AN ABSTRACT OF THE THESIS OF

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Title:

IDENTIFYING OSCILLATIONS AND TELECONNECTIONS THAT MAY IMPACT SNOWFALL IN NORTHEAST AND EAST CENTRAL KANSAS 1951-2011: A REGIONAL CLIMATE ANALYSIS AND STUDY ON PREDICTION POTENTIAL

Abstract approved:____

Several oscillations/variations in oceanic and atmospheric circulation patterns are known to influence climate over North America. The most prominent oscillations affecting the conterminous Unites States are the El Nino-Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), the Arctic Oscillation (AO), the Atlantic Multidecadal Oscillation (AMO) and the Pacific Decadal Oscillation (PDO). Limited research has been conducted on the effects of these prominent oscillations on yearly and decadal-scale winter climate over the central portion of the United States. The objective of this study was to attempt to identify which oscillations and teleconnections impacted snowfall over northeast and east central Kansas over the time period 1951-2011. For the purpose of this study, three different calculations of winter snowfall were computed from 1951-2011 for northeast and east central Kansas. Daily station data from the Global Historical Climatology Network were used to derive an October-April time series of 1) frequencies of snowfall events with a trace or more of accumulation, 2) frequencies of snowfall events with six inches or more of accumulation, and 3) snowfall totals. Correlations between the prominent oscillations and these three time series were then investigated to determine if the oscillations influence/impact snowfall patterns within northeast and east central Kansas. Statistical analyses and spatial correlations between the snowfall datasets and oscillations/teleconnections indices revealed ENSO, NAO and PDO may impact snowfall in northeast and east central Kansas.

IDENTIFYING OSCILLATIONS AND TELECONNECTIONS THAT MAY IMPACT SNOWFALL IN NORTHEAST AND EAST CENTRAL KANSAS 1951-2011:

A REGIONAL CLIMATE ANALYSIS AND STUDY ON PREDICTION POTENTIAL

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Approved by the Department Chair

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Introduction

Predictive climate research conducted on snowfall in the United States has focused primarily on the role played by oscillations and teleconnections present in a given geographic area leading up to, and during, a snowfall season. Oscillations are shifts in positions of various high and low pressure systems across the planet that in climate terms are usually defined with indices where a single numerically-derived number represents the distribution of temperature and pressure over a wide ocean area (NOAA, 2013). Similarly, two defined locations which experience a ridging and troughing, or see-saw like pressure behavior pattern with each other at some height in the troposphere are defined as being teleconnected. The impacts that the oscillations and teleconnections have on weather and climate patterns across the globe are a component of the interactions between the atmosphere, hydrosphere, cryosphere, lithosphere and biosphere which are collectively referred to as ‘internal forcings’ and dramatically influence, or force, the global weather and climate, including snowfall patterns for North America.

Multiple oscillations and teleconnections have been linked to anomalous snowfall over North America, as well as, for specific regions across the conterminous United States. The El Nino-Southern Oscillation (ENSO), which includes both the El Nino and La Nina phenomena, have been associated with large scale effects on climate across North America and the United States while other oscillations tend to have more direct impacts at regional scales. The Pacific Decadal Oscillation (PDO), which forces snowfall patterns for the Pacific Northwest and the North Atlantic Oscillation (NAO), which is thought to heavily influence snowfall in the eastern United States, are two such prominent oscillations. Other regions of the United States, such as the central portion, have seen less inquiry into which oscillations and teleconnections are responsible for anomalous snowfall. Research specifically pertaining to snowfall in northeast and east central Kansas and its relationship to oscillations and teleconnections is limited. Likewise, data on the fall and winter atmospheric conditions, which may promote or hinder snowfall for the region is even less well understood.

Construction and analysis of a northeast and east central Kansas snowfall index for a time period spanning October through April 1951-2011 based on Global Historical Climatology Network-Daily (GHCND) datasets for northeast and east central Kansas (Figure 1) has the potential to further our understanding of the reasons for historical snowfall variations and possibly lead to a degree of climate prediction potential for the area of interest. Research conducted by Seager et al. (2010) on anomalous snowfall in the central and eastern United States in the winter of 2009/10 serves as the foundation for this study as their findings identified ENSO and the NAO as the main oscillations contributing to snowfall across large portions of the central/eastern United States, including, the area of interest.

Several oscillations and teleconnections have been identified, which are known to have a marked influence on weather and climate patterns over North America. Among the most notable are the El Nino-Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), the Arctic Oscillation (AO), the Atlantic Multidecadal Oscillation (AMO) and the Pacific Decadal Oscillation (PDO).

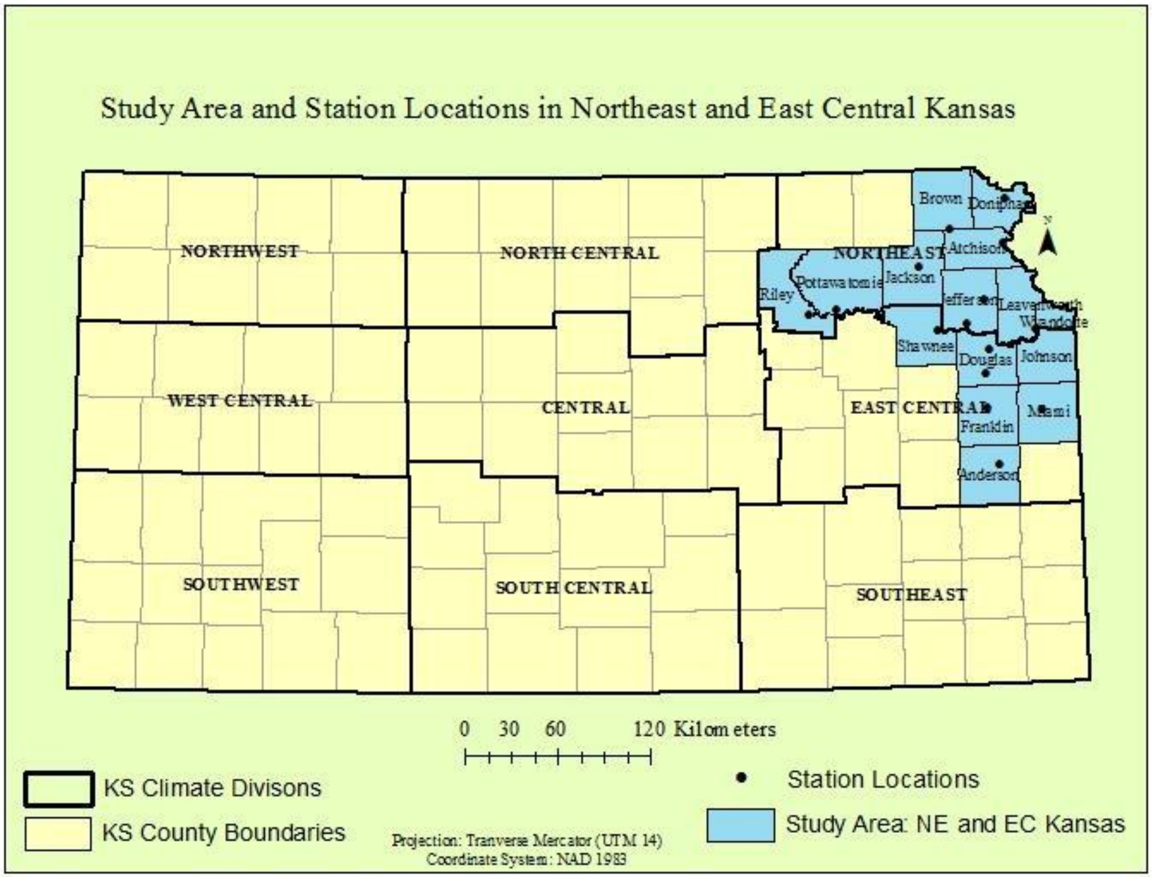

Figure 1: Stations were used for construction of snowfall index from 1951-2011. Climate Divisions are defined by the National Oceanic and Atmospheric Administration (NOAA)

The Southern Oscillation, or SO, is defined as the normalized difference in surface pressure between Tahiti, French Polynesia and Darwin, Australia and is measured by the strength of the trade winds moving from regions of high to low pressure. El Nino and La Nina events are so intricately linked to the SO that much of the scientific community refer to this full range of variability as the El Nino-Southern Oscillation Cycle or ENSO for short. A low SO index is defined by small pressure differences and thereby weak trade winds which are connected to the warming of surface layers of the eastern and central Pacific Ocean. This combination of events is known as El Nino and is linked to unusually low sea level pressure in the southern Tropical Pacific and unusually high sea level pressure in the western Pacific and Indian oceans. Conversely, a high SO index is related to unusually high pressure east of the international dateline, unusually low pressures west of the international dateline, stronger than normal trade winds and anomalously cold equatorial Pacific sea surface temperatures (SSTs). Together, these conditions are known as a La Niña event (TAO, 2013).

The timing of the ENSO cycle is irregular and usually occurs at intervals of 2-7 years and on average about once every 3-4 years, with a duration of 12-18 months, although quasi-biennial (QB) (2-2.5 year) and Low Frequency (LF) interannual sub-cycle components are also present (Allan, Lindesay and Reason, 1996; Ribera and Mann, 2003). Scientific inquiry has revealed much about the ENSO phenomenon, including the extremes of El Nino and La Nina, physical processes, magnitude, timing of onset and cessation, duration, spatial extent and its relationship to the seasonal cycle (Philander, 1992; Allan et al., 1996; Glantz, 2001). Likewise, continuing research may reveal how natural decadal-multidecadal modes in the climate system promote lower frequency modulations of ENSO characteristics (Navarra, 1999). For example, a 9-13 year quasi-decadal signal may be the cause of ‘protracted’ La Nina and El Nino episodes (Allan et al., 2003), while the LF component of ENSO may be largely modulated by the Pacific Decadal Oscillation (PDO) and the Interdecadal Pacific Oscillation (IPO) (Mantua and Hare, 2002). While much has been revealed about ENSO through decades of research, it is important to note that no two El Nino or La Nina events are alike and there is still much to learn about the cycle (Larkin and Harrison, 2002).

Pressure differences between centers of action over Iceland and the Azores define the North Atlantic Oscillation (NAO). In calculating the pressure differences which define the NAO, data from Stykkisholmur Iceland are compared to more southerly centers of action at or near the Azores Archipelago, situated in the North Atlantic Ocean. Ponta Del Garda was used by Rogers (1997) to define the southern zone of action while Lisbon, Portugal was used by Hurrell (1995) and Gibraltar by Jones, Jonsson and Wheeler (1997). Differences in pressure between the two locations, and measured between December and March (winter season), result in an NAO index, which determines the phase, positive or negative, of the oscillation. A stronger than usual subtropical high coupled with a deeper than normal Icelandic Low is characteristic of the *positive* phase of the NAO while the *negative* phase is defined by a weak subtropical high and a weak Icelandic Low. The increased pressure differences between the two centers of action associated with the positive phase of the NAO result in strong, frequent winter storms which track in a more northerly path across the North Atlantic Ocean. In contrast, infrequent and weaker winter storms track in a more southerly path across the North Atlantic during the negative phase of the NAO. Comparisons of the SO against the NAO have shown the NAO to be largely an atmospheric phenomenon which operates on a much longer time scale with changes in phases usually occurring on the order of decades. The phases of the NAO are shown to have a strong influence on winter weather and climate for eastern North America and Western Europe. The positive phase brings warm and possibly wet winters for the eastern portions of the United States and for Western Europe while more cold air invasions are common for both locations during the negative phase (Hurrell, Kushnir, Visbeck and Ottersen, 2003).

The Arctic Oscillation (AO) is defined as an index, which compares the pressure differences of the Arctic polar region with those at 45° N. Like other oscillations, the pressure differences are interpreted as phases. When higher than normal pressures are present at the poles and lower than normal at 45° N the AO is said to be in its negative phase. Opposite conditions are characteristic of the positive phase of the AO. The high pressures at mid-latitudes associated with the positive phase of the AO result in less extensive polar and arctic cold air outbursts over much of North America. Alaska and northwest Europe typically experience wetter winters during this phase as cyclonic storms are steered on a more northerly track while warmer winter conditions usually persist for the United States east of the Rocky Mountains (Thompson and Wallace, 1998). Moreover, the AO and NAO have been described as synonyms for one another and are often shown to describe the same variability, rather than different patterns of variability. The difference between the two oscillations lies in whether an annular mode with strong teleconnections in the Atlantic sector is being described or if the variability is highlighting a regional pattern controlled by the Atlantic sector processes. Early researchers collectively referred to the AO and the NAO as the Northern Hemisphere Index Cycle (Wallace and Gutzler, 1981).

The Atlantic Multidecadal Oscillation (AMO) is recognized by changes in sea surface temperatures in the North Atlantic Ocean (Schlesinger, 1994). The temperature fluctuations are long-duration and occur as a warm or cool phase, each of which operates on 20-40 year intervals with the entire cycle of the AMO occurring over ~70 years (Guan and Nigam, 2009). In its extreme, the AMO rises or falls by ~.5 degrees Celsius (1 degree Fahrenheit) and the SSTs from the equator to Greenland shift in unison across this portion of the Atlantic Ocean. Some evidence suggests portions of the North Pacific are also affected. The variation of SSTs associated with the AMO are correlated with changes in air temperatures and precipitation over much of the Northern Hemisphere, particularly, Europe and North America. Moreover, associations have been made between the frequency of North American droughts and Atlantic hurricanes (http://www.aoml.noaa.gov/phod/amo_faq.php#faq_1).

The Pacific Decadal Oscillation (PDO) also known as the Pacific Decadal Variation (PDV) and the Interdecadal Pacific Oscillation (IPO) behaves in a long-duration El Niño-like pattern on a time scale of decades. Mantua, Hare, Zhang, Wallace and Francis (1997) and Zhang, Wallace and Battisti (1997) derived a system to define the PDO largely based on an index which measures monthly SST anomalies north of 20° N in the Pacific Ocean. More specifically, the PDO is represented by the shift in SST which occurs approximately every 20-30 years. The PDO is considered to be in its negative or cool phase when positive SST anomalies occur across the northwest Pacific Ocean while negative SSTs are present in the tropical zone. Conversely, the PDO is in its positive or warm phase when SST anomalies are negative in the northwest Pacific and positive across the eastern tropical Pacific Ocean. The changes in cool and warm waters in portions of the Pacific Ocean characterized by the PDO influence the atmosphere in numerous ways and thereby climate predominately across the western portion of the United States. Studies by Mantua et al. (1997) and Minobe (1997) suggest only two full cycles of the PDO have occurred over the last 100 years. A cool phase of the PDO occurred from 1890 to 1924 and from 1947 to 1976 while a warm cycle was present from 1925 to1946 and from 1977 to the late 1990s. Research suggests a change to the cool phase began around the turn of the late 1990s or early 2000s. The cool phase of the PDO has been associated with sustained drought in the western portion of the United States, particularly the American Southwest.

The purpose of this study is to reconstruct a 60 year daily snowfall index for northeast and east central Kansas from historical records which can be used for identifying oscillations and teleconnections forcing/influencing snowfall patterns over the study area. Questions to be answered include: 1) Among the various oscillations and teleconnections influencing weather and climate over the conterminous United States, which resulted in forcing more/less snowfall across the study area over the past 60 years? 2) Have snowfall patterns across the study area changed in relation to a) the number of days that snow fell or “frequency”, b) the number of events ≥6 inches or c) with overall snowfall totals?

The goals of this research are to help encourage further snowfall climatology research for the central portion of the United States through the construction of a northeast and east central Kansas snowfall dataset and by providing a method for identifying oscillations and teleconnections embedded in historical snow data which have a prominent impact on snowfall across the study area.

Methods

Data Acquisition

Global Historical Climatology Network-Daily (GHCND) data were downloaded from the National Oceanic and Atmospheric Administration's (NOAA) National Climatic Data Center (http://www.ncdc.noaa.gov/cdo-web/). The Climate Data Online page (http://www.ncdc.noaa.gov/cdo-web/#t=secondTabLink) of the NCDC site lists two search criteria under Search Data: 1) Enter search term(s) for Station name or Location; and 2) Select a data set/product. Cities and towns existing in northeast and east central Kansas, as defined by the NCDC (http://www.ncdc.noaa.gov/img/climate/research/climate-division-map1.jpg), were entered into the search engine. Daily GHCND data was selected for the second search criteria as a daily winter snowfall index for the months of October-April (ONDJFMA) was required for subsequent snowfall analysis. The time span of 1951-2011 was chosen as the period of record for this research because far too many snowfall data gaps were present in most records available for the study area prior to 1951. Once the daily climate datasets were available they were downloaded from NOAA in Portable Document Form (PDF). Initially, station climate data from the following cities and towns of northeast and east-central Kansas were downloaded due to their availability within the NCDC database: Atchison; Blue Rapids; Bonner Springs; Concordia; Council Grove; Edwardsville; Emporia; Hiawatha; Holton; Horton; Kansas City; Lawrence; Manhattan; Marysville; Olathe; Ottawa; Paola; Perry Lake; Topeka; Troy; Valley Falls; and Wamego. To filter the most complete datasets out of those downloaded, a threshold of 50 percent was defined. The 50 percent threshold eliminated any dataset needing augmentation from nearby stations for one or more days on more than half of the snowfall years (ONDJFMA) over the 60 year period. Completion of the screening of the 23 available and downloaded stations/locations yielded only 5 stations within or at the threshold. Holton, KS was added into the list despite 62 percent of the snowfall years needing at least one day of augmentation as this station had the next most complete snowfall year data and an initial attempt to reconstruct at least six stations was desired. Those stations/sites meeting or exceeding at least the 50 percent threshold included: Atchison; Lawrence; Manhattan; Ottawa; and Topeka. Construction of additional stations was attempted with Wamego, Olathe, Hiawatha, Emporia and Leavenworth datasets (the next most complete stations) but gaps in daily snowfall climate data exceeding even the 62 percent threshold of Holton were present and these stations were later removed from the index. A portion of those stations exceeding the threshold aided in the augmentation process for the final six primary stations (and later four primary stations) of Atchison, Lawrence, Holton, Manhattan, Ottawa and Topeka.

Once the primary stations were identified, a second round of NCDC queries was performed to locate the stations in closest proximity to each of the initial stations. This method was repeated for each station until a suitable dataset needed for daily record gap augmentation was located.

Snowfall Index

Microsoft Excel was utilized in the creation of the northeast and east central Kansas snowfall index. Individual columns were labeled as follows: Winter Year (ONDJFMA); Snowfall Frequency; Large Events ≥6 Inches (~152 mm); Snowfall Total for ONDJFMA (Inches/mm); Station ID; and Augmentation. Additionally, a section was reserved at the bottom of each primary station's Excel sheet for an Average section. This area allowed for calculating and recording of mean, median and mode for decadal and 60 year sums of snowfall frequency, events and overall totals.

Augmentation

Daily climate data for stations located in northeast and east central Kansas for the time period selected (1951-2011) often lacked several days or sometimes entire months of data. Missing data can cause a winter year to appear to have unusually low snowfall amounts after monthly totals have been added together for the index. In order to correct unrepresentative winter climate data, filling in of climate data gaps, or augmentation, was performed with data collected from nearby stations. During the augmentation process, climate data from the nearest station was used to fill in identical dates missing from the chosen dataset. This process was repeated for each station and if the nearest station also lacked the desired daily climate data, then the next closest station was selected for the continuation of the augmenting process. No augmentation datasets were used for more than one primary station in order to avoid biasing any averages. Augmentation data was recorded within a unique column in the Excel snowfall index. Primary stations were augmented with data from secondary stations (see Table 1). Atchison, Holton, Lawrence, Manhattan, Ottawa and Topeka sites were designated the "primary stations" and any site used to fill in data gaps at each of these stations was defined as a "secondary station."

Primary Stations	Total Snowfall Days for 60 Year Period	Days Augmented for 60 Year Period	Percent of Station Snowfall Data Augmented	Stations Used for Augmentation
Atchison	12,720	441	3.46%	Troy, Kansas
Holton	12,720	444	3.49%	Horton, Kansas; Oskaloosa; Kansas; Valley Falls, Kansas
Lawrence	12,720	397	3.12%	Lawrence, Kansas; Bonner Springs, Kansas
Manhattan	12,720	173	1.36%	Wamego, Kansas
Topeka	12,720	63	0.49%	Perry Lake, Kansas
Ottawa	12,720	230	1.80%	Paola, Kansas; Garnett, Kansas

Table 1: Station Augmentation Summary

Frequency of Snowfall

One goal of the northeast and east central Kansas dataset creation was to create a simple tally or frequency count of how many times snow fell at each station for a given winter year for the time period of 1951-2011. For the purpose of this study, a tally was registered anytime a trace amount or larger was recorded in the GHCND datasets. The column labeled Precipitation, with the subtitles of At Observation Time and Snow, ice pellets, hail, ice on ground (in) located within the GHCND datasets was used in determining when snowfall occurred. For the defined snowfall months of ONDJFMA, any measurement recorded in this column, including trace amounts, were considered part of the snowfall frequency count and the total snowfall for the winter year if the corresponding temperature (°F) at time of observation was less than 45° Fahrenheit (Durre, Menne, Gleason, Houston, and Vose, 2010).

Snowfall Events

The National Weather Service (NWS) defines a snowfall "Event" for northeast and east central Kansas as snowstorms with six inches (~152 mm) of accumulation or more (National Weather Service, 2010). The construction of the snowfall index also included a column devoted to tallying snowfall "Events." This process proved especially important when compensating for non-first order stations which typically have undercounts with respect to small snowfall episodes. Events, on the other hand, are much harder for observers to miss and are therefore more likely to be available in the climate records (Daly, Gibson, Taylor, Doggett and Smith, 2007; Burnette and Stahle, 2013).

Snowfall Totals

A third column was created in the Excel file for snowfall totals for the period 1951-2011. A snowfall total was determined for each station and for each snowfall year (ONDJFMA) within the spreadsheet. The totals were measured and recorded in both inches and millimeters.

Historical Observation (HOB) Tools

The Historical Observation (HOB) Tools are a collection of applications used for quality control, reconstruction, adjustment and analysis of historical weather observations (Burnette and Stahle, 2013). The Time Series and Spaghetti Plot tools were primarily used to develop visual displays of the snowfall index dataset for each of the stations as well as the station network average (see Appendix for each Time Series and Spaghetti Plot). The time series plots also depict slope and trends of data for snowfall frequency, events and totals as well as summary of statistics which includes the average (mean) of the plot, standard deviation, trend per year information and a slope test for significance. Probability notation, or P-value, was the statistical analysis used in each time series. The significance level was established as alpha value $\alpha=0.05$ (5%) or that a 5 percent chance existed that the null hypothesis, stating that no significant trend in snowfall was present, was rejected in error.

The six primary stations and their corresponding snowfall indices constructed on the Microsoft Excel spreadsheets had to be converted to tab-delimited.txt files in order to run properly in the HOB Tools software. Additionally, three of the primary stations had missing data for 2012 (2012 data was later removed from the analysis due to incomplete records at the time of data collection). These stations were flagged with “-99” as HOB Tools expects all columns to be complete when performing an analysis. A tab-delimited file can be created by clicking each primary station’s sheet, selecting “Save As,” then “Text (Tab delimited)” by “Save as type,” naming the file, and finally selecting “Save.” Once the snowfall data were converted to the proper-type file, the data were input into the respective tool within the HOB software. The Spaghetti Plot Tool created plot displays for Snowfall Frequency, Events and Totals for each of the six stations while the Time Series Tool plotted mean, variability and linear trend lines. For the construction of the Time Series, the six stations (and later four) were averaged together and run through HOB tools as a single file. Therefore, the Time Series analysis depicts variability and attempts to reveal temporal changes in the slope and trends of the data for the snowfall frequency, events and totals for the average of all six stations.

Historical Observing Metadata Repository (HOMR)

During early phases of spaghetti plot analysis it became visually apparent that two primary stations appeared to "flat-line" in terms of snowfall frequency when compared to the other four primary stations. The Holton spaghetti plot (Figure 2) revealed consistently lower counts and appeared to diminish in variability in relation to the rest of the network from the mid 1960s to approximately 1990 and then again from 2000 to 2011. Likewise, visual analysis of the Ottawa spaghetti plot (Figure 3) showed the same drop in snowfall frequency from the mid 1970s to 2011. These problematic decreases in snowfall frequency were further highlighted against the spike in overall network snowfall frequency during the 2010 snowfall months as Holton and Ottawa both remained low during this period.

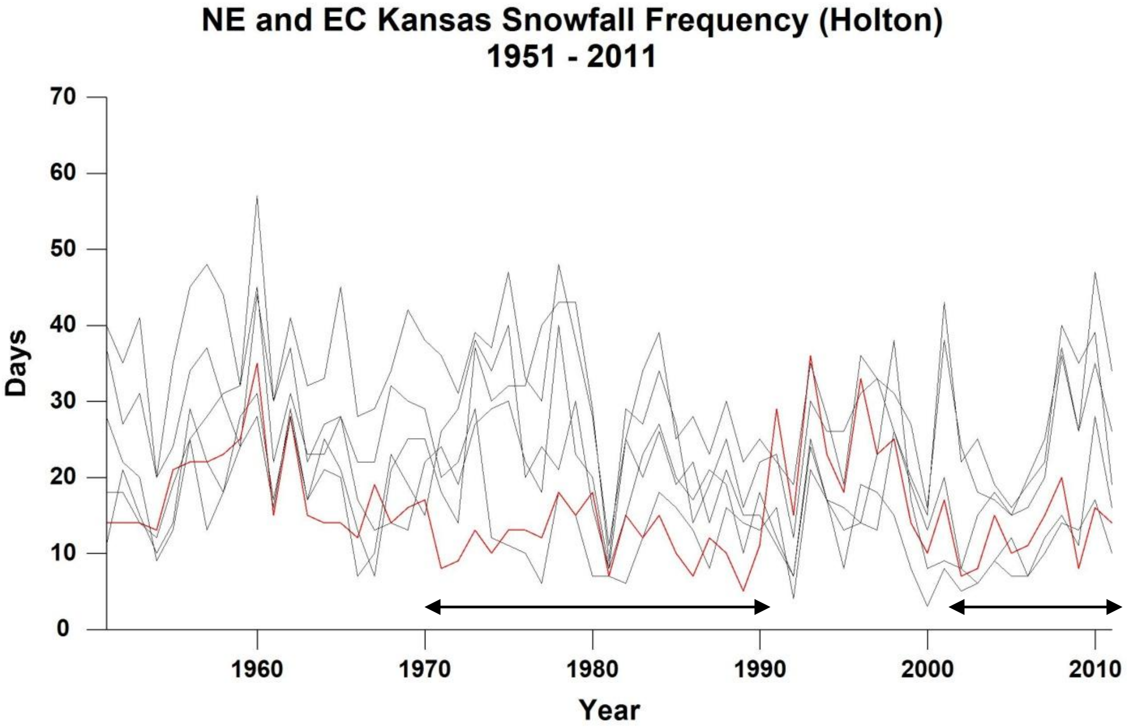

Figure 2: NE and EC Kansas Snowfall Frequency (Holton). Spaghetti plot which shows undercount issues with snowfall frequency when compared to the other stations. Each line represents an individual station with Holton highlighted in red. The visual ‘flat-line’ led to the need to search the Historical Observation Metadata Repository (HOMR) for data quality issues with the Holton station which may suggest snowfall undercounts. The Wilcoxon Signed Rank Sum test revealed a significant bias in the snowfall frequency counts for this stations which ultimately led to station removal. Black arrows indicate the ‘flat-line.’

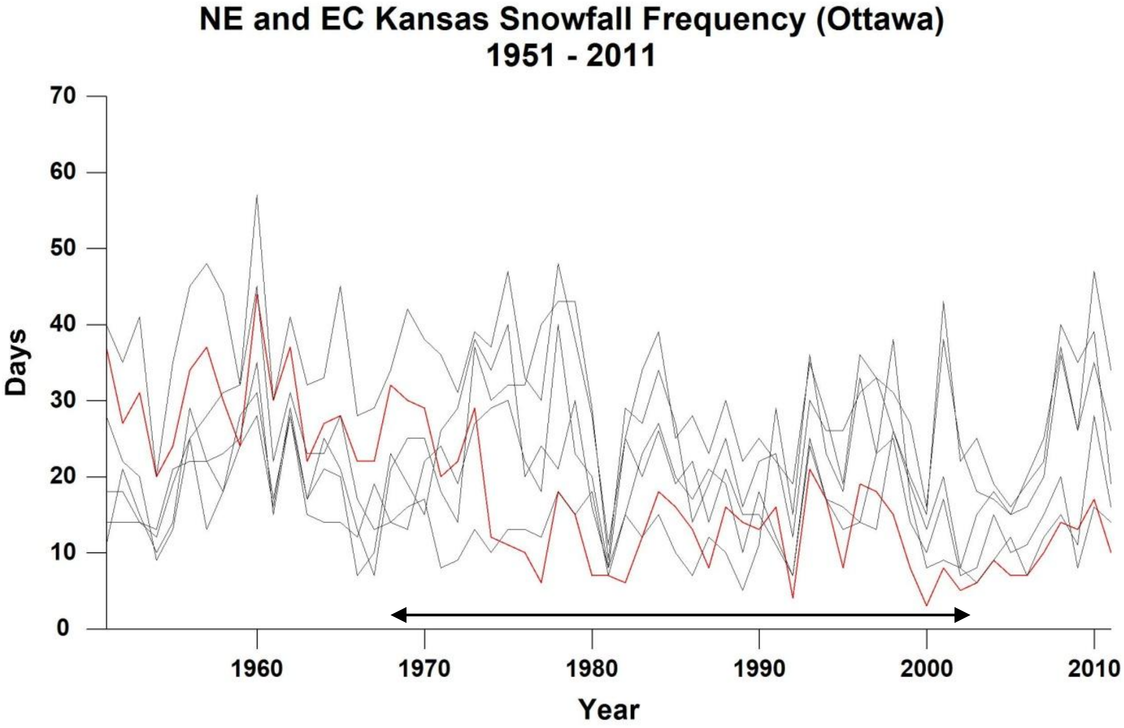

Figure 3: NE and EC Kansas Snowfall Frequency (Ottawa). Spaghetti plot which shows undercount issues with snowfall frequency when compared to the other stations. Each line represents an individual station with Ottawa highlighted in red. The visual ‘flat-line’ led to the need to search the Historical Observation Metadata Repository (HOMR) for data quality issues with the Ottawa station which may suggest snowfall undercounts. The Wilcoxon Signed Rank Sum test revealed a significant bias in the snowfall frequency counts for this station which ultimately led to station removal. Black arrow indicates the ‘flat-line.’

In order to determine if the decreases in snowfall frequency for Holton and Ottawa were due to spatial variability between stations or because of data quality and undercount issues, metadata queries for each of the six stations were conducted from NOAA’s Historical Observing Metadata Repository (HOMR). This site is the National Climatic Data Center’s (NCDC) database of integrated station history that provides *in situ* metadata for climate research. In short, this metadata provided information regarding any potential changes in the stations which may have coincided with shifts towards lower snowfall frequencies. Shifts towards lower snowfall frequencies would suggest a change in stations may have biased the snowfall data.

In addition to Holton and Ottawa, metadata were reviewed for Atchison, Lawrence, Manhattan and Topeka. The review was conducted by inserting the GHCND unique station identification (I.e USW00013996 for Topeka) into the search engine of HOMR which then displayed results for each location. The results from a HOMR query show timelines of the specified station and any gaps in data are immediately identifiable.

Wilcoxon Signed Rank Test

Potential issues with undercount in the Holton and Ottawa datasets resulted in the need to create a second set of averages for snowfall frequency, events and totals from only the stations which did not have metadata issues as confirmed by HOMR queries. The second set of averages, which consisted of data from Atchison, Lawrence, Manhattan and Topeka, were then compared statistically against the original six station averages which included the four stations mentioned above plus Holton and Ottawa. The General Public License statistical software program R was used to perform the Wilcoxon Signed Rank test to quantitatively validate the quality of snowfall data between the six and four station average datasets. The Wilcoxon Signed Rank analysis was designed as a two-tailed test and allowed for a paired difference investigation between these data. To ensure individual station data were not significantly biasing regional averages, this test was used to reveal stations which may have snowfall undercount issues, a problem commonly associated with second order stations.

P-value, or probability notation was the statistical analysis used for the test as a null hypothesis was established which stated the two population sets were not statistically different from one another. To allow for a decision between the null hypothesis and the alternative hypothesis (stating the two populations are statistically different) the alpha value $\alpha=0.05$ (5%) was set as the level of significance. If the p-value was less than this limit the results were considered to be statistically significant and the null hypothesis that they were not significantly different could be rejected. The alpha value essentially fixes the probability threshold acceptable for rejecting the null hypothesis in error.

Tab-delimited text files containing the snowfall climate data for both the six and four station averages were constructed and ran through a statistical script built by Dr. Dorian Burnette of the University of Memphis specifically for R to compare stations which appeared to have the flat-line issue with snowfall data when compared to other stations in the network.

The four station averages for snowfall frequency, events and totals were placed in the R script next to the six station averages for the same snowfall data for two time periods, 1951-2011 and 1974-2011. The time period 1974-2011 reflects the metadata gaps for Holton and Ottawa stations and their respective low snowfall frequencies when compared to the entire network. The signed rank test revealed mixed results. Significant differences in portions of the snowfall datasets were detected in the snowfall frequency and snowfall total data, while no difference was detected in the snowfall event data between the four and six station averages. Two important concepts can be gleaned from these results: 1) Small snowfall episodes have been undercounted at second order stations which can lead to biased results; and 2) Undercount issues can potentially be mitigated in future snowfall analysis by focusing on snowfall events which are not significantly affected by undercount issues in relation to the entire network. The apparent undercount issues associated with Holton and Ottawa and the subsequent bias they create in two of the three snowfall datasets were justification for removing the two locations from the regional average and narrowing further analysis to only the four stations with averages which show more year-to-year variation and spikes in years known to be more active.

Wilcoxon Rank Sum Test and Steps in Climate

The Wilcoxon Rank Sum statistical analysis test was utilized to compare two separate 30-year climate observation time periods: 1951-1980 and 1981-2011. As precipitation does not typically behave in a normalized or bell curve-like fashion, the Wilcoxon Rank Sum (nonparametric test), was necessary since it does not assume a normal data distribution like a parametric test such as a T-test would. P-value, or probability notation was the statistical analysis used for the test as a null hypothesis was established, which stated the two population sets were not statistically different from one another. To allow for a decision between the null hypothesis and the alternative hypothesis (stating the two populations are statistically different) the alpha value $\alpha=0.05$ (5%) was set as the level of significance. If the p-value was less than this limit the results were considered to be significant and the null hypothesis was rejected. The alpha value fixed the acceptable probability that the null hypothesis was rejected in error.

Again, Tab-delimited text files containing the snowfall climate data for both the six and four station averages were constructed and run through a statistical script built by Dr. Dorian Burnette of the University of Memphis specifically for R to compare the two time periods. The purpose of comparing the two time periods was to look for median differences (while evaluating significance levels) in snowfall frequency, events and totals between the two datasets which may provide evidence of any step-like changes or behaviors in climate patterns that were visually apparent in the time series' constructed in HOB Tools. The Rank Sum test results were then compared against the Time Series' constructed in HOB Tools for periods 1951-2011, 1951-1980 and 1981-2011 to further investigate the visual step-like or partial low-frequency wave-like behavior around 1980 (Figure 4).

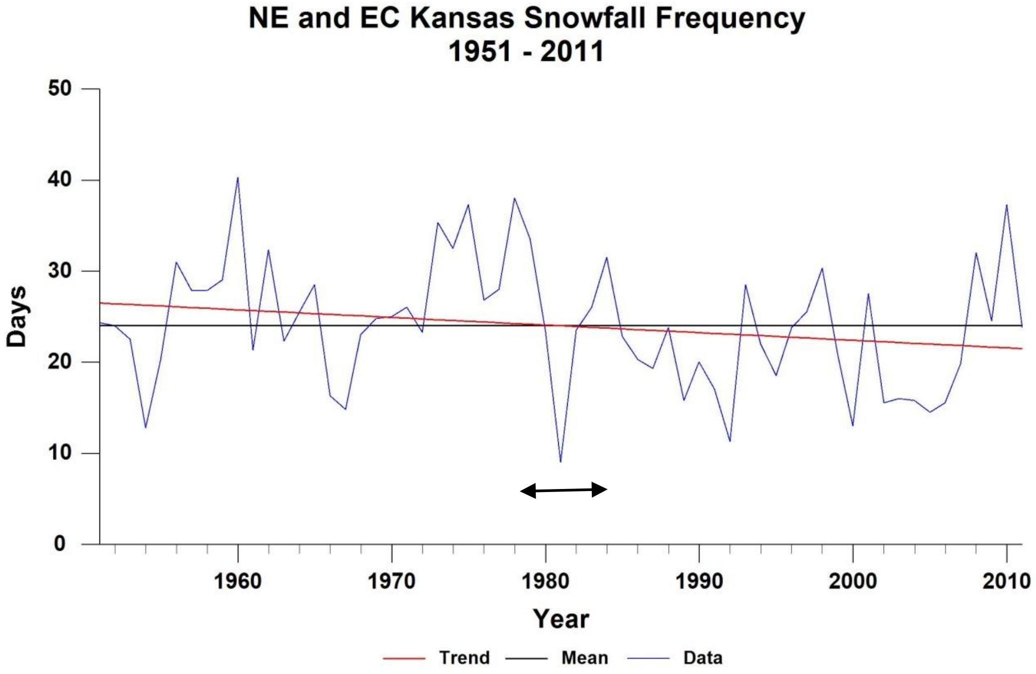

Figure 4: NE and EC Kansas Snowfall Frequency 1951-2011 (p=0.10)

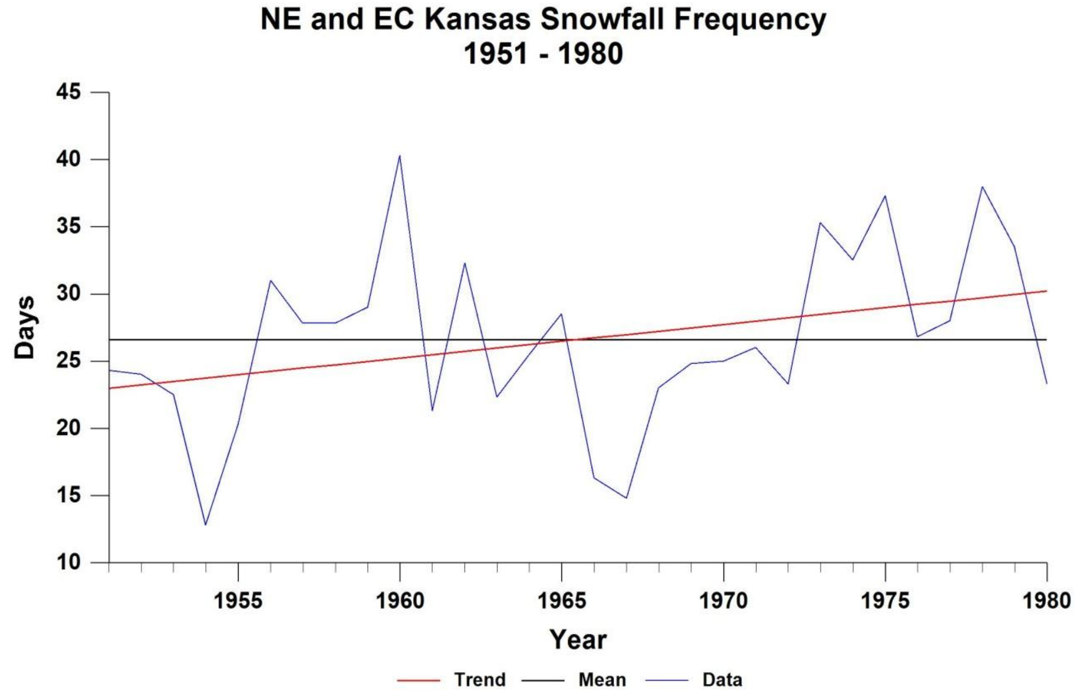

Figure 5: NE and EC Kansas Snowfall Frequency 1951-1980 (p=0.070)

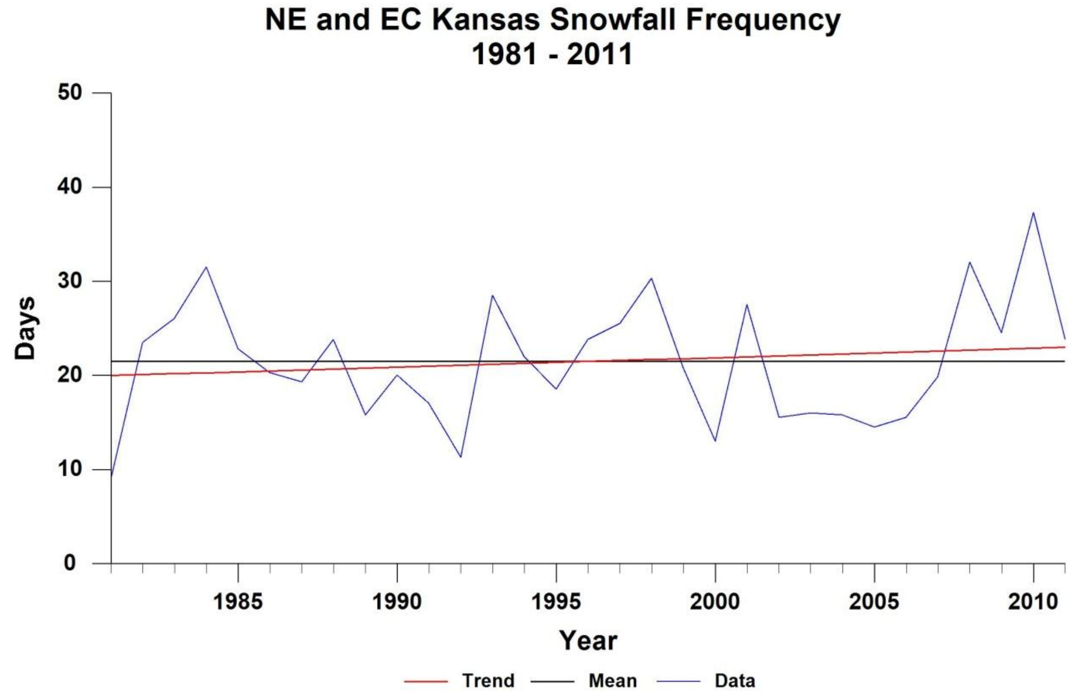

Figure 6**:** NE and EC Kansas Snowfall Frequency 1981-2011 (p=0.455)

When the 1951-2011 time series was broken into the two shorter time periods of 1951-1980 and 1981-2011, the decreasing trends in the longer time series was eliminated. Figures 5 & 6 both show increasing trends in snowfall values once the longer time series is separated into two sets. None of the time series analyses completed in HOB Tools for frequency, events or totals showed significant trends based on the predetermined alpha (α) value, but the visual displays, particularly around 1980, were compelling enough to justify performing the Wilcoxon Rank Sum statistical analyses between the two time periods for each snowfall variable. Trend significance levels are reported next to each time series figure which represents the four station average.

Initially, poor data related to snowfall undercounts for Holton and Ottawa was speculated to be affecting the averages and causing the decrease around 1980 and thereby affecting each time series plot. The removal of the Holton and Ottawa data to maximize quality in the final reconstructions and the subsequent Rank Sum analysis with the four station averages showed a weakened, but still present, step-like behavior around 1980 as the two time period observations were still shown to contain different values when compared to one another. This discovery eliminated speculation that the step-like pattern was strictly a data quality problem and led to the development of the hypothesis that an oscillation not previously considered may be present in the data which influences snowfall in northeast and east central Kansas. The Pacific Decadal Oscillation (PDO) as well as the Atlantic Multidecadal Oscillation each changed signs to positive phases around the 1980 period and are known to impact weather and climate over North America (Mantua et al., 1997; Minobe, 1997; Schlesinger, 1994; Guan and Nigam, 2009). The possible presence of additional oscillation signals in the data may indicate a complex combination of two or more atmospheric teleconnections present in the snowfall data around 1980 and may account for the changes detected between the two time periods.

Multitaper Spectral Analysis

Spectral analysis detects any periodicities in a time series by characterizing the frequency content of any signals embedded in the data. As a form of signal processing, spectral analysis attempts to detect and separate real signals, over random noise, found within a time series. Spectral analysis for this research focused on determining which oscillations and teleconnections the signals found within the time series represented. A spectral analysis can be performed in a variety of ways including the multitaper method (MTM). The MTM is a nonparametric (not dependent on the distribution of data) version of spectral analysis developed by David Thomson (Thomson, 1982). The multitaper version of spectral analysis is a technique that estimates the power spectrum of a dynamic and stochastic or random system. For the purpose of this study, a more robust method dealing specifically with climate was needed. The desired method, which makes assumptions about signal and noise more appropriate for climate studies, was developed by Mike Mann and Jonathan Lees (Mann and Lees, 1996) and was later converted into an executable program via modification of the Fortran code with the added ability to input data files from multiple other formats (largely used by the tree-ring community) by Lamont-Doherty Earth Observatory (LDEO) researcher Paul J. Krusic (LDEO, 2009). The resulting program is MtMcohere and is available from the LDEO Tree Ring Lab at: http://www.ldeo.columbia.edu/tree-ring-laboratory/resources/software.

The snowfall network averages for frequency, events and totals were converted into space-delimited files to provide a usable format for the MtMcohere program and were subsequently run through this version of the MTM spectral analysis on Windows XP or newer versions. In instrumental climate data, 3 tapers with a time-bandwidth parameter of 2 (3 x 2 pi tapers) is often the ideal setting to characterize distinct signals, or oscillations, within the data. Increasing the amount of tapers within spectral analysis yields a smoother spectral power which in turn defines the frequency content of the signal and thereby any periodicities in the data. MtMcohere generated a number of output files in text-file format after the snowfall data had been run through the program. The file of interest, labeled spec-robst.out, provided six columns of numbers. Column 1 referred to frequency, while column 2 represented spectral power and with column 3 indicating the null hypothesis. Columns 4, 5 and 6 corresponded with the confidence of the spectral signal being present at the 90 percent (p=0.10), 95 percent (p=0.05) and 99 percent (p=0.01) levels respectively. Spectral signatures and/or periodicities discovered embedded within the datasets at or above the 90 percent confidence level ($p\leq.010$) but not obtaining the 95 percent mark (p=0.05) were considered significant as this confidence level is often reported in similar research (Kunkel, Karl, Brooks, 2013).

Normalized Data

A normalized anomaly index, or data with a mean of zero, was needed for each of the oscillations and teleconnections datasets thought to influence winter climate over the study area as these indices were used for the contingency table and spatial correlation analyses. Oscillation indices containing data needed for normalization were obtained from the National Oceanic and Atmospheric Administration's (NOAA) Earth System Research Laboratory (ESRL) http://www.esrl.noaa.gov/psd/data/climateindices/list/. Data for El Nino Southern Oscillation (ENSO) is available at the ESRL site in raw sea surface temperature (SST) form but had to be normalized or standardized before anomalies for the 1951-2011 period could be determined and used in the contingency table and spatial correlation analyses. To prepare for the normalization process Microsoft Excel was used to arrange the datasets taken from ESRL into a more user-friendly format where all data from 1951 to 2011 was placed in ascending order. To normalize the NINO3 raw data the mean SST was subtracted from the raw data numbers and then divided by the standard deviation of the dataset. This normalization process converts the raw sea surface temperatures into usable anomaly form. The normalization portion of the NINO3-NAO dataset was modeled after the study on northern hemisphere winter snow anomalies in 2009/10 by Seager, Kushnir, Nakamura, Ting and Naik (2010) which used ENSO data from 1950 to 2010 and which is continuously updated.

This combined index was created by taking the normalized NINO3 index minus the normalized NAO index. This index behaved differently in that a real positive NINO3 and a real negative NAO resulted in the index increasing (NINO3=+2 and NAO=-3, then NINO3-NAO=+2-(-3)=+5). The North Atlantic Oscillation (NAO) and the Pacific Decadal Oscillation (PDO) anomaly data provided by ESRL is available in normalized form but for a different base period other than 1951-2011. The NAO dataset selected from ESRL was produced by NOAA's Climate Prediction Center (CPC) while the PDO dataset was constructed by Mantua et al. (1997). In order to correctly compare the oscillations and teleconnections in contingency table and spatial correlation analyses, the

NAO and PDO datasets had to be renormalized. To renormalize NAO and PDO datasets, the mean of each dataset was subtracted from the raw data and divided by the standard deviation. The normalization and renormalization of NINO3, NAO and PDO resulted in anomaly datasets relative to the 1951-2011 period of record. Lastly the normalized anomaly data were converted to Tab-delimited files and the Temperature Analysis tool of HOB Tools was utilized to extract only October though April (ONDJFMA) normalized anomaly data from the 1951-2011 period of record. Once the ONDJFMA normalized anomaly data had been extracted, an average anomaly, or positive/negative value, for each year in the time series was determined.

Contingency Table Analyses

The North Atlantic Oscillation (NAO) and the Pacific Decadal Oscillation (PDO), which were hypothesized to be the most likely influencers of the snowfall records as a result of the hypothesized step or change in climate apparent around 1980, as well as from Seager et al. (2010), led to the need to investigate how other variations in oceanic and atmospheric circulations may be influencing snowfall conditions for the study area between 1951-2011. A contingency table analysis was used to detect any further evidence for oscillations and teleconnections. A contingency table analysis works by assigning data into categories after the construction of two tables (Observed Frequencies and Expected Frequencies) has been completed. A chi-squared statistical test is coupled with the contingency table in order to determine statistically whether any significant difference exists between the observed and expected frequencies. The threshold for the level of significance for the contingency table analyses was established at $\alpha=0.1$ or 10 percent, α=.05 or 5 percent and α=.01 or 1 percent (Kunkel et al., 2013). P-values less than 10 percent ($P<0.1$) suggested the probability of a difference occurring between the observed and expected frequencies was greater than would normally result from chance alone. In order to perform the contingency table analyses, R statistical software was utilized. The R script was authored by Dr. Dorian J Burnette of the University of Memphis. The script featured a 4x4 analysis grid as the output which counted and separated data that fit into four categories: <25th percentile, >25th and <50th percentiles, >50th and <75th percentiles and finally >75th percentile. As oscillation indices were normalized with a mean of zero earlier in the research, any counts occurring below the 50th percentile of the oscillation segment of the table were likely to be negative. Likewise, any counts occurring above the 50th percentile were likely to be positive. The contingency analysis counts, for example, the number of times a given oscillation's index was low (negative phase), while at the same time calculating the days with ≥6'' of snowfall. This technique was used to compare snowfall frequency, events and totals to the normalized indices of the NAO and PDO both of which had been added into a single Excel sheet and then converted to a tab-delimited file for use in R. Tables 2 and 3 below are examples of the contingency table used in the analyses.

Observed Frequencies		**Snowfall Data**			
Oscillation	Quartiles	<=25th	<=50th	<=75th	>75th
	<=25th				
	<=50th				
	<=75th				
	>75th				

Table 2: Example of the Observed Frequencies 4x4 table used in the contingency analysis

Expected Frequencies		**Snowfall Data**			
Oscillation	Quartiles	<=25th	<=50th	<=75th	>75th
	<=25th				
	<=50th				
	<=75th				
	>75th				

Table 3: Example of the Expected Frequencies 4x4 table used in the contingency analysis

Spatial Correlations

Spatial correlation analysis determines if observations made at different locations are interrelated or dependant on one another. Spatial correlations were performed between a United States snow cover dataset with known values for 1966 to present and the normalized anomaly data for the El Nino-Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO) and the combined ENSO-NAO. Software known as the KNMI Climate Explorer (Trouet and van Oldenborgh, 2013) allowed for the uploading of data as well as for the ability to perform the spatial correlations. The KNMI Climate Explorer was designed as a simple web page in 1999 to study ENSO teleconnections and has grown into over 1 terabyte of climate data coupled with dozens of analysis tools. The KNMI Climate Explorer is part of the World Meteorological Organization's Regional Climate centre at the Royal Netherlands Meteorological Institute (KNMI) and is partnered with the European Climate Assessment & Dataset (http://climexp.knmi.nl/about.cgi?id=someone@somewhere).

Ultimately, the spatial correlation analysis helped to determine how the identified oscillations, teleconnections and specific phases of each phenomenon have influenced snowfall climatology over not only northeast and east central Kansas but the entire conterminous United States. Furthermore, these analyses helped determine how the study area fit in to overall snowfall climatology for the lower 48 states for the period in question while also allowing for an examination of oscillations on an independent dataset.

First, the monthly normalized data for each oscillation/teleconnection were uploaded to the KNMI database by organizing each oscillation's index into three categories: 1) Year, 2) Month and 3) Anomaly Value. Once these monthly data for each oscillation had been uploaded to the KNMI Climate Explorer the tool "Investigate this time series" was used. This tool allowed for the development of statistically significant correlations between the normalized oscillation indices and observed snow cover datasets available within KNMI's database for an area covering the conterminous United States. The snow cover dataset selected was the "1966-now Rutgers University Global Snow Lab" as these data went the furthest back in time amongst the available datasets. The Rutgers University Global Snow Lab 1966-now snow cover dataset provided modest verification for this study's analyses due to the fact it was independently constructed and had no prior relationship to this research. It should be noted the Rutgers dataset has limitations in regards to the temperature component of snow cover. As snow cover is dependant not only on snowfall but also on temperature, it becomes difficult to discern when the known snow cover between 1966-now was a result of snowfall forced by the oscillation in question or some related temperature component of another oscillation. While a temperature component of a given oscillation complicates the analyses, information gleaned from these spatial correlations certainly provides insight into oscillation/teleconnection relationships to snowfall in northeast and east central Kansas.

The level of significance threshold for these analyses was defined at $\alpha=0.10$ or as a 10 percent chance the null hypothesis (no spatial correlations exist) was rejected in error. The threshold is established by the KNMI Climate Explorer software.

Results

Wilcoxon Signed Rank Analysis of Six and Four Station Averages

The metadata issues and possible snowfall undercounts associated with Holton and Ottawa led to the need to ensure quality data were being used for analysis. After all six stations were reviewed through HOMR, the Wilcoxon Signed Rank test was further utilized through the program R to quantitatively eliminate poor data from the rest of the snowfall network. The HOMR site showed significant gaps in metadata primarily for the time period 1974-2011 for Ottawa and Holton with no notable gaps for the remaining four stations in the network. The signed rank test comparisons of the 1974-2011 and 1951-2011 periods revealed a significant difference from the Ottawa and Holton stations. An examination of the augmentation table (Table 1) reveals the Atchison and Holton stations received nearly the same amount of augmentation. The Atchison station, however, was not shown to bias the data as did the Holton station. This may have been due to all of Atchison’s augmentation occurring over eight years whereas the Holton station’s augmentation spanned over 37 years of the record. Among the three variables used for snowfall analysis, frequency and totals were shown to be potentially biased while events ≥=6’’ were not shown to be significant.

The comparison of the four to six station network averages for both 1951-2011 and 1974-2011 periods for the snowfall frequency analysis both showed possible data bias. For the period 1951-2011 a probability or p-value of $p<0.001$ was determined. The result is far below the significant p-value threshold of $p<0.05$ and highlights a large difference in snowfall frequency with the six station network average which includes Holton and Ottawa. Likewise, the period 1974-2011 had a p-value of $p<0.001$, revealing again a large difference in snowfall frequency between the four and six station network averages. The consistency of the large differences over a series of years suggests a problem with undercount and not the heterogeneous nature of snowfall. This became justification for removing Holton and Ottawa snowfall frequency data from the remainder of the network thereby reducing the final snowfall frequency network count to four stations.

The signed rank analysis for events revealed no significant bias in snowfall data. For the time period 1951-2011, p-values measured 0.926 while 1974-2011 yielded p-values of 0.438 between the four and six station event network averages. These results indicate snowfall events $\geq$6 inches for Ottawa and Holton do not have significant undercount issues in relation to the remainder of the snowfall events network. This result is noteworthy in that future research on snowfall may be able to still use many second-order station large-event data with confidence unlike the frequency data associated with second-order stations which has been shown to have significant bias due to undercount issues.

The signed rank analysis for totals for the year 1951-2011 resulted in a p-valu**e** of 0.065, which is not significant. Conversely, 1974-2011 showed a significant p-value of $p<0.001$. The significance is attributed to undercount and metadata issues within the Ottawa and Holton climate data records as evidenced within the HOMR database.

Following the Wilcoxon Signed Rank analysis two major points became clear. First, snowfall data for Holton and Ottawa should be eliminated from the analysis as these stations may significantly bias the overall network averages in both time periods for snowfall frequency and for the 1974-2011 period for snowfall totals. Despite no clear bias existing within the snowfall events averages, these data were also removed to ensure consistency across the network. The removal of Holton and Ottawa reduced the overall number of suitable stations for the averages from six to four. Second, future research on snowfall may be possible with second order stations if only events are used within the datasets as these data appear to not have significant issues with event counts.

Wilcoxon Rank Sum Analysis of 1951-1980 and 1981-2011 Datasets

The Wilcoxon Rank Sum analysis compared 1951-1980 to 1981-2011 to search for differences between the two time periods. Differences between the two climate periods would support the hypothesis a step-like behavior in climate or a partial low-frequency wave-like behavior around 1980 (representing a possible oscillation phase change) was embedded within the dataset. The Wilcoxon Rank Sum analysis indicated snowfall frequency from 1981-2011 was less than snowfall frequency from 1951-1980 while the number of snowfall events and totals have remained relatively unchanged. In terms of snowfall frequency, the rank sum test revealed snowfall was significantly less in the 1981-2011 time period (p=0.003). There was, however, no statistically significant difference in the number of snowfall events between the two time periods (p=0.465). Differences in snowfall totals were not statistically significant either (p=0.106).

The straight-line declining trend in snowfall frequency revealed in the 1951-2011 time series image is supported statistically by the Wilcoxon Rank Sum analyses. If the feature surrounding 1980 is removed by separating the 1951-2011 climate-period into two distinct dataset (1951-1980 and 1981-2011) the declining feature is non-existent on the two new time series displays. Initially, problematic data were suspected as the cause for the declining feature, but the removal of Holton and Ottawa data to maximize the quality of the final network reconstructions did not completely remove the phenomenon. The minimization of problematic data as the cause of the partial low-frequency wave-like behavior around 1980 suggests other variables may be responsible for influencing northeast and east central Kansas to have lower snowfall frequency beginning around this time period.

Multitaper Spectral Analysis

The multitaper spectral analysis was performed to detect any periodicities in the snowfall dataset which could then be associated with known oscillation intervals. The multitaper spectral analysis produced significant spectral powers for both frequencies and events. Spectral analysis of snowfall totals did not yield any significant findings.

For the snowfall frequency count, analysis confirmed multitaper frequencies of 0.2031, 0.2188, 0.2344, and 0.4375. Since period is defined as 1/frequency, the corresponding results for time periods are 4.9, 4.6, 4.3, and 2.3 years respectively. These time periods or frequencies breeched the 90 percent confidence level ($p<0.10$) as defined in the Methods section for the multitaper spectral analysis and correspond with the El Nino Southern Oscillation (ENSO). As the 95 percent confidence level was not breeched, the ENSO-band is considered a weakly significant power, yet confirmed present in the snowfall data.

Significant snowfall events at or above 6 inches yielded a frequency of 0.4531. A frequency of 0.4531 corresponds to a period of 2.2 years (1/0.4531=2.2), which is again evidence for the ENSO-band. The 2.2 year time period and the corresponding frequency breached the 90 percent confidence level within the multitaper spectral analysis and suggested the number of snowfall events or significant winter storms has a weak ENSO power.

Snowfall totals revealed no significant frequencies although one was close at 0.3750 (1/0.3750=2.67) but fell short of 90 percent confidence level. This result suggests an analysis restricted to snowfall totals may not easily detect the influence of oscillations and teleconnetions for snowfall in northeast and east central Kansas.

The results from the multitaper spectral analysis indicated that snowfall frequency data are better suited for detecting variations in atmospheric circulation being influenced by teleconnections like ENSO as these data are more spatially homogenous when compared against snowfall events or totals. The mid-continent location of northeast and east central Kansas does not exist as a key region for detecting strong influences from teleconnections, and as such, searching for these influences on atmospheric circulation through various means is an important pursuit (Woodhouse and Meko, 1997).

Contingency Table Analyses

The contingency analyses were performed between the North Atlantic Oscillation (NAO) and snowfall frequency, events and totals and between the Pacific Decadal Oscillation (PDO) and snowfall frequency, events and totals. Analysis of El Nino-Southern Oscillation (ENSO) was not performed as evidence for this oscillation/teleconnection was found in the multitaper spectral analysis. Moreover, other oscillations and teleconnections were eliminated from analysis as no evidence for them was found in any of the previous analyses or supporting literature. Among the various comparisons, three were determined to be statistically significant. The three significant contingency table analyses are discussed below.

First, the North Atlantic Oscillation was shown to be significant at the defined threshold of $\alpha=0.1$ but not at $\alpha=0.05$ as the p-value was $p=0.070$ in regards to affecting snowfall totals for the region (Tables 4&5). When the NAO is positive, snowfall totals have a tendency to be lower. Conversely, when the NAO is negative, snowfall totals tend to be higher. It should be noted extremely negative NAO values do not seem to be associated with anomalously high snowfall totals.

Observed Frequencies		**Snowfall Totals**			
North Atlantic Oscillation (NAO)	Quartiles	<=25th	<=50th	<=75th	>75th
	<=25th	3	5	4	0
	<=50th	4	2	6	2
	<=75th	1	6	3	4
	>75th	8	2	2	2

Table 4: Observed Frequencies for Snowfall Totals when compared to North Atlantic Oscillation (NAO). Snowfall data changes from left to right across the table. Oscillation data changes up and down the table. The ‘4’ and ‘6’ located in the 75th percentile column suggest higher snowfall totals when the NAO is in its negative phase. Likewise, the ‘8’ in the lower left portion suggests lower snowfall totals when the NAO is in a positive phase. (P=0.070)

Expected Frequencies		**Snowfall Totals**			
North Atlantic Oscillation (NAO)	Quartiles	<=25th	<=50th	<=75th	>75th
	<=25th	3.56	3.33	3.33	1.78
	<=50th	4.15	3.89	3.89	2.07
	<=75th	4.15	3.89	3.89	2.07
	>75th	4.15	3.89	3.89	2.07

Table 5: Expected Frequencies for Snowfall Totals when compared to the North Atlantic Oscillation (NAO). Snowfall data changes from left to right across the table. Oscillation data changes up and down the table.

Next, it is worth noting, that while the results were not significant, the snowfall frequency p-value approached the α=0.1 threshold at p=0.114 when compared to the NAO. As Tables 6 and 7 below show, there may be a tendency toward fewer snow days when the NAO index is positive.

Observed Frequencies		**Snowfall Frequency**			
North Atlantic Oscillation (NAO)	Quartiles	<=25th	<=50th	<=75th	>75th
	<=25th	2	5	5	0
	<=50th	3	4	5	1
	<=75th	3	5	2	4
	>75th	8	2	2	2

Table 6: Observed Frequencies for Snowfall Frequency when compared to the North Atlantic Oscillation (NAO). Snowfall data changes from left to right across the table. Oscillation data changes up and down the table. The '8' in the lower left portion suggests fewer snowfall days occur when the NAO is in a positive phase although the result was not statistically significant. (P=0.114)

Expected Frequencies		**Snowfall Frequency**			
North Atlantic Oscillation (NAO)	Quartiles	<=25th	<=50th	<=75th	>75th
	<=25th	3.62	3.62	3.17	1.58
	<=50th	3.92	3.92	3.43	1.72
	<=75th	4.23	4.23	3.7	1.85
	>75th	4.23	4.23	3.7	1.85

Table 7: Expected Frequencies for Snowfall Frequency when compared to the North Atlantic Oscillation (NAO). Snowfall data changes from left to right across the table. Oscillation data changes up and down the table.

The Pacific Decadal Oscillation (PDO) was also shown to have an influence on snowfall over northeast and east central Kansas. The relationship between the PDO and snowfall was statistically significant in terms of 1) the number of snowfall events $\geq$ 6 inches and 2) the frequency of snowfall days (Tables 8 & 9) where p= x and y, respectively. The contingency table analyses provided significant evidence which suggested fewer snowfall events occurred when the PDO was in a negative phase. A positive PDO was not shown to produce more snowfall events. This relationship was shown to be significant with p=0.035.

Observed Frequencies		**Snowfall Events**			
Pacific Decadal Oscillation (PDO)	Quartiles	<=25th	<=50th	<=75th	>75th
	<=25th	8	2	4	0
	<=50th	6	4	0	1
	<=75th	4	3	2	6
	>75th	5	7	1	2

Table 8: Observed Frequencies for Snowfall Events when compared to the Pacific Decadal Oscillation (PDO). Snowfall data changes from left to right across the table. Oscillation data changes up and down the table. The ‘8’ located in the upper left portion indicates a count of the number of times the number of snowfall events was at or below the 25th percentile and the PDO was at or below the 25th percentile. This suggests when the PDO is negative fewer snowfall events are likely. (P=0.035)

Expected Frequencies		**Snowfall Events**			
Pacific Decadal Oscillation (PDO)	Quartiles	<=25th	<=50th	<=75th	>75th
	<=25th	5.85	4.07	1.78	2.29
	<=50th	4.6	3.2	1.4	1.8
	<=75th	6.27	4.36	1.91	2.45
	>75th	6.27	4.36	1.91	2.45

Table 9: Expected Frequencies for Snowfall Frequency when compared to the Pacific Decadal Oscillation (PDO). Snowfall data changes from left to right across the table. Oscillation data changes up and down the table.

Lastly, the contingency analyses indicated a fair amount of snowfall days are possible when the PDO is negative but anomalously high snowfall frequency is rare during this phase of the oscillation. In other words, during the negative phase of the PDO, record amounts of snowfall days are unlikely (Tables 10 & 11). This analysis was significant with p=0.017.

Observed Frequencies		**Snowfall Frequency**			
Pacific Decadal Oscillation (PDO)	Quartiles	<=25th	<=50th	<=75th	>75th
	<=25th	4	2	8	0
	<=50th	4	6	0	1
	<=75th	5	2	3	5
	>75th	3	6	3	3

Table 10: Observed Frequencies for Snowfall Frequency when compared to the Pacific Decadal Oscillation (PDO). Snowfall data changes from left to right across the table. Oscillation data changes up and down the table. (P=0.017)

Expected Frequencies		**Snowfall Frequency**			
Pacific Decadal Oscillation (PDO)	Quartiles	<=25th	<=50th	<=75th	>75th
	<=25th	4.07	4.07	3.56	2.29
	<=50th	3.2	3.2	2.8	1.8
	<=75th	4.36	4.36	3.82	2.45
	>75th	4.36	4.36	3.82	2.45

Table 11: Expected Frequencies for Snowfall Events when compared to the Pacific Decadal Oscillation (PDO). Snowfall data changes from left to right across the table. Oscillation data changes up and down the table.

Spatial Correlations

Individual spatial correlations were completed between the Rutgers snow cover dataset and the El Nino-Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), the Pacific Decadal Oscillation (PDO) and the combined ENSO-NAO indices. A combination of the Rutgers snow cover dataset along with a given normalized oscillation index allowed the KNMI Climate Explorer to create visual representations of where snow cover existed during a given phase of a given oscillation. The display figures created by the Climate Explorer provided a color spectrum legend which defined the correlation (positive or negative) between an oscillation and snow cover and was correlated with colors found over a map of the United States. The results are seen below beginning with the ENSO (NINO3) normalized dataset.

Each normalized index was run through the Climate Explorer twice, once to test for statistically significant correlations and once to test for correlations without an associated significance assigned to the analysis in order to attempt a thorough examination of possible correlations. For the NINO3 index a significant correlation was not detected over northeast and east central Kansas. The analysis performed without a significance test revealed a correlation between the NINO3 index which extended into east central Kansas and is illustrated in Figure 7.

Once the significance test was added to the equation within the Climate Explorer the ENSO to snow cover correlation disappeared from the study area as shown in Figure 8. The spatial correlation test for the NINO3 index indicated ENSO may have a weak correlation to snowfall over east central Kansas during the El Nino phase of the oscillation although the results were not significant.

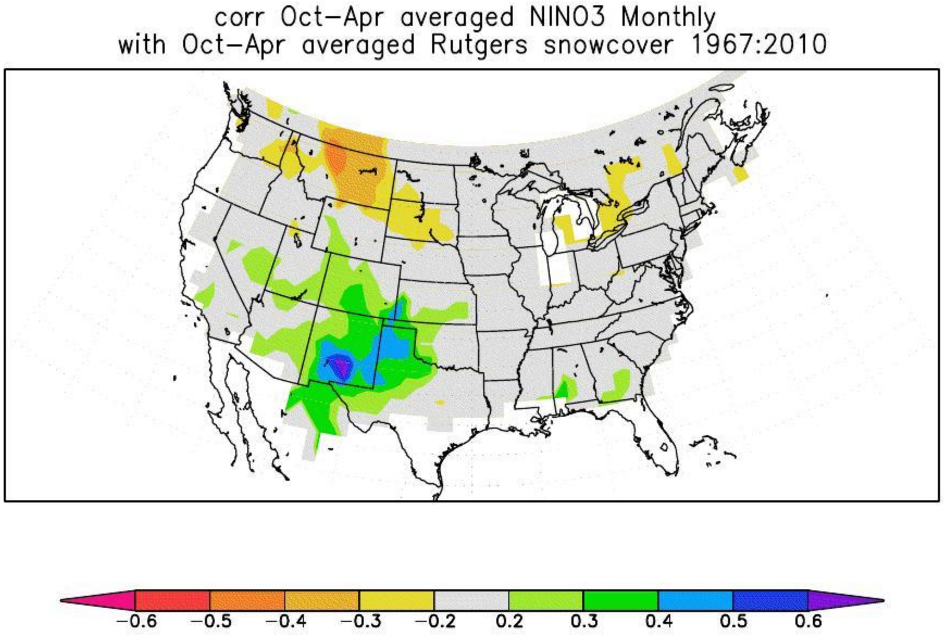

Figure 7: The numbered and colored scale bar below the figure indicates whether the correlation is positive or negative. Spatial Correlation analyses without significance test may reveal an ENSO correlation extending into east central Kansas

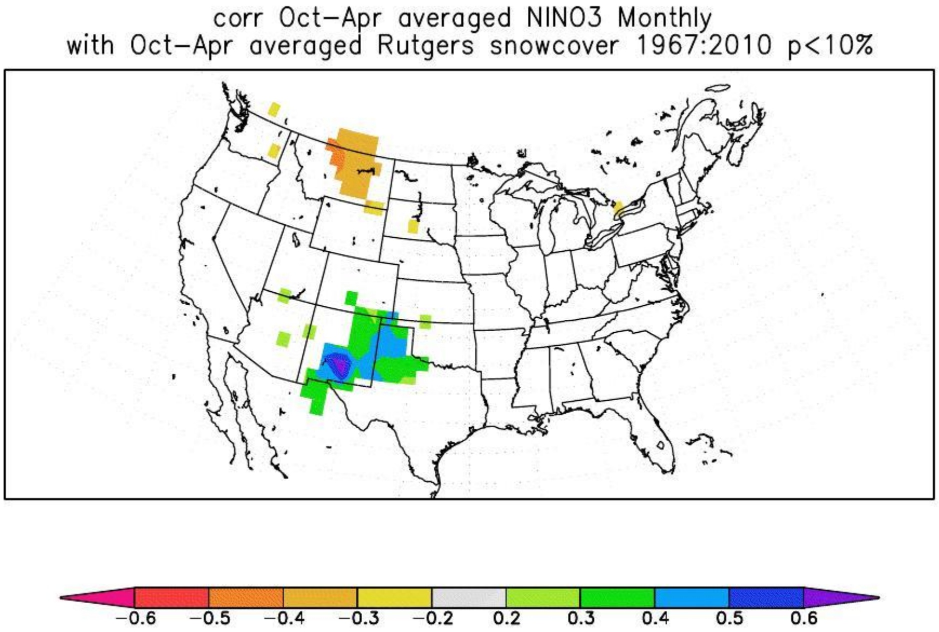

Figure 8: The numbered and colored scale bar below the figure indicates whether the correlation is positive or negative. Spatial Correlation analyses with significance test reveals no ENSO to snow cover correlation extends into east central Kansas.

For the PDO, there was neither a significant nor a non-significant correlation to snow cover across the study area as displayed in Figure 9. The contingency table analyses conducted earlier in the research process indicated when the PDO was negative fewer snowfall events were likely to occur and that the opposite (positive phase produces more events) was not necessarily true. This result, from previous analyses, may partially account for the lack of snow cover over the study area with regards to the Pacific Decadal Oscillation.

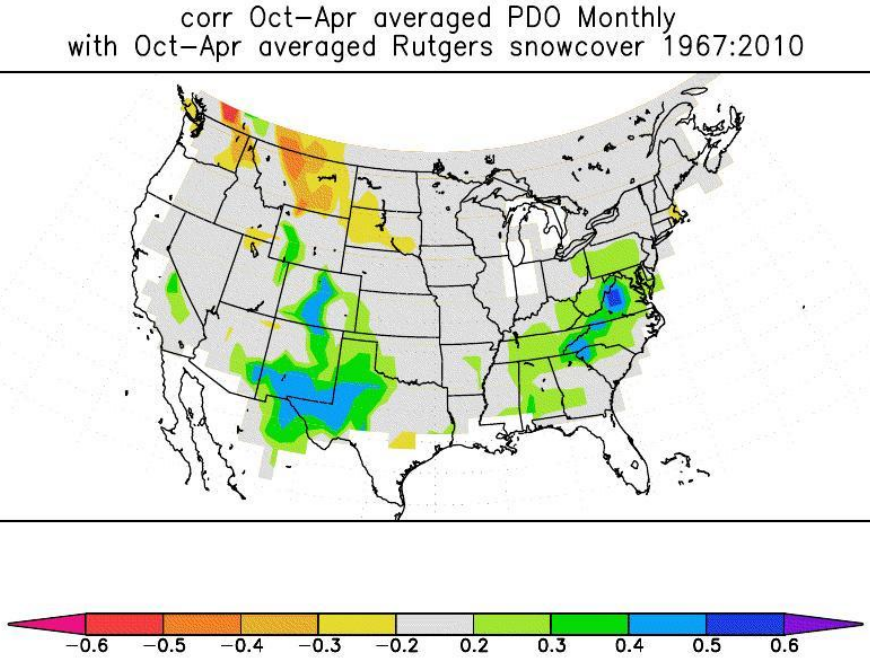

Figure 9: The numbered and colored scale bar below the figure indicates whether the correlation is positive or negative. Spatial Correlations suggested the PDO is absent from northeast and east central Kansas in relation to influencing snow cover. This result, although not significant, is supported by the contingency table analyses.

The NAO revealed both non-significant and significant correlations to snowfall over northeast and east central Kansas as shown in Figures 10 and 11. The spatial correlation analyses suggested a negative correlation between the NAO and snow cover

over the study area which may indicate increased snow cover when the NAO is low and decreased snow cover when the NAO is high. The NAO correlation to snow cover was significant ($p<0.10$) and the contingency table results from earlier NAO analyses supports the spatial correlation findings. As previously mentioned, the results of the spatial correlations of the NAO to snow cover may be stronger than the contingency table analyses suggested as the Rutgers snow cover dataset is also related to cold spell lengths (which the NAO influences) and not snowfall alone.

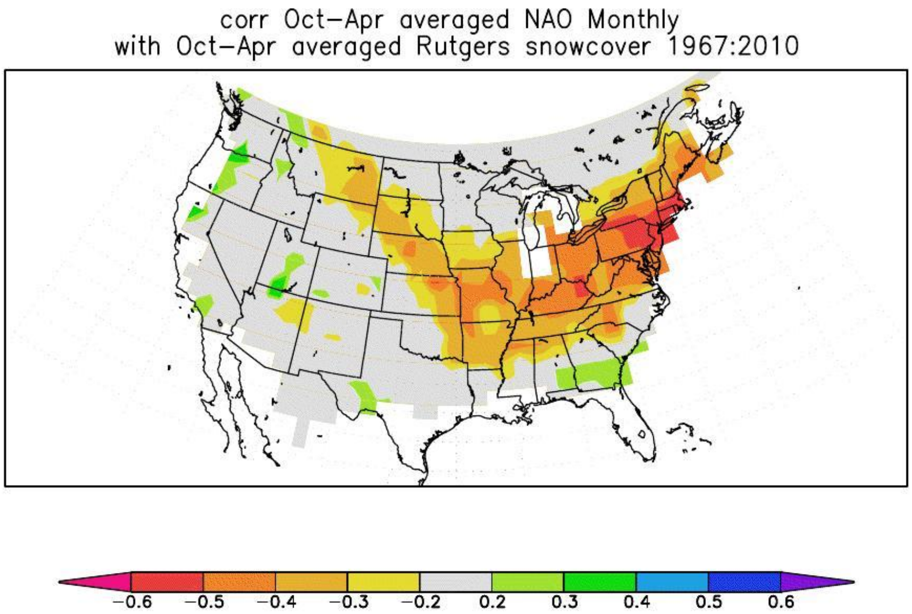

Figure 10: The numbered and colored scale bar below the figure indicates whether the correlation is positive or negative. Spatial Correlation without significance test reveals a negative correlation between the NAO and snow cover across northeast and east central Kansas. This may indicate increased snow cover when the NAO is low and decreased snow cover when the NAO is high.

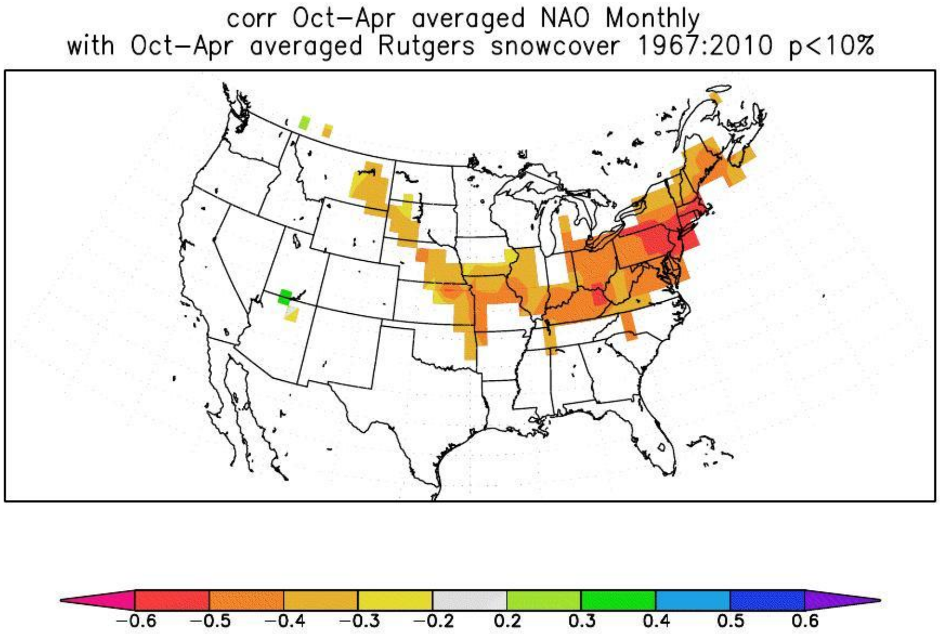

Figure 11: The numbered and colored scale bar below the figure indicates whether the correlation is positive or negative. Spatial Correlation with significance test reveals a negative correlation between the NAO and snow cover across northeast and east central Kansas. This may indicate increased snow cover when the NAO is low and decreased snow cover when the NAO is high.

Lastly, the NINO3-NAO combined index revealed both non-significant and significant correlations to the snow cover dataset as seen in figures 12 and 13. Again, this combined index was created by taking the normalized NINO3 index minus the normalized NAO index and it behaved such that a real positive NINO3 and a real negative NAO resulted in the index increasing (e.g., NINO3=+2 and NAO=-3, then NINO3-NAO=+2-(-3)=+5). The non-significant correlation showed snow cover over the study area when the combined ENSO-NAO (NINO3-NAO) was present. Note the correlations are positive suggesting the combined NINO3-NAO index may be associated with more snow cover over the study area.

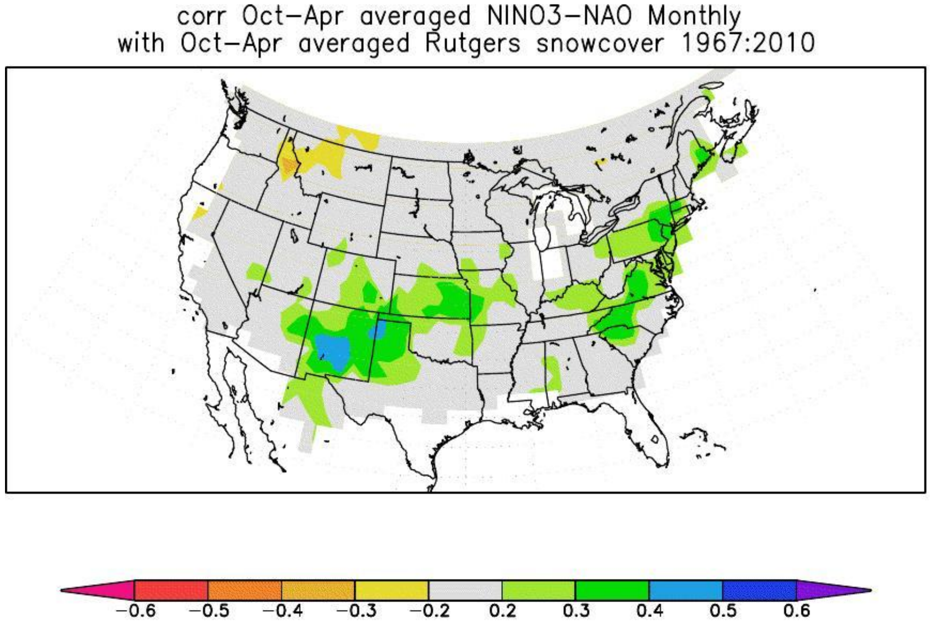

Figure 12: The numbered and colored scale bar below the figure indicates whether the correlation is positive or negative. Spatial Correlation without the significance test reveals locations of snow cover during the combined ENSO-NAO (NINO3-NAO).

When significance was once again factored into the Climate Explorer analysis the correlation was significant ($p<0.10$) and most of northeast and east central Kansas was still within the influence of the combined ENSO-NAO (NINO3-NAO) which may suggest increased snow cover over the study area.

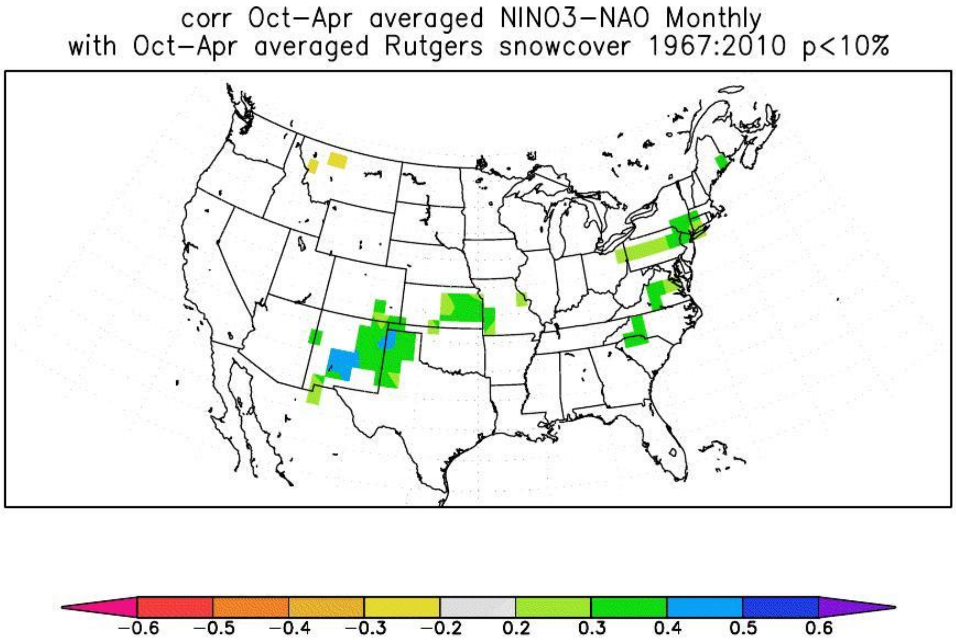

Figure 13: The numbered and colored scale bar below the figure indicates whether the correlation is positive or negative. Spatial Correlation with the significance test suggests locations of snow cover during the combined ENSO-NAO (NINO3-NAO).

Discussion and Conclusions

Among the major oscillations and teleconnections thought to influence winter climate over North America, the El Nino Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), the Pacific Decadal Oscillation (PDO) and the combined ENSO-NAO have been identified in the climate record as atmospheric and oceanic variations, which may influence snowfall across northeast and east central Kansas for the period 1951-2011. The results seem particularly valid for the ENSO-NAO (NINO3-NAO) combined index, which is supported to some degree by every method used in the study including the multitaper spectral analysis, contingency table and the spatial correlations. A combined ENSO-NAO typically enhances low pressure troughs across the eastern United States while also enhancing the subtropical jet and increasing precipitation totals across the southern United States. It is not overly surprising therefore that these conditions result in increased snowfall for the central portions of the conterminous United States (Figure 14).

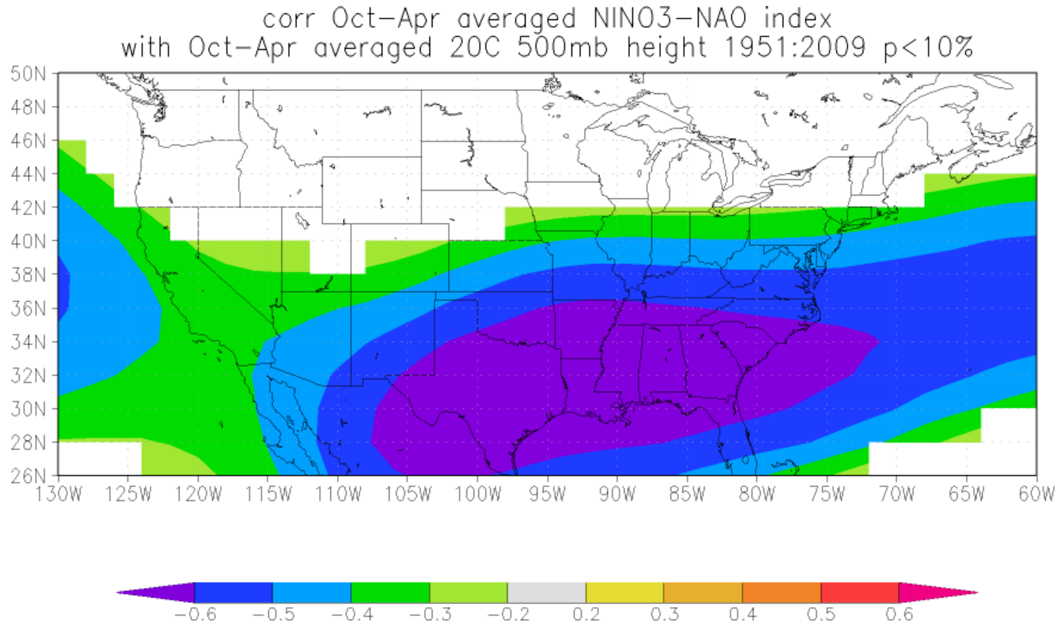

Figure 14: KNMI Climate Explorer was utilized in the construction of this figure which correlates the 20th Century Reanalysis pressure dataset (available within KNMI database) against the NINO3-NAO Index at 500 millibar heights. The negative values across the color bar indicate the NINO3-NAO index is positive and 500 millibar heights are low. This scenario represents troughs moving across the central/eastern and southeastern United States. Increased precipitation can be inferred from the presence of troughs.

Beginning on December 24th 2009, for example, a major snow storm (Figure 15) blanketed much of the central and eastern United States, including northeast and east central Kansas. Snowfall totals across the area ranged from 5.8-14.1 inches (147.3-358.14 mm) by the time the “Christmas Eve Blizzard” pushed eastward on December 27th.

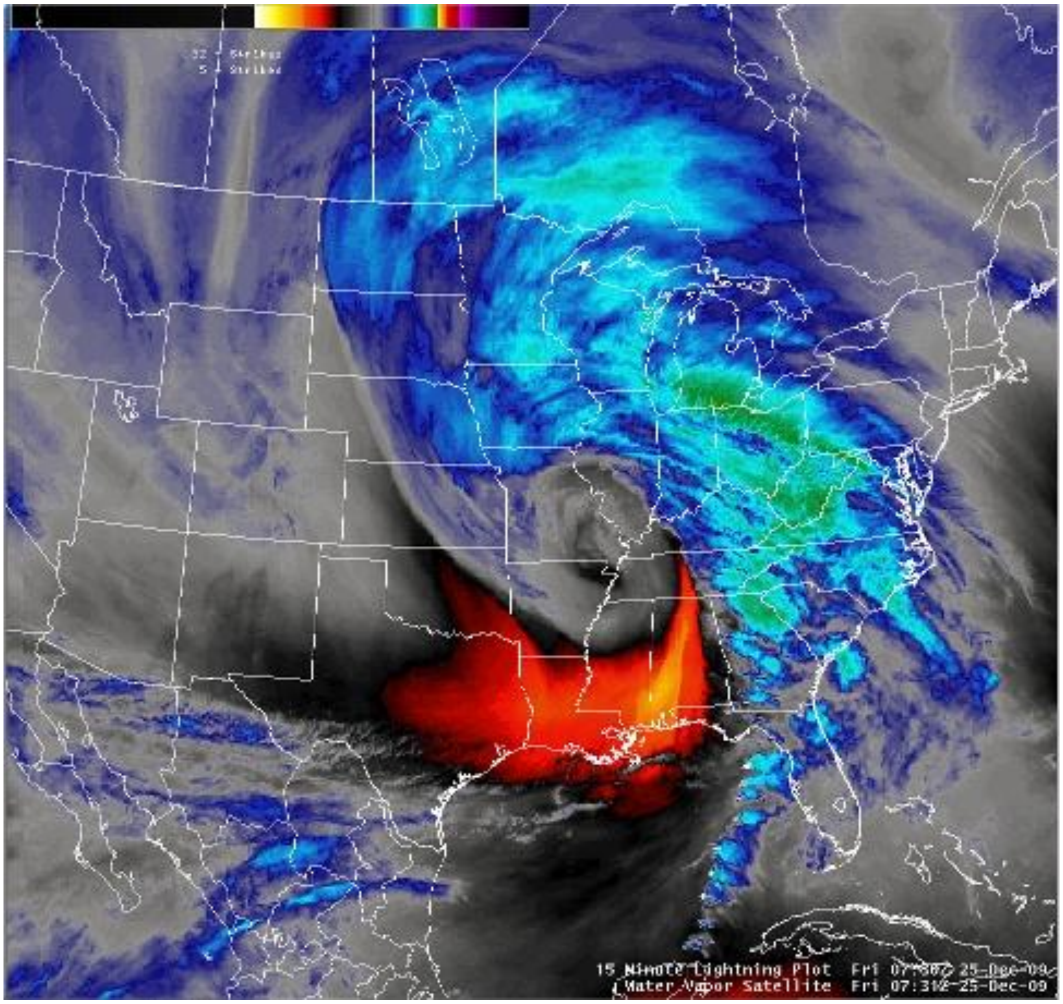

Figure 15: “Christmas Eve Blizzard” (December 24-27th 2009). Blue-green colors represent moisture while red coloring indicates dry air spiraling towards the center of the cyclone. Satellite Image courtesy of the National Weather Service

This snowfall event is particularly interesting as the following oscillation indices (Table 12) were associated with this snow storm:

Oscillation	PDO	ENSO	NAO	ENSO-NAO
Phase	0.18	0.68	-1.64	2.33

Table 12: Oscillations and corresponding phases during the “Christmas Eve Blizzard” (December 24-27th 2009).

As Table 12 shows, the ENSO, NAO, PDO and the combined ENSO-NAO oscillation indices associated with the “Christmas Eve Blizzard” are all in phases which may be associated with increased snowfall and snow cover as reported in the Results section. A combination of a positive ENSO-NAO associated with a positive PDO may represent a portion of the physical factors needed to cause large snowfall events and/or anomalous snowfall over the study area. Tables 13 and 14 located in the Appendices provide more information regarding snowfall and oscillation phases/indices.

Statistical analyses, including the Wilcoxon Signed Rank Sum Test allowed for the identification and subsequent removal of biased data, while the Wilcoxon Rank Sum Test also identified a possible step in climate or wave-like behavior occurring around the year 1980 and led to the hypothesis that the Pacific Decadal Oscillation (PDO) may also have a role in snowfall in the study area as a phase change occurred around this time period. Admittedly, the PDO did not reveal a glaring presence for snowfall over the study area and this may be due in part to the long time scale of this oscillation and the fact the time series may not have dated far enough into the past to wholly identify its presence.

Additionally, the multitaper spectral analysis program developed by Mann and Lees (1996) proved a more robust system for identifying spectral signatures related to climate and thereby in identifying ENSO as a factor in forcing snowfall during the winter in northeast and east central Kansas. The results from the multitaper spectral analysis also indicated that snowfall frequency data are better suited for detecting variations in atmospheric circulation being influenced by teleconnections like ENSO as these data are more spatially homogenous when compared against snowfall events or totals. Likewise the contingency table and spatial correlation analyses supported the hypothesis that the

NAO, PDO and combined ENSO and NAO influenced snowfall (or lack thereof) over the study area during the 1951-2011 period.

The lack of complete climate data from Global Historical Climatology Network Daily (GHCND) data led to the potential for shortcomings in reconstructing a daily winter index for the time period 1951-2011, as did the major or complete lack of data for many stations prior to approximately 1950. A winter snowfall climate time series spanning as far back as possible is ideal for discovering oscillations and teleconnections occurring on longer scales such as decades, multiple decades or perhaps even centuries. Any daily data gaps in the stations identified to have the most complete records were augmented with nearby station data and ultimately a regional average was developed for northeast and east central Kansas. The augmenting of daily gaps minimized the bias issue which would certainly have occurred had the station snowfall indices not been supplemented. Moreover, construction of a longer time series, possibly spanning back to the mid to late 1800s would have required enlarging the study area to include more stations to aid in the augmentation process. This process may have increased the likelihood of finding other oscillations and teleconnections but at the expense of increasing the study area beyond northeast and east central Kansas. Lastly, the spatial correlation analyses had limitations in regards to the temperature component of oscillations and subsequent snow cover as the Rutgers snow cover dataset records only snow cover and not whether it is a result of continued snowfall or sustained cold temperatures.

In determining the quality of individual station data, two unexpected findings occurred. First, the lack of complete *daily* climate data for the region was remarkable.

With the exception of Topeka, a major first order station in Kansas, primary and secondary stations alike, needed much augmentation to fill in daily data gaps (and ultimately led to the decision to create *network averages*. Attempting to find near to semi-complete data sets for any station became increasingly difficult preceding approximately 1950. Knowing this, future studies should focus on identifying the most complete stations in the Historical Observing Metadata Repository (HOMR) first as this site provides substantial data pertaining to a given station. Moreover, this initial screening may help in reducing the need to later eliminate stations within the network with serious undercount issues which bias results as a few complete or well augmented stations are better than several poor-moderate stations.

Second, the Wilcoxon Signed Rank analysis indicated snowfall events were largely recorded at a given station. In other words, unlike snowfall frequency and totals which were shown to have undercount issues at secondary stations, the number of snowfall events recorded at a given secondary station, were consistent when compared to the entire network. Additionally, any undercounts of events, if present, were shown to not significantly bias the snowfall indices. The implications of this finding are important as future or similar research can potentially include secondary stations into a dataset without biasing results if focus is placed on snowfall events at a given station. The effects of a combined ENSO-NAO were determined by Seager et al. (2010) to be largely responsible for anomalous snowfall in the central and eastern portions of the United States. This study's research on anomalous snowfall in northeast and east central Kansas is consistent with the Seager et al., (2010) results.

Lastly, research conducted by Boustead, Hilberg, Shulski and Hubbard (2013), focused on the creation of an accumulated winter season severity index for portions of the northern plains and upper Midwest. Boustead et al., (2013) results showed particularly severe winters for many of the study's sites in 1959-60, 1961-62 1977-78, 1978-79 and 2009-10, and distinctly mild winters between 2000-2006, all of which stand out as prominent snowfall years and low snowfall years, respectively, for northeast and east central Kansas as evidenced in this study. The Boustead et al., (2013) findings also supported a correlation between snowfall and the North Atlantic Oscillation. Similarly, studies performed by Kunkel et al., (2013) on monitoring and determining trends in extreme storms across the United States showed a decline in the top ten percent of seasonal snowfall totals from the 1970s into the 1980s, with much of the trend occurring around approximately 1980. These results support similar findings from this study.

The studies conducted by other researchers, which contain different approaches and methodologies to examining winter weather and snowfall in the central portion of the United States and the subsequent results of these studies, give support to the snowfall analyses conducted in this research as similar results have been determined.

Limited research exists on the effects of oscillations and teleconnections on snowfall patterns in the central portion of the United States, particularly northeast and east central Kansas. The development of a daily climate index for snowfall frequency, events and totals spanning the time period 1951-2011 has led not only to the construction of a more complete regional snowfall index for the study area but also to a greater understanding of the oceanic and atmospheric variations which lead to anomalous snowfall across the region. Moreover, the development of the index and screening for quality, combined with statistical, spectral and spatial analyses provides a model for future climate related research as well useful data for climate prediction studies.

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Appendix

(Additional Tables and Figures)

Frequency

Year	Frequency	NINO3 Phase*	NAO Phase	PDO Phase	NINO3-NAO Phase
1960	40.3	-0.2	-0.2	0.4	0
1978	38	0.2	-0.4	0.4	0.6
1975	37.3	-0.4	-0.2	-0.3	-0.2
2010	37.3	0.9	-1.2	0.5	2.1
1973	35.3	1.1	0.3	-0.1	0.8

Events

Year	Events	ENSO Phase	NAO Phase	PDO Phase	NINO3-NAO Phase
1960	2.75	-0.2	-0.2	0.4	0
1962	2.5	-0.4	-0.3	-1.4	-0.1
1979	2.25	0.1	0	0	0.1
1993	2.25	0.3	0.4	0.7	-0.2
2011	2.25	-0.7	-0.2	-0.7	-0.4

Total

Year	Totals	ENSO Phase	NAO Phase	PDO Phase	NINO3-NAO Phase
1960	1163.3	-0.2	-0.2	0.4	0
1979	1070	0.1	0	0	0.1
2010	949.3	0.9	-1.2	0.5	2.1
2011	868.7	-0.7	-0.2	-0.7	-0.4
1993	856.6	0.3	0.4	0.7	-0.2

*Phase values were determined from the winter season (ONDJFMA) average (mean).

Table 13: Top Five Years with Highest Frequency, Number of Events, and Total (Four Station Regional Average).

Frequency

Year	**Frequency**	**ENSO Phase**	**NAO Phase**	**PDO Phase**	**NINO3-NAO Phase**
1981	9	-0.1	-0.2	0.9	0.1
1992	11.3	1	0.5	0.5	0.5
1954	12.8	0	0.4	-0.6	-0.5
2000	13	-0.7	0.7	-0.9	-1.3
2005	14.5	0.5	-0.1	0.5	0.5

Events*

Year	**Events**	**ENSO Phase****	**NAO Phase**	**PDO Phase**	**NINO3-NAO Phase**
2005	0	0.4	-0.1	0.5	0.5
2003	0	0.7	-0.4	1.5	1.1
1992	0	1	0.5	0.5	0.5
1989	0	-0.9	0.6	-0.4	-1.4
1982	0	0.1	-0.1	0.4	0.3
1981	0	-0.1	-0.2	0.9	0.1
1972	0	-0.4	0.2	-1.3	-0.6
1966	0	0.8	-0.6	-0.3	1.3
1964	0	0.3	-0.8	-0.6	1.1
1963	0	-0.3	-0.9	-0.5	0.6
1957	0	-0.2	0.2	-1	-0.4
1956	0	-0.9	-0.8	-2.3	-0.1
1951	0	-0.3	-0.3	-1.1	0

*13 of the 60 years on record recorded ‘0’ Events

Total

Year	**Total**	**ENSO Phase**	**NAO Phase**	**PDO Phase**	**NINO3-NAO Phase**
1966	113	0.8	-0.6	-0.3	1.3
1951	197.5	-0.3	-0.3	-1.1	0
1989	205.1	-0.9	0.6	-0.4	-1.4
1992	207.6	1	0.5	0.5	0.5
1954	226.7	0	0.4	-0.6	-0.5

**Phase values were determined from the winter season (ONDJFMA) average (mean).

Table 14: Top Five Years with Lowest Frequency, Number of Events, and Total (Four Station Regional Average).

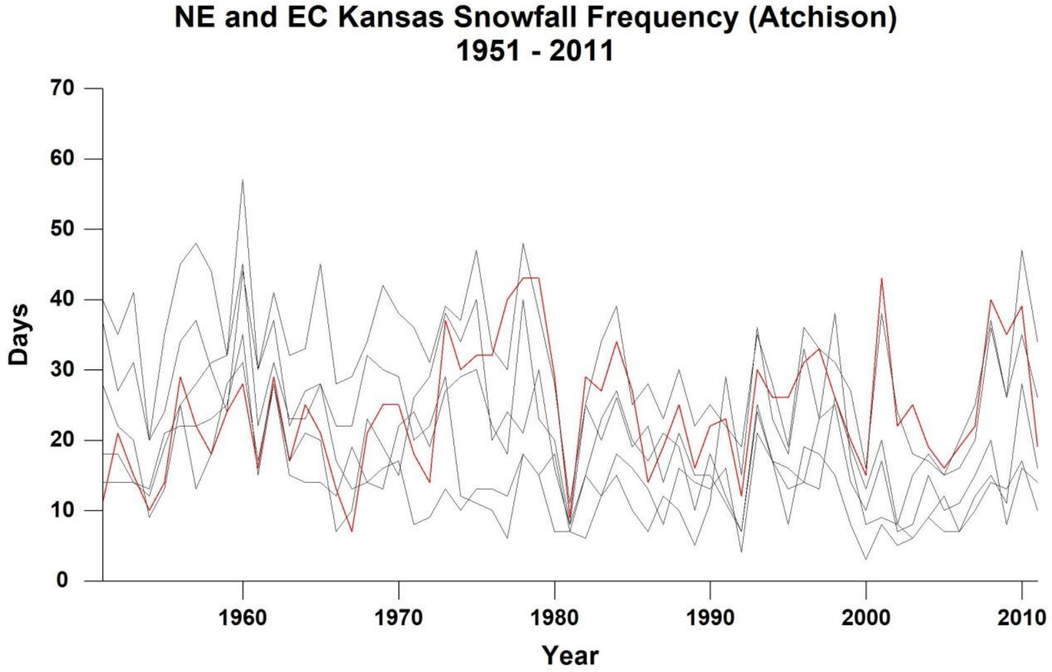

Figure 16: NE and EC Kansas Snowfall Frequency (Atchison) 1951-2011

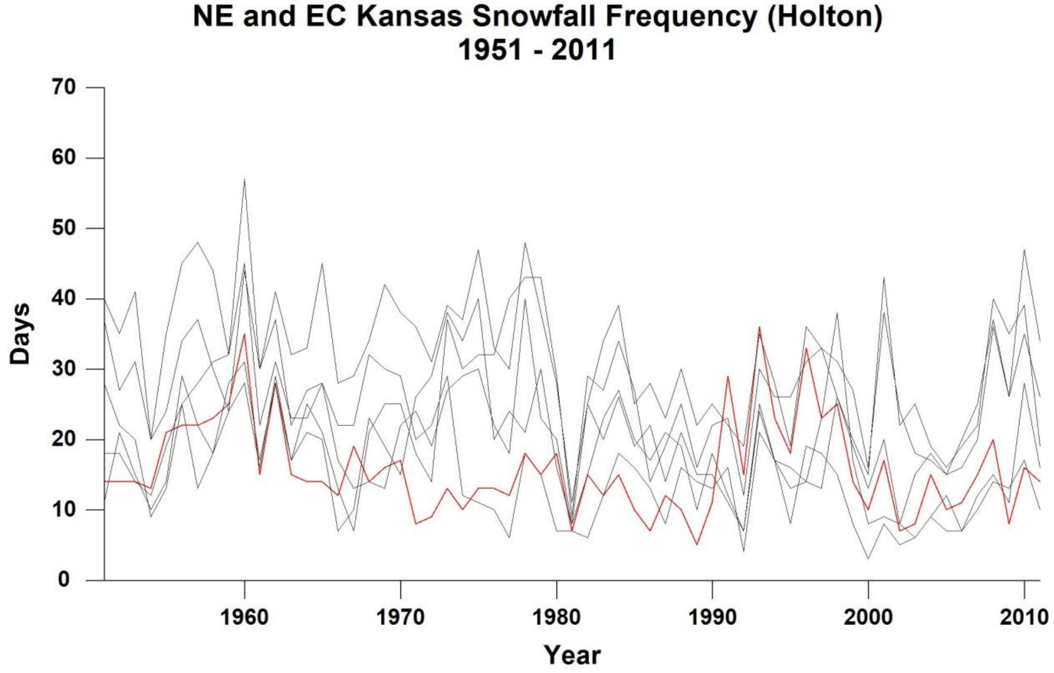

Figure 17: NE and EC Kansas Snowfall Frequency (Holton) 1951-2011

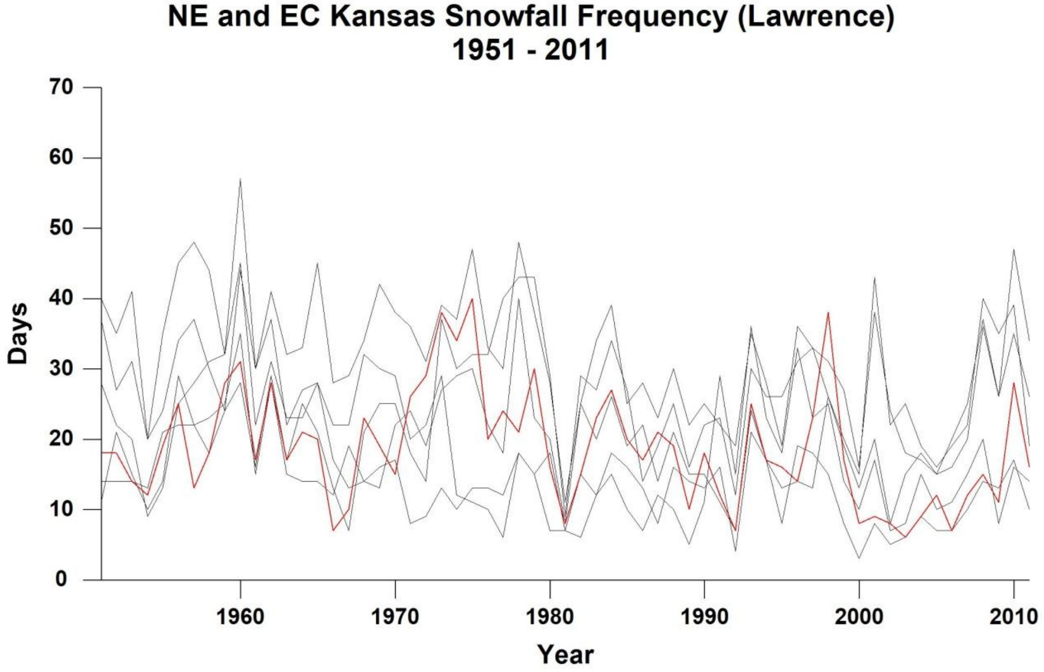

Figure 18: NE and EC Kansas Snowfall Frequency (Lawrence) 1951-2011

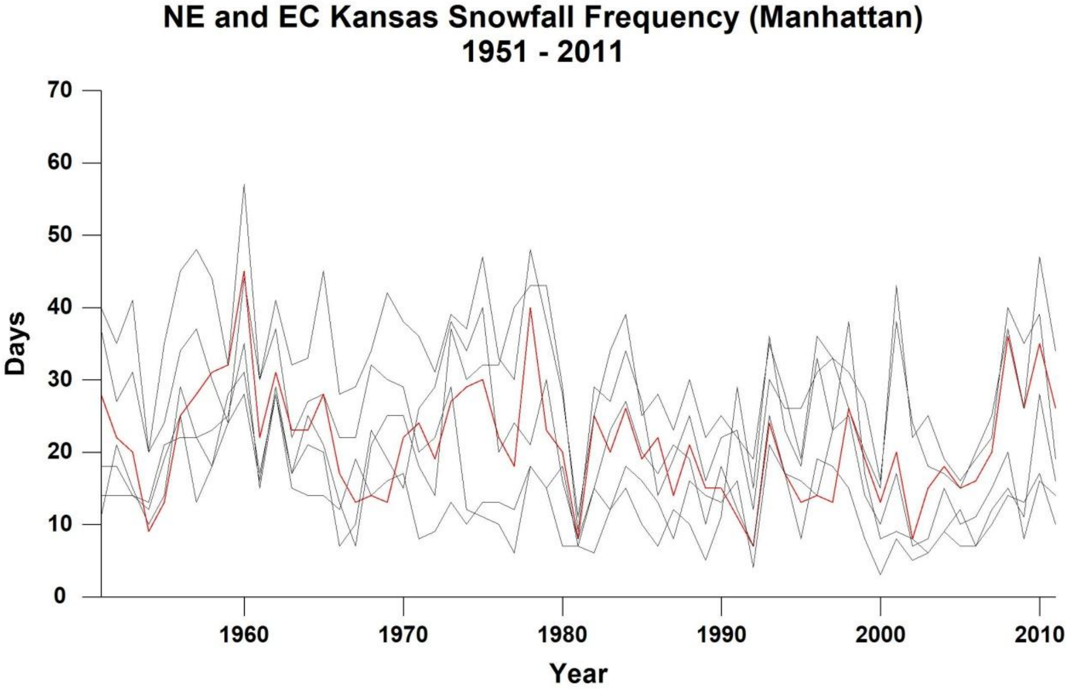

Figure 19: NE and EC Kansas Snowfall Frequency (Manhattan) 1951-2011

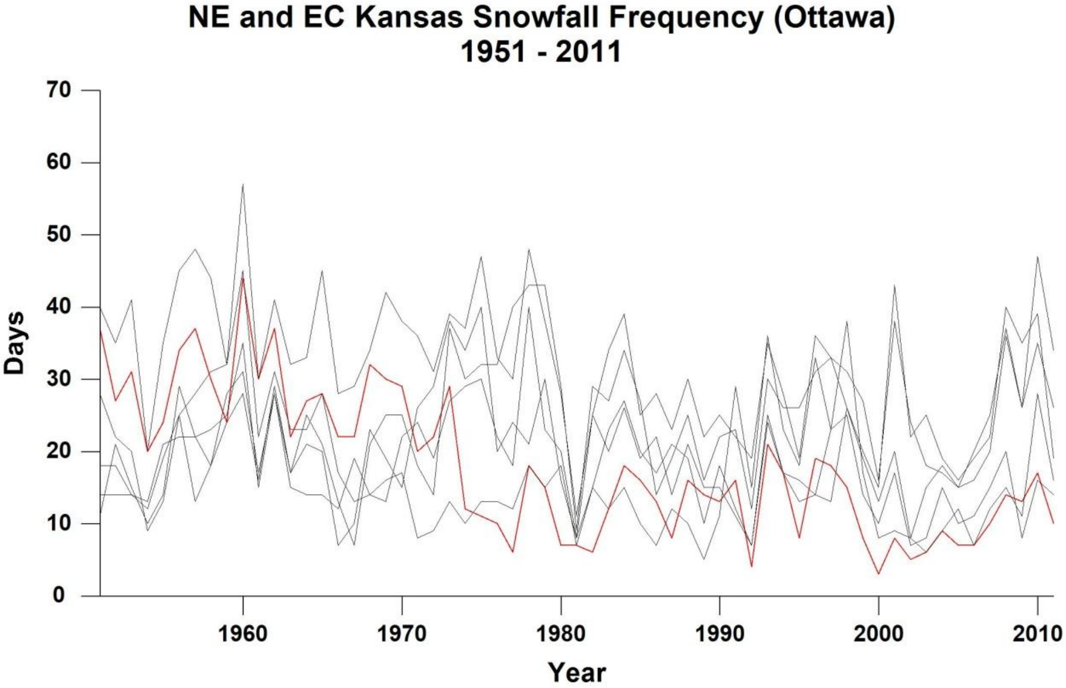

Figure 20: NE and EC Kansas Snowfall Frequency (Ottawa) 1951-2011

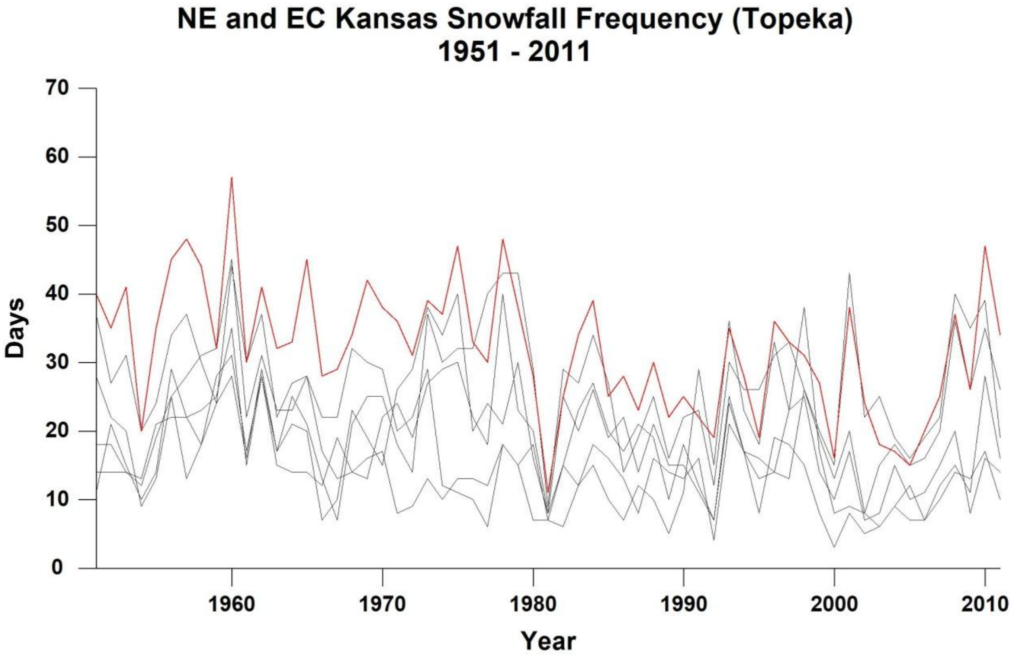

Figure 21: NE and EC Kansas Snowfall Frequency (Topeka) 1951-2011

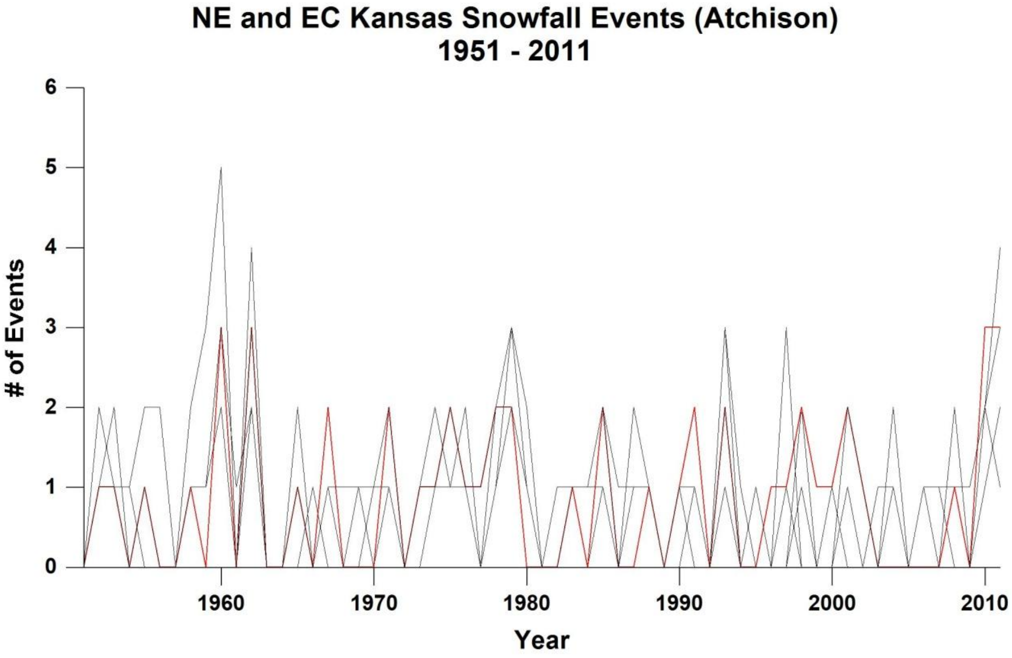

Figure 22: NE and EC Kansas Snowfall Events (Atchison) 1951-2011

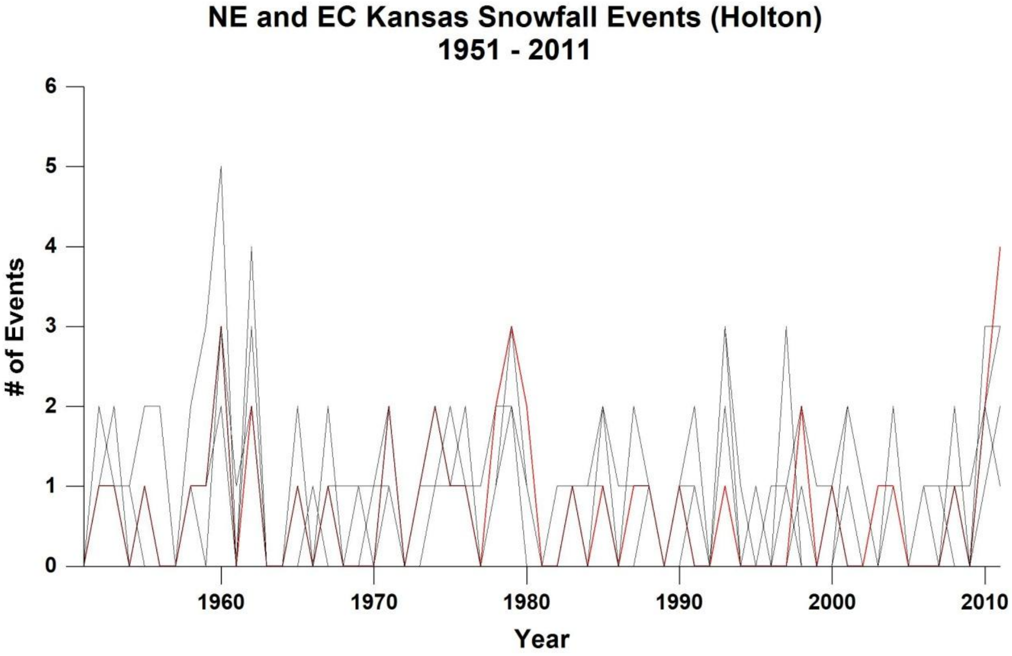

Figure 23: NE and EC Kansas Snowfall Events (Holton) 1951-2011

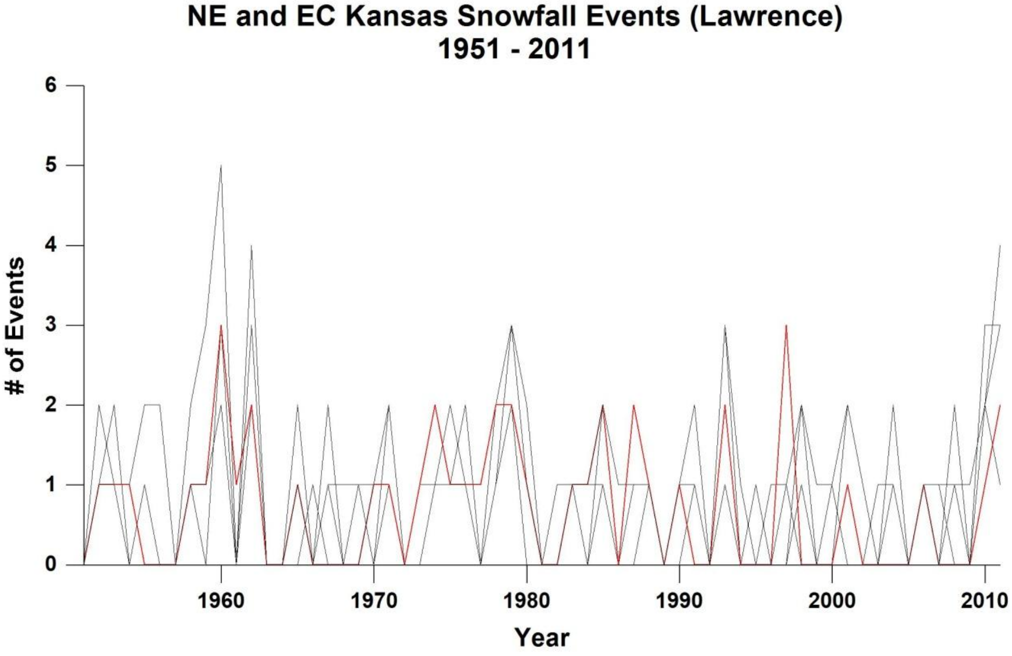

Figure 24: NE and EC Kansas Snowfall Events (Lawrence) 1951-2011

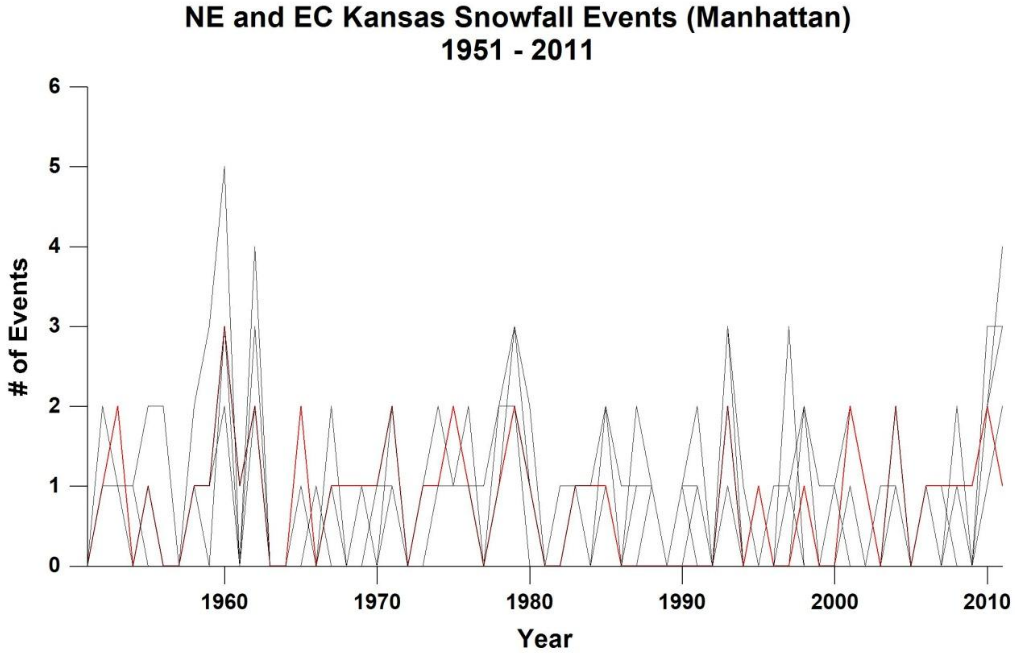

Figure 25: NE and EC Kansas Snowfall Events (Manhattan) 1951-2011

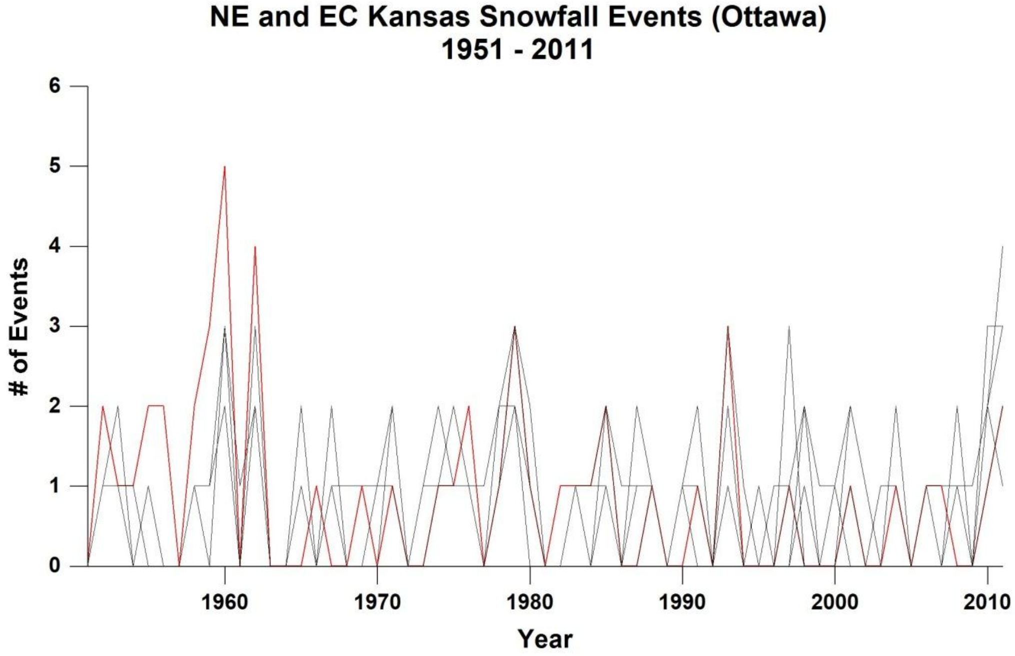

Figure 26: NE and EC Kansas Snowfall Events (Ottawa) 1951-2011

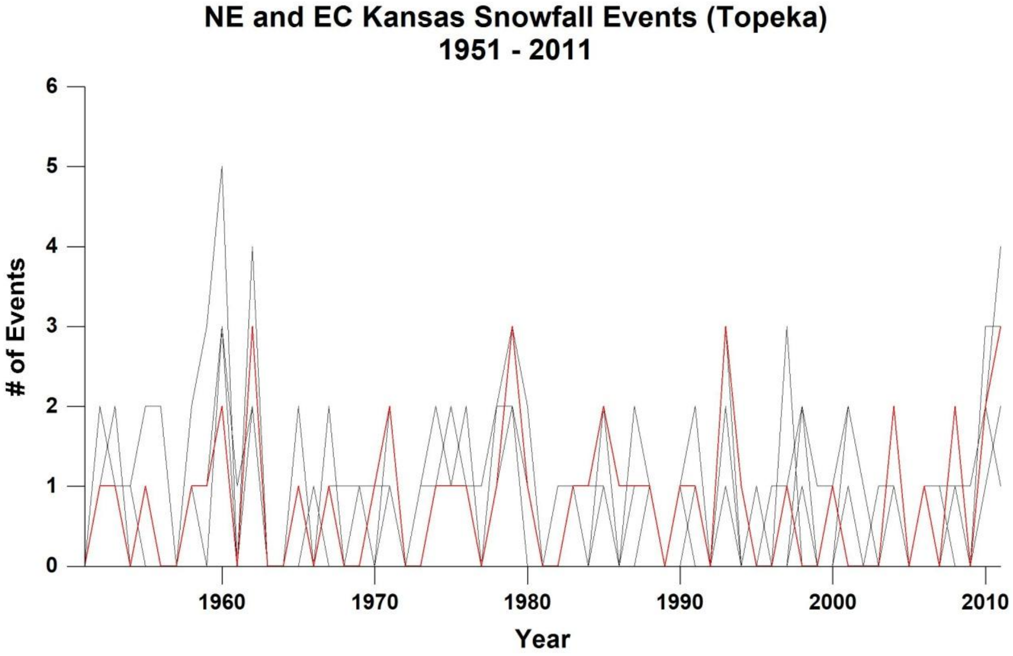

Figure 27: NE and EC Kansas Snowfall Events (Topeka) 1951-2011

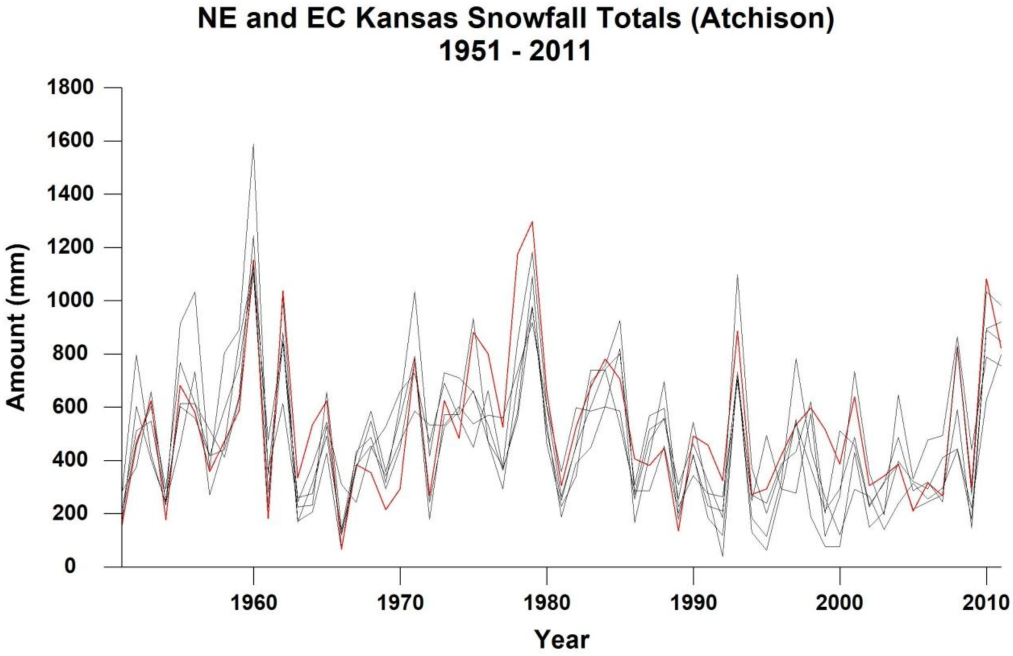

Figure 28: NE and EC Kansas Snowfall Totals (Atchison) 1951-2011

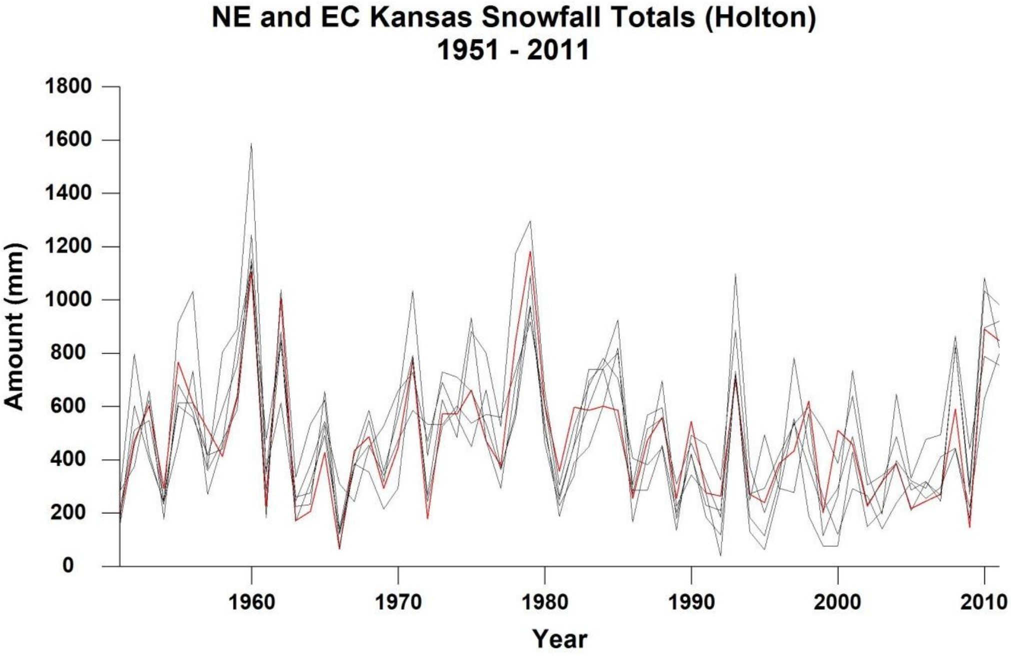

Figure 29: NE and EC Kansas Snowfall Totals (Holton) 1951-2011

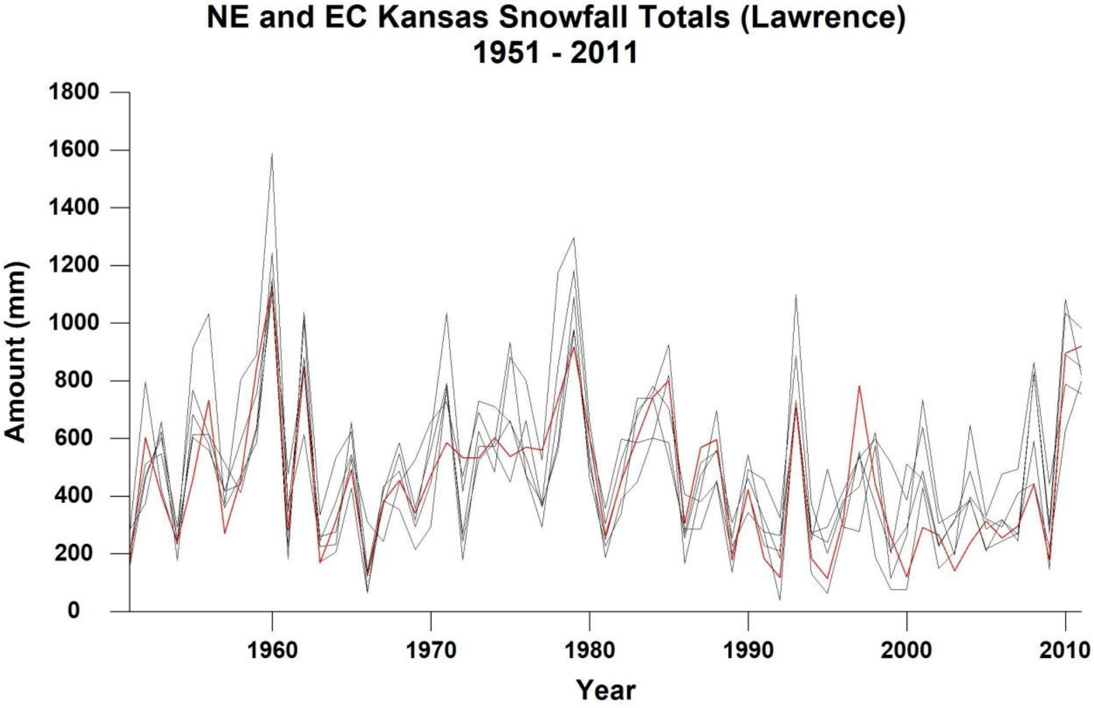

Figure 30: NE and EC Kansas Snowfall Totals (Lawrence) 1951-2011

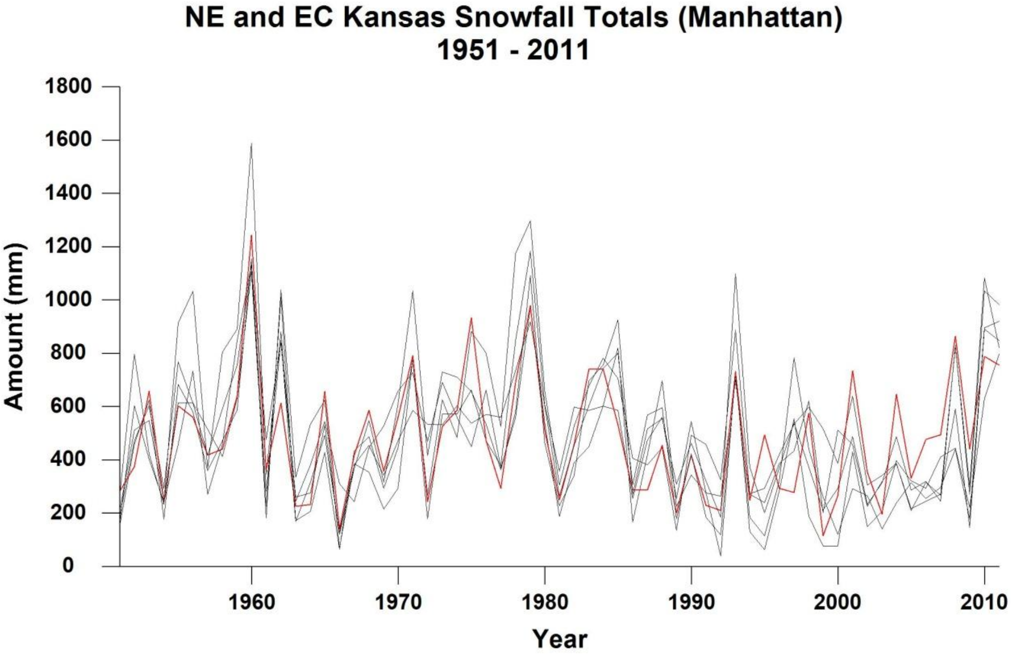

Figure 31: NE and EC Kansas Snowfall Totals (Manhattan) 1951-2011

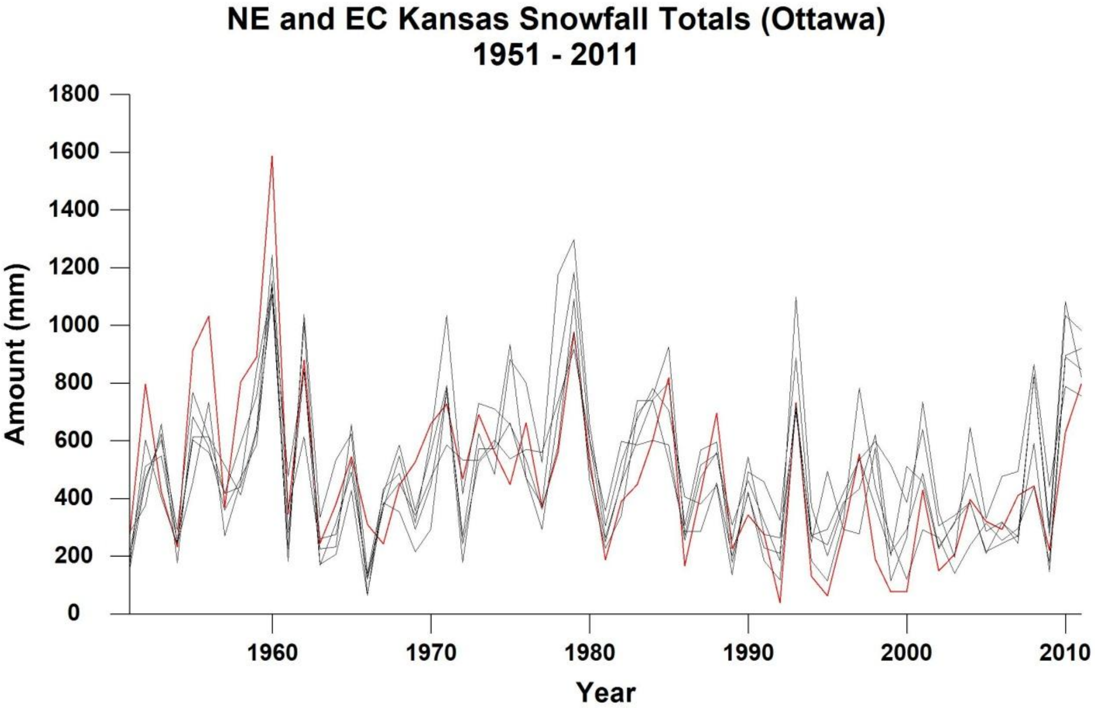

Figure 32: NE and EC Kansas Snowfall Totals (Ottawa) 1951-2011

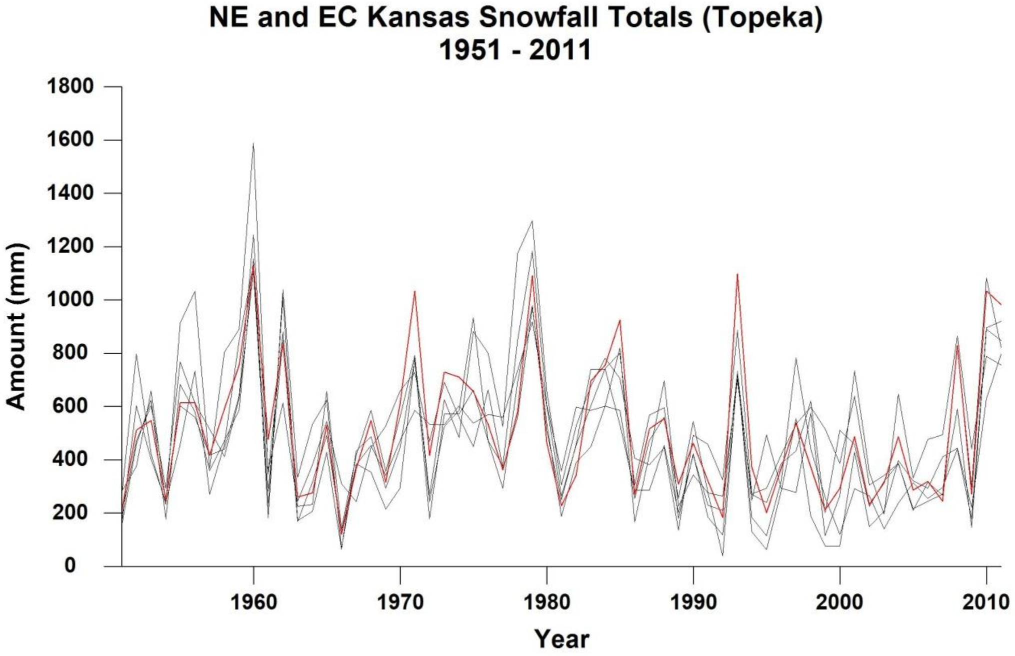

Figure 33: NE and EC Kansas Snowfall Totals (Topeka) 1951-2011

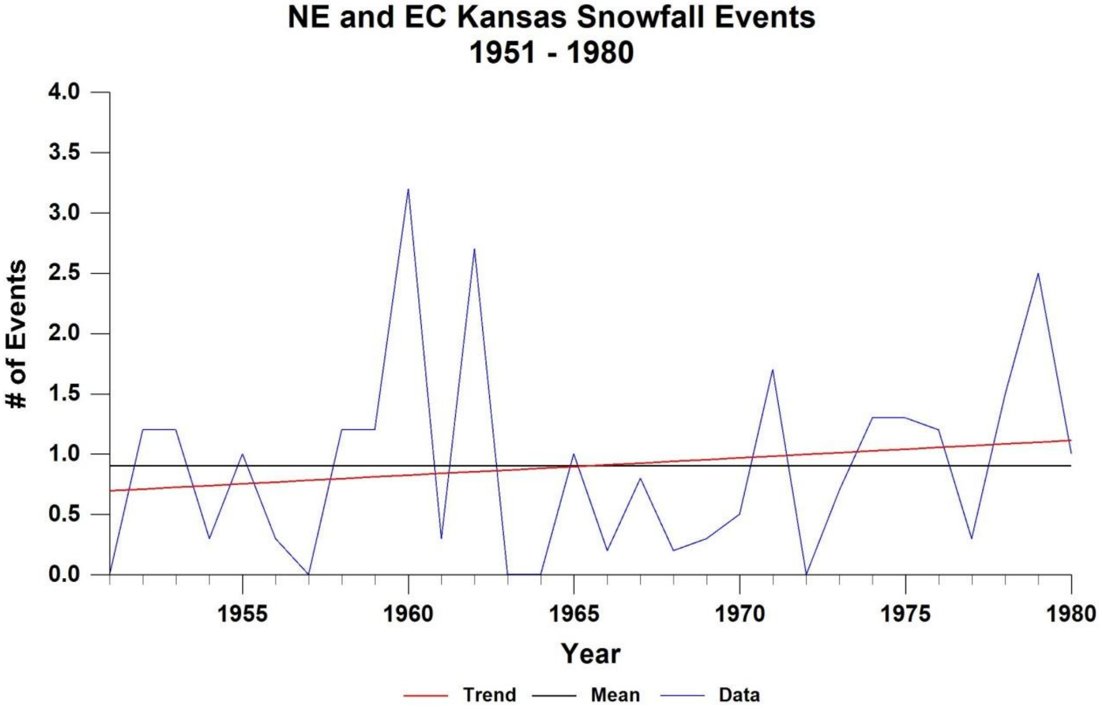

Figure 34: NE and EC Kansas Snowfall Events 1951-1980 (Four Station Average)

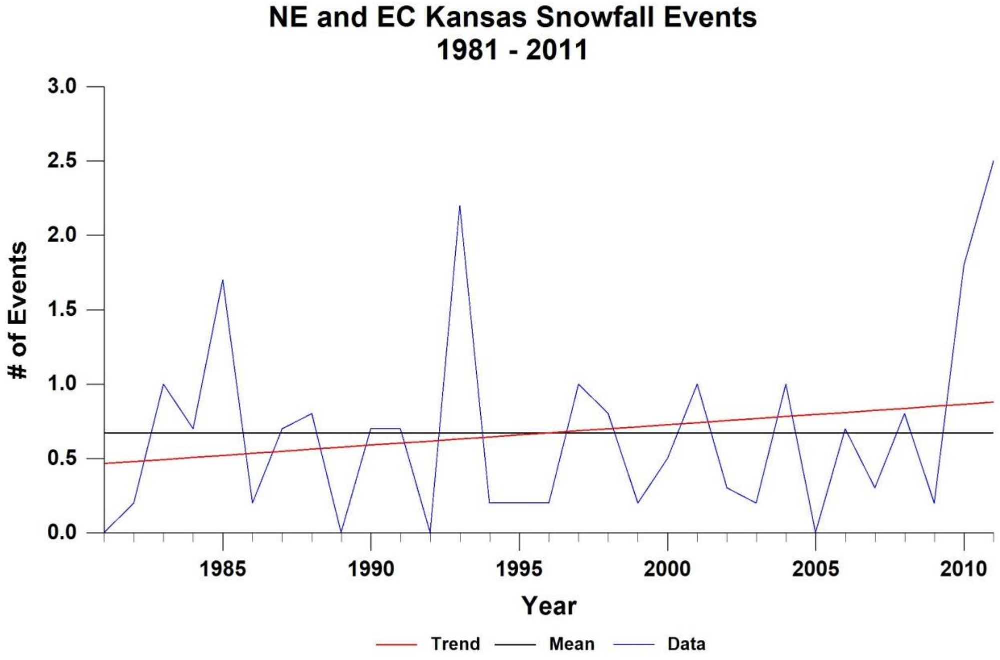

Figure 35: NE and EC Kansas Snowfall Events 1981-2011 (Four Station Average)

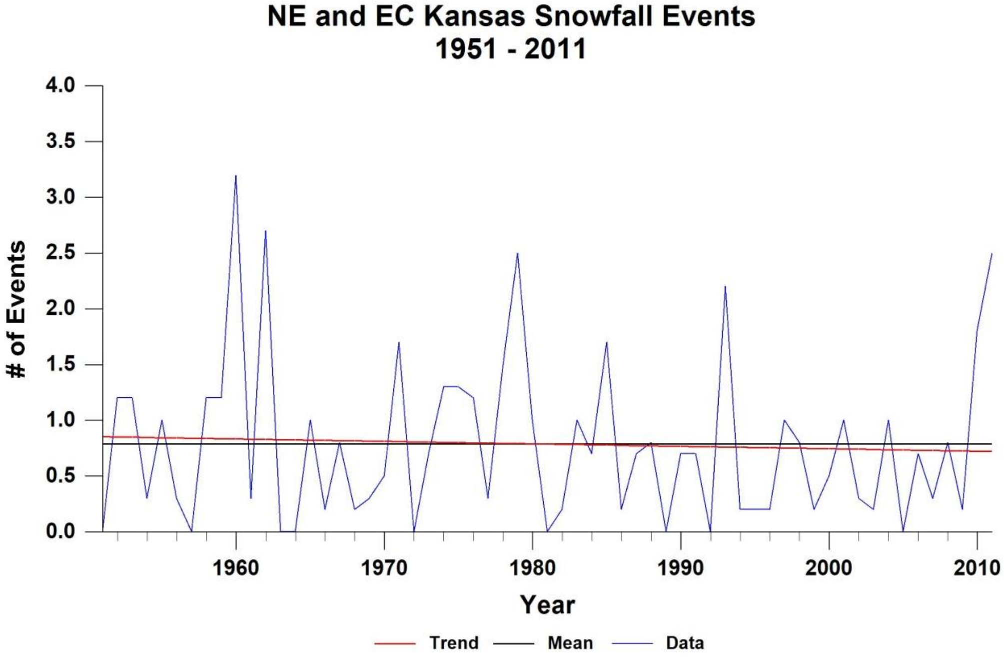

Figure 36: NE and EC Kansas Snowfall Events 1951-2011 (Four Station Average)

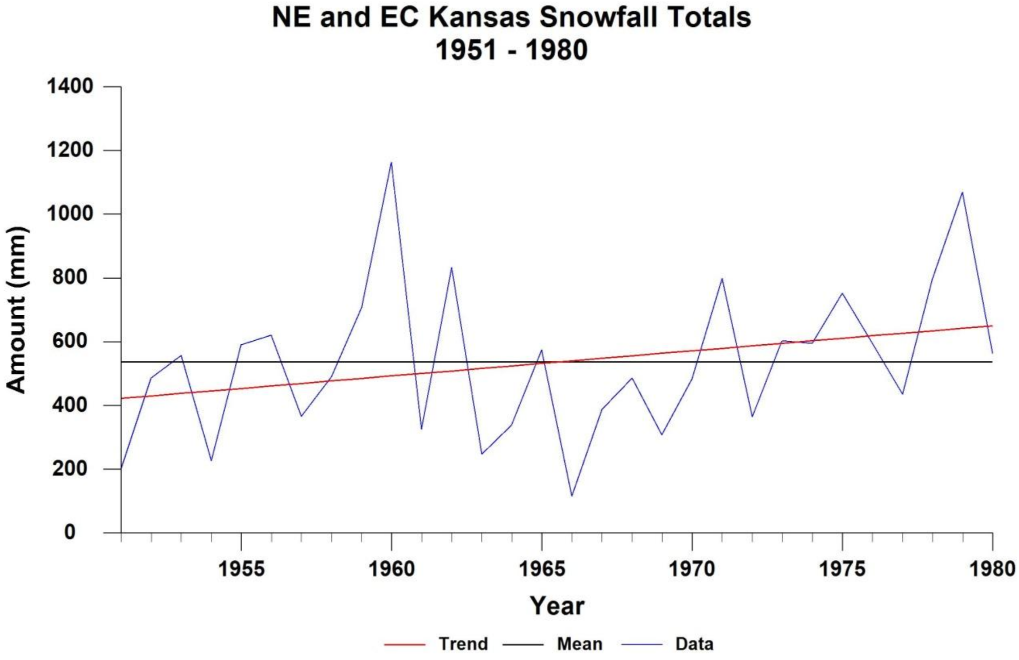

Figure 37: NE and EC Kansas Snowfall Totals 1951-1980 (Four Station Average)

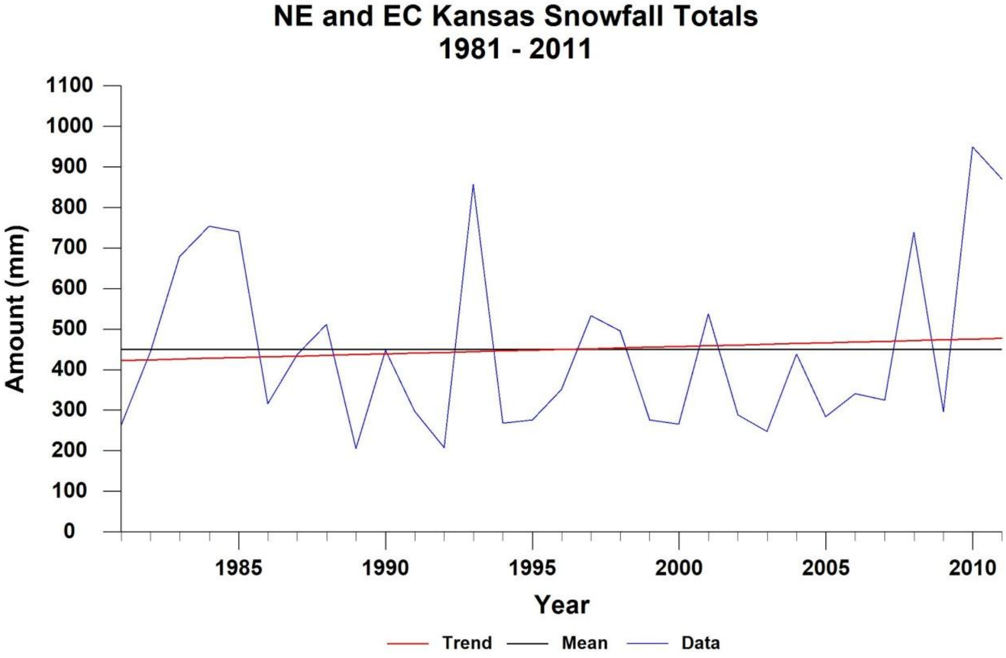

Figure 38: NE and EC Kansas Snowfall Totals 1981-2011 (Four Station Average)

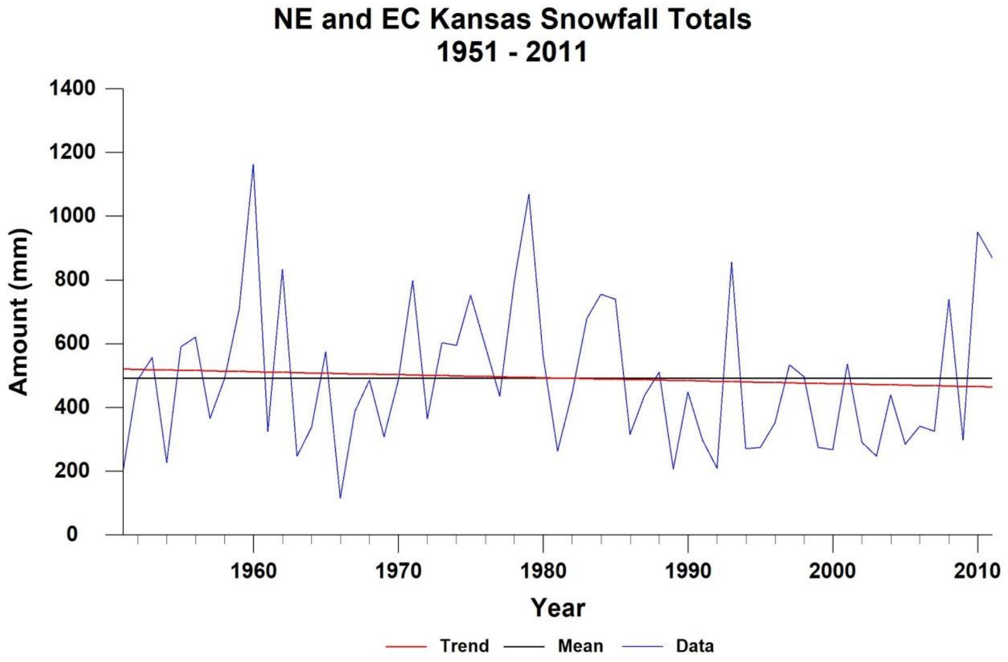

Figure 39: NE and EC Kansas Snowfall Totals 1951-2011 (Four Station Average)

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IDENTIFYING OSCILLATIONS AND TELECONNECTIONS THAT MAY IMPACT SNOWFALL IN NORTHEAST AND EAST CENTRAL KANSAS 1951-2011: A REGIONAL CLIMATE ANALYSIS AND STUDY ON PREDICTION POTENTIAL

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