DEVELOPING A DROUGHT CLIMATOLOGY FOR DELAWARE

(1948 – 2005)

by

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ABSTRACT

Drought index (Palmer Drought Severity Index and Standardized Precipitation Index), precipitation, and streamgage data were used in the development of a drought climatology for Delaware based on the period 1948 to 2005. Twelve meteorological droughts were identified during the study period, eleven of which resulted in concurrent hydrological droughts. Analysis of drought index and precipitation data revealed that meteorological drought is, on average, more severe in northern Delaware than in coastal and southern regions of the state. Through the analysis of the 500hPa height anomalies present during each respective drought, several synoptic patterns were found to be associated with the onset, duration, and termination of droughts in Delaware. Chi-square tests were used to determine if statistically significant relationships exist between incidence of drought in Delaware and variations in the Pacific Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO), El Niño Southern Oscillation (ENSO), and Pacific North American Teleconnection Pattern (PNA). A statistically significant relationship was found between drought occurrence and the combined effect of the PDO and AMO; prolonged drought events during the study period were found to occur when both the PDO and AMO were positive, or when PDO was in its positive phase and AMO negative in its negative phase.

Chapter 1

INTRODUCTION

Drought is often considered one of the least understood and most costly natural disasters (Wilhite 2000). This study intends to provide a better understanding of drought and its occurrence in Delaware through characterizing past events and identifying patterns associated with their incidence. In humid climates, drought occurrence is rarely of concern as municipalities and industries usually have an adequate water supply due to sufficient annual precipitation. But as annual precipitation decreases and the variability of precipitation increases, drought becomes more frequent and often more intense. In Delaware, the temperate climate and location along the Atlantic Coast in the southern reach of "Megalopolis" produces an average annual precipitation of approximately 115 centimeters (about 45.3 inches). However, the inter-annual variability of this precipitation is such that insufficient precipitation often leads to periods of drought.

A large percentage of the state's population is located in northern Delaware, where water supply originates from surface water storages (streams and man-made reservoirs). By contrast, agrarian southern Delaware gets most of its water from groundwater wells. Nevertheless, both sections of the state rely on water supplies that, if limited, could potentially fall short of meeting the demand of the state's residents and resident industries. It is thus critical to understand how climatic events and their spatial patterns affect the onset and persistence of drought events. This thesis seeks to better understand droughts in Delaware by examining the frequency and intensity at which they have occurred within the past half century and the synoptic patterns that may cause and exacerbate them. By characterizing the incidence of past drought in Delaware and understanding its causes, planners can be better informed when devising water supply management practices.

Chapter 2

DROUGHT, ITS DEFINITION, AND RELATED TELECONNECTIONS: A REVIEW OF THE LITERATURE

2.1 Droughts and Drought Indices

In 2002, northern Delaware experienced one of the most severe droughts in its history (DNREC *et al*. 2003). This drought was characterized by record low precipitation and reservoir, groundwater, and streamflow levels (DNREC *et al*. 2003). A large percentage of the state's residents were directly affected by this dry spell as municipal water supply levels were notably reduced and water use restrictions were mandated. As a result, the public became more aware of the potential for severe droughts in Delaware.

Other severe droughts had affected the state during the four preceding decades, albeit few were of the magnitude of that which culminated in 2002. An analysis of these droughts may provide insight into spatial and temporal patterns of drought occurrence in Delaware. Such an analysis begins with an understanding of how droughts are defined, quantified, and synoptically and dynamically forced.

A concise, universal definition for drought is difficult to provide because it is viewed differently based on the interests of the researcher, the affected parameter under study (*e.g.*, precipitation, streamflow, lake or reservoir levels, or soil moisture), or in what part of the world it occurs (Dracup *et al.* 1980; Dracup 1991). Despite the lack of a solitary definition for drought, it is generally viewed as a lack of sufficient precipitation and/or water resources that persists for a specified amount of time. Depending on the parameter considered, a 'drought' can be classified as meteorological, hydrological, agricultural, or socio-economic (Dracup *et al.* 1980; USDI and USGS 2005; Andreadis and Lettenmaier 2006). Meteorological drought is simply characterized by below normal rainfall or snowfall without regard to other environmental variables. One of the problems associated with a meteorological drought is that it is highly dependent on the starting point and time period of integration (*e.g.*, a meteorological drought may exist over the last three months but not over the last six months). Hydrological drought is characterized by streamflow and reservoir storage that falls below normal levels for an extended period of time. An agricultural drought occurs when insufficient moisture exists to produce or sustain crop growth, although, by definition, it usually ends with the end of the growing season. Finally, a socio-economic drought is described as the condition when the adverse effects of low water supply prevent society from being economically productive.

Various indices have been developed to help identify the onset and ending of droughts and to quantify their severity. Different indices are used to monitor the different drought categories. These include the Palmer Drought Severity Index, the Crop Moisture Index, and the Standardized Precipitation Index.

2.1.1 The Palmer Drought Severity Index (PDSI) and Palmer Z-index

The Palmer Drought Severity Index (PDSI – Palmer 1965) is one of the most widely used drought indices (Karl 1984; McKee *et al*. 1993; Hayes *et al*. 1999; Trnka *et al.* 2009). It is a soil moisture algorithm based on the water balance equation that determines the balance between the moisture supply (precipitation) and moisture demand (evapotranspiration). Palmer's objective in developing the PDSI was to provide a measurement of drought severity such that the variables used to calculate it allow for standardized measurements of moisture. These measurements make adequate comparisons between different time periods and different locations possible (Karl 1983; Alley 1984). Variables used to calculate the PDSI include air temperature, precipitation, available moisture capacity (a sum of the water capacity of the surface soil layer and the layer of soil underlying the surface), and the heat index term as expressed by the Thornthwaite method of calculating evapotranspiration (Karl 1983).

A two-layer bucket model is used to determine soil moisture. The model has four inherent assumptions: (1) the top layer of the soil can hold up to 25 mm of water, (2) the maximum water holding capacity of the underlying layer of soil is dependent on soil type, (3) water enters (recharges) the lower layer of soil only when the upper layer has been fully recharged, and (4) water leaves the lower soil layer only when the upper layer has been completely depleted of water (Trnka *et al.* 2009; Alley 1984). The PDSI provides an approximate account of soil moisture using the following equation:

$$\mathrm{PDSI}_t = 0.0897\ \mathrm{PDSI}_{t-1} + 0.3333\ \mathrm{Z}_t \quad (1)$$

where the subscript t denotes a specific month (*i.e.*, $PDSI_t$ is the PDSI for month t), 0.0897 is an empirically-derived Markovian persistence term, and Z is the moisture anomaly index for the given month. It is solved by the equation

$$Z = d\,K \quad (2)$$

where d denotes the departure from mean moisture and K is the weighting term. From equation (2), the PDSI of a given month depends on both the moisture anomaly for that month and for the preceding months, thus providing an idea of cumulative departure from the mean moisture of a given location.

In general, PDSI values range from -4 to +4, with positive values indicating above normal moisture levels and negative values indicating below normal moisture levels. The extreme values of -4 and +4 indicate extreme pluvials and droughts, respectively. In Table 2.1, PDSI values with their associated departure from mean moisture are given.

Table 2.1. Values of the Palmer Drought Severity Index (PDSI) and their associated moisture classification (Trnka *et al.* 2008).

PDSI Value	Moisture Category
4.00 or higher	Extreme Wet Spell
3.00 to 3.99	Severe Wet Spell
2.00 to 2.99	Moderate Wet Spell
1.00 to 1.99	Mild Wet Spell
0.50 to 0.99	Incipient Wet Spell
0.49 to -0.49	Near Normal
-0.50 to -0.99	Incipient Drought
-1.00 to -1.99	Mild Drought
-2.00 to -2.99	Moderate Drought
-3.00 to -3.99	Severe Drought
-4.00 or lower	Extreme Drought

It is important to note that soil characteristics and climate vary per region. Thus, as discussed by Karl (1983), the effect of a given numerical departure from normal precipitation is not spatially uniform. For example, a precipitation deficit of approximately 150 mm will affect soil moisture in a warm, arid climate differently than the same precipitation deficit will affect soil moisture in a more humid climate.

Equation (2) is used in the calculation of the Palmer moisture anomaly index, or Z-index. As an intermediate step in the calculation of the PDSI, the Z-index accounts for the moisture anomaly of a given month without the inclusion of antecedent moisture conditions in its computation (Karl 1986; Keyantash and Dracup 2002). The Z-index responds relatively quickly to variations in soil moisture and is thus a beneficial tool in the identification of agricultural drought. Due to this rapid response, Z-index values may indicate what appear to be exceedingly moist (dry) conditions during what is actually a long-term dry (wet) spell (Karl 1986).

2.1.2 The Crop Moisture Index (CMI)

The Crop Moisture Index (CMI) was also developed by Palmer (1965). This index was created from the PDSI to provide weekly assessments of soil moisture conditions to be used in relation to the growing season. Thus, it is used as a means by which agricultural drought can be monitored (Narasimhan and Srinivasan 2005). The CMI uses weekly air temperature and precipitation data to calculate the soil moisture over a given week in the region of interest.

As with the PDSI, positive values of the CMI indicate wetter than normal conditions, while negative values indicate drier than normal conditions. However, the CMI differs from the PDSI in that a proper interpretation of the CMI depends on knowledge of the soil moisture conditions of the previous week (Janowiak *et al*. 1986). With this index, drought is quantified by noting the difference in drought severity at the beginning of the week and comparing this with changes in evapotranspiration and precipitation throughout the week (Heim 2002). Its weekly assessment of drought makes the CMI a useful tool for monitoring agricultural drought and, as a consequence, it is widely used by the United States Department of Agriculture (USDA). However, this weekly monitoring causes the CMI to be a poor indicator of long term drought as the occurrence of a large precipitation-producing event in a given week may cause a sharp increase in the CMI which does not necessarily reflect significant changes in the longer-term drought (Keyantash and Dracup 2002).

Despite its widespread use, several shortcomings have been found with the PDSI (Alley 1984). One key issue is that the weighting term *K*, used in the calculation of *Z*, should allow for comparison between different climatic regions. This term, however, was derived by Palmer using data from nine climate divisions in Iowa and western Kansas – a very limited spatial domain. It has been argued that this limited data pool affects how accurately PDSI values can be compared between different climate regions.

Other issues with the PDSI arise from its calculation of soil moisture properties. Its use of the Thornthwaite method to calculate evapotranspiration is often criticized because this method does not consider seasonal or land use-related changes in soil properties. Further, soil moisture simulations provided by the PDSI do not provide the most accurate account of soil moisture levels as calculations of runoff and recharge are often overestimated in its calculation. The index treats all precipitation as rainfall, ignoring the effects of snowfall, snow pack, and frozen ground on soil moisture. Lastly, Palmer's assumption that the top layer of soil can hold at most 25 mm of water was made arbitrarily. This assumption does not hold true throughout the different climate divisions because soil type (and thus characteristics) varies not just from climate division to climate division, but within these divisions as well.

2.1.3 The Standardized Precipitation Index (SPI)

These (and other) shortcomings of the PDSI inspired the development of another drought index – the Standardized Precipitation Index, or SPI (McKee *et al.* 1993). The SPI provides a simpler and possibly more precise way to identify drought onset and ending and to provide a better measure of its severity. The SPI is a drought index based solely on a statistical analysis of precipitation data. To calculate the SPI for a given region, thirty years of precipitation data are used. The precipitation data are fit to a gamma distribution, from which the probability of occurrence is determined (Hayes *et al*. 1996; Trnka *et al*. 2009). These probabilities are then transformed by a normal function, allowing for a mean of zero and appropriate standard deviations (*i.e.*, the SPI value) to be established. The SPI values are based on the probability of a certain rainfall amount falling in a given location (in relation to the climate of the location). Thus, SPI values between -1 and +1 are within one standard deviation from the median value (due to the transformation using the gamma distribution) and have a probability of occurring roughly 68% of the time (Hayes *et al.* 1996). SPI values range from -3 to +3, with positive values indicating precipitation values greater than the median and negative values indicating precipitation values less than the median.

Table 2.2 displays SPI values and the departure from median precipitation with which they are associated.

Table 2.2. The Standardized Precipitation Index (SPI) and its values associated with moisture classification (Trnka *et al*. 2008).

SPI Value	**Moisture Category**
2.00 or higher	Extremely Wet Conditions
1.50 to 1.99	Very Wet Conditions
1.00 to 1.49	Moderately Wet Conditions
-0.99 to 0.99	Near Normal
-1.00 to -1.49	Moderately Dry Conditions
-1.50 to -1.99	Severely Dry Conditions
-2.00 and lower	Extremely Dry Conditions

Some advantages of the SPI include its ability to monitor drought on different time scales; that is, short-term drought (SPI-1 or the one-month SPI), medium-term drought (SPI-3, SPI-6, SPI-9, or the 3-, 6-, or 9-month SPI, respectively), and long-term drought (SPI-12 or the SPI over the previous year). Studies have shown that because the SPI can be calculated at these different time scales, it is able to detect drought occurrence, on average, about one month prior to detection by the PDSI (Hayes *et al*. 1996, Dupigny-Giroux 2001). In addition, since the SPI is based on a normal distribution of the data, hyper-frequency of extreme events (which had been observed in some areas using the PDSI) is mitigated. Because the SPI is based solely on precipitation, it can be used to provide accurate accounts of moisture even during the winter (thus overcoming a weakness of the PDSI).

There are, however, several limitations of the SPI (Hayes *et al*. 1999; Trnka *et al*. 2009). These include the fact that prior knowledge of a region's climatology is needed for a proper interpretation of calculated index values. In addition, while the SPI does a good job of indicating extreme drought, it is not a good indicator in regions that are drought prone. Moreover, it measures only precipitation amount; the effects of temperature (and thus, evapotranspiration), infiltration, and the timing of precipitation are not factored into SPI calculations. The exclusion of these factors can lead to a misrepresentation of the current moisture conditions of a given region as indicated by SPI values.

2.2 Droughts and Sea Surface Temperature Indices

Drought indices provide a good way to monitor drought occurrence and severity. It is important, however, to understand the mechanisms that are responsible for droughts. Much research has focused on the key factors (both on a regional and global scale) responsible for drought occurrence, severity, and duration (*e.g*, Seager *et al*. 2009; Dupigny-Giroux 2001; Hoerling and Kumar 2003; Mauget 2003). Research suggests that drought occurrence in the United States is related to sea surface temperature (SST) anomalies in the Pacific and Atlantic Oceans (*e.g.,* Hoerling and Kumar, 2003; Cook *et al*., 2007; Enfield *et al*., 2001; McCabe *et al,* 2004; Seager, 2007); most notably, changes in the phases of the El Niño Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and Atlantic Multidecadal Oscillation (AMO) can be linked to changes in North American hydroclimate. Table 2.3 lists the geographic locations of these indices and the variables which they measure.

Table 2.3. Geographic location of indices used in the study and the variable measured by each index.

Index	Geographic Location	Variable(s) Measured
Pacific Decadal Oscillation	Pacific Basin north of 20º N	Sea surface temperature, sea level pressure
Atlantic Multidecadal Oscillation	Atlantic Basin from 0º to 70 ºN	Sea surface temperature
Pacific North American Teleconnection Pattern	Three anomaly centers at the following locations: (47.9ºN, 170.0ºW), (49.0ºN, 111.0ºW), and (29.7ºN, 86.3ºW)	700hPa geopotential height anomalies
ENSO (Niño 3.4 region)	5ºN to 5ºS, 120º to 170ºW	Sea surface temperature

For example, drought occurrence in the United States is most often associated with the La Niña phase of ENSO, where SSTs in the eastern tropical Pacific are cooler than normal. These below-normal SSTs affect global atmospheric circulations (Cook *et al*. 2007; Seager 2007). When La Niña conditions are in place, the upper troposphere is characterized by anomalously cool temperatures. Effects of the SST cooling on ocean-atmosphere interactions become evident in anomalous eddy momentum flux. During La Niña events, transient eddies penetrate the troposphere less deeply; instead, much of their momentum is transferred further poleward (in the midlatitudes). This is evidenced by a weakening of the subtropical jets. Enhanced mass convergence in the upper troposphere in the midlatitudes, by mass continuity, results in anomalous subsidence. This subsidence, which is characterized by compression, warming, and low-level divergence, does not allow for enhanced precipitation; rather, it hinders the occurrence of precipitation as the associated dynamics do not support its creation (rising motion is necessary for the creation of precipitation). Thus when the anomalous subsidence occurs over extended periods of time, as during prolonged La Niña events, the regions in which the descent is occurring experience conditions drier than usual, and these conditions tend to persist.

Eddy momentum flux that occurs during prolonged La Niña events affects precipitation in another mechanism described by Seager (2007). Eddy momentum flux also influences the mean meridional circulation, causing anomalous northerly flow to counteract the climatically normal advection of moist, warm air from the Gulf of Mexico into the southwest and Great Plains regions. The advection of the cold, more stable air (via differing mechanisms depending on the season) counters that of the warm, more unstable air from the Gulf and works to reduce the number of precipitation events (as well as precipitation amounts) during the prolonged La Niña/drought events.

Research by Hoerling and Kumar (2003) has indicated that the presence of large annular-like modes in the upper atmosphere can be responsible for the displacement of jet streams in the westerlies. This is followed by further meridional displacement of storm systems, which results in the drying of regions within the normal storm tracks as storm systems no longer traverse those locations (or do so at a much lesser frequency, resulting in less measurable precipitation). These results are further supported by findings made by Cook *et al.* (2007) that when persistent La Niña events occur, a Rossby wave regime is established in which a blocking pattern is maintained due to the presence of anomalous centers of high pressure. Hoerling and Kumar (2003) report in their study of the global drought from 1998-2002 that four-year observations show a zonal "belt" of high pressure that circled the midlatitudes. This belt is believed to be responsible for the dry conditions, and it was indeed forced by the anomalously cool eastern tropical Pacific.

Another SST index used to help understand the relationship between SST anomalies and hydroclimate in North America is the Pacific Decadal Oscillation (PDO). The PDO is characterized by inter-decadal variability in Pacific SST and sea level pressure (SLP). This variability encompasses the entire Pacific Ocean and has a recurrence interval of approximately 50 to 70 years (Mantua *et al.* 1997). It is largely dichotomous, with a positive phase and negative phase. Some of the major effects of the PDO on SSTs, SLP, and hydroclimate resemble (and correspond to) ENSO warm phases in the tropics; that is, SSTs in the tropics are above average during positive PDO phases. The amount of warming is usually more pronounced during ENSO warm phases than positive phases of the PDO. Positive PDO phases are characterized by cooler than normal SSTs in the north-central Pacific Ocean and warmer than normal SSTs along the northwest coast of North America. Negative SLP anomalies occur between 20° and 60° north during positive PDO events and lead to increased precipitation in the central Gulf of Alaska and Northern Mexico, and decreased precipitation in western Washington, the Hawaiian Islands, and the Great Lakes. Enhanced flow of warm, humid air via cyclonic motion occurs in central Alaska, leading to increased precipitation. An increased influx of warm, humid air tends to extend to British Columbia and Washington, but with anti-cyclonic conditions that do not favor precipitation. Thus, these regions become drier during positive phases of the PDO.

Understanding the effects of the PDO on North American hydroclimate is easier when it is coupled with the Atlantic Multidecadal Oscillation (AMO). The AMO is an index of average SSTs in the North Atlantic from 0 to 70° north. Like the PDO, the AMO has a period of approximately 50 to 80 years (McCabe *et al*. 2004), and is characterized by both a cold and warm phase (referred to as negative and positive AMO, respectively). McCabe *et al.* (2004) found that the combined effect of the AMO and PDO accounted for nearly 52% of drought occurrence. These indices were helpful in determining the spatial and temporal patterns in conterminous United States drought frequency. McCabe *et al.* (2004) found that different combinations of phases of these indices resulted in various regional effects on hydroclimate. A combination of positive PDO and positive AMO results in increased drought frequency throughout the northern two-thirds of the United States (reminiscent of the 1930s drought). When PDO is positive and AMO is negative, above normal drought frequencies occur in the Pacific Northwest and Maine. A combination of negative PDO and positive AMO is characterized by increased drought frequency in the Midwest, southwest, Rocky Mountains, and Great Plains regions (reminiscent of the 1950s drought). Lastly, when both PDO and AMO are negative, increased drought frequency occurs in southern California and the Central High Plains.

Further investigation of the combined effects of phases of the AMO and ENSO on hydroclimate in the continental United States shows the spatial relationships of the drought patterns associated with the AMO and their notable effects on streamflow (Enfield *et al.* 2001). Sections of the Northeast, Florida, and the Pacific Northwest have drought patterns that are positively correlated with the AMO while the Ohio River Valley, the Great Plains, and areas west of the Continental Divide are negatively correlated.

The Pacific North American (PNA) teleconnection serves as another source of climatic forcing that influences temperature and precipitation patterns in the conterminous United States (Leathers *et al*. 1991). The PNA is measured according to geopotential height anomalies over three western hemisphere reference locations – the North Pacific Ocean near approximately 45ºN, the mountains of the northwestern United States, and the southeast region of the United States (Wallace and Gutzler 1981; Leathers *et al*. 1991). Height anomalies in the North Pacific region and southeastern United States are positively correlated to each other (as they are generally characterized by regional troughing) and negatively correlated to anomalies in the western mountains (where synoptic scale ridging is the climatic norm). Fluctuations in PNA phase affect the placement of atmospheric flow patterns such that when the PNA phase is positive, a greater meridional displacement from the mean flow occurs. When the PNA phase is negative, flow patterns become more zonal in nature. Leathers *et al.* (1991) found that significant linkages exist between PNA fluctuations and temperature and precipitation patterns in the conterminous United States.

2.3 The Purpose of This Study

Knowledge of the large scale phenomena responsible for drought occurrence can then be applied to smaller scale studies of droughts to understand how these contributing factors work to produce signatures on a regional scale. Therefore, this study seeks to identify the large scale phenomena that were factors in drought occurrence in Delaware and to track how signatures on the landscape vary spatially and temporally with each of the studied events.

Several studies have been conducted that have investigated the effects of the aforementioned large scale phenomena at regional and state levels (*e.g.*,Trnka *et al.* 2009; USDI and USGS 2005; Dupigny-Giroux 2001; Hayes *et al.* 1997). Each of these studies was unique in that it focused on drought events for a specific region. However, many similarities exist in their methodologies. Except for the report by the Department of the Interior and USGS (2005), each of the case studies used the SPI to monitor droughts. They found that this index was able to detect drought onset before

PDSI or variations of this index that were used (*i.e.*, Modified Palmer Drought Severity Index or a Relative Palmer Drought Severity Index). These studies verify the importance of using the SPI to pinpoint the onset of drought.

Further, all of these studies established certain criteria upon which data selection would be based. Drought monitoring was not just limited to the indices; rather, actual observations were used to supplement data provided by the indices. These additional data included observed precipitation totals collected from weather stations within the state/region of study, streamflow data, and well data (the latter two being used to quantify hydrological drought). Trnka *et al.* (2009) devised a drought climatology for the Czech Republic using 233 of 738 stations that contained the most consistent and complete data sets. Similarly, when selecting sites for gage data in North Carolina, USGS (2005) selected sites with a minimum of ten years of consistent data to assess properly the effect of the 1998-2002 drought on surface water supplies in the state.

Another similarity was the division of the larger area being studied (*i.e.*, the states of North Carolina, Vermont, and the Czech Republic) into smaller subregions. Determination of these subregions was based upon characteristics that provided homogeneity. These include, but were not limited to, similarities in topography, soil properties, and climate. Dividing the larger region of interest into these smaller, near-homogeneous regions was beneficial in that it allowed for a more clear understanding as to why certain locations within the state, country, or region of interest responded to the droughts in the manner observed.

Chapter 3

DATA AND METHODOLOGY

Proper development of a drought climatology for Delaware requires the selection of a suitable study period and an appropriate plan. In 1948, a marked increase occurred in the number of locations within the United States at which regular daily weather observations were recorded, thus making this year a good choice for the beginning of the study period. The last drought period in Delaware occurred in 2005 and thus this year marks the end of the analysis period. This fifty-eight year period includes several climatically important events, including some of the region's most prolonged severe droughts. In addition, all of the sea surface temperature (SST) and teleconnection indices used in this study experienced multiple phase changes during this period, allowing for the analysis of the effects of such changes on drought occurrence in Delaware.

The research objectives of this study include the identification of (1) drought occurrence within the study period, (2) spatial patterns in drought severity within the state, (3) teleconnections between drought occurrence and anomalous Atlantic and Pacific Basin SSTs, and (4) patterns of synoptic conditions associated with the onset, continuation, and cessation of drought in Delaware.

3.1 Identification of Meteorological Drought

Drought index data – from the PDSI, the SPI-1, and SPI-3 – were acquired from the National Climatic Data Center (NCDC)[1]. For all three indices, monthly data were collected for the two climate divisions that cover Delaware[2]. This includes the Northern Climate Division, which is comprised of New Castle County, and the Southern Climate Division, which encompasses Kent and Sussex Counties (Figure 3.1).

Initial identification of drought occurrence was made using PDSI values. A drought was defined when the PDSI fell below –1.0 for a minimum of three months and reached –2.0 for at least one month within the dry spell. Because studies have shown that a lag exists between actual drought onset and onset marked by the PDSI (*e.g.* Hayes *et al.* 1996), the SPI-3 was also used to determine drought occurrence. Successive negative SPI-3 values over the course of at least three consecutive months were also used to indicate a drought, provided a value equal to or less than –1.0 was recorded for a minimum of one month during the dry spell.

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[1] The Z-index and Crop Moisture Index (CMI) were described in detail in Chapter 2. These indices are most beneficial in the identification of agricultural drought. Because this study focuses primarily on the occurrence of meteorological and hydrological drought in Delaware (as opposed to agricultural drought), the Z-index and CMI were not used in this project.

[2] Climate divisions are determined by NCDC. There are 344 climate divisions within the contiguous Unites States. The delineation of their boundaries is based on several factors, including but not limited to, homogeneous climatic characteristics and geography (Guttman and Quayle 1996).

Drought cessation was marked by the return of the observed PDSI to values greater than –1.0 and positive SPI-3 values over the course of multiple consecutive months. This method is similar to that used by Svoboda *et al*. (2009) in the creation of a drought climatology for the Czech Republic. Successive monthly measurements of PDSI values below –1.0 and negative SPI-1 values were used to mark the occurrence of a drought in the Svoboda *et al.* (2009) study (provided PDSI values fell below –2.0 at least once within the dry spell and SPI-1 values below –1.0). For the current study, SPI-3 values were used rather than SPI-1 because the latter produced relatively noisy time series plots, whereas SPI-3 yielded clearly distinguishable patterns of droughts and returns to normal conditions. Further, SPI-3 values incorporate antecedent and current precipitation data which make it possible to understand better the return to normal moisture conditions for a given climate division.

It is to be noted that only dry spells that extended into the summer months were included in this study. Those occurring solely during the cooler months (with the dry spell being observed only at some time between October and February) were excluded from the final list of identified drought events. This decision was based on the fact that the effects of precipitation shortages are more evident during the warm season as temperatures are warmer, thus leading to higher rates of evapotranspiration. In addition, greater anthropogenic demand also is placed on water resources during the warm season (*e.g.* increased use for agriculture, horticulture, recreation), thus exacerbating the stresses on the system during a dry spell. Such additional strain on the system is generally not associated with reduced moisture during the cold season.

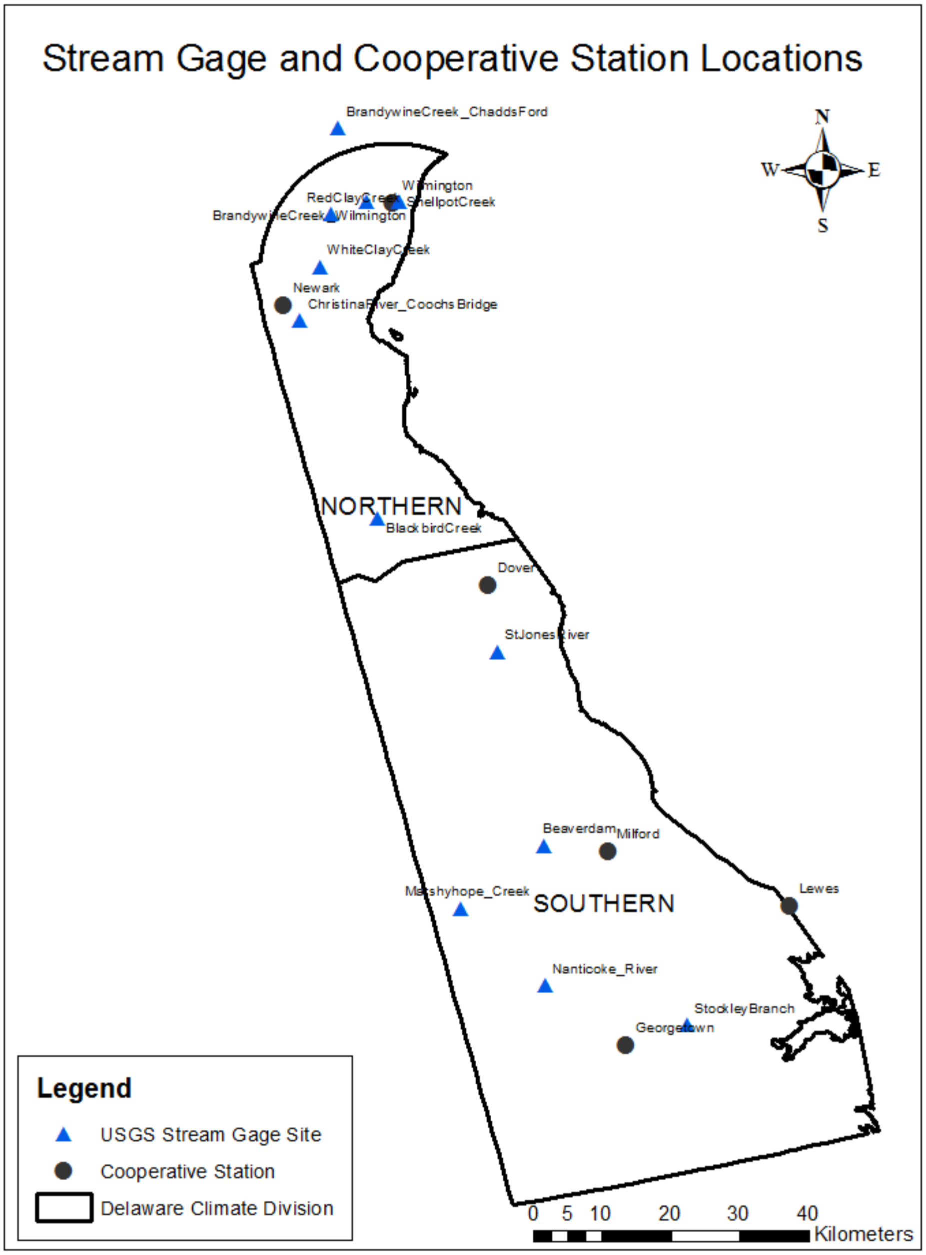

Figure 3.1. Stream gage and cooperative station locations used in study.

3.2 Identification of Spatial Patterns in Drought Severity

Monthly precipitation data from six of Delaware's cooperative station network weather observation sites (after referred to as COOP sites/stations) were used to quantify the severity of each drought event observed across the state. COOP station data were obtained from the NCDC for the study period (*i.e.*, January 1948 through December 2005). It is important to note that the number of COOP sites used in the study is relatively low. Although twenty-three COOP stations exist in Delaware, all do not share a common period of record. That of most stations did not extend through the majority of the study period. Thus, the six stations chosen (Figure 3.1) were selected based on the completeness of their records (although several stations had missing data for several of the events) and the relatively even spatial distribution they provided.

Severity of each drought event was identified by the departures from the mean total water year precipitation using climate normals based on the period from 1971 to 2000. Each event was quantified using standard deviation units from the climate normal period to determine whether the observed departure from mean annual precipitation was within the range of normal variability or indicative of drought conditions. Total water year values within one standard deviation were considered to be 'normal', those less than -1σ were classified as indicative of drought, and those greater than +1σ were classified as 'wetter than normal'.[3] Larger negative departures from the mean thus are indicative of greater drought severity.

To analyze spatial patterns in drought occurrence, the preceding methods were used to create a dataset comprised of this information for all of the COOP sites used in the study. These data were evaluated to discover whether there were identifiable trends as to which parts of the state tended to be more or less severely impacted during the occurrence of meteorological drought.

3.3 Identification of Hydrological Drought

Mean monthly streamflow data from twelve United States Geological Survey (USGS) stream gages were used to define hydrological drought during the study period (Figure 3.1). One stream gage used in the study (USGS stream gage 01481000) was located in Pennsylvania on the Brandywine Creek at Chadds Ford. This site was included as part of the analysis because the Brandywine River serves as a major source of drinking water for the greater Wilmington, DE area, providing water for more than 500,000 people (Kauffman and Vonck, 2011). Drought-induced flow changes in this river can potentially affect a large percentage of the Delaware populace, making it important to understand how this surface water body is affected

[3] The return to normal conditions following a drought is marked by water year precipitation totals that are within one standard deviation from the mean, and not necessarily those that are greater than one standard deviation from the mean.

by deficient precipitation.[4] All of the remaining eleven stream gages were located in Delaware.

For this study, hydrological drought was defined by successive months in which mean monthly streamflow fell below the twenty-fifth percentile (Q25). Similarly, Dupigny-Giroux (2001) used Q25 as the truncation level below which flows were classified as low and indicative of hydrological drought. The monthly Q25, mean, and Q75 (*i.e.* the seventy-fifth percentile) values were calculated for all streams using their respective period of record. These values were then plotted with event observed streamflow to identify the occurrence, duration, and recovery from hydrological drought, with recovery marked by the return of observed monthly streamflows above the Q25 level.

Recovery from hydrological drought (as well as meteorological drought) can occur relatively quickly with the occurrence of a major precipitation event (*e.g.*, the passing of a tropical storm over a drought-stricken region). Stream hydrographs may indicate that the return to normal streamflow occurred within a relatively short period of time, such as a day. Thus, monthly streamflow data may be insufficient to capture the essence of recovery from hydrological drought. For this reason, daily streamflow data were collected for the months in which the drought indices indicated the ending of meteorological drought and those in which observed monthly streamflow returned

[4] It is important to note that hydrological drought is often exacerbated by anthropogenic stresses introduced to the system (*i.e.*, increased water withdrawals during the warm season). Thus, deficient precipitation should not be accepted as the only cause for changes in streamflow during meteorological drought.

to the normal range (between Q25 and Q75). The data were analyzed so that the timing of the return to normal streamflow could be pinpointed.

3.4 Identification of Teleconnections

To determine potential causal factors for drought occurrence in Delaware, data were gathered from four sea surface temperature (SST) and teleconnection indices. Monthly data were acquired for the Pacific Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO), Pacific/North American teleconnection (PNA), and Niño 3.4 region SST (hereon shortened to Niño 3.4) indices. Monthly data for the PDO was obtained from the Joint Institute for the Study of the Atmosphere and Environment (Mantua et. al 1997)[5]; monthly data for the AMO, PNA, and Niño 3.4 indices were obtained from the NOAA/OAR Earth Science Research Laboratory[6]. With the exception of the Niño 3.4 dataset, data were available for the entire study period. For that dataset, however, data were available only since 1950. Thus, the Niño 3.4 analysis will not be available for 1948 and 1949.

Chi-square one-sample and contingency tests were used to identify statistically significant relationships between drought occurrence and the specific phases of each of the indices. SPI-1 values were utilized in the categorization of drought incidence. Each month was classified as either drought or non drought, where SPI-1 $\leq$ -1

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[5] Pacific Decadal Oscillation index data was accessed via the internet at http://jisao.washington.edu/pdo/PDO.latest.

[6] National Climatic Data Center data obtained online at http://www.esrl.noaa.gov/psd/.

indicated drought conditions during a given month, and SPI-1 > -1 indicated non-drought conditions. In a similar fashion, the SST and teleconnection indices were categorized based on their phase. These phases served as the basis for the classification scheme used in the statistical analysis. The phases identified for each index were as follows:

PDO as either positive or negative

AMO as warm, cool, or neutral

ENSO as El Niño (warm), La Niña (cool), or neutral

PNA as positive, negative, or neutral.

The categorization developed for drought incidence and SST/teleconnection index phase was applied in the creation of a numerical classification of the two datasets. This numerical classification was then used in the chi-square and contingency tests, which were run using the Statistical Package for the Social Sciences (SPSS). The statistical analysis consisted of two sets of tests, each of which was performed for each climate division. In the first set, chi-square one-sample and contingency tests were performed to see if statistically significant relationships existed between drought occurrence and each of the individual SST/teleconnection indices. The second set of tests was used to investigate whether various combinations of the indices could be found to influence drought occurrence (*i.e.*, if combinations of PDO and AMO, ENSO and PNA, *etc*. lead to droughts within Delaware). Six combinations of index phases were tested: PDO/PNA, PDO/AMO, PDO/ENSO, AMO/ENSO, PNA/AMO, and PNA/ENSO. Each test run included data for drought occurrence and each respective SST/teleconnection index phase or phase combination over the study period (1948-2005).

This form of statistical analysis was chosen because it provided a means by which conclusions could be drawn regarding the relationship between observed variations in the SST and teleconnection indices and drought occurrence in Delaware[7]. Only relationships found to be significant at the $\alpha = 0.05$ level were considered to have a significant influence on the occurrence of drought in the study region[8].

3.5 Identification of Patterns in Synoptic Conditions Associated with the Onset, Duration, and Cessation of Drought

To identify if synoptic patterns were associated with drought occurrence in Delaware, 500hPa geopotential height (or simply 500hPa height) maps were obtained for each of the drought events. The 500hPa pressure level is within the mid-troposphere and has an average altitude of approximately 5500m. This level was chosen because trough and ridge patterns can be identified easily there. Two sets of map images were obtained from the NCEP/NCAR Reanalysis 1 dataset (made available through the NOAA/OAR Earth Science Research Laboratory as provided

[7] Other statistical analyses (*i.e.* correlation analysis) would have required linear relationships amongst the variables.

[8] The $\alpha = 0.05$ level is the most commonly used significance level. For this study, test results in which $P > 0.05$ were not considered significant as such results may have led to the inclusion of relationships that cannot be explained beyond chance.

through their website[9]) for this part of the analysis. The first set consisted of the mean monthly 500hPa plots, which were analyzed to identify the trough/ridge patterns present during drought events. The second set was comprised of monthly and seasonal height anomalies, which were included to assist in detecting how changes in the mean circulation pattern over the study region may cause or affect the occurrence of drought.

Both sets of maps obtained had the same spatial extent. The area plotted extended from 20°N to 60°N latitude. This allowed for the inclusion of the entire conterminous United States. The meridional extent ranged from 10°W to 140°W longitude. This extent provides a better examination of the effects of a more northern or westward expansion of the Azores high on circulation patterns potentially affecting weather systems and thus drought in the United States, specifically Delaware (and the Mid-Atlantic region).

3.6 Summary

These data and techniques were utilized in the development of a drought climatology for Delaware. The events identified, as well as spatial patterns in drought occurrence, effects on surface hydrological systems (*i.e*. state rivers and streams), and teleconnections and synoptic patterns associated with drought occurrence in Delaware are discussed in the following chapter.

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[9] NCEP Reanalysis 1 dataset accessed online at http://www.esrl.noaa.gov/psd/.

Chapter 4

RESULTS AND DISCUSSION

4.1 Drought Identification

Using the data and methods of the previous chapter, a total of twelve drought events were identified and placed within their larger historical context (Table 4.1). Severity and extent of meteorological drought is then quantified based on COOP station data, and that of hydrological drought is analyzed using stream gauge data.

Table 4.1: Summary of drought events identified during study period 1948-2005[10].

Event	Drought Period	Low Flow/ Hydrological Drought In Majority of Streams	Drought Characterized as Extreme at Some Point During Event in Climate Division 1	Drought Characterized as Extreme at Some Point During Event in Climate Division 2
1	04/1949 - 11/1951	X		
2	08/1953 - 05/1956	X	X	
3	02/1957 - 09/1957	X		
4	09/1961 - 11/1970	X	X	X
5	02/1976 - 11/1977	X		X
6	01/1980 - 02/1982	X		
7	09/1984 - 02/1989	X	X	X
8	04/1991 - 10/1992			
9	10/1994 - 09/1995	X		
10	04/1997 - 12//1997	X		
11	08/1998 - 09/1999	X		X
12	08/2001 - 09/2002	X	X	X

4.2 Characterizing the Events Identified

4.2.1 Event 1: April 1949 to November 1951

Precipitation deficits were not observed during this event until the 1950 water year, during which all sites recorded totals significantly below the mean (Table 4.2). Exceptionally dry conditions were not isolated to any particular section of the state, although stream response to this dry spell did vary (Figure 4.1). At the majority of stream gauge sites, low flow observations were made only briefly, with no prolonged

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[10] Occurrence of extreme drought in both climate divisions as listed in the table is confirmed by Northeast Regional Climate Center (NRCC 2012).

trends of streamflow below the Q25 level. Extended periods of low flow were measured at four stream gauge sites: Nanticoke River, Stockley Branch, Shellpot Creek, and Marshyhope Creek (consult Figure 3.1 for a map of all stream gauge locations). As expected, a lag exists in the onset of meteorological drought and low flow conditions; occurrence of the latter did not begin until late 1949. As the drought persisted through 1950 and into 1951, streamflow levels remained generally below average, but within the range of normal ($Q25 \leq Q \leq Q75$). A gradual decline in streamflow was observed at most locations through the 1951 calendar year, and many measurements were made in the low end of the normal range. The drought ended in late 1951 following a significant precipitation-producing event that occurred on December 1, 1951. Subsequently, streamflow levels increased, and precipitation totals for the 1952 water year were above the annual mean at all COOP stations.

Table 4.2. Cumulative departures from mean annual precipitation as observed at each COOP station during event 1. All values are given in millimeters; those in bold print exceed +/- 1σ.

COOP Site	**1949 Water Year**	**1950 Water Year**	**1951 Water Year**	**1952 Water Year**
Newark	18.0	-151	-74.9	**424**
Wilmington	-95.5	**-240**	**-296**	**270**
Dover	48.8	**-210**	**-211**	**437**
Lewes	106	**-242**	**-199**	149
Georgetown	203	-160	**-290**	145
Milford	1.78	**-258**	-----	**288**

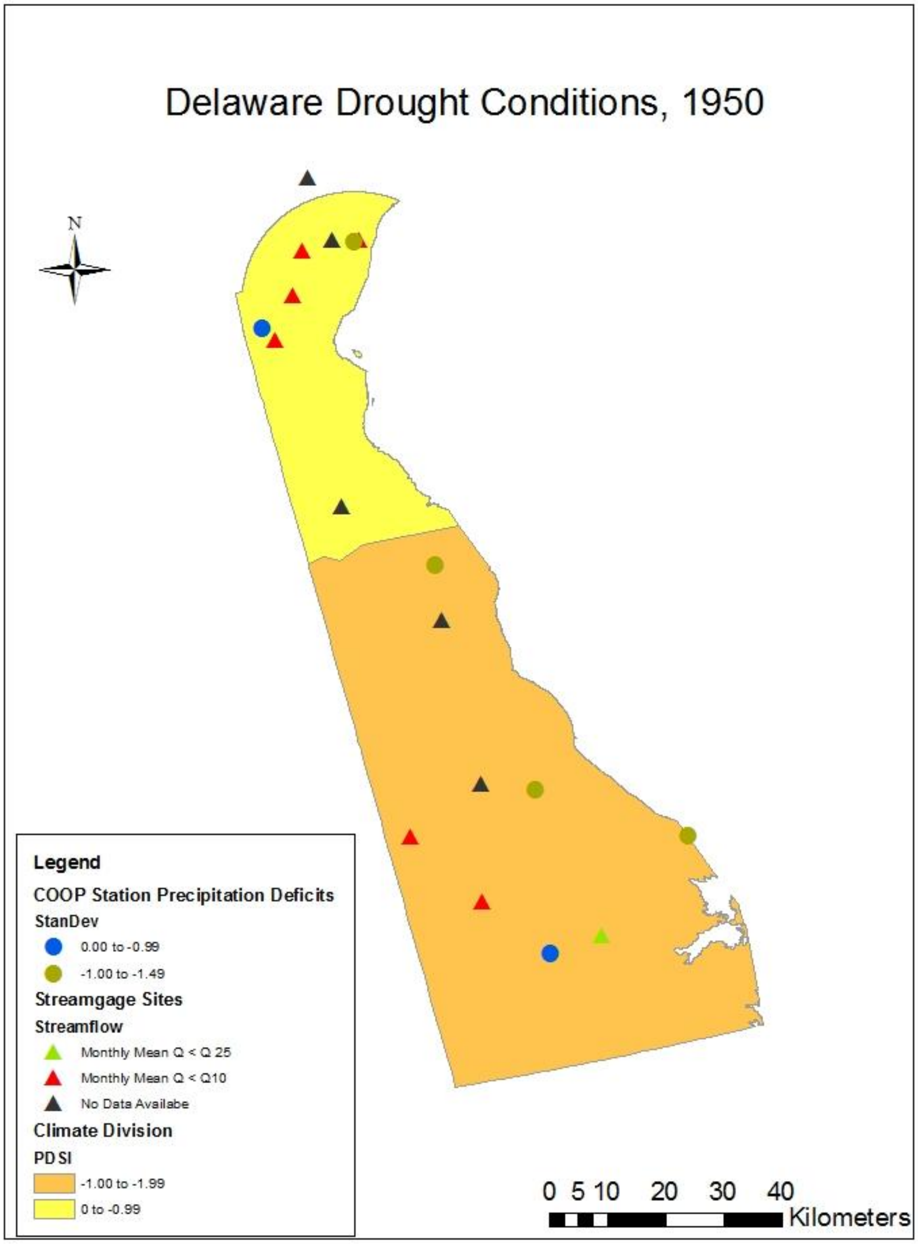


Figure 4.1. Spatial patterns of meteorological and hydrological drought in Delaware during the height of Event 1 (January 1949-November 1951).

4.2.2 Event 2: August 1953 to May 1956

Since this event began in August, precipitation totals for the 1953 water year did not exhibit any signs of meteorological drought. Drought conditions worsened quickly during the 1954 water year (Table 4.3). Conditions were driest (meteorologically speaking) in the northern half of the state, as Newark, Dover, and Wilmington recorded large cumulative departures from mean precipitation over the duration of the event. Cumulative water year totals in the three southernmost COOP stations (Milford, Georgetown, and Lewes) were largely within the range of normal for the years during which this event occurred (with the exception of Milford in the 1956 water year).

Low flow observations were made in several streams relatively early during this event. At the Brandywine Creek at Wilmington, Christina River at Coochs Bridge, and the White Clay Creek near Newark gauge sites, low flows began in August/September 1953. Periodic intense low flows ensued in all streams throughout the duration of this event. Notable periods include approximately May through September 1954 and March/April through August 1955. Stream gauge records indicate a nearly instantaneous recovery as of August 13, 1955. This is associated with the land fall of Tropical Storm Connie, which brought record-breaking rainfall to the region. Within one week of TS Connie, Hurricane Diane traversed the mid-Atlantic region, bringing large rainfall to already saturated land. This helped to restore streamflow fully and end the low flow period. Drought conditions at the height of the drought (1954) are displayed (Figure 4.2).

Table 4.3. Cumulative departures from mean annual precipitation as observed at each COOP station during event 2. All values are given in millimeters; those in bold print exceed +/- 1σ.

COOP Site	1953 Water Year	1954 Water Year	1955 Water Year	1956 Water Year
Newark	45.7	**-349**	-37.6	-98.6
Wilmington	-31.5	**-343**	**-241**	**-282**
Dover	-73.9	-203	-55.9	**-229**
Lewes	**257**	-137	-84.6	41.1
Georgetown	37.8	-124	66.0	134
Milford	**213**	-23.9	-22.9	**-227**

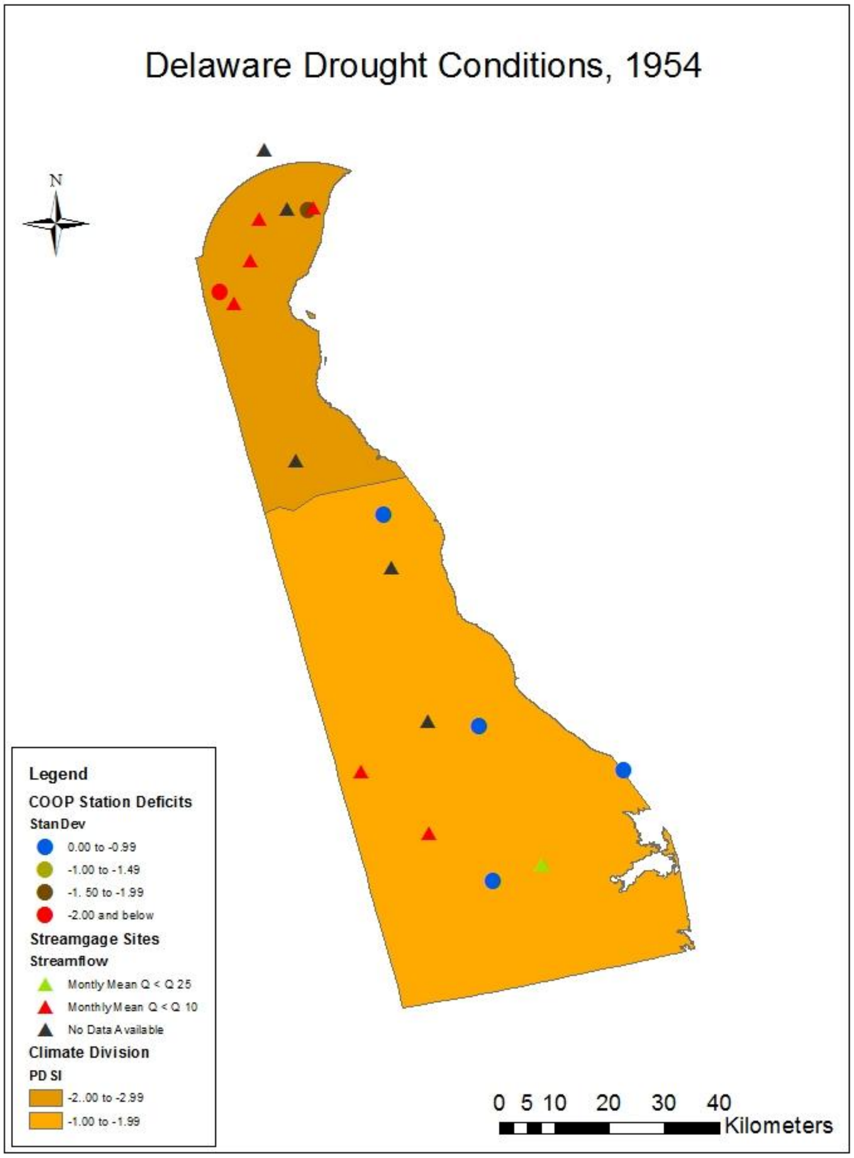


Figure 4.2. Spatial patterns of meteorological and hydrological drought in Delaware during the height of Event 2 (August 1953 – May 1956).

4.2.3 Event 3: February 1957 to September 1957

Following a brief break in drought conditions during the latter half of the 1956 calendar year (as indicated in all three drought indices), the dry spell recommenced in the late winter of 1957. With the exception of Lewes, all COOP stations recorded cumulative water year precipitation totals that were below the mean (Table 4.4). While these values may not have exceeded -1.0σ at all locations, they are significant as they represent the fourth consecutive year of deficient precipitation at the majority of the sites. Precipitation totals were significantly above normal during the 1958 water year, thereby ending the dry spell.

Low streamflow observations began in the late spring of 1957, lagging the onset of this event by several months. With the gradual return to normal precipitation patterns, there was no specific date at which streamflow returned to mean levels across the state. Several gauge sites in northern Delaware displayed a return to normal flow in September 1957 (*i.e.,* the Christina River, the Red Clay Creek, and the Shellpot Creek). Several streams in southern Delaware began to exhibit normal flow in October 1957 (the Nanticoke River and Marshyhope Creek). Figure 4.3 displays the spatial patterns of meteorological and hydrological drought observed during this event.

Table 4.4. Cumulative departures from mean annual precipitation as observed at each COOP station during event 3. All values are given in millimeters; those in bold print exceed +/- 1σ.

COOP Site	**1957 Water Year**	**1958 Water Year**
Newark	-149	**275**
Wilmington	**-305**	183
Dover	-192	**355**
Lewes	129	**536**
Georgetown	**-223**	**351**
Milford	-100	**465**

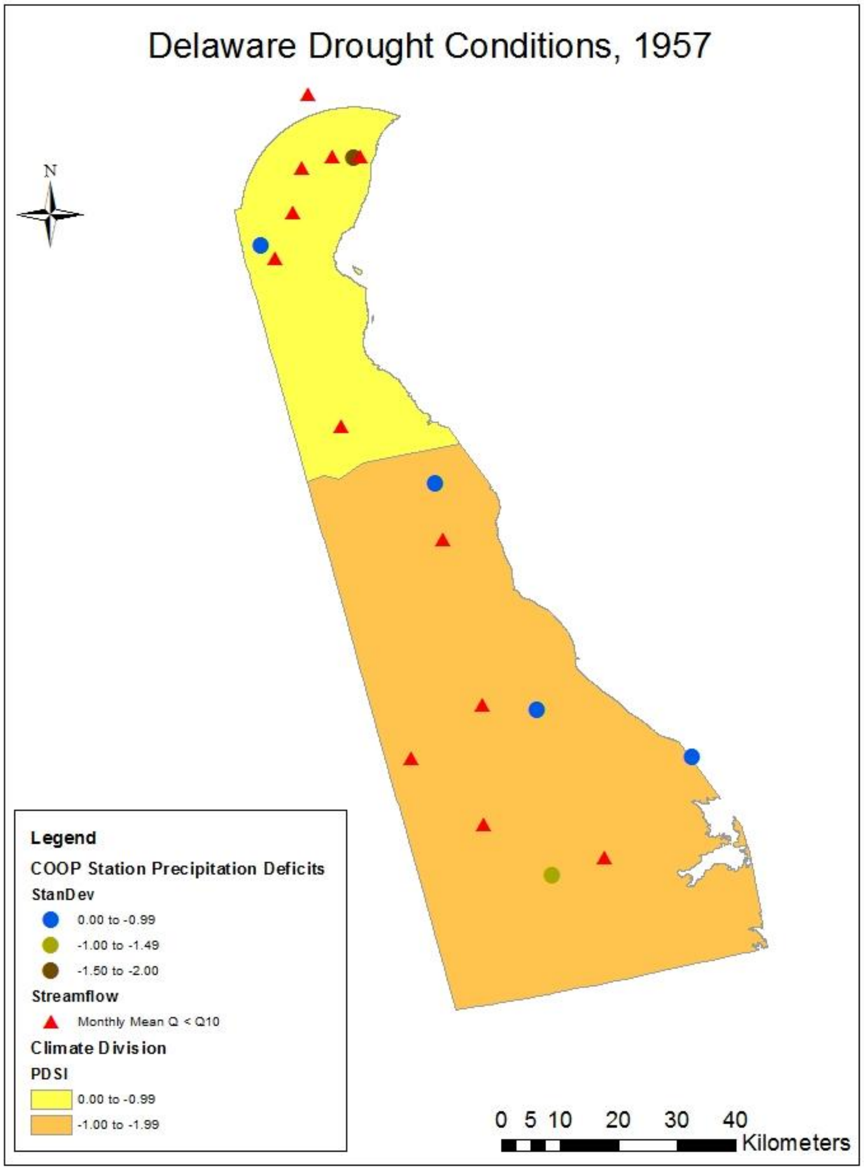


Figure 4.3. Spatial patterns of meteorological and hydrological drought in Delaware during the height of Event 3 (February 1957 – September 1957).

4.2.4 Event 4: September 1961 to November 1970

This event, which covered nearly a decade, is one of the most well-known and widespread droughts to have affected the Northeast and Mid-Atlantic Regions. Over the course of the event, numerous records were set in the region for driest months on record and lowest recorded daily streamflow amounts. The persistence of the drought created conditions so dry that federal water shortage emergencies were declared by FEMA in August 1965 for Pennsylvania, New York, New Jersey, and Delaware (FEMA 2012). In Delaware, the intensity of this prolonged event severely reduced soil moisture, prompting the declaration of an agricultural disaster in the state by Governor Charles L. Terry on September 21, 1967. Drought conditions gradually lifted following the return to normal precipitation patterns beginning in late 1969.

Precipitation deficits grew progressively worse over the course of this event (Table 4.5). With the exception of the 1967 water year, significantly large cumulative departures from mean annual precipitation were recorded every year. The 1965 and 1968 water years exhibit the greatest intensity in meteorological drought; precipitation deficits during these two years were, on average, approximately equal to -1.7σ. The intensity of the drought during 1965 is displayed in Figure 4.4. By the end of the 1970 water year, cumulative event departures had reached exceptionally high levels at all COOP sites, for example Newark: -2.37×10^3mm; Wilmington: -2.37×10^3mm, Dover: -1.91×10^3mm, Lewes: -1.25×10^3mm, Georgetown: -9.85×10^2mm, and Milford: -1.50×10^3mm (the Milford dataset did not have values for the 1966 and

1967 water years). These values indicate that the greatest drought intensity (meteorological) occurred in northern portions of the state.

The majority of streams displayed a similar pattern from the onset of the event through the fall of 1966 – normal streamflow during the winter and early spring, and low flow during the late spring through autumn. The intensity of hydrological drought peaked during the summer of 1966 as the majority of stream gauge sites reported streamflow well below the Q25 level for several prolonged periods (*i.e.*, daily observations below the Q25 level for consecutive days and weeks). Both the White Clay Creek near Newark and Red Clay Creek at Wooddale recorded their lowest flows on record in September 1966, nearly running dry (streamflow was equal to 0.134 and 0.082 cubic meters per second, respectively). Streamflow returned to normal levels in 1967 following the gradual increase in monthly precipitation totals and the landfall of Hurricane Doria in September 1967. Following this, the event was characterized by periodic low flow, without a uniform recovery for all streams. The majority of streams began to recover following a large precipitation-producing event that occurred on December 10 and 11, 1969. The remaining streams recovered at various times between 1970 and 1971, including October 1970 (the Red Clay Creek), February 1971 (Stockley Branch), and autumn 1971 (Blackbird Creek, St. Jones River, and White Clay Creek).

Table 4.5a. Cumulative departures from mean annual precipitation as observed at each COOP station during event 4. All values are given in millimeters; those in bold print exceed +/- 1σ.

COOP Site	1961 Water Year	1962 Water Year	1963 Water Year	1964 Water Year	1965 Water Year
Newark	**-195**	**-253**	**-304**	**-373**	**-371**
Wilmington	-113	**-282**	**-325**	**-326**	**-279**
Dover	-67.6	**-251**	**-278**	**-250**	**-496**
Lewes	-14.0	-31.0	-139	-107	**-216**
Georgetown	107	-52.6	-158	-189	-172
Milford	-185	-226	-116	**-252**	**-308**

Table 4.5b. Cumulative departures from mean annual precipitation as observed at each COOP station during event 4. All values are given in millimeters; those in bold print exceed +/- 1σ.

COOP Site	1966 Water Year	1967 Water Year	1968 Water Year	1969 Water Year	1970 Water Year	1971 Water Year
Newark	**-310**	46.7	**-309**	-146	-160	103
Wilmington	**-355**	152	**-386**	**-230**	**-229**	**206**
Dover	**-458**	175	**-295**	**213**	**-206**	188
Lewes	**-226**	-35.3	**-390**	-62.2	-29.0	-145
Georgetown	**-254**	**279**	**-334**	-55.9	-154	35.6
Milford	---	---	**-378**	103	-140	15.24

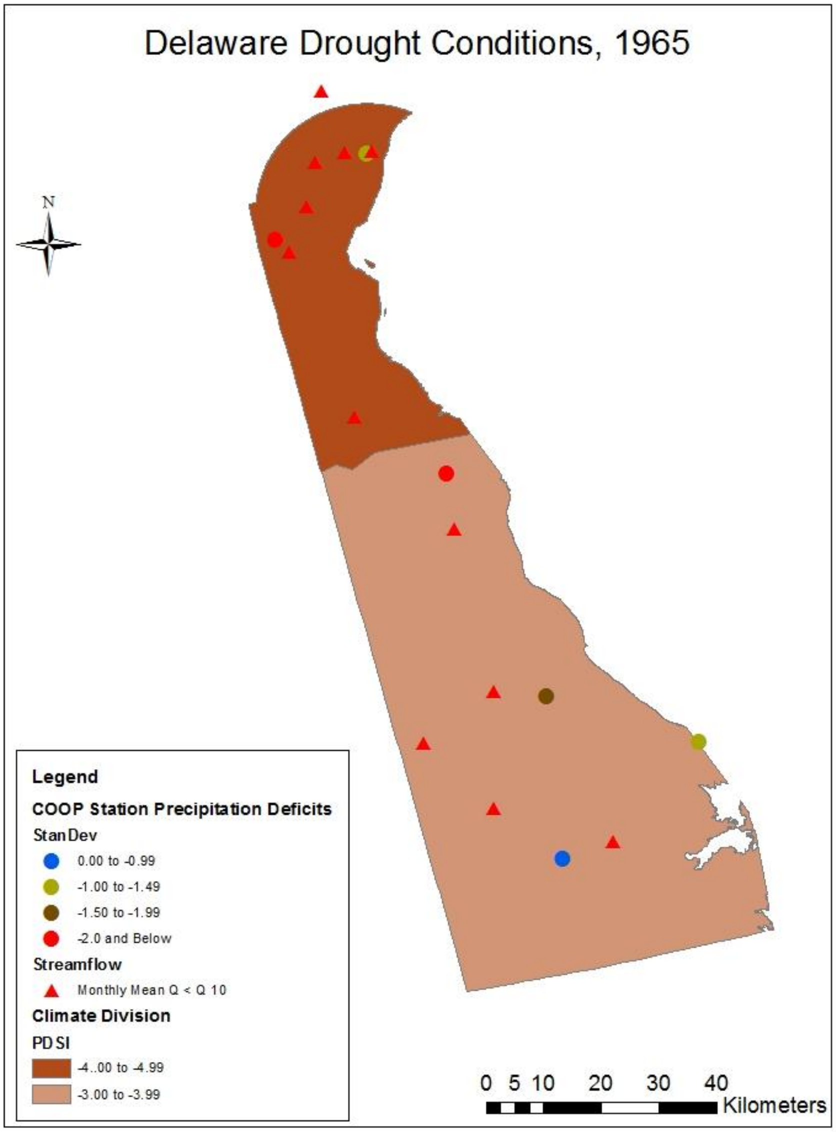


Figure 4.4. Spatial patterns of meteorological and hydrological drought in Delaware during the height of Event 4 (September 1961 - November 1970).

4.2.5 Event 5: February 1976 to November 1977

The spatial extent of this event was not as far-reaching in the Northeast as the drought of the 1960s. In particular, the drought in Delaware was unusual in that only moderate drought conditions were observed in the Mid-Atlantic region while many parts of the western United States experienced severe drought during this period (Matthai 1979). Significant cumulative departures from mean precipitation were recorded in Delaware during both the 1976 and 1977 water years (Table 4.6). Precipitation deficits varied during this event, with no bias toward drier conditions in any particular portion of the state (Figure 4.5).

During this event, several stream gauge sites showed no signs of hydrological drought (streamflow did not fall below the Q25 level); rather, streamflow remained at the low end of the normal range. These sites include the Brandywine Creek at Chadds Ford and Wilmington and Blackbird Creek. Intermittent periods of low flow were observed at the remaining sites, with two main prolonged periods occurring from April through October 1976 and April through November 1977. Cessation of both the meteorological and hydrological droughts resulted from the gradual return to normal precipitation patterns following a large precipitation-producing event that occurred on November 7, 1977.

Table 4.6. Cumulative departures from mean annual precipitation as observed at each COOP station during event 5. All values are given in millimeters; those in bold print exceed +/- 1σ.

COOP Site	**1976 Water Year**	**1977 Water Year**	**1978 Water Year**
Newark	**-206**	-137	**187**
Wilmington	**-263**	-185	**386**
Dover	-204	**-229**	**287**
Lewes	**-201**	**-327**	**182**
Georgetown	**-226**	-192	**243**
Milford	-106	**-278**	**218**

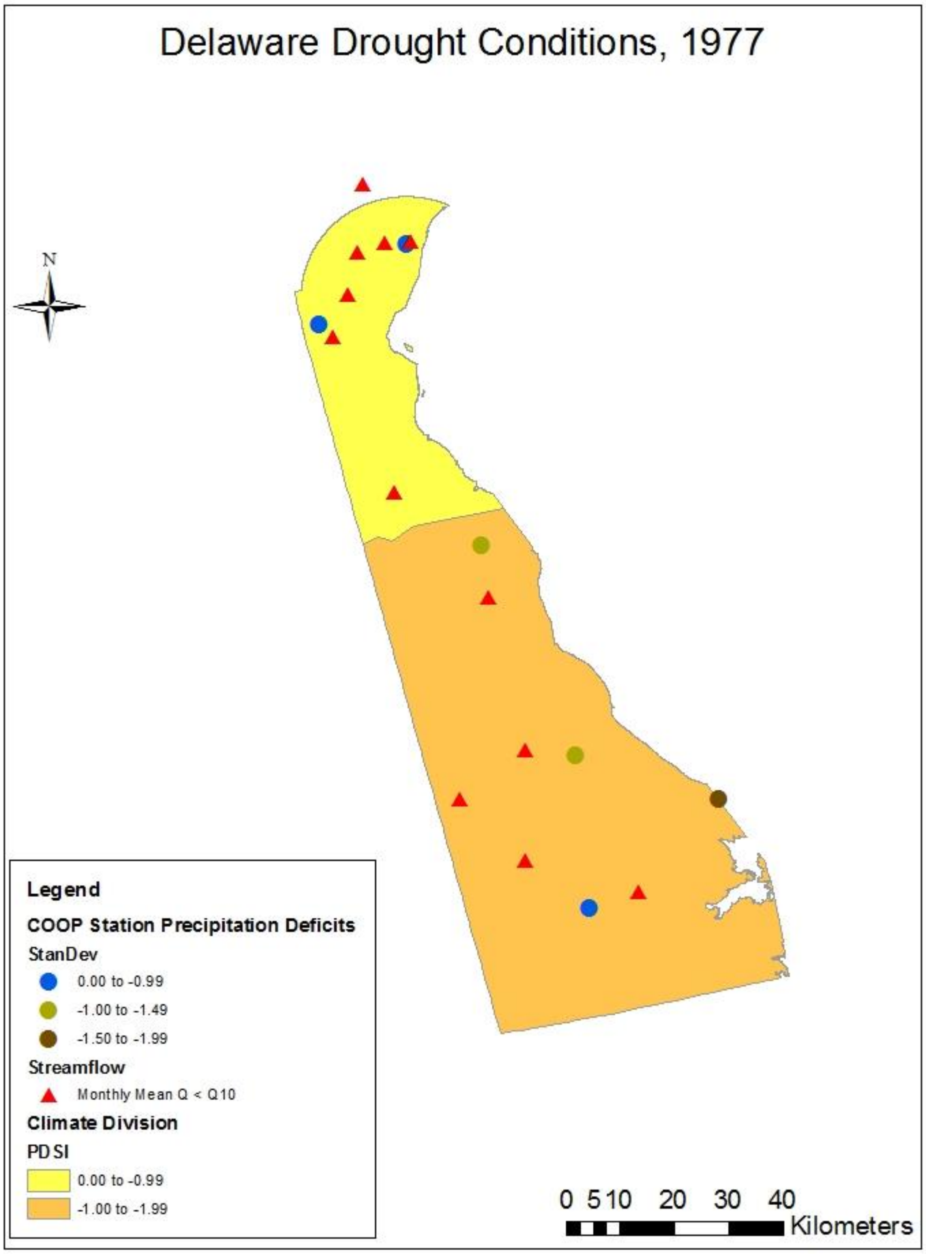


Figure 4.5. Spatial patterns of meteorological and hydrological drought in Delaware during the height of Event 5 (February 1976 – November 1977).

4.2.6 Event 6: January 1980 to February 1982

The effects of this event were observed in many portions of the Mid-Atlantic region. Conditions had grown so severe in the Delaware River Basin during its duration that the Delaware River Basin Commission (DRBC 2011) declared a basin-wide drought from January 16, 1981 to April 27, 1982. Within Delaware, moderate drought conditions were observed during this event, with an evident trend toward drier conditions in the northern parts of the state (Table 4.7; Figure 4.6). Interestingly, the lowest drought index values during this event were observed during the winter and early spring, and not necessarily the warmer months.

Periodic low flow was observed in most streams during this event. The two distinct periods during which low flows were observed were August 1980 through January 1981 and late summer 1981 through January 1982. Following the first low flow period, streamflow returned to normal in approximately half of the streams and remained at the low end of the normal range. For the remaining streams, recovery from the second low flow period began on February 1, 1982 following a large precipitation-producing event. While recovery did occur (*i.e.*, streamflow measurements above the Q25 level were made), observations at many streams remained at the low end of the normal range.

Table 4.7. Cumulative departures from mean annual precipitation as observed at each COOP station during event 6. All values are given in millimeters; those in bold print exceed +/- 1σ.

COOP Site	**1980 Water Year**	**1981 Water Year**	**1982 Water Year**	**1983 Water Year**
Newark	**-253**	**-185**	-146	-57.7
Wilmington	**-269**	**-268**	-50.5	-56.4
Dover	-14.5	**-240**	**-219**	181
Lewes	-0.52	-72.9	19.6	137
Georgetown	-160	-146	**-279**	**281**
Milford	-101	-112	**-233**	173

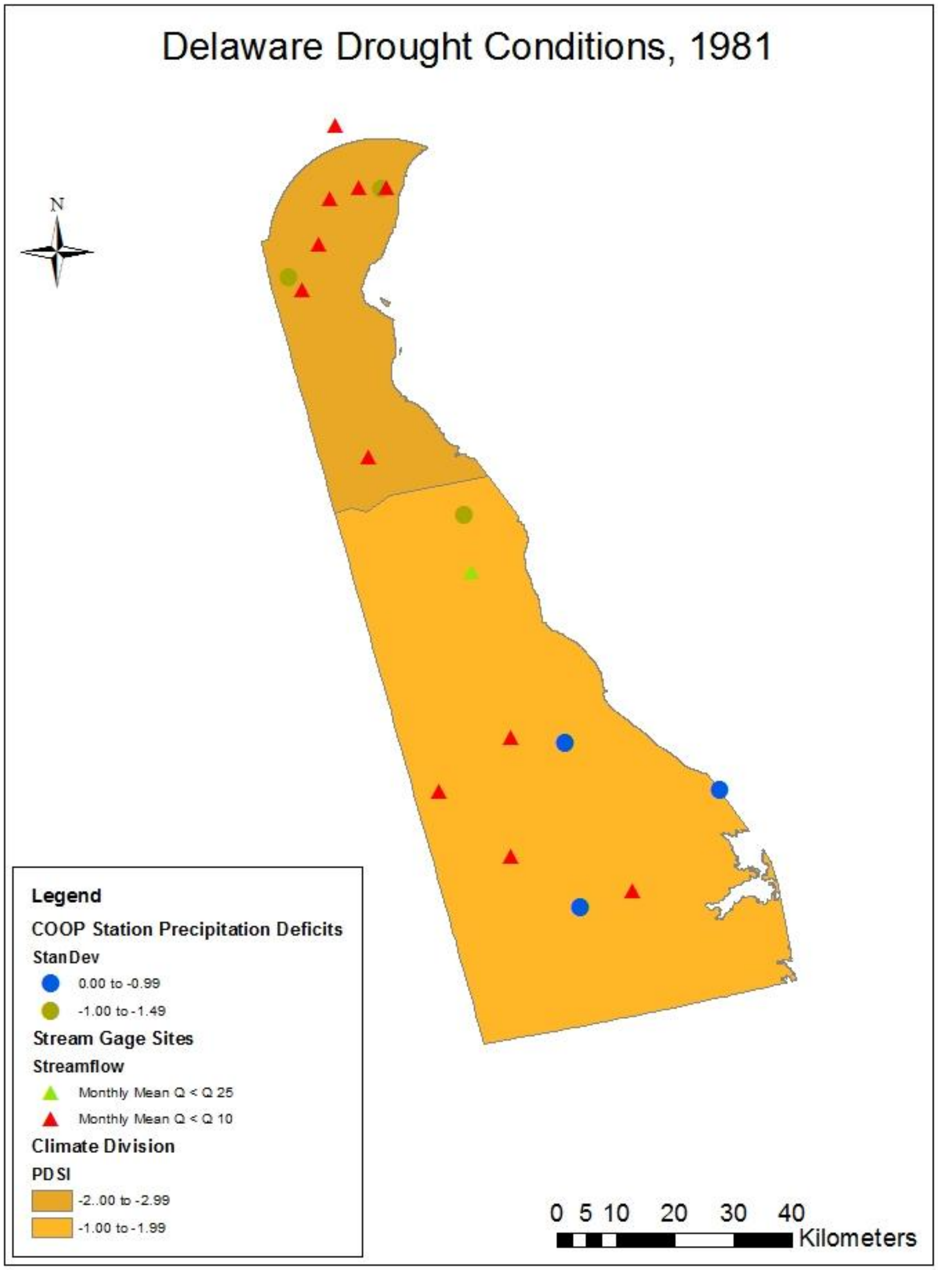


Figure 4.6. Spatial patterns of meteorological and hydrological drought in Delaware during the height of Event 6 (January 1980 – February 1982).

4.2.7 Event 7: September 1984 to February 1989

During this event, severe drought conditions developed across Delaware and a large portion of the Mid-Atlantic region. As in the previous event, the DRBC declared a drought warning with the Delaware River Basin beginning in January 1985. Records for driest month within the respective histories of several weather station sites were made in the region. Extreme drought intensity within Delaware prompted the declaration of multiple drought warnings by Governor Michael Castle in 1985 and 1986. The progressing intensity of this event (with respect to meteorological drought) through the 1989 water year indicates that approximately four consecutive years of deficient precipitation occurred (Table 4.8). Anomalously large precipitation amounts fell in the spring and early summer of 1989, leading to the cessation of this event (NWS, 2005).

Several streams in southern Delaware had a relatively fast response to the onset of this event, including the Beaverdam, the Nanticoke River, the St. Jones River, and Stockley Branch. In the remaining streams, low flow conditions began in the late spring and early summer of 1985 and persisted through September 27, 1985. On that day, streamflow was restored following the landfall of Hurricane Gloria. Low flow conditions returned in the spring of 1986 and persisted through November/December of that year across the state (Figure 4.7). Following the recovery in late 1986, low flow was observed only sporadically at both Brandywine Creek gauges, as well at the gauges along the White Clay Creek and Red Clay Creek. For the remaining streams, a return to low flow conditions began in the summer of 1987 and persisted through the

1988-1989 winter. Precipitation patterns gradually became normal again during the late 1988-1989 winter, resulting in a return to normal streamflow in these streams in late March 1989.

Table 4.8. Cumulative departures from mean annual precipitation as observed at each COOP station during event 7. All values are given in millimeters; those in bold print exceed +/- 1σ.

COOP Site	**1984 Water Year**	**1985 Water Year**	**1986 Water Year**	**1987 Water Year**	**1988 Water Year**	**1989 Water Year**
Newark	**228**	**-218**	**-423**	106	-103	**312**
Wilmington	**332**	**-206**	**-283**	-8.38	-169	**253**
Dover	84.8	-13.5	**-435**	-87.4	-181	**467**
Lewes	205	-77.5	**-410**	-146	**-183**	**386**
Georgetown	157	-68.6	**-310**	-127	-116	**399**
Milford	**---**	-134	**-465**	-94.7	-181	165

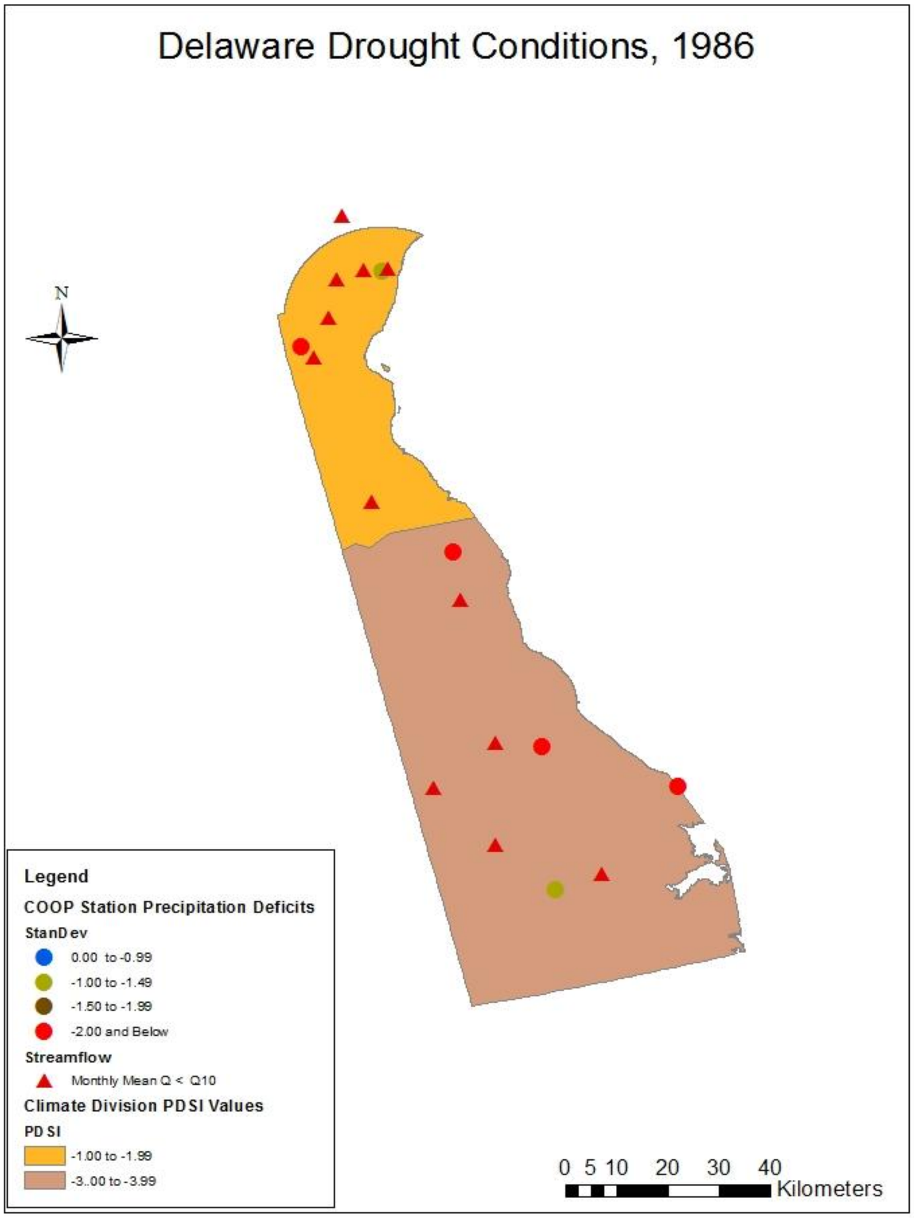


Figure 4.7. Spatial patterns of meteorological and hydrological drought in Delaware during the height of Event 7 (September 1984 – February 1989).

4.2.8 Event 8: April 1991 to October 1992

A large portion of the Mid-Atlantic region was affected by drought conditions during this event. In Pennsylvania, a drought emergency was declared in thirty-nine counties in July 1991 resulting from the intensity of this event (Earth and Environmental Systems Institute 1998) and dry conditions subsequently led to the declaration of a drought warning by the DRBC (DRBC, 2011). In Delaware, the drought was relatively mild compared to several of the previous events. Cumulative departures from mean precipitation were low for most COOP station sites during the 1991 water year and increased only slightly in 1992 (Table 4.9).

With the exception of Blackbird Creek and St. Jones River, none of the streams exhibited low flow at any point during this event. Thus, hydrologic response to this event was limited to the lower New Castle County and upper Kent County region. Figure 4.8 displays the spatial characteristics of this drought at its height in 1992.

Table 4.9. Cumulative departures from mean annual precipitation as observed at each COOP station during event 8. All values are given in millimeters; those in bold print exceed +/- 1σ.

COOP Site	1991 Water Year	1992 Water Year	1993 Water Year
Newark	-143	-94.0	108
Wilmington	3.30	**-280**	132
Dover	-117	-163	**-207**
Lewes	16.51	-80.0	-45.2
Georgetown	-55.9	-87.9	-91.7
Milford	---	---	---

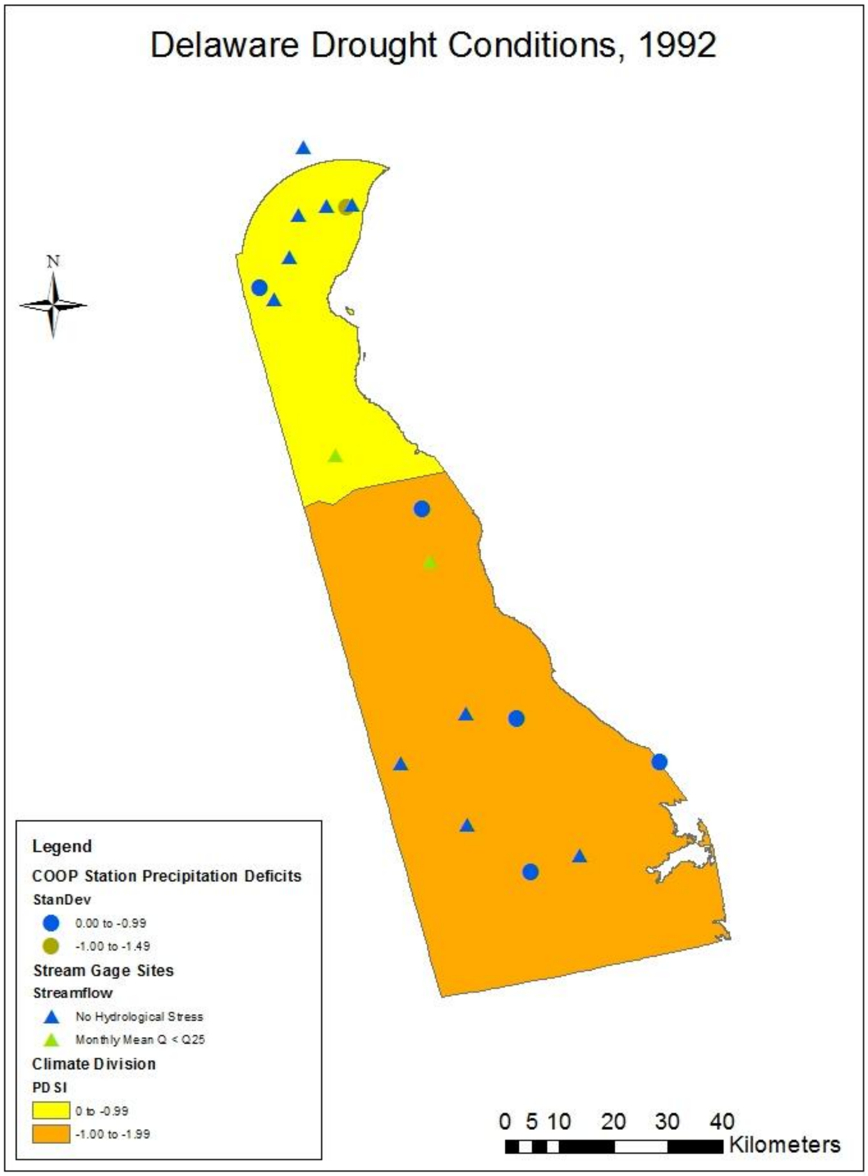


Figure 4.8. Spatial patterns of meteorological and hydrological drought in Delaware during the height of Event 8 (April 1991 – October 1992).

4.2.9 Event 9: October 1994 to September 1995

Though relatively brief, the drought which occurred for a large part of the 1995 water year was an extreme intense drought event in Delaware. Drought severity had grown so increasingly severe during its duration, especially in northern New Castle County, that it prompted the declaration of several drought-based executive orders, including a drought warning for northern New Castle County on August 25, 1995, a drought emergency for the same region on September 4, 1995, and a mandatory restriction of water use in all state-run agencies on September 12, 1995. All precipitation deficits were significantly large in all parts of the state (Table 4.10; Figure 4.9). For example, precipitation deficits recorded at Georgetown exceeded -2σ. This event ended gradually as precipitation patterns returned to normal during the 1996 water year. Consequently, the drought emergency was lifted on November 6, 1995, although the drought warning remained in effect through February 6, 1996.

Hydrological drought was observed earlier in the streams of northern Delaware than those of the southern region of the state. In the northern portion of the state, stream gauge records indicate the beginning of low flow conditions as early as March 1995. In many of the southern streams, low flow observations were not made until late July/August 1995. The passing of storm systems over the region on September 17 and October 6, 1995 led to the recovery of normal streamflow in most streams across the state.

Table 4.10. Cumulative departures from mean annual precipitation as observed at each COOP station during event 9. All values are given in millimeters; those in bold print exceed +/- 1σ.

COOP Site	**1994 Water Year**	**1995 Water Year**	**1996 Water Year**
Newark	51.6	**-334**	**281**
Wilmington	**307**	**-334**	**428**
Dover	188	**-379**	**351**
Lewes	192	**-237**	**262**
Georgetown	14.7	**-513**	**408**
Milford	---	---	

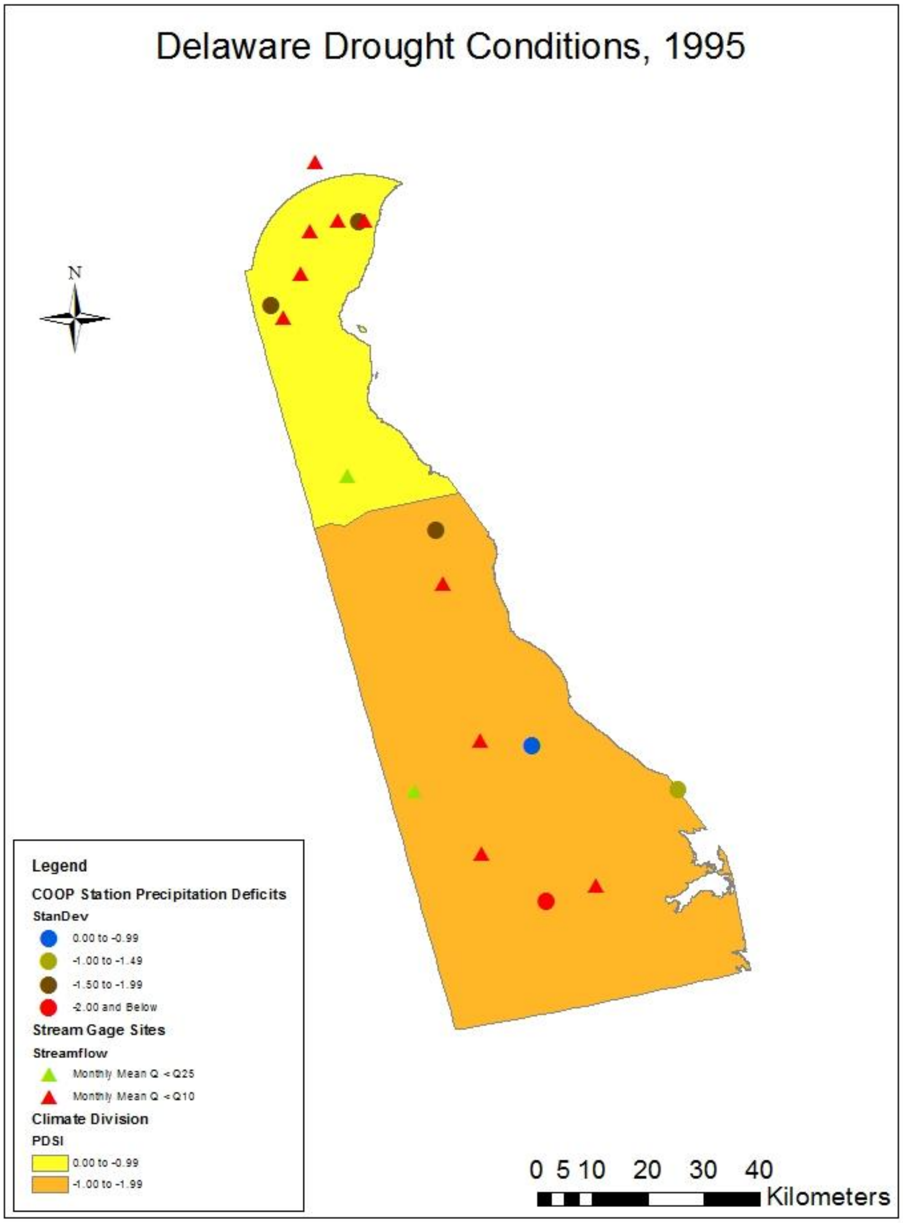


Figure 4.9. Spatial patterns of meteorological and hydrological drought in Delaware during the height of Event 9 (October 1994 – September 1995).

4.2.10 Event 10: April 1997 to December 1997

This event was brief with relatively mild intensity. It can in some measure be viewed as a precursor to the drought that occurred the following year. The biggest indication of this drought was observed in the PDSI values; precipitation deficits do not indicate particularly noteworthy drought conditions (Table 4.11). Stream response to this event varied across the state as many streams did not experience low flow conditions (Figure 4.10). Those streams that were affected during this event exhibited low flow from June through October 1997. Recovery began on October 27, 1997 with the passing of a non-tropical storm system.

Table 4.11 Cumulative departures from mean annual precipitation as observed at each COOP station during event 10[11]. All values are given in millimeters; those in bold print exceed +/- 1σ.

COOP Site	**1997**
Newark	-30.0
Wilmington	-10.2
Dover	-23.1
Lewes	-64.7
Georgetown	---
Milford	---

[11] Cumulative departures from mean annual precipitation for the 1998 water year are included in Table 4.12.

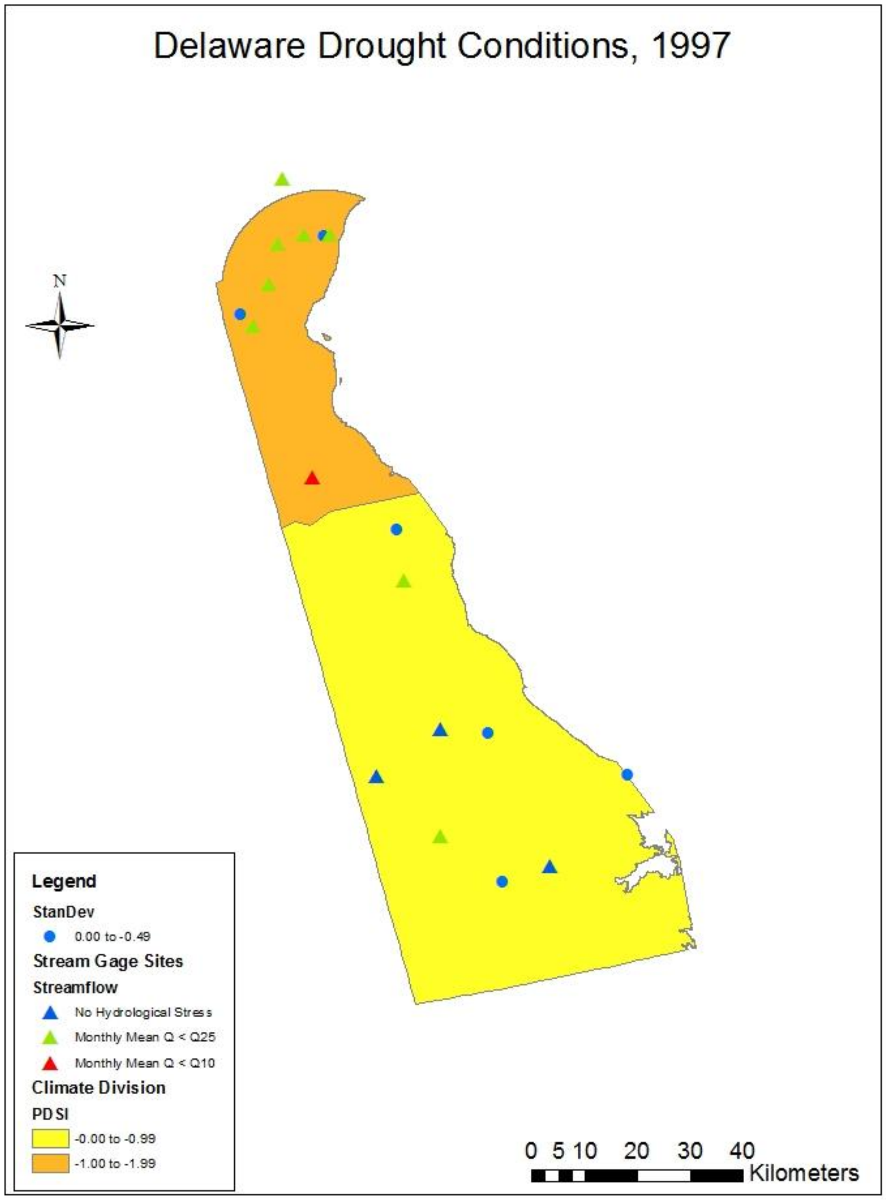


Figure 4.10. Spatial patterns of meteorological and hydrological drought in Delaware during the height of Event 10 (April 1997 – Decemeber 1997).

4.2.11 Event 11: August 1999 to September 1999

In recent studies, this event and that of 2001-2002 have been considered part of a global scale drought that occurred from 1998 to 2002 (*e.g.*, Seager 2007; Hoerling *et al*. 2003). In Delaware, drought conditions were most evident at two distinct times, interrupted by Tropical Storm Floyd in 1999. Therefore, these events will be examined as two separate droughts.

Because Tropical Storm Floyd deposited large precipitation totals in September 1999, cumulative departures from mean water year totals had to be calculated prior to September (Table 4.13). Though precipitation deficits were greater in southern Delaware, drought severity was worse in the northern parts of the state. Consequently, a statewide drought warning was issued on July 24, 1999 by Governor Thomas R. Carper. In northern New Castle County, mandatory water use restrictions were enforced, and on August 5, 1999, a drought emergency was declared for the region. The drought ended abruptly after the substantial, flood-producing rainfall of Tropical Storm Floyd in September 1999.

Stream response to this event occurred relatively quickly as observations indicated reductions in flow in several streams across the state as early as October 1998 (Figure 4.11). Low flow observations began in all streams in April and May 1999 and persisted through the passing of Tropical Storm Floyd on September 16 and 17, 1999.

Table 4.12. Cumulative departures from mean annual precipitation as observed at each COOP station during event 11. All values are given in millimeters; those in bold print exceed +/- 1σ.

COOP Site	**1998 Water Year**	**1999 Water Year**	**1999 Water Year (September Precipitation Excluded)**	**2000 Water Year**
Newark	**-192**	55.6	-141	85.6
Wilmington	-151	111	-126	83.3
Dover	47.2	-115	**-266**	171
Lewes	-12.7	-162	**-272**	**207**
Georgetown	---	---	---	---
Milford	---	---	---	---

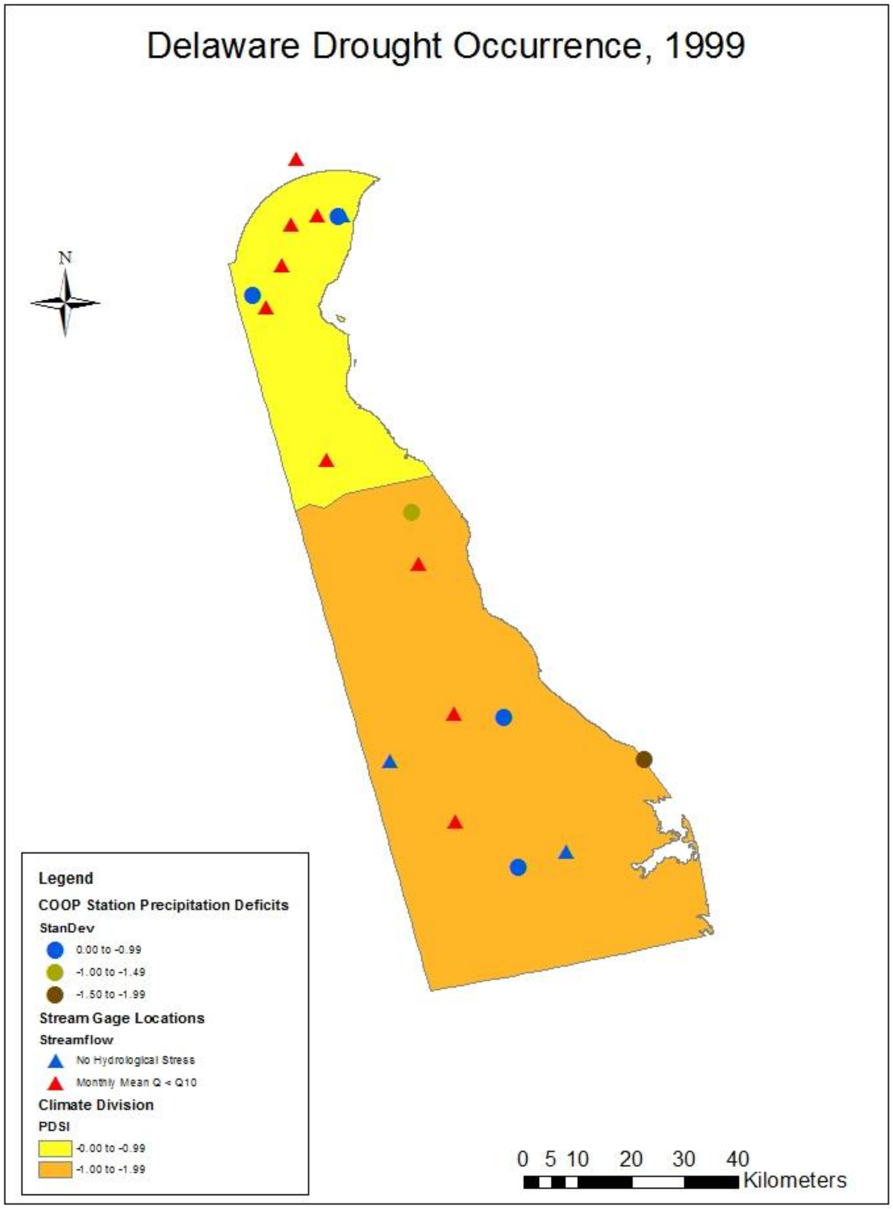


Figure 4.11. Spatial patterns of meteorological and hydrological drought in Delaware during the height of Event 11 (August 1999 – September 1999).

4.2.12 Event 12: August 2001 to September 2002

This event has been referred to in previous studies as Delaware's drought of record (*e.g.*, Kauffman and Vocnk 2011). Deficient precipitation during the cool season led to rapid declines in streamflow that, when coupled with heat wave conditions during the summer of 2002, created an extremely intense drought in the state. This was evidenced by the relatively early declaration of a statewide drought warning on March 5, 2002 by Governor Ruth Ann Minner (most previous drought warnings were issued during the summer months, whereas this one was issued in the late winter). A drought emergency was declared in northern New Castle County on August 2, 2002 and mandatory water use restrictions were enforced.

Precipitation deficits were significantly large throughout the state during this event (Table 4.13), with all COOP stations reporting departures from mean precipitation that exceeded -1σ by the height of the event in 2002 (see Figure 4.12). Streamflow records indicate low flow conditions in all streams as early as the first quarter of the 2002 water year (OND). Many streams nearly ran dry at the height of the drought in the summer of 2002; the Brandywine Creek at Wilmington did run dry on August 23, 2002 (Kauffman and Vocnk 2011). Normal streamflow returned gradually in all streams throughout the state with the passing of storm systems that produced reasonable precipitation amounts in September and October 2002.

Table 4.13. Cumulative departures from mean annual precipitation as observed at each COOP station during event 12. All values are given in millimeters; those in bold print exceed +/- 1σ.

COOP Site	**2001 Water Year**	**2002 Water Year**	**2003 Water Year**
Newark	-156	**-355**	**315**
Wilmington	**-239**	**-380**	**478**
Dover	-115	**-281**	**564**
Lewes	-145	**-239**	**352**
Georgetown	---	---	---
Milford	-55.1	-195	**342**

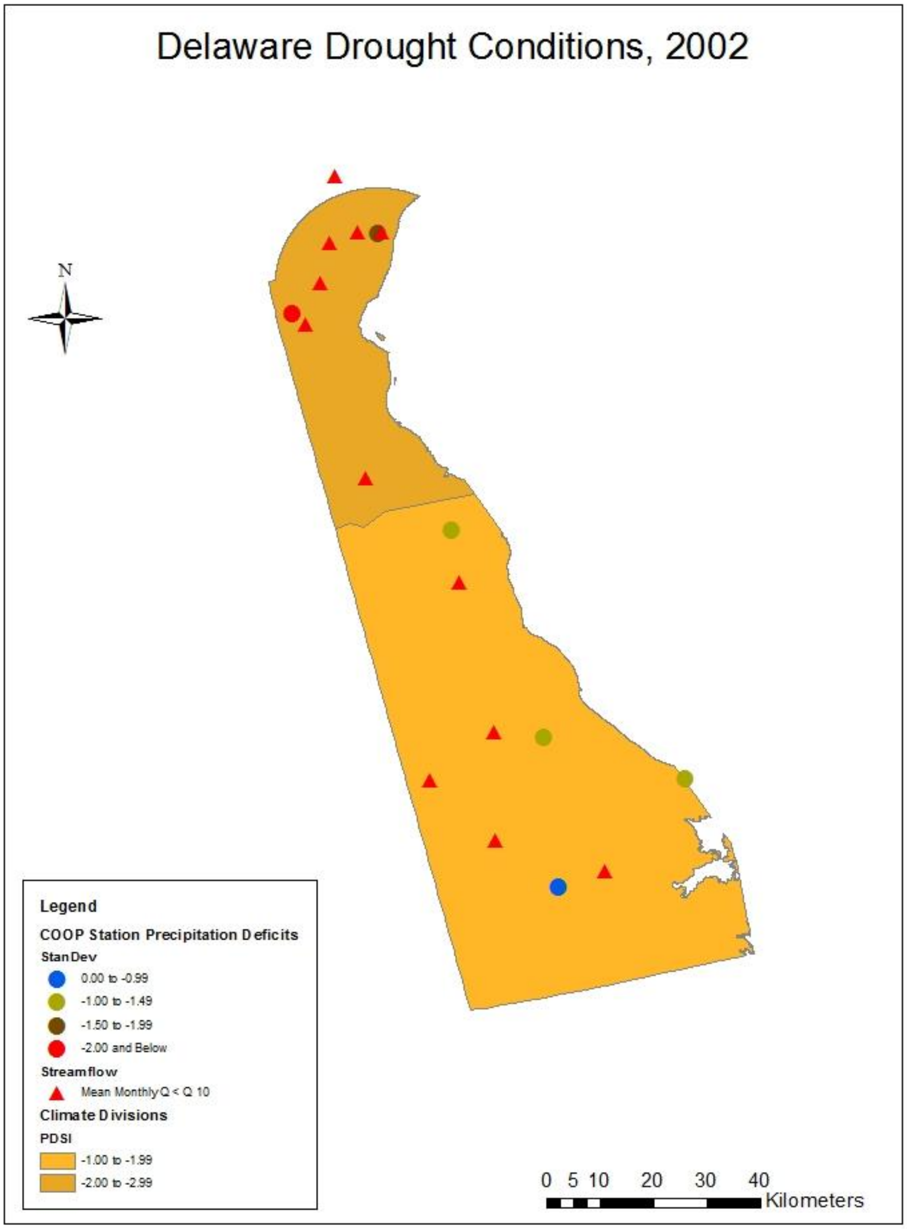


Figure 4.12. Spatial patterns of meteorological and hydrological drought in Delaware during the height of Event 12 (August 2001 – September 2002).

4.3 Identification of Spatial Patterns

4.3.1 Climate Division Level

Initial attempts to identify spatial patterns were based on the use of drought index values for each climate division. These datasets were used to determine if, when using average annual index values for (only) the years during which droughts occurred, one climate division tended to be drier than the other. A total of thirty-eight years exist during which the identified drought events occurred. Table 4.14 shows the number of years each climate division was classified as driest (had lower index values recorded) for each of the three drought indices used.

Table 4.14. Driest climate division (bold) during years of drought occurrence (1949 through 1982).

	PDSI		SPI-1		SPI-3	
Drought Years	Climate Division 1	Climate Division 2	Climate Division 1	Climate Division 2	Climate Division 1	Climate Division 2
1949	**-0.673**	-0.353	-0.022	**-0.197**	0.149	**0.061**
1950	-0.104	**-1.553**	-0.093	**-0.188**	**-0.185**	-0.433
1951	0.264	**-0.511**	0.153	0.030	-0.054	**-0.247**
1953	**0.306**	0.890	0.273	**0.233**	**0.408**	0.485
1954	**-2.612**	-1.212	**-0.499**	-0.171	**-0.803**	-0.336
1955	**-1.851**	0.147	**-0.742**	-0.364	**-0.398**	-0.143
1956	0.576	**0.248**	0.262	**0.210**	**-0.088**	0.036
1957	-0.652	**-1.139**	-0.158	**-0.204**	-0.351	**-0.454**
1961	**0.039**	1.693	**0.032**	0.355	**0.124**	0.429
1962	**-1.707**	-0.759	**-0.231**	-0.108	**-0.501**	-0.348
1963	**-2.876**	-1.388	**-0.593**	-0.406	**-0.789**	-0.381
1964	**-3.088**	-1.263	**-0.434**	-0.329	**-0.826**	-0.459
1965	**-4.208**	-3.149	-0.708	**-0.722**	**-1.058**	-0.958
1966	-2.583	**-2.822**	**-0.317**	-0.164	**-0.623**	-0.518
1967	**0.051**	0.510	**-0.034**	0.001	**-0.018**	0.069
1968	-1.626	**-2.117**	-0.512	**-0.658**	-0.629	**-0.994**
1969	**-1.379**	-0.741	**-0.249**	0.167	**-0.633**	0.114
1970	**-0.498**	0.521	**-0.234**	-0.041	**-0.117**	0.068
1976	-0.963	**-1.165**	**-0.436**	-0.303	**-0.492**	-0.383
1977	-0.886	**-1.323**	0.044	**-0.222**	**-0.378**	0.843
1980	**-1.223**	-0.332	**-0.419**	-0.128	**-0.521**	-0.035
1981	**-2.194**	-1.243	**-0.346**	-0.303	**-0.799**	-0.703
1982	-0.080	**-0.432**	0.094	**-0.018**	0.074	**-0.194**

Table 4.15. Driest climate division (bold) during years of drought occurrence (1984 through 2002).

	PDSI		SPI-1		SPI-3	
Drought Years	Climate Division 1	Climate Division 2	Climate Division 1	Climate Division 2	Climate Division 1	Climate Division 2
1984	1.173	**0.158**	0.142	**0.010**	0.658	**0.216**
1985	-2.259	**-2.927**	**-0.452**	-0.281	**-0.660**	-0.369
1986	-1.193	**-3.133**	0.071	**-0.373**	-0.317	**-0.994**
1987	-0.594	**-2.560**	-0.215	**-0.262**	-0.147	**-0.326**
1988	-0.408	**-2.553**	-0.136	**-0.345**	-0.055	**-0.248**
1989	**1.438**	2.026	**0.426**	0.636	**0.792**	0.931
1991	-0.993	**-1.802**	**-0.061**	-0.033	0.006	**-0.038**
1992	-0.422	**-1.013**	-0.118	**-0.266**	-0.191	**-0.297**
1994	1.357	**0.182**	0.278	**0.248**	0.556	**0.538**
1995	-0.582	**-1.368**	-0.053	**-0.218**	-0.168	**-0.481**
1997	**-1.067**	-0.330	**-0.253**	0.083	**-0.215**	0.216
1998	**-0.821**	-0.521	**-0.176**	0.043	**-0.208**	0.116
1999	-0.368	**-1.233**	0.251	**-0.035**	0.406	**-0.016**
2001	**-0.849**	-0.539	**-0.252**	-0.216	**-0.360**	-0.323
2002	**-2.421**	-1.047	**0.085**	0.242	**-0.348**	0.049

Unexpectedly, agreement exists between both SPI-1 and SPI-3 that the Northern climate region was drier more often than the Southern climate region. The PDSI, however, classified both climate divisions as "driest" an equal number of times. This is an interesting observation when the factors which make the two indices different are considered. SPI values are based solely on observed precipitation amounts, whereas PDSI values are calculated using precipitation and several additional variables, including temperature and soil moisture. Thus, while the

Northern climate region appears to receive less precipitation during drought events (based on data solely from the study period), neither of the climate divisions emerges as that which is, on average, more severely affected during drought when environmental factors are considered in addition to precipitation.

4.3.2 Cooperative Station Level

Data from each of the COOP stations were used to identify spatial patterns at a finer scale. For each year during which drought occurred, cumulative water year deficits were calculated for each station. Years during which recovery occurred were excluded as these years seldom had deficient precipitation. Recorded deficits for each year were ranked on a scale from 1 to 6, where 6 represented the COOP site with the greatest observed deficit of the year and 1 indicated that station which exhibited the smallest deficit. COOP sites which ranked highest in categories 5 and 6 were the most severely affected during meteorological drought events. Of the six COOP sites included in the study, Wilmington and Newark consistently ranked high in these two categories. In category 6, Wilmington and Newark ranked as the two driest COOP sites in a combined total of approximately 54% of cases. Similarly in category 5, these two sites ranked as the two driest in approximately 44% of observed drought years. This indicates a strong northern bias towards greater severity when examining statewide patterns in meteorological drought.

Categories 3 and 4 represent moderate drought severity; that is, those stations that were moderately affected with respect to all COOP sites used in the study. In both categories, Dover ranked the highest, accounting for 25 and 33% of the cases in each respective category. If Dover is used as the COOP site representative of locations in central Delaware, this finding indicates that the central portions of the state, are, on average, moderately affected during meteorological droughts, with respect to the northern and southern regions of the state (not to be confused with the Northern and Southern climate regions).

For both categories 1 and 2, Georgetown and Lewes ranked most frequently; that is, these sites had the smallest annual precipitation deficits during the identified drought events. Combined, Georgetown and Lewes were classified as the sites least affected by meteorological drought approximately 50% of the time. While there were fewer total cases from which these observations were made, this finding is still relevant as it indicates a considerable southern bias towards (relatively) minimally severe impacts during meteorological droughts.

4.4 Delaware Drought Occurrence and Anomalies in 500hPa Height Patterns

Through the analysis of monthly and seasonal 500hPa height anomalies, various patterns were found that relate changes at the 500hPa level and drought occurrence in Delaware (and the surrounding region). Several patterns identified were observed during most of the events. The first of these patterns was a trend toward positive height anomalies over the region at drought onset. The strength of these anomalies varied from weak (approximately 10-20mb) to moderate (approximately

35-45mb). No relationship between the intensity of the dry spells and the strength of the 500hPa height anomalies present at their onset is apparent.

Another pattern common to a large number of events was associated with the cessation of the dry spells. As previously mentioned (Section 4.2), the termination of many of the events began with the passing of tropical storm systems and mid-latitude cyclones. Analysis of the seasonal 500hPa height patterns indicate that long-term recovery from droughts in the study region is likely related to a transition away from the anomalous pattern that persisted during each of the respective events. For example, in events dominated by negative (positive) height anomalies, the return to normal conditions was often accompanied by an anomaly reversal (*i.e.* from negative to positive height anomalies) or a switch to a pattern in which there were no height anomalies over the region. In the majority of events in which this was observed, the 500hPa pattern associated with the end of the drought persisted for more than one season. This may explain why drought recovery continued after the initial return to normal moisture levels resulting from the traversing of both tropical and non-tropical cyclones across the region.

Unexpectedly, drought occurrence in Delaware was found to be associated with both positive and negative height anomalies at the 500hPa level. There are different mechanisms by which each of these regimes can prolong the occurrence of drought. When negative height anomalies characterize the 500hPa level, there is an increased likelihood for the deepening of troughs over a region. When this occurs in the eastern United States, it allows for the advection of relatively cool, stable continental polar air masses from the northern regions of the continent (*i.e.* Canada) into a region. If this pattern dominates seasonal flow patterns, the persistent presence of stable air masses in place can prevent the formation of storm systems and limit convective events. In addition, mid-latitude cyclones may follow storm tracks that have a more southern displacement than normal. Consequently, affected regions are likely to experience notable reductions in precipitation. If this type of upper air pattern persists, it can be very influential in establishing and prolonging a dry spell.

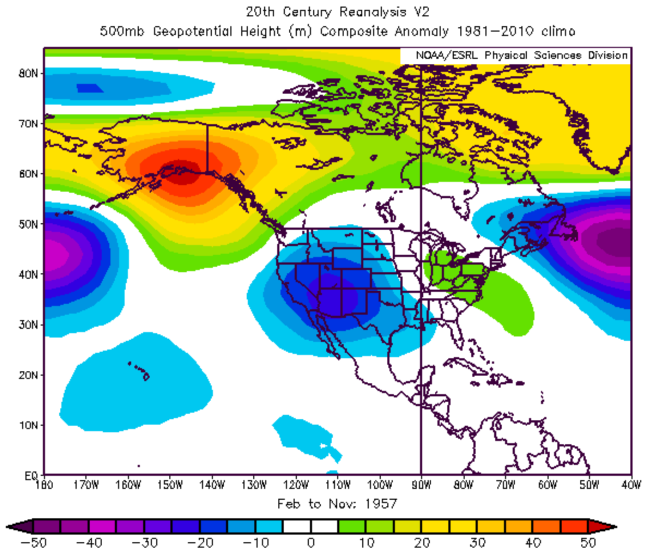
Several mechanisms exist by which positive height anomalies help to prolong drought events. In cases of strong positive height anomalies, strong ridges are generally located over the region. Storm systems are averted around areas under the ridge. In addition, high pressure associated with these ridges is characterized by subsidence that inhibits the upward vertical motion required for the production of precipitation. Related changes in the overall jet stream pattern (*i.e.,* negative vorticity associated with the anticyclonic circulation of high pressure systems) further hinder the formation of cyclones. This results in reduced precipitation amounts over the period during which the height anomaly exists. Cases of both strong and mild positive height anomalies result in the advection of warmer air from southern origins. The effect of this warm air advection is especially important during the warm season as it results in the potential for greater evaporative moisture loss, which helps to further exacerbate antecedent drought conditions.

When event-long anomalies are observed, half of the events exhibit negative height anomalies at the 500hPa level, while the remaining half exhibit positive height anomalies. Droughts associated with the former include events 2 (1953-1956), 4 (1961-1970), 5 (1976-1977), 6 (1980-1982), 7 (1984-1989), and 10 (1997). Though these events displayed overall negative height anomalies, analysis of the 500mb heights at a finer temporal resolution (seasonal time scale) revealed interesting patterns within the time frame of each respective event. In three of the events (events 6, 7, and 10), negative height anomalies persisted for the majority of the events' duration.

Events 2, 4, and 7 differed from the three dry spells mentioned above in that they were not solely characterized by negative anomalies throughout their extent, but rather by a combination of various patterns. During event 2 (1953-1956), with the exception of the positive anomaly observed at the onset of the event, height anomalies were absent for the first half of the dry spell (autumn 1953 through autumn 1954). Negative height anomalies were not observed until winter 1955 and persisted through spring 1956. In addition, several trends were observed during the drought of the 1960s (event 4). There were three consecutive years in which no height anomalies were observed during the winter and summer seasons (1964 to 1967). From spring 1967 through winter 1970, positive height anomalies were observed in the spring and summer months, and negative anomalies in the fall and winter months. A somewhat similar pattern was observed during the drought of the mid-1980s (event 7, 1984-1989). For three and a half years (fall 1984 through winter 1987 - 1988) the following pattern was exhibited: negative height anomalies during the winter months (DJF) and positive anomalies during the spring and fall seasons. Further investigation is needed to help better understand what significance, if any, these intra-event patterns may have with respect to the duration and intensity of droughts in Delaware.

Events 1 (1949-1951), 3 (1957), 8 (1991-1992), 9 (1994-1995), 11 (1998-1999), and 12 (2001-2002) were characterized by event-long positive 500hPa height anomalies. As with the previous group of events, analysis of the anomalies at a seasonal time scale revealed interesting 500hPa patterns during each respective event. In the initial stages of their duration, events 1, 3, and 8 exhibited positive seasonal anomalies, followed by a switch to negative anomalies during the latter part of these events. Contrarily, positive height anomalies persisted for the duration of events 9 and 12, with seasonal anomalies of approximately 20hPa recorded. Cessation of both of these events happened with a concurrent transition to negative 500hPa height anomalies over the region.

The current review of the events characterized by positive anomalies indicates a potentially strong relationship between the strength of positive 500hPa height anomalies and the intensity of dry spells. Both events 3 and 8 had the weakest positive height anomalies (approximately 5-10hPa each) and the smallest precipitation deficits. In the remaining events, height anomalies ranged from approximately 10-20hPa above normal. Precipitation deficits at the height of these events were markedly higher than those of the two former dry spells. In fact, positive height anomalies were greatest over the Northeast and Mid-Atlantic regions during events 9(1994-1995) and 12 (2001-2002) as 500hPa heights over the region were approximately 25hPa above normal (Figure 4.13). Departures from normal precipitation were greatest during these events, with mean deficits (taken at the height of the event) equal to -1.82σ and -1.52σ, respectively. Further statistical analysis is needed to better understand what factors have a significant role in determining the relationship between the strength of positive 500hPa height anomalies and drought intensity in Delaware.



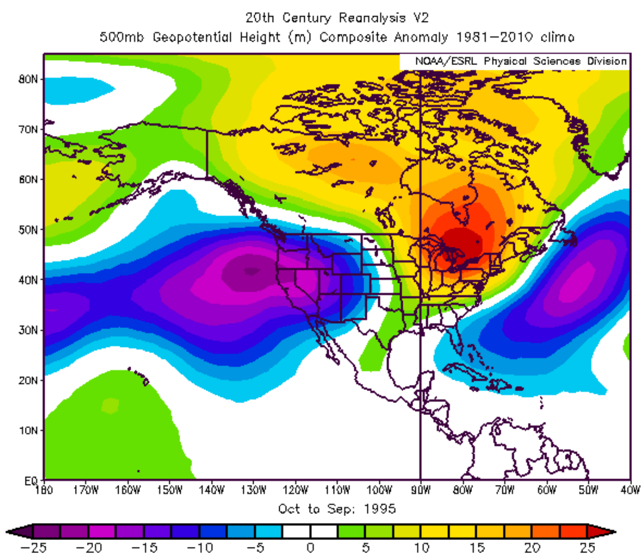


Figure 4.13. Event-long 500hPa height anomalies for Event 3 (February – November 1957) and Event 9 (October 1994 – September 1995). Height anomalies observed over the region during Event 3 were significantly weaker than those of Event 9. *Source*: NOAA Earth System Research Laboratory.

4.5 Identification of Teleconnections

The results of the chi-square tests indicate that the most statistically significant relationship between the SST and teleonnection indices used in this study and meteorological drought occurrence in Delaware is found in the combined effect of the PDO and AMO[12]. These findings suggest that there is no significant association between the remaining indices and index combinations and drought incidence in the study region (Table 4.15).

[12] When the p-values of the chi-square test are less than 0.05, the relationship between the two variables being examined is significant and cannot be explained by random chance.

Table 4.16. Results (p-values) of the chi-square contingency tests used to identify statistically significant relationships between atmospheric and oceanic indices and drought occurrence in Delaware. Values listed in the table are averages of the values calculated for each climate division.

SST Index	Level at Which Relationship Found to be Significant
Pacific Decadal Oscillation (PDO)	0.23
Atlantic Multidecadal Oscillation (AMO)	0.72
El Niño Southern Oscillation (ENSO)	0.91
Pacific North American Teleconnection Pattern (PNA)	0.17
PDO/AMO	0.04[13]
PDO/ENSO	0.79[14]
PNA/AMO	0.30[15]
PNA/ENSO	0.49[16]
AMO/ENSO	0.34[17]
PDO/PNA	0.18[18]

This study's finding that the PDO and AMO have a combined effect on drought occurrence in Delaware is supported by McCabe *et al*. (2004). McCabe's Figure 4 demonstrates that the likelihood of drought frequency in Delaware (and the surrounding region) is greatly increased when (a) both PDO and AMO are negative, and (b) PDO is positive and AMO is negative. During the study period (1948-2005),

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[13] All possible combinations of PDO and AMO phases included in calculation.

[14] All possible combinations of PDO and ENSO phases included in calculation.

[15] All possible combinations of PNA and AMO phases included in calculation.

[16] All possible combinations of PNA and ENSO phases included in calculation.

[17] All possible combinations of AMO and ENSO phases included in calculation.

[18] All possible combinations of PDO and PNA phases included in calculation.

the first of these regimes occurred from approximately 1963 to 1976; the latter occurred from 1976 to 1994. Because the McCabe study focuses on probability of increased drought frequency, it should be noted that noteworthy dry spells occurred in Delaware throughout the study period, regardless of the phases of both the PDO and AMO. Interestingly, however, the time periods found by McCabe *et al*. to have increased probability of drought frequency in the state (1963-1994) directly correspond to the two most persistent droughts identified during the study period: the drought of the 1960s (1961-1970) and that of the mid-1980s (1984-1989). Dry spells that took place outside of this time period were of respectable intensity, but did not persist for as long as those during the 1963 to 1994 period. This finding suggests that when both PDO and AMO are negative, or PDO is positive and AMO is negative, it is highly likely that the region will experience prolonged dry spells.

There are several potential reasons why the remaining indices tested appear to exert no influence on drought occurrence in the study region. Many studies have associated droughts in the mid-latitudes with the La Niña phase of ENSO (*e.g*., Seager 2007, Hoerling *et* al. 2003). Currently, much of the current body of research focuses in the linkage between ENSO and the hydroclimate of the eastern United States, with an emphasis put on either the Northeast or Southeast regions (*e.g*. Seager *et al*. 2009 and Barlow *et al*. 2000). These regions are often studied as both represent individual action centers, or portions of the eastern seaboard most directly affected by fluctuations in ENSO phase. Delaware's geographic location places it (and the immediate surrounding region) directly between these two action centers.

Consequently, there are episodes of drought occurrence (and other climatic phenomena) during which the state's weather patterns are influenced by one particular dominant center of action as opposed to the other (depending on the relative strength of each respective action center). As a result, it is difficult to associate specific weather patterns (*i.e.* drought occurrence) in Delaware with specific phases of ENSO as its location is not directly within one of the regions specified above.

It should also be noted that no two episodes of a specific ENSO phase produce the exact same weather patterns. Temperature and precipitation trends observed during various warm and cool ENSO episodes tend to vary (Figure 4.13). While there are some mild similarities in areas that receive more (less) precipitation or higher (lower) temperatures, this is often restricted to a small number of locations and a limited number of events. This provides further confidence in the finding of the current study that in Delaware, ENSO phase alone cannot serve as a single determining factor in drought occurrence and intensity.

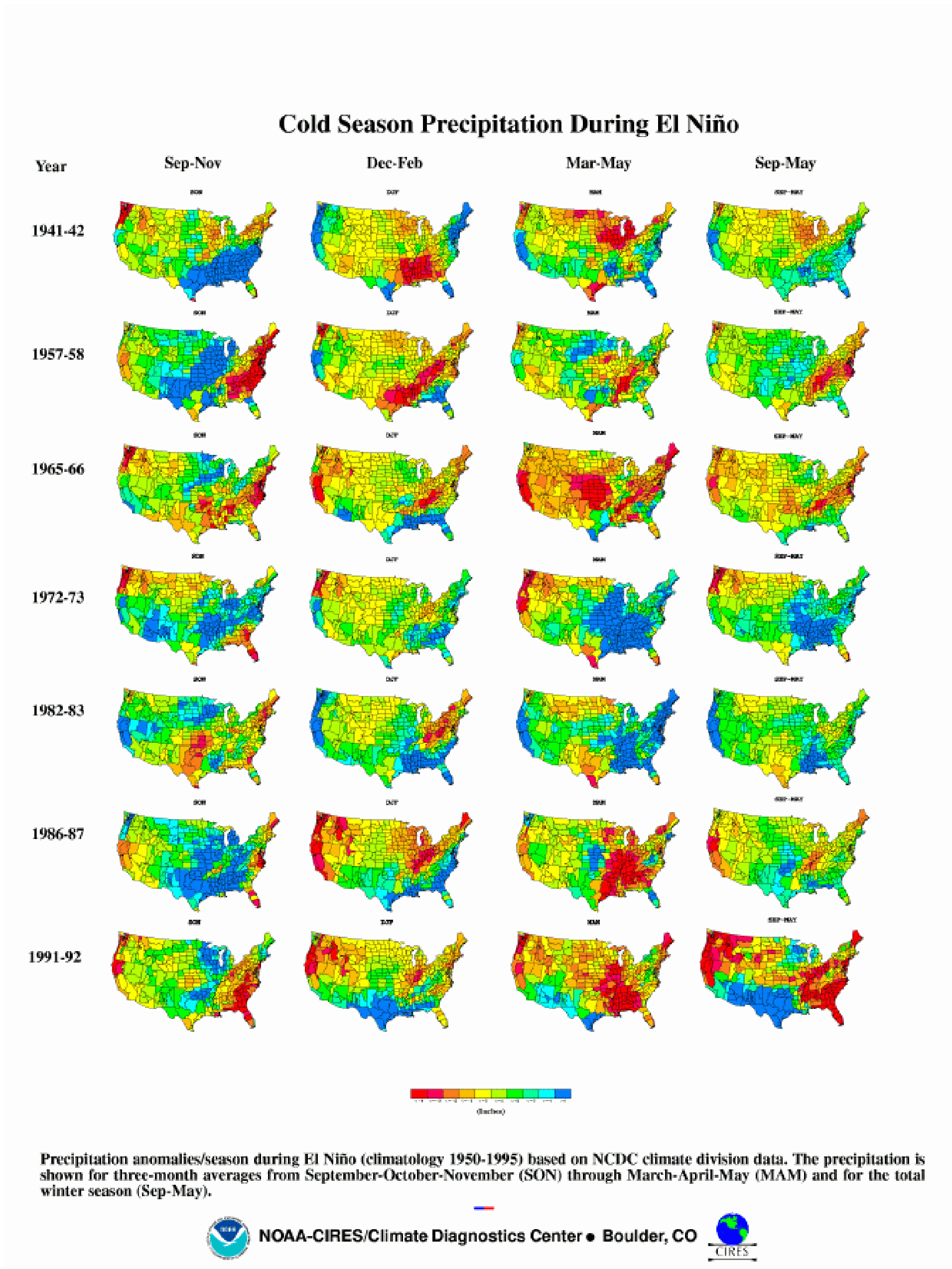

Figure 4.14. Observed precipitation patterns during El Niño episodes of greatest strength. *Source:* NOAA Earth System Research Laboratory.

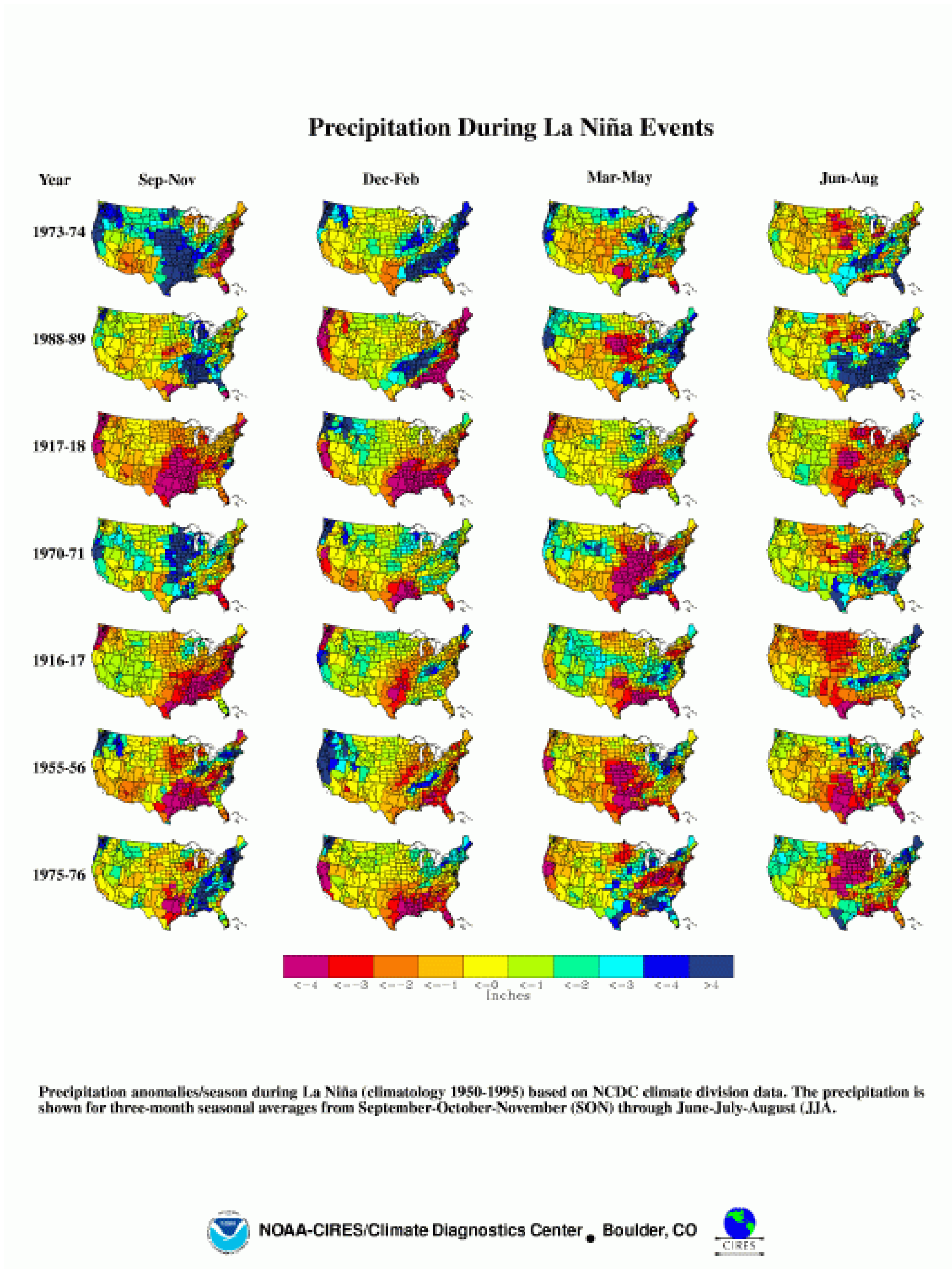

Figure 4.15. Observed precipitation patterns during La Niña episodes of greatest strength. *Source:* NOAA Earth Science Research Laboratory.

The results of the chi-square tests are further supported by the findings of existing research and knowledge of multivariate statistics. A recent study by Leathers *et al.* (2008) concluded that the PNA teleconnection had only a weak influence on the hydroclimate of the Susquehanna River Basin. While Delaware does not lie within this basin, the state's relatively close proximity to the basin's lower extent may allow it to be classified with the hydroclimatic characteristics of the Susquehanna River Basin. As such, the PNA would have only a weak influence on precipitation patterns and (meteorological) drought occurrence in Delaware, if any at all.

The lack of significant results when examining the combined effect of ENSO and the PDO likely results from the fact that the two are highly interrelated; observed phases of ENSO tend to correlate to those in the PDO (Mantua *et al*. 1997). This introduces a high level of collinearity which may work to mask any actual influences that these two indices may have on the formation of droughts in Delaware.

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In the development of a drought climatology for Delaware based on the period 1948 – 2005, several important findings were made:

- Twelve distinct meteorological droughts were identified using the Palmer Drought Severity Index (PDSI) and the Standardized Precipitation Index (SPI) over the fifty-seven year study period. With the exception of one event (Event 8: 1991-1992), each meteorological drought resulted in hydrological drought evidenced by below normal streamflow (*i.e.*, mean monthly streamflow below the Q25 level) as observed in 13 state/regional USGS-operated stream gages.
- When solely precipitation is considered, the intensity of meteorological drought (as identified/measured by the SPI) was found to be, on average, greatest in the Northern climate division (encompasses New Castle County); lesser impacts observed in the Southern climate division (includes Kent and Sussex counties, thus, the central, southern, and coastal portions of the state). When various factors related to drought occurrence were considered (*i.e*, when the PDSI was used in identifying and quantifying drought incidence), neither climate division was found to be more intensely affected than the other.

- Various patterns observed in 500hPa height anomalies were found to be associated with drought occurrence in Delaware. Drought onset was recognized to occur concurrently with positive height anomalies at the 500hPa level. Drought incidence was associated with both positive and negative height anomalies. The droughts of 1953 – 1956, 1961 – 1970, 1976 – 1977, 1980 – 1982, 1984 – 1989, and 1997 were characterized by event-long negative 500hPa height anomalies. This set included the events of greatest duration (Event 4: 1961 – 1970 and Event 7: 1984 – 1989). The droughts of 1949 – 1951, 1957, 1991 – 1992, 1994 – 1995, 1998 – 1999, and 2001 – 2002 were characterized by positive 500hPa height anomalies. In addition, the findings suggest a possibly strong relationship between the strength of positive event-long height anomalies and precipitation deficits during dry spells; events with stronger positive height anomalies were characterized by greater precipitation deficits (*e.g.*, height anomalies and precipitation deficits were greater during the drought of 1994 – 1995 than those of the drought of 1991 – 1992).
- Drought occurrence in Delaware was found to have a statistically significant relationship with the combined effect of the Pacific Decadal Oscillation (PDO) and Atlantic Multidecadal Oscillation (AMO); that is, certain combinations of PDO and AMO phase were determined to affect drought incidence. When both PDO and AMO were negative (1963 – 1976), and when PDO was positive and AMO negative (1977 – 1994), drought persistence in Delaware

was greater (the droughts of greatest duration over the study period occurred during these times).

5.2 Recommendations

Several important findings have been made relating the spatial characteristics, synoptic conditions, and teleconnections associated with drought occurrence in Delaware. Uncertainties regarding the effects of intra-event variations in 500hPa height patterns and phase changes of the various SST and teleconnection indices on drought incidence (in the study region) indicate areas in which further research must be done. Statistical analyses should be used in future studies to better understand and quantify the relationship between the magnitude, sign (positive, negative), and location of 500hPa height anomalies and the duration and intensity of drought events in Delaware (and the surrounding region). Further investigation is also needed to better explain the relationship between the identified global and synoptic influences on drought and additional moisture parameters in Delaware (*i.e.*, soil moisture, groundwater).

With large population centers located in the northern part of the state and the sizable agriculture industry in its southern regions, water demand in Delaware is an important issue. Extreme hydroclimatic events such as droughts can introduce sudden (or gradual) changes to water availability within the state that can have large negative impacts on municipal water supply, agriculture, and the economy. The current study provides an understanding of spatial and temporal patterns of drought occurrence in Delaware, as well as a means by which future dry spells may potentially be predicted. Should the suggested additional research reveal meaningful connections between global and synoptic patterns and Delaware drought incidence, the findings of this study can be used as a drought prediction tool. Predictive measures made possible by the findings should be adopted by the Delaware Water Supply Coordinating Council in the creation of water management policies used to help mitigate severe reductions in Delaware's water supply resulting from droughts.

REFERENCES

Alley, W.M., 1984. The Palmer Drought Severity Index: Limitations and Assumptions. Journal of Climate and Applied Meteorology, 23(7): 1100-1109.

Andreadis, K.M. and D.P. Lettenmaier, 2006. Trends in 20th Century Drought Over the Continental United States. Geophysical Research Letters, 33(10). L10403. doi:10.1029/2006GL025711.

Cook, E.R., Seager, R., Cane, M.A., Stahle, D.W., 2007. North American Drought: Reconstructions, Causes, and Consequences. Earth-Science Reviews, 81: 93-134.

Davis, J.M. and P.N. Rappoport, 1974. The Use of Time Series Analysis Techniques in Forecasting Meteorological Drought. Monthly Weather Review, 102(2): 176-180.

Delaware Department of Natural Resources and Environment, University of Delaware, College of Human Services, Education, and Public Policy Institute for Public Administration - Water Resources Agency; Delaware Geological Survey, 2003. Fifth Report to the Governor and the General Assembly Regarding the Delaware Water Supply Coordinating Council (The Drought of 2002).

Delaware River Basin Commission, 2011. DRBC Declared Drought Actions (1980 To Present). DRBC. Web. 17 Feb. 2012.

Diaz, H.F., 1983. Drought in the United States: Some Aspects of Major Dry and Wet Periods in the Contiguous United States, 1895-1981. Journal of Climate and Applied Meteorology, 22(1): 3-16.

Dracup, J.A., 1991. Drought Monitoring. Stochastic Hydrology and Hydraulics, 5: 261-266.

Dracup, J.A., Lee, K.S., Paulson Jr., E.G., 1980. On the Definition of Droughts. Water Resources Research, 16(2): 297-302.

Dupigny-Giroux, L., 2001. Towards Characterizing and Planning for Drought in Vermont - Part 1: A Climatological Perspective. Journal of the American Water Resources Association, 37(3): 505-525.

Earth and Environmental Systems Institute, 1998. Pennsylvania Disaster History: 1954-1998. The Pennsylvania State University. Web. 18 Feb. 2012.

Enfield, D.B., Mestas-Nuñez, A.M., Trimble, P.J., 2001. The Atlantic Multidecadal Oscillation and its Relation to Rainfall and River Flows in the Continental US. Geophysical Research Letters, 28(10): 2077-2080.

Eltahir, E.A.B., 1998. A Soil Moisture-Rainfall Feedback Mechanism 1. Theory and Observations. Water Resources Research, 34(4): 765-776.

Federal Emergency Management Agency, 2012. Declared Disasters by Year or State. United States Department of Homeland Security. Web. 17 Feb. 2012.

Guttman, N.V. and R.G. Quayle, 1996. A Historical Perspective of U.S. Climate Divisions. Bulletin of the American Meteorological Society, 77: 293-303.

Hayes, M.J., Svoboda, M.D., Wilhite, D.A., and Vanyarkho, O.V., 1999. Monitoring the 1996 Drought Using the Standardized Precipitation Index. Bulletin of the American Meteorological Society, 80(3): 429-438.

Heim, R.R., 2002. A Review of Twentieth Century Drought Indices Used in the United States. Bulletin of the American Meteorological Society, 83: 1150-1165.

Hoerling, M. and A. Kumar, 2003. The Perfect Ocean for Drought. Science, 299: 691-694. doi10.1126/science.1079053

Janowiak, J.E., Ropelewski,C.F., and Halpert. M.S., 1986. The Precipitation Anomaly Classification: A Method for Monitoring Regional Precipitation Deficiency and Excess on a Global Scale. Journal of Climate and Applied Meteorology, 25(4): 565-574.

Karl, T.R., 1983. Some Spatial Characteristics of Drought Duration in the United States. Journal of Climate and Applied Meteorology, 22(8): 1356-1366.

Keyantash J and J.A. Dracup, 2002. The Quantification of Drought: An Evaluation of Drought Indices. Bulletin of the American Meteorological Society, 83: 1167-1180.

Kothavala, Z., 1997. Extreme Precipitation Events and the Applicability of Global Climate Models to the Study of Floods and Droughts. Mathematics and Computers in Simulation 43: 261-268.

Leathers, D.J., Grundstein, A.J., and Ellis, A.W. 2000. Growing Season Moisture Deficits Across the Northeastern United States. Climate Research, 14(1): 43-55.

Leathers, D.J., Malin, M.L., Kluver, D.B., Henderson, G.B., and Bogart, T.A., 2008. Hydroclimate Variability Across the Susquehanna River Basin, USA, Since the 17th Century. International Journal of Climatology. 28. 1615-1626. DOI: 10.1002/joc.1668

Leathers, D.J., Yarnal, B., Palecki, M.A. 1991. The Pacific/North American Teleconnection Pattern and United States Climate. Part 1: Regional Temperature and Precipitation Association. Journal of Climate. 4(5): 517-528.

Matthai, Howard F. Hydrologic and Human Aspects of the 1976-1977 Drought. Geological Survey Professional Paper 1130. Geological Survey Professional Paper 1130. United States Government Printing Office. Washington. 1979.

Mantua, N.J., Hare,S.R., Zhang,Y., Wallace, J.M., Francis,R.C., 1997. A Pacific Interdecadal Climate Oscillation with Impacts on Salmon Production. Bulletin of the American Meteorological Society, 78(6): 1069-1079.

Mantua, N. Pacific Decadal Oscillation Index Monthly Values. Joint Institute for the Study of Atmosphere and Ocean. Web. 13 Jun 2011.

Matthai, H.F., 1979. Hydrologic and Human Aspects of the 1976-1977 Drought. Geological Survey Professional Paper 1130.

Mauget, S.A., 2003. Intra– to Multidecadal Climate Variability over the Continental United States: 1932-1999. Journal of Climate, 16(13): 2215-2231.

McCabe,G.J., Betancourt, J.L., Gray, S.T., Palecki, M.A., and Hidalgo, H.G., 2008. Associations of Mulit-decadal Sea-Surface Temperature Variability with US Drought. Quaternary International. 188: 31-40.

McCabe, J.G., Palecki, M.A., Betancourt, J.L., 2004. Pacific and Atlantic Ocean Influences on Multidecadal Drought Frequency in the United States. Proceedings of the National Academy of Sciences of the United States of America. 101(12): 4136-4141.

McKee, T.B., Doeskin, N.J., Kliest, J., 1993. The Relationship of Drought Frequency and Duration to Time Scales. Preprints, Eighth Conference on Applied Climatology, American Meteorological Society, Anaheim, January 17-22, 179-184.

Mo, K.C. and M. Chellah, 2006. The Modified Palmer Drought Severity Index Based on the NCEO North American Regional Reanalysis. Journal of Applied Meteorology and Climatology, 45(10): 1362-1375.

National Climatic Data Center. Cooperative Station and Climate Division Climate Index Datasets. Web. 6 Apr 2011.

National Oceanic and Atmospheric Association/ Oceanic and Atmospheric Research/ Earth System Research Lab/ Physical Sciences Division. "Cold Season Precipitation During El Niño Events" (Figure 4.13a). Web. 6 Apr 2012.

National Oceanic and Atmospheric Association/ Oceanic and Atmospheric Research/ Earth System Research Lab/ Physical Sciences Division. "Precipitation During La Niña Events" (Figure 4.13b). Web. 6 Apr 2012.

National Oceanic and Atmospheric Association/ Oceanic and Atmospheric Research/ Earth System Research Lab/ Physical Sciences Division. NCEP Reanalysis Products. Web. 3 Jan 2012.

National Weather Service Philadelphia/Mount Holly Forecast Office, 2005. Historical Weather Facts for the Philadelphia/Mt. Holly, NJ Forecast Area. NWS. Web. 29 Jan. 2012.

Namias, J., 1983. Some Causes of United States Drought. Journal of Climate and Applied Meteorology, 22(1): 30-39

Narasimhan, B. and R.Srinivasan, 2005. Development and Evaluation of Soil Moisture Deficit Index (SMDI) and Evapotranspiration Deficit Index (ETDI) for Agricultural Drought Monitoring. Agricultural and Forest Meteorology, 133: 69-88.

Northeast Regional Climate Center, 2012. Delaware Drought Periods. National Climatic Data Center. Web. 18 Feb. 2012.

Oglesby, R.J. and D.J. Erickson III, 1989. Soil Moisture and the Persistence of North American Drought. Journal of Climate, 2(11): 1362-1380.

Palmer, W.C., 1965. Meteorological Drought. Weather Bureau, Research Paper No. 45. U.S. Department of Commerce. Washington, D.C.

Quiring, S.M. and T. M. Papakryiakou, 2003. An Evaluation of Agricultural Drought Indices for the Canadian Prairies. Agricultural and Forest Meteorology, 118: 49-62.

Robeson, S.M., 2008. Applied Climatology: Drought. Progress in Physical Geography, 32(3): 303-309.

Seager, R., 2007. The Turn of the Century North American Drought: Global Context, Dynamics, and Past Analogs. Journal of Climate, 20(22). 5527-5552. DOI: 10.1175/2007JCLI1529.1

Seager,R., Tzanova, A., Nakamura, J., 2009. Drought in the Southeastern United States: Causes, Variability Over the Last Millennium, and the Potential for Future Hydroclimate Change. Journal of Climate, 22(19) 021-5045. DOI: 10.1175/2009JCLI2683.1

Trenberth, K.E., 1997. The Definition of El Niño. Bulletin of the American Meteorological Society, 78(12): 2771-2777.

Trenberth, K.E. and D.J. Shea., 2005. Relationship Between Precipitation and Surface Temperature. Geophysical Research Letters, 32. L14702. doi:10.1029/2005GL022760.

Trnka, M., Dubrovsky, M., Svoboda, Semeradova, D., Hayes, M., Zalud, Z., 2009. Developing a Regional Drought Climatology for the Czech Republic. International Journal of Climate, 29: 863-883.

United States Department of the Interior and United States Geological Survey, 2005. The Drought of 1998-2002 in North Carolina - Precipitation and Hydrologic Conditions. Scientific Investigation Report 2005-5053.

Wallace, J.M. and D. S. Gutzler, 1981. Teleconnections in the Geopotential Height Field During the Northern Hemisphere Winter. Monthly Weather Review, 109: 784-812

Wang,Z., Chang,C.P., Wang, B., 2007. Impacts of El Niño and La Niña on the U.S. Climate During Northern Summer. Journal of Climate, 20(10). 2165-2177. doi:10.1175?JCL14118.1.

Wilhite, D.A., 1997. Responding to Drought: Common Threads from the Past, Visions for the Future. Journal of the American Water Resources Association, 33(5): 951- 959.

Wilhite, D.A., 1997. State Actions to Mitigate Drought: Lessons Learned. Journal of the American Water Resources Association, 33(5): 961-968

Whilihte, D.A., 2000. Drought as a Natural Hazard: Concepts and Definitions. Drought: A Global Assessment, D.A. Whilite, Ed., Routledge, 3-18.

Wu, R. and J.L. Kinter III, 2009. Analysis of the Relationship of U.S. Droughts with SST and Soil Moisture: Distinguishing the Time Scale of Droughts. Journal of Climate, 22(17): 4520-4538.

Appendix A

TIME SERIES PLOTS FOR OBSERVED VS. Q25 STREAMFLOW FOR SELECTED STREAM GAGE SITES

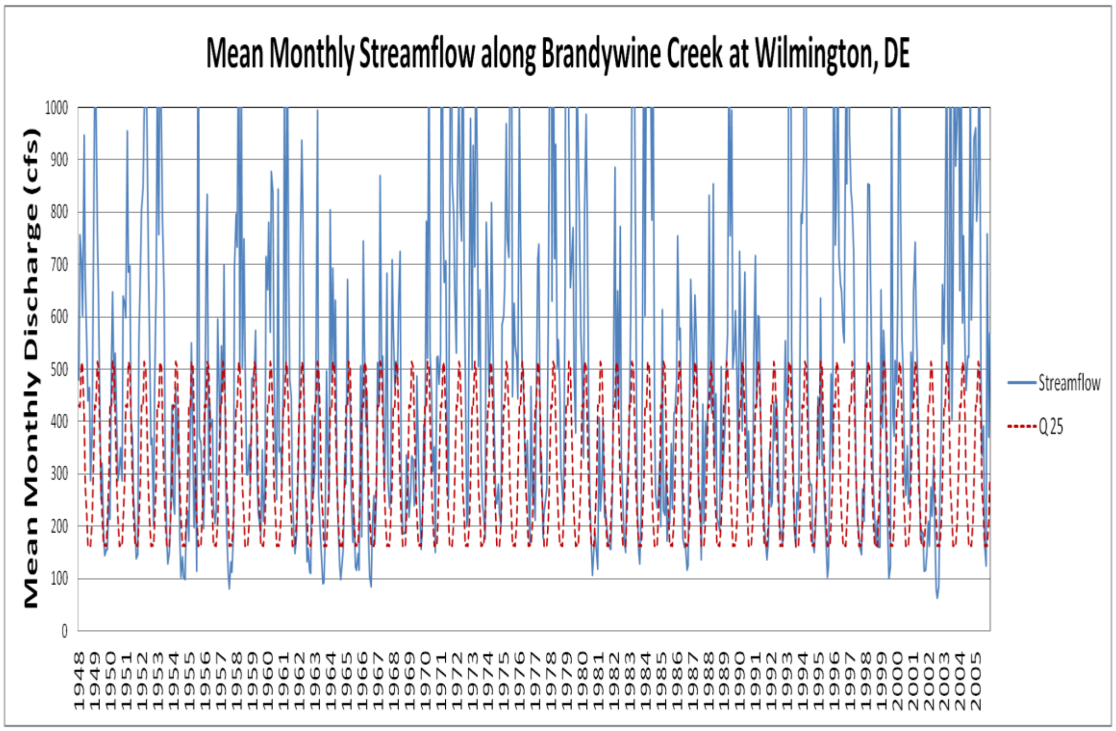

Figure A-1. Mean monthly streamflow along Brandywine Creek at Wilmington, DE for USGS stream gage 01481500.

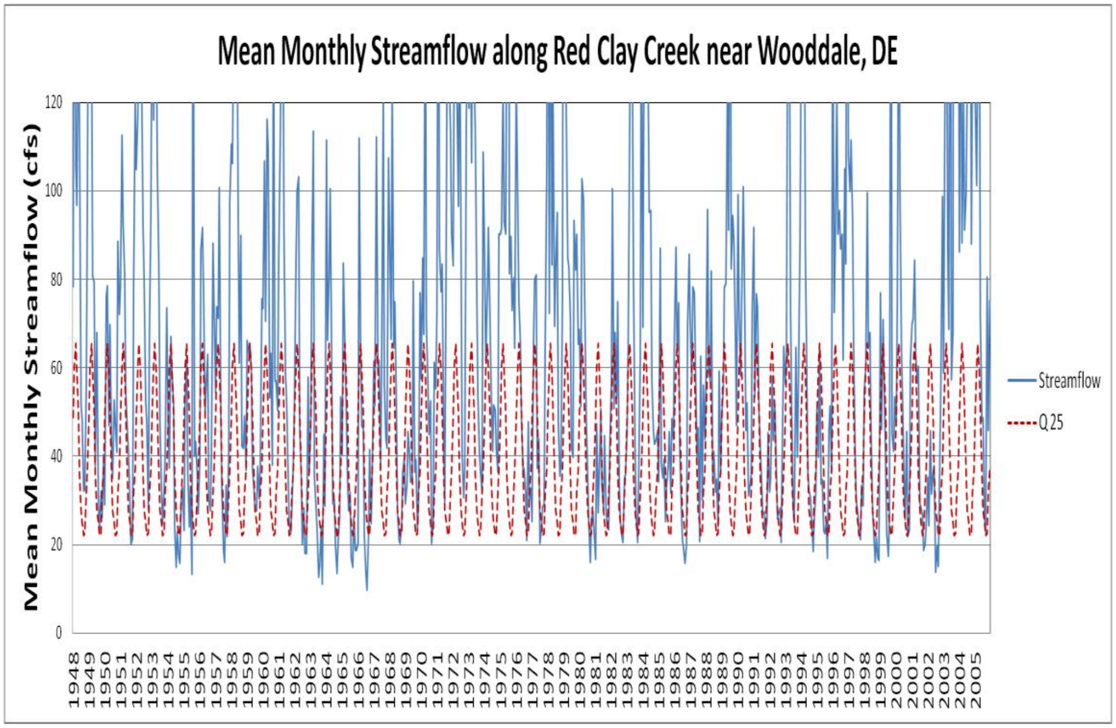

Figure A-2. Mean monthly streamflow along Red Clay Creek near Wooddale, DE for USGS stream gage 01480000.

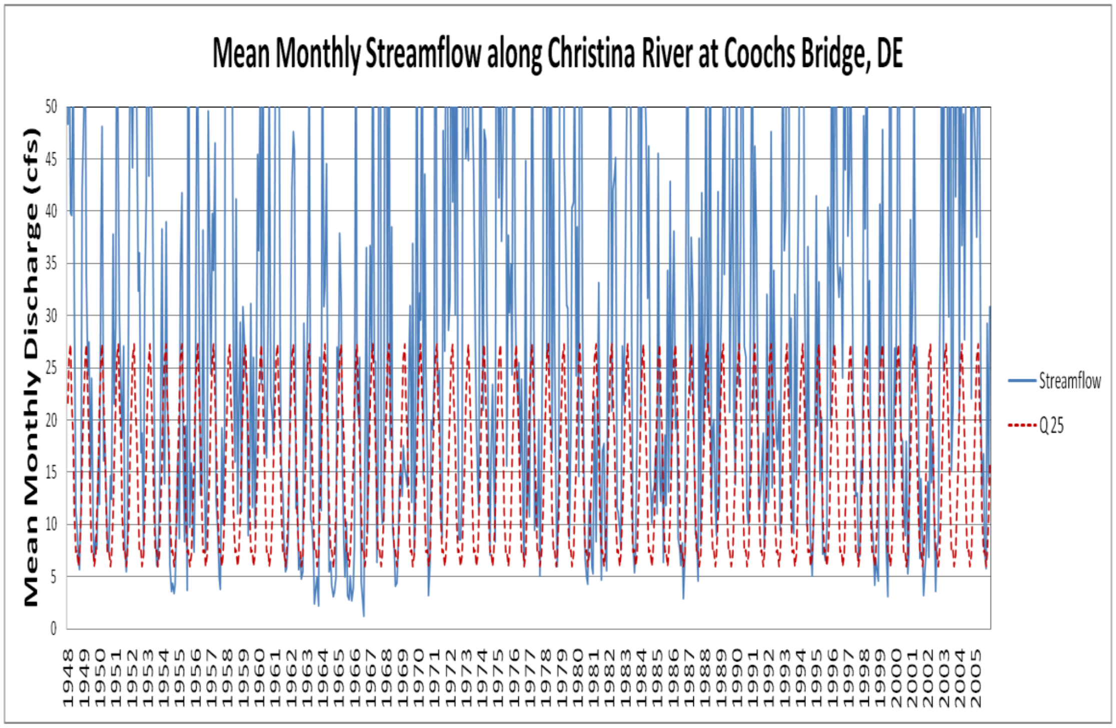

Figure A-3. Mean monthly streamflow along Christina River at Coochs Bridge, DE for USGS stream gage 01478000.

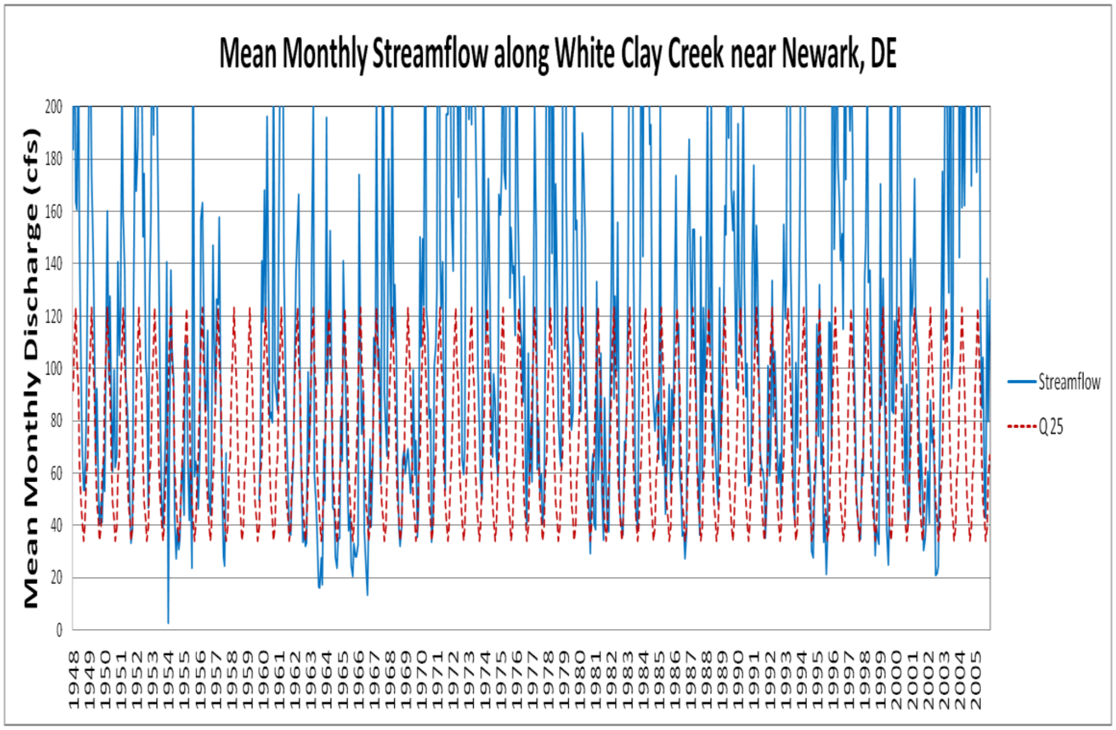

Figure A-4. Mean monthly streamflow along White Clay Creek near Newark, DE for USGS stream gage 01479000.

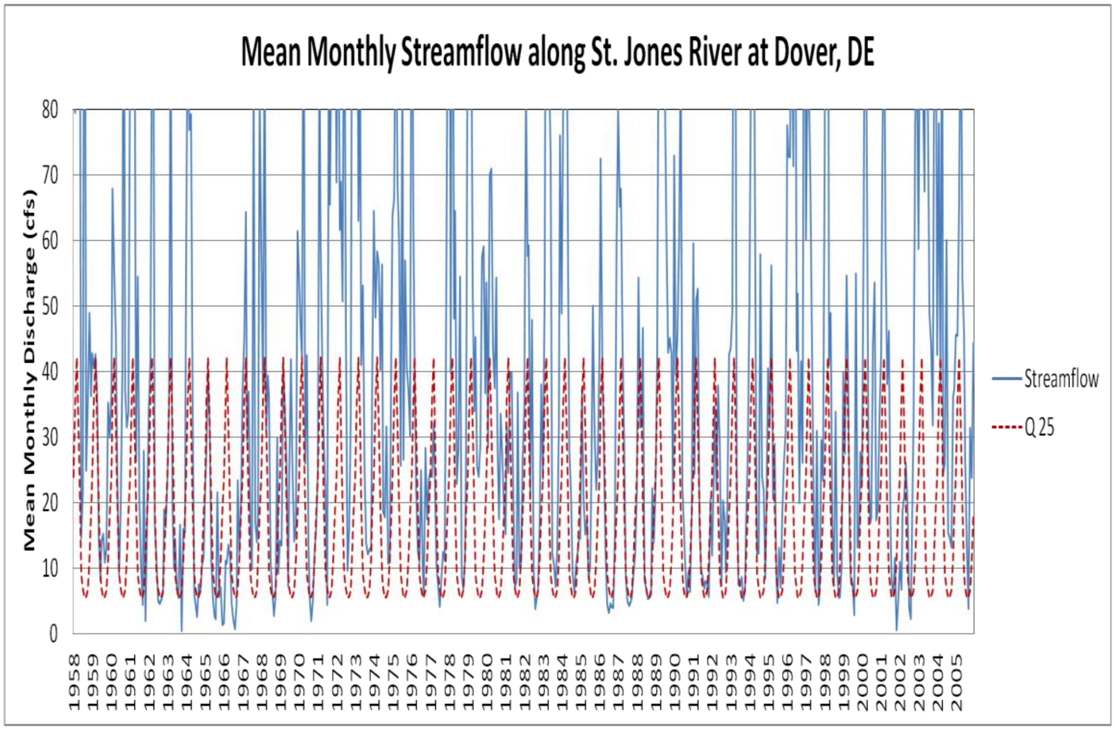

Figure A-5. Mean monthly streamflow for St. Jones River at Dover, DE for USGS stream gage 01483700.

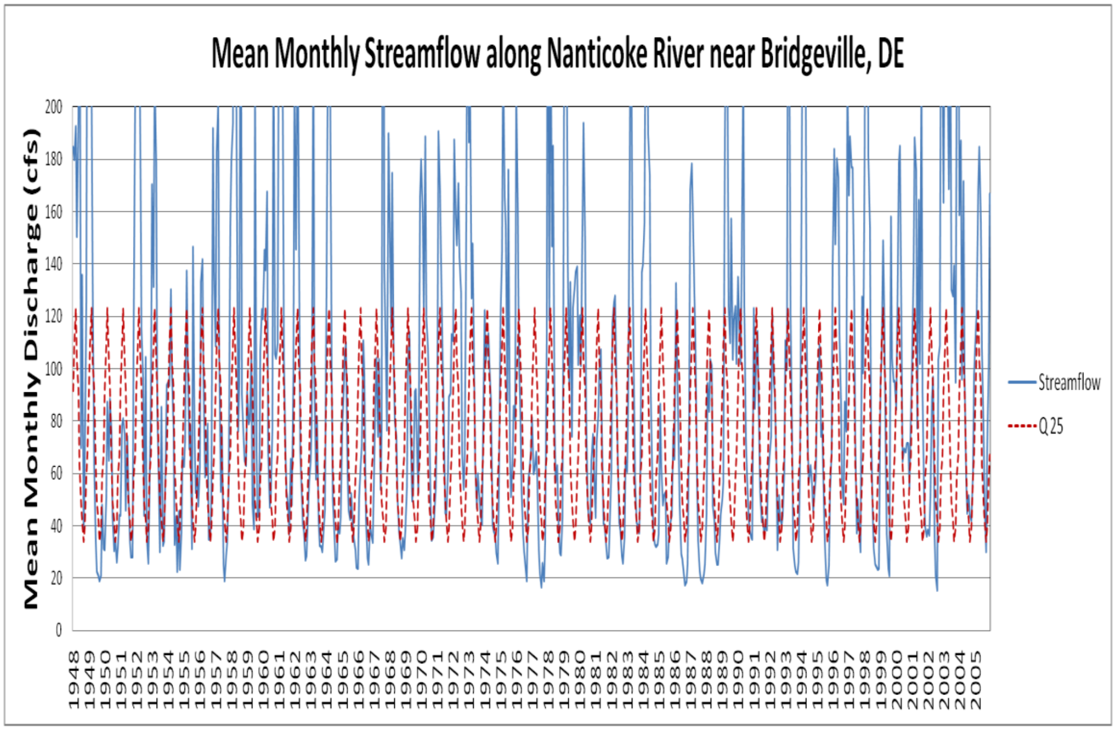

Figure A-6. Mean monthly streamflow for Nanticoke River near Bridgeville, DE for USGS stream gage 01487000.

Appendix B

SCATTERPLOTS OF SPI-01 AND SELECTED SEA SURFACE TEMPERATURE AND TELECONNECTION INDICES

The figures herein displayed show the relationship between SPI-1 (used as an indicator of meteorological drought) and selected sea surface temperature (SST) and teleconnection indices. The scatterplots provide further evidence of the findings listed in Table 4.15; that is, the lack of statistically significant relationships between meteorological drought in Delaware and several of the SST and teleconnection indices used in the study. Plotted values for all indices are from the period 1950-2005 (with data from 1948 – 1949 withheld due to the unavailability of data for one of the indices). SPI-1 values are for the Northern Climate Division; those from the Southern Climate Division were not included as values between the two are relatively close.

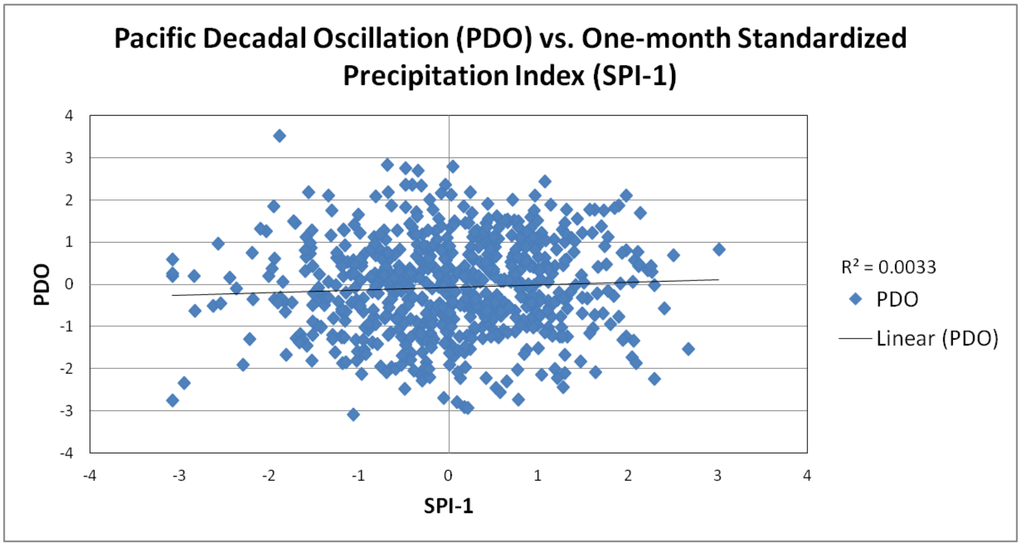

Figure B-1. PDO index values vs. SPI-1 index values. Monthly values from 1950 – 2005 were used for both indices.

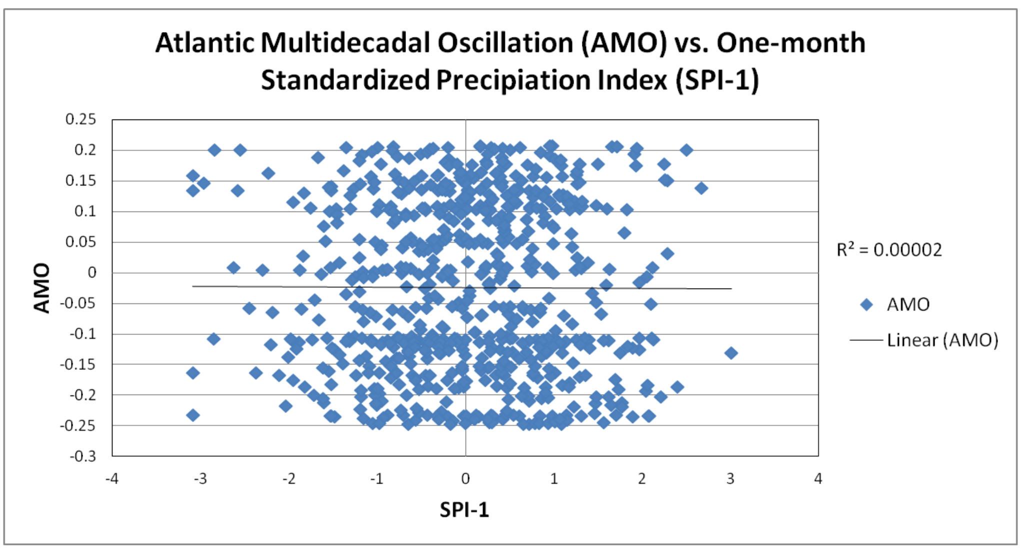

Figure B-2. AMO index values vs. SPI-1 index values. Monthly values from 1950 – 2005 were used for both indices.

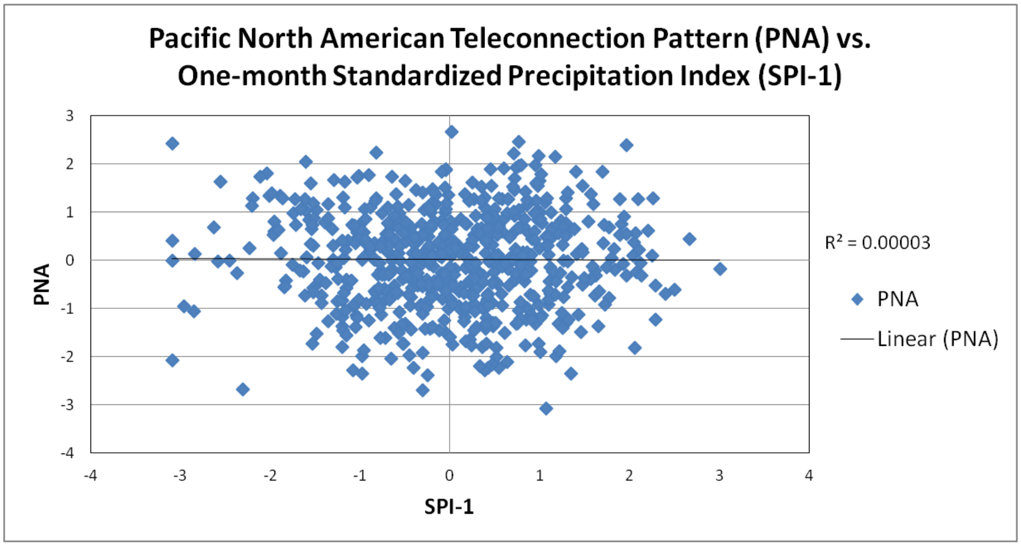

Figure B-3. PNA index values vs. SPI-1 index values. Monthly values from 1950 – 2005 were used for both indices.