The Influence of Patterns of Climate Variability on the Significance of Major Snowstorms and Seasonal Snowfall for the city of New Brunswick, New Jersey

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Abstract

Various patterns of climate variability are examined to show their impact on seasonal snowfall and the frequency of major snowstorms for the Northeastern United States with particular emphasis on the city of New Brunswick, NJ. The patterns of interest here are the North Atlantic Oscillation, Pacific-North American Index, Arctic Oscillation, and the El-Nino Southern Oscillation. It has been statistically found that the NAO and AO are the most statistically significant for snowfall and major snowstorms with also some relationship between the two. The PNA is also significant but to a lesser degree. The two indexes with ENSO, the Southern Oscillation Index and Nino 3.4 showed very little significance with the results. The results show that patterns in the North Atlantic have more of a relationship to the snowfall in New Brunswick than the Pacific patterns. However, no physical evidence is shown as to why this may be, but some explanations are explained as to why this may be true.

Introduction

There have been many modes of climate variability discovered over the past few decades. Many of them have a big influence on winter weather in the United States, more specifically the Northeast US. They can affect the amount of snowfall that occurs during the winter season as well as the number of winter storms that will develop. Climate variability has shown to affect the number of winter storms and the total seasonal snowfall for the New Jersey area, and more specifically the city of New Brunswick.

Major Patterns

NAO

The North Atlantic Oscillation(NAO) is a mode of climate variability that affects a large area of North Atlantic during the winter months. The areas affected most are Europe, Eastern Canada, and the Eastern United States. Basically, the NAO is a battle of masses between the Polar(Iceland) Low and the Subtropical(Azores) High. Changes in both features affects the pressure field and ultimately the track and strength of low-pressure systems. The strength of each of these two features determines the phase of the NAO, whether it be positive or negative. The phase of the NAO can have major affects on the weather on these areas. The positive phase results in a stronger Iceland Low and subtropical high which increases the pressure gradient and results in more fast moving storm systems with a more northerly track. This results in warm and wet winters in Europe, cold and dry winters in Eastern Canada and Greenland, and mild and dry winters in the Eastern US. The negative phase results in a weaker Iceland Low and subtropical high which reduces the pressure gradient, and hence slower and weaker moving low-pressure systems. A “blocking” type pattern has also been show with the negative phase.

A study was done by the Meteorological Service of Canada, Environment Canada, that showed how in the negative phase of the NAO, thermal forcing(warm ocean/cold land) acted in concert with topographic forcing to create a blocking environment. This was proved statistically by showing that the NAO index and Atlantic blocking index are negatively correlated with cross correlation = -0.54, significant at 5% level.

PNA

The Pacific-North American Pattern(PNA) is a teleconnection pattern, characterized by atmospheric flow in which the west coast of North America is out of phase with the Eastern Pacific and Southeast United States. The anomalies of the PNA represent a wave-like pattern. There is a positive and a negative phase of the PNA and the wave-like pattern of the PNA will cause one-half of the US to see a much different weather pattern than the other half. In the negative phase, the West Coast of North America sees cooler temperatures and frequent storminess. Synoptically, 500 mb heights are lower and there is a trough-like pattern. The eastern US has a ridge-like pattern and more specifically, the Northeastern US will see warm and dry conditions. In the positive phase, the West Coast of North America sees warmer temperatures and dry weather. Synoptically, 500 mb heights are higher and there is a ridge-like pattern. The Eastern US develops a trough-like pattern with cooler temperatures and more storminess.

AO

The Arctic Oscillation(AO) is a mode of climate variability over the United States, the North Atlantic and Europe during winter. It refers to the strength of atmospheric pressure patterns in the middle and high latitudes. Thompson and Wallace (1998) defined the AO as the leading empirical orthogonal function (EOF) of the wintertime monthly mean SLP. The strength of each determines the phase of the AO. In the positive phase, sea-level pressures are lower near the poles, and higher at mid-latitudes(38-45º N). This creates stronger westerlies and this keeps the cold air further north towards the higher latitudes, as well as storm tracks. Most of the United States has warmer temperatures as a result of this. In the negative phase, the opposite occurs, where there are higher atmospheric pressures in the artic and northern latitudes and lower atmospheric pressures in the mid-latitudes. This results in weaker westerlies, which bring colder air farther south and most of the United States has colder temperatures. An index is determined to calculate the strength of it and the trend.

ENSO

El-Nino Southern Oscillation(ENSO) is a global event that arises from the interaction between the ocean and the atmosphere. It is an oscillation in surface pressure between the southeastern tropical Pacific and the Australian-Indonesian regions. The prime area for this phenomenon is the central and eastern Pacific Ocean. Normally, there is low-pressure in the western pacific and high pressure in the eastern pacific. This causes strong trades winds; since winds blow from high to low pressure, warmer water is pushed further west to the western Pacific waters.

However, changes in the atmosphere cause these winds to relax and cause waters to go through a warming and cooling phase, which can drastically affect the weather on a global scale, affecting large-scale weather patterns. The warm-phase is called El-Nino. El-Nino is the warming of the pacific waters. The trade winds relax, and warmer ocean water flows eastward, causing much warmer waters in the eastern pacific. The cold phase is called La-Nina. La-Nina is the cooling of the pacific waters. The trade winds increase, causing more upwelling of the waters and thus much cooler sea-surface temperatures.

Methodology

All the patterns just described have an index to calculate the strength of each, as well as the phase they are in during an interval of time. In the data and observations that will be shown later on, these index values will be used to show the correlation between seasonal snowfall and the number of major winter storms during the winter season based on monthly measurements.

The NAO index determines the strength and phase at any given time. It has more of an influence in the winter season than the summer season. The index is based on the sea-level pressure difference between the subtropical(Azores) High and the Polar(Iceland) Low. Measurements are taken twice a day, then averaged, resulting in the final value. The measurements are taken from a stations on Iceland, and either the Azores or Portugal. The equation to determine only the monthly values is defined as:

$$\text{NAO Index} = \frac{x - \bar{x}}{\sigma x} - \frac{y - \bar{y}}{\sigma y}$$

where x= the Azores High average sea-level pressure for the respective month, y = the Iceland Low average sea-level pressure for the respective month, $\bar{x}$= the long-term average (1950-1990) Azores High sea-level pressure for the respective month, $\bar{y}$ = the long-term average (1950-1990) Iceland Low sea-level pressure for the respective month, σ_x = the standard deviation of the Azores High sea-level pressure for the respective month from 1950-1990 and σ_y = equals the standard deviation of the Iceland Low sea-level pressure for the respective month from 1950-1990.

The PNA Index is a measure of the 500mb height pattern in four different locations. Similar analomies are located at the Aleutian Islands and SE United States with opposite signs near Hawaii and over eastern Canada. The equation proposed by Wallace and Gutzler (1981) is calculated as:

PNA = 0.25 * [Z(20N,160W) - Z(45N,165W) + Z(55N,115W) - Z(30N,85W)]

where Z are standardized 500 hPa geopotential height values.

The Southern Oscillation Index(SOI) is a measure of the sea-level pressure at Darwin compared with the sea-level pressure at Tahiti. A positive value indicates a warm phase and the presence of El-Nino, and a negative value indicates cold phase and the presence of La-Nina. The SOI is measured by the following equation:

$$SOI(month, year) = \frac{[T(month, year) - D(month, year)]}{S}$$

where T&D are the sea-level pressures at Tahiti and Darwin, and S is the standard deviation of the numerator for all months combined for the years 1951 to 1980.

Besides the SOI, there are other methods of measuring the strength of El Nino/La Nina events. There are four regions in the pacific ocean where indices based sea-surface temperatures are measured. These regions are Nino 1 through 4 and are measured by taking the average value over a particular region. A relatively new index, The Nino 3.4 was added in April 1996 to allow researchers gain a better understanding what is happening with the SST's in the critical regions between the Nino 3 and Nino 4 regions(CPC). When a major change is taking place between the Nino 3 and 4 regions, this index can better view the changes taking place in the sea-surface temperatures. The locations that are averaged are 120°W-170°W and 5°N-5°S with a base period from (1971-2000).

Data and Methods

In this study, the data I wanted to look at were monthly and seasonal statistics for snowfall and the number of major snowstorms from the period 1950-2002 for the New Brunswick area during the winter season. The winter season in my data runs from December through March. I used all the index values in this period. Two sets of data were constructed using contingency tables. Two snow variables were used with one set being the number of major snowstorms and the other the total snowfall in that four month period. The two variables were first done by monthly values for each year, and then again for seasonal values. The index values were assigned a low, medium, and high value. The range was delineated by the total number of trials and dividing it by three. For major snowstorms, the numbers were assigned zero, one and two or more. The threshold for a major storm was 5" or more of snow for any single event. For snowfall, the same strategy as with the index values was performed. Finally, statistically analysis was performed at the end using the Chi- Square Test to see the significance of the results.

Results

The statistical analysis that was performed showed very different results and outcomes between the number of major snowstorms and total snowfall. The results were even more drastic when comparing them by month and season. As a reference for the significance of the results, all the contingency tables except for the seasonal statistics for major winter storms had a 3x3 column with degrees of freedom being 4. The seasonal statistics for major winter storms had a 4x4 column with degrees of freedom being 6. The tables shown will show the results from the statistics but for all the data in the sample, refer to the charts at the end of the paper.

Monthly Statistics for Major Winter Snowstorms			
Pattern	Chi-value	P-Value	Significance
NAO	5.453	≥ .10	Insignificant
PNA	2.608	≥ .10	Insignificant
AO	13.137	≤ .01	Highly Significant
SOI	1.135	≥ .10	Insignificant
Nino 3.4	2.342	≥ .10	insignificant

Table 1.1

Seasonal Statistics for Major Winter Snowstorms			
Pattern	Chi-value	P-Value	Significance
NAO	8.86	≥ .10	Insignificant
PNA	8.534	≥ .10	Insignificant
AO	11.115	.01 - .05	Mildly Significant
SOI	7.906	≥ .10	Insignificant
Nino 3.4	3.81	≥ .10	insignificant

Table 1.2

The results for the number of major winter storms shows that the statistical significance of the patterns is very low except for the Artic Oscillation, which was the only pattern to show any significance. While both tests showed similar results, the seasonal statistics did show higher values, despite still being too low to show any significance and this proves that there is somewhat of a relationship to the number of winter storms over a seasonal period than monthly period. Since the arctic oscillation was very significant for all tests, this pattern is likely to have a big effect on the number of storms and should be considered when making long range forecasts. Below are the strongest results for the number of major winter storms and seasonal snowfall for the AO.

	AO			
Snowfall	Low	Med	High	Total
7" to 28.4"	33(24)	24(24)	15(24)	72
1.8" to 6.7"	30(24)	20(24)	22(24)	72
0 to 1.8"	9(24)	28(24)	35(24)	72
Total	72	72	72	216

χ= 25 p-value ≤ .01

result: highly significant

Figure 1(Monthly Snowfall)

	AO			
# Storms	Low	Med	High	Totals
2 or 3	4(4)	6(4)	2(4)	12
1	29(19.67)	11(19.67)	19(19.67)	59
0	39(48.33)	55(48.33)	51(48.33)	145
Total	72	72	72	216

χ= 13.137 result: Highly Significant

Figure 2(Monthly Major Snowstorms)

The figures at the end of the paper show the number of occurrences based on the value of the pattern, whether it be low, medium or high. Despite the fact that in the end all the values total up the final value, the statistics show that the phase of the pattern does not necessarily mean that the setup for that phase will happen all the time.

Monthly Statistics for Total Snowfall			
Pattern	Chi-value	P-Value	Significance
NAO	15.539	≤ .01	Highly Significant
PNA	10.415	.01 - .05	Significant
AO	25	≤ .01	Highly Significant
SOI	-	-	-
Nino 3.4	-	-	-

Table 1.3

Seasonal Statistics for Total Snowfall			
Pattern	Chi-value	P-Value	Significance
NAO	10.669	.01 - .05	Significant
PNA	10.668	.01 - .05	Significant
AO	11.004	.01 - .05	Significant
SOI	10.669	.01 - .05	Significant
Nino 3.4	3.669	$\geq$ .10	Insignificant

Table 1.4

The results for the monthly and seasonal statistics for snowfall show much more significance than for the total number of major snowstorms. The PNA stayed constant for both the monthly and seasonal snowfall data sets. There was a slight relationship to the NAO and AO in that they showed the most significance and had the highest values. I did not perform any statistics for the SOI and Nino 3.4 for monthly because of the lack of evidence in showing any significance in the previous data sets. While the SOI did show significance in the seasonal statistics, it would have been a waste of time to perform an analysis for the monthly data and probably would have had a lesser value and little significance. The Nino 3.4 showed no significance once again and was a non-factor in all the data sets and is why I did not bother to do the analysis for the monthly snowfall.

Analysis and Discussion

The analysis of the results shows that some of the patterns of climate variability used in this study are important for snowstorms and total snowfall and some are have no bearing whatsoever on the outcome. Based on the results the NAO and AO should be looked at very closely in determining these two factors and also the relationship between the two should studied more closely to find so sort of correlation between the two. Both patterns arise in the North Atlantic which is more of a reason for a higher significance at least in the New Brunswick area. The PNA, SOI, and Nino 3.4 arise in the Pacific ocean and could explain for them having less of a significance, but of the three the PNA should be used the most in dealing with snowfall and snowstorms. The reason for the SOI and Nino 3.4 being less important is because these patterns evolve over the course of a few months where the PNA, AO, and NAO can change in the matter of a few days or weeks and hence is why they have a stronger bearing on the distribution of snowstorms and snowfall over the course the time period used in this experiment. Also, in dealing with major snowstorms it shows that even though the patterns might be in the right phase, that does not mean it will always happen.

There are many other factors synoptically that are needed for a classic snowstorm. Some of them are the positioning of the polar vortex(PV) and the strength of the jet stream and how the polar and subtropical jet streams interact. Also, the the positioning of the east coast trough and where the axis sets up can have a major effect on how and where snowstorms will develop and track. There are indexes for measuring the east coast trough and these might have to also be looking at for future research. While the SOI and Nino 3.4 indexes are for showing the patterns of SST's, the fact that they are measured over the Pacific ocean could be the reasoning for why they did not show much significance. I think that measuring SST's over the western Atlantic Ocean and observing their trends may have more significance for snowfall in the New Jersey area, and more specifically New Brunswick, NJ.

Past Studies

There has not been much research to relate one specific location to the amount of snowfall they will receive, but there has been extensive research on a more regional picture, such as the Northeastern United States. However, most of that research has been done to relate seasonal snowfall than to the frequency of major snowstorms. With that said, some findings have been correlated to major snowstorms. David Groenert, a University of Albany graduate student found that significant precipitation events in the Northeast United States are due to large-scale circulation regime changes. (Bosart 2003) This means that when a pattern is the transitioning from one phase to the other(Neutral Phase), this is when significant events are more likely to occur. They showed this tendency by using the 12-14 March 1993, 18-18-20 Jan 1996, and 24-26 Jan 2000 events. This was discovered based on their disproved hypothesis that a negative NAO and positive PNA are associated with increased monthly and seasonal precipitation.

Heavy snow years over the eastern United States are associated with an enhanced eastern U.S. trough, with the large-scale situation similar to what is now termed the Pacific–North American (PNA) teleconnection pattern (Wallace and Gutzler 1981). For the PNA it has been shown that snowfall is more a function of the mean maximum temperature on precipitation days in the Northeastern US. (Robinson 1997) The same paper also showed a relationship to increased snowfall under positive extremes of the pattern.

Previous studies have linked variability in ENSO and the NAO to spatial and temporal changes in major northern hemisphere storm tracks (Bradbury 2003). East Coast winter storms are know to increase during El Nino Events(Hirsch, DeGaetano, and Colucci 2001), with greater cyclone occurrence in the Southern US and lower atmospheric pressures (Kunkel and Angel 1999). La Nina winters have been characterized by lower atmospheric pressures over central and western Canada (Rodgers

1984; Trnberth and Caron 2000), and favoring more continental storm activity in the Midwest and St. Lawrence storm tracks (Kunkel and Angel 1999). Rogers (1990) showed that during extreme negative NAO conditions, East Coast cyclones often diverge to the east (near 45 degrees N), as opposed to the more common northeast trajectory (Serreze et al. 1997). Thompson and Wallace (2001) observed an increase in frequency of nor'easters during low AO/NAO conditions. Rogers (1984) investigated the association between the NAO and the ENSO in the NH. He found that both teleconnections are associated with significant SLP differences over much of the NH except for Siberia and western North America. In the 80 winters with data, simultaneous appearance of the two modes only seems to occur by chance.

Raymond Bradbury and a few other researchers, from the University of Massachusetts also did a study relating cyclone occurrence and track, and seasonal snowfall using rotated principal component analysis. For ENSO, they showed that the SOI produced greater precipitation events along the coast during El Nino and less during La Nina years. This also showed higher frequency of coastal track storms than continental storms tracking further west into the Great Lakes for El Nino year, with the opposite being true for La Nina. With the NAO, the results showed blocking near Greenland and higher snowfall totals in the Northeast United States during a negative NAO. The blocking resulted in U.S. coastal storms being directed on a more eastward track than the normal flow.

Conclusions

The results in this study were done to show how different modes of climate variability affect the frequency of major winter storms affecting an area as well as the seasonal snowfall totals. The city of New Brunswick, New Jersey was chosen as a specific location for this study. Statistical analysis was done using the Chi-Square Test to show the significance of these patterns and how they affect these two variables.

It has been shown that the AO is the most significant in determining the number of major winter storms and the overall seasonal snowfall. The NAO and PNA also showed significance but to a lesser degree. The least amount of significance came with the SOI and Nino 3.4 indexes. The evidence was shown using past data from the 1950-2002 winter seasons. There is less of a relationship to the Pacific patterns than the Atlantic patterns and for the ENSO; this is due to the fact that the patterns change over the course of a few weeks or even months. Future work needs to be done to observe SST's in the Atlantic ocean and how they relate to the NAO and AO. Also, besides studying these patterns, one should also look at the synoptic situation to further explain the results. The patterns may indicate that the necessary conditions are there for a snowy winter or frequent and powerful winter storms, but the all the ingredients must be in place for one to occur.

Other studies have been done to show these types of results. However, most of them have been correlating snowfall totals to this patterns and little research has been done to determine the frequency of major snowstorms. The tests in this paper do show similar relationships to those studies with respect to snowfall. The NAO and AO have significantly been shown to increase snowfall in the New Brunswick area and on a regional standpoint, the Northeastern United States under the proper phase of each pattern. The PNA and NAO have a relationship to one another as well as ENSO with the AO and NAO. The findings on this paper and from previous studies show that as we better understand the role of climate variability in winter weather, the better we will become in forecasting snowfall for an entire season and predicting major snowstorms on a medium and long-range scale.

References

Bradbury A. James, B. D. Klein, and C. P. Wake. 2003. The Influence of Regional Storm Tracking and Teleconnections on Winter Precipitation in the Northeastern United States. Annals of the Association of American Geographers 93: 3544-546

Bosart F. Lance, D. Keyser. 2004. Continuing Studies of Cool- and Warm-Season Precipitation events over the Northeastern United States.

Serreze C. Mark, Martyn P. Clark and David L. McGinnis. 1998. Characteristics of Snowfall over the Eastern Half of the United States and Relationships with Principal Modes of Low-Frequency Atmospheric Variability. American Meteorological Society.

International Research Institute for Climate Prediction, 2002, Monitoring ENSO, viewed 20 March 2004, http://iri.columbia.edu/climate/ENSO/background/monitoring.html#soi

Daly, L. John, 2004, El-Nino Southern Oscillation, http://www.vision.net.au/~daly/elnino.htm

Bell, Ian, North Atlantic Oscillation, http://www.ldeo.columbia.edu/res/pi/NAO/

Stephenson, B. David, 1997, The North Atlantic Oscillation thematic Website, http://www.met.rdg.ac.uk/cag/NAO/

Mitchell, Todd, 2003, Pacific North American(PNA) Index 1948-2003, http://tao.atmos.washington.edu/data_sets/pna/

Climate Diagnostics Center, 2001, Pacific North-American Index(PNA), http://www.cdc.noaa.gov/Teleconnections/pna.html

Mitchell, Todd, 2000, High and Low Index Arctic Oscillation(AO), http://tao.atmos.washington.edu/analyses0500/ao_definition.html