F, 70 °F, and 85 °F) over a 54.2 ft flight distance for fastballs (FB), curveballs (CB), and sliders (SL). Movement was tracked via Kinovea high-speed video analysis, with solid lines representing linear best-fit trends (*n* = 12 pitches per temperature per pitch type; total *N* = 36 per group). Curveballs exhibited the greatest vertical change (-0.081 in/°F, $p < 0.001$), followed by sliders (-0.069 in/°F, $p < 0.001$) and fastballs (-0.043 in/°F, $p < 0.001$).

Vertical movement (induced vertical break) also changed with temperature, but the effect was smaller than the effect observed for horizontal movement. The magnitudes of vertical movement were evaluated across 55°F, 70°F, and 85°F using linear best-fit regressions (Figure 3). We measured vertical breaks for fastballs, curveballs and sliders across all temperatures. The curveball showed the largest change, with the magnitude of vertical movement dropping from 20.7 inches at 55°F, to 19.3 inches at 70°F, and to 18.3 inches at 85°F (-0.081 in/°F) [$F(2, 33) = 121.49, p < .001, \eta^2 = 0.88$]. The magnitude of the slider's vertical break decreased from 11.5 inches at 55°F, to 10.3 inches at 70°F, and finally 9.4 inches at 85°F (-0.069 in/°F) [$F(2, 33) = 56.97, p < .001, \eta^2 = 0.78$]. In comparison, the fastball showed the smallest temperature-related change, moving from 18.3 inches at 55°F, to 17.5 inches at 70°F, and to 17.0 inches at 85°F (-0.043 in/°F) [$F(2, 33) = 36.26, p < .001, \eta^2 = 0.69$]. These results indicate that the horizontal and vertical components of pitch movement did not respond equally to temperature. Because horizontal and vertical movement describe only separate parts of a pitch's path, total movement was then calculated to compare the overall effect of temperature.

Section 4: Total Movement

METRIC	FASTBALL	CURVEBALL	SLIDER
Average Movement (in)			
Horizontal 55 Degrees	1.4 $\pm$ 1.3	11.5 $\pm$ 0.8	22.0 $\pm$ 0.7
Vertical 55 Degrees	18.3 $\pm$ 0.5	20.7 $\pm$ 0.4	11.5 $\pm$ 0.5
Total 55 Degrees	18.4 $\pm$ 0.5	23.7 $\pm$ 0.4	24.8 $\pm$ 0.5
Horizontal 70 Degrees	0.7 $\pm$ 0.7	9.6 $\pm$ 0.8	21.4 $\pm$ 0.7
Vertical 70 Degrees	17.5 $\pm$ 0.3	19.3 $\pm$ 0.3	10.3 $\pm$ 0.5
Total 70 Degrees	17.5 $\pm$ 0.3	21.6 $\pm$ 0.2	23.8 $\pm$ 0.6
Horizontal 85 Degrees	0.7 $\pm$ 0.5	8.8 $\pm$ 0.6	18.5 $\pm$ 0.4
Vertical 85 Degrees	17.0 $\pm$ 0.3	18.3 $\pm$ 0.4	9.4 $\pm$ 0.4
Total 85 Degrees	17.0 $\pm$ 0.3	20.3 $\pm$ 0.4	20.8 $\pm$ 0.3
Percent Increase: 55° vs 85° Movement			
Horizontal Movement	100.0% more	30.7% more	18.9% more
Vertical Movement	7.7% more	13.1% more	22.3% more
Total Movement	7.9% more	16.7% more	19.4% more

Table 1: Horizontal, vertical, and total pitch movement (inches) for fastballs, curveballs, and sliders evaluated across cold (55 °F), average (70 °F), and hot (85 °F) ambient temperatures. Total movement represents the resultant vector ($\sqrt{Horizontal^2 + Vertical^2}$). Relative movement gains are expressed as percentage increases from 85 °F to 55 °F. Data presented as Mean ± Standard Deviation ($n = 12$ pitches per condition; total $N = 36$ per pitch type).

Total movement was calculated as the resultant vector (hypotenuse) of the horizontal and vertical movement components for each pitch. The change in movement was then quantified into relative percentage increases from 85°F to 55°F (Table 1). The average total fastball movement changed from 17.0 inches to 18.4 inches, representing a 7.9% increase [$F(2, 33) = 36.11, p < .001, \eta^2 = 0.69$]. The curveball changed from 20.3 inches to 23.7 inches, yielding a 16.7% increase [$F(2, 33) = 290.28, p < .001, \eta^2 = 0.95$]. Finally, sliders rose from 20.8 inches to 24.8 inches, showing a 19.4% increase [$F(2, 33) = 223.93, p < .001, \eta^2 = 0.93$]. Therefore, sliders showed the greatest overall temperature-related change, followed by curveballs, while fastballs showed the smallest change. The physical experiment established how pitch movement changed with temperature. A computational simulation was then used to investigate whether temperature-related changes in air density and drag could help explain this pattern.

Section 5: Computational simulation setup and overview

The simulation compared baseball motion at 55°F, 70°F, and 85°F under controlled computational conditions. It included temperature-dependent air density, drag force, starting velocity, velocity loss, and flight time. Because the model did not include spin-induced Magnus lift, it was used to study a possible aerodynamic mechanism rather than directly reproduce the measured horizontal and vertical break. The simulation first examined how temperature changed air density and the drag force acting on the baseball.

Section 6: Effect of Air Density and Drag

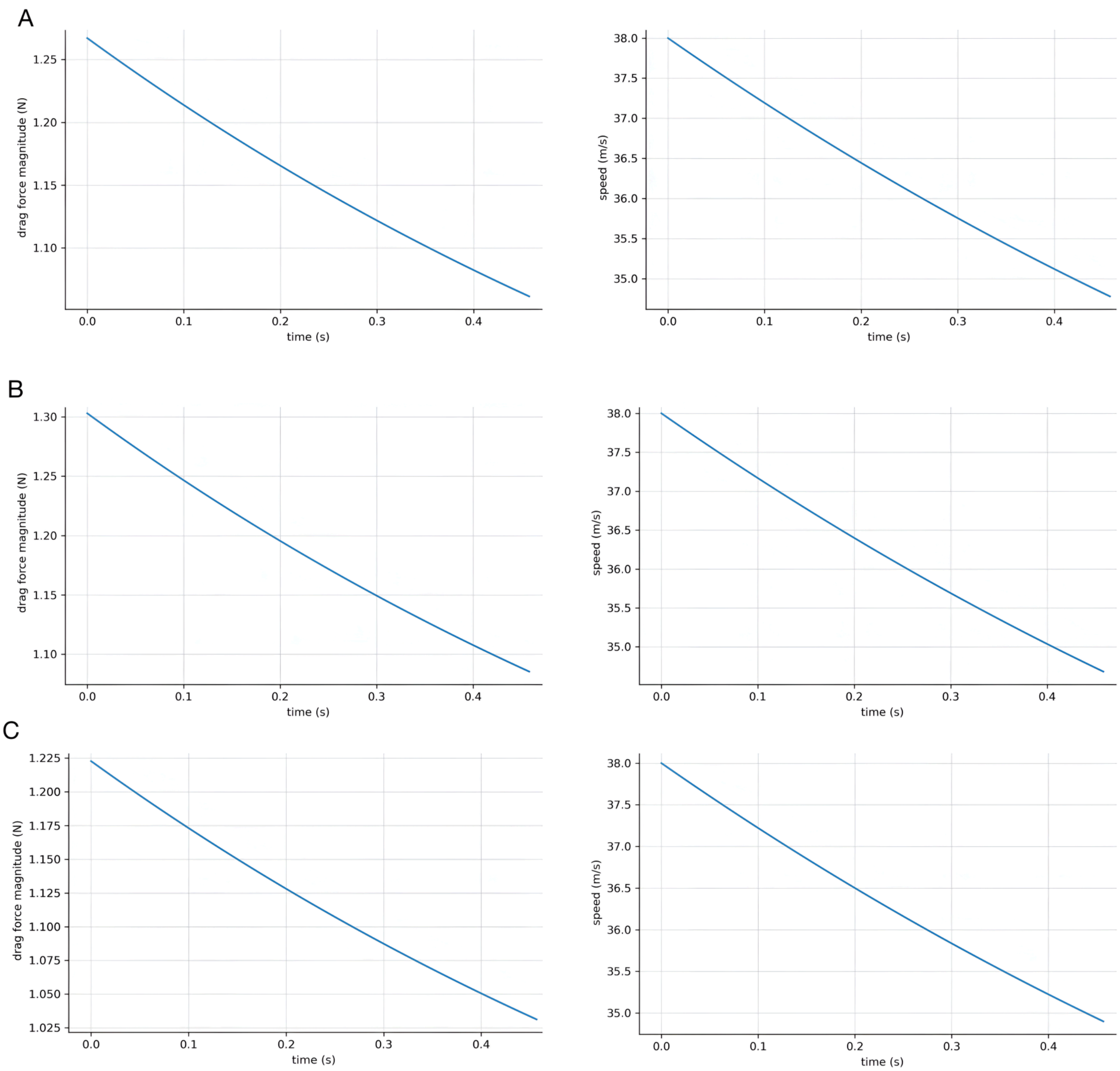

Figure 4: Drag force and pitch speed over time across ambient temperatures. Python simulation modeled drag and speed for an 85-mph fastball across three ambient temperatures: (A) 55 °F, (B) 70 °F, and (C) 85 °F. Each panel displays plots of instantaneous drag force (N) and pitch speed (m/s) as a function of flight time (seconds) from release to plate arrival (54.2 ft).

As temperature decreases, air density increases. This was reflected in the simulation where temperature dependent air density adjustments were incorporated into quadratic drag calculations. We calculated instantaneous drag forces for an 85-mph fastball at 70°F (1.198 kg/m^3) baseline, comparing it to 55°F (1.232 kg/m^3) and 85°F (1.156 kg/m^3). The simulation showed the drag force was greatest at 55°F, starting at 1.31 N and ending at 1.07 N (Figure 4A). The initial 38.0 m/s velocity ended at 34.7 m/s due to the deceleration which was directly proportional to drag. At 70°F, the starting drag force was 1.27 N and the ending was 1.07 N (Figure 4B). The ending speed was 34.7 m/s. Drag force was least at 85°F, starting at 1.22 N and ending at 1.03 N (Figure 4C). The ending velocity was 34.9 m/s. This pattern occurred for all three pitch types, although the magnitude of the drag force differed because the pitches had different starting velocities.

Section 7: Simulated comparison amongst pitch types

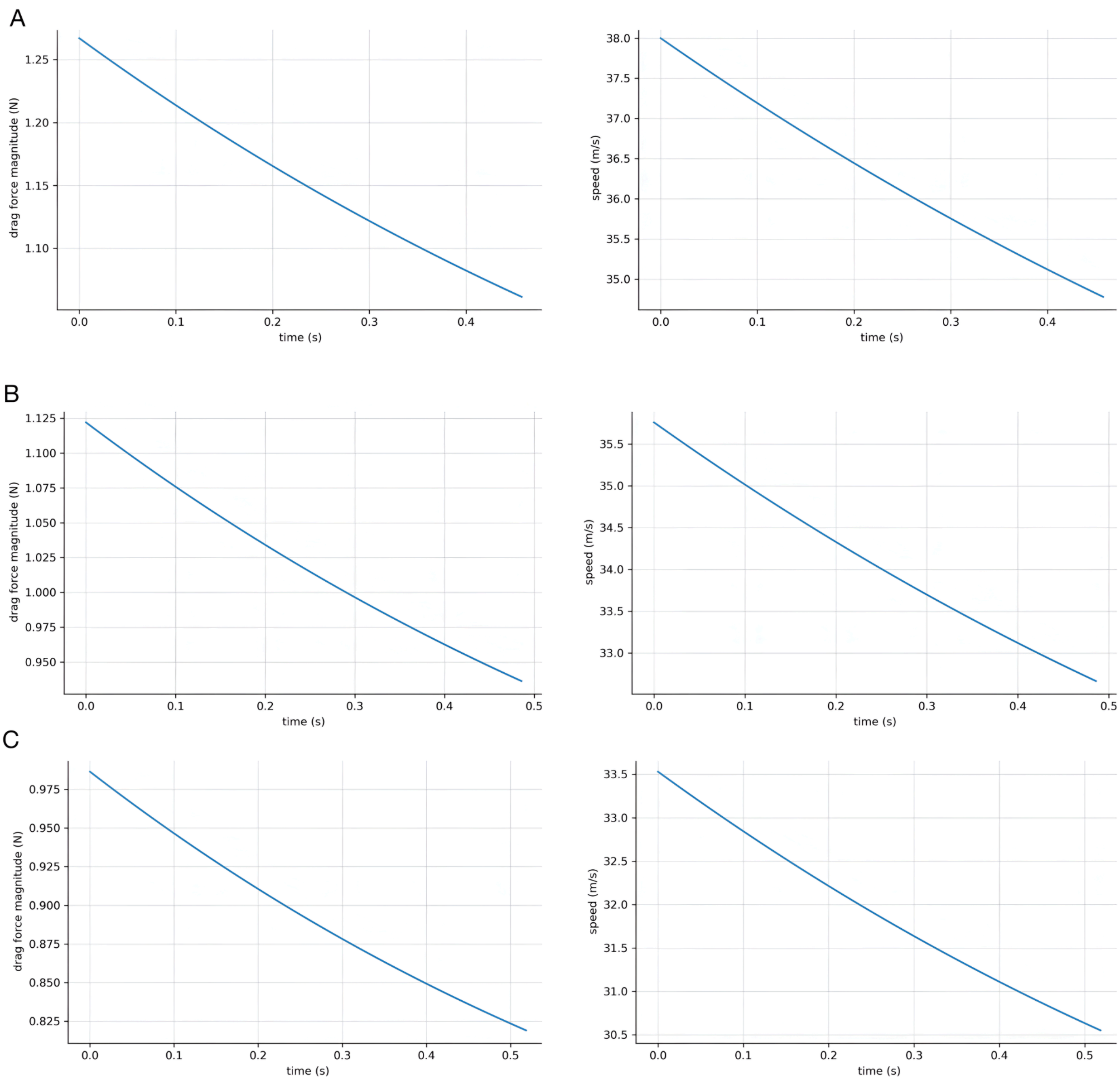

Figure 5: Drag force and pitch speed over time across pitch classifications at 70 °F. Python simulation modeled drag and speed at a 70 °F baseline for three pitch profiles: (A) an 85-mph fastball, (B) an 80-mph slider, and (C) a 75-mph curveball. Each panel displays plots of instantaneous drag force (N) and pitch speed (m/s) as a function of flight time (seconds) from release to plate arrival (54.2 ft). Initial release velocities and flight time varied by pitch type (fastball: 0.47 s; slider: 0.48 s; curveball: 0.52 s).

The simulated drag force differed among the three pitch types. Pitch dynamics were evaluated at 70°F baseline for an 85-mph fastball, an 80-mph slider, and a 75-mph curveball. Initial drag forces, speed loss, and total flight times were recorded across each pitch profile. The fastball experienced the greatest starting drag force (1.27 N) because it had the highest starting velocity (Figure 5A). In addition, it lost 3.3 m/s of speed over 0.47 s of flight time. The slider generated intermediate drag force (1.12 N) and lost 3.1 m/s over 0.48 s (Figure 5B). Curveballs experienced the least drag force (0.98 N) and lost the least total speed (3.0 m/s) (Figure 5C). These drag values should not be interpreted as directly predicting which pitch had the most movement because the simulation did not model the spin-induced forces responsible for horizontal and vertical break.

In addition to temperature, the simulation tested wind conditions to determine how headwinds and tailwinds affected the baseball's movement.

SECTION 8: WIND

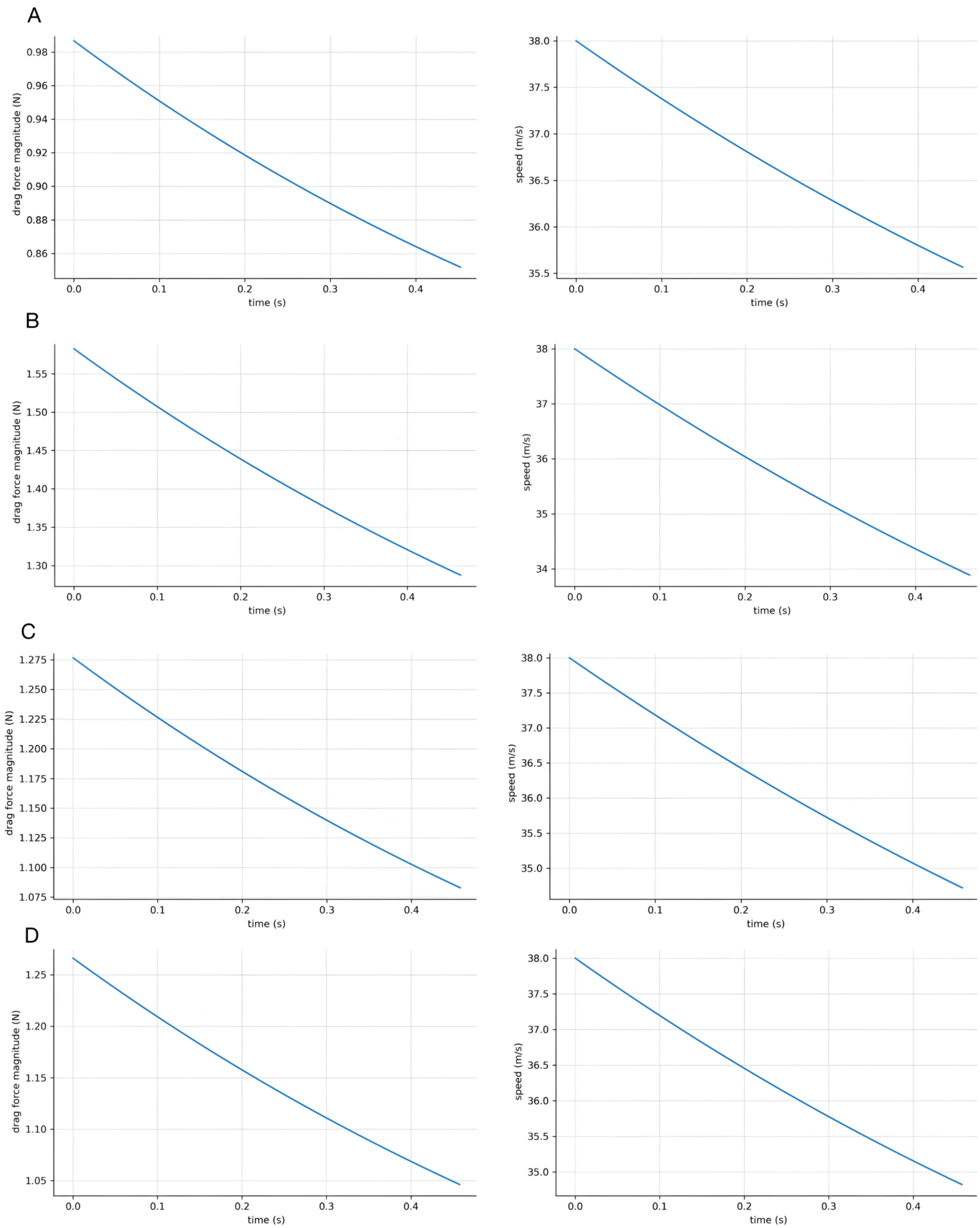

Figure 6: Drag force and pitch speed over time across directional wind conditions. Python simulation modeled drag and speed for an 85-mph fastball at a 70 °F baseline across four wind conditions: (A) 10-mph tailwind, (B) 10-mph headwind, (C) 5-mph upward wind, and (D) 5-mph downward wind. Each panel displays plots of instantaneous drag force (N) and pitch speed (m/s) as a function of flight time (seconds) from release to plate arrival (54.2 ft).

Wind conditions influenced drag force and pitch motion under constant temperature. Horizontal (10-mph headwind/tailwind) and vertical (5-mph up/down) wind vectors were introduced into the 70°F baseline simulation. A 10-mph tailwind reduced the relative airspeed between the baseball and the surrounding air, producing less initial drag (0.99 N) and velocity loss (2.4 m/s) (Figure 6A). In contrast, a 10-mph headwind increased the relative speed between the baseball and the surrounding air, producing greater drag (1.57 N) and velocity loss (4.2 m/s) (Figure 6B). For the 5-mph vertical wind vectors, initial drag force magnitudes were near-identical between upward and downward conditions (Figures 6C and 6D). Because temperature was the primary focus of this study, the wind simulation was treated as a secondary analysis. Together, the experimental and simulated results provide related but different information about the effects of temperature on a baseball.

Section 9: Connection Between Experimental and Simulated Results

The physical experiment showed that pitch movement was generally greater at lower temperatures, with sliders and curveballs showing larger changes than fastballs. These experimental findings were cross-referenced with our computational simulation outputs. The simulation showed that air density, drag force, and velocity loss increased as temperature dropped. These findings are consistent with the idea that temperature affects pitch behavior by changing the aerodynamic drag force and speed decay of a baseball pitch. However, because the simulation did not include Magnus lift forces, it could not directly reproduce or confirm the experimental measurements of horizontal and vertical movement.

IV. DISCUSSION

The primary objective of this study was to isolate and quantify the impact of ambient air temperature on the aerodynamic movement of pitched baseballs under controlled conditions. This study provides experimental evidence that ambient temperature is an independent variable influencing the movement of a pitched baseball. This result supports the central hypothesis, demonstrating that ambient temperature acts as an independent variable directly altering pitch trajectory. Unlike real-world games, where performance is confounded by factors such as grip changes, arm fatigue, or variations in release angle, this study eliminated those variables. By maintaining near-identical launch velocities and spin rates, the pitching machine isolated ambient temperature as a primary driver of the observed movement changes. This provides an objective, reliable, and repeatable result that traditional observational studies cannot achieve.

This research validates previous aerodynamic principles, which emphasized the role of atmospheric conditions—particularly air density—in shaping drag and lift forces (3). By supplying direct quantitative evidence, this study provides an important data point supporting previous theoretical framework, especially regarding the impact of temperature. Similarly, the finding that the curveball is a pitch that is especially sensitive to temperature aligns with previous analysis of spin-induced lift (4, 12) which implies that breaking pitches are highly sensitive to aerodynamic changes.

Beyond validation, this study fills a critical gap in existing literature. While previous studies identified correlations between hotter environments and decreased pitching effectiveness, they acknowledged the inability to isolate confounding factors such as fatigue or humidity (7). By holding major experimental variables as controlled as possible, this study provides the isolated evidence previous approaches could not. Likewise, the effect of seams and drag have been systematically analyzed, but the effect of ambient temperature has not. This work therefore bridges the space between theoretical models and real-world results.

The results of this study reveal clear differences in how pitch types respond to temperature. The slider, which depends heavily on spin-induced lift, showed the greatest sensitivity, with movement increased by 19.4% between 85°F and 55°F. Curveballs, which rely on both vertical and horizontal spin, also increased substantially (16.7%). In contrast, fastballs showed only a 7.9% increase, consistent with their reliance on velocity rather than movement. Although fastballs technically doubled in horizontal movement, the overall horizontal movement change remained insignificant due to their low baseline movement. These patterns suggest that the more a pitch depends on spin-induced break, the more susceptible it is to changes in ambient temperature.

To fully understand these results, it is necessary to consider the physics of air density and its effect on aerodynamic forces. At the molecular level, colder air is denser because particles move more slowly and remain more tightly packed. Warmer air, in contrast, contains faster-moving molecules spread farther apart, making it less dense. This change in density directly alters lift and drag through fluid dynamic principles (13). The Magnus effect explains spin-induced lift: airflow accelerates on one side of the ball and slows on the other, creating a pressure difference in accordance with Bernoulli's principle (13). Faster airflow corresponds to lower pressure, generating a net force perpendicular to the ball's motion (4, 13). Because lift is proportional to air density (ρ), a drop in density under warmer conditions reduces the magnitude of this force and thus the amount of break (3). Drag behaves similarly, increasing with air density, which slows the ball more in colder conditions (3).

The results also highlight that horizontal movement was more affected by temperature changes than induced vertical break. Standard aerodynamic models offer no obvious theoretical mechanism to account for this dimensional discrepancy. Directly isolating the physical mechanism behind this heightened lateral responsiveness remains an open area for future aerodynamic research.

The computational Python simulation further expanded on the role of drag by providing a theoretical baseline. By modeling a non-spinning hard sphere, the simulation established that increasing air density from 85°F (1.156 kg/m^3) to 55°F (1.232 kg/m^3) increases drag force. In cold air, initial drag force rose from 1.22 N to 1.31 N, causing heightened velocity decay. Comparing this drag model to experimental field data helps clarify the physical forces at work. While pure quadratic drag accounts for linear speed loss and deceleration decay, variations in total pitch break are primarily driven by the Magnus forces acting on the spinning ball. The model thus serves as an essential baseline, isolating movement because of drag, leaving room for spin-induced break to be properly evaluated.

Additionally, the simulation revealed key differences across pitch types. Fastballs sustained the highest initial drag force due to their higher release velocity, resulting in the greatest total speed loss (3.3 m/s). Slower pitches generated lower initial drag forces (1.12 N for sliders and 0.98 N for curveballs), but their longer flight durations (0.48 s and 0.52 s, respectively) allowed drag to act over a longer timeframe, narrowing the gap in total velocity decay across pitch classifications. This demonstrates that overall speed loss over the pitch trajectory is governed by both initial drag force and flight time

Furthermore, wind vector modeling demonstrated that headwind and tailwind can create significant relative velocity shifts compared to upward or downward wind. Headwind increased initial drag force to 1.57 N, while tailwind decreased drag to under 1 N. Horizontal wind forces impacted drag significantly, while vertical wind forces had minimal effect.

While these findings provide valuable insight, it is important to acknowledge certain limitations. One drawback was the small sample size, as only a limited number of consistent pitches were recorded per temperature. Another limitation was the use of a pitching machine, which, while excellent for controlling variables, does not perfectly replicate the nuanced release and seam orientation of a human pitcher. Additionally, the Python simulation simplified pitch movement and neglected spin-induced forces, which limited the scope of the simulation but provided key insights on the importance of temperature, density, drag, pitch type, and wind on pitch movement. These limitations, however, do not undermine the central conclusions. Colder and denser air was associated with greater total movement, with aerodynamic drag affecting individual pitch types in distinct ways based on flight duration and release velocity.

These findings have practical implications for pitching strategy and performance analysis. Analysts can now attribute part of a pitcher's diminished effectiveness on a hot day to measurable changes in aerodynamic forces rather than only unpredictable and unmeasurable factors such as pitcher fatigue or grip. Because temperature's effect is consistent, measurable, and reliable, it offers an important consideration that can always be incorporated into game decisions, statistical models, and performance analysis. Furthermore, findings from the simulation surrounding wind offer new and important information. The findings suggest that while temperature affects pitch movement, wind is a factor too. Even moderate real-world wind fluctuations can potentially alter pitch trajectory and affect player performance, opening room for further investigation.

Overall, this study demonstrates that ambient temperature is a factor that influences baseball pitch movement through predictable changes in air density and drag, with breaking pitches exhibiting the greatest movement sensitivity in cold air. By providing a theoretical baseline that separates environmental fluid dynamics from physical factors such as pitcher fatigue, this work provides a framework for continued research in sports fluid dynamics and integrating atmospheric factors into pitch strategy and evaluation.

References

1. Nagami, Tomoyuki, et al. "How Baseball Spin Influences the Performance of a Pitcher." *The Journal of Physical Fitness and Sports Medicine*, vol. 2, no. 1, 2013, pp. 63–68, https://doi.org/10.7600/jpfsm.2.63.
2. Nathan, Alan, and Charles Young. "Exploring the Variation in the Drag Coefficient of the Baseball." *FanGraphs*. https://blogs.fangraphs.com/exploring-the-variation-in-the-drag-coefficient-of-the-baseball/. Accessed 7 July 2025.
3. Bahill, A. Terry, et al. "Effects of Altitude and Atmospheric Conditions on the Flight of a Baseball." *International Journal of Sports Science and Engineering*, vol. 3, no. 2, Jan. 2009, pp. 109–28.
4. Nathan, Alan M. "The Effect of Spin on the Flight of a Baseball." *American Journal of Physics*, vol. 76, no. 2, 1 Feb 2008, pp. 119–24. https://doi.org/10.1119/1.2805242.
5. Griesmer, Andrew. "The Physics Behind Baseball Pitches." *COMSOL Blog*. https://www.comsol.com/blogs/physics-behind-baseball-pitches. Accessed 3 Aug. 2026.
6. Adler, David. "Identifying Pitch Types: A Fan's Guide." *MLB.com*. https://www.mlb.com/news/identifying-pitch-types-a-fan-s-guide. Accessed 4 Aug. 2026.
7. Huang, Jyh-How, et al. "Influence of Hot Environment on Pitching and Hitting Performance in Professional Baseball." *Journal of Strength and Conditioning Research*, vol. 35, no. 11, 1 Nov. 2021, pp. 3251–55. https://doi.org/10.1519/JSC.0000000000004066.
8. "Release Extension… Why It's Important and How to Maximize It?" *Rockland Peak Performance*. https://rocklandpeakperformance.com/extension-at-release-why-its-important-and-how-to-maximize-it/. Accessed 26 July 2026.
9. "College Baseball Pitching Averages and How to Reach Them." *Rapsodo*, https://rapsodo.com/blogs/baseball/college-pitching-averages-and-how-to-reach-them. Accessed 21 Aug. 2026.
10. "Pitch Arsenals Leaderboard." *Baseball Savant*, https://baseballsavant.mlb.com/leaderboard/pitch-arsenals. Accessed 21 Aug. 2026.
11. Rosen, Michael. "It's Release Angles All the Way Down." *FanGraphs*, https://blogs.fangraphs.com/its-release-angles-all-the-way-down/. Accessed 22 Aug. 2026.
12. Bin, Lyu, et al. "The Dependence of Baseball Lift and Drag on Spin." *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*, vol. 239, no. 2, 1 Aug. 2022. https://doi.org/10.1177/17543371221113914.
13. Escalera Santos, Gerardo J., et al. "On the Aerodynamic Forces on a Baseball, with Applications." *Frontiers in Applied Mathematics and Statistics*, vol. 4, 27 Jan. 2019, p. 1-9. https://doi.org/10.3389/fams.2018.00066.