NAO

The North Atlantic Oscillation Impact on Temperatures, Precipitation, Snowfall, and Snow Depth

Abstract

Daily North Atlantic Oscillation (NAO) values computed using NCEP reanalysis data were compared to temperature, precipitation, snowfall, and snow depth along the Eastern United States. Significant correlations exist between the NAO and these meteorological variables. The strongest relationship is between temperature and the NAO with a weaker but still significant relationship seen between the NAO and precipitation. A much greater amount of snowfall is seen during the negative phase of the NAO and that along with lower temperatures leads to a deeper snow depth during these days. Also, using daily NAO values allowed us to see some relationships that might be missed when using monthly values.

Introduction

One of the earliest known writings of what we now call the North Atlantic Oscillation occurred in the diary of Hans Egede Saabye. Saabye was a missionary in Greenland during the late 18th century and he wrote: "In Greenland all winters are severe yet they are not all alike. The Danes have noticed that when the winter in Denmark was severe, as we perceive it, the winter in Greenland in its manner was mild, and conversely" (van Loon and Rogers 1978).

The term North Atlantic Oscillation (NAO) was originated by Sir Gilbert Walker in the 1920's (Walker 1924). The traditional definition of the NAO is the difference of normalized sea level pressure anomaly between Iceland and the subtropical eastern North Atlantic (Portis et al. 2001). The two most common NAO indexes are Rogers (1984), which uses sea level pressure data from Akureyri, Iceland and Ponta Delgada, Azores and Hurrell (1995), which uses Stykkisholmur, Iceland and Lisbon, Portugal. Most recently Portis et al. (2001) showed that their "mobile" NAO index (NAOm), which varies geographically depending on the time of year, has a higher correlation with the westerly wind intensity across North Atlantic midlatitudes then traditional NAO indexes.

The NAO has been found to work on a variety of time scales from weekly to monthly all the way to decadal. The weekly and monthly changes in the NAO were found in some cases to be led by polar stratospheric circulation (Baldwin and Dunkerton 2001). The annual to decadal changes seem to be affected by the underlying sea surface temperatures anomalies and can have a significant impact on temperatures and precipitation in Europe (Hurrell 1995). The NAO has also been shown to influence snowfall in the Northeastern United States, with more snow falling during the negative phase (Hartley and Keables 1998).

During a positive NAO there is a strengthening of the Icelandic low and Azores high. This strengthening results in an increased pressure gradient over the North Atlantic, which cause the westerlies to increase in strength. The increased westerlies allow cold air to drain off the North American continent rather then letting it build up and move south. This also works to advect relatively warm and moist ocean water air into Europe causing increased temperatures and precipitation (Hurrell 1995). During a negative NAO there is a weakening of both the Icelandic low and Azores high, which act to decrease the pressure gradient across the North Atlantic. This decreased pressure gradient results in a slackening of the westerlies. The decrease in the westerlies allows cold air to build up over Canada and has a greater chance to move south and affect the United States. In Europe less warm air off the Atlantic Ocean allows more cold air to build up over the continent and causes it to be drier.

These sea level pressure changes are a reflection of what is going on in the mid and upper levels of the atmosphere. During a negative NAO unusually high geopotential height occurs across the high latitude North Atlantic. This is typically looked for at the 500 mb level and is referred to as blocking. This blocking ridge across the high latitude North Atlantic causes both upstream and downstream troughs across Eastern North America and Western Europe. Portis et al. (2001) showed that the NAOm is strongest in March followed by February and January. Since the oscillation is strongest in winter the extended winter (December - March) was chosen for this particular study. Looking for impacts along the Eastern United States on a daily time scale level by comparing the NAO index to meteorological station data.

Modeled Daily NAO Index

In this study focus was placed on examining the NAO on a daily time scale. This is in contrast to the majority of the studies, which have focused on monthly NAO index data (Hurrell 1995, Hartley and Keables 1998, van Loon and Rogers 1978). Gary Bates of the National Oceanic and Atmospheric Administration - Cooperative Institute for Research in Environmental Sciences (NOAA/CIRES) Climate Diagnostics Center put together a daily NAO Index based on the National Centers for Environmental Prediction (NCEP) reanalysis provided by NOAA/CIRES Climate Diagnostics Center, Boulder Colorado (Kalnay et al. 1996). This consisted of 53 years (1948-2000) of reanalysis data. Portis et al. (2001) points out some of the advantages and disadvantages of using reanalysis data. An advantage is the dataset is internally consistent in time and space because the same model physics and computational schemes are used, also it includes a large set of meteorological data from diverse sources. Disadvantages include data streams that have changed over time like the inclusion of satellite data more recently. Another disadvantage that is well known is that there are fewer input observations during the first 10 years of the reanalysis. All of these factors must be understood when using NCEP reanalysis data.

In order to calculate this NAO index, daily values of 500 mb heights were used. Based on the Barnston and Livezey (1987) study, the centers of action for the NAO were defined as 2 regions across the North Atlantic (Figure 1). Region 1 is defined as an area

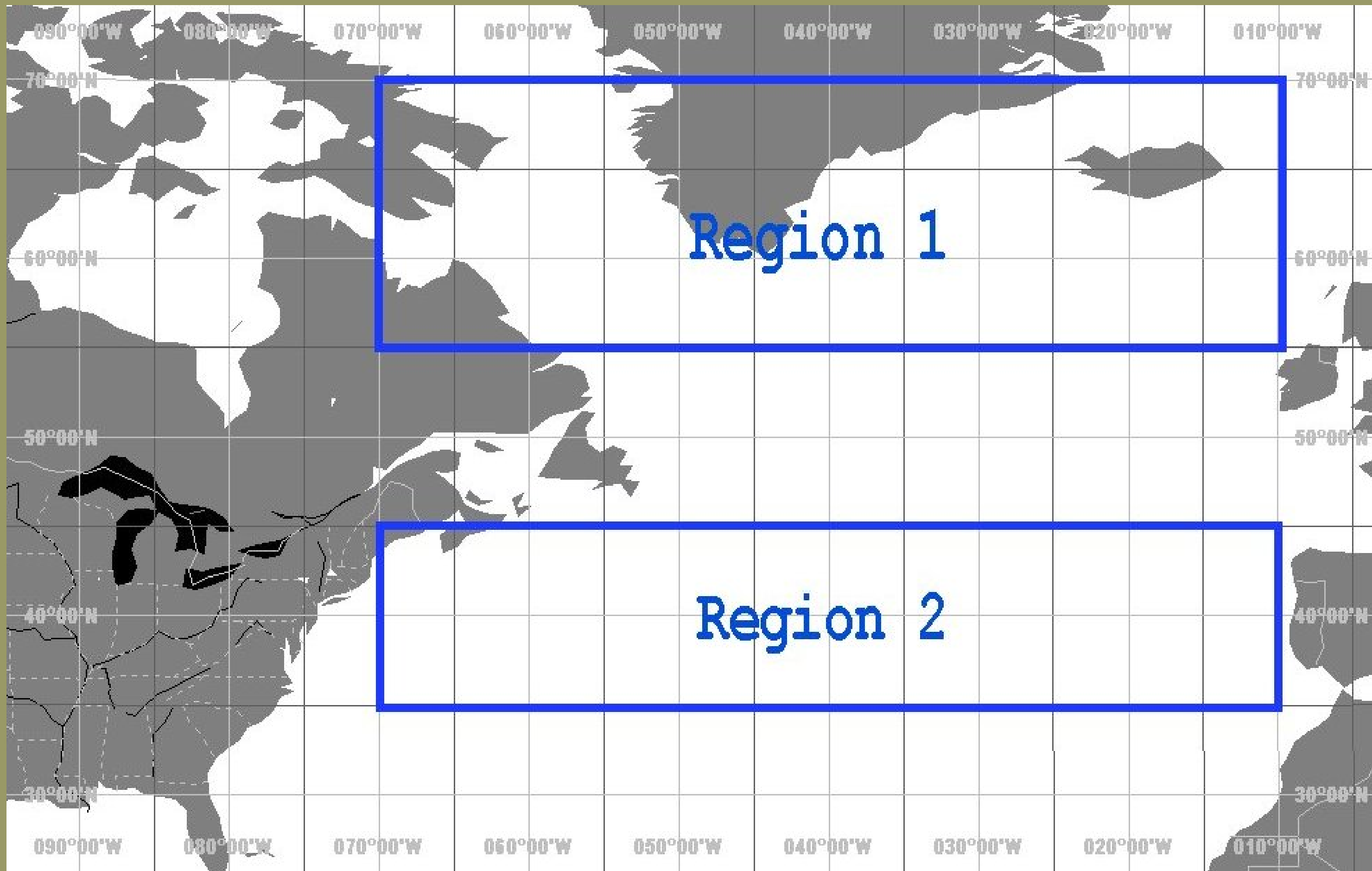

Figure 1

from 70°W to 10°W and 55°N to 70°N and Region 2 is an area from 70°W to 10°W and 35°N to 45°N. The daily average value of 500 mb height within each area was calculated. This value was then subtracted from the climatological mean based on the average daily value from 1968-1996. This produced anomalies for both regions and by subtracting Region 1 anomaly from Region 2 anomaly a daily NAO index was produced. The last step was to apply a 3-day centered average filter to remove some of the highest frequency noise.

By using regions rather than point data we are better able to follow the Icelandic low and Azores high, which makes this index closer to Portis et al. (2001) NAOm. The majority of the time the center of these pressure systems will be included in these regions which is rarely the case when using point data. The use of regions allows this index to more closely mimic the westerly wind index.

An example of why daily NAO index can be helpful can be seen in Figure 2. This

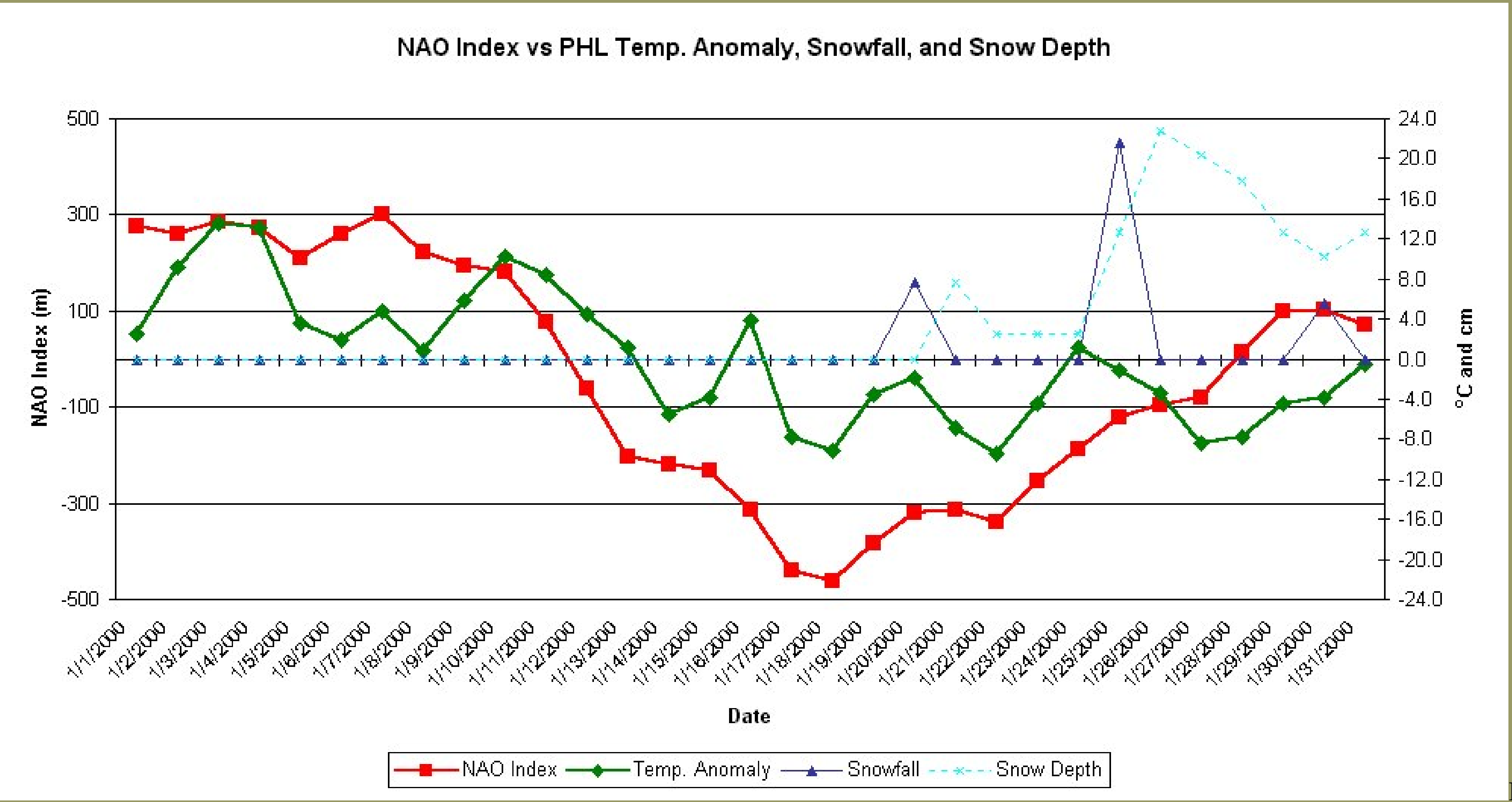

Figure 2

shows the daily NAO index versus Philadelphia, PA temperature anomaly, snowfall, and snow depth during January 2000. The average NAO index for the month was slightly below normal at -39 m and the average temperature anomaly was near normal at 0.07°C, however those numbers tell you very little about what took place during the month. There were actually two completely different 2-week regimes. The first was from the 1st to the 12th, which had a very strong positive NAO and well above normal temperatures. The second from the 13th to the 27th, which had a very strong negative NAO and well below normal temperatures with 2 sizable snow events and the establishment of a significant snow cover. This snow cover could possibly be one reason why the temperatures stayed below normal despite the NAO going positive at the end of the month. By averaging on a monthly basis you can lose these kinds of relationships. There were 15 days where the NAO was positive and the average value was 188 m, the average temperature anomaly during those days was 3.8°C. There were 16 days where the NAO was negative and the average value was -252 m, the average temperature anomaly was -3.4°C. Figure 3 shows the average extended winter (DJFM) value of the NAO and

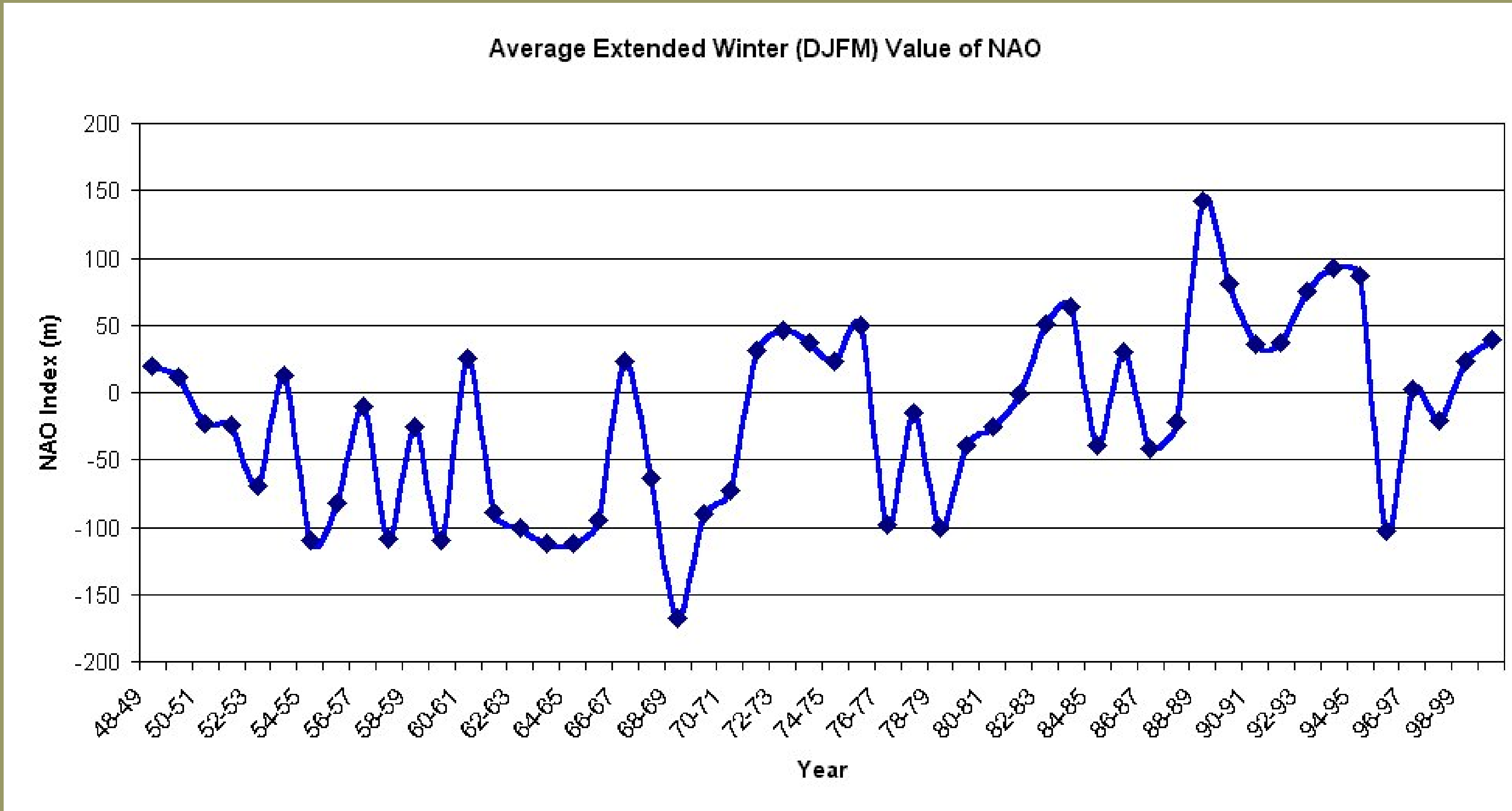

Figure 3

allows you to see some of the decadal variations of the NAO. The 1950's and 1960's exhibited a predominantly negative NAO and the 1980's and 1990's saw mainly a positive NAO. Figure 4 shows the number of positive and negative NAO days for each extended winter and the same pattern can be seen with more negative NAO days in the 1950's and 1960's and more positive NAO days in the 1980's and 1990's. The standard deviation was also examined to see if there has been any significant trend in the variability over the last 50 years but nothing significant was seen. The average standard deviation during the extended winter was 166 m.

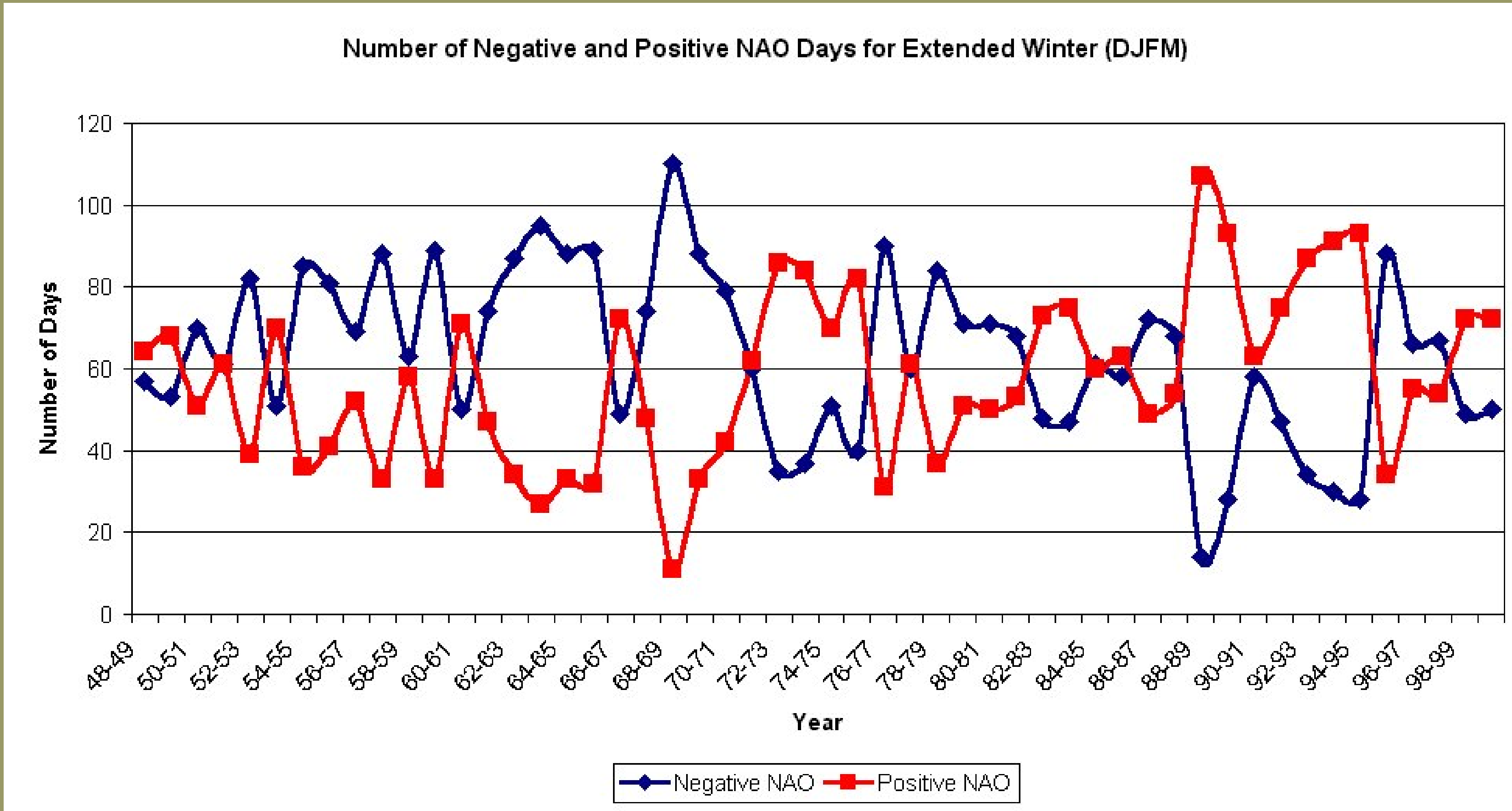

Figure 4

During the 52 extended winter a total of 6305 days were examined. The positive phase of the NAO occurred in 2993 of the days and the negative phase of the NAO occurred in 3312 of the days. Also, the 1 standard deviation (SD) level was examined and there was a total of 2059 days in this category. It showed that 855 days exceeded the positive 1 SD level (NAO > 166 m) and 1204 days were more extreme than the negative 1 SD level (NAO < -166 m). By looking at these days you eliminate the effects of marginal NAO days when its impact should be minimal.

Statistical Methods and Stations

Seven stations along the Eastern United States were chosen to examine the NAO relationship. The stations were chosen because of their long history (at least 1948 to present) and fewest missing data points. Care was taken in selecting a geographically diverse sample with both mountainous and coastal locations from Massachusetts to North Carolina (Figure 5). Table 1 shows the information for each of the seven locations. Data was acquired from the National Climatic Data Center (NCDC) for each of the stations. The variables included temperature, precipitation, snowfall, and snow depth.

Figure 5

The 1971-2000 normals were also acquired and used in calculating the temperature anomalies for each station.
The two main statistical methods used are composite analysis and Spearman rank correlation. Composite analysis was done by separating the positive and negative NAO days and getting average values for temperature anomaly, precipitation, snowfall, and snow depth for both of the NAO regimes. This was done to see if and how much of a difference there was between positive and negative NAO days. This was also calculated using the 1 SD level of the NAO index to compare with all cases in general. Spearman rank correlation and t-test was used to test for significance between the station data and

Table 1

City, State	Abbreviation	Latitude	Longitude	Elevation
Boston, MA	BOS	42°22'N	71°01'W	6.1 m
Albany, NY	ALB	42°45'N	73°48'W	83.8 m
Philadelphia, PA	PHL	39°52'N	75°14'W	1.5 m
Washington DC	DCA	38°52'N	77°02'W	3.0 m
Charleston, WV	CRW	38°23'N	81°35'W	277.4 m
Raleigh, NC	RDU	35°52'N	78°47'W	126.8 m
Asheville, NC	ASH	35°36'N	82°32'W	682.8 m

the NAO. The Spearman rank correlation analytical method (Equation 1) has distinct

$$r_s = 1 - \frac{6\sum d^2}{n(n^2-1)} \qquad (1)$$

advantages when compared to standard parametric methods. In equation 1 rs is the rank correlation coefficient for sample paired data, n is the number of data points, and d is the difference between ranks for the two observations within a pair. Rank correlation can be used to detect both linear and nonlinear relationships and is not overly sensitive to outlying data points. The t-test was used to determine statistical significance of the Spearman rank correlation and is shown in equation 2. In equation 2 t is the value used to determine the two-tailed p-value.

$$t = r_s \sqrt{\frac{n-2}{1-r_s^2}} \qquad (2)$$

NAO and Temperature

The pattern defining the NAO is strongest during the winter so the extended winter was chosen to examine the NAO relationship to meteorological variables along the Eastern United States. Temperature anomalies were calculated for the 52 winters (1948-1949 to 1999-2000) for each of the 7 stations. These anomalies were then separated based on the sign of the NAO during that day and a separate set for the extreme 1 SD level days (positive NAO > 166 m and negative NAO < -166 m). Average temperature anomalies were calculated based on the sum of the departures divided by the number of days the NAO was that particular sign. Table 2 shows the results of that composite analysis for all cases and the 1 SD level cases. As you can see from the table, temperatures are much colder when we are in the negative phase of the NAO. When we

Table 2

Location	+NAO all cases	-NAO all cases	Difference Negative -Positive all cases	+NAO 1 SD cases	-NAO 1 SD cases	Difference Negative -Positive 1 SD cases
BOS	1.26°C	-0.34°C	-1.60°C	1.61°C	-0.76°C	-2.37°C
ALB	1.02°C	-0.84°C	-1.86°C	1.37°C	-1.36°C	-2.73°C
PHL	0.77°C	-1.03°C	-1.80°C	1.13°C	-1.65°C	-2.78°C
DCA	1.16°C	-0.57°C	-1.73°C	1.54°C	-1.17°C	-2.71°C
CRW	1.61°C	-0.34°C	-1.95°C	1.88°C	-1.16°C	-3.04°C
RDU	0.82°C	-0.96°C	-1.78°C	1.22°C	-1.56°C	-2.78°C
ASH	1.65°C	0.03°C	-1.62°C	2.00°C	-0.71°C	-2.71°C

are in the positive phase temperatures are between 0.77°C at Philadelphia and 1.61°C at Charleston above normal. Conversely, when we are in the negative phase temperatures go from between little change at Asheville to -1.03°C at Philadelphia. Temperatures are just under 2°C colder during a negative NAO then when it is in its positive phase. Looking at the 1 SD cases the differences get even larger with most stations close to 3°C colder in the negative phase as compared to the positive phase. These differences increased in all cases by about 1°C when looking at the more extreme NAO cases. All stations showed close to the same differences but the strongest was Charleston, which is one of our further west stations and the weakest one was Boston, which is our furthest east. There was very little elevation difference noticed in the temperature composite. Spearman rank correlation values were between 0.17 and 0.20 for all 7 stations over the 6305 days giving a p-value of less than 0.0001. This indicates that a significant relationship does exist between the NAO and temperature anomalies along the Eastern United States.

NAO and Precipitation

Similar composite analysis was done for precipitation and table 3 shows the results. The negative NAO phase tended to produce less precipitation then the positive NAO cases. Considering all extended winter days negative NAO phase produced close to 0.5 mm/day less precipitation. The difference seemed to be greater for the northern stations and less for the southern ones. The 1 SD level cases showed more variability overall with Asheville and Washington DC seeing less of a difference but all other stations seeing more of a difference. Albany and Charleston saw about 0.9 mm/day less

Table 3

Location	+NAO all cases (mm/day)	-NAO all cases (mm/day)	Difference Negative -Positive all cases (mm/day)	+NAO 1 SD cases (mm/day)	-NAO 1 SD cases (mm/day)	Difference Negative -Positive 1 SD cases (mm/day)
BOS	3.52	2.96	-0.56	3.47	2.86	-0.61
ALB	2.48	1.96	-0.52	2.64	1.72	-0.92
PHL	2.98	2.53	-0.45	3.07	2.45	-0.62
DCA	2.80	2.36	-0.44	2.77	2.36	-0.41
CRW	3.09	2.64	-0.45	3.59	2.70	-0.89
RDU	3.10	2.74	-0.36	3.10	2.57	-0.53
ASH	2.85	2.46	-0.39	2.72	2.55	-0.17

precipitation in the negative phase then in the positive phase. The same correlation test was performed and although the relationship was weaker all stations except Asheville showed a significant relationship.

NAO and Snowfall, Snow Depth

The NAO relationship to snowfall and snow depth was also examined. Table 4 shows a similar analysis as previous but with snowfall. The analysis reveals that there is more snowfall when the NAO is in the negative phase even though the overall precipitation is less. This seems to suggest more of a dependence on temperature then precipitation for snowfall along the Eastern United States. Every station showed a significantly higher percentage increase in snowfall for the 1 SD level cases versus when all cases were considered. The 1 SD level cases show that the percentage increase of snowfall for negative NAO days is smallest for Boston and Albany, our 2 northernmost

Table 4

Location	+NAO all cases (mm/day)	-NAO all cases (mm/day)	Difference Neg. -Pos. all cases (mm/day)	Percent increase for -NAO	+NAO 1 SD cases (mm/day)	-NAO 1 SD cases (mm/day)	Difference Neg. -Pos. 1 SD cases (mm/day)	Percent increase for -NAO
BOS	7.23	8.48	1.25	16%	7.16	9.19	2.03	28%
ALB	11.66	11.69	0.03	0%	10.19	11.73	1.54	15%
PHL	3.37	4.86	1.49	44%	1.81	5.40	3.59	198%
DCA	2.43	3.75	1.33	55%	1.09	4.87	3.78	347%
CRW	4.96	6.74	1.79	36%	4.14	8.65	4.51	109%
RDU	1.08	1.55	0.47	44%	0.92	1.80	0.88	96%
ASH	1.71	3.52	1.81	106%	1.13	4.84	3.71	328%

locations. In winter temperatures are usually cold enough to produce snow in these locations whereas, the other stations typically have temperatures just above freezing and a couple of degrees can make a big difference in precipitation type. The other 5 stations saw between 96% and 347% more snowfall during the more extreme negative NAO phase as compared to the more extreme positive NAO phase. Spearman rank correlation and t-test indicates that a significant relationship exists at all stations although it was somewhat weaker for Boston and Albany. Table 5 shows the composite analysis of snow depth for all extended winter days and extreme 1 SD level days. The results show that the negative NAO days tend to have

Table 5

Location	+NAO all cases (mm/day)	-NAO all cases (mm/day)	Difference Neg. -Pos. all cases (mm/day)	Percent increase for -NAO	+NAO 1 SD cases (mm/day)	-NAO 1 SD cases (mm/day)	Difference Neg. -Pos. 1 SD cases (mm/day)	Percent increase for -NAO
BOS	25.27	38.77	13.50	53%	26.94	46.00	19.06	71%
ALB	55.41	82.14	26.73	48%	51.51	99.03	47.52	92%
PHL	7.35	11.79	4.44	61%	7.69	14.37	6.68	87%
DCA	6.83	11.38	4.55	67%	5.97	14.43	8.46	142%
CRW	11.13	17.19	6.06	55%	12.12	22.40	10.28	85%
RDU	2.51	3.58	1.07	43%	2.40	4.51	2.11	88%
ASH	2.91	4.97	2.06	71%	3.77	8.00	4.23	112%

a much deeper snow depth than positive NAO days. This is what you would expect to see based on the previous information of snowfall and temperature. All 7 stations showed a greater difference in snow depth between positive and negative NAO days for the 1 SD level case as compared to when just the sign of the NAO was considered. Albany had an average of about 47 mm/day more snow on the ground during an extreme negative NAO day then an extreme positive one. Again, all stations showed a significant relationship and were greater than the snowfall relationship. Very little geographical or elevation differences were seen in the change of snow depth.

Conclusion

The NAO clearly shows a relationship to temperature, precipitation, snowfall, and snow depth along the Eastern United States. Significant differences in these variables exist between the respective phases of the NAO and these differences are even greater when looking at the more extreme NAO days. Since a greater amount of snow is present when we are in the negative NAO phase its effects could last into spring, possibly increasing the predictive potential of spring or winter temperatures following an extreme negative phase of the NAO.

This analysis revealed the relationship could be seen on a variety of time scales from weekly to decadal. By looking at these relationships on a daily versus monthly time scale interesting relationships could be seen that might be missed when looking at monthly composites, like the January 2000 example. The results show a good relationship when looking at all extended winter days and this gets even stronger when just looking at the extreme NAO days, something one would expect to see if the relationship was significant.

It is interesting to note that these relationships can be seen so strongly in Charleston, which was one of our furthest west locations selected for this study and suggests that possibly this relationship can be seen in the Midwest as well. This is one area I would like to examine in a future study as well as possibly look at the Pacific - North American pattern (PNA), which has been shown to have an effect on temperature in the United States. Another issue that could be studied is the year round relationship to the NAO as well as monthly and seasonal variations. It would also be valuable to use climate models to try and force the NAO from sea surface temperatures to see if we can reproduce the annual and decadal variations, or from the stratosphere to try and reproduce the weekly to monthly variations. Clearly, more work needs to be done in order to better understand the driving forces behind the NAO. This would potentially allow better prediction of the NAO, which could lead to better monthly and seasonal temperature prediction based on the relationships seen in this study.

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