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Quantifying The Impact Of Temperature And Wind On NFL Passing And Rushing Performance

Max A. Zipperman
Claremont McKenna College

CLAREMONT MCKENNA COLLEGE

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SUBMITTED TO

PROFESSOR DARREN FILSON

AND

DEAN NICHOLAS WARNER

BY

MAX ZIPPERMAN

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Abstract

This paper utilizes NFL game data from the 2002-2013 seasons in an investigation into the effects of temperature and wind on NFL passing and rushing performance. There are three separate analyses: (1) the general effects of weather on performance and the advantages/ disadvantages of playing at home with respect to weather, (2) a comparison of how teams respond to weather when at home vs. on the road, and (3) an examination of the effect of transitioning weather conditions on visitor performance. Teams tended to have inferior passing success in low temperatures and consequently supplant passing attempts with rushing attempts in those conditions. The results suggest that teams perform better at home and that visiting teams are more sensitive to extreme weather conditions. The results also indicate that visiting teams playing in significantly colder conditions than their home stadium are the most vulnerable to inclement weather.

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Introduction

When asked if he thought severe weather can affect National Football League (NFL) player performance and team general strategy, former Dallas Cowboys Super Bowl winning Head Coach Jimmy Johnson responded with a definitive “Yes”. Many other fans, athletes, and coaches agree that sufficiently inclement weather can significantly impact the performance of even the most highly skilled professional athletes. Anecdotal evidence of freezing temperatures and strong winds influencing passing, rushing, and play-calling abound; Jimmy Johnson remembers “being on the sideline during a winter game at the Meadowlands (home of the New York Jets and New York Giants) when it was so cold I didn’t know what down it was, much less what play to use!” (Advanced NFL Stats).

The NFL season spans early September until late January or early February, and stadiums in cold-weather and windy climates can prove hostile in the later months of the season. There is a reason teams fear visiting “The Frozen Tundra” in Green Bay or facing the Bears in “The Windy City”. Temperatures can reach into the single digits and winds can top 30 miles per hour in those stadiums. In my sample of over 3,000 games from the 2002-2013 seasons, roughly 12% of games were played in freezing conditions and over 33% were played with winds over 10 miles per hour.

The negative performance effects associated with hostile conditions make intuitive sense. Imagine the effects high winds and low temperatures can have on quarterback performance; scanning the field for open receivers, releasing the football with just the right finesse for the perfect pass, and audible play-calling from the line of scrimmage all would seem to be much more difficult in windy & freezing conditions. The same logic applies to running backs and wide receivers, who might find it more difficult to retain possession of the football or sustain endurance in the taxing environment.

Despite the abundance of anecdotal evidence, there is a dearth of econometric literature on weather's effect on NFL performance. In this paper, I attempt to quantify the impact of weather on individual position achievement and general offensive strategy. My first analysis will explore how teams react to weather differently when at home or on the road. My second analysis will investigate the relationship between temperature and performance, comparing home game performance to home game performance, and visitor performance only to visitor performance. My third analysis will estimate the performance effects associated with visiting teams transitioning climates for games.

Literature Review

Physiological Responses to Cold

There is a robust literature on the impact of ambient temperature on mental and physical performance. Phetteplace (2000) explored the relationship between cold weather and the performance of soldiers, and his results indicate exposure to low temperatures produces significant physical, cognitive, and emotional performance impacts.

Physical impacts are the most acute and universal. Phetteplace explains that the body initially responds to cold with vasoconstriction, the reduction in blood supply to the skin and extremities. While vasoconstriction helps the body preserve heat by decreasing the potential for heat transfer, it also reduces touch sensitivity in the hands and increases blood pressure. Involuntary shivering, another reaction to cold ambient temperatures, can exacerbate the problems associated with increased blood pressure—when combined, they can lead to a four-fold increase in metabolic heart rate, accelerating fatigue.

Dehydration is another major concern for athletes subjected to extremely low temperatures. As the water vapor capacity of air is closely correlated with temperature, extremely cold air tends to have very little humidity. When athletes inhale low-humidity, low-temperature air, their lungs warm the air molecules and consequently increase their water vapor capacity. This leads the athlete to exhale more moisture than was inhaled. Intense physical exertion also leads to sweating. The combined effects of respiratory water loss and sweating are amplified by the increase in metabolic heart rate; together, they are a recipe for significantly expedited dehydration. Interestingly, cold also reduces thirst. Although NFL teams employ dedicated nutritionists and physical therapists to monitor their players' health, it is conceivable that reduced thirst might manifest itself in insufficient fluid replenishment during games.

Altogether, these physiological effects diminish dexterity, strength, endurance, and maximum performance levels. They also reduce muscle strength and stiffen joints. While all effects are significant, dexterity losses appear most pronounced. When analyzing the difference in task efficiency at 78°F and 49°F, Yeshnik (1988) found that task efficiency drops 35% for those requiring modest dexterity and substantial strength, and 60% for those requiring more dexterity and less strength.

The effect of cold temperatures on cognitive performance, while not as well understood as the effects on physical performance, are believed to result from dehydration and lower core body temperatures. In an attempt to quantify the effect of temperature on information processing accuracy, awareness and response times, Vaughn and Strauss (1975) tested and compared the cognitive abilities of divers in 60°F and 40°F water. In their study, divers in the colder water detected only 3% fewer targets than they did in warm water, but it took them 26% longer to do so.

<u>Previous NFL Analyses</u>

Much of the current literature on the relationship between NFL performance and weather is amateur and/or focused specifically on ascertaining the influence of weather on odds-setting. While neither of these types of analyses have econometrically quantified the effect of weather on various performance metrics, they help inform my methodology.

Brian Burke of AdvancedNFLStats.com calculated the road team win-percentage by game temperature of all non-preseason games from the 2000 through 2011 seasons, and discovered that teams from domes did not win a single game in 11 - 22 degree weather in his entire sample. According to his analysis, visitors from domes win less than 20% of games played at or below freezing. Teams from warmer climates do slightly better, winning roughly 35% of their games at or below freezing. Compared to the league average of 43%, it appears as though teams from warmer weather are at a significant disadvantage when playing in cold environments. While interesting, this analysis is plagued by selection bias. A significant percentage of freezing games are played during the playoffs, when teams earn home team advantage by virtue of having a higher ranking. Home teams are thus more likely to be better than visiting teams during the playoffs, which might help explain the difference in visiting team winning percentage.

Burke then plotted average yards per pass attempt for both the visiting and home team against temperature and wind. Not surprisingly, he found that high winds and low temperatures correlate negatively with passing yards per attempt for both groups. He also looked at the relationship between wind speed and play-type count, and found that teams tend to run more and pass less as wind velocity increases.

Borghesi (2007) analyzed the relationship between game day temperatures and NFL betting line forecast errors with a sample of 5,463 games from the 1981 – 2004 seasons. His paper was the first to introduce acclimation advantage as an independent variable in addition to temperature. Motivated by the idea that the body requires between five and ten days of acclimation before resuming peak physical performance after a large and sudden change in temperature, Borghesi explored the idea that differences in game day temperature and the mean five day temperature at each team's home stadium might bias performance and create inefficiencies in betting markets. After comparing the relative differences for the home and visiting team, he assigned the acclimation advantage to the team whose practice conditions were closer to game day conditions. As hypothesized, the teams with an acclimation advantage outperformed their opponents.

Borghesi's results make intuitive sense, and reinforce the idea that stresses of transitioning weather can significantly augment performance effects resulting from severe conditions. Home team players practice in more similar weather conditions to game day than the visiting team, and the visiting team most likely does not have sufficient time to adjust to the new conditions. The NFL is a particularly interesting sports league in this regard, as the nationwide dispersion of teams means climates can vary greatly, especially in the later weeks of the season.

Wind can be especially erratic in the winter months, when certain stadiums often produce "wind tunnels". Cold weather is associated with large differences in air pressure, which cause more wind. The gusts enter the stadium through the paths of least resistance, which often produce unpredictable wind outcomes. The Meadowlands is notorious for this effect; strong gusts can be blowing north in the south end of the field, south in the north end of the field, and sideways in the center—a pattern reminiscent of a figure eight (New York Times).

Hypotheses

Determining the impact of inhospitable weather on NFL team performance considering contributing factors. Does inclement weather affect home and visiting teams equally? Are teams visiting from mild and inhospitable climates affected similarly or differently by extreme wind, cold, and heat? How do wind and temperature affect a quarterback's ability to successfully complete passes? Do teams adjust their offensive strategy when the conditions inhibit a quarterback's ability to pass? In these situations, do teams opt to put a larger offensive emphasis on rushing? Do cold and wind affect a team's rushing and passing ability equally?

These questions suggest the following testable hypotheses:

Hypothesis 1: Visiting teams' passing performance will be more vulnerable than home teams' to freezing conditions.

Hypothesis 1A: Visiting teams are more likely than home teams to modify their offensive strategy and substitute rush attempts for pass attempts as a result of anticipated performance effects in conditions of extreme weather.

Hypothesis 2: Large and negative differences between game temperatures and average weekly temperatures will significantly inhibit visiting teams' passing ability.

Hypothesis 2A: These large and negative temperature differences will push visiting teams to modify their offensive strategy, superseding pass attempts with rush attempts.

Hypothesis 3: Wind will affect the passing performance of teams visiting from stadiums with low average wind speeds more than teams visiting from windy stadiums.

Hypothesis 3A: Wind will cause teams to bias their offensive strategy from passing towards rushing. Wind will affect teams visiting from non-windy stadiums more than it will affect teams visiting from windy stadiums.

The lack of a robust literature on the relationship between weather conditions and NFL performance leads me to rely on common sense and generalized information on the impacts of cold weather on motor skills, cognition, and emotion in forming these hypotheses.

To assess what weather conditions impact a team's offensive capabilities and overall strategy, we will regress a variety of performance outcome variables on weather condition variables. The first analysis will focus on quantifying the general impacts weather has on individual and team performance. It also compares how teams respond differently to weather when at home compared to when away, and estimates performance advantages and disadvantages enjoyed by teams when playing at home.

The second analysis will compare the effects of temperature and wind on home and away performance. The second analysis is distinct from the first in that it analyzes home and away performance separately.

The third analysis will differentiate the performance impacts of weather on teams visiting from home stadiums with significantly different weather conditions. Through these analyses I hope to reveal whether certain weather factors are "statistically significant", meaning they have a clear impact on the performance outcome, and whether the influence on performance is economically important.

Data

The data used in the analysis comprises 3,133 regular season and postseason games from the 2002-2013 NFL seasons. I collected the data from www.pro-football-reference.com using a web scraper built with Beautiful Soup 4 in Python. The web scraper was necessary because the information for each game was hosted on a unique web page. While the website was fairly consistent with standardizing their data formatting, some games, usually those played in domes, lacked weather information. For those cases, I applied the most common dome weather conditions, 72 degrees with no wind. In the cases where weather information was available, the information was taken from the official NFL game book, with temperature expressed in degrees Fahrenheit and wind expressed in mph.

Many cold games are also very windy, and high winds can drastically reduce perceptions of temperatures on the field. In order to better represent the player experience on the field, I created the wind chill equivalent temperature value from the temperature and wind values. The formula for windchill is: $T_{WC} = 35.74 + 0.6215T_a – 35.75V^{0.16} + 0.4275T_aV^{0.16}$, where T_{WC} is the wind chill equivalent temperature, T_a is air temperature, and V is wind speed in mph (NOAA). Merriam Webster defines windchill as “a still-air temperature that would have the same cooling effect on exposed human skin as a given combination of temperature and wind speed”. This value is crucial to the analysis because games that are both cold and windy can seem to be much colder than the raw temperature reading might indicate. Seeing as performance outcomes are influenced by physiological condition, I use the wind chill equivalent temperature as a proxy for raw temperature because physiological responses stem from temperature perception. Games are considered freezing if the wind chill temperature is at or below 32°F, and “temperature” hereinafter refers to wind chill temperature equivalent.

To test the hypotheses, I created a week-by-week temperature differential variable by subtracting the visiting team's average temperature for the week from the temperature at the game. I applied the temperature differential separately to three different segments of visiting teams: those with home stadium temperature averages of 70°F or above for the week ("Warm"), those whose home stadium averages 32°F to 70°F for the week ("Mid"), and those whose average home temperatures are at or below freezing ("Cold").

In search of the specific effects of warm climate teams playing at or below freezing temperatures, I further segmented the temperature differential to control for visitors from warm and moderate climates playing in freezing conditions ("Freezing").

The wind statistic is applied separately to three segments of visiting teams: those whose home stadium is a dome ("Dome"), those who play in open-air home stadiums but average less than 10 mph of wind per home game that season ("Light Wind"), and those whose home stadiums average wind speeds in excess of 10 mph ("Heavy Wind"). The wind is not expressed as a difference, but instead as simply mph. While high winds can contribute to the perception of extreme cold, the effect of wind on temperature has already been accounted for in the temperature variable. Aside from the influence on temperature, wind does not induce the same physiological effects as temperature; instead wind is a playing condition in which athletes can improve their performance through practice. With this theory, I segmented wind, using team and season fixed effects to account for players added to or removed from rosters between years who might not yet be accustomed to their new home stadium's wind patterns.

I control for the quality of each team's offense and defense by including team and season fixed effects. While this controlled for their average performance both at home and away, it has some minor limitations. The data is aggregate for the team as a whole and does not account for injuries or other modifications to the roster or depth chart.

Unfortunately, information on precipitation was not available. I would expect precipitation significantly affects team performance.

I evaluate the impact of weather on team performances with an eye towards individual position achievement and team performance. Variables used in the regressions, their descriptions, and summary statistics can be found in Tables 1, 2, 3, & 4.

Models:

All estimates are from OLS (ordinary least squares) regressions with heteroskedastic-robust standard errors. The results are found in Tables 5 through 9. All regressions included fixed effects for home and visiting team and season, but those results are omitted from the tables.

The results in Table 5 are produced with the following model:

(1)*

$$\ln(y_{it}) = a_{iT} + \sum_{j=1}^{n} \varphi_j D_{jT} + \beta' \mathrm{x}_{\mathrm{it}} + \theta_{iT}(Home) + \sum_{j=1}^{n} \varphi_j (Home) D_{jT} + \delta'(Home)\mathrm{x}_{\mathrm{it}} + \varepsilon_{it}$$

Variable	Description
y	Performance outcome of interest
i	Team
t	Season
a	Constant
T	Game
j	Opposing team
φ	Quality of opponent
D	Dummy variable for weather effects
β'	Vector of weather effects
θ	Dummy for home advantage/disadvantage
δ’	Vector of weather effects

*QBR is expressed in levels, not logs

The results in tables 6 & 7 were produced with the following model:

(2)

$$\ln(y_{it}) = a_{iT} + \beta\text{temperature}_{\text{t}} + \beta\text{wind}_{\text{t}} + D\text{freezing}_{\text{t}} + D\text{hot}_{\text{t}} \sum_{i=1}^{n} \varphi_i D_{iT} \; + \varepsilon_{it}$$

The results in tables 6 & 7 were produced with the following model:

(3)

$$\ln(y_{it}) = a_{iT} + \beta' i\text{x}_{\text{it}} + \sum_{i=1}^{n} \varphi_i D_{iT} \; + \varepsilon_{it}$$

Table 1: Description of Weather Variables

Variable	Description
Wind	Wind, expressed in miles per hour (mph)
Temperature	Temperature adjusted for wind chill, used as a proxy for temperature throughout analysis. Formula: $T_{WC} = 35.74 + 0.6215T_a - 35.75V^{0.16} + 0.4275T_aV^{0.16}$ T_{WC}: the wind chill equivalent temperature; T_a: air temperature; V: wind speed in mph
Hot	A dummy variable that takes the value 1 if the game was played in temperatures equal to or greater than 80 degrees
Freezing	A dummy variable that takes the value 1 if the game was played in temperatures equal to or below 32 degrees
Dome	A dummy variable that takes the value 1 if the visiting team is from a dome
Light Wind	A dummy variable that takes the value 1 if the visiting team is from an open-air stadium with average winds less than 10 mph
High Wind	A dummy variable that takes the value 1 if the visiting team is from an open-air stadium with average winds equal to or greater than 10 mph
VT Dome Wind	Wind * Dome
VT Light Wind	Wind * Light Wind
VT High Wind	Wind * High Wind
Warm	A dummy variable that takes the value 1 if the visiting team comes from temperatures ≥70
Mid	A dummy variable that takes the value 1 if the visiting team comes from temperatures <70 & >32
Cold	A dummy variable that takes the value 1 if the visiting team comes from temperatures ≤32
VT Temperature Difference	The difference in temperature between the visiting team's home stadium that week and the game temperature
VT Warm Freezing	VT Temperature Difference, interacted with Warm and Freezing
VT Mid Freezing	VT Temperature Difference, interacted with Mid and Freezing
VT Warm Not Freezing	VT Temperature Difference, interacted with Warm
VT Mid Not Freezing	VT Temperature Difference, interacted with Mid
VT Cold Freezing	VT Temperature Difference, interacted with Cold and Freezing
VT Cold Not Freezing	VT Temperature Difference, interacted with Cold

Table 2: Description of Performance Variables

Variable	Description
HT	Home Team
VT	Visiting Team
QBR	Official NFL Quarterback Rating (Passer Rating)*. $QBR_{NFL}=\left(\frac{mm(A)+mm(B)+mm(C)+mm(D)}{6}\right) * 100$ $A = \left(\frac{\#\ of\ Completions}{\#\ of\ Passing\ Attempts} - .3\right) * 5$ $B = \left(\frac{Passing\ Yards}{\#\ of\ Passing\ Attempts} - 3\right) * 0.25$ $C = \left(\frac{Touchdown\ Passes}{\#\ of\ Passing\ Attempts}\right) * 20$ $D = 2.375 - \left(\frac{Interceptions\ Thrown}{\#\ of\ Passing\ Attempts} * 25\right)$ mm(x) = max(0, min(x, 2.375)) *(NFL.com)
Pass Yards	The natural logarithm of a team's passing yards per game
Completion Percentage	The natural logarithm of a team's passing completion percentage
Yards/ Completion	The natural logarithm of a team's yards per pass completion
Rush Percentage	The natural logarithm of a team's percentage of total offensive plays that are rush attempts
Rush Attempts*	The natural logarithm of a team's total rush attempts per game
Rush Yards	The natural logarithm of a team's total rush yards per game
Rush Yards/ Attempt	The natural logarithm of a team's rush yards per attempt per game
Sacks	The natural logarithm of the number of times a team's quarterback was sacked per game
Fumbles	The natural logarithm of a team's number of fumbles per game
INT/ Attempts	The natural logarithm of a team's interceptions per pass attempt
Total Yards	The natural logarithm of a team's total yards per game
Penalties	The natural logarithm of a team's total penalties for the game
Turnovers	The natural logarithm of a team's turnovers per game

Table 3: Summary Statistics of Weather Variables, Segmented

Variable	Observations	Mean	Std. Dev.	Min	Max
Wind	3133	7.370252	5.869334	0	70
Wind Chill	3133	56.94754	18.92553	-27.0113	96
VT Dome Wind	541	7.160813	5.598778	0	40
VT Light Wind	1587	6.981096	5.90143	0	70
VT High Wind	1005	8.097512	5.89892	0	40
VT Warm Freezing	53	-51.4488	9.835253	-81.0429	-39.9192
VT Mid Freezing	239	-28.7124	13.88633	-72.6286	-2.28013
VT Warm Not Freezing	841	-8.73291	12.47204	-50.6605	21.625
VT Mid Not Freezing	1654	5.453792	15.3781	-36.6513	52.03329
VT Cold Freezing	90	-4.63733	12.68496	-56.3784	14.61554
VT Cold Not Freezing	234	31.71067	15.97613	0.592613	65.49712

Table 4: Summary Statistics of Performance Outcomes

Variable*	Observations	Mean	Std. Dev.	Min	Max
HT QBR	3133	85.57405	27.9569	0	158.3333
VT QBR	3133	81.4768	28.00847	0	158.3333
HT Pass Yards	3133	232.6406	75.81441	31	527
VT Pass Yards	3133	229.0153	78.04035	23	520
HT Completion Pct.	3133	0.608712	0.100528	0.259259	0.933333
VT Completion Pct.	3133	0.597167	0.102162	0.076923	0.947368
HT Yards/ Completion	3133	11.75968	2.625259	5.083333	31.6
HT Yards/ Completion	3133	11.57316	2.705787	4.333333	34.5
HT Rushing Pct.	3133	0.462028	0.112739	0.122807	0.816667
VT Rushing Pct.	3133	0.445923	0.11576	0.105263	0.892857
HT Rush Attempts	3133	28.32142	7.971119	7	60
VT Rush Attempts	3133	26.98213	8.066118	6	57
HT Rush Yards	3132	120.0418	52.5358	6	378
VT Rush Yards	3132	110.7168	51.47832	1	351
HT Rush Yards/Attempt	3132	4.179884	1.288857	0.5	12.23077
VT Rush Yards/Attempt	3132	4.028095	1.270325	0.0625	13.5625
VT INT/Attempt	3133	0.030862	0.031806	0	0.210526
VT Sacks	3133	2.317268	1.736528	0	12
VT Total Yards	3132	339.7107	84.01924	70	623
VT Fumbles	3133	1.461538	1.27063	0	8
VT Penalties	3133	6.438557	2.856476	0	21
VT Turnovers	3133	1.739547	1.392769	0	8

*Variables are expressed as levels in this table but are converted to their logarithm in the results. This is because it is easier to understand general performance standards when expressed as absolute statistics, and changes in performance are most easily understood through logarithms.

Results

The Effect of Weather on Offense: Home vs. Away

Table 5 presents the results of an OLS regression that considers the effects of weather on general passing and rushing performance. The model accounts for how teams respond to weather differently when at home vs. when on the road, and estimates a team's advantage or disadvantage in performance outcomes when playing at home.

"Home" is a binary variable indicating the general advantage or disadvantage attributed to the home team in that particular outcome variable, and "Home" before a weather variable means "Home" has been interacted with that weather variable. The coefficients represent percentage increases for every incremental increase in x, except for QBR, which is expressed as an absolute figure. For the purposes of facilitating interpretation of the regression results, I often refer to the effect of wind at 10 mph or a change in temperature of 10 degrees. To calculate the effect of a different wind speed or temperature difference, simply multiply the coefficient in the table by a wind or temperature value.

Home Advantage

The results of the regression suggest teams perform better at home in all offensive respects. When at home and assuming no weather effects, quarterbacks are estimated to earn passer ratings 6.8 points higher, throw for 3.7% more yards, complete 4.6% more of their passes, and gain 2.1% more yards per completion. Of these results, only the effect on completion percentage is statistically significant at the 10% level; no other effects were found to be statistically significant.

Rushing offenses are also stronger at home, with home team offenses relying on rushing attempts 7.4% more than when they are on the road, increasing their rushing attempt total 11.5%, rushing for 25.5% more yards, and earning 14% more rush yards per attempt when at home. These results are not only potentially game changing in their magnitude, but also statistically significant—the effects on rush yards per attempt and total rush yards are significant at the 1% level, the effect on total rush attempts is significant at the 5% level, and the effect on reliance on rushing is significant at the 10% level.

It is important to note that these results of home advantage are not complete without being contextualized with the other coefficients from the model. For example, although it appears as though teams rush for 25.5% more when at home, when considering the unique effects of weather on home teams, the realized home advantage can be reduced by over 11% if winds exceed 30 mph, or eliminated entirely if the game is played in 80 degree weather. I will explore the unique effects of weather on home teams later in this section.

Wind

Wind is the most consistently statistically significant variable influencing performance outcome variables. Wind has a uniformly negative effect on passing and positive effect on rushing. Wind speeds of 10 mph are estimated to reduce quarterback ratings by 1.7 points, total passing yards by 6.8%, completion percentage by 2.4%, and yards per completion by 1.6%. Winds of 10 mph increase rush percentage by 2.7%, rush attempts by 3.2%, rush yards by 4.5%, and rush yards per attempt by 1.4%. All of these estimates are statistically significant at the 1% level, except for the effect on quarterback rating, yards per completion, and rush yards per attempt. The effect on QBR and yards per completion are statistically significant at the 10% level. The unique effect of wind on home teams is never statistically significant at the 5% level.

Temperature

The regression results suggest teams are better at rushing and worse at passing in low temperatures, but fewer effects are statistically significant than wind. When controlling for temperature, the effect of freezing conditions is not a statistically significant predictor of any outcome.

The effect of temperature on pass yards and completion percentage are statistically significant at the 1% level, and the effect on quarterback rating is statistically significant at the 10% level. Temperature decreases of 10 degrees are estimated to lower pass yards by 1.7%, reduce completion percentage by 0.8%, and cut 0.8 points off a quarterback's passer rating. Hot conditions are estimated to reduce completion percentage by 3.9% and shave 6.5% off a team's pass yards for the game. The data estimates with 95% confidence that the teams respond differently to temperature when at home, losing 2.3% of their rush yards with every 10 degree drop in temperature.

Home Vs. Away

Tables 6 & 7 contrast the ordinary least squares (OLS) estimates for the effect of weather on passing ability and rushing success. The results are different than those in Table 5 because they compare home game performance only to performance in other home games and visitor performance only to performance in other road games. Table 5 estimated both the general effects of weather on performance and how teams respond differently to weather when at home vs. when away.

Wind

Wind is the most consistently statistically significant variable influencing the passing outcome variables. The effect is important across most variables, with potentially game-changing effects on pass yards and completion percentage. The regression estimates with 99% confidence that wind has an effect on pass yards and completion percentage, predicting 10 mph winds to decrease pass yards for the visiting team by over 9% and reduce completion percentage by over 3% relative to expected performance on the road. The regression estimates home teams to be roughly half as sensitive to wind, earning only 5% fewer pass yards and completing 2% fewer passes in similar conditions compared to other home games. Wind is estimated to decrease passer rating by 0.459 and 0.217 points per mph for the home and visiting teams, respectively.

When looking at rushing strategy and success, the weather regression is only able to demonstrate wind's statistical significance on the visiting team. The effect of wind is both highly statistically significant and economically important, with high winds increasing a visiting team's dependence on strong rushing competencies while also improving the rushing team's ability. Winds of 10mph are estimated to increase rush attempts 5%, rush yards per attempt 2%, and total rush yards 7%. Wind is also expected to significantly alter a team's offensive strategy, as visiting teams playing in 10 mph are estimated to substitute a rush attempt for a pass attempt in 4% of all offensive attempts compared to their strategy in other road games.

Temperature

The three variables used to describe game temperature conditions are wind chill adjusted temperature and binary variables for whether the game is freezing or hot, in this case classified as being equal to or above 80 F. As I controlled for temperature, the binary variables for freezing games and hot games are statistically significant for a smaller portion of performance outcome variables than the raw temperature variable. In general, teams perform worse in colder conditions.

Similar to the case with wind, visiting teams seem to be affected by temperature roughly twice as much as home teams. Temperature has a statistically significant effect on the total pass yards for both the home and visiting teams. The model estimates visiting teams to gain 2.22% pass yards for every ten degrees, while home teams gain only 1.62%. When flipped, this translates to visiting teams to lose 2.22% of their pass yards for every 10 degree reduction in temperature, while home teams are affected less so. While not statistically significant at the 5% level, the estimates for the effect of temperature on completion percentage and yards per completion follow in this pattern of visiting teams being twice as sensitive to temperature; it should be noted, however, that the coefficients on these variables are nominally small.

Interestingly, temperature seemed to affect the relative rushing performance of home teams more so than visiting teams. Home teams are expected to prefer passing attempts to rushing 1.2% more for every 10 degree increase in temperature. This ten degree increase in temperature is also shown to reduce total rush attempts by 1.5%, total rush yards by 3.9%, and reduce rush yards per attempt by 2.5%. Interestingly, the effect for visiting teams is nominal, indicating visitors do not prioritize temperature as highly as the home team when formulating offensive strategy.

Freezing games are shown to reduce total rush yards by an additional 8.7% and passing completion percentage by an additional 3.3% for the home team. Hot games are shown to reduce pass yards by an additional 7.7% and completion percentage by 4.3% for the visiting teams.

Visitors: Acclimation Disadvantages

The third set of OLS regression analyses compare the differing effects of wind and temperature on visiting teams in a variety of climate transition circumstances. The results can be found in tables 8 & 9 in the appendix, where coefficients represent percentage increases for every incremental increase in x unless otherwise noted.

The effect of wind is tested separately on teams visiting from domes, from open-air stadiums with an average of 10 mph of wind or less for the season, and teams visiting from windy open-air stadiums. The wind variable represents wind in mph.

Temperature should be interpreted as temperature differential, the difference in the game day temperature and the visitor's average home stadium temperature for the week. A positive number indicates a team moving from colder to warmer climates, and a negative differential indicates a team moved from warmer to colder climates. This differential is applied tested separately on teams from warm, mild, and cold climates. It is further interacted with a binary variable representing freezing games to highlight the effect of temperature on performance specifically in games played in freezing conditions.

Wind

Interestingly, the regression output indicates wind has a larger impact on the passing success of teams visiting from windy stadiums and domes than those visiting from stadiums with light wind. The results show high statistical significance for effects on total pass yards and completion percentage. For teams from a dome, winds of 10 mph are estimated to reduce total pass yards 6.3% and completion percentage by 5.1%. For teams from stadiums with light and heavy wind, those numbers are 8.3% & 2.0%, and 13.4% & 4.4%, respectively. All of these results are statistically significant at the 1% level, except for the estimation regarding the effect of wind on pass yards for visitors from domes, which is statistically significant at the 10% level.

Wind also proves to have a statistically significant effect on rushing ability for teams visiting from all types of stadiums. 10 mph winds are expected to increase rushing's share of total offensive attempts 4.6%, 4.0%, and 6.1% for teams from domes, light wind, and heavy wind, respectively. Visiting teams are estimated to attempt between 1.2 and 1.8 more rush attempts per game for every 10 mph of wind, and visiting teams increase their total rush yards by as much as 9.4% for every 10mph of wind. Wind is also associated with an increased success in visitor's rush attempts; teams visiting from domes carry the ball 6.3% farther per attempt for every 10 mph of wind. Translated into real game statistics, that means dome visitors could gain an extra yard per rush attempt in 20mph wind conditions.

Although not statistically significant, wind is expected to have material and detrimental results with respect to fumbles. 10 mph winds are associated with an increase in fumble likelihood as large as 7.5%. It is also predicted to reduce the amount of sacks on the quarterback, but that number is commensurate with the reduction in pass attempts.

Temperature

As expected, the most statistically significant and important performance impacts due to weather came in games with extreme weather acclimation disadvantages. The results for freezing games are the strongest, and teams from warmer climates are invariably more affected by temperature than their peers from milder regions.

Freezing games hurt teams from warm climates the most. In these games, each 10 degree difference in temperature is responsible for a 3.6% reduction in pass yards, a 1.6% reduction in completion percentage, a 1.5% reduction in yards per completion, and a 1.7% drop in total yards. Teams visiting from milder climates are affected at almost the same rate, with negative 10 degree temperature differentials explaining the loss of 2.4% of pass yards, 0.9% of completion percentage, and 1.5% of total yards. These numbers are extremely large when considering the minimum temperature differential required to be in this category is 38 degrees, which would occur if a team accustomed to 70 degree weather were to play an opponent in 32 degree weather. When applied to the game with the largest temperature differential in the dataset, 81 degrees, the model predicts weather to account for over 29% in the variation in pass yards and an estimated 12% drop in completion percentage, yards per completion, and total yards.

Temperature differential is not shown to be a significant predictor of variation in visiting team rushing strategy and success. It did, however, suggest a strong relationship between colder temperatures and fewer penalties, but that is accounted for in the reduced number of plays on the field.

Conclusion

The results of this analysis are relevant to coaches, fans, and fantasy sports competitors alike. The results are intuitive and corroborate anecdotal accounts. Wind has a uniformly negative impact on an NFL team's ability to pass the football, and teams tend to rely on their rushing offense more heavily when playing in windy conditions. Temperature also has a negative effect on passing, but actually produces a small benefit to teams' rushing initiatives. Professional football teams are likely to perform better at home, but are also more sensitive to extreme temperatures when surprised with inclement weather in their own stadium.

The most important and consistently statistically significant results came from the analysis of visiting team performance when transitioning climates. The results indicated that teams from warm climates playing in freezing conditions are the most significantly impacted by the cold. Teams from moderate climates are influenced by freezing temperatures less than teams from warm climates, and teams from freezing climates actually tend to improve their performance when playing in freezing conditions, perhaps because they have a comparative acclimation advantage.

This analysis could be improved by incorporating precipitation into the regressions. Precipitation is sure to be another important and significant determinant of NFL performance. The paper could also be appropriately expanded to investigate the impact of weather on punting and kicking performance.

Appendix

Table 5: Weather Effects on Offense

	(1) QBR	(2) Pass Yards	(3) Completion Percentage	(4) Yards/ Completion	(5) Rush Percentage	(6) Rush Attempts	(7) Rush Yards	(8) Rush Yards/Attempt
Temperature	0.0760*	0.00169***	0.000776***	0.000508	-0.000446	-0.000389	-0.000583	-0.000198
	(0.0444)	(0.000576)	(0.000288)	(0.000370)	(0.000419)	(0.000492)	(0.000854)	(0.000608)
Wind	-0.170*	-0.00679***	-0.00236***	-0.00157*	0.00271***	0.00315***	0.00452***	0.00138
	(0.0997)	(0.00135)	(0.000764)	(0.000868)	(0.000953)	(0.00110)	(0.00175)	(0.00117)
Freezing	0.370	-0.00775	-0.00314	0.0131	0.0250	0.0276	0.00996	-0.0180
	(2.227)	(0.0307)	(0.0151)	(0.0197)	(0.0206)	(0.0243)	(0.0411)	(0.0288)
Hot	-3.298	-0.0653*	-0.0391**	-0.0122	-0.00514	-0.0274	-0.0319	-0.00456
	(2.527)	(0.0338)	(0.0157)	(0.0212)	(0.0220)	(0.0268)	(0.0460)	(0.0308)
Home	6.795	0.0373	0.0460*	0.0218	0.0744*	0.115**	0.255***	0.140***
	(4.155)	(0.0520)	(0.0265)	(0.0342)	(0.0384)	(0.0451)	(0.0752)	(0.0523)
Home Temperature	-0.0225	-0.000612	-0.000438	-0.000227	-0.000370	-0.000770	-0.00229**	-0.00150*
	(0.0622)	(0.000783)	(0.000394)	(0.000515)	(0.000577)	(0.000671)	(0.00112)	(0.000790)
Home Wind	-0.182	0.00275	0.0000580	0.00103	-0.00200	-0.00268*	-0.00391*	-0.00126
	(0.135)	(0.00180)	(0.000979)	(0.00117)	(0.00130)	(0.00150)	(0.00237)	(0.00160)
Home Freezing	-2.197	0.00390	-0.0253	0.0105	-0.0220	-0.0206	-0.0498	-0.0282
	(3.183)	(0.0412)	(0.0207)	(0.0267)	(0.0284)	(0.0332)	(0.0548)	(0.0382)
Home Hot	1.077	0.0367	0.0340	0.000765	0.0196	0.0554	0.0614	0.00565
	(3.415)	(0.0437)	(0.0208)	(0.0281)	(0.0317)	(0.0371)	(0.0620)	(0.0418)
_cons	71.97***	5.224***	-0.616***	2.365***	-0.773***	3.336***	4.773***	1.437***
	(9.252)	(0.100)	(0.0602)	(0.0770)	(0.0825)	(0.106)	(0.185)	(0.125)
N	6266	6266	6266	6266	6266	6266	6264	6264
R^2	0.270	0.319	0.304	0.219	0.301	0.283	0.287	0.225

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 6: Weather Effects on Passing – Home versus Away

	(1) HT QBR	(2) VT QBR	(3) HT Pass Yards	(4) VT Pass Yards	(5) HT Completion Percentage	(6) VT Completion Percentage	(7) HT Yards/ Completion	(8) VT Yards/ Completion
Temperature	0.0514	0.0711	0.00162***	0.00222***	0.000311	0.000691**	0.000324	0.000806*
	(0.0517)	(0.0517)	(0.000621)	(0.000680)	(0.000305)	(0.000337)	(0.000417)	(0.000433)
Wind	-0.459***	-0.217*	-0.00521***	-0.00925***	-0.00241***	-0.00304***	-0.000728	-0.00185*
	(0.123)	(0.123)	(0.00157)	(0.00172)	(0.000798)	(0.000959)	(0.00101)	(0.00111)
Freezing	-1.742	-0.326	0.0289	0.00745	-0.0326**	-0.01000	0.0311	0.0291
	(2.480)	(2.464)	(0.0296)	(0.0331)	(0.0151)	(0.0171)	(0.0198)	(0.0221)
Hot	-2.263	-3.787	-0.0176	-0.0765**	0.00244	-0.0431**	0.00565	-0.0172
	(2.652)	(2.696)	(0.0315)	(0.0363)	(0.0156)	(0.0176)	(0.0218)	(0.0230)
_cons	97.83***	50.58***	5.271***	5.060***	-0.468***	-0.727***	2.331***	2.385***
	(12.92)	(14.03)	(0.126)	(0.157)	(0.0843)	(0.0860)	(0.108)	(0.116)
N	3133	3133	3133	3133	3133	3133	3133	3133
R^2	0.368	0.358	0.394	0.427	0.404	0.384	0.335	0.308

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 7: Weather Effects on Rushing – Home versus Away

	(1) HT Rush Percentage	(2) VT Rush Percentage	(3) HT Rush Attempts	(4) VT Rush Attempts	(5) HT Rush Yards	(6) VT Rush Yards	(7) HT Rush Yards/ Attempt	(8) VT Rush Yards/ Attempt
Temperature	-0.00123***	-0.000524	-0.00145***	-0.000242	-0.00393***	-0.000927	-0.00248***	-0.000677
	(0.000460)	(0.000483)	(0.000540)	(0.000565)	(0.000859)	(0.000969)	(0.000582)	(0.000683)
Wind	0.00125	0.00443***	0.000656	0.00502***	0.00163	0.00776***	0.000962	0.00274*
	(0.00111)	(0.00120)	(0.00133)	(0.00140)	(0.00203)	(0.00226)	(0.00138)	(0.00154)
Freezing	-0.0178	0.0213	-0.00387	0.0270	-0.0878**	-0.0156	-0.0836***	-0.0425
	(0.0216)	(0.0227)	(0.0256)	(0.0269)	(0.0394)	(0.0451)	(0.0266)	(0.0314)
Hot	0.0340	-0.00829	0.0460	-0.0342	0.0322	-0.0357	-0.0140	-0.00183
	(0.0256)	(0.0242)	(0.0292)	(0.0304)	(0.0466)	(0.0517)	(0.0312)	(0.0348)
_cons	-0.653***	-0.725***	3.486***	3.358***	5.077***	4.882***	1.591***	1.523***
	(0.0999)	(0.144)	(0.116)	(0.180)	(0.206)	(0.327)	(0.169)	(0.200)
N	3133	3133	3133	3133	3132	3132	3132	3132
R^2	0.400	0.403	0.386	0.370	0.396	0.369	0.356	0.315

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 8: Acclimation and Wind Effects on Visitor Passing

	(1) VT QBR	(2) VT Pass Yards	(3) VT Completion	(4) VT Yards/ Completion	(5) VT INT/ Attempts	(6) VT Sacks	(7) VT Total Yards
VT Dome Wind	-0.264	-0.00626*	-0.00510***	0.00293	-0.00102	-0.00115	0.000448
	(0.250)	(0.00334)	(0.00194)	(0.00209)	(0.00632)	(0.00610)	(0.00212)
VT Mid Wind	-0.125	-0.00827***	-0.00209**	-0.00238*	0.00228	-0.00262	-0.00263*
	(0.147)	(0.00200)	(0.00106)	(0.00130)	(0.00397)	(0.00347)	(0.00135)
VT High Wind	-0.404**	-0.0134***	-0.00436***	-0.00234	0.00657	-0.00632	-0.00402**
	(0.191)	(0.00257)	(0.00150)	(0.00172)	(0.00497)	(0.00468)	(0.00164)
VT Warm Freezing	0.0970	0.00361***	0.00166***	0.00151**	0.00185	-0.000979	0.00168**
	(0.0775)	(0.00121)	(0.000614)	(0.000753)	(0.00166)	(0.00219)	(0.000755)
VT Mid Freezing	0.0851	0.00239**	0.000890**	0.0000894	-0.00287*	0.000635	0.00146**
	(0.0662)	(0.000972)	(0.000435)	(0.000591)	(0.00167)	(0.00155)	(0.000707)
VT Warm Not Freezing	-0.0835	-0.000383	-0.000715	-0.000366	-0.00317	0.00584***	-0.00000249
	(0.0879)	(0.00107)	(0.000567)	(0.000764)	(0.00223)	(0.00214)	(0.000785)
VT Mid Not Freezing	0.0828	0.00136	0.000384	0.000763	0.00111	0.00210	0.00105*
	(0.0610)	(0.000849)	(0.000427)	(0.000544)	(0.00161)	(0.00148)	(0.000579)
VT Cold Freezing	-0.311	-0.00246	-0.000709	-0.000703	0.00891	-0.00456	-0.000994
	(0.237)	(0.00269)	(0.00146)	(0.00197)	(0.00751)	(0.00555)	(0.00188)
VT Cold Not Freezing	-0.0906	0.000103	-0.000354	0.000213	0.00168	0.00242	0.000120
	(0.0639)	(0.000760)	(0.000376)	(0.000523)	(0.00160)	(0.00153)	(0.000555)
_cons	52.64***	5.186***	-0.708***	2.441***	-2.880***	0.289	5.712***
	(13.80)	(0.150)	(0.0817)	(0.113)	(0.365)	(0.326)	(0.149)
N	3111	3111	3111	3111	1960	2698	3110
R^2	0.365	0.431	0.389	0.313	0.429	0.367	0.416

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 9: Acclimation and Wind Effects on Visitor Rushing

	(1) VT Rushing Percentage	(2) VT Rush Attempts	(3) VT Rush Yards	(4) VT Rush Yards/ Attempt	(5) VT Fumbles	(6) VT Penalties	(7) VT Turnovers
VT Dome Wind	0.00457^{**}	0.126^{*}	0.0112^{***}	0.00631^{**}	0.00745	-0.00345	0.00253
	(0.00232)	(0.0696)	(0.00426)	(0.00297)	(0.00606)	(0.00403)	(0.00591)
VT Mid Wind	0.00399^{***}	0.137^{***}	0.00642^{**}	0.00167	0.00144	-0.00406	-0.000103
	(0.00149)	(0.0460)	(0.00272)	(0.00181)	(0.00391)	(0.00263)	(0.00353)
VT High Wind	0.00609^{***}	0.178^{***}	0.00937^{***}	0.00314	0.00413	-0.000590	0.000275
	(0.00170)	(0.0534)	(0.00325)	(0.00227)	(0.00459)	(0.00339)	(0.00467)
VT Warm Freezing	-0.000830	-0.0138	-0.000989	-0.000219	-0.000428	0.00327^{*}	0.000910
	(0.000769)	(0.0216)	(0.00154)	(0.00117)	(0.00227)	(0.00171)	(0.00202)
VT Mid Freezing	-0.000960	-0.0201	0.000225	0.000786	-0.000362	0.00619^{***}	-0.000362
	(0.000633)	(0.0198)	(0.00126)	(0.000860)	(0.00149)	(0.00134)	(0.00159)
VT Warm Not Freezing	-0.000372	-0.00310	-0.000118	0.0000512	0.000500	0.000262	-0.000805
	(0.000853)	(0.0248)	(0.00163)	(0.00118)	(0.00206)	(0.00152)	(0.00210)
VT Mid Not Freezing	0.000287	0.0188	0.00139	0.000604	0.00145	-0.0000898	0.00101
	(0.000583)	(0.0180)	(0.00113)	(0.000784)	(0.00149)	(0.00116)	(0.00146)
VT Cold Freezing	-0.00129	-0.0586	-0.00171	0.000801	-0.00277	0.0111^{**}	0.00795
	(0.00221)	(0.0667)	(0.00415)	(0.00243)	(0.00631)	(0.00502)	(0.00525)
VT Cold Not Freezing	-0.000144	0.00519	0.000496	0.000415	0.000140	-0.000392	0.000455
	(0.000553)	(0.0172)	(0.00109)	(0.000788)	(0.00156)	(0.00111)	(0.00151)
_cons	-0.767^{***}	28.91^{***}	4.817^{***}	1.491^{***}	-0.422	1.395^{***}	0.469
	(0.143)	(4.371)	(0.326)	(0.197)	(0.262)	(0.280)	(0.319)
N	3111	3111	3110	3110	2348	3097	2498
R^2	0.400	0.371	0.368	0.317	0.360	0.336	0.332

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

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