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Effects of the North Atlantic Oscillation on Snow in the Midwest

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ABSTRACT

The North Atlantic Oscillation (NAO) is caused by the difference in strengths between the subtropical high and the polar low. The differing strengths between the high and low cause a fluctuating pressure gradient over the north Atlantic which can affect weather thousands of miles away, from Europe, to the Middle East, to the United States. In the eastern United States, a positive index (large pressure gradient) brings milder weather while a negative index (small pressure gradient) brings colder weather with more snow. This study was done to see the effects of the NAO on snow in the Midwest to see if the pattern was like the east coast. Eleven locations were selected with daily and monthly snowfall and NAO index data. Several statistical tests were run to find any correlation and statistical significances between the two variables. After the tests, both the daily and monthly data showed a negative correlation with the monthly data having a slightly stronger correlation; however, the location in the region with the best results was shifted west when looking at the monthly results. This shows that the North Atlantic Oscillation does impact snowfall in the Midwest with storms being more frequent or producing more snow when the NAO index is negative.

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1. Introduction

The North Atlantic Oscillation (NAO) is a large teleconnection located in the North Atlantic Ocean, that can have drastic effects all around the world, thousands of miles away from the Atlantic. There have been observed effects in Europe, the Middle East, and the east coast of the United States (Bell).

The NAO occurs due to the strengths of the subtropical high and the polar low. The differing strengths between the two causes the pressure gradient between them to fluctuate. The normalized sea level pressure of Lisbon, Portugal and Stykkisholmur/Reykjavik, Iceland are taken, then subtracted from each other (Hurrell). This difference is the Index (**Figure 1**). A large pressure gradient between them leads to

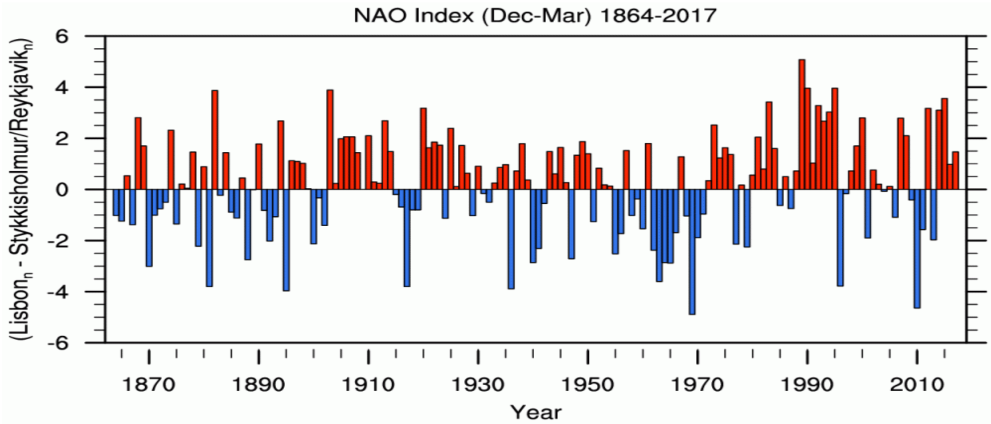

FIG 1. Graph showing the positive and negative index values for the winter months from 1864-2017 (Hurrell).

a positive index value while a small pressure gradient gives a negative index value. The index values fluctuate from year-to-year and even month-to-month, and there is no set pattern for whether the index will be positive or negative at a certain time. If the index is positive one year, it can be positive the next year and vice-versa.

The NAO affects many regions around the world, depending on the index value. When there is a positive index value, there is a strong pressure gradient between the low and high. The stronger pressure gradient causes stronger winds across the northern Atlantic Ocean. With stronger winds, stronger winter storms move across the Atlantic Ocean into Europe bringing heavier precipitation and warmer temperatures (Diao, et al, 2015). On the other hand, eastern Canada and Greenland are drier and colder than normal. The eastern United States tends to be milder and wetter with a positive NAO Index value (Bell) (**Figure 2**).

When the NAO Index is negative, there is a smaller pressure gradient in the area. With a smaller pressure gradient, there are weaker winds across the Atlantic Ocean. This lowers the frequency of storms going across the ocean into Europe, and those storms are also not as powerful. Because of this, Europe is colder than average, Greenland is milder, and the eastern United States has more cold outbreaks with heavier snow (Bell) (**Figure 3**).

A study done by Cattiux, et al, looked at the winter of 2010 which seemed to be abnormally cold and had many snowstorms. This study cited high snow totals and extreme cold bursts in Europe. The eastern United States had record-breaking snow totals as well as record cold daily temperatures. The

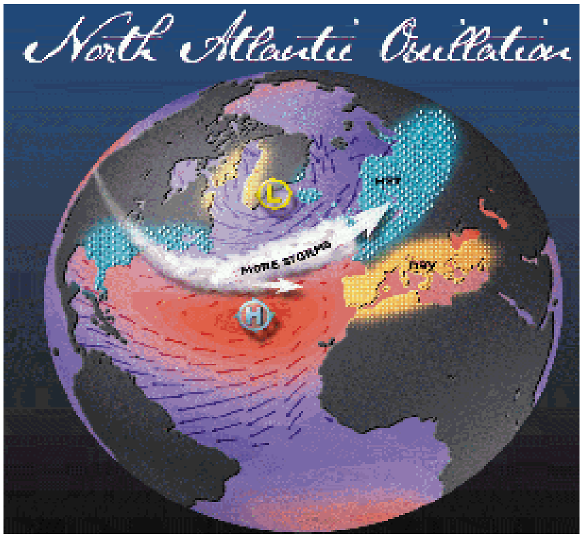

FIG 2. Visual representation of a positive index value showing where the high and low pressures are, and the weather conditions each region faces (Bell).

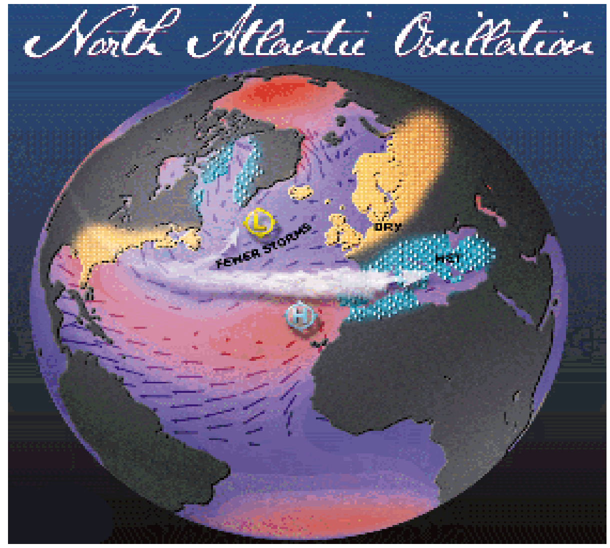

FIG 3. Visual representation of a negative index value showing where the high and low pressures are, and the weather conditions each region faces (Bell).

researchers for this study looked at geopotential heights for the areas as well as surface temperature. After comparing that data, they determined that the abnormal winter conditions were caused by the North Atlantic Oscillation that had been negative for quite some time.

Another study done by Diao, et al. (2015) looked to explain the asymmetry of surface air temperature extremes during winter in Europe. In this study, they stated how the negative NAO index is responsible for cold temperatures over Europe, and the negative index is accompanied with Greenland blocking which causes the colder temperatures. They also stated there is an increase in maximum temperature extremes when the NAO index is positive. Diao and the other researchers found that the extremes occur at different locations on the continent, but those extremes follow the pattern of which one occurs with a positive index, and which one occurs with a negative index.

A study done by Yao, et al. (2016) also looked at the North Atlantic Oscillation and its effects, but this time, looked in the Middle East. Here, when the NAO index is positive, there are cold winter outbreaks in this region. This is due to the stronger zonal winds over the Atlantic Ocean which are caused by the increased pressure gradient. When the index is negative, the zonal winds are weaker because of the pressure gradient, leading to drier conditions in the Middle East.

The studies listed were all done to show how the North Atlantic Oscillation affects Europe and the Middle East. There have been other studies that show what happens on the east coast of the United States; however, no studies have examined the impact over the Midwestern United States. This study will apply what is known about the North Atlantic Oscillation to see what happens to winter snowfall in the state of Iowa and the rest of the Midwest. The Index value will be looked at, as well as snowfall data to see if there is a correlation between the two. Based on previous studies, there should be a correlation between the negative index with increased winter precipitation in the state, similar to the eastern United States. This study will look to see if that is true.

2. Data and Methods

a. Study Region

The focus of this study is to see how the North Atlantic Oscillation affects winter precipitation in Midwest with the primary focus on Iowa. Five points were selected to cover the state of Iowa as evenly as possible. Des Moines, Iowa, was used as the center point of the study region with four locations

FIG 4. Map showing the eleven locations selected for data.

at the four corners of Iowa. Those four locations were: Burlington, Iowa, Decorah, Iowa, Sioux Falls, South Dakota, and Omaha, Nebraska. After those five were selected, locations were selected in surrounding states that were approximately an equidistance away from the Iowa border. Six of these locations were selected: Chicago, Illinois, Green Bay, Wisconsin, Minneapolis, Minnesota, Pierre, South Dakota, Grand Island, Nebraska, and Columbia, Missouri (**Figure 4**).

b. Data

The period of 1981-2010 was used for the index and snowfall data. This was done so because thirty years is the definition of climate and is consistent with all the Action Reports (AR) done by the Intergovernmental Panel on Climate Change (IPCC). Daily and monthly index data for the North Atlantic

Oscillation was used and was obtained from the Climate Prediction Center (CPC). Daily snowfall data for the same period for each location was obtained from National Weather Service (NWS) Cooperative Observer Program (COOP) via the Iowa Environmental Mesonet (IEM). The study focused on the months of November, December, January, February, and March for each location. These five months are the most likely to have snow as the main precipitation. The daily data was also used to find the total amount of snowfall for each of the months in the thirty years.

c. Methods

The data then went through quality control for each location. There were few days with missing data, but for any day that was missing, climatology was used to determine a value. With missing data replaced, the remaining data was separated into data tables for each location that included the date, NAO index, and snowfall for that day (**Table 1**).

TABLE 1: The date (year, month, day), North Atlantic Oscillation (NAO) Index for that day, and the total snow amount for that day in Des Moines, Iowa. Table is sorted by the NAO Index in descending order.

Year	Month	Day	NAO Index	DSM Snow
1990	3	21	2.359	0
1990	3	20	2.355	0
1982	12	16	2.341	0
1983	1	2	2.309	0

Statistical tests were then performed to find a possible correlation between the NAO Index and snowfall. The first test was a Pearson Correlation test. A Spearman's rho test was also performed, and it was followed by a t-test. These tests compare two variables to find a possible correlation between them. For the Pearson and Spearman tests, positive values represent a positive correlation and negative values represent a negative correlation.

After tests were performed using the daily NAO index and the corresponding snowfall for that day, the same tests were run using the monthly NAO index for the month, along with the total snow accumulation for that month. This was done to find a more general trend, rather than it being broken into each day as each day is highly variable.

3. Results and Discussion

a. Daily Data

The statistical tests gave a variety of values for each location. The values for each test and each city are shown (**Table 2)**.

The Pearson and Spearman's rho values for each location were negative meaning

TABLE 2: Table showing the Pearson Correlation (p), Spearman's rho, and t-test results (t-value, degrees of freedom, and p-value) for all eleven locations using daily snowfall and index data.

Location (Station Id)	p	rho	t-value	df	p-value
Des Moines, Iowa (IA2203)	-0.022	-0.052	-1.60	8897	0.110
Decorah, Iowa (IA2110)	-0.046	-0.059	-2.77	8781	0.006
Burlington, Iowa (IA1063)	-0.022	-0.026	6.98	8156	0.000
Omaha, Nebraska (NE6255)	-0.019	-0.045	1.72	8883	0.085
Grand Island, Nebraska (NE3395)	-0.003	-0.035	1.70	8963	0.089
Sioux Falls, South Dakota (SD7667)	-0.026	-0.056	-2.62	8754	0.009
Pierre, South Dakota (SD6597)	-0.024	-0.021	1.94	9039	0.052
Minneapolis, Minnesota (MN5435)	-0.044	-0.05	-4.85	8151	0.000
Green Bay, Wisconsin (WI3269)	-0.039	-0.048	-6.16	8484	0.000
Chicago, Illinois (IL1549)	-0.022	-0.062	-1.67	8733	0.096
Columbia, Missouri (MO1791)	-0.01	-0.028	5.75	8824	0.000

there was a negative correlation between the NAO and snowfall at each location. However, there is a difference in location for where the best correlations occur.

When looking at the Pearson correlation, the best correlations occur at the stations in the most northeastern part of the area (**Figure 4).** When looking at this area, Decorah, Iowa, has the best correlation. Minneapolis, Minnesota, and Green Bay, Wisconsin, have similar values as Decorah. The values decrease to the south and west of this area. Columbia, Missouri, and Grand Island, Nebraska have the values closest to zero and the least amount of correlation.

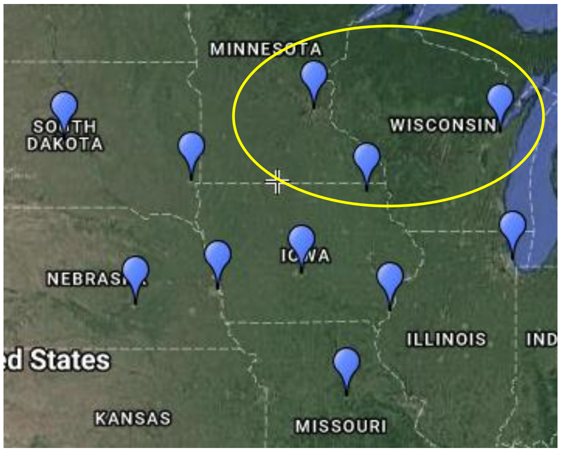

FIG. 4: Map of the Midwest showing the location of the three stations with the highest Pearson correlation when using daily data.

The area shifts slightly when looking at the values for Spearman's rho. Areas a little farther south are included in the areas of best correlation (**Figure 5**). Chicago, Illinois, had the highest Spearman's rho value with Decorah, Iowa, and Sioux Falls, South Dakota, close to it. Omaha, Nebraska, and

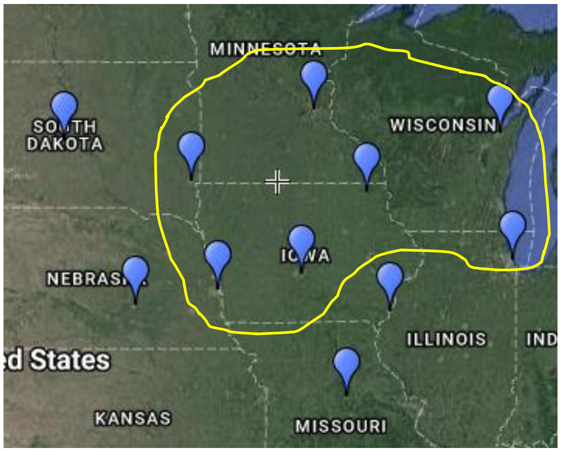

FIG. 5: Map of the Midwest showing the location of the stations with the highest Spearman's rho value when using daily data.

Des Moines, Iowa, are also included in the area with best correlation when looking at this statistic. Although the overall area is larger, it follows the same idea as the Pearson correlation. The values begin to decrease when moving to the west and south of Chicago, Illinois, with the exception of Sioux Falls, South Dakota. Pierre, South Dakota, Burlington, Iowa, and Columbia, Missouri, have the smallest values, and weakest correlation of the area, when looking at Spearman's rho.

A t-test was also performed to find any potential statistical significance. With the t-test, p-values were calculated for each location. Any p-value that is less than or equal to 0.05 shows a statistical significance. Decorah, Iowa, Burlington, Iowa, Sioux Falls, South Dakota, Minneapolis,

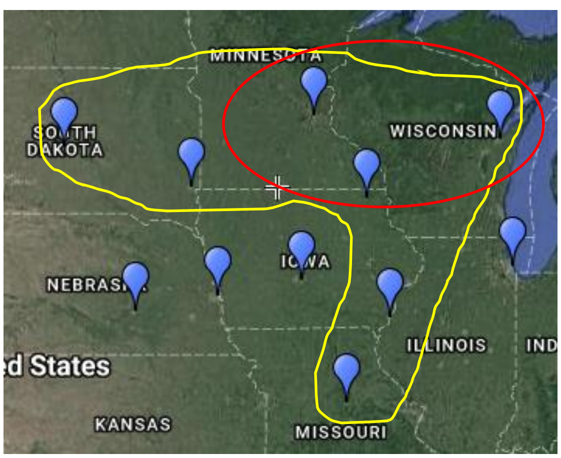

FIG. 6: Map of the Midwest showing the location of the stations with the best t-test p-values (yellow), and the three stations that had the best of all three statistical tests (red) when using daily data.

Minnesota, and Columbia, Missouri, were all less than 0.05. Pierre, South Dakota, was barely over the limit (0.052), so if that is compared to the locations that were less than 0.05, it shows that the five most northern locations have the best statistical significance (**Figure 6**). This includes some of the same areas that had the best correlations based on the Pearson correlation and Spearman's rho.

All eleven locations showed a negative correlation between the North Atlantic Oscillation and snowfall, so the NAO does impact snowfall in the Midwest. With the negative correlations, there is a greater effect when the NAO index is negative than when it is positive; there are more snowfall events when the NAO index is negative.

The results of the statistical tests showed that the stations in Minneapolis, Minnesota, Green Bay, Wisconsin, and Decorah, Iowa, had the best correlations between the North Atlantic Oscillation and snowfall amounts. Those locations also had the best statistical significance of the eleven locations. Based on this, snowfall at these three locations are most affected by the North Atlantic Oscillation.

These three locations are in the most northeast area of the study region. Values get smaller, so the NAO has less of an effect, the farther west and south from the three in the northeast. This makes sense because these three locations are closest to the oscillation itself in the Atlantic Ocean. Previous studies have shown strong effects from the North Atlantic Oscillation in the northeast United States, affecting snowfall amounts and frequency, as well as temperatures. With the Midwest being farther away from the oscillation than the northeast, the correlation values would decrease, with the best correlations in the northeast part of the Midwest, as shown.

b. Monthly Data

The statistical tests were also used using the total monthly accumulation and the NAO index for that month (**Table 3**).

Similar to the results for the daily data, the Pearson correlation and Spearman's rho values were negative for each location, meaning a negative correlation. However, the values were more negative this time indicating a stronger correlation than when only daily data was used.

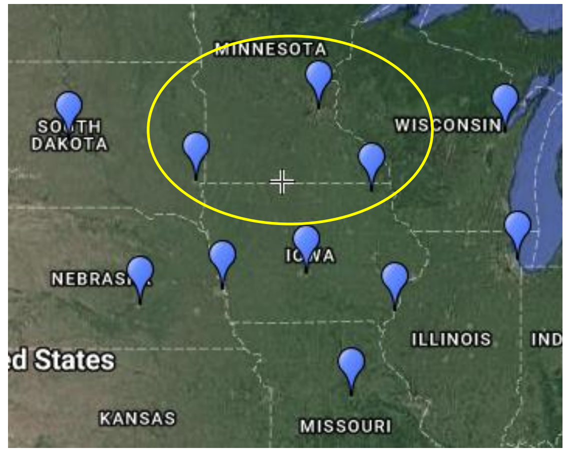

FIG. 7: Map of the Midwest showing the location of the three stations with the highest Pearson correlation when using monthly data.

The Pearson correlation had the best values in the northern part of the region (**Figure 7**) with Decorah, Iowa, Sioux Falls, South Dakota, and Minneapolis, Minnesota,

TABLE 3: Table showing the Pearson Correlation (p), Spearman's rho, and t-test results (t-value, degrees of freedom, and p-value) for all eleven locations using monthly snowfall and index data.

Location (Station Id)	p	rho	t-value	df	p-value
Des Moines, Iowa (IA2203)	-0.129	-0.102	-13.31	156	0
Decorah, Iowa (IA2110)	-0.151	-0.08	-12.13	154	0
Burlington, Iowa (IA1063)	-0.1	-0.014	-7.53	162	0
Omaha, Nebraska (NE6255)	-0.103	-0.077	-11.94	160	0
Grand Island, Nebraska (NE3395)	-0.046	-0.002	-11.86	160	0
Sioux Falls, South Dakota (SD7667)	-0.143	-0.09	-14.77	156	0
Pierre, South Dakota (SD6597)	-0.047	-0.032	-11.52	159	0
Minneapolis, Minnesota (MN5435)	-0.141	-0.082	-12.8	152	0
Green Bay, Wisconsin (WI3269)	-0.107	-0.07	-14.4	153	0
Chicago, Illinois (IL1549)	-0.099	-0.069	-11.04	154	0
Columbia, Missouri (MO1791)	-0.068	-0.03	-8.42	162	0

having the greatest correlations. This area is shifted slightly west when compared to the daily values. The smallest values occurred in Columbia, Missouri, Pierre, South Dakota, and Grand Island, Nebraska. These three locations are the most western or the most southern, so that is similar to what was found with the daily values. However, the general pattern is not the same; it does not decrease as you go farther south and west from the northeast. Sioux Falls, South Dakota, had one of the best correlations, whereas Pierre, South Dakota, had one of the worst.

The Spearman's rho values were highest in the north-central part of the region (**Figure 8**). Des Moines, Iowa, Sioux Falls, South Dakota, and Minneapolis, Minnesota, had the three highest values. Again, this is a little different from what was previously seen. The lowest values were in Columbia, Missouri, Burlington, Iowa, and Grand Island, Nebraska. These three include the two most southern stations as well as the most western one, but it, too, does not follow the pattern that was previously found.

Like before, a t-test was also performed to find the statistical significance between the variables. All eleven locations had a value of zero which shows a very strong statistical significance.

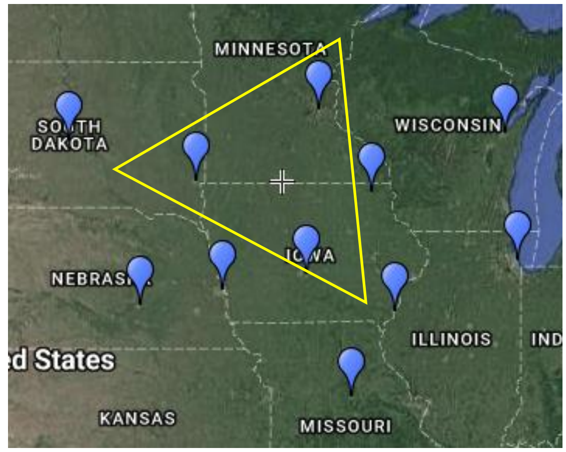

FIG. 8: Map of the Midwest showing the location of the three stations with the highest Spearman's rho value when using monthly data.

Although the monthly values do not follow the general spatial pattern found with the daily values, it did show a slightly stronger correlation between the North Atlantic Oscillation and snowfall. When looking at each day in the thirty years, there were many days that did not include snow, which could lower the correlation values. The monthly data was able to show a better correlation by removing some of that variability.

Both sets of tests showed a negative correlation between the North Atlantic Oscillation and snowfall at each location. This negative correlation implies that snowfall is more likely when the Oscillation is negative, rather than when it is positive. However, it does not guarantee that a very negative index value will give snow. In Des

TABLE 4: a) The ten most negative daily NAO indices with the snowfall (inches) that occurred. **b)** The ten most positive daily NAO indices with the snowfall (inches) that occurred.

a)

NAO Index	DSM Snow (in)
-2.711	0.0001
-2.696	0.0001
-2.632	0
-2.527	0
-2.522	0
-2.504	0
-2.317	0
-2.308	0
-2.255	0
-2.25	0

b)

NAO Index	DSM Snow (in)
2.359	0
2.355	0
2.341	0
2.309	0
2.306	0
2.296	0
2.278	0
2.254	0
2.252	0
2.212	0

Moines, Iowa, the ten most negative daily NAO index values did not produce much snow (**Table 4a**). There was also no snow with the ten most positive daily index values (**Table 4b**). When looking at all index and snowfall values together, it also shows that the heaviest or most frequent events do not occur at either extreme of the

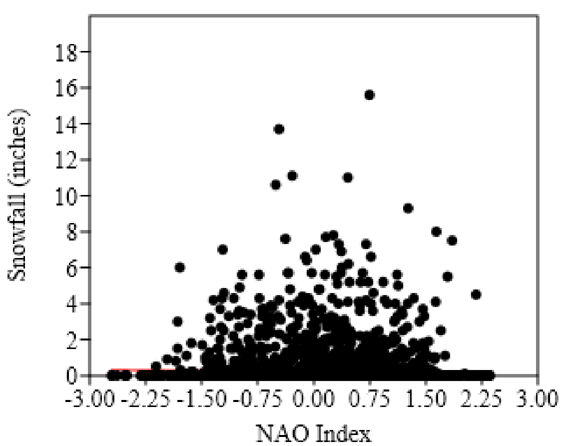

FIG 9: Graph showing the daily NAO index values plotted with the snowfall (inches) that occurred with that index.

index; there is a normal distribution (**Figure 9**). All eleven locations showed a similar distribution, so only Des Moines, Iowa, was shown.

TABLE 5: a) The ten most negative monthly NAO indices with the snowfall (inches) that occurred. **b)** The ten most positive monthly NAO indices with the snowfall (inches) that occurred.

a)

NAO Index	DSM Snow (in)
-1.985	19.701
-1.926	28.201
-1.847	9.701
-1.830	1.200
-1.670	7.500
-1.616	0.000
-1.610	7.701
-1.410	5.900
-1.380	6.500
-1.278	5.000

b)

NAO Index	DSM Snow (in)
2.56	0.90
2.29	4.10
2.02	12.40
2	16.30
1.85	1.20
1.78	3.60
1.71	0.30
1.7	18.40
1.7	8.90
1.66	12.50

The monthly data can also be looked at in a similar way. In Des Moines, Iowa, the ten months with the most negative NAO index values had very variable amounts of snow: from very trace amounts to over 28 inches (**Table 5a**). The same was found with the ten months with the most positive NAO index values (**Table 5b**). There are some very small amounts in these months and some larger amounts. The graph does not show the same normal distribution as the daily data did, but it does show that large amounts are possible with a positive index. The graph also shows a

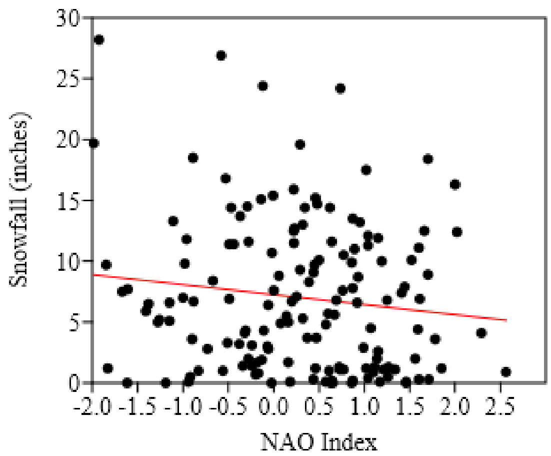

FIG 10: Graph showing the monthly NAO index values plotted with the snowfall (inches) that occurred with that index.

negative trend which helps illustrate the conclusion that heavier or more frequent events occur when there is a negative NAO index than when it is positive (**Figure 10**). Like before, all eleven locations were similar, so only Des Moines, Iowa, was shown.

4. Conclusion

The North Atlantic Oscillation does affect snowfall in the Midwestern United States. All eleven stations had a negative correlation between the NAO index and snowfall when looking at both daily and monthly data, meaning snowfall is more likely and potentially heavier when the NAO index is negative.

This agrees with what previous studies have found when looking at the possible effects in Europe and the Eastern United States. Results from the daily data also show a pattern that would be consistent with previous studies where the areas in the northeast part of the region experience more of a correlation than the southwest part of the region; however, the results from the monthly data did not show this same pattern.

One thing that was observed was that the heaviest or most frequent events did not occur when the index was most negative and the lightest or scarcest events did not occur when the index was most positive. This makes sense because the North Atlantic Oscillation is not the only force that is acting on weather in the Midwest. There are other oscillations, such as the Arctic Oscillation and El Niño-Southern Oscillation, that influence the same variables that the NAO does. Even though this was observed, there was a clear correlation between the NAO and snowfall.

In the future, this study could be expanded to include other forms of precipitation and temperature to see if they are also affected by the North Atlantic Oscillation. If that is done, a more definitive conclusion could be reached that the North Atlantic Oscillation does have a large effect on weather in the Midwest. This study, however, found there is a negative correlation between the NAO and snowfall which shows that there is some effect from the negative North Atlantic Oscillation index and the amount of snow that falls in the Midwest.

5. Acknowledgements

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References:

Bell, Ian: North Atlantic Oscillation. Accessed 24 February 2017. [Available online at http://www.ldeo.columbia.edu/res/pi/NAO/.]

Cattiaux, J., Vautard, R., Cassou, C., Yiou, P., Masson-Delmotte, V., and Codron, F., (2010), Winter 2010 in Europe: A cold extreme in a warming climate, *Geophys. Res. Lett.*, **37**, L20704, doi:10.1029/2010GL044613.

Dahlman, LuAnn, 2009: Climate variability: North Atlantic Oscillation. Accessed 24 February 2017. [Available online at https://www.climate.gov/news-features/understanding-climate/climate-variability-north-atlantic-oscillation.]

Department for Communities and Local Government, 2014: Winter 2013/14 severe weather recovery progress report. Accessed 24 February 2017. [Available online at https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/380573/Winter_2013-14_severe_weather_recovery_progress_report.pdf.]

Diao, Y., Xie, S.-P., and Luo, D. (2015). Asymmetry of winter European surface air temperature extremes and the North Atlantic Oscillation. *Journal of Climate*, **28**(2), 517–530. doi:10.1175/jcli-d-13-00642.1

Hurrell North Atlantic Oscillation (NAO) Index (station-based). Hurrell North Atlantic Oscillation (NAO) Index (station-based) | NCAR - Climate Data Guide. https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based. Accessed 22 October 2017

Song, Sora, 2011: Forecast: what happened to winter? just wait. Time. Accessed

24 February 2017. [Available online at http://content.time.com/time/magazine/article/0,9171,1001472,00.html?iid=sr-link2.]

State Climate Office of North Carolina: Global Patterns - Arctic & North Atlantic Oscillations (AO & NAO). Accessed 21 February 2017. [Available online at http://climate.ncsu.edu/climate/patterns/NAO.html.]

The Independent, 2014: Whether is blows hot or cold, Britain's winter will be extreme. Accessed 24 February 2017. [Available online at http://bi.galegroup.com.proxy.lib.iastate.edu/essentials/article/GALE%7CA381984499/ab079eeldec2db33af796cc654ce3875?u=iastu_main.]

Vicente-Serrano, S. M., & Trigo, R. M., 2013: *Hydrological, socioeconomic and ecological impacts of the North Atlantic Oscillation in the Mediterranean Region*. Dordrecht: Springer, 239 pp.

Yao, Y., Luo, D., Dai, A., and Feldstein, S. B. (2016). The Positive North Atlantic Oscillation with Downstream Blocking and Middle East Snowstorms: Impacts of the North Atlantic Jet. *Journal of Climate*, **29**(5), 1853–1876. doi:10.1175/jcli-d-15-0350.1