The Arctic Oscillation and Wintertime Climatology of the Midwest and Tennessee Valley Regions of the USA (1951-2010)

by Greg Soliday, Bachelor of Science

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ABSTRACT

THE ARCTIC OSCILLATION AND WINTERTIME CLIMATOLOGY OF THE MIDWEST AND TENNESSEE VALLEY REGIONS OF THE USA (1951-2010)

by

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Chairperson: Professor Mark L. Hildebrandt

An analysis was conducted to assess the relationship between the Arctic Oscillation (AO) and wintertime climatology of the Midwest and Tennessee Valley regions of the USA. In particular, this study focuses on variation in wintertime temperatures and snowfall totals during the top ten most positive and negative AO winters for the aforementioned regions. In addition, NCEP/NCAR reanalysis composite maps were created and examined to evaluate the relationship between certain atmospheric parameters and the opposing phases of the AO. In the Midwest and Tennessee Valley regions, variation in wintertime mean temperature and snowfall totals are associated with strong phases of the AO. The top ten most negative AO winters resulted in below average temperatures and above average snowfall totals. In contrast, the top ten most positive AO winters resulted in above average temperatures and below average snowfall totals. In addition, variation in mean wintertime temperature and snowfall totals is less significant during positive AO winters in comparison to negative AO winters. The top 10 most positive and negative AO winters appear to provide a significant link between anomalous middle and upper atmospheric circulation and atypical surface weather patterns across the Midwest and Tennessee Valley regions.

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CHAPTER I

INTRODUCTION

In 1950, atmospheric scientists began building in-depth archives of various weather parameters, such as air temperature and sea level pressure, which are used to explain surface weather patterns. Repeated and persistent, large scale patterns of pressure and circulation anomalies that stretch across extensive geographical areas are referred to as "teleconnection patterns" (CPC 2013). Forecasters rely on these teleconnections to make medium and long-range forecasts, and they have proven to be fairly reliable in certain regions of the world.

The most relevant teleconnection for regions involved in this study is the Arctic Oscillation (AO). This teleconnection and its corresponding fluctuating index is measured based on sea-level pressure differences between two separate locations. During a positive AO winter, below normal pressure anomalies exist across the eastern half of the United States of America (USA) and the central North Atlantic. In contrast, above normal pressure anomalies are present across Greenland and much of the Arctic region. An opposing pressure anomaly pattern is evident during a negative AO winter. On a very basic level, one can generally expect warmer and drier conditions across the Midwest and Tennessee Valley regions of the USA in the event of a positive phase AO, and contrasting conditions during a negative phase (NSIDC 2014).

Problem Statement

The point at issue is the difficulty of accurately forecasting the future progression of complex atmospheric processes that propagate downward to observable surface weather conditions. Modern technology and archived weather parameters have allowed meteorologists and climatologists to more accurately depict short and long-range weather patterns for different regions of the world. However, due to the relatively recent discoveries of these teleconnections, a great deal of uncertainty still exists with respect to the life cycle of these synoptic scale climate trends and their implications for associated surface weather patterns for a given region. Although atmospheric scientists such as Thompson and Wallace (1998) and Wu et al. (2006) continue to publish studies related to teleconnections and surface weather interactions across the Arctic and North Atlantic regions, many cities throughout the USA have yet to be studied in depth.

Purpose of the Study

This study examines variations in surface air temperature and snowfall totals during years experiencing the top ten most negative AO winters (1958, 1960, 1963, 1966, 1969, 1970, 1977, 1979, 2001, 2010) and the top ten most positive AO winters (1973, 1976, 1989, 1990, 1992, 1993, 1995, 2000, 2007, 2008) for cities in the Midwest and Tennessee Valley regions of the USA. Furthermore, an additional analysis was conducted to determine certain surface/atmospheric relationships between teleconnections and wintertime (December-March) ambient air temperature and snowfall totals for the aforementioned years. I attempted to answer the following questions:

1) How has surface weather differed between the top ten most positive and negative AO winters in comparison to the climatological mean for cities located within the above-mentioned regions?

2) What effects does the AO have on wintertime weather patterns for the Midwest and Tennessee valley regions of USA?

3) What types of weather parameters can be linked to the AO and what effects do their relationship have on one another?

Significance of the Study

This study will be a significant endeavor in promoting the use of the AO as a fundamental tool for short and long-range forecasting. Additionally, this study will help to determine the level of significance associated with the interrelationship between anomalous atmospheric parameters and surface weather patterns during the top ten most positive and negative AO winters for cities located in the Midwest and Tennessee Valley regions of the USA. The review of literature chapter will focus on the atmospheric background of the AO, as well as tropospheric and stratospheric interactions associated with this teleconnection. In addition, the review of literature describes the effects of the AO on regional geopotential heights (GPH) and surface air temperatures (SAT). The methodology chapter provides a background of the study area, as well as statistical and analytical methods involved in this study. Lastly, the results and discussion chapters display and describe the results from the independent samples t-tests and climate and AO comparison graphs. Furthermore, NCEP-NCAR reanalysis composite maps were examined and discussed.

CHAPTER II

REVIEW OF LITERATURE

This literature review investigates prior studies pertaining to the essential atmospheric processes associated with the life cycle of AO. In addition, this literature review examines the relationship between the wintertime AO and SAT and GPH throughout different regions of the USA.

Arctic Oscillation Background

The AO is a meridional fluctuation of the atmospheric flow with a primary center of action over the Arctic region (north of 60°N) and opposing anomalies across much of the middle latitudes (Deser 2000). A study by Ambaum et al. (2001) examines the definitions and dynamical processes behind the North Atlantic Oscillation (NAO) and AO. Their research suggests that the AO is a favorable linear settlement between two stationary areas of low and high pressure in the Northern Hemisphere (Tanaka and Tokinaga 2002). The AO pattern has been linked to a hemispheric scale pattern of climate variability that stretches through the entire field of the stratosphere and troposphere. This pattern is responsible for variations in the zonally symmetrical wind flow over the Arctic region. Nevertheless, the atmospheric flow is not zonally symmetrical in the Northern Hemisphere (Ambaum 2001). Differences in sea level pressure over the Arctic are suggestive of either a positive AO index or a negative AO index. When sea level pressure is in flux, "the positive value AO(+) indicates negative pressure anomaly over the Arctic whereas, the negative value AO(-) indicates positive pressure anomaly there" (Tanaka and Tokinaga 2002, 72). The stationary Arctic high (also known as the Beaufort high) is located in the Beaufort Sea directly north of eastern Alaska and the Yukon and northwest territories of Canada. This high-pressure system weakens during a positive state of the AO and strengthens during a negative state.

A study by Tanaka and Tokinaga (2002) examines the sea level pressure and GPH associated with the AO throughout the winter months (November-April) for the years 1950-1998. They discovered two rapid alterations in the AO during the years of 1976-77 and again in 1988-89. There was a great transition from a largely positive AO prior to 1977 to a negative AO thereafter, then a transition back to a strong positive AO after 1988 (Tanaka and Tokinaga 2002). The AO implies that the Arctic high was powerful between the years 1977 to 1988, and then became faint in the following years until it regained strength toward the end of the 1990s. The Arctic high rotates anticyclonically during a positive AO and cyclonically during a negative AO (Tanaka and Tokinaga 2002). Arguably, the most notable characteristic of the AO is its corresponding polar vortex.

The polar vortex is a persistent, synoptic-scale cyclone positioned almost directly over the North Pole. This circumpolar wind flow is present in the top half of the troposphere and stratosphere surrounding the Arctic high. These cold-core low-pressure systems strengthen during the winter months and fade during the summer. They typically stretch a distance of 1,600 kilometers in which the air rotates in a cyclonic fashion. When the circulation of winds is intense, the westerlies strengthen. Conversely, when the polar vortex loses strength, the westerlies weaken, which then allows for major intrusions of cold air into the eastern half of the USA and Europe. A weak polar vortex is related to the northward transfer of energy induced by baroclinic eddies at 30°N and a southward transfer at 60°N, joining forces at 45°N (Tanaka and Tokinaga 2002). This allocation of momentum adequately intensifies the northern boundaries of the subtropical jet. Although these eddies provide momentum for the strengthening of the subtropical jet, their relationship is not symbiotic because these eddies rely on the positive feedback of energy from the subtropical jet. Baroclinic eddies by definition are mesoscale features that originate from the available potential energy provided by meridional temperature gradients along the boundary of the subtropical jet (Tanaka and Tokinaga 2002). When these eddies displace their momentum towards the subtropical jet, it signifies a weaker polar vortex. A strong polar vortex can be explained by a northwest-southeast tilt with respect to the meridional oriented GPH structure, allowing for the northward transfer of eddy heat energy. This negatively tilted GPH structure provides a gradient to facilitate the movement of eddy energy through the entire northern latitudes, effectively strengthening the polar vortex (Tanaka and Tokinaga 2002). When the polar vortex is strong, the intense circulation of winds around the North Pole sufficiently locks cold air in place, ensuring warmer weather for the middle latitudes.

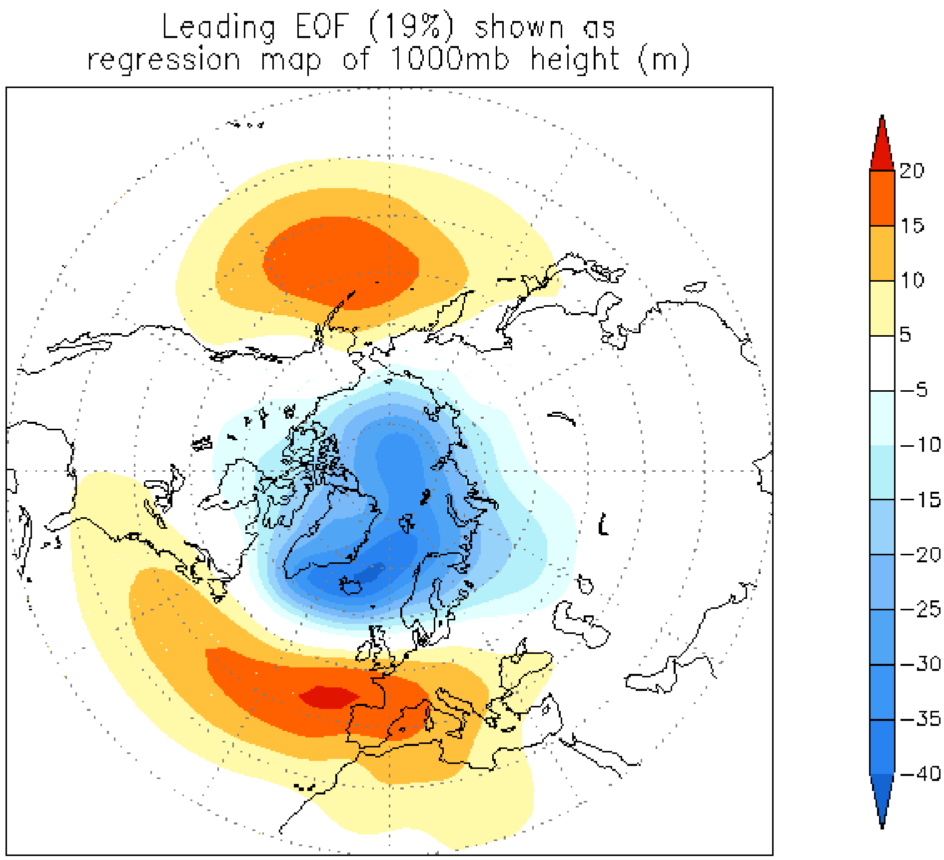

Figure 1. The loading pattern of the AO shown as a regression map of monthly mean 1000 mb height during 1979-2000 period (CPC 2012).

The AO can be characterized by having two centers of action (differences in sea level pressure), one over the Pacific near (55°N, 165°W) and the other over the Atlantic near (30°N) (Figure 1). The Pacific center of action corresponds to the Aleutian low whereas, the Atlantic center of action is linked to the Azores high (Ambaum et al. 2001). On average, a positive AO index is connected to the strengthening of the Azores high but a mitigation of the Aleutian low. A positive AO index is also indicative of an intensifying polar and subtropical jet stream and a diminishing Pacific jet stream. Often as the AO index increases, there becomes a visible separation between the polar and subtropical jets. The polar jet consists of strong atmospheric wind circulations located on the outer boundary of a tightening pressure gradient. This results in frontogenesis (the sharpening of temperature gradients to produce fronts) which causes areas of low or high pressure to form. This can be linked to the development of cyclones or anticyclones along the polar frontal boundary. The tropical jet stream transports warm moist air toward the polar boundary of the Hadley cell (model of the earth's atmospheric circulation) where it is deflected from west to east due to the Coriolis force.

Tropospheric and Stratospheric Interactions

There is accumulating evidence suggesting that the stratospheric polar vortex has an effect on low and high frequency climate variability at the earth's surface (Thompson and Wallace 1998). The dynamical processes of the stratosphere often have major implications for the tropospheric circulation which consequently affect weather at the surface. The stratospheric polar vortex often referred to as the polar night jet, is located at an altitude of nearly 24 km (50 mb), and is essentially a reflection of the tropospheric polar vortex. Alterations in the polar night jet may act as a precursor to transformations in the composition of the tropospheric vortex (Hitchcock et al. 2013). Similar to the upper tropospheric jet stream, the polar night jet forms along a sharp temperature gradient which resides along a boundary between sunlight and a nearly six-month long, wintertime polar night. The cyclonic flow of the polar night jet is strongest in the upper stratosphere and strengthens over the course of the winter. The stratospheric vortex is located within the center of the polar night jet and is one of the most variable characteristics of the mean atmospheric circulation. This variation can be attributed to highly asymmetrical interactions between the stratospheric vortex and mid-latitude atmospheric Rossby waves traveling upwards from lower levels in the atmosphere (Hitchcock et al. 2013). These processes are largely evident in the form of sudden stratospheric warmings (SSWs). Annular fluctuation in the Northern Hemisphere mean-flow provides a significant interconnection between the wintertime polar vortex and tropospheric climate patterns (Thompson et al. 2002). In the event of a SSW, there is an appreciable increase in stratospheric temperatures over the North Pole, and the circumpolar flow weakens considerably over a brief period of time (Limpasuvan et al. 2004). In the most extreme occurrences, stratospheric temperatures may increase by 50°C and the stratospheric circulation can switch direction in a matter of days. In contrast to the abruptness of this onset, the stratospheric vortex has been known to take numerous months to completely regain strength (Hitchcock et al. 2013). A disruption to the amplification of the polar night jet in the event of a SSW often affects the configuration of the tropospheric vortex at a typical lag time of two or three weeks. In addition, past studies have revealed an equatorward fluctuation of the tropospheric jet streams in response to a weak polar vortex (Hitchcock et al. 2013).

During strong SSWs, anomalously warm temperatures persist in the lower stratosphere, while cold temperatures exist in the middle and upper stratosphere, and warm temperatures are prevalent throughout the mesosphere. The latter coincides with an abnormally heightened stratopause (Hitchcock et al. 2013). While this warm anomaly lingers in the lower stratosphere, the stratopause gradually subsides over the course of a few months. This anomalous atmospheric temperature pattern is an exceptionally vigorous feature of the polar vortex, and occurs in the wake of nearly half of all SSWs (Hitchcock et al. 2013).

There are numerous theoretical explanations behind the extended persistence of these anomalies. According to Hitchcock et al. (2013, 2097), “One simple idea is that the depth to which warming descends during a SSW is linked to its persistence via radiative time scales, which increase with decreasing altitude and are at their longest in the lower stratosphere.” The extent of this sinking warm air can be linked to the persistence of the shortwaves (eddies) that triggered the warming. SSW events induced by a succinct influx of shortwaves were shown to interrupt only the upper stratospheric flow, which allows the vortex to sufficiently deflect future wave pulses. However, SSWs induced by a prolonged influx of shortwaves disrupts the climatological flow at all levels of the stratosphere, which leads to the rapid breakdown of the stratospheric vortex (Hitchcock et al. 2013).

At the end of every winter season the stratospheric polar vortex experiences a rapid breakdown due to a sudden warming, referred to as the stratospheric final warming (SFW). This marks the final transition from a strong westerly flow during the winter to a weak easterly flow during the summer (Black and McDaniel 2007). There is exceptional temporal variability with respect to the timing of the yearly SFW occurrences, given that they are reliant on low and high frequency wave interactions between the troposphere and stratosphere. However, SFW events occur more frequently than SSW events, which typically only occur slightly over once every two years on average (Black and McDaniel 2007). SSW events often trigger a phase change in the AO index at lag time of two to three weeks. On the other hand, SFW events occur as a result of a diminished temperature gradient over the polar region during the transition from winter to spring, therefore, their effect on the AO is rather negligible (Black and McDaniel 2007).

Effects of the AO on GPH and SAT

Although the climate impacts of the NAO are primarily restricted to the region of the northern hemisphere stretching from eastern North America to Central Russia, the impacts of the AO are plainly visible across nearly all longitudes (Wu et al. 2006). Hodges (2000) showed that, in the event of a positive AO, below normal pressure over the polar region generates intense westerly winds in the upper troposphere at high latitudes, which confines bitter Arctic air to north (Hodges 2000). This often results in a mild winter for the majority of the eastern half of the USA and central Canada whereas, Greenland and Newfoundland experience colder conditions than normal. At the same time, with greater than normal pressure stationed over the central Atlantic, powerful westerly winds advect warm and humid air in the direction of northern Europe. This typically results in above normal precipitation in Scotland and Scandinavia, as opposed to below normal precipitation across much of the western USA (Hodges 2000). During a negative AO, above normal atmospheric heights over the Arctic region effectively weakens the westerly winds in the upper troposphere, which permits frigid Arctic air to spill equatorward across more southern latitudes than usual. This results in below normal temperatures throughout much of the USA, but above normal temperatures for northeastern Canada (Wu et al. 2006).

The typical supposition is that atmospheric climate anomalies connected to positive and negative modes of the AO are antipodal to one another, which means the influence on the climate is linear (Wu et al. 2006). Contrary to popular belief, there is some indication that a nonlinear relationship exists between the AO and wintertime climate. For example, "Pozo Vazquez et al. (2001) found that the winter temperatures in most of Europe do not vary in a linear manner with respect to phase and intensity of the NAO. Similarly, composite anomaly patterns of low AO index winter temperatures in the USA are considerably different from their counterparts during high AO index winters" (Wu et al. 2006, 866). Shabbar and Bobsal (2003) revealed considerably greater occurrences of cold outbreaks over eastern Canada, and a greater prevalence of mild spells over south central Canada during positive AO winters in comparison to negative AO winters (Shabbar and Bobsal 2003). Nevertheless, the alterations in the regularity of the mild spells between positive and negative AO modes are not quite proportionate to those of the cold outbreaks. Recognizing patterns in the GPH field is fundamental to understanding the opposing phases of the AO.

When the AO index is strongly positive, the 500 mb GPH field is comprised of negative anomalies across the north and positive anomalies throughout the south. The significant anomalies across the eastern portions of the domain bear a resemblance to a positive NAO (Wu et al. 2006). Increased zonal flow across Alaska and northwest Canada transport mild maritime air, while atypical southerly flow over the eastern half of the USA offsets the flow of frigid Arctic air (Wu et al. 2006). This results in above normal temperatures across central and western portions of Canada and the majority of the USA. The anomalous low pressure stationed over Greenland is conducive to cold air advection into much of northeastern and eastern Canada. When the AO index is strongly negative, the height pattern is essentially reversed. With respect to linearity, Wu et al. states, “the 500 mb GPH and SAT anomaly patterns for low AO-index months are not exactly anti-symmetric to those for high AO-index months, implying a nonlinear association between the AO and North American winter climate” (Wu et al. 2006, 868). For example, the 500 mb GPH anomaly core for the positive AO composite displays an eastward movement in comparison to the core of the anomaly for the negative AO composite. It may be noted that the AO is primarily linear, especially across the eastern half of North America and the North Atlantic, while areas such as the Pacific Northwest experience more of a nonlinear relationship between the AO and winter climate (Wu et al. 2006).

Wu et al. (2006) conducted a study to examine the nonlinear association between the AO and fluctuation in North American winter climate using a nonlinear projection (NLP) via neural networks (NN). Using the NLP to extract the 500 mb GPH anomaly fields, they determined that when the AO index is in a strong positive phase (+1.0), the linear element has significant negative anomalies centered over Baffin Island, and significant positive anomalies across the eastern half of the USA, North Atlantic and Europe. Nonetheless, the anomalies are much less significant over the western domain. This height anomaly pattern is reminiscent of a positive NAO (Wu et al. 2006). When the principal component of the nonlinear element of the AO experiences a strong positive phase (+1.0), the 500 mb GPH field has significant positive anomalies spanning the northeast Pacific to Greenland, and significant negative anomalies stretching from subtropical eastern Pacific across the continental USA to the North Atlantic (Wu et al. 2006). In comparison to the linear element, the 500 mb GPH anomalies of the nonlinear element are considerably weaker in the eastern domain but are similar or even more robust across the west. Therefore, the linear element prevails in the Atlantic region whereas, the nonlinear element controls the Pacific Northwest region. An analogous spatial distribution can be seen when comparing SAT anomalies between linear and nonlinear elements of the AO.

During a strongly negative AO winter, substantial positive SAT anomalies are evident across Alaska and northeast Canada, while negative anomalies exist across the majority of North America focused over the Great Plains (Wu et al. 2006). In the event of a strongly positive AO winter, considerable negative anomalies are evident over portions of the western USA and eastern Canada, while positive anomalies exist over the remainder of the continent, focused over the eastern USA and northwestern Canada. Wu et al. (2006) extracted the linear and nonlinear elements of SAT anomalies in the same way that the 500 mb GPH field anomalies were extracted. When the wintertime AO index is strongly positive, the linear element has substantial negative SAT anomalies over Alaska and eastern Canada, and largely positive anomalies across the remainder of North America, focused over the Great Plains. When the principal component of the nonlinear element is strongly positive, the SAT experiences negative anomalies across the majority of the USA and southwestern Canada, and positive anomalies throughout the remainder of North America, focused over Alaska and northeastern Canada (Wu et al. 2006). Compared to the linear element, the nonlinear element is considerably weaker across northeastern portions of North America, but is only half the significance of the linear element over the Great Plains. Wu at el. (2006) discovered that 500 mb GPH and SAT anomaly patterns display extensive asymmetry during opposite modes of the AO, which results in a nonlinear relationship among the AO and North America wintertime climate (Wu et al. 2006).

Abramyan and Vaughan (2014) conducted a study to examine the association between extreme negative AO values and noteworthy outbreaks of cold air in the southeastern USA. Their analysis consists of 23,100 daily AO values sorted from negative to positive dating back to 1950. Eleven periods of four days or more within the minimum 100 values were considered distinct events. This study includes three stations (Columbia, SC; Raleigh, NC and Atlanta, GA) in which minimum temperatures and deviations from normal were investigated and compared to the AO mode before, during and after each event (Abramyan and Vaughan 2014).

Abramyan and Vaughan (2014) found that during mid-February of 1969, a lengthy period of negative AO values occurred in conjunction with an unrelenting trough stationed near the east coast of the USA. Although this airmass was not record breaking, mean minimum temperatures averaged 2.8°C to 5.6°C below normal (5.0°F to 10.0°F). From late December 1976 through the majority of January 1977, the AO remained exceptionally negative. A very strong quasi-stationary (nearly stationary) ridge of high pressure formed over the Pacific Northwest, while pieces of the polar vortex periodically became displaced further south across eastern Canada. This southward displacement of the polar vortex resulted in a persistent trough throughout the eastern half of the USA (Abramyan and Vaughan 2014). Many locations within the eastern half of the U.S. experienced record cold temperatures including Raleigh, NC, where the temperature fell to -18.3°C (-1.0°F) on January 17. During the anomalous cold air outbreak in early 1977, Abramyan and Vaughan (2014) stated, "A very pronounced trough pushed as far south as Cuba with 500 mb level heights at 5,580 m and 500 mb temperatures at -26.1°C (-15.0°F) over Miami, FL. Minimum surface temperatures remained at or below -6.7°C (20.0°F) in Columbia, Raleigh, and Atlanta for four consecutive days" (Abramyan and Vaughan 2014, poster). January 19, 1977 marks the only date in the 20th century in which Miami experienced snowfall. The lowest AO value ever recorded (-7.43) occurred four days prior, on January 15. In addition, January 1977 was the coldest January on record in the continental USA (Abramyan and Vaughan 2014). Only one year later in February 1978, mean minimum temperatures were 5.6°C to 8.3°C (10.0°F to 15.0°F) degrees below normal for much of the month. An extended period of strongly negative AO values engendered a persistent trough over the east coast and ridge across the Pacific Northwest. In January 1985, a strong closed low-pressure system near the Great Lakes corresponding to a broad long wave trough advected Arctic Air into the Southeast USA. breaking several all-time minimum temperature records (Abramyan and Vaughan 2014). The record-breaking airmass occurred only two days after the AO index attained its lowest value for the month. February 2010 featured a strong ridge over the Pacific Northwest and deep trough across the eastern U.S. Mean minimum temperature anomalies were -3.9°C (-7.0°F) at all three of the aforementioned sites and the monthly mean AO value was -4.27 (Abramyan and Vaughan 2014).

Abramyan and Vaughan (2014) state, "Results suggest that after a period of highly negative AO values, there is a temperature response on the east coast that lags the negative

AO episode by a few days. Each of the eleven events analyzed for the southeast was either a record temperature event, a prolonged significant cold air outbreak, or both. Winter precipitation was reported in at least one of the three locations during or after each event" (Abramyan and Vaughan 2014, poster). Composite maps of GPH anomalies display well above normal heights poleward of 55°N, signifying a weakened polar vortex. The related AO index values vacillated, although the majority ranged from -4.6 to -7.4. The largest minimum temperature differences during the extreme negative AO events ranged from -6.16°C to -22.2°C (-11.0°F to -40.0°F), with an average near -11.2°C (-20.0°F) (Abramyan and Vaughan 2014). The largest minimum temperature differences following extreme negative AO events (when the AO experienced a slight rebound) ranged from -9.5°C to -23.4°C (-17.0°F to -42.0°F), with an average of -14.8°C (-26.6°F) and generally occurring around nine days after the peak of the event. This indicates that the most significant cold air did not impact the region until after the AO event had ended (Abramyan and Vaughan 2014).

A similar study by Wettstein and Mearns (2002) involved the analysis of detailed associations between the North Atlantic Oscillation-Arctic Oscillation (NAO-AO) and local temperature response across much of New England and adjacent regions of Canada. They state that, "In particular, the study focuses on how contrasts in the mean and daily variance, based on AO phase, are associated with contrasts in the frequency and intensity of extreme temperature events in both winter and spring" (Wettstein and Mearns 2002, 3586). In order to ascertain the magnitude of discrepancies between climate variables when divided by positive and negative AO values, they conducted t-tests on variables with typical distributions such as mean maximum and minimum temperatures. They discovered that across New England and Quebec, Canada, significant differences in mean wintertime temperatures and daily variance during spring is linked to phases of the NAO-AO. Above normal temperatures throughout

New England and below normal temperatures across Quebec occur in combination with positive NAO-AO values (Wettstein and Mearns 2002). Although the mean temperature response is less robust during the spring, the daily temperature variance is greater and rises with the NAO-AO index. Shabbar and Bonsal (2003) conducted a supplemental study to assess the changes in winter cold and warm spells over Canada. They found that there has been a reduction in the regularity, duration, and magnitude of wintertime cold snaps across western Canada and increases in the regularity and magnitude of wintertime warm spells across most of Canada during the second half of the 20th century (Shabbar and Bonsal 2003). In addition to temperature variation, sea level pressure (SLP) variance can also be attributed to differing phases of the NAO-AO index (Wettstein and Mearns 2002).

Wettstein and Mearns (2002) concluded that, "During positive phases of the NAO-AO in winter, positive anomalies in the SLP field exist over the mid-Atlantic Ocean. At the same time, negative anomalies in SLP exist over much of the North Atlantic and Arctic Oceans. The combined influence of these mean states in positive phases is to create stronger-than-average cyclonic flow over the Arctic and stronger-than-average anticyclonic flow over the midlatitude Atlantic Ocean" (Wettstein and Mearns 2002, 3598). The consequential enhancement in zonal flow over the middle latitudes, in conjunction with the previously mentioned vigorous circulation patterns, should promote the southward advection of Arctic air under the influence of cyclonic flow and the northward advection of warm air from the Atlantic poleward under the influence of anticyclonic flow. The boundary between these contrasting circulation patterns should represent the prolonged mean positioning of the wintertime polar jet stream (Wettstein and Mearns 2002).

Recent studies have shown that the NAO and AO indices have generally been anomalously positive over the past thirty years (Thompson and Wallace 1998, Hurrell 1995).

In response to the variability of the AO index, Thomspson and Wallace (1998) state, “If the deepening of the wintertime polar vortex continues into the 21st century, it could have ramifications beyond the wide range (but thus far subtle) changes in surface climate” (Thompson and Wallace 1998, 1300). Deser (2000) performed a study to examine the teleconnectivity of the Arctic Oscillation. Her research suggests the two indices (NAO and AO), which typically exemplify a synonymous large-scale component of climate variability, have the greatest effect on the climate for North America and Europe and thus may potentially impact the regularity and magnitude of extreme events in these regions (Deser 2000).

Concluding Statement

This literature review examines the fundamental dynamical mechanisms that are linked to the synoptic processes behind the alternating phases of the AO. These teleconnections have a major influence on our long-term sensible weather and climatology. In order to recognize low-frequency (interannual and decadal) climate variability associated with strong phases of the AO, it is crucial to understand the corresponding atmospheric dynamics. Therefore, I examined specific atmospheric parameters (composite maps) that are representative of anomalous weather and climate patterns in the Midwest and Tennessee Valley regions of the USA during the top ten positive and negative AO winters. Furthermore, a regional study involving SAT anomalies and snowfall totals will be carried out to determine whether their are statistically significant differences between strong AO winters and surface weather observations throughout the regions.

CHAPTER III

METHODOLOGY

Study Area Background

The purpose of this study is to examine the climatic impacts of the AO on certain regions within the USA. In order to locate a study area, I first chose winters in which the AO experienced its top ten most positive and negative phases. It has been demonstrated that there is a link between fluctuations in the AO modes and SAT within the USA (ESRL 2014). NCEP-NCAR reanalysis data were utilized by inputting the aforementioned wintertime criteria to generate a map of SAT anomalies throughout the USA. Spatial distribution within anomalous SAT regions is key to determining which cities to use in this study. The cities included in this study all fell within or along the periphery of the greatest SAT anomalies. This suggests that each city experienced its greatest deviation from the mean climatology during the top ten most positive and negative AO winters as shown in Figure 2.

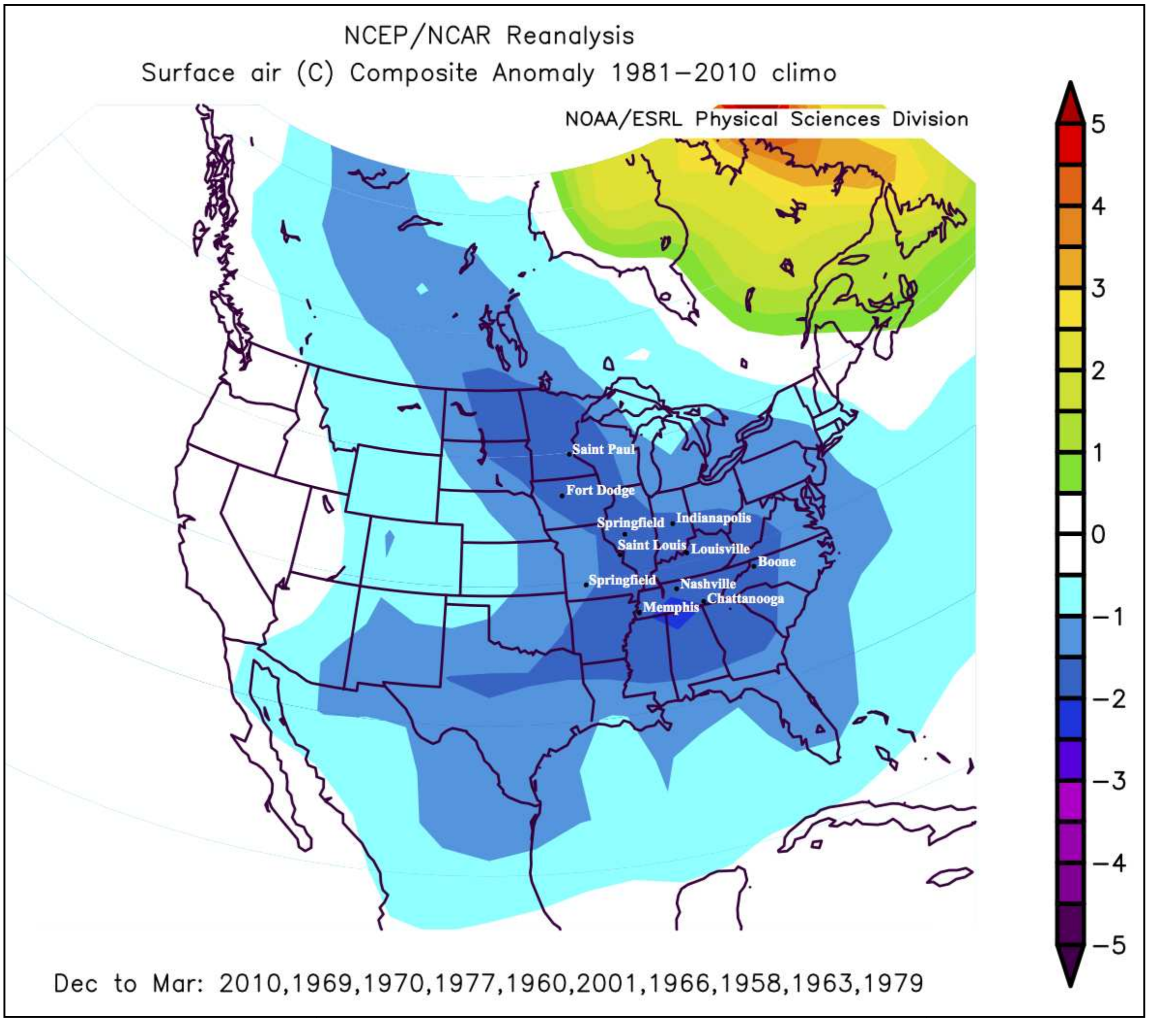

Figure 2. USA surface air temperature (°C) anomaly for the top ten most extreme negative AO winters (ESRL 2014).

A limiting factor with respect to the selection of appropriate locations was a lack of complete climate records. Most cities with International or regional airports have ample records whereas, many smaller cities have incomplete climate data. Eleven cities (Figure 3) all having complete climate records were chosen for this study to ensure consistency. The eleven cities selected for this study are as follows: Saint Paul, MN, Ft. Dodge, IA, Springfield, IL, Indianapolis, IN, Saint Louis, MO, Louisville, KY, Springfield, MO, Boone, NC, Nashville, TN, Memphis, TN, Chattanooga, TN.

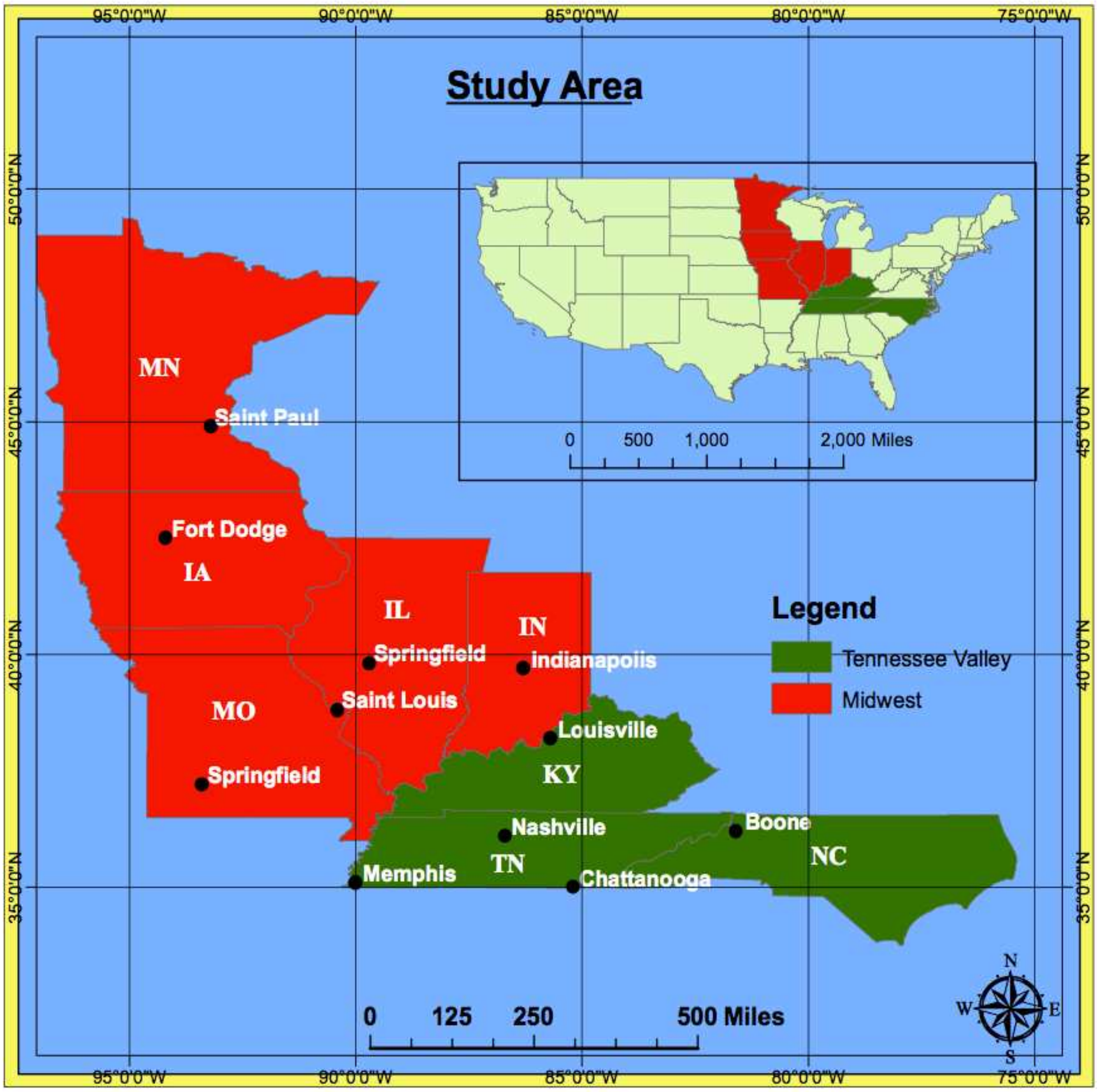

Figure 3. Midwest and Tennessee valley regions of the USA.

In order to explain the effects of the AO on regional climate, it is also important to understand the different climate zones within the study area. Latitude and continentality have a major influence on the climate of any given location. Therefore, the cities were divided into groups according to the Köppen climate classification (Pidwirny 2011). The study area is comprised of three different climate zones, which are: humid subtropical (Cfa), humid continental (Dfa), and highland subtropical (Cfb).

Within the boundaries of the study area, the humid subtropical climate zone extends from 35°N to 38.7°N. This includes the cities of Chattanooga, TN, Memphis, TN, Nashville, TN, Springfield, MO, and Louisville KY. The humid subtropical climate generally features hot and humid summers and cool and moist winters. The mean wintertime temperatures (Dec-Mar) range from 7.2°C in the far south to 3.5°C in the far north. The average wintertime precipitation ranges from 52.3 cm in the far south to 38.1 cm in the far north. Average wintertime snowfall amounts are as low as 9.7 cm in the southernmost regions to as much as 41.7 cm in the northern most regions.

The humid continental climate zone lies between 38.8°N and 44.9°N. Saint Louis, MO actually represents the transitional zone between a humid subtropical and humid continental climate. Other cities located within this climate zone are: Indianapolis, IN, Springfield, IL, Fort Dodge, IA and Saint Paul, MN. The humid continental climate zone can be characterized by hot and humid summers under the influence of a southwest flow, and cold harsh winters under the influence of a northwest flow. The mean wintertime temperature ranges from 2.9°C in the far south to -0.9°C across the extreme north. The average wintertime precipitation runs from 27.4 cm across the southern regions to 12.2 cm inches along the northern boundary. The average wintertime snowfall ranges from 42.2 cm in the southern most locations to 93.7 cm across the far north.

Despite Boone, NC's southern latitude (36.2°N), it features a highland subtropical climate zone as a consequence of its higher elevation. During the summer, Boone experiences cooler and less humid conditions than locations at similar latitudes. Wintertime is especially long and harsh in Boone compared to surrounding lower elevations. Boone sits at an elevation of 987.9 m which allows for orographic lifting to enhance precipitation throughout the year. On average, Boone receives 40.9 cm of wintertime precipitation and has a mean wintertime temperature of 2.0°C. The average wintertime snowfall for Boone is 76.9 cm.

Study Variables

This study uses twenty years of monthly mean temperature and snowfall data associated with the top ten most positive and negative AO winters. These data were obtained from the Weather Warehouse (Weather Warehouse 2014), which provides data from the National Climatic Data Center (NCDC). Table 1 shows the station data and associated geographic coordinates of each city used in this study (Table 1).

	Location	Wx Station	Wx source ID	Latitude	Longitude	Elevation (Meters)
1	Chattanooga, TN	Chattanooga Lovell Field Arpt	19766	35.0	-85.2	210.9
2	Memphis, TN	Memphis Intl Arpt	19777	35.1	-90.0	82.3
3	Nashville, TN	Nashville Intl Arpt	19899	36.1	-86.7	180.7
4	Boone, NC	Boone	17568	36.2	-81.6	987.9
5	Springfield, MO	Springfield Rgnl Arpt	39727	37.2	-93.4	389.5
6	Louisville, KY	Louisville Standiford Field	39718	38.2	-85.7	147.5
7	Saint Louis, MO	Saint Louis Lambert Int'l Arpt	16368	38.8	-90.4	172.2
8	Indianapolis, IN	Indianapolis Intl Arpt	39904	39.7	-86.3	240.8
9	Springfield, IL	Springfield Abraham Lincoln Ca	13118	39.8	-89.7	182.0
10	Fort Dodge, IA	Fort Dodge	26106	42.5	-94.2	339.9
11	Saint Paul, MN	Minneapolis St Paul Int'l Arpt	15746	44.9	-93.2	266.4

Table 1. Weather station data for all eleven cities in the study area (Weather Warehouse 2014).

The objective of this study was to investigate the effects of the AO on regional wintertime climate. To better understand the implications of the AO for wintertime climate, it is imperative to select years in which this teleconnection was exceptionally strong. The inclusion of additional less significant AO winters would likely minimize the effectiveness of this study. The years representing the top ten most negative AO wintertime periods are: 2010, 1969, 1970, 1977, 1960, 2001, 1966, 1958, 1963 and 1979 (listed in order from most to least significant and all falling below negative one on the AO index). In contrast, the years depicting the top ten most positive AO wintertime periods are: 1989, 1990, 1993, 1992, 2007, 1973, 1976, 2008, 2000, and 1995 (listed in order from most to least significant). Although all of the top ten negative AO winters experience index values less than -1.0, only five of the top ten positive AO winters experience index values greater than +1.0.

Monthly standardized wintertime AO indices are available from the Climate Prediction Center (CPC 2012). Researchers such as Abramyan and Vaughan (2014) use the meteorological winter (Dec-Feb) as their study period of strongly negative AO Values. Nonetheless, I chose to use the astronomical winter (Dec-Mar) as the study period because it demonstrates the behavior of the AO over the entire wintertime period and does not exclude months in which the AO experiences significant variability. Researchers such as Wettstein and Mearns (2002) consider AO values to be statistically significant if they are more than one standard deviation from the mean (e.g., >1.0 and <-1.0). However, because my study utilizes AO values averaged over the entire wintertime period, some of the positive AO values are less than one standard deviation from the mean. All negative AO values included in the study are less than -1.0; whereas, all positive AO values are greater than +0.6. I've determined the top ten positive and negative AO winters by averaging the wintertime (Dec-Mar) AO values from 1951-2010 provided by the CPC. I sorted the mean values from least to greatest and the top ten positive and negative AO values were then selected for this study (Table 2).

Rank	Year	Negative AO Value (Dec-Mar)	Year	Positive AO Value (Dec-Mar)
1	2010	-2.68	1989	2.40
2	1969	-2.11	1990	1.69
3	1970	-1.92	1993	1.52
4	1977	-1.88	1992	1.07
5	1960	-1.59	2007	1.05
6	2001	-1.41	1973	0.95
7	1966	-1.35	1976	0.89
8	1958	-1.34	2008	0.79
9	1963	-1.25	2000	0.74
10	1979	-1.18	1995	0.64
Average		-1.67		1.17

Table 2. Top 10 positive and negative AO winters and their corresponding AO values listed from most to least significant (CPC 2012).

Statistical Methods

An analysis of monthly temperature and snowfall totals was conducted for the study cities during the top then most positive and negative AO winters. Climate data (temperature and snowfall totals) for these cities was collected and input into an Excel spreadsheet for further examination. Line graphs were created to show the differences between SAT and snowfall totals for each city during the most positive and negative AO winters in comparison to their climatological means for 1951-2010. Furthermore, a statistical analysis was carried out to determine whether there is a significant relationship between SAT and snowfall totals and AO indices. Independent samples t-tests were run using SPSS to compare air temperature and snowfall during the most positive and negative AO winters to one another and longer-term climatological means. This statistical method was used to compare the means of two separate variables for a single group. The procedure calculates the differences between values of the two variables for each data set and tests whether the mean of temperature and snowfall differs from one another (Statistics Glossary 2014). In addition, a Pearson

Correlation Coefficient was performed to assess the relationship between the mean wintertime temperatures and snowfall totals for all cities and each corresponding AO value. Subsequently, a linear regression was performed between the same variables to show the linearity between wintertime temperatures and snowfall totals and AO values.

Analytical Methods

This study also uses data for the same twenty years from the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis project (ESRL 2014). The data set consists of the mean and anomalous wintertime GPH at 500 mb, 300 mb and 50 mb and 500 mb vector winds. GPH is an approximation of the actual height of a pressure surface above mean sea-level. The 500 mb level is an important height for analysis because it represents the level of non-divergence (the division of primary regions of horizontal convergence and divergence in connection with the quintessential perpendicular structure of transient synoptic-scale weather systems) and; therefore, represents the boundary at which fifty percent of atmospheric mass exists above it and fifty percent is contained below (AMS). The 300 mb height is significant because it depicts the pressure level of the polar jet stream, which is largely responsible for variation in wintertime temperatures. Although the 250 mb height is generally used to study the jet stream during the summer months, the 300 mb height is preferred during the winter months because air masses are colder and denser and sink closer to earth's surface. As stated in the literature review, the 50 mb height is a representation of the stratospheric polar night jet. This height is useful to determine associations between anomalous stratospheric circulation and fluctuation in the tropospheric climate. For study purposes, the vector wind parameter was used to represent the polar vortex which is analyzed at 500 mb.

Wind vectors are shown using black arrows to indicate wind direction and the associated background color is used to display wind speed (m/s). Additionally, Surface Air Temperature (SAT) anomalies are a fundamental component of this study. SAT anomalies are crucial to this research because they provide surface level evidence for anomalous weather patterns to support the evidence provided by upper atmospheric parameters. SAT anomaly composite maps were generated to demonstrate the non-linear relationship between positive and negative AO winters as previously discussed in the literature review. I utilized the aforementioned parameters by plotting seasonal composites (averages) of the wintertime mean and anomalies of GPH at 500 mb, 300 mb and 50 mb, as well as 500 mb vector winds and SAT anomalies using the NCEP reanalysis datasets.

Finally, NCEP-NCAR reanalysis maps were examined and discussed to reveal and determine associations between certain upper tropospheric/lower stratospheric processes and surface weather patterns observed over the Midwest and Tennessee Valley regions of the USA.

Limitations and Future Considerations

The greatest limitation with respect to this study is the availability of climate data. Historical climate data is often recorded for larger cities with international or municipal airports. However, many smaller cities have inadequate climate records for the purpose of this study. Furthermore, the weather parameters that comprise the AO have only existed since the year 1950. Therefore, the scope of this study is limited to data obtained over the past 63 years. An additional limitation with respect to this study is the use of only one teleconnection. There are several known teleconnections that have regional effects of varying magnitudes. This study could potentially be improved by examining simultaneous teleconnections during their strong phases to determine if greater variation in regional wintertime temperatures and snowfall is more evident during these events.

CHAPTER IV

RESULTS AND DISCUSSION

The results of the independent samples t-tests suggest that the AO has a greater effect on weather patterns across the Tennessee Valley region in comparison to the Midwest region of the USA (Table 3). Eleven cities were involved in this study, with four tests being performed on each individual city. The tests compared both positive and negative AO wintertime temperatures to the mean wintertime temperatures for each city. In addition, snowfall totals during positive and negative AO winters were compared to mean wintertime snowfall totals for each city. Five cities in the study area are located in the Tennessee Valley region (Chattanooga TN, Nashville TN, Memphis TN, Boone, NC and Louisville, KY). Out of the twenty independent samples t-tests performed on those cities, twelve tests yielded significant results with $p < 0.05$. On the other hand, six cities in the study area are located within the Midwest region (Springfield, MO, Saint Louis, MO, Indianapolis, IN, Springfield, MO, Fort Dodge, IA, and Saint Paul, MN). Out of the twenty-four independent samples t-tests performed on those cities, nine tests yielded significant results with $p < 0.05$.

Results of Independent Samples t-tests

Location	Variable	Samples	Neutral Mean (°C/cm)	AO_Mean (°C/cm)	T-value	df	P-value
Chattanooga, TN	Temp	Neutral_vs_Neg AO	6.9°C	4.8°C	**4.91**	**49**	**0.000**
	Temp	Neutral_vs_Pos AO	6.9°C	7.8°C	**-2.19**	**49**	**0.033**
	Snow	Neutral_vs_Neg AO	8.2 cm	22.6 cm	**-3.82**	**49**	**0.000**
	Snow	Neutral_vs_Pos AO	8.2 cm	8.7 cm	-0.13	49	0.896
Memphis, TN	Temp	Neutral_vs_Neg AO	7.6°C	5.7°C	**4.99**	**49**	**0.000**
	Temp	Neutral_vs_Pos AO	7.6°C	8.4°C	**-2.26**	**49**	**0.028**
	Snow	Neutral_vs_Neg AO	3.0 cm	4.5 cm	-1.17	49	0.249
	Snow	Neutral_vs_Pos AO	3.0 cm	0.9 cm	1.78	49	0.081
Nashville, TN	Temp	Neutral_vs_Neg AO	5.9°C	4.0°C	**4.53**	**49**	**0.000**
	Temp	Neutral_vs_Pos AO	5.9°C	7.1°C	**-2.74**	**49**	**0.009**
	Snow	Neutral_vs_Neg AO	17.8 cm	44.3 cm	**-3.45**	**49**	**0.001**
	Snow	Neutral_vs_Pos AO	17.8 cm	10.0 cm	1.24	49	0.222
Boone, NC	Temp	Neutral_vs_Neg AO	1.7°C	-0.7°C	**4.55**	**49**	**0.000**
	Temp	Neutral_vs_Pos AO	1.7°C	2.5°C	-1.47	49	0.147
	Snow	Neutral_vs_Neg AO	82.4 cm	135.7 cm	**-3.39**	**49**	**0.001**
	Snow	Neutral_vs_Pos AO	82.4 cm	55.4 cm	1.77	49	0.084
Louisville, KY	Temp	Neutral_vs_Neg AO	3.7°C	2.0°C	**3.74**	**49**	**0.000**
	Temp	Neutral_vs_Pos AO	3.7°C	5.1°C	**-2.92**	**49**	**0.005**
	Snow	Neutral_vs_Neg AO	37.0 cm	52.5 cm	-1.89	49	0.065
	Snow	Neutral_vs_Pos AO	37.0 cm	20.9 cm	1.99	49	0.052
Springfield, MO	Temp	Neutral_vs_Neg AO	3.2°C	1.5°C	**4.18**	**49**	**0.000**
	Temp	Neutral_vs_Pos AO	3.2°C	4.3°C	**-2.46**	**49**	**0.017**
	Snow	Neutral_vs_Neg AO	37.7 cm	55.3 cm	**-2.14**	**48**	**0.037**
	Snow	Neutral_vs_Pos AO	37.7 cm	34.3 cm	0.45	48	0.652
Saint Louis, MO	Temp	Neutral_vs_Neg AO	2.4°C	0.6°C	**3.64**	**49**	**0.001**
	Temp	Neutral_vs_Pos AO	2.4°C	3.7°C	**-2.58**	**49**	**0.013**
	Snow	Neutral_vs_Neg AO	42.5 cm	53.6 cm	-1.08	49	0.285
	Snow	Neutral_vs_Pos AO	42.5 cm	42.9 cm	-0.04	49	0.968
Indianapolis, IN	Temp	Neutral_vs_Neg AO	0.5°C	-1.1°C	**3.19**	**49**	**0.002**
	Temp	Neutral_vs_Pos AO	0.5°C	1.8°C	**-2.62**	**49**	**0.012**
	Snow	Neutral_vs_Neg AO	62.7 cm	62.0 cm	0.06	49	0.950
	Snow	Neutral_vs_Pos AO	62.7 cm	45.5 cm	1.59	49	0.119
Springfield, IL	Temp	Neutral_vs_Neg AO	-2.3°C	-3.9°C	**2.77**	**49**	**0.008**
	Temp	Neutral_vs_Pos AO	-2.3°C	-1.3°C	-1.78	49	0.081
	Snow	Neutral_vs_Neg AO	63.7 cm	72.5 cm	-1.02	49	0.315
	Snow	Neutral_vs_Pos AO	63.7 cm	61.4 cm	0.02	49	0.858
Fort Dodge, IA	Temp	Neutral_vs_Neg AO	-4.7°C	-6.0°C	1.39	49	0.172
	Temp	Neutral_vs_Pos AO	-4.7°C	-3.8°C	-0.97	49	0.337
	Snow	Neutral_vs_Neg AO	80.2 cm	102.0 cm	-1.77	47	0.084
	Snow	Neutral_vs_Pos AO	80.2 cm	69.1 cm	1.00	47	0.332
Saint Paul, MN	Temp	Neutral_vs_Neg AO	-6.4°C	-7.5°C	1.57	49	0.170
	Temp	Neutral_vs_Pos AO	-6.4°C	-4.9°C	**-2.096**	**49**	**0.040**
	Snow	Neutral_vs_Neg AO	100.5 cm	105.0 cm	-0.281	49	0.779
	Snow	Neutral_vs_Pos AO	100.5 cm	86.3 cm	0.931	49	0.355

Table 3. Displays results from independent samples t-tests comparing temperatures and snowfall totals during the top 10 positive and negative AO winters to mean wintertime temperatures and snowfall totals for each city in the study area. All temperatures are listed in degrees Celsius and all snowfall totals are listed in centimeters. All values in **bold** represent a significant result at 0.05 (Weather Warehouse 2014).

The two cities in the Tennessee Valley that experienced the most significant relationship between AO winters and temperatures and snowfall totals were Chattanooga, TN and Nashville, TN (Table 3), in which three of the four independent samples t-tests yielded significant results. All units below are in degrees Celsius for air temperatures and centimeters for snowfall totals. When comparing independent samples t-test results for negative AO temperatures, Chattanooga experienced a significant difference between negative AO wintertime temperatures (M = 4.8) and mean wintertime temperatures (M = 6.9) at the 0.05 level; $t(49) = 4.91$, $p = 0.000$. Nashville also experienced a significant difference between negative AO wintertime temperatures (M = 4.0) and mean wintertime temperatures (M = 5.9) at the 0.05 level; $t(49) = 4.53$, $p = 0.000$. These results suggest that there is a significant relationship between the negative phase AO and wintertime temperatures for these cities. Specifically, the results suggest that as the AO value decreases wintertime temperatures decrease accordingly. When comparing independent samples t-test results for positive AO temperatures, Chattanooga experienced a significant difference between positive AO wintertime temperatures (M = 7.8) and mean wintertime temperatures (M = 6.9) at the 0.05 level; $t(49) = -2.19$, $p = 0.033$. Nashville also experienced a significant difference between positive AO wintertime temperatures (M = 7.1) and mean wintertime temperatures (M = 5.9) at the 0.05 level; $t(49) = -2.74$, $p = 0.009$. These results suggest that there is a significant relationship between the positive phase AO and wintertime temperatures for these cities. Specifically, the results suggest that as the AO value increases, temperatures increase accordingly. When comparing independent samples t-test results for negative AO snowfall totals, Chattanooga experienced a significant difference between negative AO wintertime snowfall totals (M = 22.6) and mean wintertime snowfall totals (M = 8.2) at the 0.05 level; $t(49) = -3.82$, $p = 0.000$. Nashville also experienced a significant difference between negative

AO wintertime snowfall totals (M = 44.3) and mean wintertime snowfall totals (M = 17.8) at the 0.05 level; t(49) = -3.45, p = 0.001. These results suggest that there is a significant relationship between the negative phase AO and mean wintertime snowfall totals for these cities. Specifically, the results suggest that as the AO decreases, snowfall totals increase accordingly.

Additional cities in the Tennessee Valley region in which independent samples t-tests yielded significant results for both negative and positive AO wintertime temperatures were Memphis, TN and Louisville, KY (Table 3). When comparing independent samples t-test results for negative AO temperatures, Memphis showed a significant difference between negative AO wintertime temperatures (M = 5.7) and mean wintertime temperatures (M = 7.6) at the 0.05 level; t(49) = 4.99, p = 0.000. Louisville also experienced a significant difference between negative AO wintertime temperatures (M = 2.0) and mean wintertime temperatures (M = 3.7) at the 0.05 level; t(49) = 3.74, p = 0.000. These results suggest that there is a significant relationship between the negative phase AO and wintertime temperatures for these cities. Specifically, the results suggest that as the AO value decreases wintertime temperatures decrease accordingly. When comparing independent samples t-test results for positive AO temperatures, Memphis experienced a significant difference between positive AO wintertime temperatures (M = 8.4) and mean wintertime temperatures (M = 7.6) at the 0.05 level; t(49) = -2.26, p = 0.028. Louisville also experienced a significant difference between positive AO wintertime temperatures (M = 5.1) and mean wintertime temperatures (M = 3.7) at the 0.05 level; t(49) = -2.92, p = 0.005. These results suggest that there is a significant relationship between the positive phase AO and wintertime temperatures for these cities. Specifically, the results suggest that as the AO value increases wintertime temperatures increase accordingly.

Boone, NC experienced significant results for both negative AO temperatures and snowfall totals. When comparing independent samples t-test results for negative AO temperatures, Boone showed a significant difference between negative AO wintertime temperatures (M = -0.7) and mean wintertime temperatures (M = 1.7) at the 0.05 level; t(49) = 4.55, p = 0.000. This result suggests that there is a significant relationship between the negative phase AO and wintertime temperatures for Boone. Specifically, the result suggests that as the AO value decreases wintertime temperatures decrease accordingly. When comparing independent samples t-test results for negative AO snowfall totals, Boone experienced a significant difference between negative AO wintertime snowfall totals (M = 135.7) and mean wintertime snowfall totals (M = 82.4) at the 0.05 level; t(49) = -3.39, p = 0.001. This result suggests that there is a significant relationship between the negative phase AO and mean wintertime snowfall totals for Boone. Specifically, the result suggests that as the AO decreases, snowfall totals increase accordingly.

The only city in the Midwest region in which three of the four independent samples t-tests yielded significant results was Springfield, MO (Table 3). When comparing independent samples t-test results for negative AO temperatures, Springfield experienced a significant difference between negative AO wintertime temperatures (M = 1.5) and mean wintertime temperatures (M = 3.2) at the 0.05 level; t(49) = 4.18, p = 0.000. This result suggests that there is a significant relationship between the negative phase AO and wintertime temperatures for Springfield. Specifically, the result suggests that as the AO value decreases wintertime temperatures decrease accordingly. When comparing independent samples t-test results for positive AO temperatures, Springfield experienced a significant difference between positive AO wintertime temperatures totals (M = 4.3) and mean wintertime temperatures (M = 3.2) at the 0.05 level; t(49) = -2.46, p = 0.017. This result suggests that there is a significant relationship between the positive phase AO and wintertime temperatures for Springfield. Specifically, the result suggests that as the AO value increases wintertime temperatures increase accordingly. When comparing independent samples t-test results for negative AO snowfall totals, Springfield experienced a significant difference between negative AO wintertime snowfall totals (M = 55.3) and mean wintertime snowfall totals (M = 37.7) at the 0.05 level; t(49) = -2.14, p = 0.037. This result suggests that there is a significant relationship between the negative phase AO and mean wintertime snowfall totals for Springfield. Specifically, the result suggests that as the AO decreases, snowfall totals increase accordingly.

Cities in which independent samples t-tests yielded significant results for negative and positive AO wintertime temperatures were Saint Louis, MO and Indianapolis, IN (Table 3). When comparing independent samples t-test results for negative AO temperatures, Saint Louis experienced a significant difference between negative AO wintertime temperatures (M = 0.6) and mean wintertime temperatures (M = 2.4) at the 0.05 level; t(49) = 3.64, p = 0.001. Indianapolis also experienced a significant difference between negative AO wintertime temperatures (M = -1.1) and mean wintertime temperatures (M = 0.5) at the 0.05 level; t(49) = 3.19, p = 0.002. These results suggest that there is a significant relationship between the negative phase AO and wintertime temperatures for these cities. Specifically, the results suggest that as the AO value decreases wintertime temperatures decrease accordingly. When comparing independent samples t-test results for positive AO temperatures, Saint Louis experienced a significant difference between positive AO wintertime temperatures totals (M = 3.7) and mean wintertime temperatures (M = 2.4) at the 0.05 level; t(49) = -2.58, p = 0.013. Indianapolis also experienced a significant difference between positive AO wintertime temperatures (M = 1.8) and mean wintertime temperatures (M = 0.5) at the 0.05

level; $t(49) = -2.62$, $p = 0.012$. These results suggest that there is a significant relationship between the positive phase AO and wintertime temperatures for these cities. Specifically, the results suggest that as the AO value increases wintertime temperatures increase accordingly.

The only cities in the Midwest in which only one independent samples t-test yielded a significant result were Springfield, IL and Saint Paul, MN. Springfield experienced a significant difference between negative AO wintertime temperatures ($M = -3.9$) and mean wintertime temperatures ($M = -2.3$) at the 0.05 level; $t(49) = 2.77$, $p = 0.008$. This result suggests that there is a significant relationship between the negative phase AO and wintertime temperatures for Springfield. Specifically, the result suggests that as the AO value decreases wintertime temperatures decrease accordingly. Saint Paul experienced a significant difference between positive AO wintertime temperatures ($M = -4.9$) and mean wintertime temperatures ($M = -6.4$) at the 0.05 level; $t(49) = -2.096$, $p = 0.040$. This result suggests that there is a significant relationship between the positive phase AO and wintertime temperatures for Saint Paul. Specifically, the result suggests that as the AO value increases wintertime temperatures increase accordingly.

Although Fort Dodge, IA is located within the anomalous SAT region (Figure 1), independent samples t-tests do not yield a significant relationship between the AO and wintertime temperatures and snowfall amounts.

The independent samples t-tests displayed in Table 4, below, shows that the top ten most negative and positive AO winters have a greater effect on wintertime temperature in comparison to snowfall totals. In addition, nine of the ten independent samples t-tests yielded significant results for cities located in the Tennessee Valley region. In contrast, only five of the twelve independent samples t-tests yield significant results for cities located in the Midwest (Table 4).

Location	AO Phase	Mean	T-value	df	P-value
Chattanooga	Neg AO_Temp	4.8ºC	**-8.43**	**18**	**0.000**
TN	Pos AO_Temp	7.6ºC			
	Neg AO_Snow	21.6 cm	1.74	18	0.099
	Pos AO_Snow	8.9 cm			
Memphis	Neg AO_Temp	5.7ºC	**-8.19**	**18**	**0.000**
TN	Pos AO_Temp	8.4ºC			
	Neg AO_Snow	17.9 cm	**2.87**	**18**	**0.010**
	Pos AO_Snow	3.5 cm			
Nashville	Neg AO_Temp	4.1ºC	**-11.04**	**18**	**0.000**
TN	Pos AO_Temp	7.1ºC			
	Neg AO_Snow	44.6 cm	**3.60**	**18**	**0.002**
	Pos AO_Snow	8.4 cm			
Boone	Neg AO_Temp	0.6ºC	**-6.38**	**18**	**0.000**
NC	Pos AO_Temp	2.9ºC			
	Neg AO_Snow	134.2 cm	**4.19**	**18**	**0.000**
	Pos AO_Snow	53.2 cm			
Louisville	Neg AO_Temp	2.0ºC	**-11.12**	**18**	**0.000**
KY	Pos AO_Temp	5.1ºC			
	Neg AO_Snow	52.5 cm	**3.73**	**18**	**0.002**
	Pos AO_Snow	20.9 cm			
Location	**AO Phase**	**Mean**	**T-value**	**df**	**P-value**
Springfield	Neg AO_Temp	1.5ºC	**-5.28**	**18**	**0.000**
MO	Pos AO_Temp	4.3ºC			
	Neg AO_Snow	55.3 cm	2.01	18	0.060
	Pos AO_Snow	34.3 cm			
Saint Louis	Neg AO_Temp	0.6ºC	**-6.36**	**18**	**0.000**
MO	Pos AO_Temp	3.7ºC			
	Neg AO_Snow	53.6 cm	0.98	18	0.340
	Pos AO_Snow	42.9 cm			
Indianapolis	Neg AO_Temp	-1.1ºC	**-6.55**	**18**	**0.000**
IN	Pos AO_Temp	1.8ºC			
	Neg AO_Snow	62.0 cm	1.28	18	0.215
	Pos AO_Snow	49.4 cm			
Springfield	Neg AO_Temp	-3.9ºC	**-3.92**	**18**	**0.001**
IL	Pos AO_Temp	-1.3ºC			
	Neg AO_Snow	75.5 cm	1.06	18	0.302
	Pos AO_Snow	61.4 cm			
Fort Dodge	Neg AO_Temp	-5.2ºC	-1.43	18	0.169
IA	Pos AO_Temp	-3.8ºC			
	Neg AO_Snow	102.0 cm	1.67	18	0.111
	Pos AO_Snow	69.1 cm			
Saint Paul	Neg AO_Temp	-7.5ºC	**-3.35**	**18**	**0.004**
MN	Pos AO_Temp	-4.9ºC			
	Neg AO_Snow	105.0 cm	1.22	18	0.237
	Pos AO_Snow	86.3 cm			

Table 4. Displays results from independent samples t-tests comparing temperatures and snowfall totals between the top 10 positive and negative AO winters for each city in the study area. All temperatures are listed in degrees Celsius and all snowfall totals are listed in centimeters. All values in bold represent a significant result at $p = 0.05$
(Weather Warehouse 2014).

Each city in the Tennessee Valley experienced a significant difference between mean wintertime temperatures during the top ten most negative and positive AO winters. Chattanooga experienced a significant difference between negative AO wintertime temperatures (M = 4.8) and positive AO wintertime temperatures (M = 7.6) at the 0.05 level; t(18) = -8.4, p = 0.000. Memphis experienced a significant difference between negative AO wintertime temperatures (M = 5.7) and positive AO wintertime temperatures (M = 8.4) at the 0.05 level; t(18) = -8.19, p = 0.000. Nashville experienced a significant difference between negative AO wintertime temperatures (M = 4.1) and positive AO wintertime temperatures (M = 7.1) at the 0.05 level; t(18) = -11.04, p = 0.000. Boone experienced a significant difference between negative AO wintertime temperatures (M = 0.6) and positive AO wintertime temperatures (M = 2.9) at the 0.05 level; t(18) = -6.38, p = 0.000. Louisville experienced a significant difference between negative AO wintertime temperatures (M = 2.0) and positive AO wintertime temperatures (M = 5.1) at the 0.05 level; t(18) = -11.12, p = 0.000. These results suggest that there is a significant relationship between the top ten most negative and positive AO winters and mean wintertime temperatures for cities located in the Tennessee Valley region.

With the exception of Chattanooga, each city in the Tennessee Valley also experienced a significant difference between mean wintertime snowfall during the top ten most negative and positive winters AO winters. Memphis experienced a significant difference between negative AO wintertime snowfall (M = 17.9) and positive AO wintertime snowfall (M = 3.5) at the 0.05 level; t(18) = 2.87, p = 0.010. Nashville experienced a significant difference between negative AO wintertime snowfall (M = 44.6) and positive AO wintertime snowfall (M = 8.4) at the 0.05 level; t(18) = 3.60, p = 0.002. Boone experienced a significant difference between negative AO wintertime snowfall (M = 134.2) and positive

AO wintertime snowfall (M = 53.2) at the 0.05 level; t(18) = 4.19, p = 0.000. Louisville experienced a significant difference between negative AO wintertime snowfall (M = 52.5) and positive AO wintertime snowfall (M = 20.9) at the 0.05 level; t(18) = 3.73, p = 0.002. These results suggest that there is a significant relationship between the top ten most negative and positive AO winters and mean wintertime snowfall for cities located in the Tennessee Valley region.

With the exception of Fort Dodge, each city in the Midwest experienced a significant difference between mean wintertime temperatures during the top ten most negative and positive AO winters. Springfield, MO experienced a significant difference between negative AO wintertime temperatures (M = 1.5) and positive AO wintertime temperatures (M = 4.3) at the 0.05 level; t(18) = -5.28, p = 0.000. Saint Louis experienced a significant difference between negative AO wintertime temperatures (M = 0.6) and positive AO wintertime temperatures (M = 3.7) at the 0.05 level; t(18) = -6.36, p = 0.000. Indianapolis experienced a significant difference between negative AO wintertime temperatures (M = -1.1) and positive AO wintertime temperatures (M = 1.8) at the 0.05 level; t(18) = -6.55, p = 0.000. Springfield, IL experienced a significant difference between negative AO wintertime temperatures (M = -3.9) and positive AO wintertime temperatures (M = -1.3) at the 0.05 level; t(18) = -3.92, p = 0.001. Saint Paul experienced a significant difference between negative AO wintertime temperatures (M = -7.5) and positive AO wintertime temperatures (M = -4.9) at the 0.05 level; t(18) = -3.35, p = 0.004. These results suggest that there is a significant relationship between the top ten most negative and positive AO winters and mean wintertime temperatures for cities located in the Midwest region.

No cities in the Midwest experienced a significant difference between snowfall totals during the top ten most negative and positive AO winters.

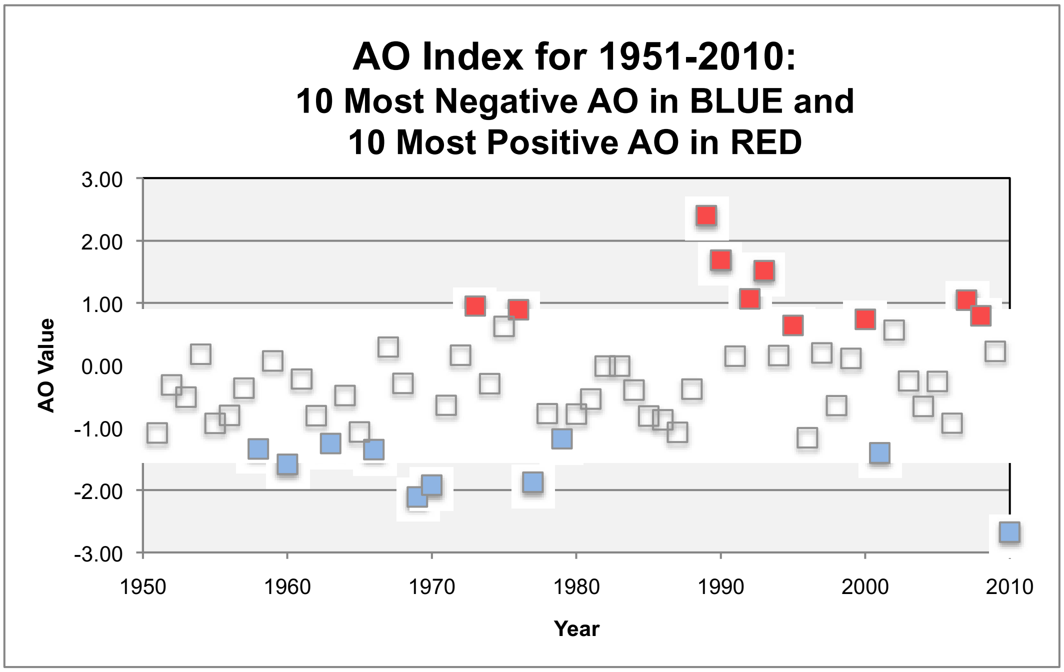

Figure 4. Wintertime (Dec-Mar) AO values from 1951-2010 (CPC 2012).

Shown in Figure 4, the top ten most positive AO winters are depicted in red and the top ten most negative AO winters are displayed in blue. All the transparent points exclude the top ten most positive and negative AO winters. It can be seen that the majority of the top ten most negative AO winters fall within the period from 1958-1980 (Figure 4). In contrast, it can be seen that the majority of the top ten positive AO winters fall within the 1990-2009 period (Figure 4). This graph suggests that the AO may experience a low-frequency pattern of climate variability.

Climate and AO Comparison Graphs

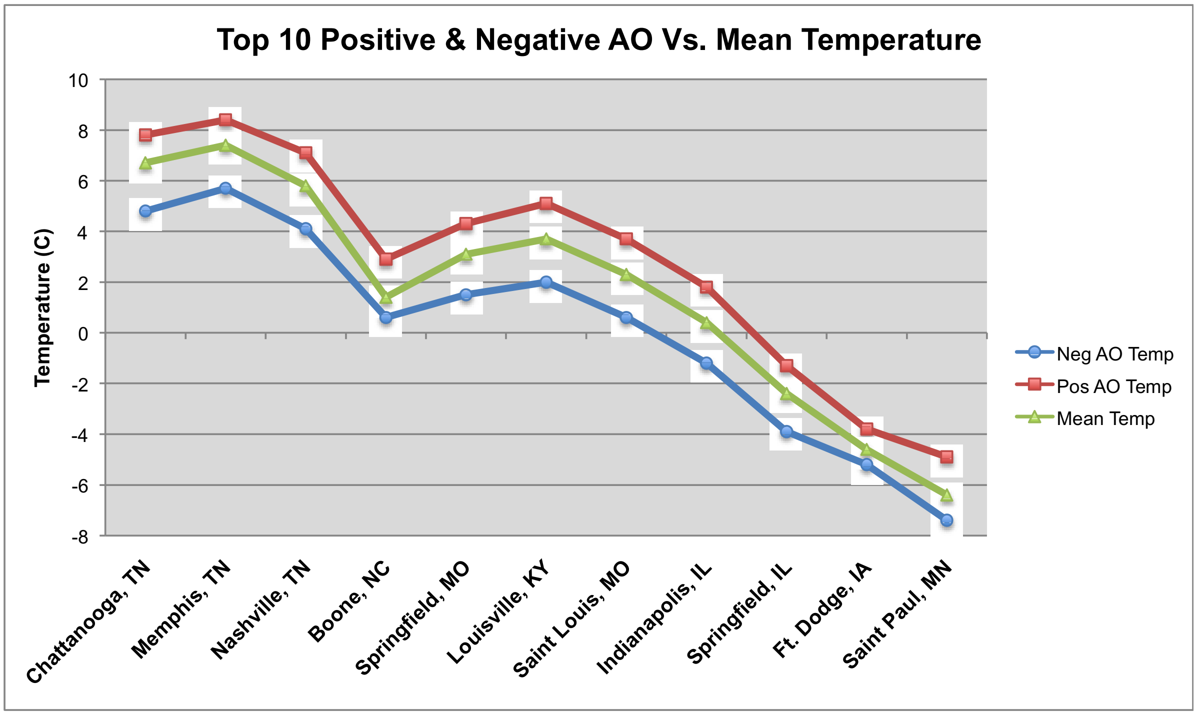

Figure 5. Represents 20 years of data, which includes the Top 10 positive and negative AO wintertime temperatures in comparison to the mean wintertime temperatures for each city in the study area. The cities are organized by latitude (lowest to highest) from left to right (Weather Warehouse 2014).

Figure 5 demonstrates that all of the cities in the study area experience cooler than average wintertime temperatures during negative AO winters. In contrast, each city experiences warmer than average wintertime temperatures during positive AO winters. In addition, there is a greater temperature difference between positive and negative AO winters across the Tennessee Valley region in comparison to the Midwest region (Table 3). For instance, cities in the Tennessee Valley region experience a mean wintertime temperature difference of 2.8°C between positive and negative AO winters. In comparison, the cities in the Midwest region experience a wintertime temperature difference of only 2.55°C between positive and negative AO winters (Table 3). These results suggest that the AO has a more significant impact on wintertime temperatures across the Tennessee Valley region in comparison to the Midwest region.

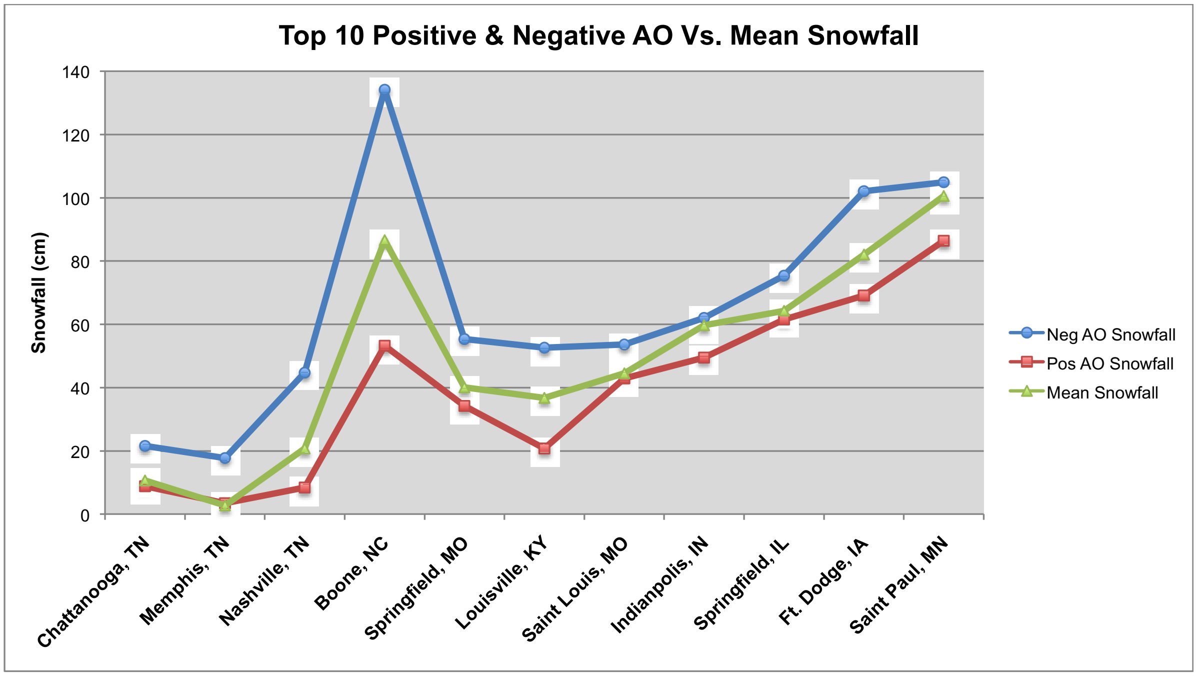

Figure 6. Represents 20 years of data, which includes the Top 10 positive and negative AO wintertime snowfall totals in comparison to the mean wintertime snowfall totals for each city in the study area. The cities are organized by latitude (lowest to highest) from left to right (Weather Warehouse 2014)

Figure 6 shows that all cities in the study area experience well above average snowfall totals during negative AO winters. In contrast, each city experiences much below average snowfall totals during positive AO winters. As shown in Figure 6, as latitude increases, the differential between snowfall totals during AO winters of opposing phases decreases. This trend can be explained by the temperature contrast between southern and northern locations. In reference to Table 3, it can be seen that the mean and above/below average wintertime temperatures in lower latitude locations are much warmer than the mean and above/below average wintertime temperatures associated with higher latitude locations. Cities located at higher latitudes often experience temperatures at or below freezing during both positive and negative AO winters, which results in comparatively uniform mean wintertime snowfall totals. On the other hand, cities located at lower latitudes often experience mean wintertime temperatures well above freezing during both positive and negative AO winters. However, during negative AO winters southern locations experience a greater number of days at or below freezing, which consequently results in significantly greater snowfall totals in comparison to positive AO winters.

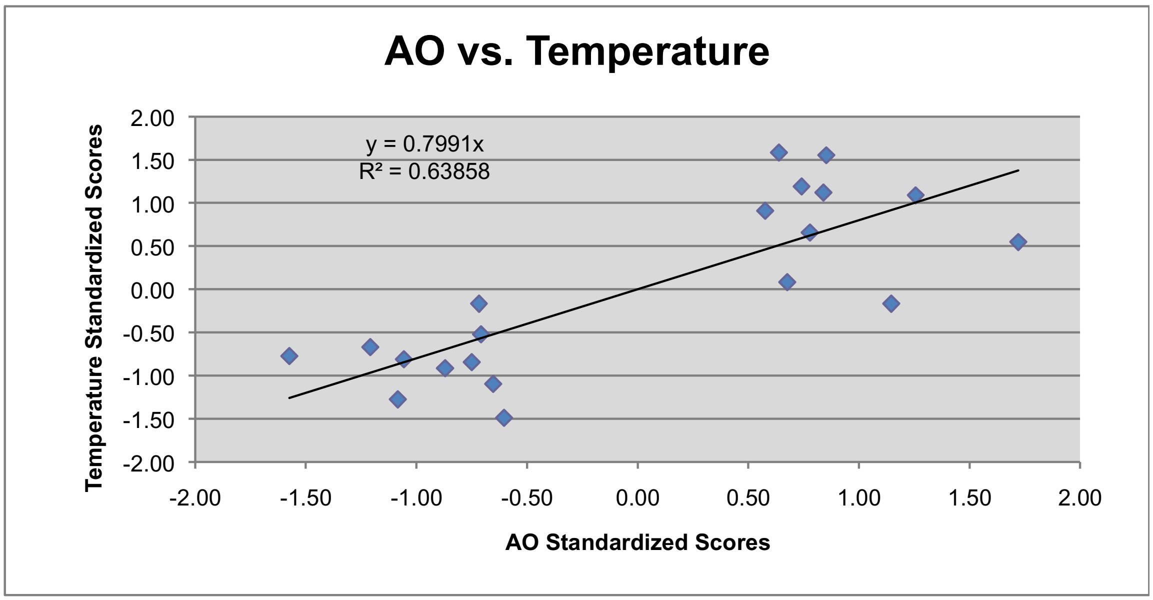

Figure 7. A scatterplot demonstrating the linear relationship between cities mean temperature standardized scores and the AO standardized scores for the top 10 positive and negative AO winters (Weather Warehouse 2014).

The Pearson Correlation Coefficient was performed between the mean wintertime temperatures for all cities and each corresponding AO values. The Pearson Correlation Coefficient of R = 0.799 (n = 20) was significant at the 95-percent level of significance (p=0.000). This suggests that strong phases of the AO and wintertime temperatures are strongly associated with one another. Subsequently, a linear regression was performed between the two variables (Figure 7). The AO served as the Independent variable while

Wintertime Temperature was the dependent variable. The R^2 of 0.639 suggests that, based on this dataset, the AO accounts for approximately 64% of wintertime temperature variation for strong AO winters. The regression results were statistically significant at the 95-percent level of significance (F = 31.88; p = 0.000).

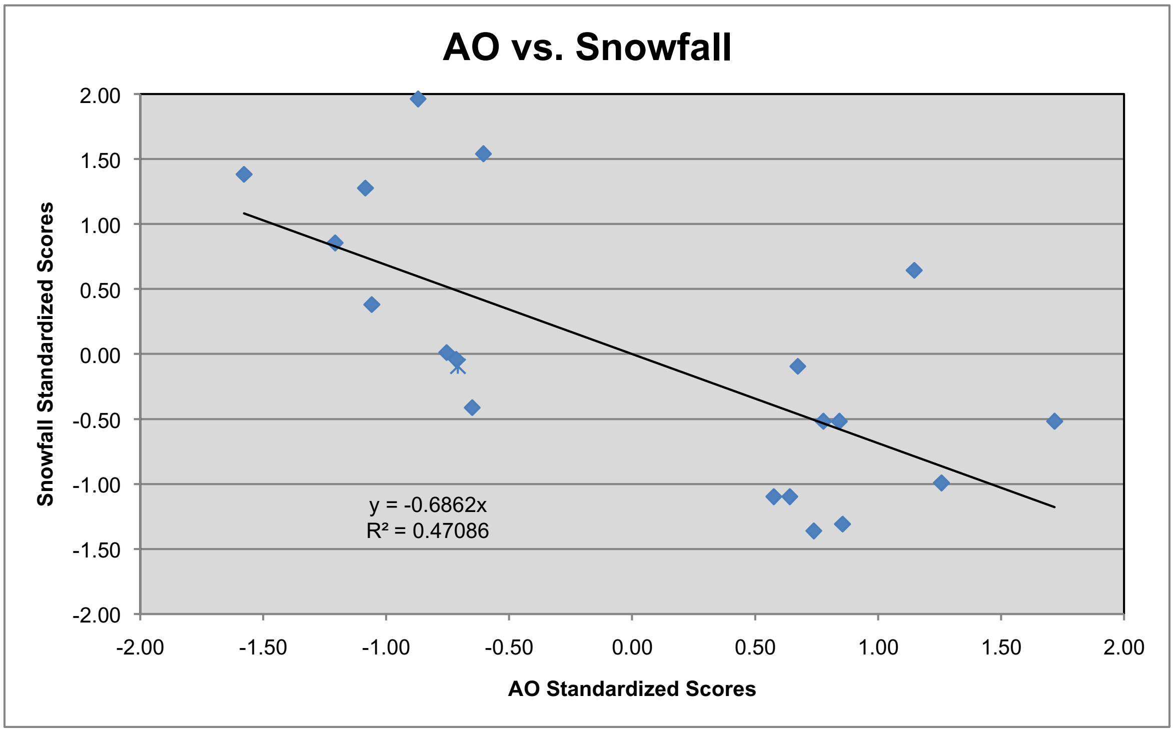

Figure 8. A scatterplot demonstrating the linear relationship between cities snowfall standardized scores and the AO standardized scores for the top 10 positive and negative AO winters (Weather Warehouse 2014).

Much like the analyses between wintertime air temperatures and the AO, correlation and linear regression were performed between the AO and snowfall totals for all twenty of the top ten positive and negative AO winters. The calculated Pearson Correlation Coefficient was R = -0.684 (p = 0.001), suggesting that there was a negative yet statistically significant association between strong phases of the AO and snowfall. In other words, as the AO value increases, snowfall totals typically decrease. A linear regression was then performed between the AO and snowfall totals. Like the analysis for air temperature, AO again served as the Independent variable, though snowfall served as the dependent variable. Though the results were not as strong as they were for air temperature, the regression coefficient of $R^2 = 0.468$ was statistically significant at the 95-percent level of significance ($p = 0.001$) (Figure 8). The linear regression results ($F = 15.845$; $p = 0.001$) demonstrate that the strength of the AO does, in fact, have an influence on snowfall totals in the Midwest and Tennessee Valley regions of the USA during the top ten positive and negative AO winters.

NCEP-NCAR Reanalysis Composite Maps

Negative & Positive AO

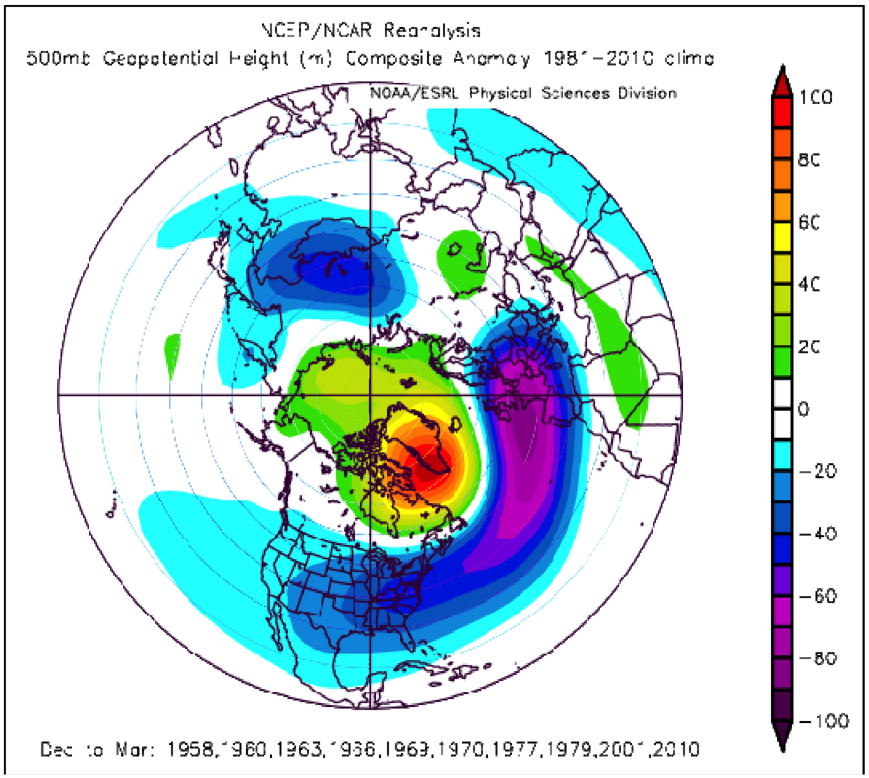

Figure 9. Northern Hemisphere 500 mb geopotential height anomaly during the top 10 negative AO winters (ESRL 2014).

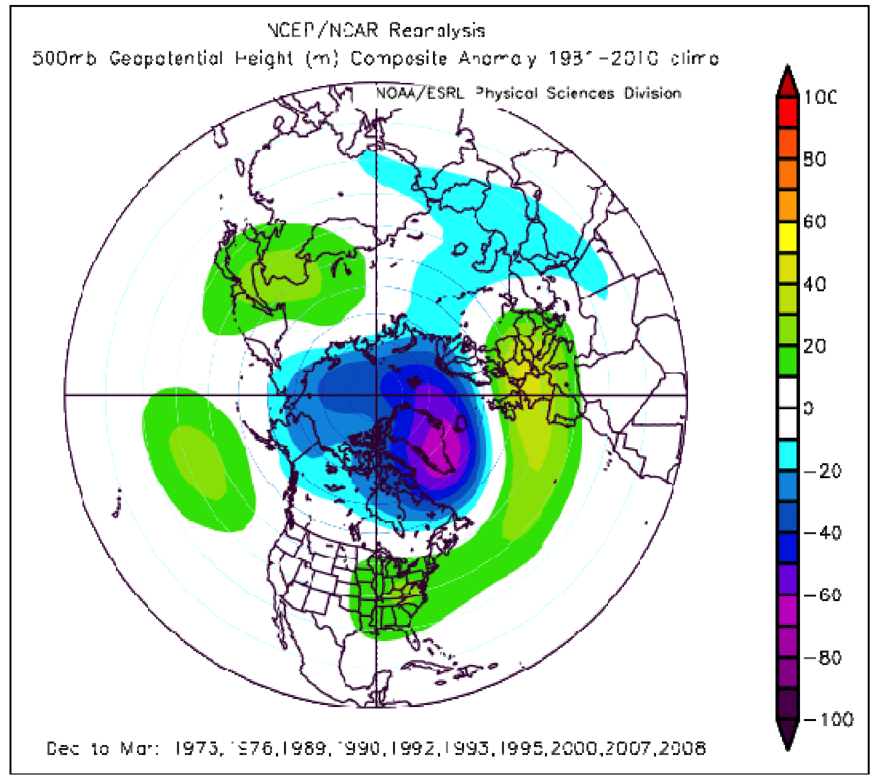

Figure 10. Northern Hemisphere 500 mb geopotential height anomaly during the top 10 positive AO winters (ESRL 2014).

When analyzing the 500 mb GPH field for the top ten most negative AO winters, the notorious high-over-low height pattern is clearly visible throughout the northern hemisphere (Figure 9). Positive height anomalies as great as 100 meters above normal can be observed over southern Greenland and the Davis Strait region (60°N, 55°W). On the contrary, negative height anomalies as great as 90 meters below normal are evident in the vicinity of the Azores Islands (45°N, 20°E). Although less robust than the above-mentioned regions, negative height anomalies averaging as much as 50 meters below normal, stretch zonally across the entire continental USA. In addition, the majority of the Midwest and Tennessee Valley regions experienced GPH anomalies as much as 40 to 50 meters below normal during the top ten most negative AO winters. Tanaka and Tokinaga (2002) stated, "The AO has an equivalent barotropic structure from the surface to the lower stratosphere in that the positive or negative geopotential anomaly occurs consistently from the troposphere to the stratosphere" (Tanaka and Tokinaga 2002, 69). The term barotropic refers to an environment consisting of homogenous temperature dispersion (the absence of frontal boundaries). This implies that the GPH anomalies associated with the 1000 mb and 300 mb levels will have remarkably similar spatial consistencies as the 500 mb GPH. However, the magnitude of the anomalies tends to increase with height. Because of the weakened state of the polar vortex during this time period, its associated cyclonic flow decreased in intensity which allowed the vortex to propagate further south than typical. This southward displacement of the polar vortex and its accompanied frigid airmass, resulted in increasing heights over the polar region in response to above normal surface pressure and air temperatures. Due to the closer proximity of the polar vortex, lower heights were forced equatorward into the central and eastern USA.

From the 500 mb GPH anomalies it can be seen that well below normal heights exists over the Arctic region whereas; well above normal heights are present stretching from the eastern half of the USA to Europe (Figure 10). This classic low-over-high GPH pattern is suggestive of a positive AO. During the top ten most positive AO winters, GPH anomalies were greater than 50 meters below normal over Greenland and as much 20 meters below normal across the entire Arctic region. In contrast, GPH anomalies as much as 20 meters above normal across much of the Tennessee Valley region and eastern seaboard of the USA. Nevertheless, the greatest positive GPH anomalies existed over France and Germany closest to the center of the Azores high, where GPH anomalies were as much as 40 meters above normal. Due to the strong positive nature of the AO during these winters, the polar vortex stationed near Greenland was exceptionally strong. As the polar vortex intensifies, the low-pressure center continues to deepen, consequently sharpening the pressure gradient and strengthening the band of winds around the periphery of the vortex. This cold core low-pressure system and its associated intense cyclonic flow successfully trapped the cold air over the polar region, thus lowering GPH across the area. Conversely, the northerly positioning of the polar vortex gave way to a predominately zonal flow across much of the USA. This influx of warm, moist air which originated in both the Pacific Ocean and Gulf of Mexico, induced a rise in GPH across much of the eastern half of the USA.

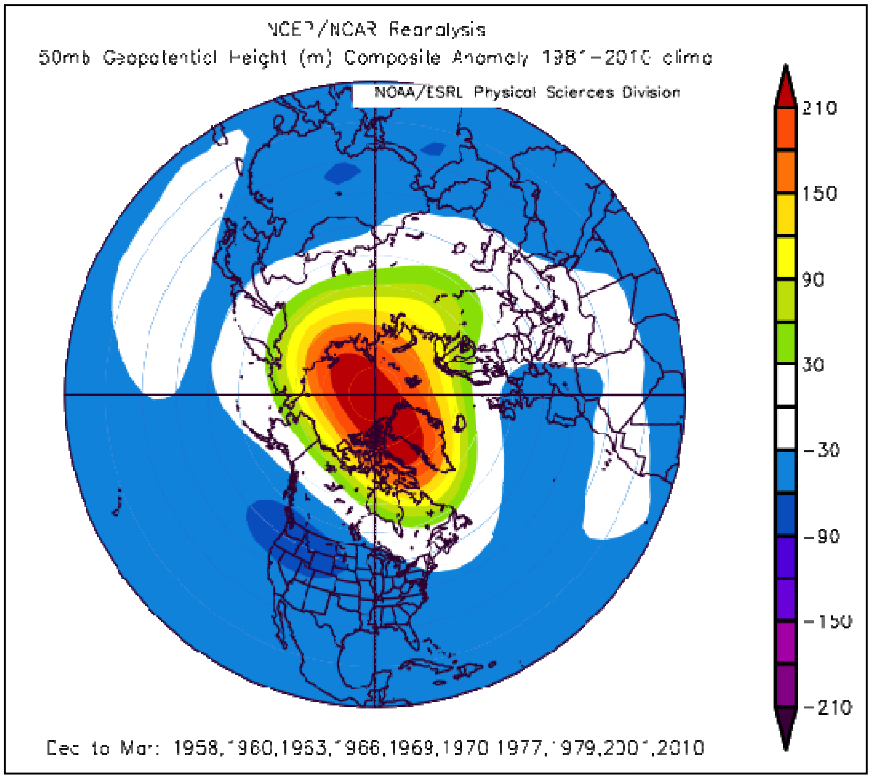

Figure 11. Northern Hemisphere 50 mb geopotential height anomaly during the top 10 negative AO winters (ESRL 2014).

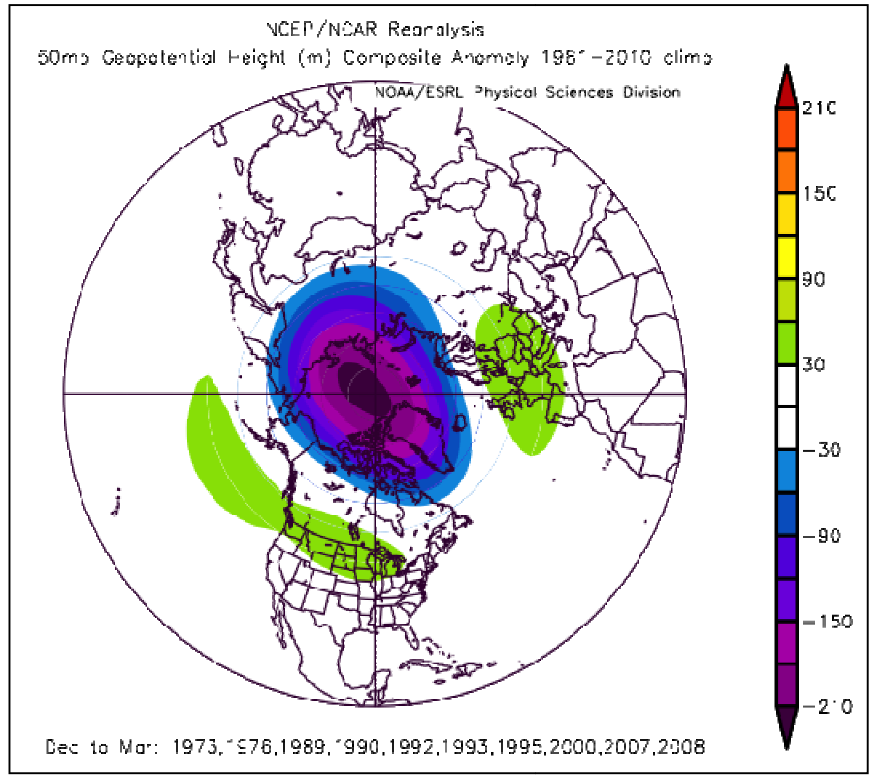

Figure 12. Northern Hemisphere 50 mb geopotential height anomaly during the top 10 positive AO winters (ESRL 2014).

The 50 mb height is an effective level for the analysis of the stratospheric polar vortex (Figure 11). It can be seen that the lower stratosphere experienced well above normal heights during the top ten most negative AO winters in response to SSW events. GPH anomalies were greater than 210 meters above normal for the majority of the Arctic region. As stated in the literature review, SSWs occur during the winter months over the polar regions and generally result in a negative phase AO at a typical lag time of two to three weeks. Although the mean wintertime GPH anomalies were much above normal during the top ten negative AO winters, that does not mean the stratosphere was continuously warming during these periods. As stated in the literature review, during significant SSWs the lower stratosphere may warm by as much as 50.0°C over just a few days. Despite this relatively brief intense warming, the stratosphere has been known to take several months to return to its mean climatological state. It is clearly evident based on the 50 mb GPH anomalies (Figure 11) that the stratosphere experienced SSW events during the top ten most negative AO winters. This sudden increase in stratospheric temperatures resulted in the breakdown of the stratospheric polar vortex and eventual breakdown of the tropospheric polar vortex, given the well above normal heights at 500 mb during the most negative AO winters (Figure 9). When the stratospheric polar vortex and the tropospheric vortex begin to breakdown, their corresponding cyclonic flow begins to weaken which allows for an intrusion of warmer air into the Arctic region, consequently forcing the frigid air further south.

The 50 mb height is an effective level for examining the polar night jet, which encompasses the stratospheric polar vortex. The stratospheric polar vortex at 50 mb (Figure 12) is essentially a reflection of the tropospheric polar vortex at 500 mb (Figure 10). As stated in the literature review however, GPH anomalies tend to tilt northwest with height. Therefore, the greatest GPH anomalies at 50 mb will be positioned further northwest than the greatest GPH anomalies at 500 mb. As can be seen in Figure 12, much below normal heights exist in the lower stratosphere over the Arctic region during the top ten most positive AO winters. This signifies a strong stratospheric polar vortex on account of its deepened low pressure and strengthened cyclonic flow. If the stratospheric vortex maintains its strength, the tropospheric polar vortex will typically follow suit. Although the tropospheric vortex still has potential to meander slightly north or south despite a persistent stationary stratospheric polar vortex; the tropospheric vortex will not completely breakdown unless the stratospheric vortex does so first. The strong stratospheric polar vortex stationed over the Arctic region during the most positive AO winters resulted in above normal wintertime temperatures in the Midwest and Tennessee Valley regions due to the majority of the polar air staying confined to the far northern latitudes.

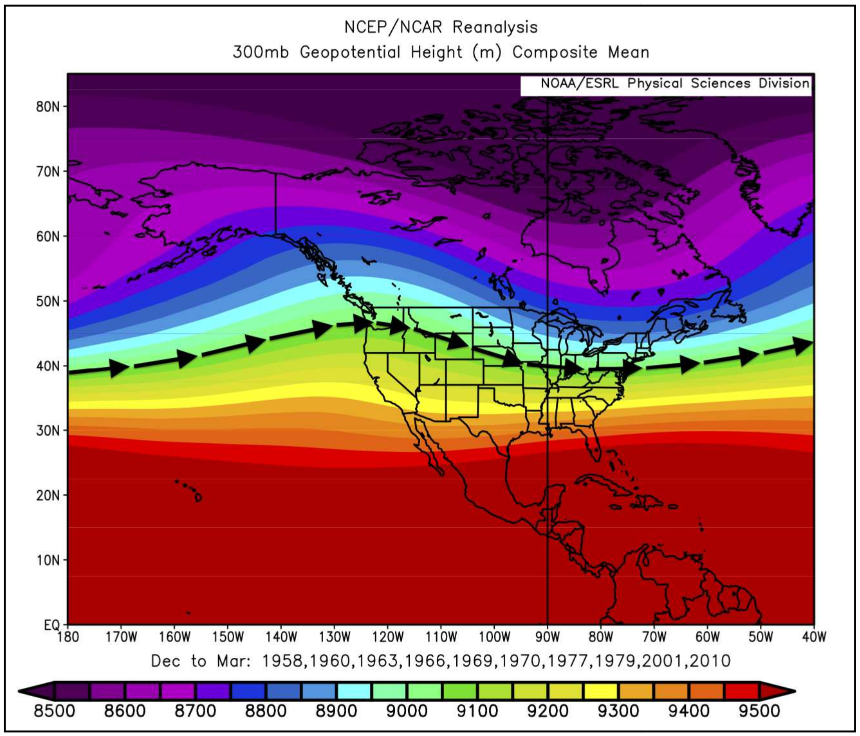

Figure 13. North American mean 300 mb geopotential height during the top 10 negative AO winters (ESRL 2014).

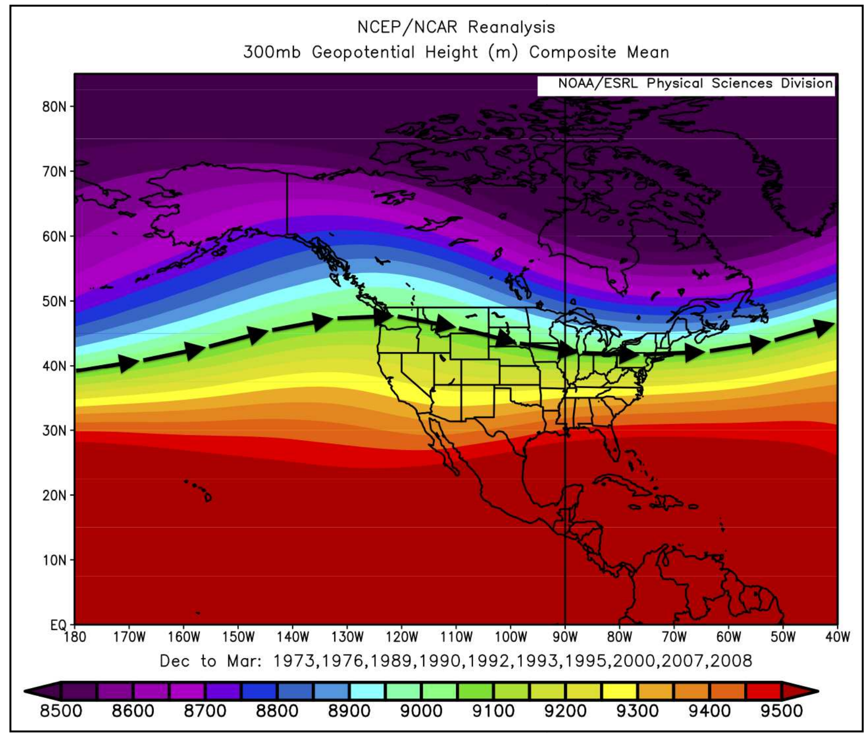

Figure 14. North American mean 300 mb geopotential height during the top 10 positive AO winters (ESRL 2014).

A jet stream is a fast moving, narrow current of air situated in the upper troposphere. Jet streams are great predictors of the eventual movement of air masses and storm systems, given that they typically form along boundaries of contrasting air masses and work as a steering mechanism high in the troposphere. When examining the 300 mb GPH field, it is essential to understand the height of the jet stream to determine a precise boundary between warm and cool temperatures both aloft and at the surface. The jet stream is generally located around 250 mb. During the cold season however, the jet stream is located closer to 300 mb (with an average height around 9,000 meters) due to cold air being more dense and sinking closer to the surface. As shown in Figure 13, the arrows indicate the mean wintertime position of the polar jet stream during the top ten most negative AO winters. During these winters, the polar jet entered the USA near southern Washington (46.2°N) and exited the USA near Atlantic City New, New Jersey (39.4°N), which also marks the southernmost extent of the mean wintertime jet stream. When examining the mean 300 mb heights, it can be seen that a fairly pronounced ridge exists over the Pacific Northwest, with a subsequent downstream trough stationed over the central and eastern USA. This map demonstrates that GPH is not zonally symmetric and varies depending on the temperature of an air mass and the corresponding dynamics (rising or sinking air). The region to the north of the jet may be under the influence of a polar air mass, consequently leading to lower heights, with contrasting conditions to the south of the jet. A jet stream is often characterized by a sharp thermal gradient on either side. The southward displacement of the polar jet stream during the top ten most negative AO winters (Figure 13) in comparison to the positioning of the polar jet stream during the top ten most positive AO winters (Figure 14) suggests the Midwest and Tennessee valley regions experienced much colder air masses due to the jet stream transporting Arctic air further south than normal.

As previously mentioned, the 300 mb (9,000 meters) level is the most appropriate height to analyze the polar jet stream because its generally located around 9,000 meters above earth's surface (Figure 14). During a pronounced southward dip in the jet stream, a trough (area of low pressure) forms over a region, which signals lower heights and cooler temperatures. The opposite is generally true under a pronounced ridge (area of high pressure) in the jet stream. As shown in Figure 14, the arrows indicate the mean wintertime positioning of the polar jet stream. The jet entered the west coast of North America near Seattle Washington (47.6°N) and exited the east coast of the USA near southern Massachusetts (41.6°N). The mean wintertime jet stream never dipped below 41.5°N anywhere throughout the continental USA. Again, the mean positioning of the polar jet stream during the positive AO winters (Figure 14) is around 2.2 degrees latitude (approximately 150 miles) further north, than the mean positioning of the polar jet stream during negative AO winters (Figure 13). This means that polar air masses were predominantly confined to regions north of this boundary, leaving places to the south under the influence of a zonal to southwesterly flow for the majority of the winter. Because of the northward displacement of the polar jet stream, the subtropical jet encroached further on the Midwest and Tennessee Valley regions, which resulted in more moderate air masses throughout the wintertime.

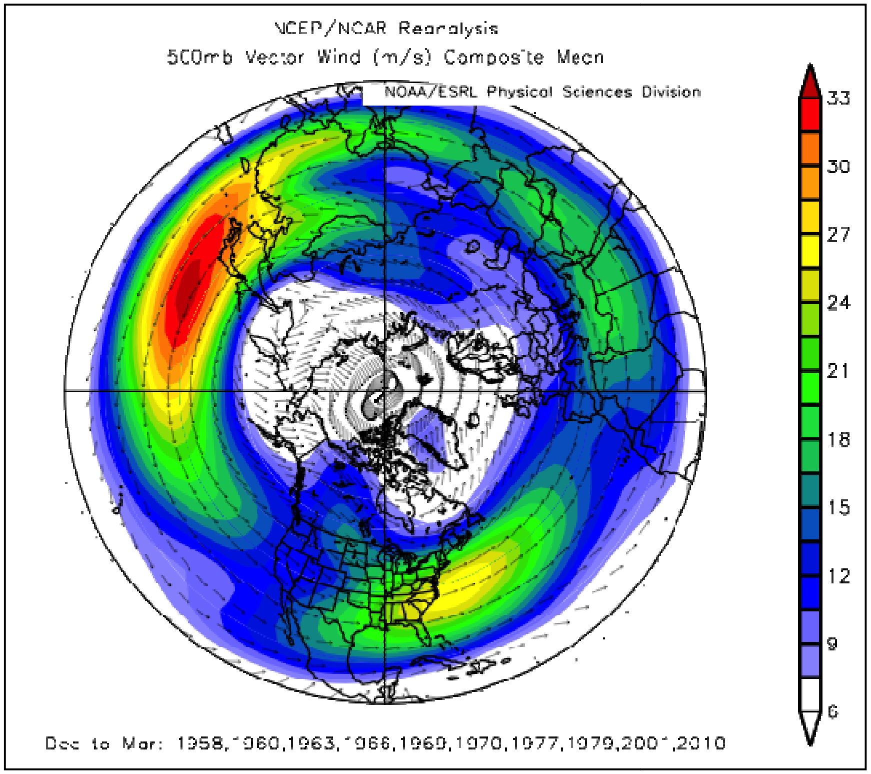

Figure 15. Northern Hemisphere mean 500 mb vector wind during the top 10 negative AO winters (ESRL 2014).

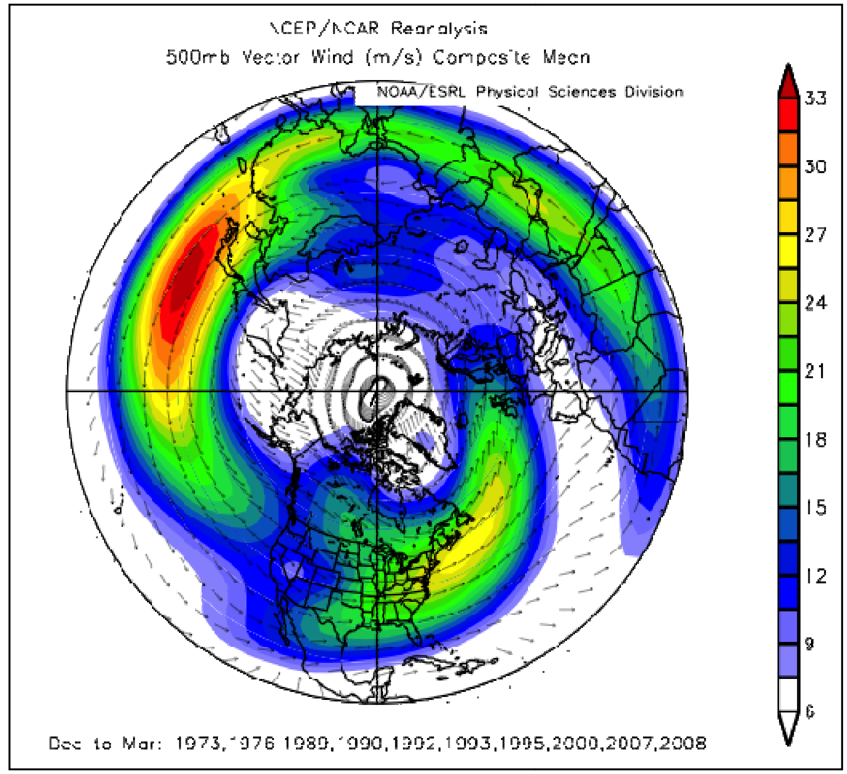

Figure 16. Northern Hemisphere mean 500 mb vector wind during the top 10 positive AO winters (ESRL 2014).

The 500 mb vector wind parameter displays the mean wind speed (m/s) and direction for the top 10 most negative AO winters (Figure 15). During a negative phase AO, the polar vortex experiences a counterclockwise flow with wind speeds ranging from <6 to 9 m/s. The magnitude of the winds is often much greater around the periphery of the vortex in conjunction with the polar jet stream. During a prolonged negative state of the AO, the polar vortex is subject to more extensive meridional perturbations of atmospheric mass, which allows troughs and ridges to become increasingly amplified. The polar vortex behaves very similarly to a spinning top. When the momentum is strong, the rotation is very tight around its vertical axis. However, as the polar vortex loses momentum, it begins to wobble and deviates further from its center. This movement often causes pieces of the polar vortex to become dislodged and migrate much further south than usual. Frigid air that is typically bottled up over the northern most latitudes suddenly plunges southward, while warmer air wraps into the Arctic region to fill the voided atmospheric space. As can be seen via the wind vectors in Figure 15, the eastern half of the USA experienced a northwest flow as cold air continuously funneled down from Canada. The eastern half of the USA experienced mean 500 mb wind speeds of greater than 18 m/s. This stronger band of zonal winds located on the southern boundary of the polar vortex is associated with a steep pressure gradient, owing to a more southward displacement of the polar jet stream. The interaction between cold polar air from the north and warm tropical air from the south results in frontogenesis (tightening of horizontal temperature gradients to produce fronts). When surface low-pressure systems form along these boundaries, they trigger cold air advection in response to southeastward propagating cold fronts. This influx of Arctic air from the northwest results in below normal temperatures across much the Midwest and Tennessee Valley regions.

The polar vortex is best estimated at the 500 mb height. During a strong positive phase AO, the polar vortex deepens and its corresponding cyclonic flow intensifies. This results in a much tighter circulation, therefore, minimizing the areal coverage of the polar vortex. The polar vortex derives its energy from zones of baroclinicity (distinct air masses separated by a frontal boundary). In the event of a strong positive phase AO, cold air is limited to the polar region whereas, much warmer air is present to the south of this boundary. These contrasting air masses generate a much stronger pressure gradient force (a flow from high to low pressure), which supplies additional momentum to the polar vortex. As can be seen in Figure 16, the polar vortex is the area depicted in white over the Arctic. This region of white is much less expansive than the region during the most negative AO winters (Figure 15). The band of winds along the periphery of the polar vortex represents a broad-brush depiction of the mean wintertime position of the polar jet stream. During the top ten most positive AO winters, the southern extent of the polar vortex was stationed along the northern shores of the Hudson Bay. This poleward allocation of the vortex caused the polar jet to retract to more northern latitudes than usual. The 500 mb wind vectors indicate that the eastern half of the USA experienced a predominate westerly flow, while wind speeds averaged 18-22m/s across much of the Midwest and Tennessee Valley regions.

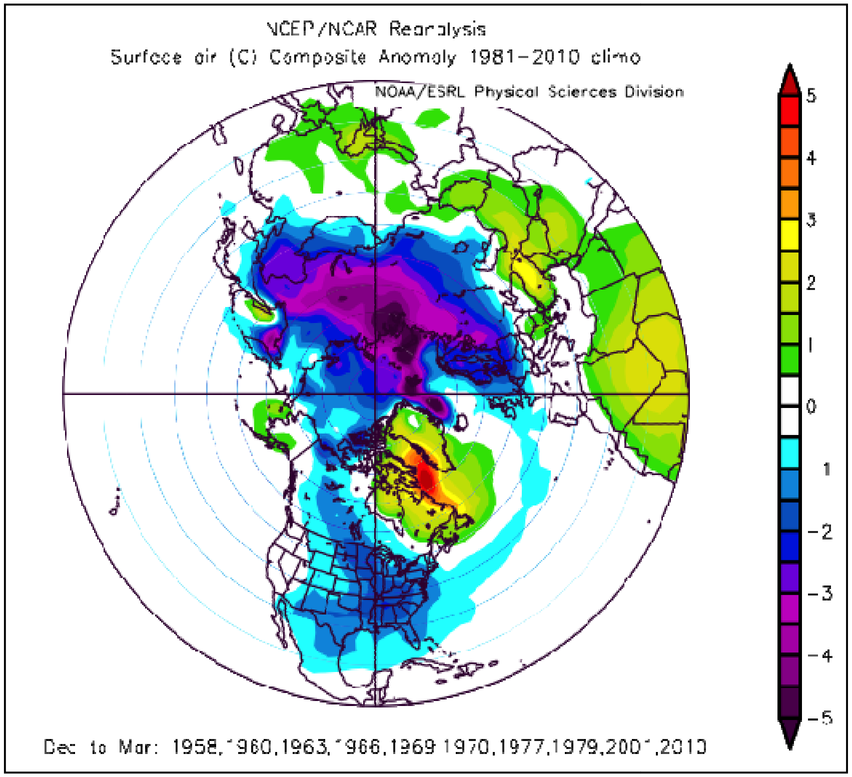

Figure 17. Northern Hemisphere surface air temperature (°C) anomaly during the top 10 negative AO winters (ESRL 2014).

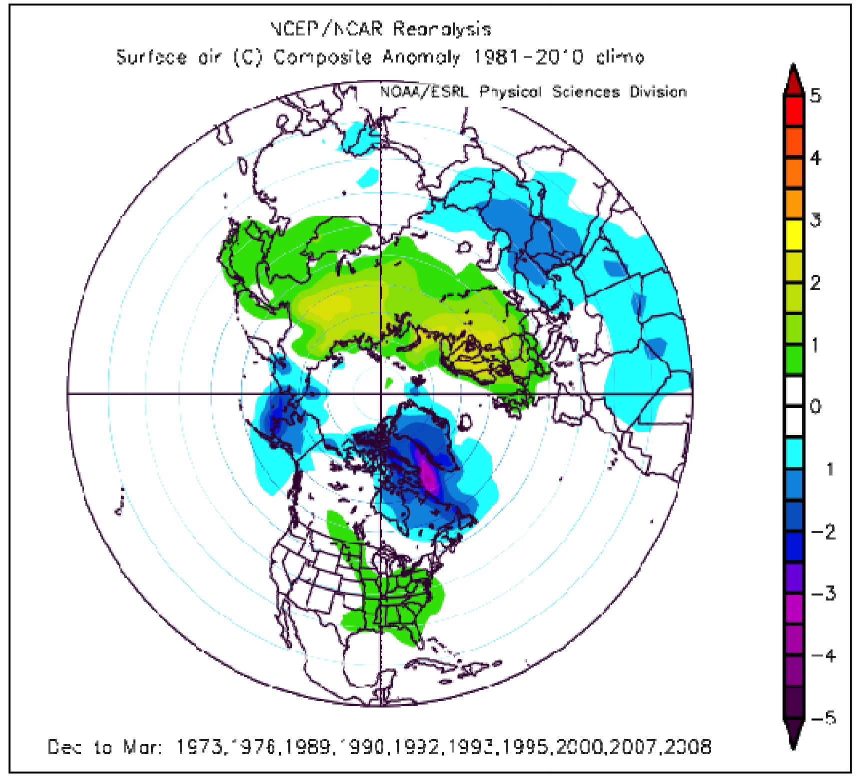

Figure 18. Northern Hemisphere surface air temperature (°C) anomaly during the top 10 positive AO winters (ESRL 2014).

When analyzing SAT anomalies associated with the top ten most negative AO winters (Figure 17), it can be seen that they are arranged in a comparable spatial pattern to the 500 mb GPH anomalies (Figure 9). Displayed in Figure 17, positive SAT anomalies can be observed throughout the Icelandic region, with the most significant positive anomalies of greater than 5.0°C located near 60°N, 55°W. Conversely, negative SAT anomalies are visible throughout the entire eastern two-thirds of the USA (excluding Maine), with the Midwest and Tennessee Valley regions experiencing the most significant negative anomalies of around -2.0 to -2.5°C. A prolonged period of abnormally high pressure stationed over Greenland caused an invasion of warm moist subtropical air into the northern latitudes (between 50°N and 70°N). Additionally, the persistent high pressure disrupted the mean zonal flow across Canada, which consequently led to a transition to a more meridional flow across the central USA. This shift in wind direction across the Midwest and Tennessee Valley regions resulted in a rapid change from a moderate air mass influenced by the Pacific to cold polar air mass originating in the Arctic.

SAT anomalies are used to further support evidence provided by parameters pertaining to the middle and upper levels of the atmosphere. Due to the presence of a strong polar vortex in association with the top ten most positive AO winters, below normal temperatures were restricted to the northern latitudes (Figure 18). The greatest SAT anomalies occurred over the Davis Strait (65°N, 58°W), where temperatures averaged as much as -4.0°C below normal. Further south, SAT anomalies averaged as much as -0.75°C above normal across a majority of the Tennessee Valley. However, anomalies were less significant across the Midwest, where mean SAT were only 0.5°C above normal.

Discussion of Results

As stated in the literature review, The AO is a meridional fluctuation of the atmospheric flow with a primary center of action over the Arctic region (north of 60°N) and opposing anomalies across much of the middle latitudes (Deser 2000). Based on the results of the 500 mb GPH maps it was determined that this study supports previous literature suggesting that the greatest height anomalies occur over the Arctic region and across much of the USA and North Atlantic regions during the most positive and negative AO winters. In addition, based on the results of the SAT maps, it was determined that this study supports the research carried out by Abramyan and Vaughan (2014), which concluded that the strong negative AO results in much below average temperatures for the Southeast USA. Similarly, Wettstein and Mearns (2002) study, "The Influence of the North Atlantic-Arctic Oscillation on Mean, Variance, and Extremes of Temperature in the Northeastern United States and Canada", concluded that above normal temperatures over the Northeastern USA are synonymous with positive AO values and opposing conditions are true in combination with negative AO values (Wettstein and Mearns 2002). This study also contributes to the existing literature on the AO due to the fact that there hasn't been a similar study for the same regions involved. In addition to the known effects of strong phases of the AO on temperatures and snowfall for the northeast and southeast USA, it has now been determined that strong phases of the AO also have a significant effect on wintertime temperatures and snowfall across much of the Midwest and Tennessee Valley regions. This evidence suggests the AO has a significant effect on wintertime temperatures and snowfall across the majority of the eastern half of the USA.

Shown in Table 4, it can be seen that 90% of the independent t-tests performed for the Tennessee Valley region yielded significant results. In contrast, only 42% of the independent samples t-tests in the Midwest yielded significant results. Based on these results, it was determined that the top ten most positive and negative AO winters have the greatest effects on the Tennessee Valley regions, with a significant, although, slightly diminished effect over the Midwest. This is likely in part, due to spatial configuration of the GPH during these same periods. The greatest height anomalies were focused over the Tennessee Valley and eastern seaboard of the USA. Because SAT and GPH are synonymous with one another, it's not surprising that the top ten positive and negative AO winters have the most significant effect on wintertime temperatures and snowfall totals across the Tennessee Valley region.

Shown in Table 4, it can be seen that 91% of the independent samples t-tests performed for temperature yielded significant results. In contrast, only 36% of the independent samples t-tests performed for snowfall yielded significant results. Given that snowfall is dependent on a greater number of atmospheric variables and require specific ingredients to come together at an exact time, it makes sense that temperature would be more greatly affected by the top ten most positive and negative AO winters.

Furthermore, 59% of the independent samples t-tests performed for the negative AO yielded significant results. In contrast, only 32% of the independent samples t-tests performed for the positive AO yielded significant results (Table 3). The NCEP-NCAR reanalysis maps further support this statistical evidence that the most negative AO winters do indeed have a much greater effect on atmospheric processes responsible for variation in wintertime temperatures and snowfall for cities in the Midwest and Tennessee Valley regions of the USA. A simple explanation involving the differences in significance of the effects between the opposing phases of the AO is that the average AO value for the top ten most negative AO winters is -1.67, where as, the average AO value for the top ten most positive AO winters is 1.17 (Table 2). There is clearly a link between the magnitude of the negative

AO value and its effects on temperature and snowfall amounts. However, despite the resounding body of evidence that the top ten most negative AO winters are much more significant than the top ten most positive AO winters, the causes of this phenomenon have yet to be determined.

Based on the wintertime AO values shown in Figure 4, it was determined that the AO experiences low-frequency climate variability. Although these results are significant between the top ten most positive and negative AO winters and wintertime climate variability in the Midwest and Tennessee Valley regions, it may be possible that these results have been amplified by other teleconnections occurring in conjunction with the AO. Researchers such as Newman et al. (2003) conducted a study that determined that the variability of the Pacific Decadal Oscillation (PDO) is the result of direct forcing by El Nino-Southern Oscillation (ENSO) (Newman et al. 2003). It is well known that certain teleconnections can have a significant influence on one another, however, it has not yet been discovered whether the AO is significantly influenced by other teleconnections.

CHAPTER V

CONCLUSION

Atmospheric and Surface Weather Patterns Associated With Strong AO Phases

To reiterate, I attempted to answer the following questions:

1) How has surface weather differed between the top ten most positive and negative AO winters in comparison to the climatological mean for cities located within the above-mentioned regions?

2) What effects does the AO have on wintertime weather patterns for the Midwest and Tennessee valley regions of USA?

3) What types of weather parameters can be linked to the AO and what effects do their relationship have on one another?

In a continued effort to understand the effects of the AO on regional wintertime climate, this study examined variation in wintertime temperature and snowfall totals throughout the Midwest and Tennessee Valley regions of the USA during the top ten most positive and negative AO winters. In addition, this study analyzed atmospheric parameters corresponding to surface weather observations for the same time periods using NCEP-NCAR reanalysis composite maps.

Through the use of independent samples t-tests, it was determined that during the top ten most positive and negative AO winters, the AO has a significant effect on wintertime temperature and to some degree snowfall totals for the Midwest and especially Tennessee Valley regions of the USA. Results from the independent samples t-tests indicate that there is a significant difference between the top ten most negative AO wintertime temperatures and mean wintertime temperatures for nine of the eleven locations in the study area. In comparison, only eight of the eleven locations experienced a significant difference between the most positive AO wintertime temperatures and mean wintertime temperatures. With respect to snowfall, four of the eleven locations experienced a significant difference between the most negative AO wintertime snowfall and mean wintertime snowfall. In comparison, none of the locations in the study area experienced a significant difference between the most positive AO wintertime snowfall and mean wintertime snowfall. These results indicate that the top ten most negative AO winters have a greater overall effect on wintertime temperature and snowfall amounts than the top ten most positive AO winters for the Midwest and Tennessee Valley regions.

These results also determined that well below average wintertime temperatures and above average snowfall occur during the most negative AO winters across the Midwest and Tennessee Valley regions. In contrast, well above average wintertime temperatures and below average snowfall occur during the most positive AO winters. A Pearson Correlation was used to determine that there is a significant positive correlation between AO values and cities mean wintertime temperatures. Specifically, increases in the AO value causes temperature to increase whereas, decreases in the AO value result in a subsequent drop in temperature. In addition, the Pearson Correlation was used to determine that there is a significant negative correlation between AO values and cities mean wintertime snowfall. In particular, increases in the AO value causes snowfall totals to decrease whereas, decreases in the AO value results in a subsequent increase in snowfall totals.

NCEP-NCAR reanalysis composite maps were created and analyzed to determine variation in middle and upper tropospheric parameters as well as upper stratospheric parameters during the top ten most positive and negative AO winters. In addition, these maps were created to help visualize the atmospheric dynamics behind strong phases of the AO and its associated effects on wintertime temperature and snowfall throughout the Midwest and Tennessee Valley regions of the USA. Through the examination of 500 mb GPH anomalies it can be determined that the Midwest and Tennessee Valley regions experience well below normal heights during the most negative AO winters and above normal heights during the most positive AO winters. The 50 mb GPH anomalies show that during the most negative AO winters the Arctic region experiences well above normal heights. In contrast, the most positive AO winters result in well below normal GPH across the same region at the 50 mb level. Through the analysis of 300 mb GPH fields it can be determined that the polar jet stream is displaced further south than normal during the most negative AO winters, thus exposing the Midwest and Tennessee Valley regions to more frequent intrusions of Arctic airmasses than typical. In contrast, the mean positioning of the polar jet stream is further north during the most positive AO winters therefore, sparing the Midwest and Tennessee Valley regions from the more intense Arctic airmasses. The 500 mb vector wind parameter shows that the polar vortex was weaker and further south during the most negative AO winters and stronger and further north during the most positive AO winters. The position of the polar vortex and its associated cyclonic flow (jet stream) has a major influence on the amount of Arctic air a particular region is subject to. Lastly, the SAT anomaly map shows that the Midwest and Tennessee Valley regions experience well below normal temperatures during the most negative AO winters and above normal temperatures during the most positive AO winters.

Future Studies

A future study that may extend this study involves the examination of the synoptic and mesoscale dynamics behind the opposing phases of the strong AO. This study determined that the negative AO is much more significant than the positive AO. However, the causes behind this phenomenon have yet to be revealed. It would beneficial research to uncover the atmospheric processes that are responsible for the varying strengths in alternating phases of the AO. If possible, this study may help to increase the scientific community's understanding of the life cycle of the AO, consequently leading to more accurate long-range forecasts. In addition, the AO appears to experience low-frequency climate variability that may be associated with other teleconnections. It would be essential research to examine the potential influence of various teleconnections on the life cycle of the AO. If possible, this research may help atmospheric scientists more accurately predict the future behavior of the AO, which could greatly reduce overall forecast error.

Who Might be Interested in This Study?

The strong AO has a significant impact on wintertime climate for certain regions the earth, especially the Midwest and Tennessee Valley regions. Given the potential for increased forecasting accuracy through the application of the AO index, certain groups of people may find this study especially useful. There are various groups and organizations that rely on daily weather forecasts to effectively plan and execute specific job duties. Examples of a few of these companies and professions that may benefit from this study are: utility companies, city planners and farmers. Utility companies require knowledge of heating and cooling degree days to understand the amount of energy consumption required to heat and cool buildings. City planners require knowledge of climate to determine appropriate infrastructure necessary for different regions. Farmers rely heavily on forecasting to determine the length of growing seasons throughout different regions, as well as ideal times to plant and harvest various crops.

Final Remarks

This research filled a hole in literature for the Midwest and Tennessee Valley regions. In addition to the known effects of the AO on wintertime temperatures in the northeast and southeast USA, this study determined that the wintertime AO has a significant impact on both atmospheric conditions and sensible weather across much of the Midwest and Tennessee Valley regions. In these regions, the utilization of the AO as a fundamental tool for short and long-range forecasting will be useful to meteorologists and climatologists attempting to produce the most accurate regional weather forecasts. Meteorologists create Numerical Weather Prediction (NWP) models by writing complex algorithms (calculations) consisting of several atmospheric variables, which when run through a computer, predict how current weather will appear in the future. If meteorologists were to use the AO index as a primary variable for their NWP model, it may help to increase the accuracy of forecasting for certain regions of the earth, specifically the Midwest and Tennessee Valley regions.

References

Abramyan, I. and Vaughan, L. 2014. “Analysis of Negative Arctic Oscillation (AO) Values and the Relationship to Southeast U.S. Cold Air Outbreaks.” *South Carolina Department of Natural Resource.*

Ambaum, M. H. P., B. J. Hoskins, and D. B. Stephenson. 2001. "Arctic Oscillation Or North Atlantic Oscillation?" *Journal of Climate* 14 (16): 3495-3507.

Black, R. X. and B. A. McDaniel. 2007. "The Dynamics of Northern Hemisphere Stratospheric Final Warming Events." *Journal of the Atmospheric Sciences* 64 (8): 2932-2946.

Climate Prediction Center (CPC). 2013. “Teleconnection Introduction.” Last modified May 8, 2008, accessed August 28, 2013, http://www.cpc.ncep.noaa.gov/data/teledoc/teleintro.shtml.

Deser, C. 2000. "On the Teleconnectivity of the 'Arctic Oscillation'." *Geophysical Research Letters* 27 (6): 779-782.

Earth System Research Laboratory (ESRL). 2014. Last modified May, 2014, accessed May, 2013, http://www.esrl.noaa.gov/psd/cgi-bin/data/composites/printpage.pl.

Hitchcock, P., T. G. Shepherd, and G. L. Manney. 2013. "Statistical Characterization of Arctic Polar-Night Jet Oscillation Events." *Journal of Climate* 26 (6): 2096-2116.

Hodges G. 2000. The new cold war. Stalking arctic climate change by submarine. National Geographic, March, 30–41

Hurrell, J. W. 1995. "Decadal Trends in the North Atlantic Oscillation: Regional Temperatures and Precipitation." *Science* 269 (5224): 676-679.

Limpasuvan, V., D. W. J. Thompson, and D. L. Hartmann. 2004. The life cycle of the Northern Hemisphere sudden stratospheric warmings. *Journal of Climate* 17, no. 13: 2584-2596.

National Snow & Ice Data Center (NSIDC). 2014. “Patterns in Arctic Weather and Climate.” Last modified 2014, accessed September 15, 2012, https://nsidc.org/cryosphere/arctic-meteorology/weather_climate_patterns.html

Newman, M., and G. P. Compo, and M. A. Alexander. 2003. "ENSO-Forced Variability of the Pacific Decadal Oscillation." *Journal of Climate* 16 (23): 3853-3857.

Pidwirny, M. 2011. "Koppen Climate Classification System.", http://www.eoearth.org/view/article/162263/

Pozo-Vazquez D, and Esteban-Parra MJ, and Rodrigo FS, and Castro-Diez Y. 2001. A study of NAO variability and its possible nonlinear influences on European surface temperature. *Climate Dynamics* 17*, no.* 9:701– 715

Shabbar, A. and B. Bonsal. 2003. "An Assessment of Changes in Winter Cold and Warm Spells Over Canada." *Natural Hazards* 29 (2): 173-188.

Statistics Glossary. 2014. “Independent Sample t-test.” Last accessed February, 2014, http://www.stats.gla.ac.uk/glossary/?q=node/355

———. 2004. "Associations between Low Frequency Variability Modes and Winter Temperature s in Canada." *Atmosphere - Ocean* 42 (2): 127-140.

Tanaka, H. L. and H. Tokinaga. 2002. "Baroclinic Instability in High Latitudes Induced by Polar Vortex: A Connection to the Arctic Oscillation." *Journal of the Atmospheric Sciences* 59 (1): 69-82.

Thompson, D. W. J., and M. P. Baldwin, and J. M. Wallace. 2002. "Stratospheric Connection to Northern Hemisphere Wintertime Weather: Implications for Prediction." *Journal of Climate* 15 (12): 1421-1428.

Thompson, D. W. J. and J. M. Wallace. 1998. "The Arctic Oscillation Signature in the Wintertime Geopotential Height and Temperature Fields." *Geophysical Research Letters* 25 (9): 1297-1300.

Weather Warehouse. 2014. Last modified May 31, 2014, accessed May, 2013, http://weather-warehouse.com/WeatherHistoryListing/monthlyWeatherDataStart.html.

Wettstein, J. J. and L. O. Mearns. 2002. "The Influence of the North Atlantic-Arctic Oscillation on Mean, Variance, and s of Temperature in the Northeastern United States and Canada." *Journal of Climate* 15 (24): 3586-3600.

Wu, A., W. W. Hsieh, A. Shabbar, G. J. Boer, and F. W. Zwiers. 2006. "The Nonlinear Association between the Arctic Oscillation and North American Winter Climate." *Climate Dynamics* 26 (7-8): 865-879.