A Hydroclimatological assessment of the regional drought vulnerability: A Case Study for Indiana drought

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ABSTRACT: Characterizing and developing drought climatology continues to be a challenging problem. Also as decision makers seek guidance on water management strategies, there is a need for assessing the performance of drought indices. This requires the adaptation of regionally appropriate, drought indices for monitoring droughts and hydrological vulnerability at a regional scale. This study focuses on hydroclimatological assessment of drought variability to develop a statewide water shortage and assessment plan (WSP) for the state of Indiana, USA. Drought climatology was assessed using in-situ observations and regional reanalysis data. A summary of precipitation and evaporation trends, as well as the estimation of drought variability, the worst case droughts, drought return period, and frequency and duration, using multiple drought indices, and stream flow analysis was undertaken. Results indicate regional and local variability in drought susceptibility. In the worst case (200 year return period), Indiana has a 0.4% probability to receive 45% of normal precipitation over 12 month drought in any years. Consistent with other studies, the Standard Precipitation Index (SPI) was found to be appropriate for detecting short-term drought conditions over Indiana. This recommendation has now been incorporated in the 2009 Indiana Water Shortage Plan. The study also highlights the difficulties in identifying the past drought from climatic data and the results suggest high degree of uncertainty in making drought predictions using future climatic projections.

KEYWORDS: Climatology; Drought Indices; Precipitation; Indiana; Water Shortage Plan

1. Introduction

Drought is one of the most costly natural disasters globally. The 1988 drought in the central and eastern US region and caused an estimates $40 billion in damages (Owens et al. 2004). At a state level, when severe drought hit the eastern US including Indiana in 2002, it was estimated that the impacts cost $10 billion in damages (Ross and Loft 2003). Thus, drought impacts agricultural and economic loss as well as environmental and social changes. Current IPCC assessments warn of potential increase in the vulnerability and impacts due extreme drought conditions and extreme heat events (IPCC, 2007). The premise of this study is that reviewing the magnitude, timing, distribution and persistence of impacts as well as the potential for adaptation can identify drought vulnerabilities. The study of the climatology of drought, in terms of history, frequency, duration and spatial extent can help ascertain the probability of droughts and their severity. Drought severity depends on water shortage and water use. A drought is defined as "a period of abnormally dry weather sufficiently prolonged for the lack of water to cause serious hydrologic imbalance in the affected area" (AMS 1995). Drought has been defined in terms of meteorological drought, agricultural drought, hydrological drought, and socio-economic drought. The primary focus of this study is on meteorological drought, which is defined as a lack of rainfall over a prolonged period. The effects of drought are dependent on our factors: the amount of precipitation, its intensity, its timing and spatial coverage.

This study aims to evaluate regional drought conditions and their triggers in more detail. The study focuses over the state of Indiana, which is an important agricultural economy in the Midwest U.S. Study objectives are:

1. To evaluate the state level seasonal trends and distribution of precipitation and evaporation to understand the changing risk of drought.

2. To create a base map of mean precipitation so that drought potential can be identified (by developing anomaly maps).
3. To identify the worst-case drought occurring over the study.
4. Estimate the return period, frequency, and duration of droughts across the study.
5. To evaluate the relationship between drought indices and its consistency.

Arvin (Arvin 2006) and Winstanley et al. (Winstanley et al. 2006) analyzed the water-use trend from 1986-2006 and reported that in Indiana the withdrawal of ground water was increasing. This increase was especially high during summer because of the agriculture and community water supply demand. Interestingly, the energy utility and industry were the main consumers and used more than 94% of the surface water.

Indiana developed a formal water shortage plan in 1994, and revised it in 2000 (DNR,2000). The plan consists of four water shortage phases: (i) normal, (ii) water shortage watch, (iii) water shortage warning, and (iv) water shortage emergency. The plan addresses the minimum stream flow equivalent to 7Q10 (the lowest seven-day average flow having a ten-year recurrence interval) as an absolute minimum flow. When stream flow in Indiana is less than 7Q10, the water withdrawal from streams is to be prohibited due to severe drought and poor water quality. The plan also uses Q80% (that is 80% of streamflow), as the desirable minimum flow requirement and the net withdrawal from a stream is to be restricted when the stream is less than Q80%.

Rao et al. (Rao et al. 1997) studied different drought indicators for the state of Indiana. The study divided the state into three drought regions from the nine climatic divisions. The indicators included meteorological and hydrological variables such as precipitation anomaly, summer temperatures, river flow, ground-water levels, reservoir volumes, and the Palmer Hydrological Drought Index (PHDI). The Rao et al. (Rao et al

1997) study concluded that the monthly average river flow series was the best indicator for detecting drought in Indiana. The percentage of exceeding monthly river flow (7Q10) and the monthly PHDI was recommended as a threshold value to declare drought in Indiana.

Drought indices and monitoring methods have been developed and studied by many researchers (Mo et al. 2006; Ntale et al. 2003; Keyantash et al. 2002; Heim et al. 2002; Guttman et al. 1992 and 1991; Oladipo 1985). Two popular indices, are included the Palmer Drought Severity Index (PDSI), and Standard Precipitation Index (SPI). The U.S. Drought Monitor is the default drought status indicator now and uses multiple factor such as the surface water supply index, the crop moisture index, deciles, and reclamation drought index (Svoboda et al. 2002). The comparison of each drought index is shown in Table 1. However, the U.S. Drought Monitor is a relatively new pursuit and rainfall analysis is still needed to understand the climatology of the return period of droughts. Therefore, a study of climatological droughts and its variability to identify drought conditions and appropriate index in Indiana is necessary so that policy makers are able to plan drought mitigation methods and their management. The results of this study are also expected to be applicable to the broader U.S. Midwestern region.

2. Data and Methods

Precipitation data from the 61 National Oceanic and Atmospheric Administration (NOAA) Cooperative Observer Program (COOP) stations were averaged for each consecutive 3, 6, 9 and 12 month period over a 50-year (1957-2006) period. The averaged data was used as the base precipitation values for each period and then compared with current data to identify drought conditions in each region. The driest precipitation in a 2, 3, 5, and 10-year period and extreme drought return periods were estimated.

The 32-km grid North America Reanalysis (NARR) 1979-2005 precipitation and potential evaporation data were analyzed and mapped to identify the trends in precipitation and evaporation for each climate division. Drought indices such as SPI, PDSI, and PHDI were used to evaluate the duration and frequency of drought in different climate divisions (figure 1) from a 110-year record from 1897 to 2006. The indices have obtained from the National Oceanic and Atmospheric Administration (NOAA) and National Climatic Data Center (NCDC).

Each drought index and precipitation was cross-correlated with the ONI (ENSO Oscillation Index), PNA (Pacific North American Index), AMO (Atlantic Multi decadal Oscillation), and PDO (Pacific Decadal Oscillation). Regression model was applied to a time series of precipitation and PDSI, PHDI, and SPI for 1897 to 2006. The time series regression trend of low flow, 7-day minimum and extreme flow duration in each climatological region was also calculated and analyzed using the Indicators of Hydrologic Alteration (IHA) software (Mathews et al. 2007)

3. Analysis of drought conditions and variability

3.1 Precipitation and Its Trends in Indiana

Figure 2(a) shows the mean annual precipitation for Indiana, based on 27 years (1979 – 2005) of NARR data (Mesinger et al. 2006). The mean monthly precipitation is 3.3 inches (83.82 mm) (1 inch = 25.4 mm). The precipitation in the northern part of climate divisions 1, 2 and 3 ranges from 2.2 to 3 inches. Climate regions 4, 5, and 6 have a higher average precipitation —up to 3 to 3.6 inches, and greater than 3.6 inches in regions 7, 8, and 9 in the south. The driest season is winter with a statewide average of 1.8 inches (Figure 2(b)). Figure 2(b) shows the statewide averages in fall, spring, and summer are 3, 3.6, and 3.9 inches respectively. The highest average precipitation occurs in spring over the southern part of Indiana and is greater than 4.2 inches.

Precipitation for Indiana in all climate divisions shows an overall increasing trend from 0.1 to 0.4 inches per decade (Figure 3). The statewide average trend is 0.2 inches per decade. The spring and fall rainfall have shown a reduction ranging from -0.1 to -0.3 inches per decade as seen in Figure 3(b). The largest decreasing trend occurs during fall (SON) particularly over the northern part of Indiana (at approximately 0.3 inches per decade). At the beginning of growing season (MAM), the precipitation trend shows decreased rainfall in the southwestern part of the state and an increase during the growing season (JJA). The highest increasing trend (0.6 inches per decades) occurs in the northwestern part of the state (Figure 3b).

3.2 Evaporation and its trend in Indiana

Figures 5-8 show the mean and trends of evaporation (E) and precipitation minus evaporation (P-E). Figure 5(a) shows the mean evaporation. As expected the highest evaporation values occurs in summer (JJA), it is approximate 6 inches in central and southern Indiana. The statewide evaporation means for each season are 0.6, 2, 3.2, and 5.8 inches in winter, fall, spring, and summer, respectively (Figure 5(b)). Figure 6(a) shows that the statewide evaporation trend shows an increase of about 0.1 inch per decade. The largest increasing evaporation trend in Indiana, (~ 0.3 inch per decade) is during the spring in southern Indiana (MAM), and during the summer in west-central Indiana (JJA) (Figure 6(b)).

Evaporation and precipitation show similar spatial distribution. Lower precipitation with lower evaporation occurs in the north of the state and higher precipitation with higher evaporation occurs in the south. Figure 7(a) shows the effective precipitation (P-E). Areas that have large negative P-E values are more susceptible to drought. Figure 7(b) shows the lowest P-E value occur mostly in the summer or the growing season and ranges from (-1.6)–(- 2.2) inches per month over northern and southern parts of Indiana. The statewide P-E value equals 0.4 inches (Figure 7(a)). Figure 8(a) shows the statewide P-E trend is 0.1 inches per decade, and the largest decreasing P-E trend,-0.3 inches per decade, occurred over northern Indiana in the fall season and over southwest Indiana in the spring season, as shown in Figure 8(b). These negative P-E trend increases the likelihood of drought.

3.3 Estimating Meteorological Drought

To assess drought conditions in Indiana, the precipitation departure/anomaly has been used as one of the indicators (Changnon 1987). Therefore, the mean precipitation for 3, 6, 9, and 12-month periods over a 50-year time span was compared to the 3, 6, 9, and 12 -month averages for each particular year. We used 50 year period rather the normal precipitation (30 years) to cover the significant drought events in Indiana. We used precipitation data from 61 cooperative observer stations (Figure 9) to calculate the average precipitation. Drought occurrence can be indicated by rainfall as a fraction of normal values and comparing them with the criteria in Table 2. The 50 year rainfall base maps for 3, 6, 9, 12 month are shown in figure 10 -13.

3.4 Assessing Potential Worst Case Drought in Indiana

The statewide annual normal precipitation for Indiana is 41.5 inches (1 inch = 25.4 mm). The driest year for Indiana (Table 2) occurred in 1963 with mean precipitation of 29.32 inches (30% deficit). Seasonwise, 1895 had the lowest rainfall (55% deficit) in the spring season (MAM). The driest summer (JJA) occurred in 1936, with 51% deficit (Table 3). The Palmer Drought Severity Index (PDSI) is an indicator of meteorological drought (Palmer 1965) that uses precipitation, temperature, evapotranspiration, runoff, and moisture loss from the surface layer in a water balance equation. PDSI typically has a 9-month time scale and requires the soil layer and soil moisture data of the region. The 9 month SPI (Standardized Precipitation Index, Mckee et al, 1993) was also estimated. Figure 14 (a-c) shows the Palmer Drought Severity Index for each climate division in Indiana. Using PDSI and SPI as a criterion, most severe droughts occurred in 1964 over region 1 with drought indices equal to -

3.91 (PDSI) and -1.57 (SPI09) respectively. For region 2, the most severe drought occurred in 1931 (-4.92), while the SPI09 indicates the most severe drought occurred in 1934 (-1.75). For region 3, both the PDSI and SPI09 indicate the most severe drought occurred in 1931 (PDSI = -6, SPI = -2). For regions 4 and 9, both drought indices indicate the most severe drought occurred in 1934 (PDSI = -5.8,-4.5 SPI = -1.8, -2). For region 5, 1934 and 1941 appear as the most severe drought records according to PDSI (-4.2) and SPI09 (-2) respectively. For region 6 indicates 1934 with the SPI09 (-1.8) while PDSI (-4) indicating 1935 as the most severe year. For regions 7 and 8, the PDSI ((-4.5) – (-5.0)) showed 1954 as the most severe drought year, while the SPI09 (-2) showed 1941 was the severe drought year for regions 7 and 8. On the whole, PDSI and SPI09 have not agreed and each indicated severe drought for different years, highlighting the difficulty of assessing worst drought conditions from climatology.

Figure 15 (a-c) shows the “worst-case” meteorological drought scenario in each region in Indiana. Several stations in Indiana do not have 100 years of complete data precipitation records and stations. Those stations missing more than 10 % of data were removed. The average precipitation from 34 cooperative stations has been used to determine the annual and seasonal driest of 2-, 3-, 5-, and 10-year periods over 10 decades from 1907-2006. The percent of normal in summer (JJA) for the driest period is lower than the driest period of spring (MAM). For the 2-year driest period in summer (Figure 15(c)), the central part of Indiana appears to be generally susceptible to drought. However, in spring, the dry condition in the northwestern and southeastern parts of the state appears to increase. Figure 15 (a-c) show that when the duration and intensity are inversely relates. Consequently, most parts of Indiana have never faced 5 or 10-year periods of meteorological drought. This feature seems to be consistent of the Midwest US (J. Angel, personal comm., 2009)

However, some parts of north-central and western Indiana may be susceptible to long periods of drought (5 or 10 years) in summer and spring.

Figure 16 shows the driest area based on the maps shown in Figure 15. In the two driest year periods, 73% of normal precipitation covers a 50% area of the state; 74% of normal precipitation covers 40% of Indiana for a record 3-year dry period, and 77% of normal precipitation covers 35% of the state for a record 5-year dry period. For the longest period of the 10 driest years, the precipitation of 79% of normal covers only 15% of the state. The northern and eastern parts of state remain the driest regions. The wettest region is in the south.

Figure 17 shows the precipitation area calculated from North America Reanalysis Data (NARR). The graph shows that majority of the state has received 80% of normal precipitation. In 1989, 30% of Indiana was susceptible to abnormal drought conditions with precipitation showing at 70% of normal.

3.5 Drought Return Period

The drought return period is the probability of recurrence interval between events equaling or exceeding a specific level or magnitude. The drought returns period maps in Figures 18 (a) and (b) show the probability of risk in rainfall frequency that may occur once in a specific time period. This map can be used for planning and managing for drought in the region by presenting choices in the level of protection against droughts. The map shows the percent of normal precipitation during the drought period for 12 and 24 months which identifies each decade of each return period for 25, 50, 100 and 200 years. First, the 10 driest precipitation values were calculated from two methods (A and B) (Winstanley et al. 2006). Method A has been used to determine the driest precipitation measures of each decade from 1906 to 2006 to obtain the independent dry event between each decade. Method A selects the lowest precipitation value for each decade. However, if the data of the first decade is missing, Method B will be used to select the 10 driest values from 1906 to 2006 by ignoring the first and last six months from the first selected value. Second, the 10 driest precipitations of all 10 decades have been used to determine the return period by General Extreme Value distribution. The data has been analyzed from 24 stations in Indiana which have less than or equal to 10% missing data. The overall state return period for the 12 and 24 driest months is shown in Table 3.

In Table 3, the 20-year return period shows that the lowest probability of precipitation below 64.1 % of normal may occur once in 20 years, or it has a 4% chance of occurring in any year. Method A shows a higher return period than method B. However the values are closer when the return period increases. Figure 18 shows Indiana has a 4% chance to receive precipitation over the eastern part at 45% of normal and 65% of normal over 12 months and 24 months, respectively. A 0.04% chance exists that the worst dry conditions will occur in central and southern Indiana, this being 45% of normal in 12 months. The dry area covers the northern and eastern parts of Indiana for a lower return period; when the return period increases, the dry area moves to the south and the west. The driest in 24 month measure shows a higher precipitation than the driest 12 months, which indicates that Indiana has not faced severe drought conditions over a long-term period (e.g. 2 year) consecutively.

3.6 Drought frequency and duration

Figure 19 (a-i) shows frequency and duration of drought indices, PHDI, PDSI and SPI for each climate division over the 100 year period. At the time this analysis was undertaken (2007), PHDI was used in Indiana for drought declaration (Rao et al. 1997). The PHDI is based on moisture inflow (precipitation), outflow, storage, and use for short-term drought periods (Karl and Knight 1985). The PHDI detected drought in Indiana in 11% of 1344 months in 9 regions). The longest duration of drought is 18 months in division 7 as shown in Figure 19 (g). In this study, we divided drought into 3 categorizes; watch, warning, and emergency as in Table 5 so as to be consistent with the definition used over the study region (Rao et al 1997). The highest frequencies of drought emergency as indicated by PDSI occur in climate divisions 7 (Figure 19 g), there were 16 occurrences within a 1, 2, 3, 4,10 and 18-month period. Also, climate division 6 (Figure. 19f) has the highest frequency of drought with 160 occurrences of drought emergency, warning and watch.

The SPI (Standard Precipitation Index) was developed based on the standardized precipitation deficit using multiple time scales. As seen in the Figure 19, the SPI for 1, 3, 6, and 9 months shows a higher frequency of detecting drought within a shorter time period in Indiana when compared to the PDSI and PHDI index in most climate divisions. The highest frequencies of drought emergency as detected by the SPI occurred in climate division 6 with 75 occurrences within a 1 and 2 month period (figure 19(f)). Over a short time period, SPI appeared to detect drought emergencies more frequently than the drought watch and/or warning for shorter time scales (1- 3 month). For longer periods, the drought warning frequency increases more than the watch or emergency. Typically, drought emergencies occur over a relatively short time period in Indiana. Therefore, the frequency of drought emergency detection decreases when the SPI time period is increased. When the frequency of drought occurrences using PHDI as an indicator is compared with the PDSI, the PHDI appears to be a better warning tool and detected higher frequency of droughts over the same time period. These results highlight that in absence of SPI, it was appropriate that Indiana used PHDI as a drought indicator. However, SPI has a better ability to detect drought emergency in its early stages for the study region. Indeed, for the time period inherently considered in estimating SPI, studies such as Goodrich et al. (Goodrich et al. 2007) suggest that SPI may not show clear spatial signal for a long-term drought.

Figure 20 shows the consistency of indices over Indiana by comparing the two time series indicators for different drought severities. The indices have been transformed to severity level as 1 (no drought), 2 (watch), 3 (warning), and 4 (emergency). The drought conditions have been marked according to the severity level. The result shows that the SPI behaved similar to PHDI and PDSI when the time period increased to 9 and 12. The slope of the surface increased when a higher frequency of same severity is detected. For the shorter time period, the PHDI indicates no drought (1), while the SPI03 indicates a drought watch (2) for 605 events, drought warning (3) for 541 events and drought emergency (4) for 91 events. The inconsistency between (PDSI and PHDI = 1) indicating no drought and SPI suggesting a drought emergency reduces when the time scale of the SPI increases (Figure 20). These results suggest that SPI 01, 03, and 06 can be used as a better trigger for short-term droughts (meteorological drought) as compared to the PDSI and PHDI for Indiana. The SPI indicates more instances and increased intensity of drought formation across all the Indiana climate divisions. These results are consistent to broader conclusion presented in Mckee et al. (Mckee et al. 1993) and Hayes et al. (Hayes et al. 1996) highlighting that SPI is a better tool for short term droughts.

Figure 21 shows the cross-correlation in the regional time series between indices and precipitation. By definition, SPI at 1 month has the highest correlation with precipitation, while PDSI and PHDI have the second and third highest respectively.

3.7 Drought Indices and Multi-Decadal Trend

Many parts of the United States have experienced persistent arid periods (e.g. Cook et al. 2004; Herweijer et al. 2006; Fye et al. 2003; Booth et al. 2006). Figures 22 show the 10-, 30- and 100- year period trends of drought duration over Indiana using the PDSI, PHDI, SPI01, SPI03 and SPI09 indices from 1895 to 2006. Drought occurrences in 10-year period show a decreasing trend during 1907-1916, 1927-1936, 1947-1956 and 1957-1966 due to the significant drought events in that period. Interestingly, the most significant drought period on record after 1966 does not have a major impact on the decadal trend. The decadal trend of the drought index shows an increase in 1987-1996 and 1997-2006. Interestingly, when we look at the 30 and 100 year period, the drought trend is replaced by a increasing trend of wet period.

Drought in Indiana may be caused by preponderance of high pressure cells that keep the Gulf of Mexico moisture from reaching Indiana; moisture which normally arrives in the spring and summer. If the winter northwesterly winds have kept the spring moisture away from Indiana, what is known as a blocking event occurs. Blocking events are the large-scale ridges in the jet stream that lead to the downward motion of the air, suppress cloudiness, and cut off rain (Lupo 2006).

Also, many studies show that La Niña and El Niño (ENSO) have influenced precipitation variability inducing a multi-decadal drought in the United States in the past decade (Goodrich et al. 2007 and 2004; Neelin et al. 2003; Barlow 2002; Nicholson et al. 2001; Nakagawa et al. 2000; Chiew et al. 1998) Similarly, the Atlantic Multi-decadal Oscillation (AMO), Pacific Decadal Oscillation (PDO) and North Atlantic Oscillation (NAO) also influence the temperature and precipitation in North America (Enfield et al. 2001; McCabe et al. 2004; Sutton and Hodson 2005). Moreover, the PDO (Pacific Decadal Oscillation) is a major cause of drought in the Central United States (Englehart et al. 2003).

For Indiana, Figure 23 shows the cross-correlation between the ENSO (ONI) index and the precipitation and temperature anomaly, AMO, NAO, Pacific North Atlantic Index (PNA) and PDO. In the summer, the NAO and temperature have a high inverse correlation with precipitation (~ -0.4) followed by the PDO, which correlates with precipitation positively to 0.3. In the winter time, the PNA (-0.58) and the NAO (-0.42) have a stronger inverse relationship with precipitation as compared to the ONI or ENSO (-0.3) relation at zero lag time. Thus, the drought changes in Indiana appear to have linkages to teleconnection events. There is higher relation to PNA and NAO and low dependence on ENSO. While we have some predictive skill with ENSO but the lack of predictive skill in PNA and NAO means we cannot anticipate drought one or two seasons ahead in Indiana.

3.8 Stream flow Analysis

The flow index as 7Q10 (7-day minimum streamflow with a 10-year return period) has been widely used to indicate severe drought conditions and regulate water withdrawal (Rao et al. 1997 and 2001; Pyrce 2004). The flow index was calculated for the 9 stations in each region (Figure 24). The extreme flow condition durations are particularly important as they cause stress for living organisms and impact water quality. The 7-day annual mean minimums of streamflow (7Q) from 1957-2006 are shown in Figures 25 (a-c). The lowest values and the 10th percentiles are listed in Table 6. In Region 7, the minimum low flow was highest (7Q = 760), the lowest record occurred in 1964, and the longest dry duration was 72 days. Regions 8 and 9 have only a small stream, which goes dry in the summer.

Analysis shows that 1987-1988, 1991-1992, 1997-2000 were particularly dry and the low duration events generally ranged from 14 to 18 days in 1961 and 1998 respectively. Also in Region 9, the Vernon River dries almost every year with the highest streamflow values of only 22 cfs in 2001. The lowest 7-day minimum streamflow occurred in 1963–1964, which was the longest drought on record in Indiana. Most of the region shows an increasing trend of low flow and a decreasing trend of extreme flow duration. However, low pulse duration does not correspond to the lowest 7Q for each year. Drought planning records for small community water systems show drought occurrence in Indiana from 1931-1935 and 1963-1964 that indicate an average flow of less than 20% of the long term period (between 12-18 months). Table 4 indicates the lowest statewide average ratio of the low flow in the 54 month-drought period over the long-term mean flow is 0.552 (Winstanley et al.,2006).

4. Conclusions

Our understanding of future climate change in Indiana continues to evolve and, we recommend that the vulnerability of drought and the planning for drought be done on a frequent basis. In other words, rather than treating the assessment as a one-time exercise, it would be useful to re-evaluate every decade. The main conclusions from this study are (i) There are regional differences in the precipitation and evaporation rates across Indiana with strong north to south gradients. Overall there is a higher drought vulnerability in the northern parts of the state due to low precipitation and evaporation rates for most seasons. (ii) During the growing season (summer), negative precipitation minus evaporation (P-E) values occurred in the southern parts of Indiana making it increasingly vulnerable for agricultural droughts. (iii) The driest spell over a 2-year interval with precipitation lower than 73 % of normal precipitation covers a 50% area of the state and 45% of normal precipitation occurred in the summer and covered all of central Indiana. The results show that Indiana has a 4 % chance of receiving precipitation at 60% of normal over a 12-month period, and a 0.4% chance to receive precipitation at 45% of normal over 12 months. (iv) The precipitation in Indiana is also influenced by climatic variability introduced through PNA and NAO oscillation, and ENSO effect was relatively minor making drought predictions challenging over the region. (v) SPI efficiently identified drought emergency and warnings and drought severity in its early stages. (vi) The multi index comparison brings out an interesting feature that it is quite difficult to identify past droughts, and a variety of indices required to capture the different flows. This statement has some implications for climate modeling studies that seek to understand the projections for drought changes.

These findings were communicated to the Indiana water shortage task force. As a result, Indiana now does not use PHDI to identify drought. Indiana’s water shortage plan (DNR, 2009) now states the following: *“SPI is recommended as the drought index for*

Indiana. This index should be used in addition to the information available from the US drought monitor and input from agencies such as the State Climate Office, National Weather Service, United States Geological Survey, and other local agencies to accurately assess the threat of drought".

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Table 1. Drought Monitoring Index.

Indices	Method	Application
Percent of Normal	Percent of Normal is a simple method to detect drought. It is calculated by dividing actual precipitation by normal precipitation –typically a 30-year mean and multiplying it by 100% for each location. Data are not normalized.	Pros: Percent of Normal is effective in single region or season. Cons: Percent of Normal cannot determine the frequency of the departures from normal or compare with different locations. Also, it cannot identify specific impact of drought or the inhibition factor for drought risk mitigation plans.
Standardized Precipitation Index (SPI)	SPI is a simple index which is calculated from the long term record of precipitation in each location (at least 30 years). The data will be fitted to normal distribution and be normalized to a flexible multiple time scale such as 3-,6-,12-,24- 48- and etc .	SPI is used to identify the meteorological drought or deficit of precipitation. Pros: SPI can provide early warning of drought and its severity because it can specify for each location and is well-suited for risk management. Cons: The data can be changed from the long term precipitation record. The long time scale up to 24 months is not reliable.
Palmer Drought Severity Index(PDSI)	PDSI complexity is calculated from precipitation, temperature and soil moisture data. Soil moisture data has been calibrated to the homogeneous climate zone. PDSI has an inherent time scale of 9 months. PDSI treats all forms of precipitation as rain.	Pros: PDSI has been widely used to identify agricultural drought. PDSI can be used to identify the abnormality of drought in a region and show the historical aspects of current conditions.. Cons: The PDSI may lag in the detection of drought over several months because the data depend on soil moisture and its properties which have been simplified to one value in each climate division. The PDSI will not present accurate results in winter and spring due to the effects of frozen ground and snow. PDSI also tends to underestimate runoff conditions.
Palmer Hydrological Drought Index (PHDI)	PHDI has been derived from the PDSI index to quantify long term impact from hydrological drought.	Pros: The PHDI has been officially used by NCDC to determine the precipitation needed for drought termination and amelioration which has a PHDI equal to -0.5 and -2.0 consecutively. Cons: The PHDI is developed from precipitation, outflow, and storage. PHDI may change more slowly than PDSI and it cannot represent long term drought.
Experimental Objective Blends of Drought Indicators (Drought monitor)	Drought Blend Indicators are divided into short-term and long-term blends. The short term blend includes PDSI, Z, SPI 1, 3-month, and soil moisture. The long-term blend includes PHDI, SPI 06 12 24 and 60-month, and soil moisture. The drought blend method has been used for US drought monitoring: http://www.drought.unl.edu/dm/monitor.html	In the short-term blend method, the indicators are weighted to the precipitation and soil moisture which use to identify the impacts of no irrigated agriculture, wildfire dangers, top soil moisture, and pasture conditions. The long blend index indicates the impacts of hydrological drought such as reservoir and well levels and irrigated agriculture.

Source: *Modified from Drought Indices, Michael J. Hayes, person. comm. 2007 National Drought Mitigation Center (http://www.drought.unl.edu/whatis/indices.htm).*

Table 2. % of precipitation used to identify drought.

Precipitation average	% of precipitation used to identify drought
3-months	<=60%
6-months	<=70%
12-months	<=80%
24-months	<=90%
30-months	<=95%

Table 3. Rainfall deficit of the driest years from 1897 to 2006 in Indiana.

Year	Annual	Year	MAM	Year	JJA
1963	29	1895	55	1936	51
1930	29	1934	52	1933	50
1934	28	1941	50	1930	48
1901	26	1930	48	1908	45
1953	25	1925	42	1940	41
1914	24	1932	42	1991	41
1940	21	1971	40	1922	40
1941	21	1988	37	1944	40
1976	20	1910	35	1919	37
1960	18	1928	35	1983	36

Table 4. Return period for precipitation using methods A and B (% of normal).

Return Period	12A	12B	24A	24B
20	73.4	64.1	80.5	74.5
25	72.8	63	79	74.1
50	64.3	60.9	74.9	72.6
100	63.2	59.1	71.1	70.9
200	58.6	55.3	67.7	69.3

Table 5. The drought period low flow to mean flow ratio (Winstanley et al., 2006).

Drought Period (month)	Ratio
6	0.092
12	0.241
18	0.243
24	0.368
30	0.371
36	0.476
42	0.479
48	0.552
54	0.552

Table 6. Level of drought condition (www.drought.unl.edu)

Level	SPI	PDSI&PHDI
Drought watch	- 1.0 to -1.49	-2.99 - -1.00
Drought warning	- 1.5 to -1.99	-3.00 - - 4.99
Drought emergency	- 2.0 and less	-4.99 and less

Table 7. 7 day minimum stream flow (cfs) and duration.

Division	7 day minimum streamflow(cfs)	Year	Extreme low flow duration (day)	7 day minimum streamflow (10%)(cfs)
1	280	1963	31	387.9
2	79	1964	26	109.1
3	58	1964	12	102.6
4	580	1964	15	794.4
5	72	2002	21	89.1
6	52	1977,1999	130	53.9
7	760	1963	72	894.5
8	2	1998,2000	19	3.3
9	0	1958,1983, 1987 and 1988	14	0.7

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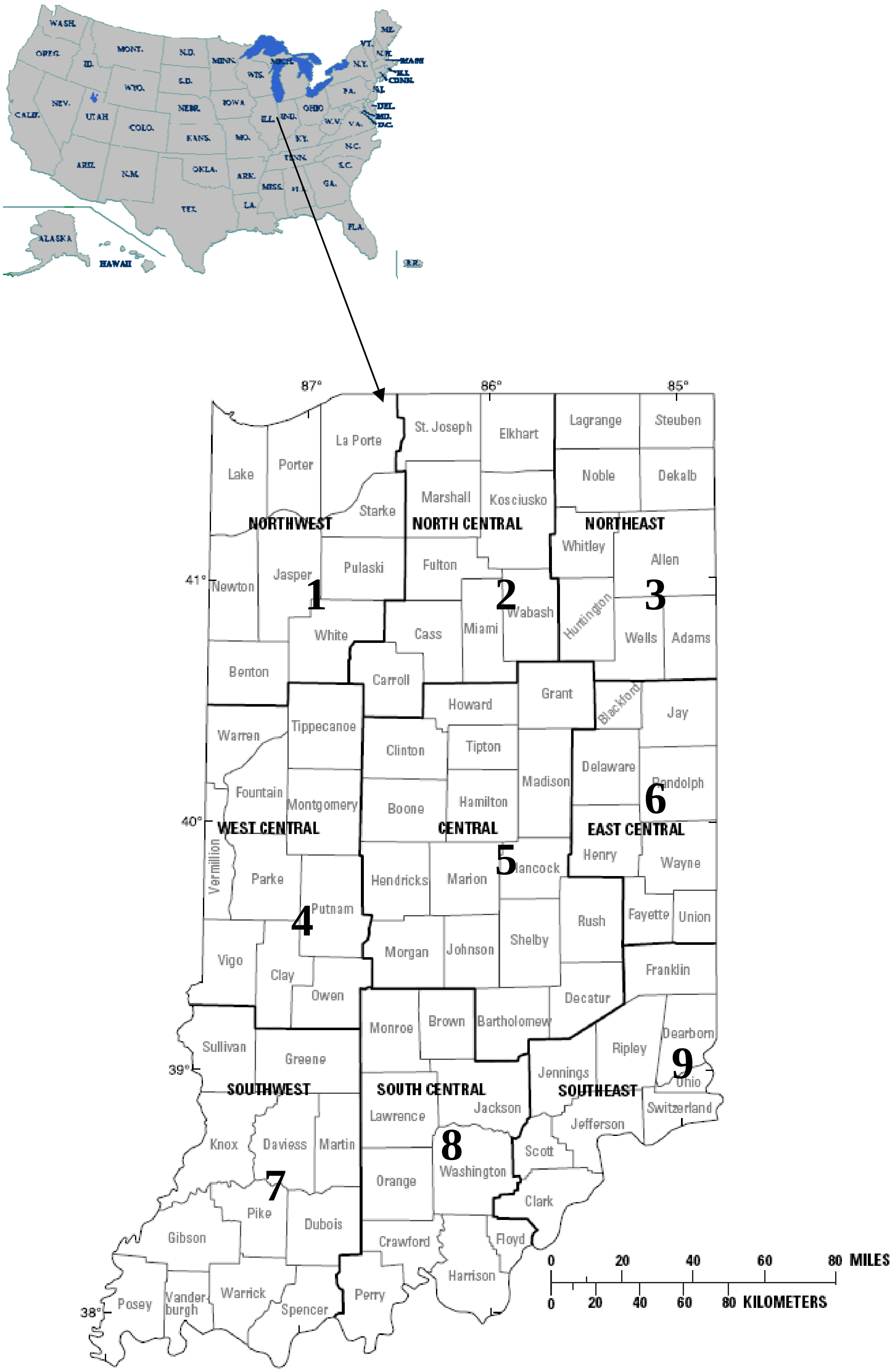
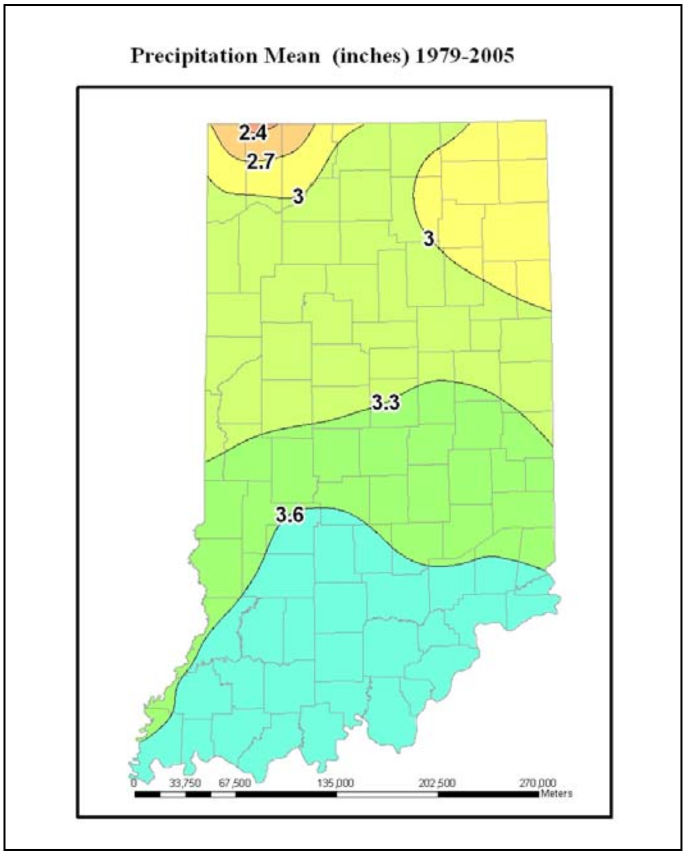


Figure 1. Climate divisions in Indiana (NOAA, 1994).



Precipitation Mean (inches) 1979-2005

Figure 2(a). Mean precipitation (inches) from 1979 to 2005.

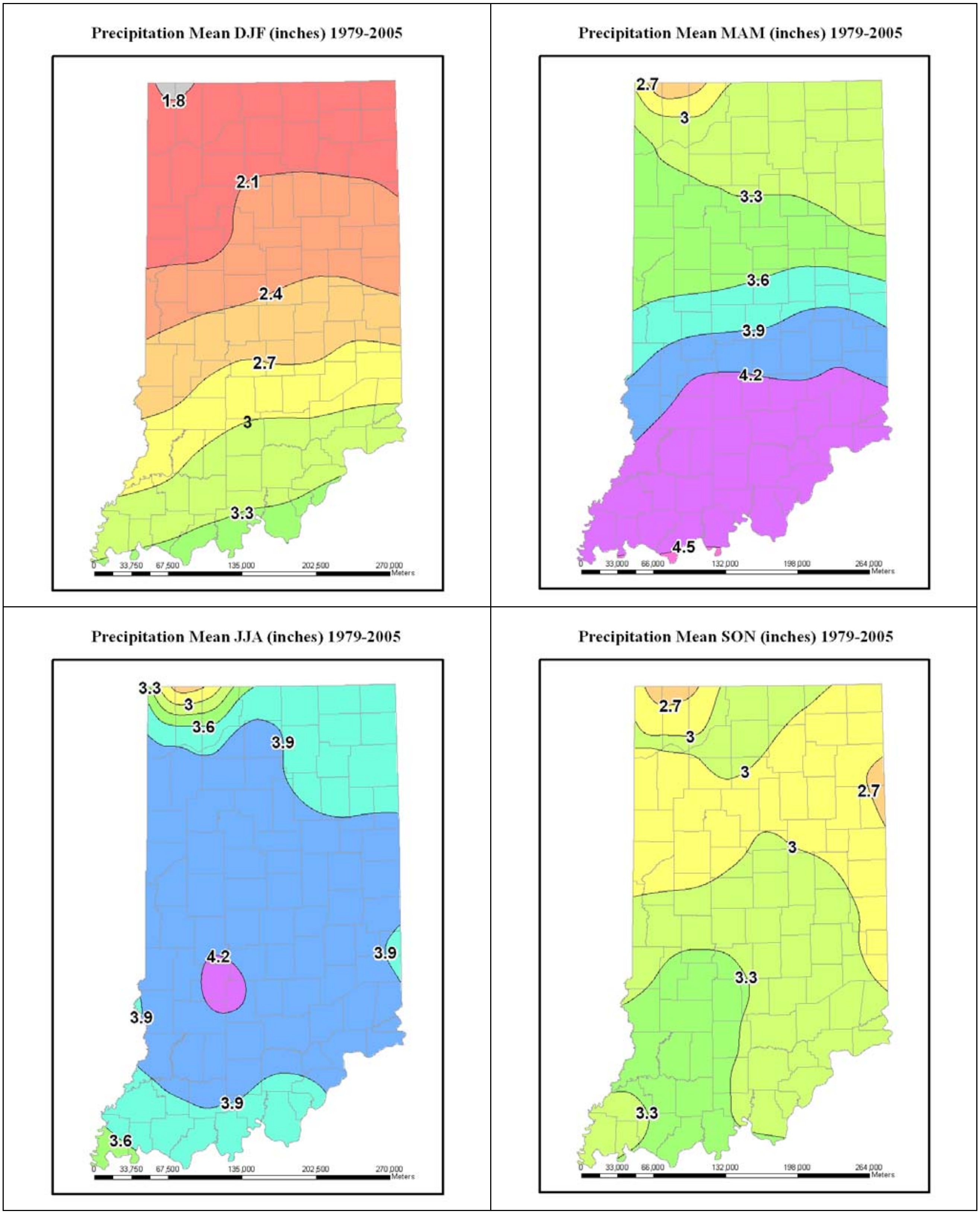


Figure 2(b). Mean seasonal precipitation (inches) from 1979 to 2005.

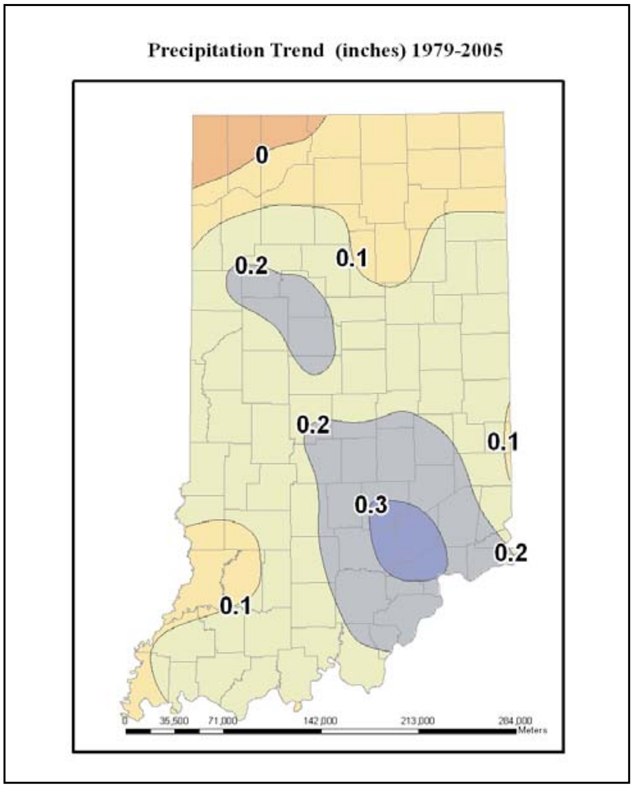
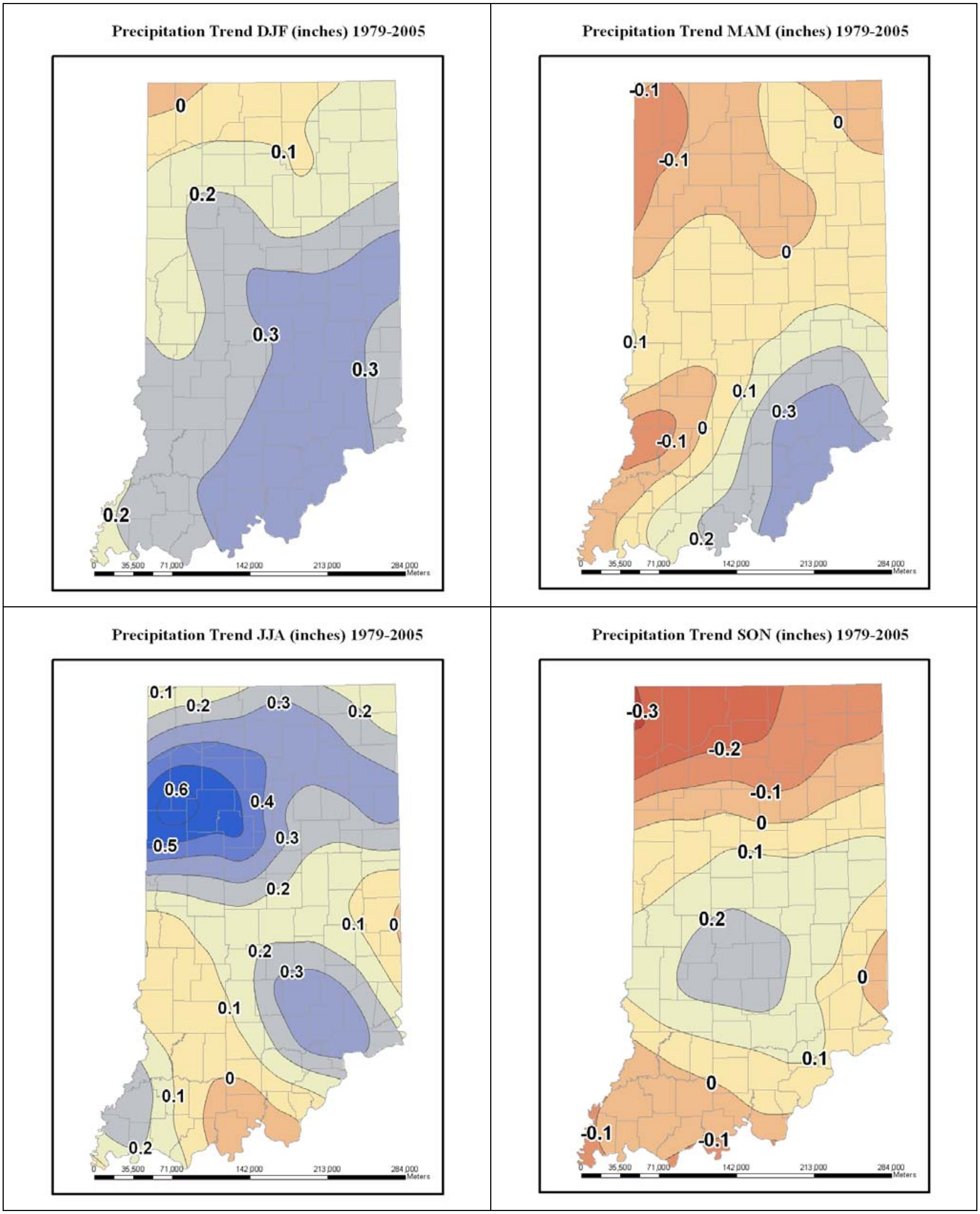


Figure 3(a). Mean precipitation trend (inches/decade) from 1979 to 2005.



Precipitation Trend DJF (inches) 1979-2005

Precipitation Trend MAM (inches) 1979-2005

Precipitation Trend JJA (inches) 1979-2005

Precipitation Trend SON (inches) 1979-2005

Figure 3(b). Seasonal precipitation trend (inches/decade) from 1979 to 2005.

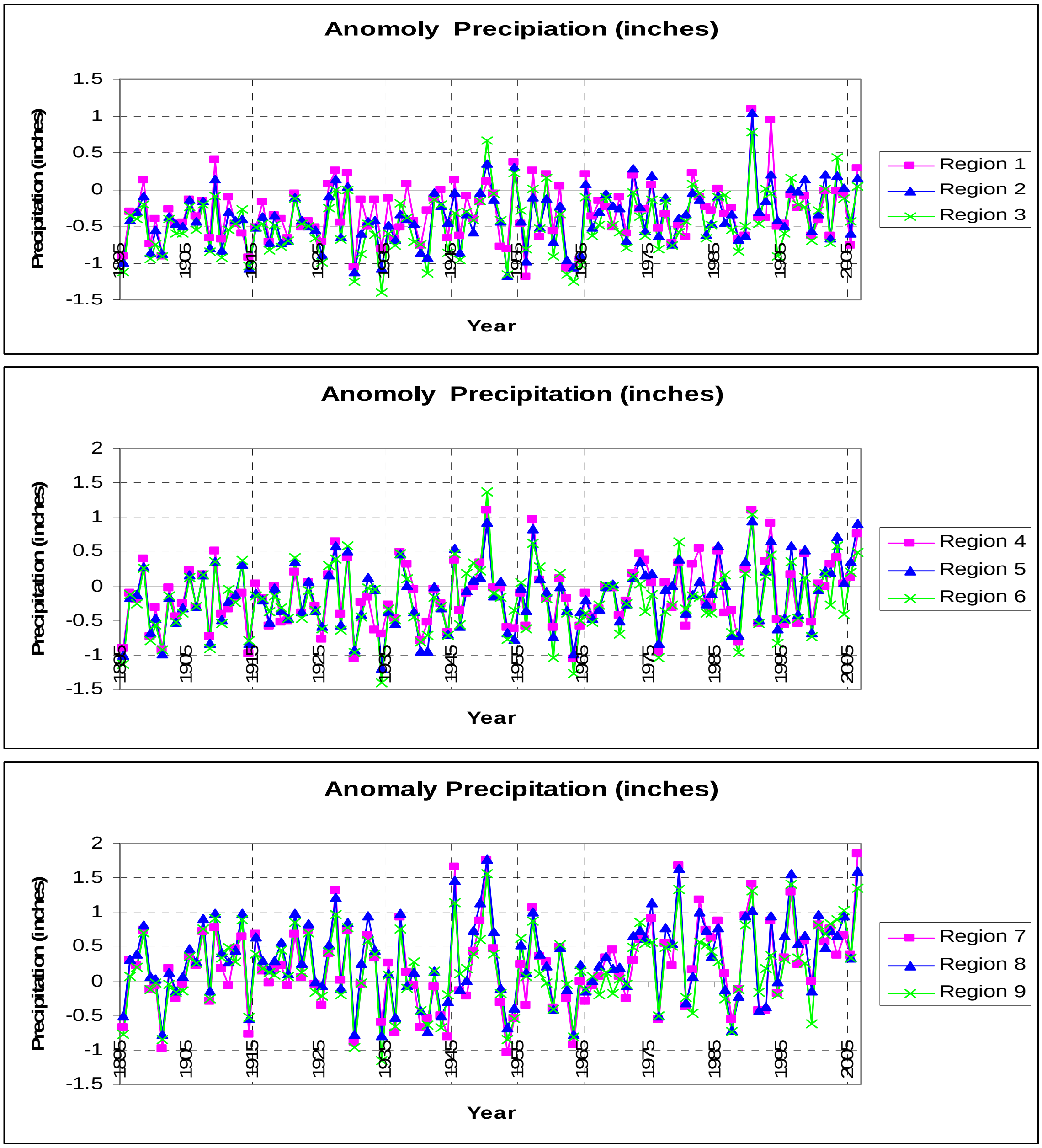


Figure 4. Precipitation anomaly in climate regions 1 to 9 from 1895 to 2006.

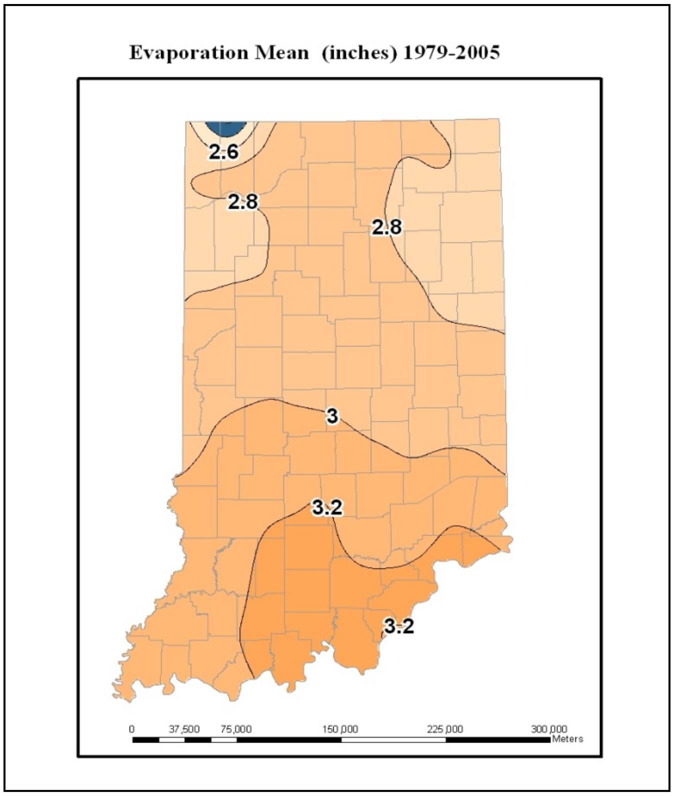
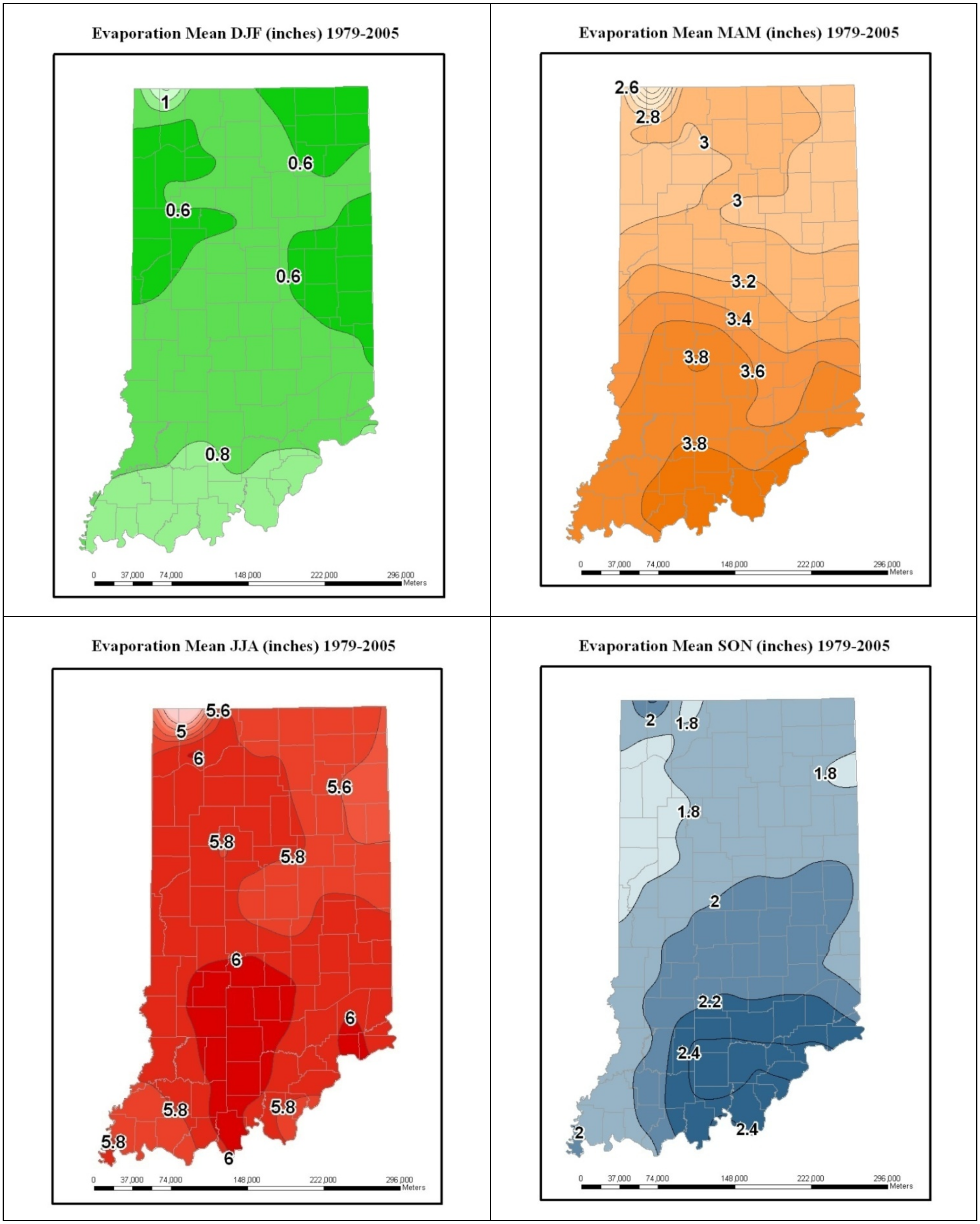


Figure 5(a). Mean evaporation (inches) from 1979 to 2005.



Evaporation Mean DJF (inches) 1979-2005

Evaporation Mean MAM (inches) 1979-2005

Evaporation Mean JJA (inches) 1979-2005

Evaporation Mean SON (inches) 1979-2005

Figure 5(b). Mean seasonal evaporation (inches) from 1979 to 2005.

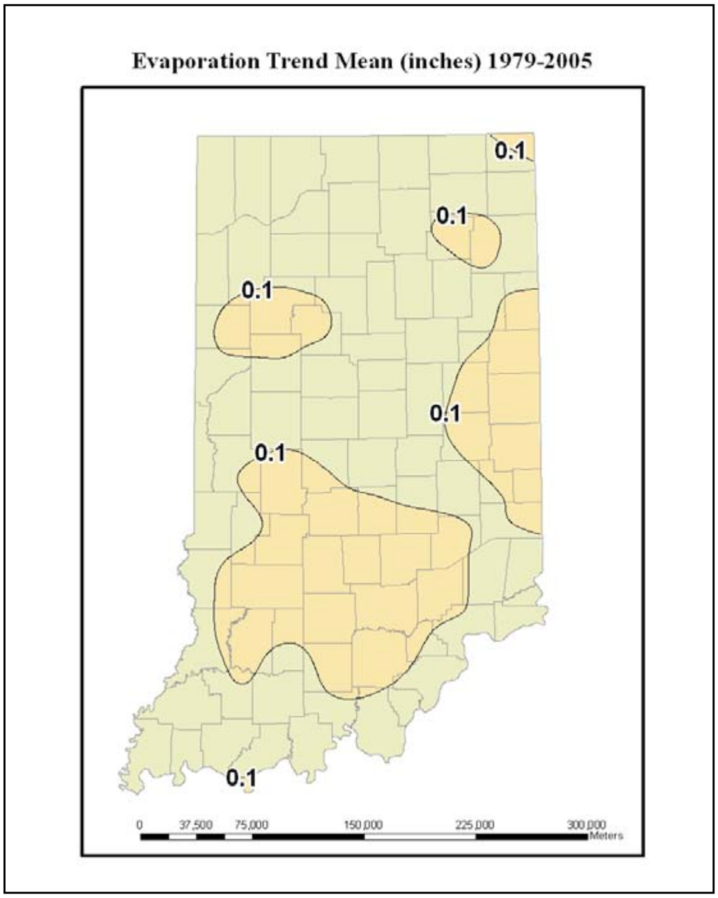


Figure 6(a). Mean evaporation trend (inches/decade) from 1979 to 2005.

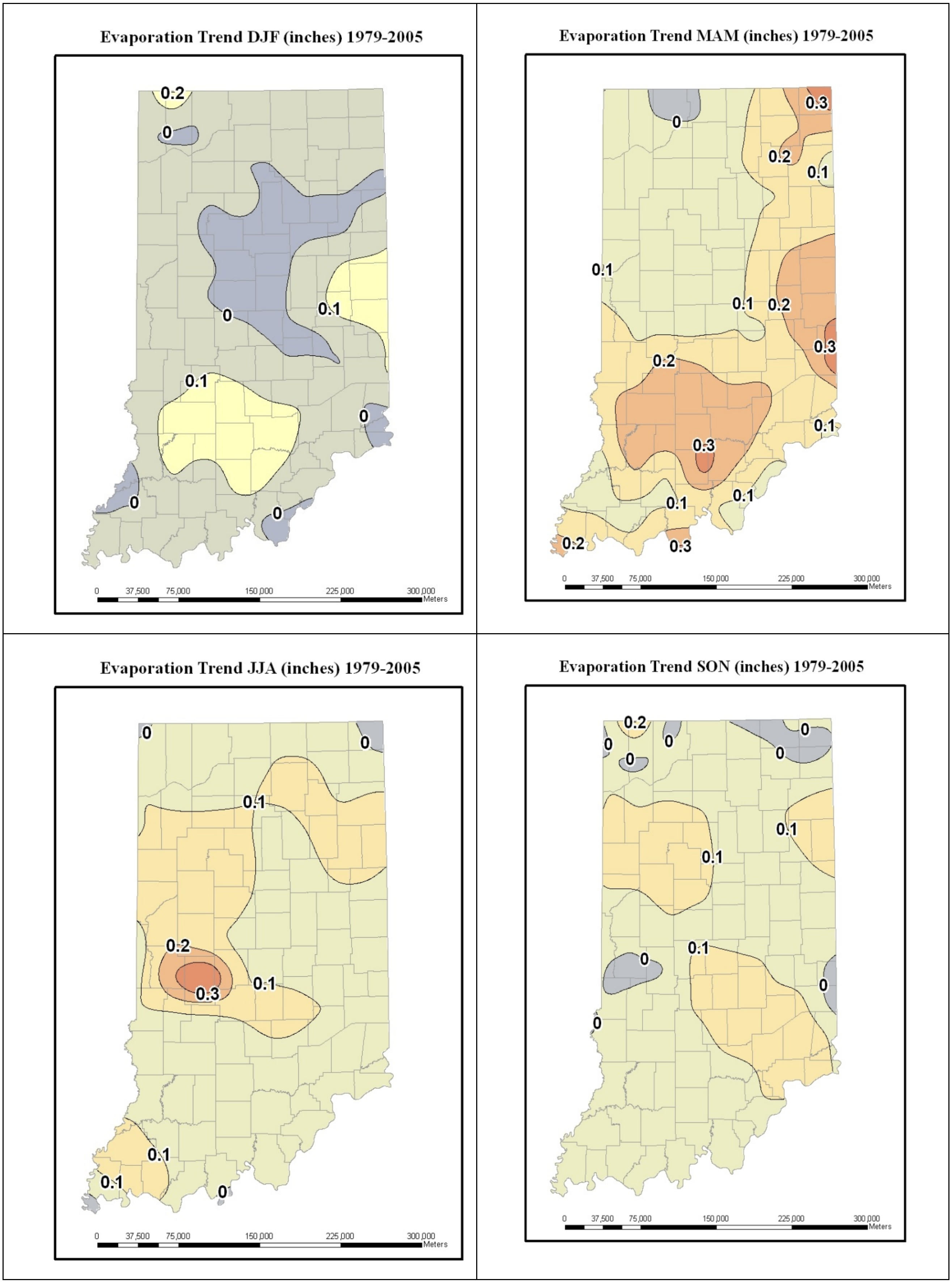


Figure 6(b). Seasonal evaporation trend (inches/decade) from 1979 to 2005.

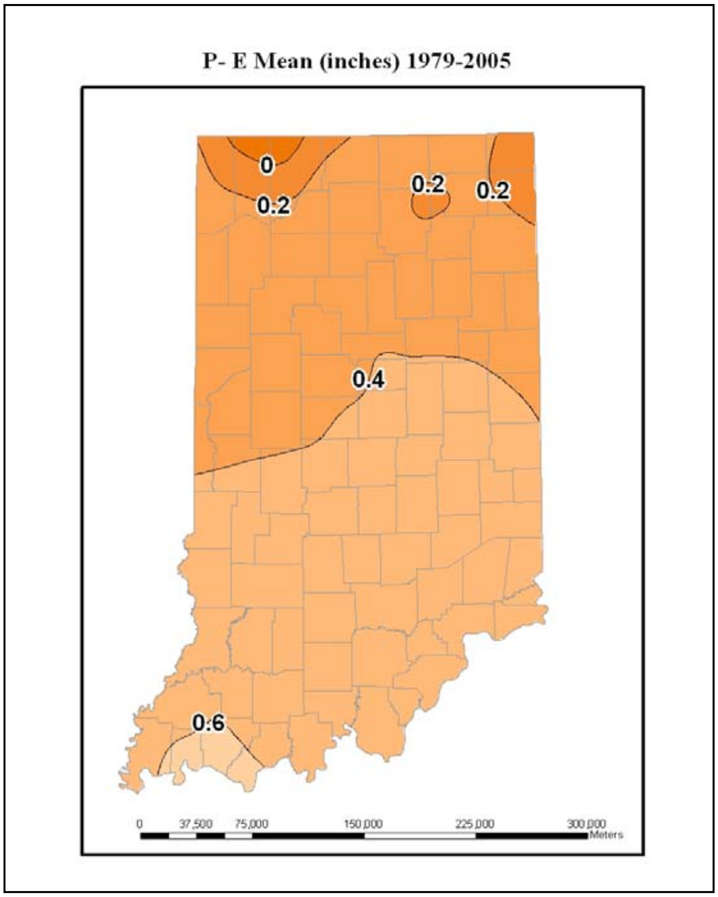
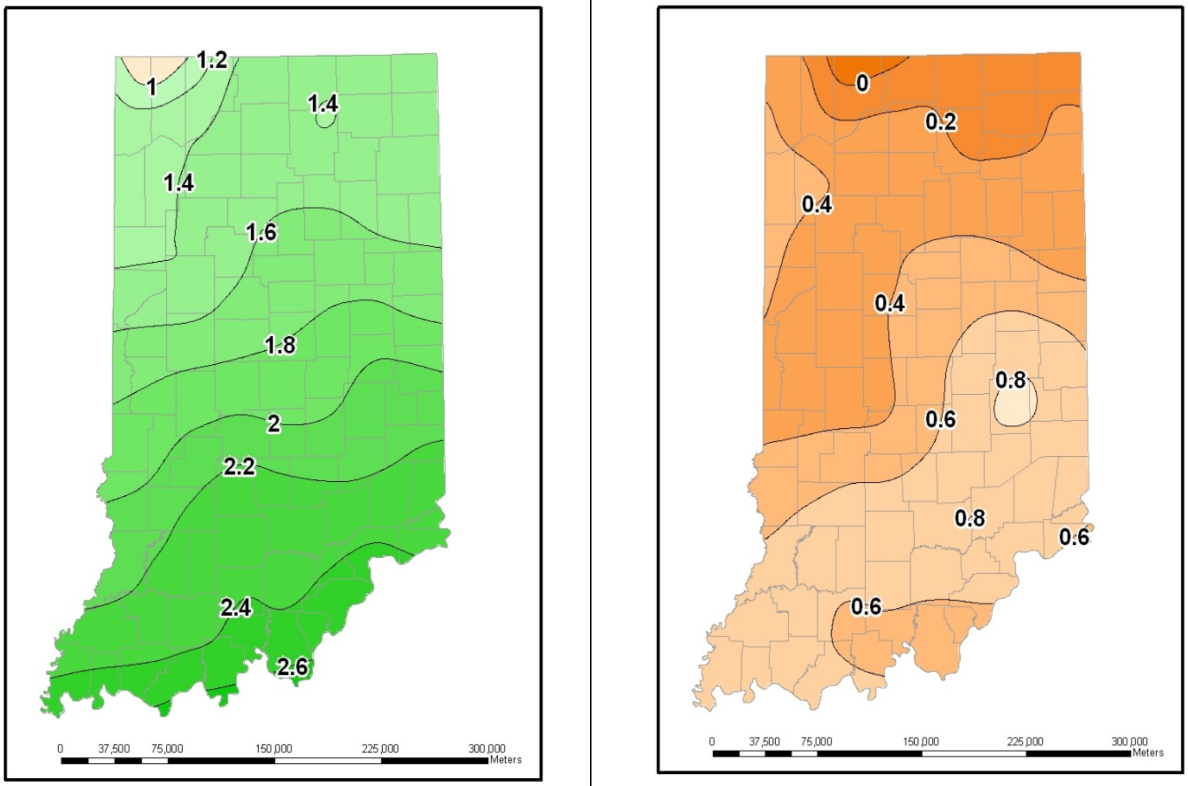
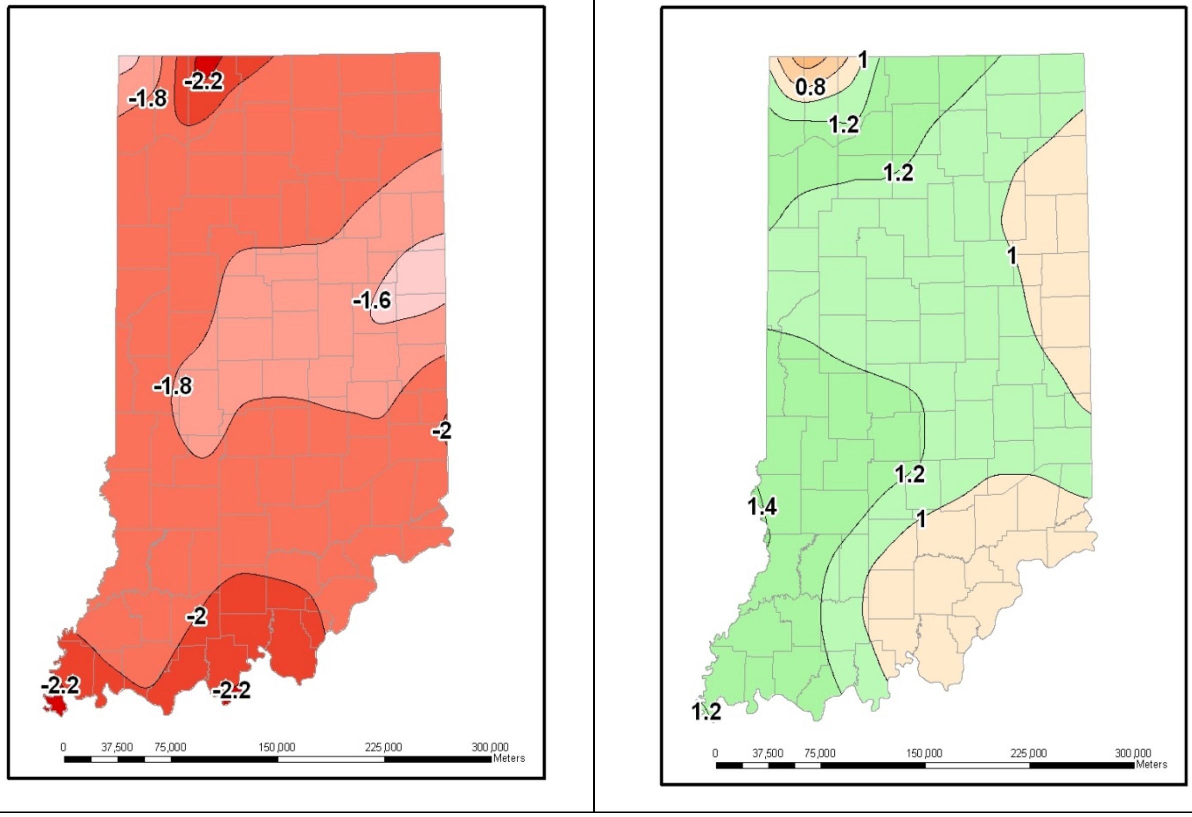


Figure 7(a). Mean precipitation minus evaporation (inches) from 1979 to 2005.


P- E Mean DJF (inches) 1979-2005

P- E Mean MAM (inches) 1979-2005


P- E Mean JJA (inches) 1979-2005

P- E Mean SON (inches) 1979-2005

Figure 7(b). Mean seasonal precipitation minus evaporation (inches) from 1979 to 2005.

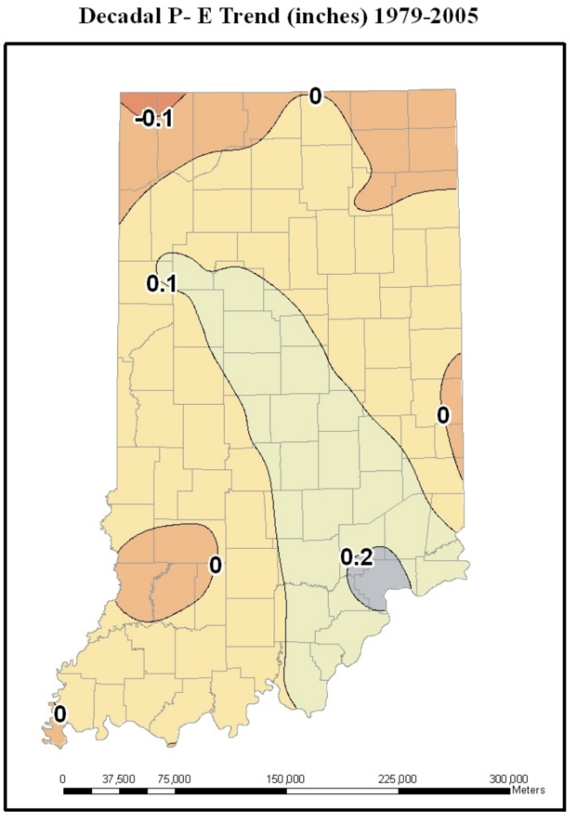
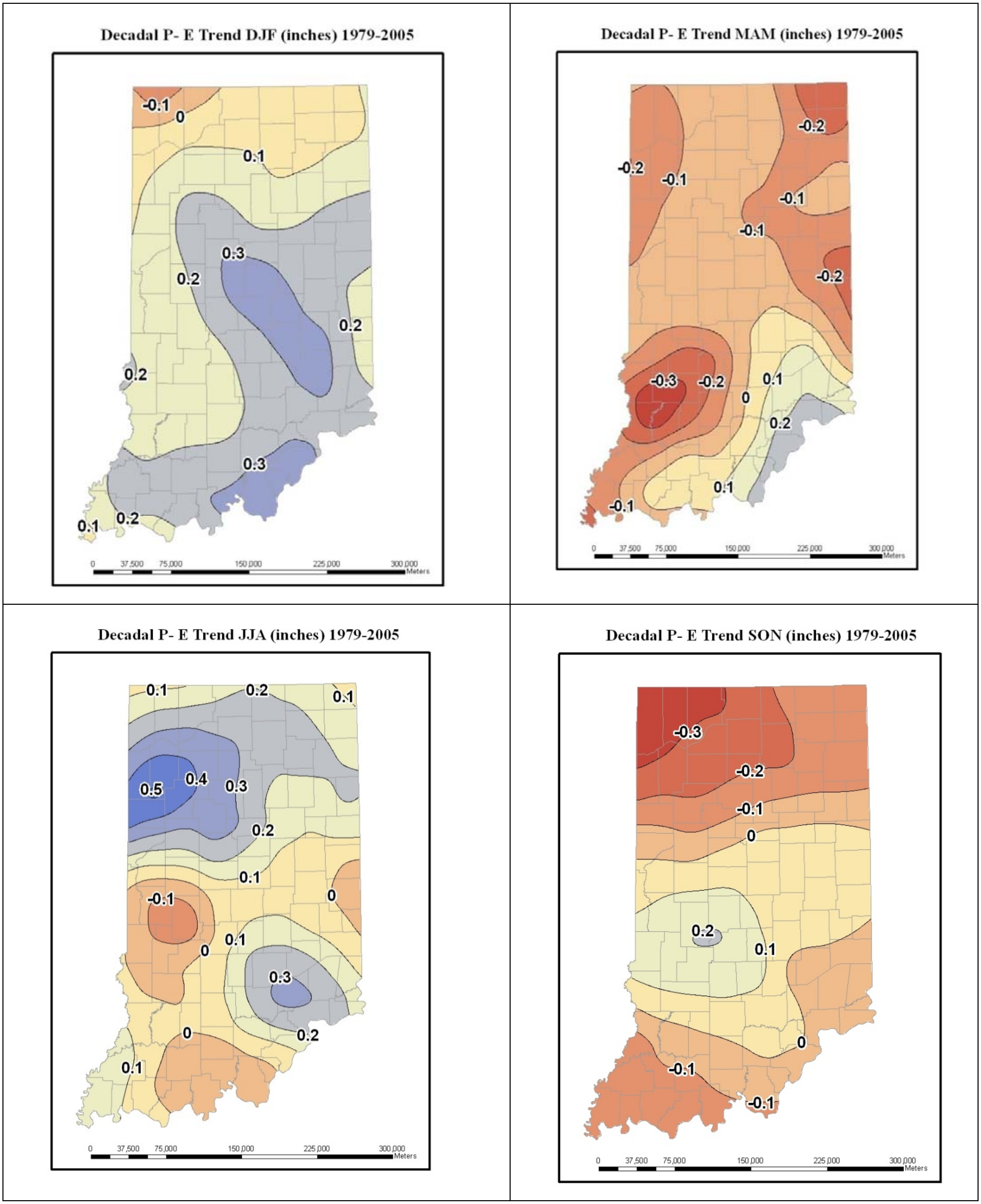


Figure 8(a). Precipitation minus evaporation trend (inches/decade) from 1979 to 2005.



Decadal P- E Trend DJF (inches) 1979-2005

Decadal P- E Trend MAM (inches) 1979-2005

Decadal P- E Trend JJA (inches) 1979-2005

Decadal P- E Trend SON (inches) 1979-2005

Figure 8(b). Seasonal precipitation minus evaporation trend (inches/decade) from 1975-2005.

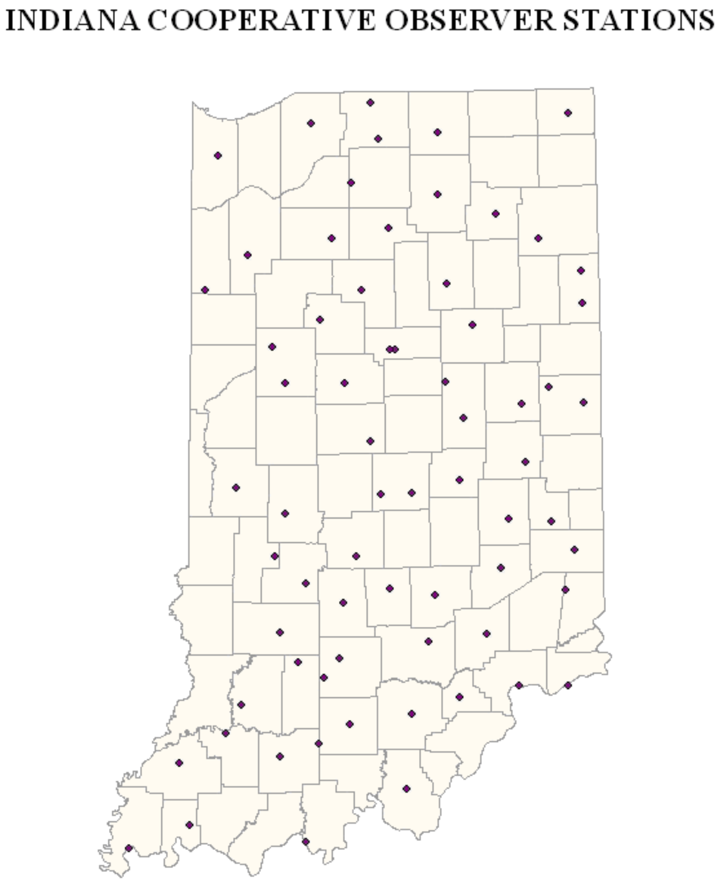


Figure 9. The 50 Indiana cooperative observer stations used in the analysis.

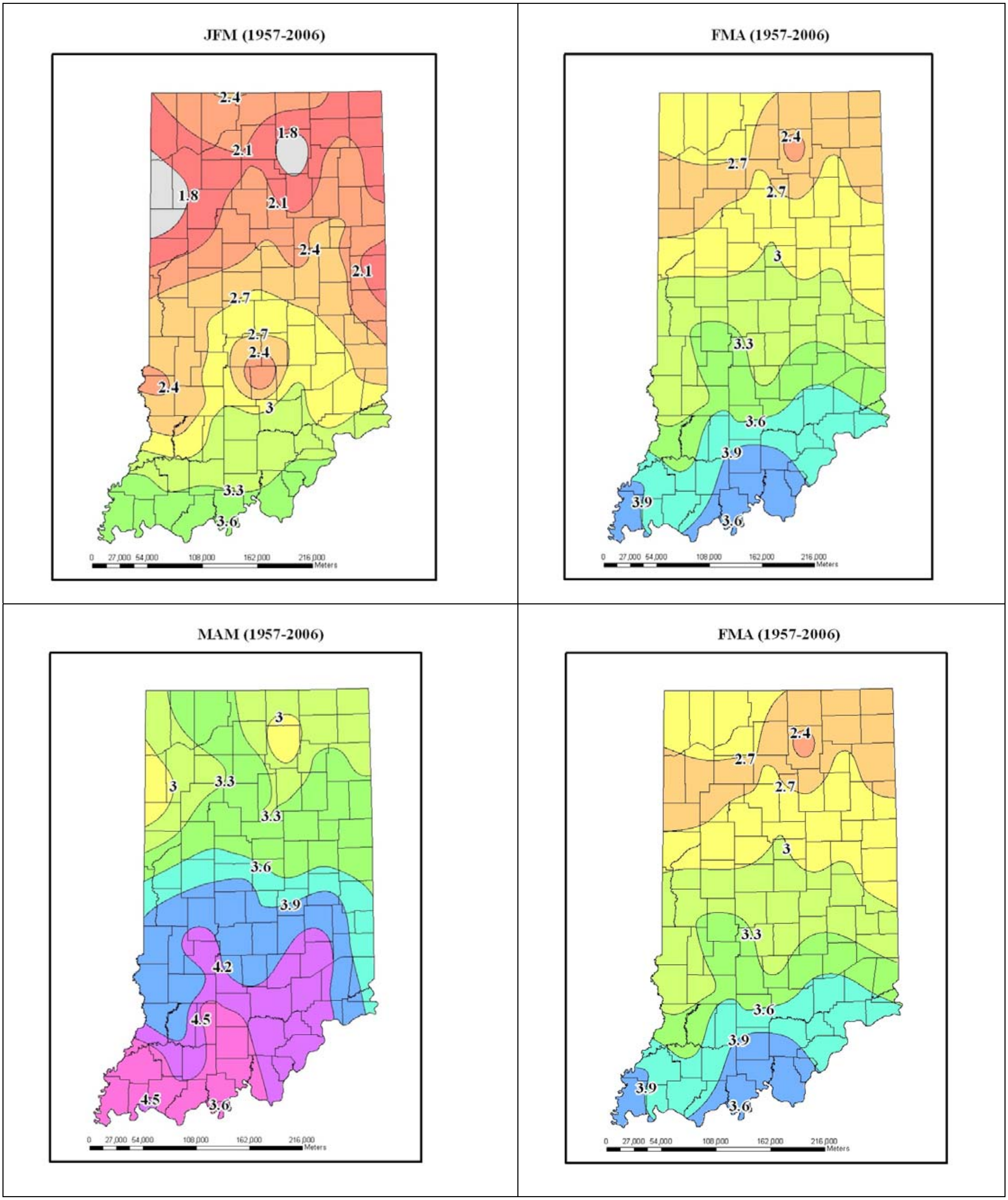
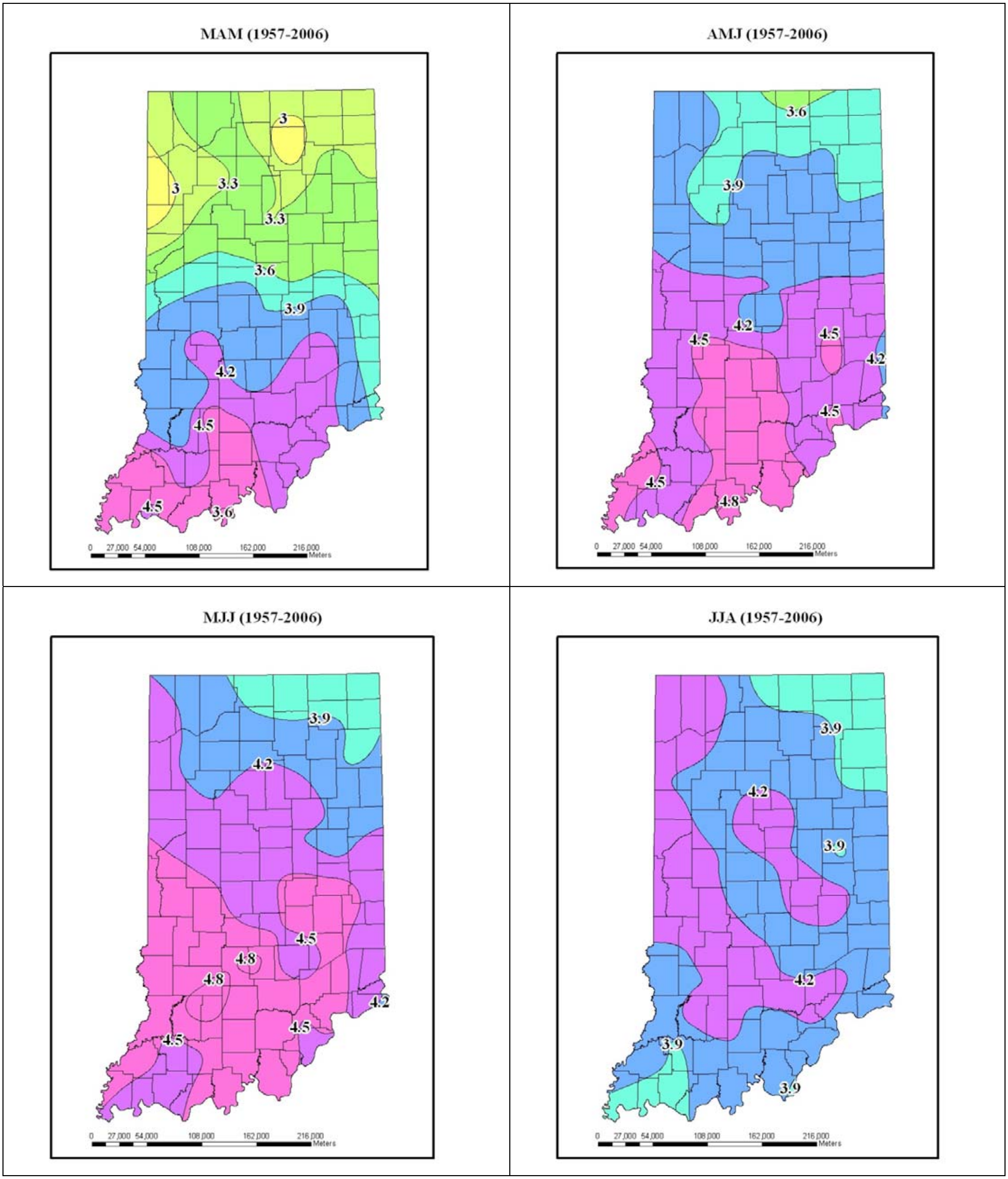


Figure 10(a). Three month precipitation mean (JFM – FMA) for 50 years (1957-2006).



MAM (1957-2006)

AMJ (1957-2006)

MJJ (1957-2006)

JJA (1957-2006)

Figure 10(b). Three month precipitation mean (MAM – JJA) for 50 years (1957-2006).

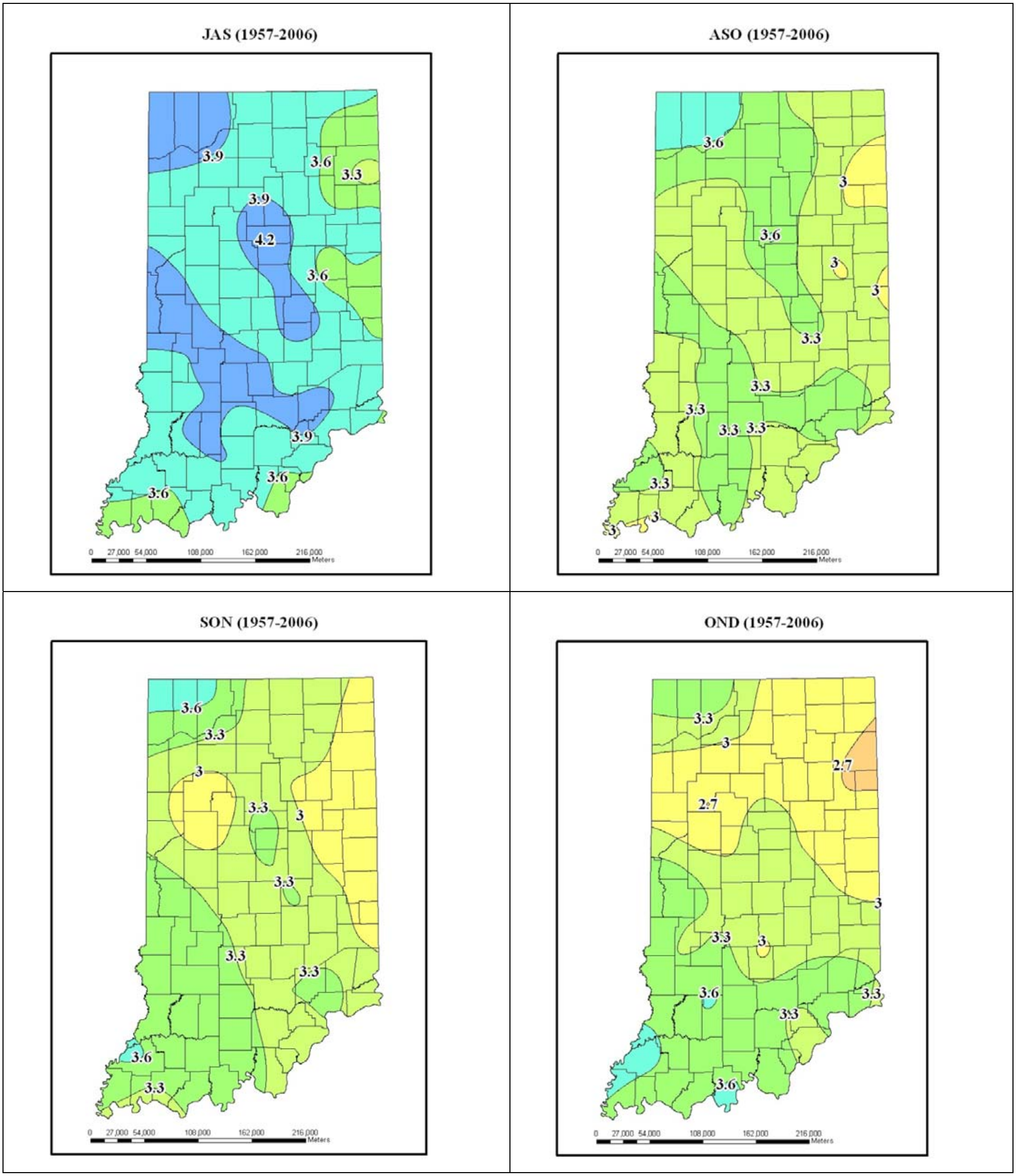
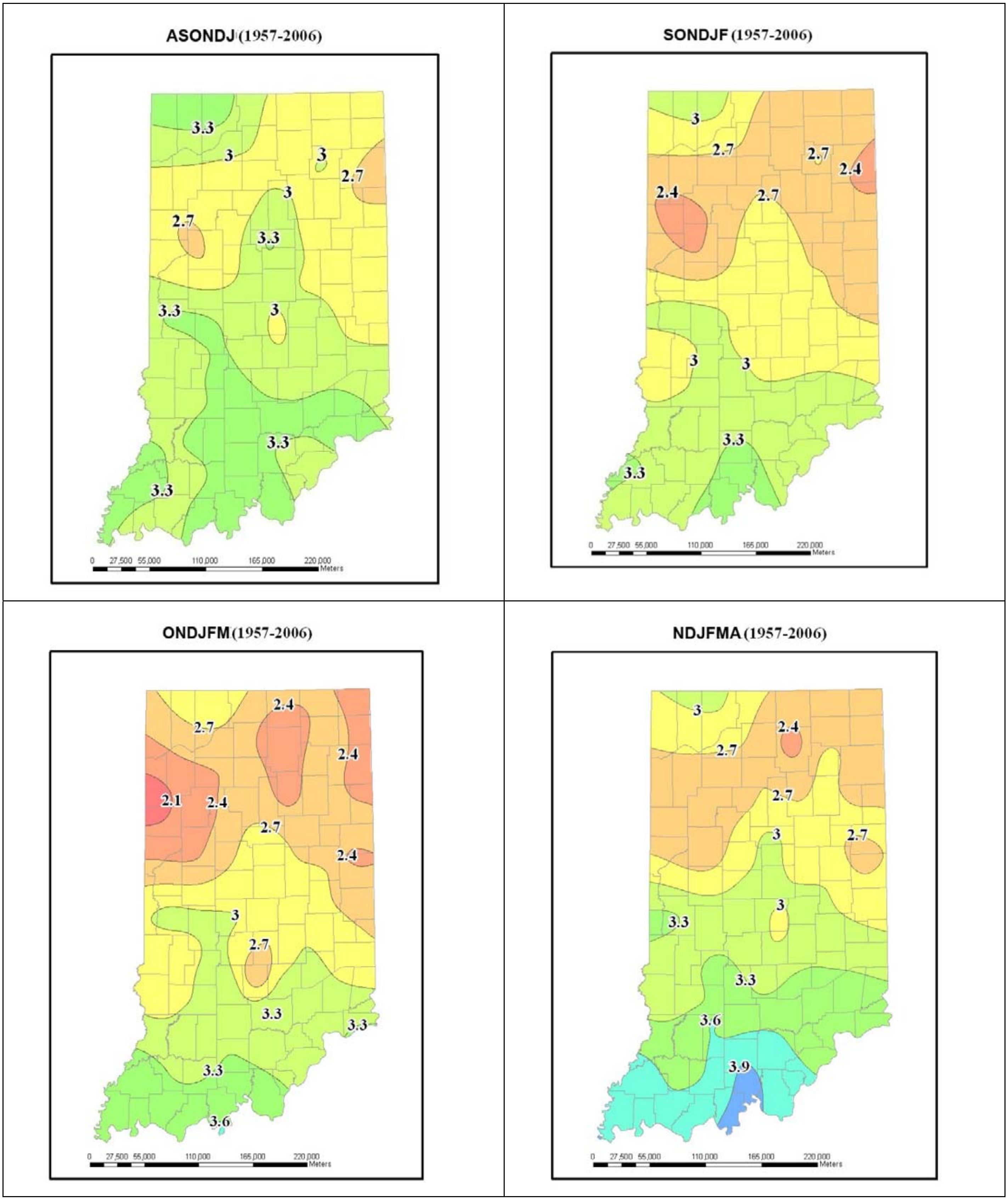


Figure 10(c). Three month precipitation mean (JJA-OND) for 50 years (1957-2006).


ASONDJ (1957-2006)

SONDJF (1957-2006)

ONDJFM (1957-2006)

NDJFMA (1957-2006)

Figure 11(a). Six month precipitation mean (ASONDJ-NDJFMA) for 50 years (1957-2006).

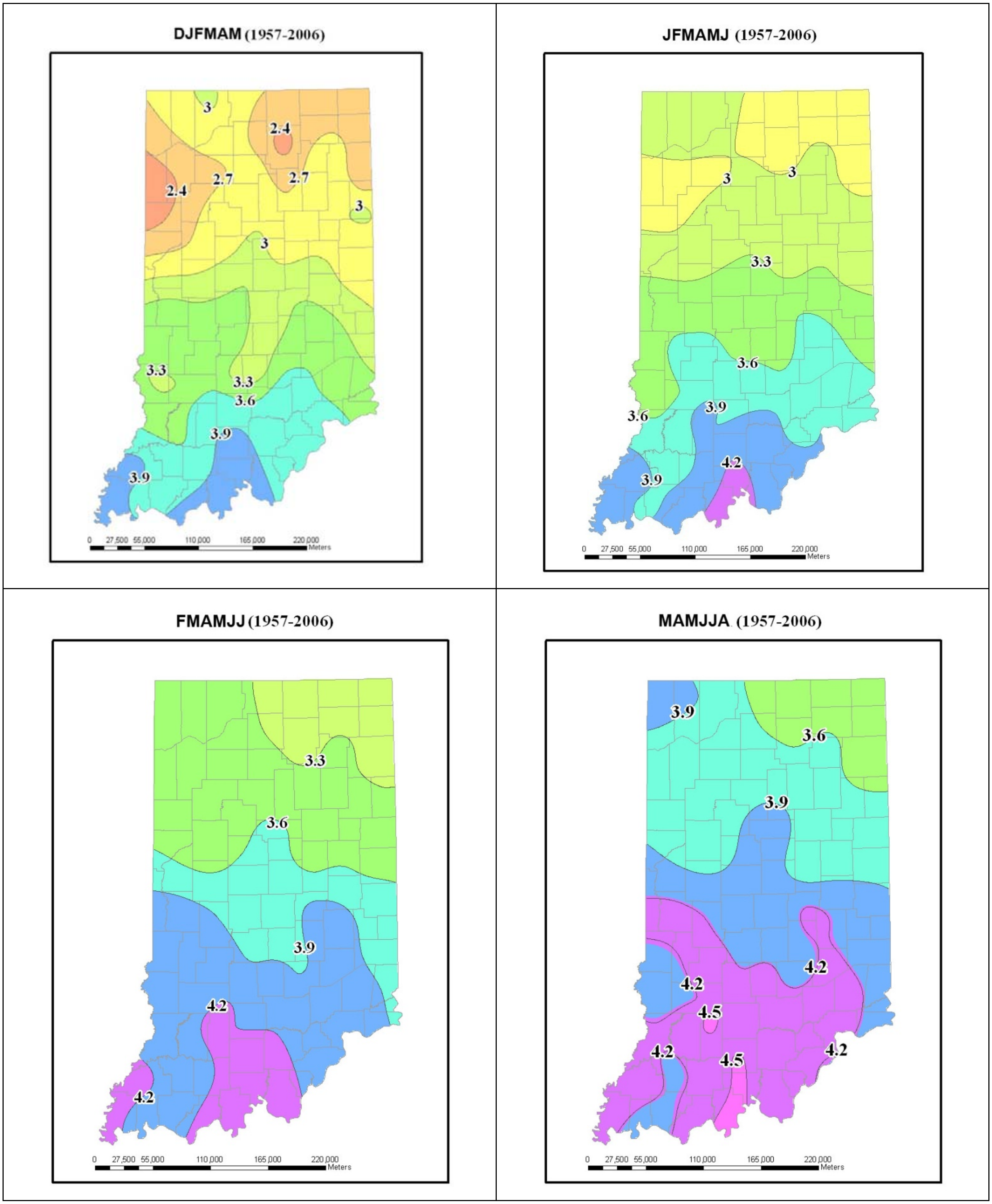


Figure 11(b). Six month precipitation mean (DJFMAM-MAMJJA) for 50 years (1957-2006).

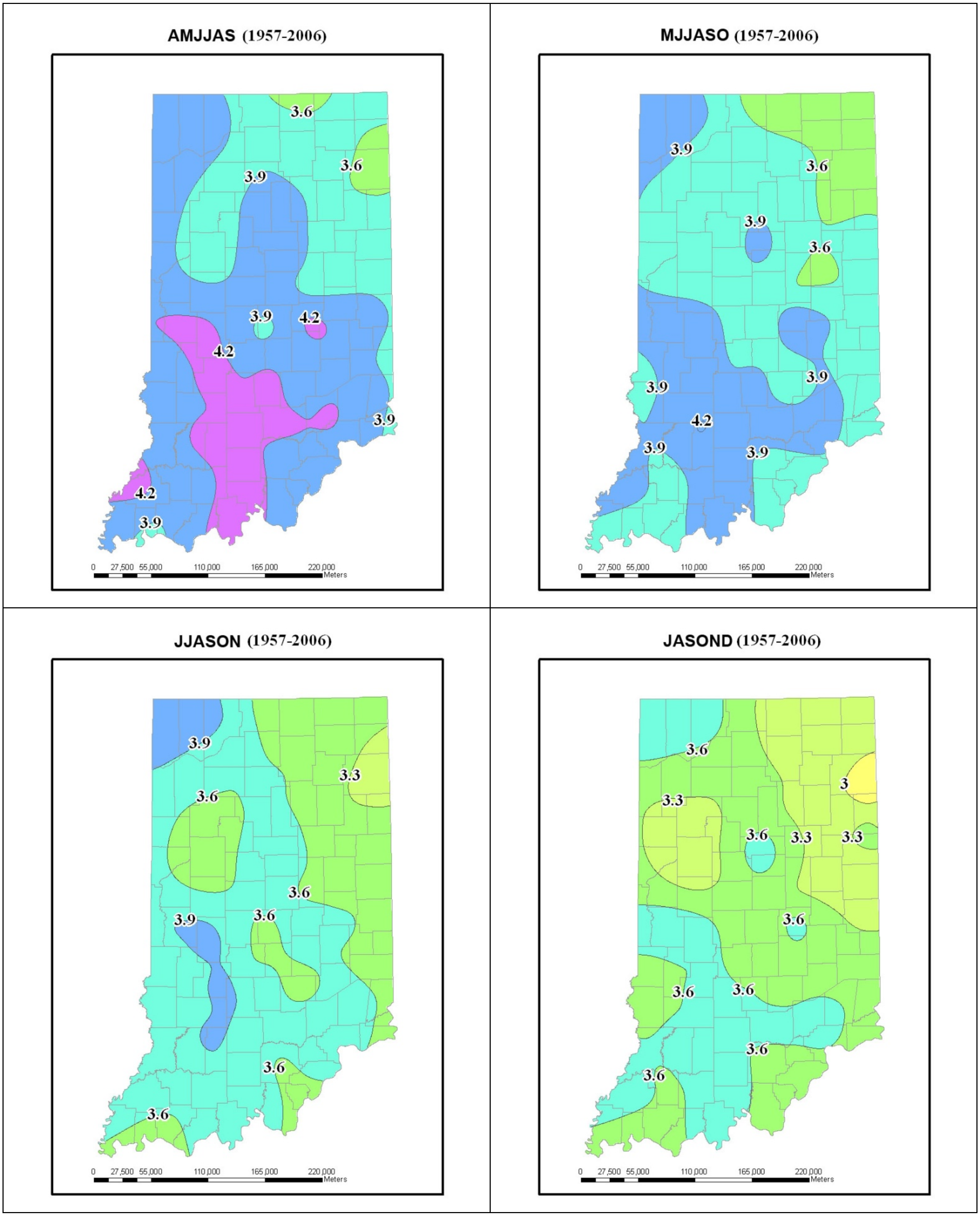
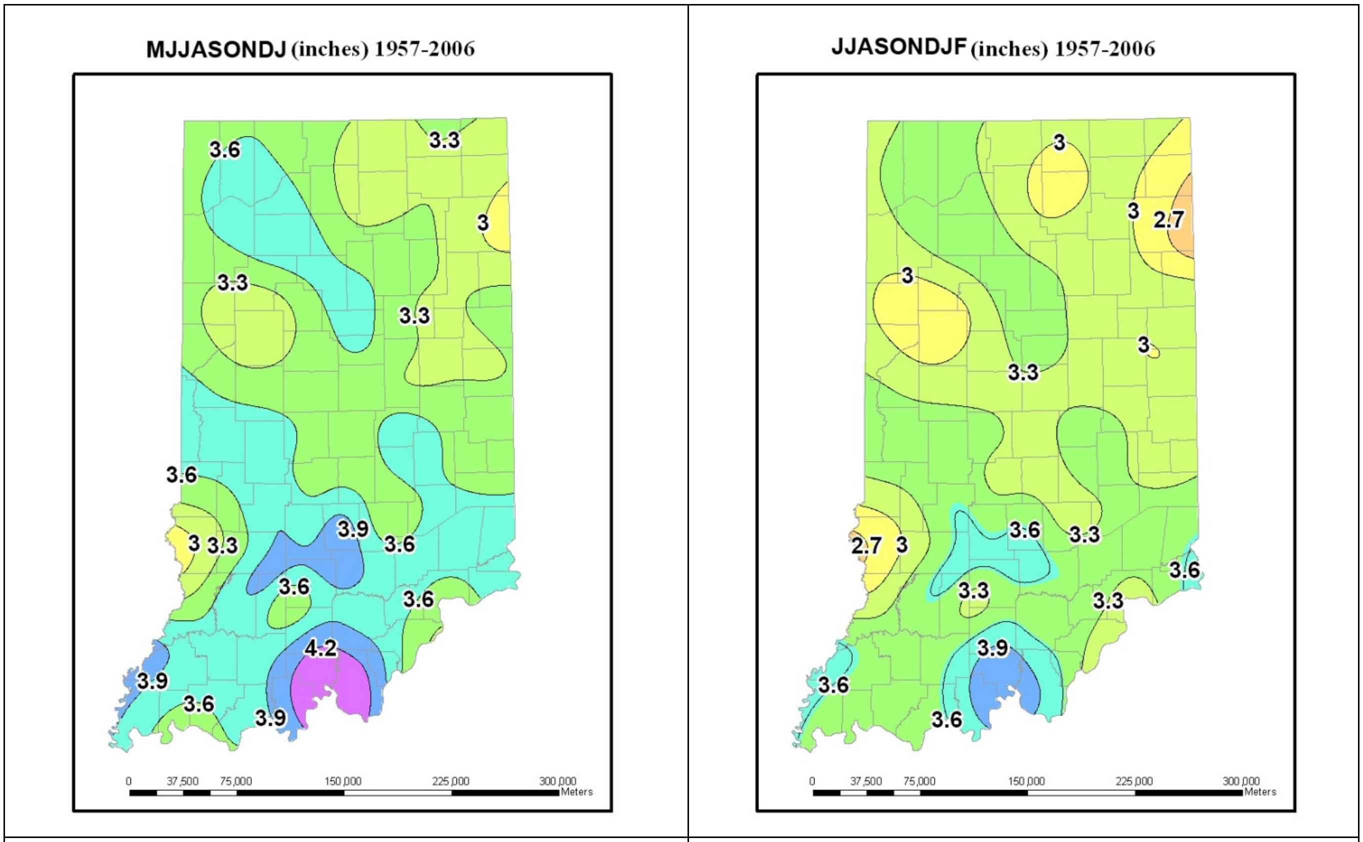
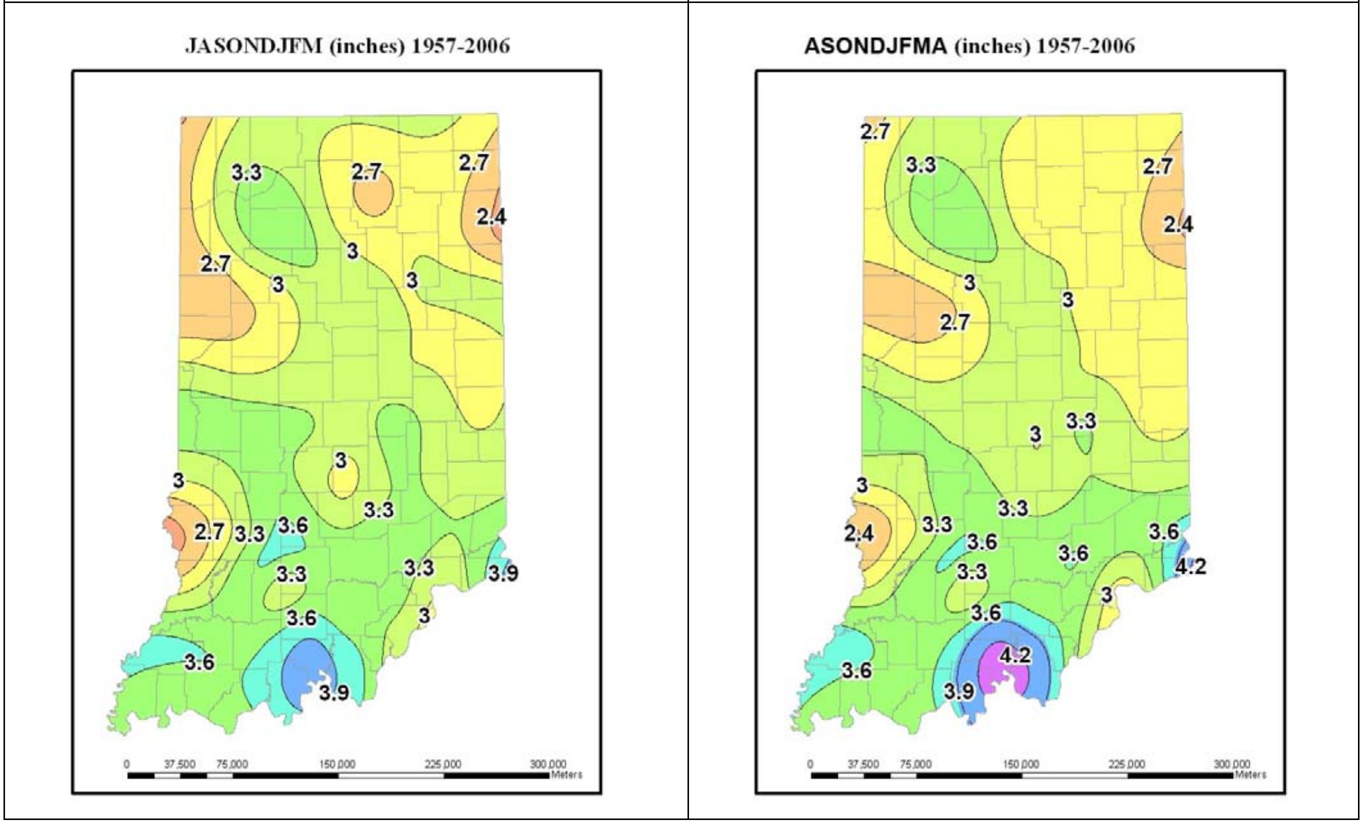


Figure 11(c). Six month precipitation mean (AMJJAS-JASOND) for 50 year (1957-2006).



MJJASONDJ (inches) 1957-2006

JJASONDJF (inches) 1957-2006



JASONDJFM (inches) 1957-2006

ASONDJFMA (inches) 1957-2006

Figure 12(a). Nine month precipitation mean (MJJASONDJ-ASONDJFMA) for 50 years (1957-2006).

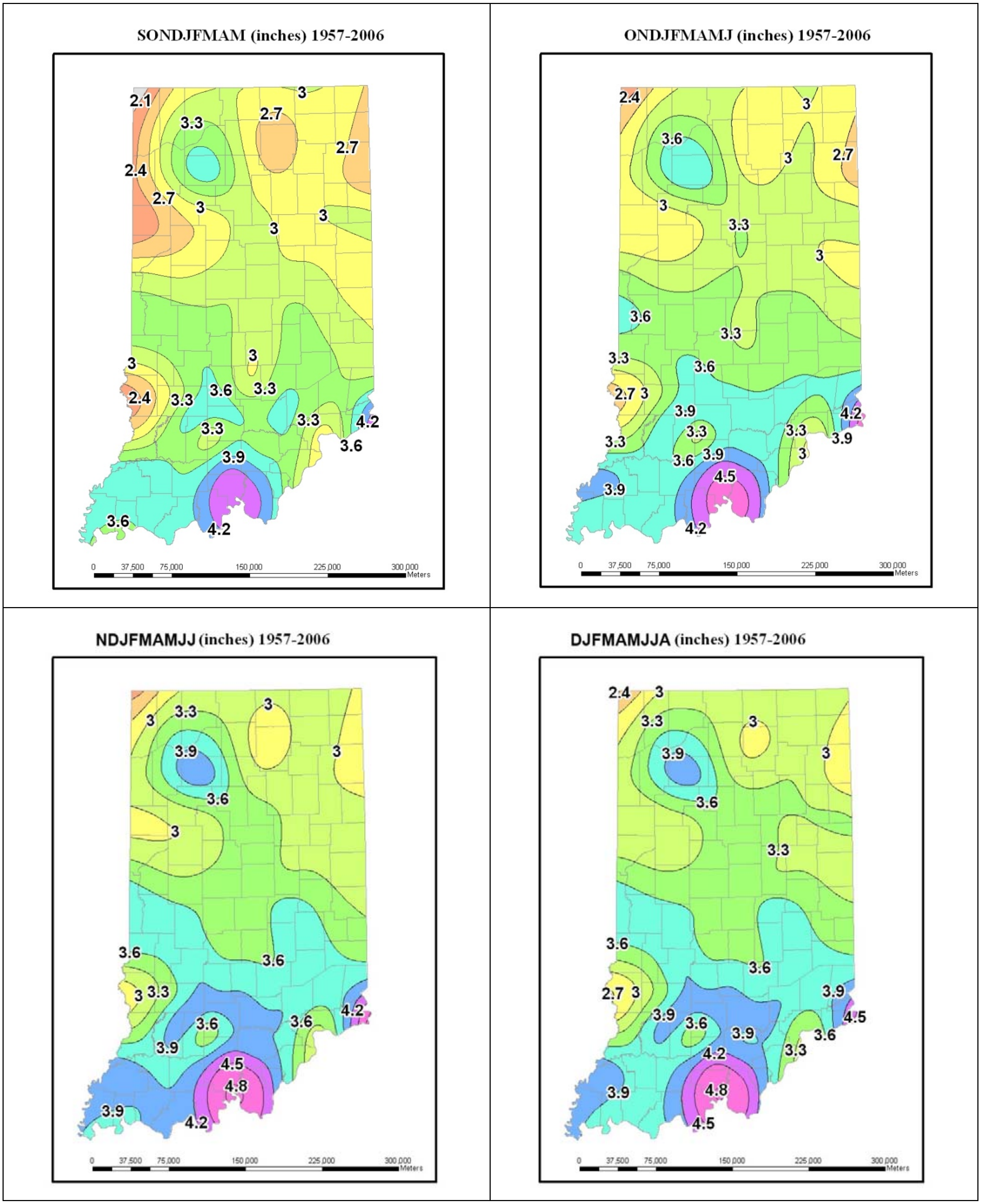


Figure 12(b). Nine month precipitation mean (MJJASONDJ-ASONDJFMA) for 50 years(1957-2006)

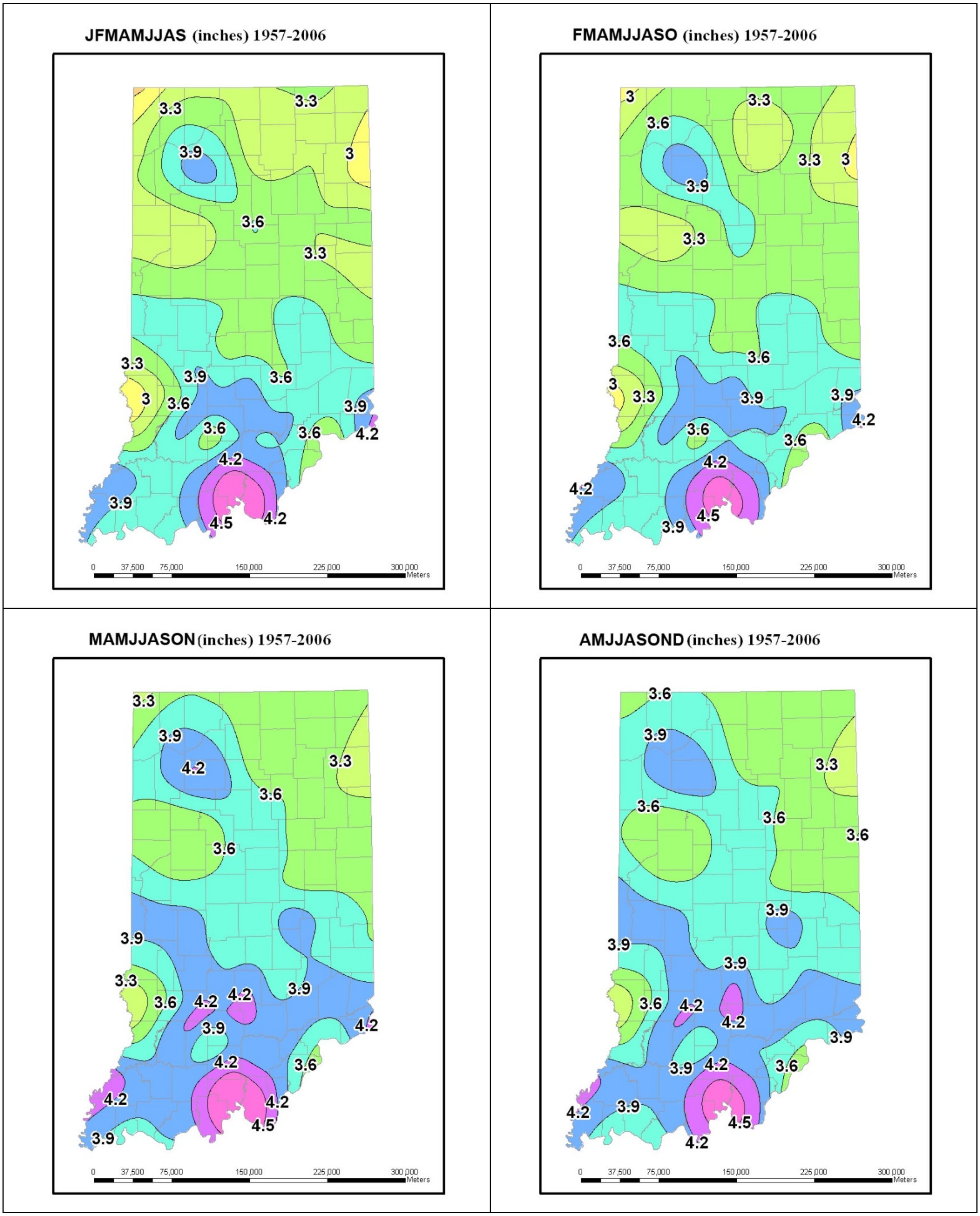


Figure 12(c). Nine month precipitation mean (MJJASONDJ-ASONDJFMA) for 50 years (1957-2006)

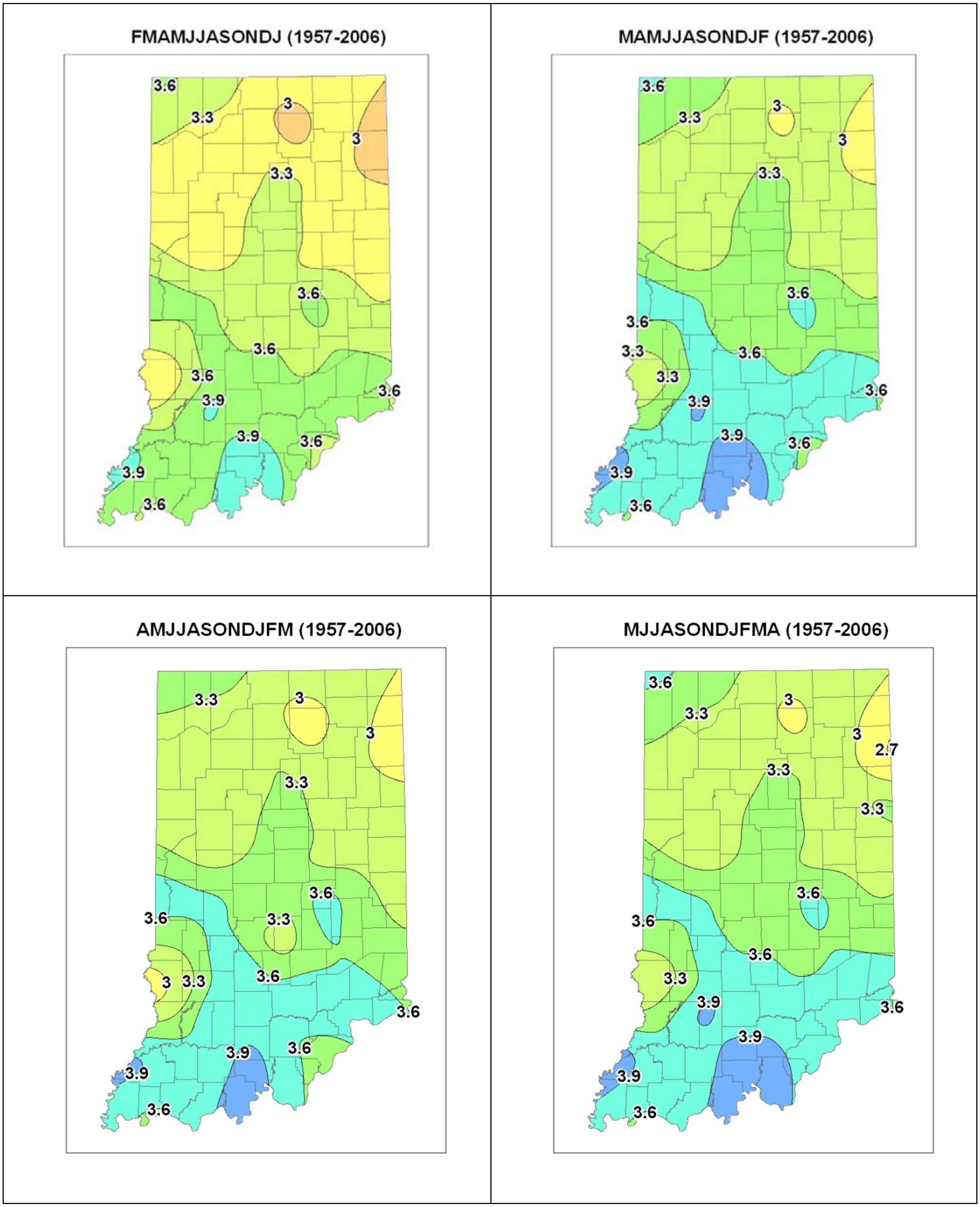
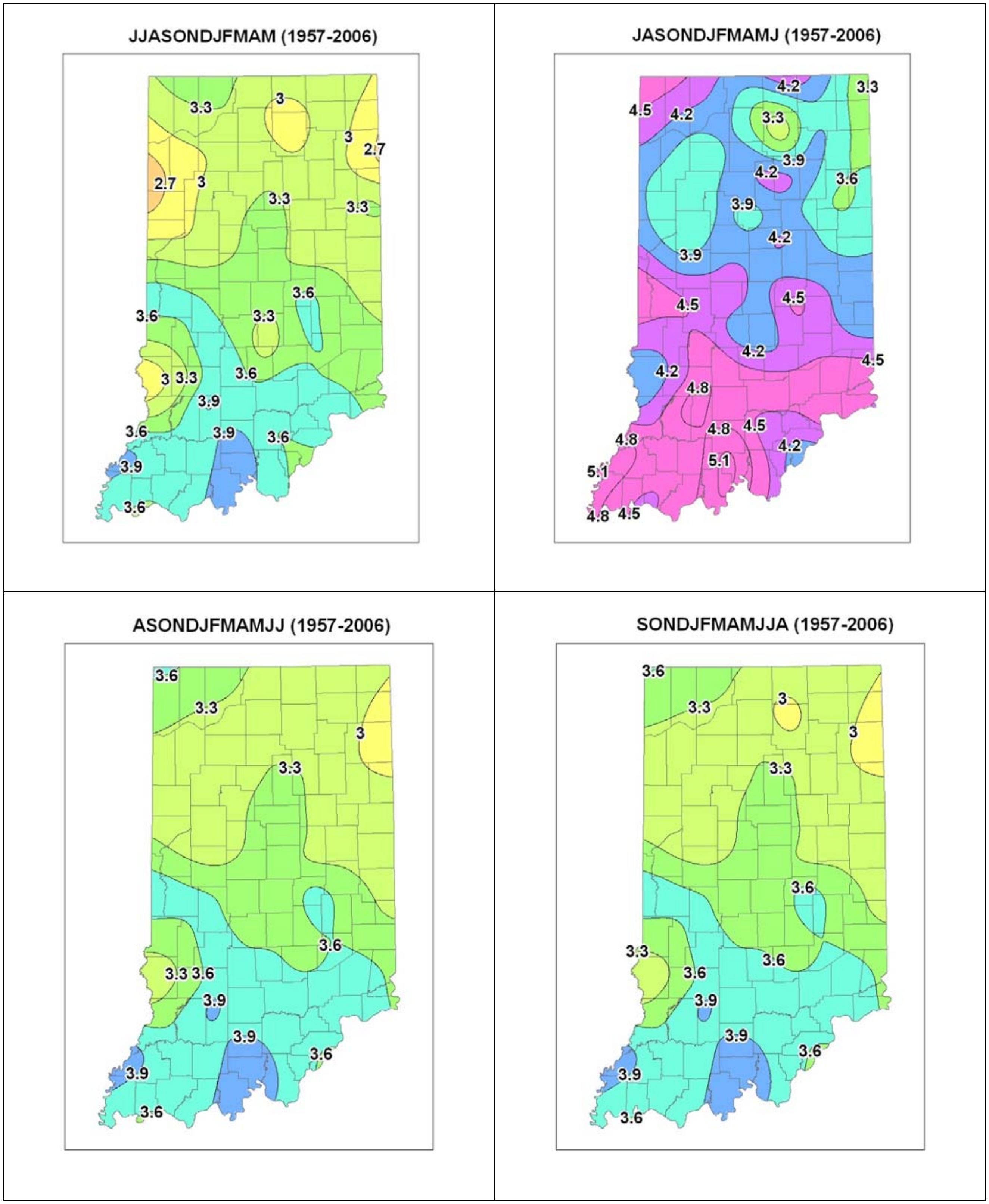


Figure 13(a). Twelve month precipitation mean (FMAMJJASONDJ-MJJSONDJFMA) for 50 years (1957-2006).



JJASONDJFMAM (1957-2006)

JASONDJFMAMJ (1957-2006)

ASONDJFMAMJJ (1957-2006)

SONDJFMAMJJA (1957-2006)

Figure 13: (b) Twelve month precipitation mean (JJASONDJFMAM-SONDJMAMJJA) for 50 years (1957-2006).

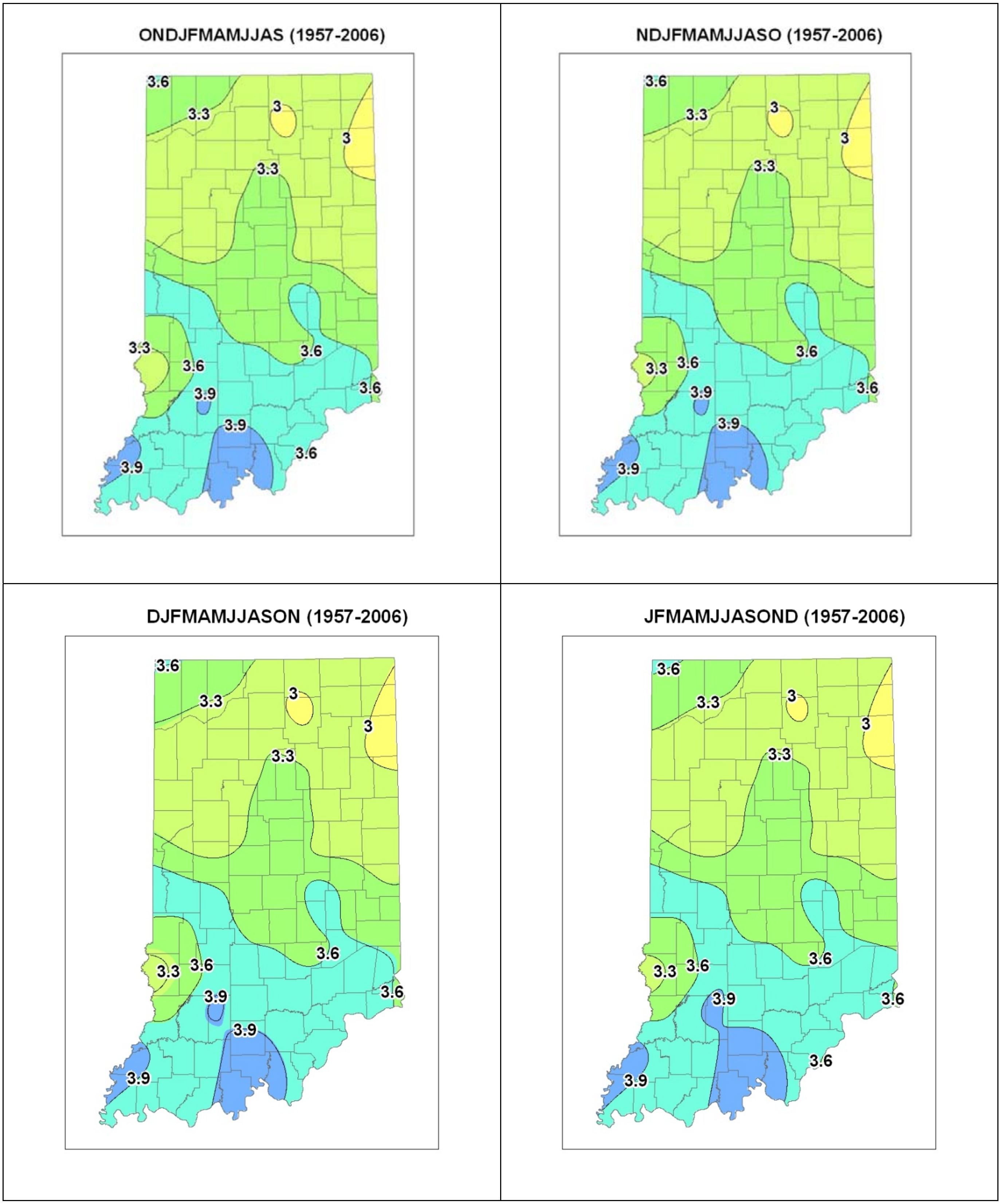
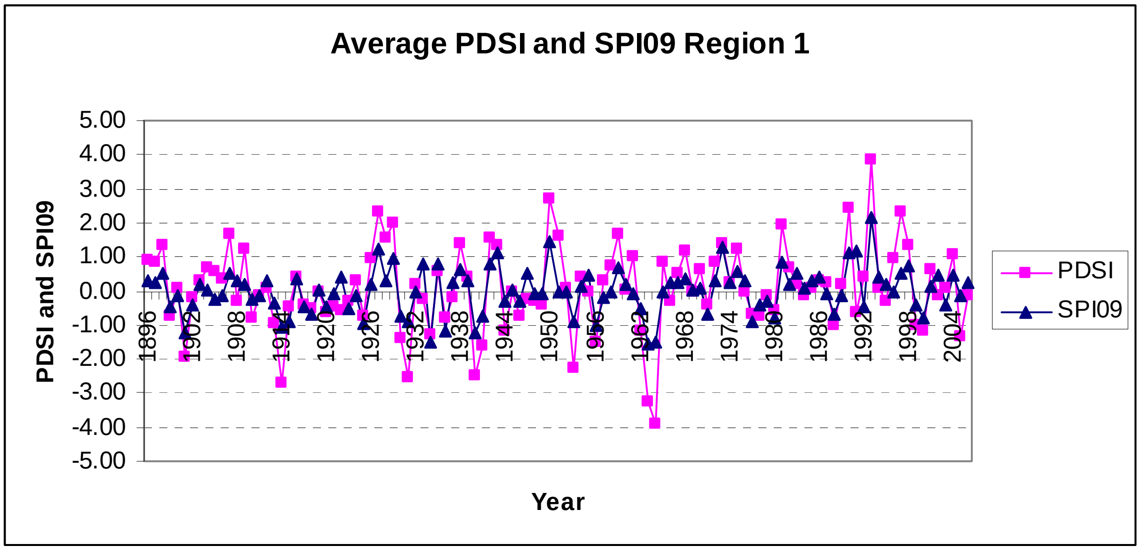
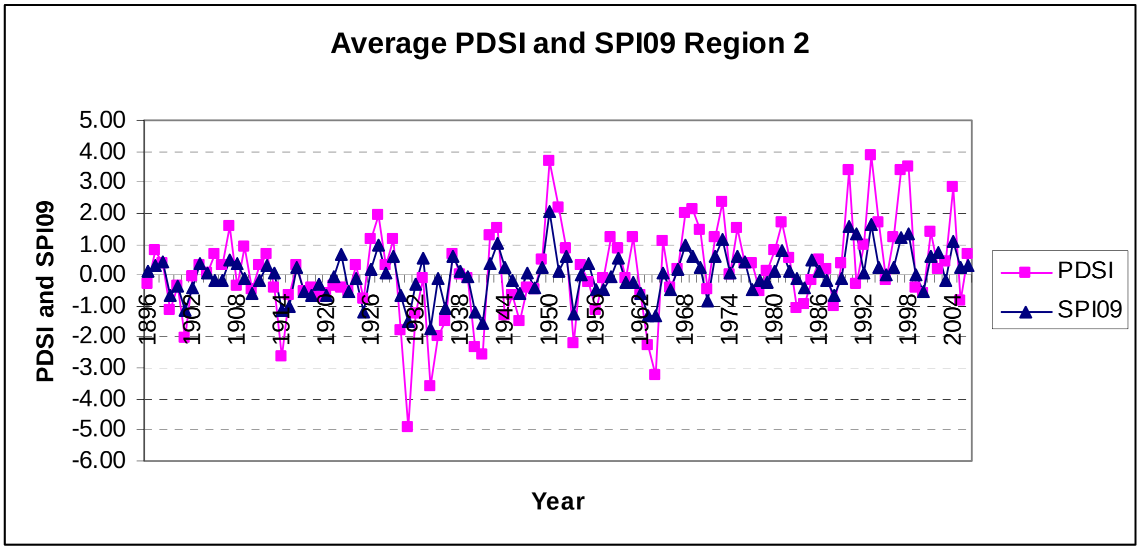


Figure 13(c). Twelve month precipitation mean (ONDJFMAMJJAS-JFMAMJJASOND) for 50 years (1957-2006).





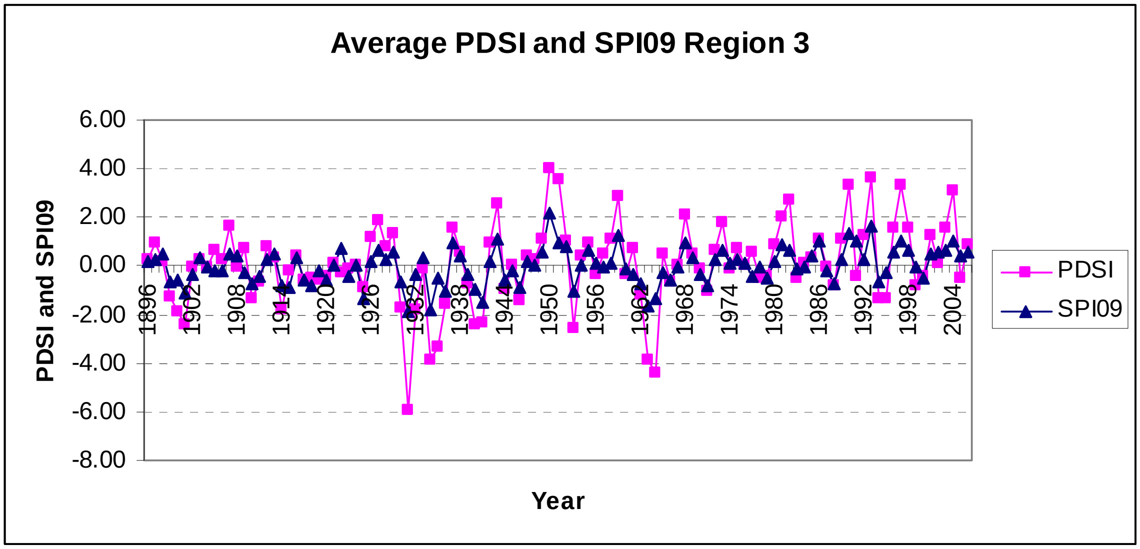
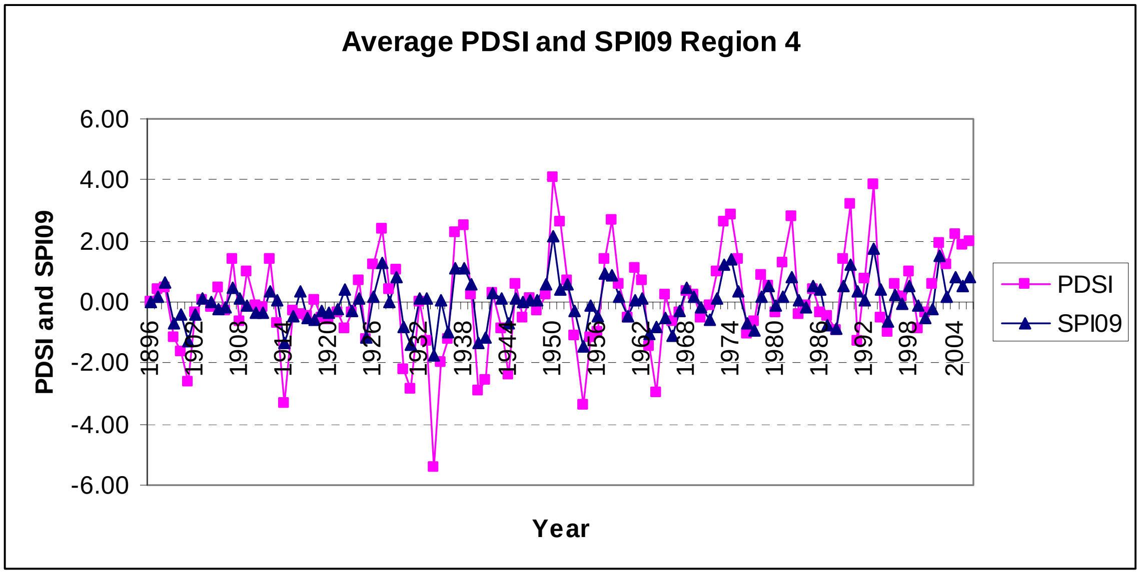
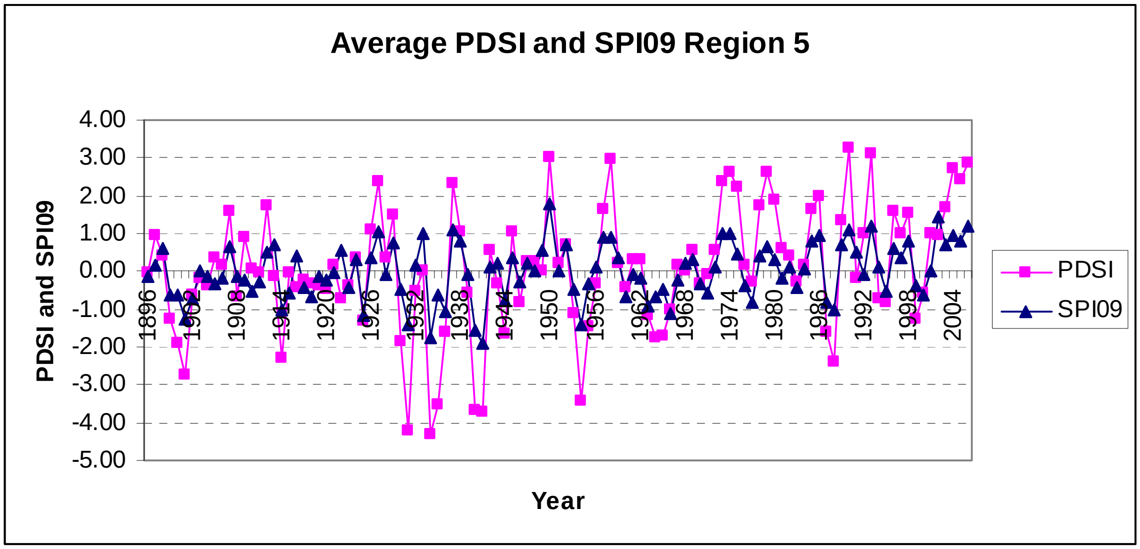


Figure 14(a). Time series of PDSI and SPI09 for each climate division (1,2,3).





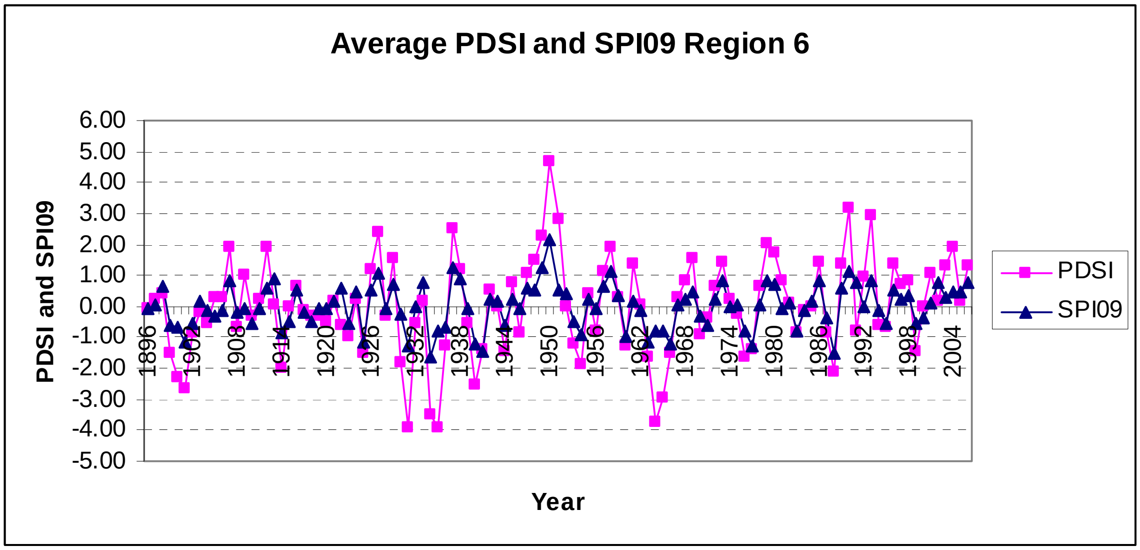


Figure 14(b). Time series of PDSI and SPI09 for each climate division (4,5,6).

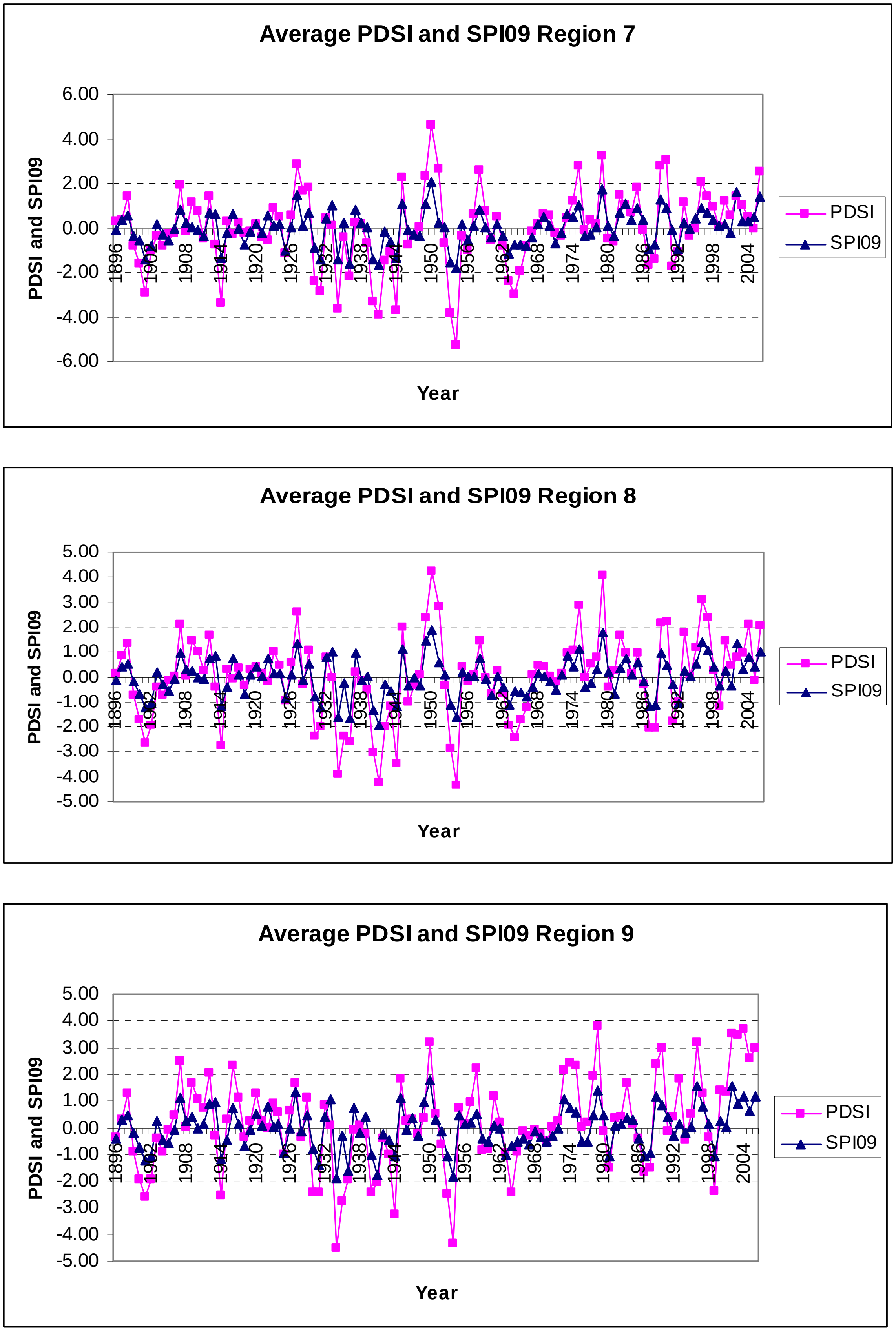


Figure 14(c). Time series of PDSI and SPI09 for each climate division (7,8,9).

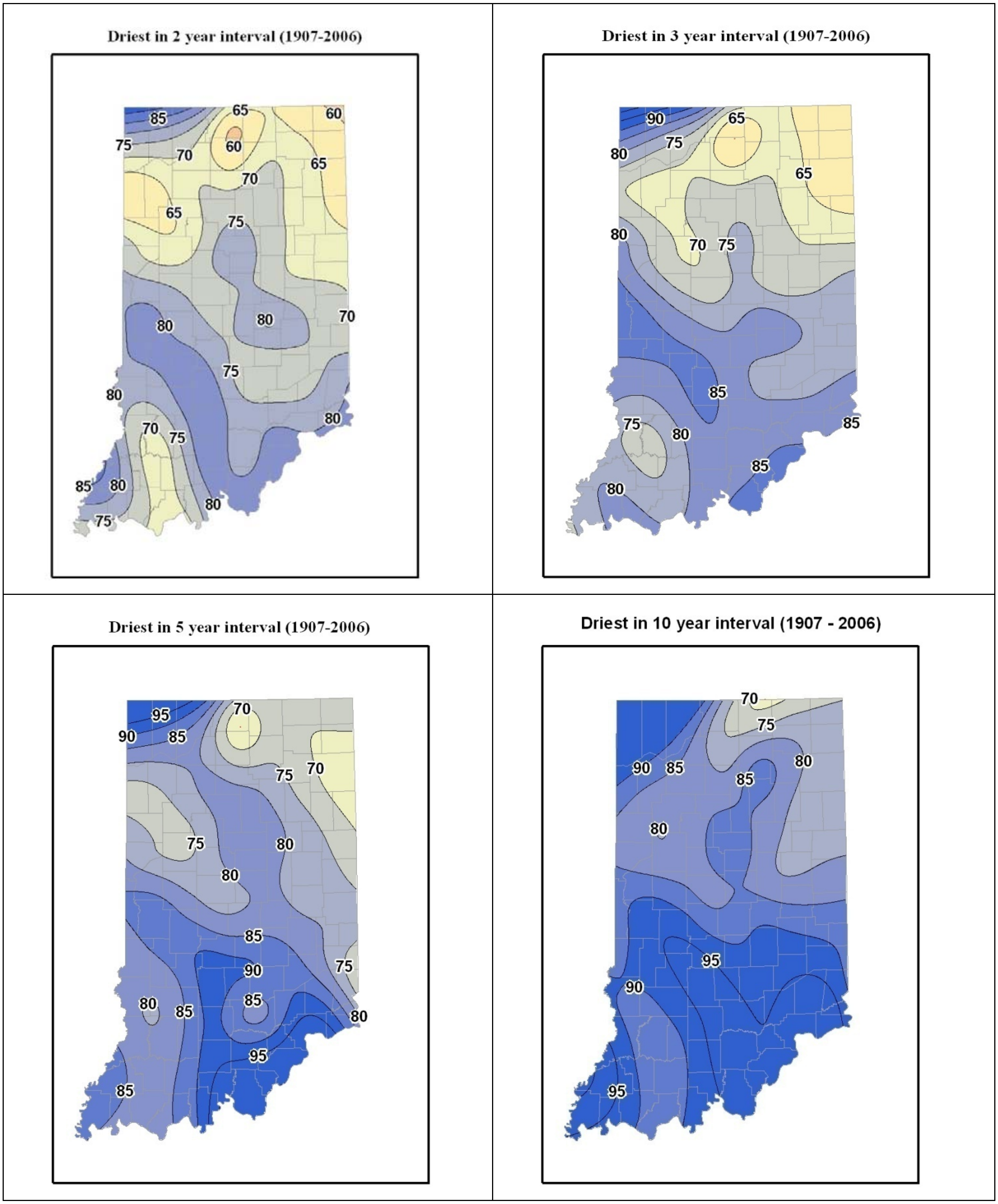
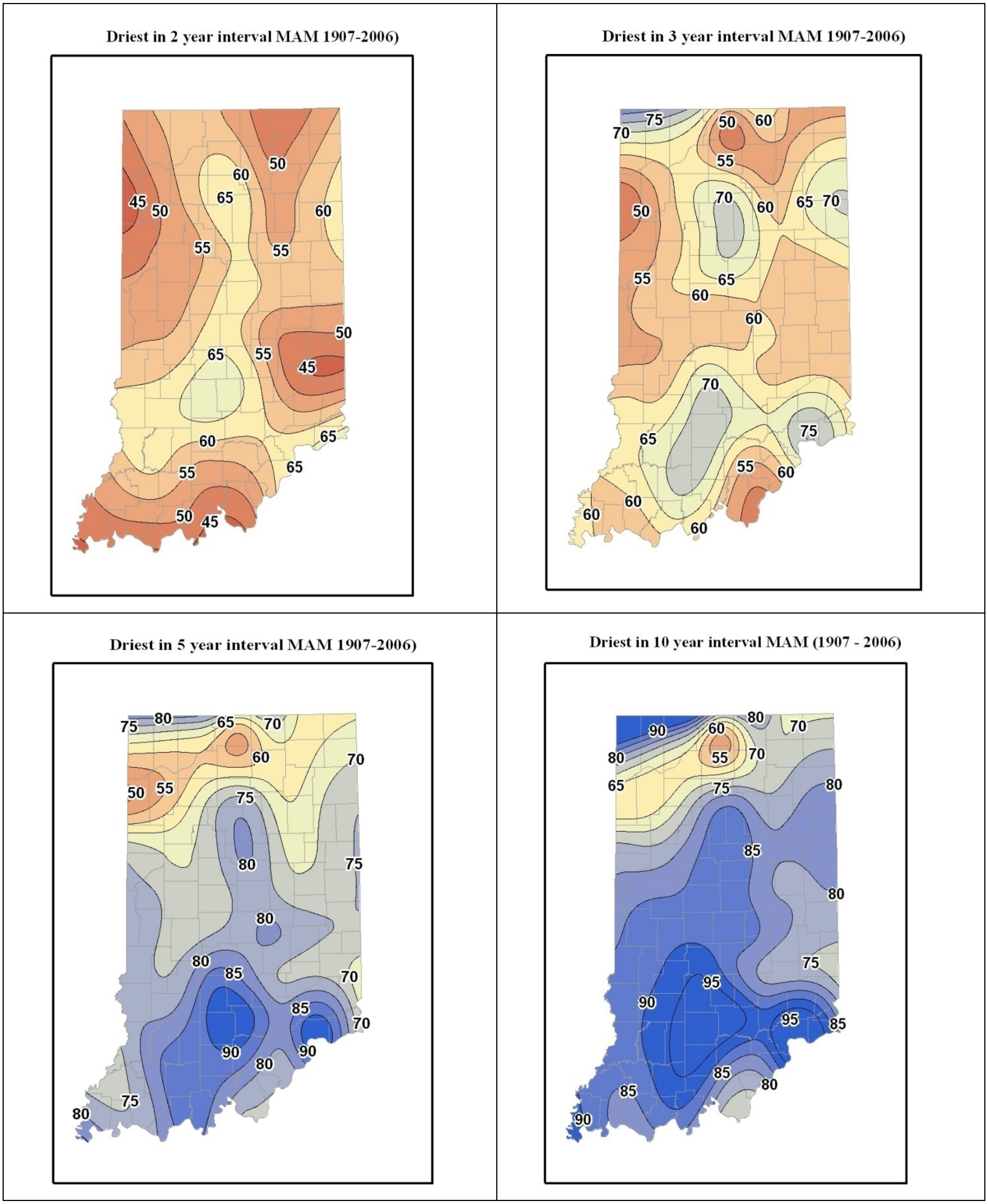


Figure 15(a). The driest years in Indiana for 2-years, 3-years, 5-years and 10-years.



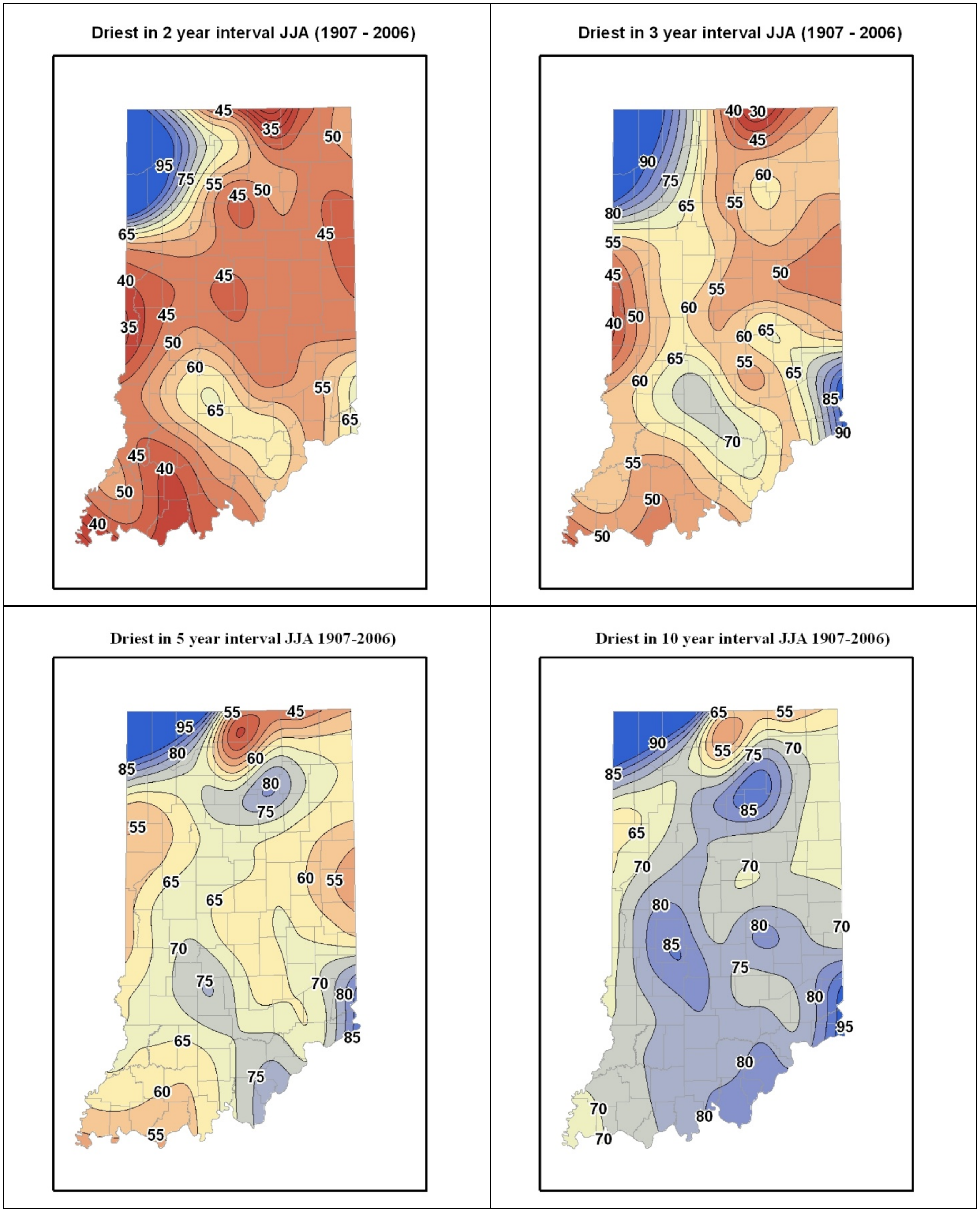
Driest in 2 year interval MAM 1907-2006)

Driest in 3 year interval MAM 1907-2006)

Driest in 5 year interval MAM 1907-2006)

Driest in 10 year interval MAM (1907 - 2006)

Figure 15(b). Percentage precipitation for the driest spring in Indiana for 2-years, 3-years, 5-years and 10-years in spring.



Driest in 2 year interval JJA (1907 - 2006)

Driest in 3 year interval JJA (1907 - 2006)

Driest in 5 year interval JJA 1907-2006)

Driest in 10 year interval JJA 1907-2006)

Figure 15(c). Percentage precipitation for the driest summer in Indiana for 2-years, 3-years, 5-years and 10-years in summer.

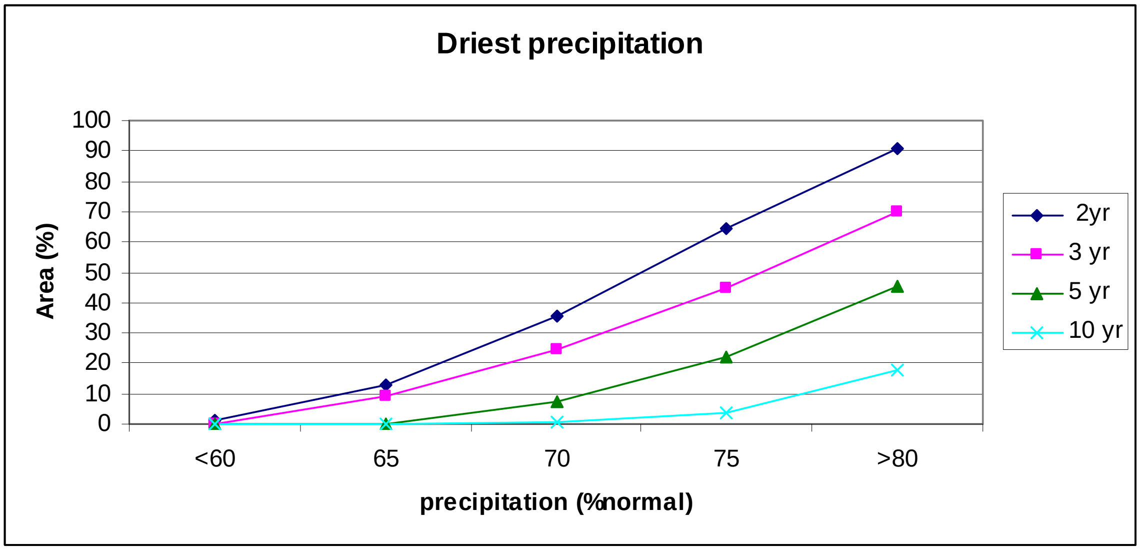


Figure 16. The area percentiles of normal precipitation during the driest periods in Indiana.

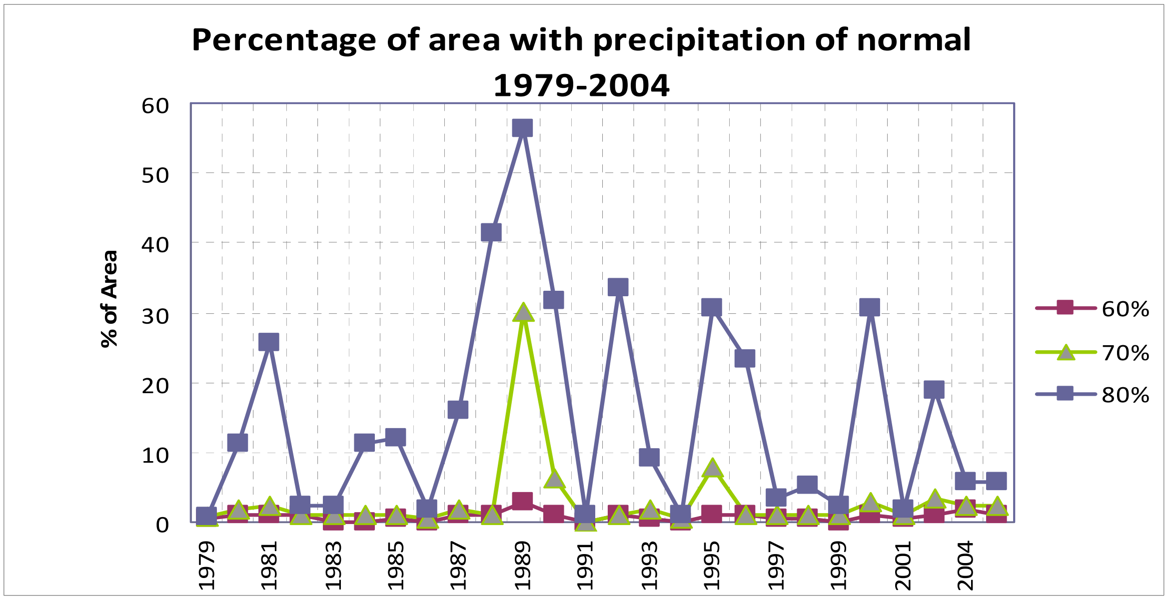


Figure 17. The area percentiles of below normal precipitation in Indiana from 1979-2003: < 80%, <70%, and <60%, using NARR data.

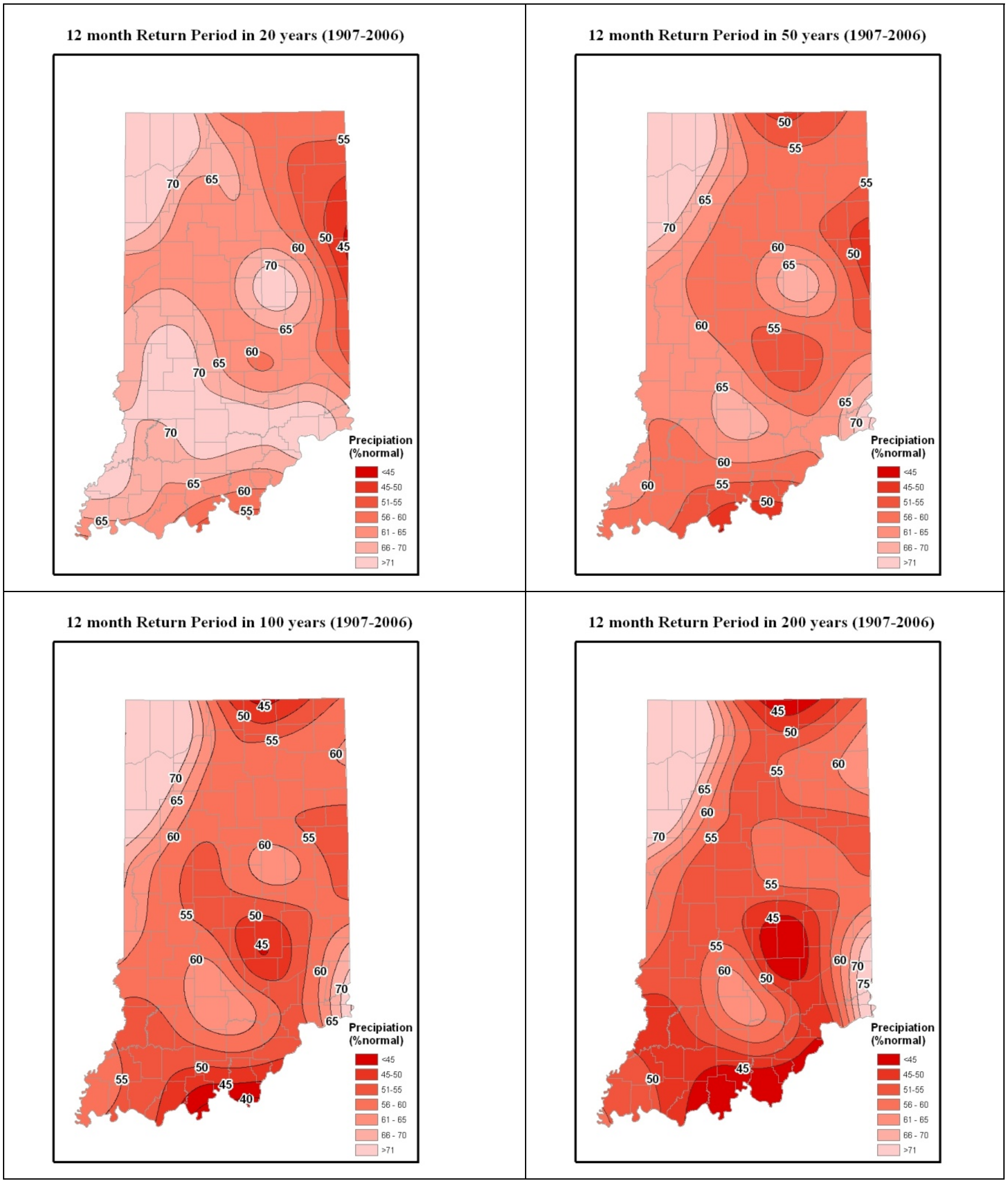
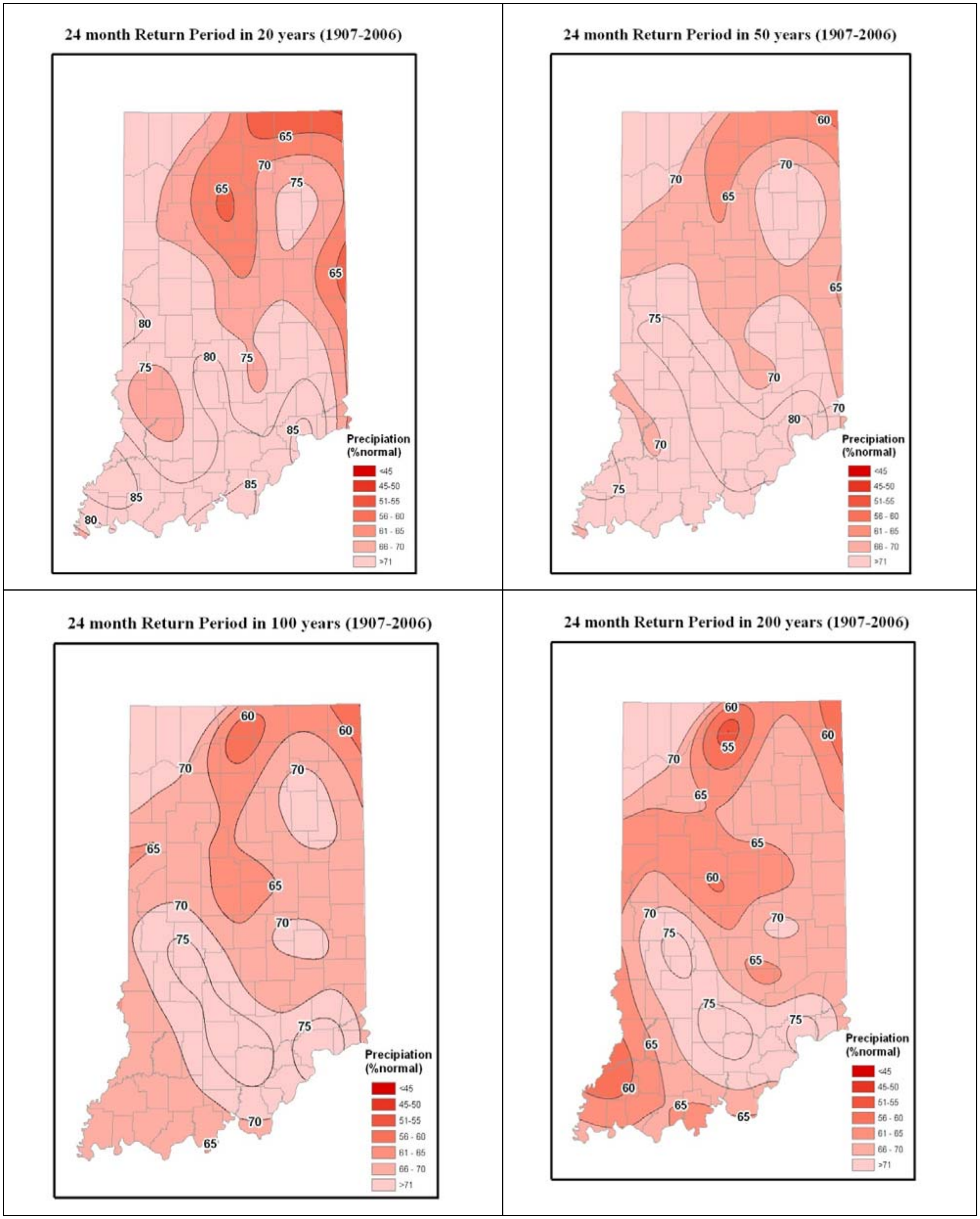


Figure 18(a). Drought return period for 20-year, 50-year, 100-year, and 200- years in Indiana for twelve months. Numbers indicate percentage of normal precipitation.


24 month Return Period in 20 years (1907-2006)

24 month Return Period in 50 years (1907-2006)

24 month Return Period in 100 years (1907-2006)

24 month Return Period in 200 years (1907-2006)

Figure 18(b). The drought return period for 20-year, 50-year, 100-year, and 200- years in Indiana for twenty four months. Numbers indicate percentage of normal precipitation.

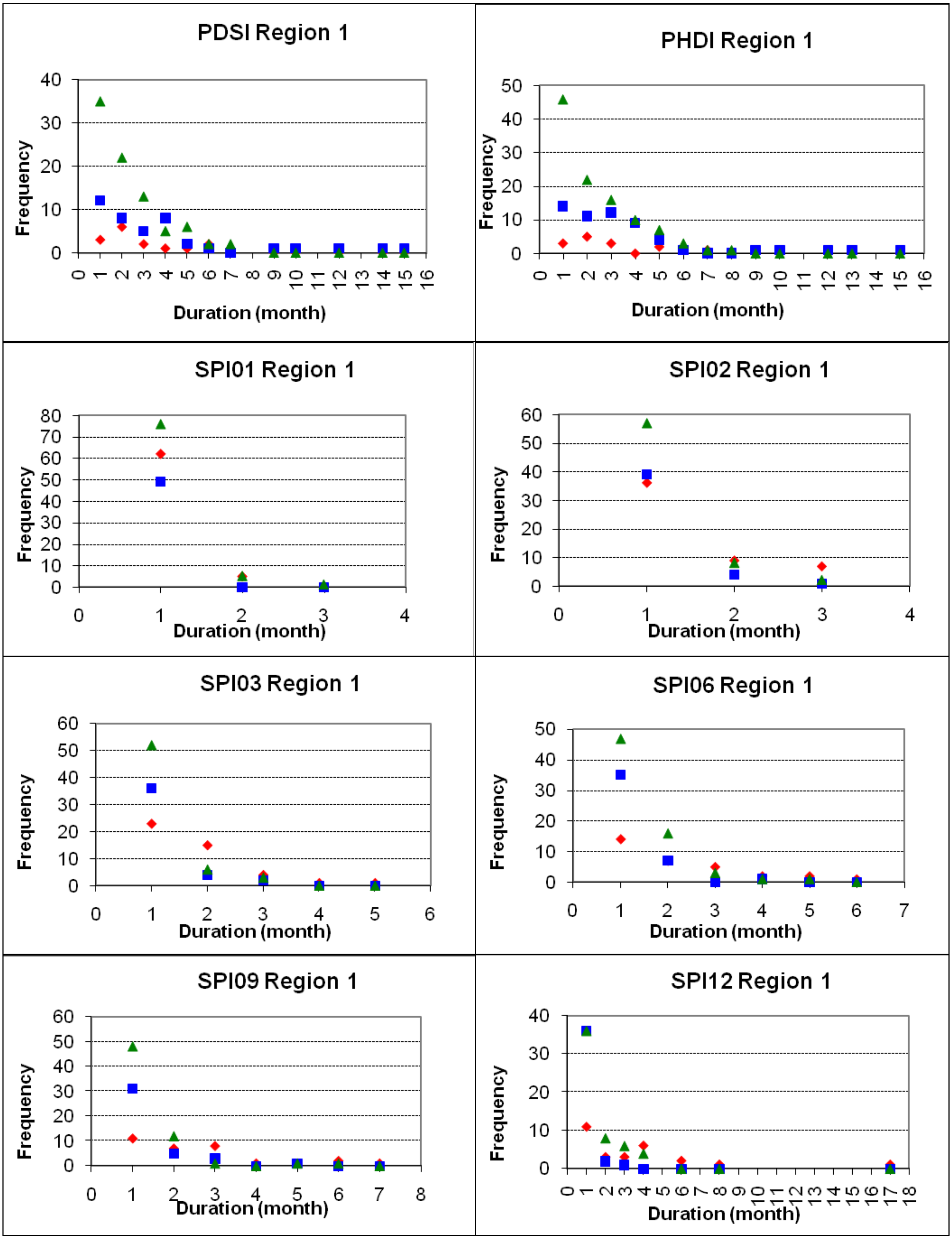


Figure 19(a). Drought frequency based on PHDI, PDSI, SPI01 – 12 for climate division 1.

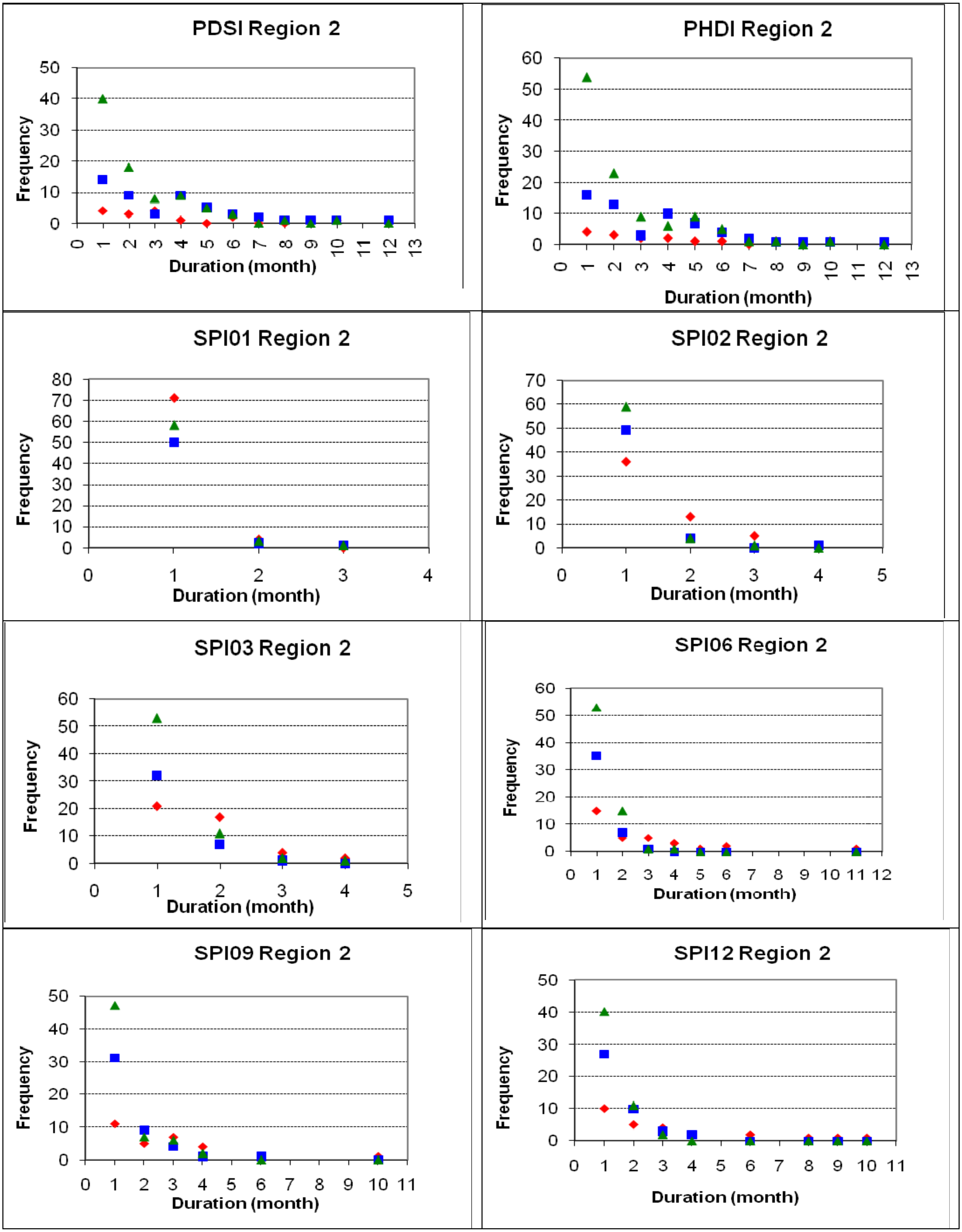
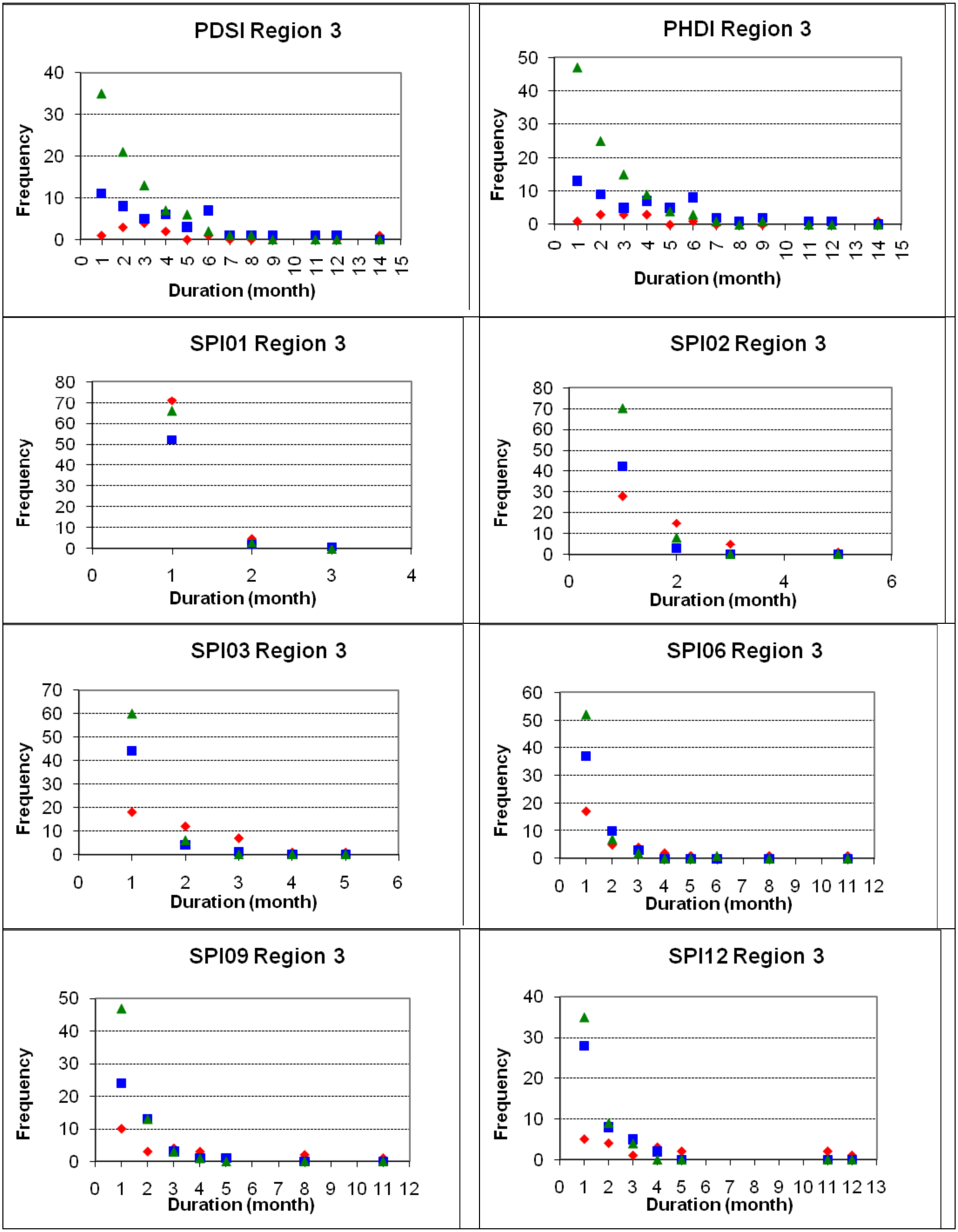


Figure 19(b). Drought frequency based on PHDI, PDSI, SPI01 – 12 for climate division 2.


PDSI Region 3

PHDI Region 3

SPI01 Region 3

SPI02 Region 3

SPI03 Region 3

SPI06 Region 3

SPI09 Region 3

SPI12 Region 3

Figure 19(c). Drought frequency based on PHDI, PDSI, SPI01 – 12 for climate division 3.

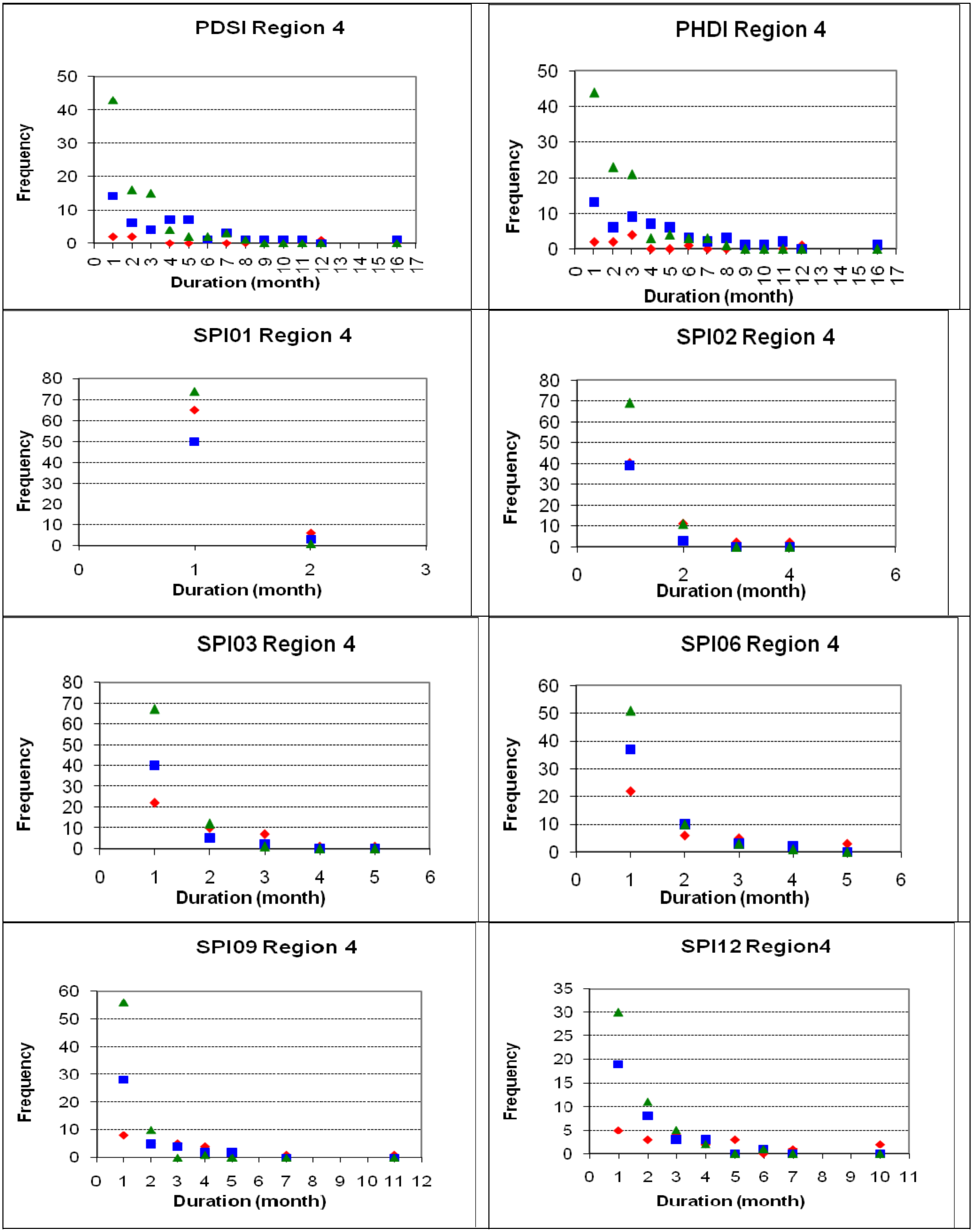


Figure 19(d). Drought frequency based on PHDI, PDSI, SPI01 – 12 for climate division 4.

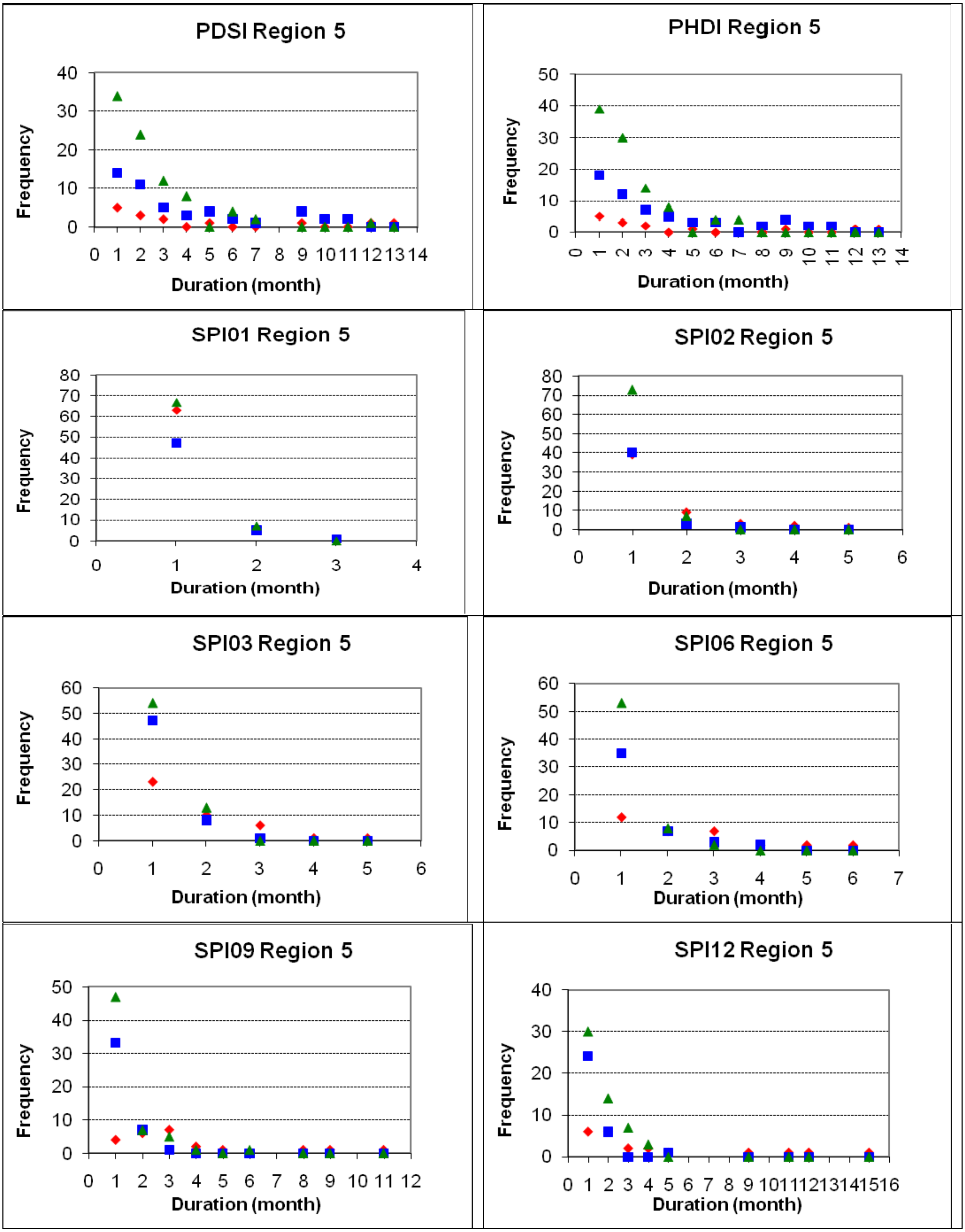
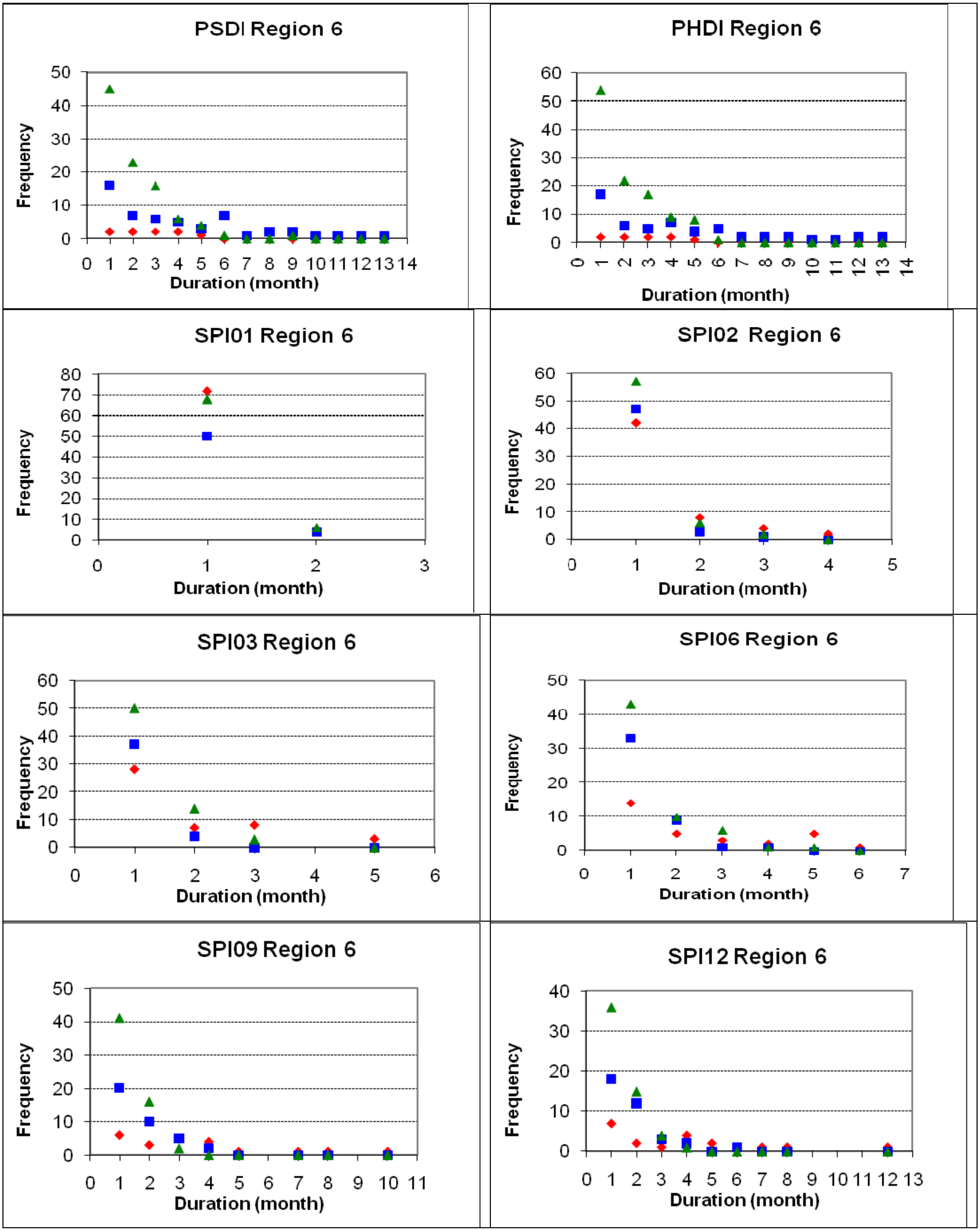


Figure 19(e). Drought frequency based on PHDI, PDSI, SPI01 – 12 for climate division 5.


PSDI Region 6

PHDI Region 6

SPI01 Region 6

SPI02 Region 6

SPI03 Region 6

SPI06 Region 6

SPI09 Region 6

SPI12 Region 6

Figure 19(f). Drought frequency based bon PHDI, PDSI, SPI01 – 12 for climate division 6.

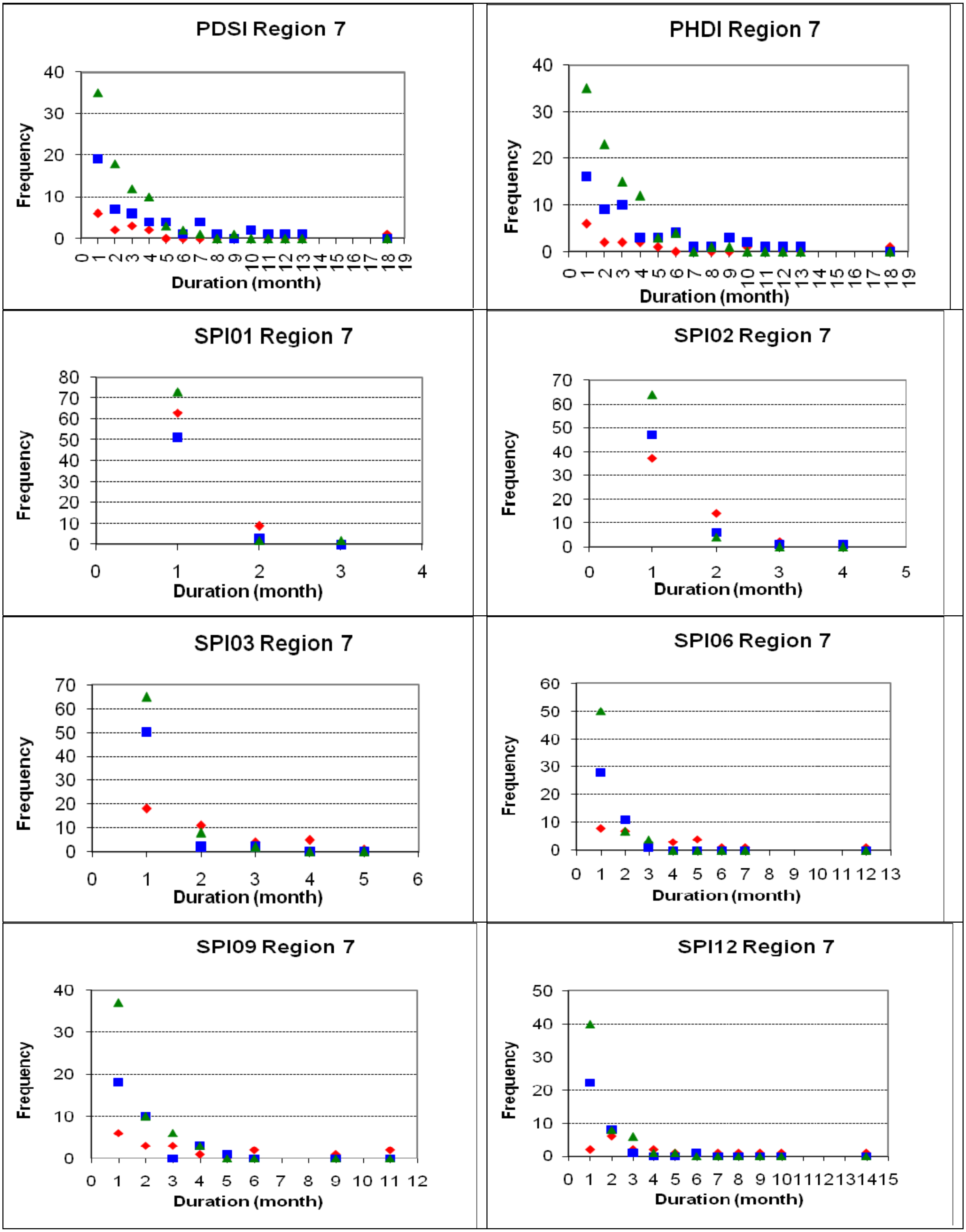


Figure 19(g). Drought frequency based on PHDI, PDSI, SPI01 – 12 for climate division 7.

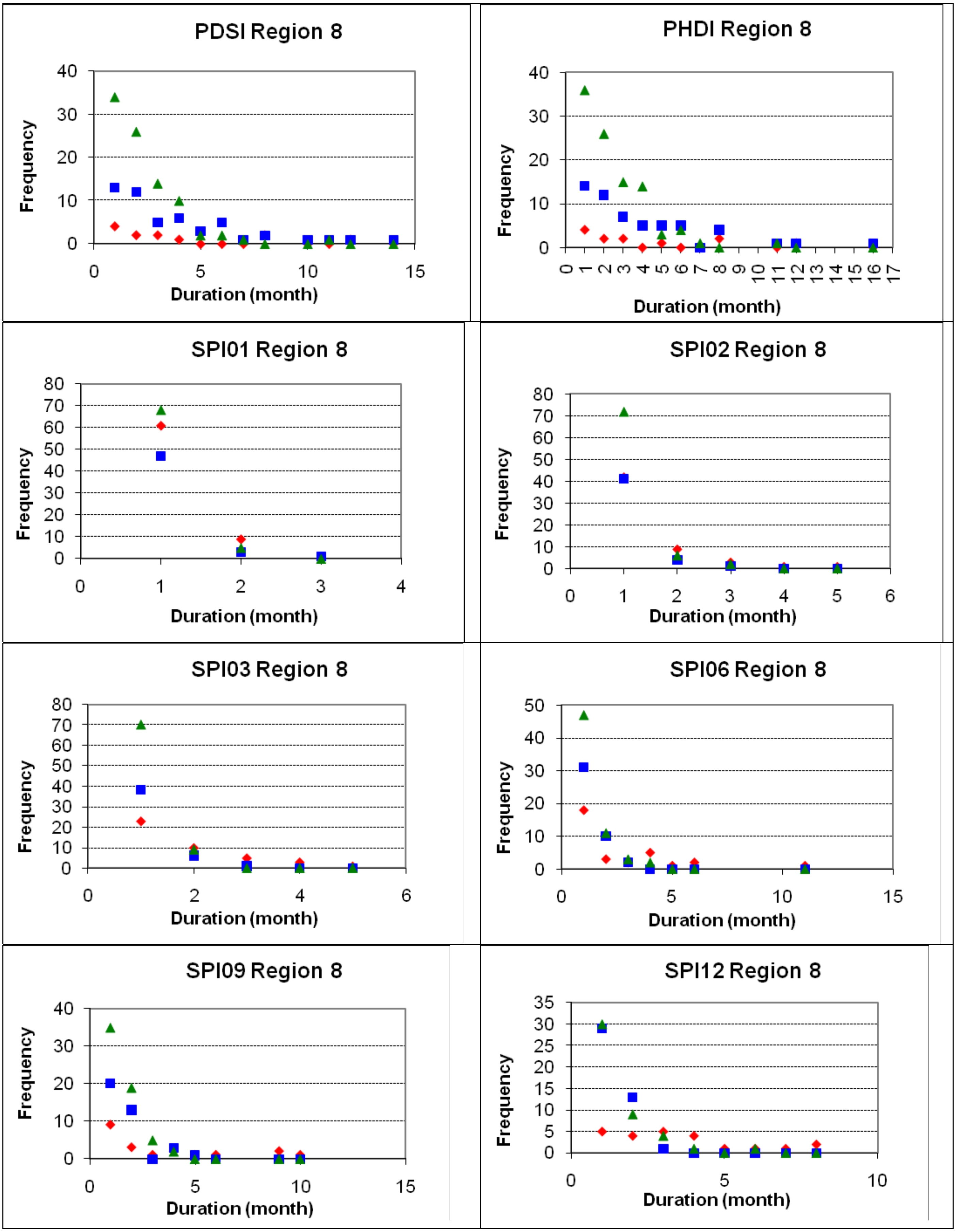
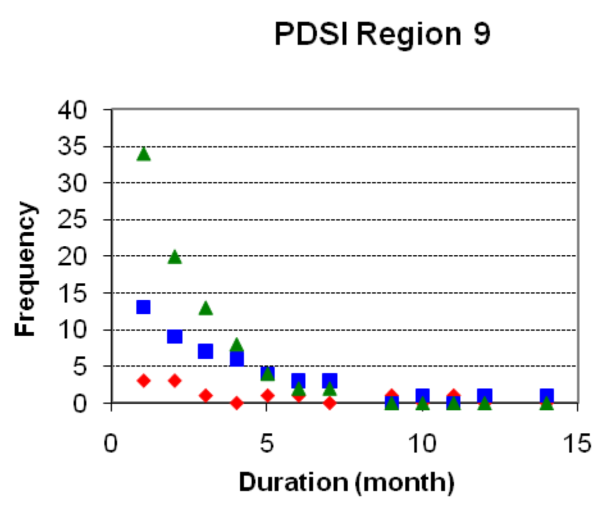
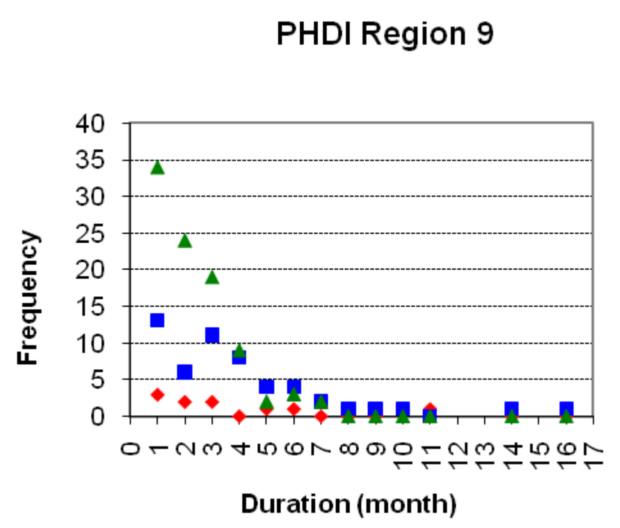
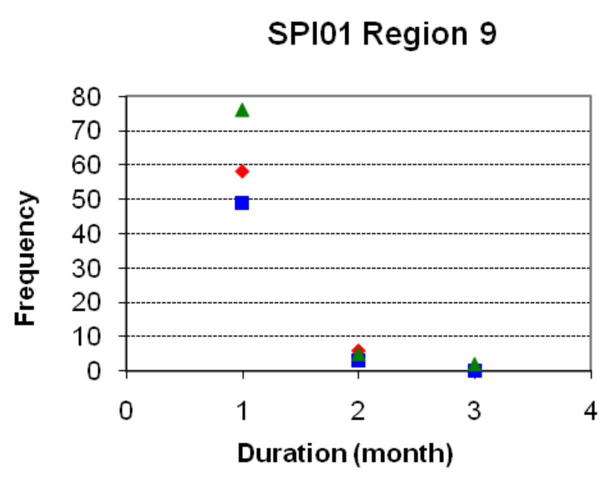
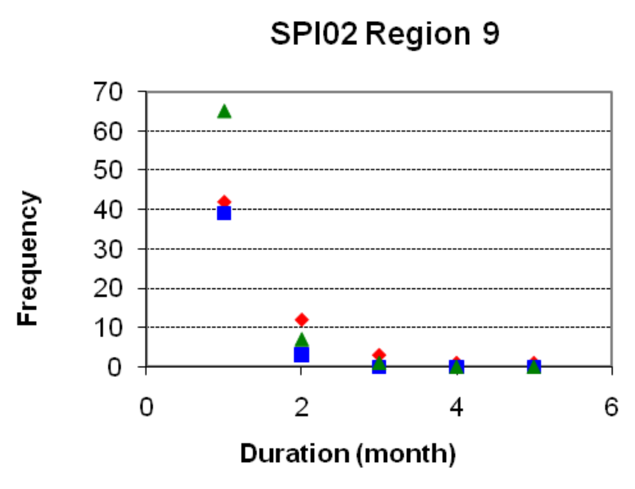


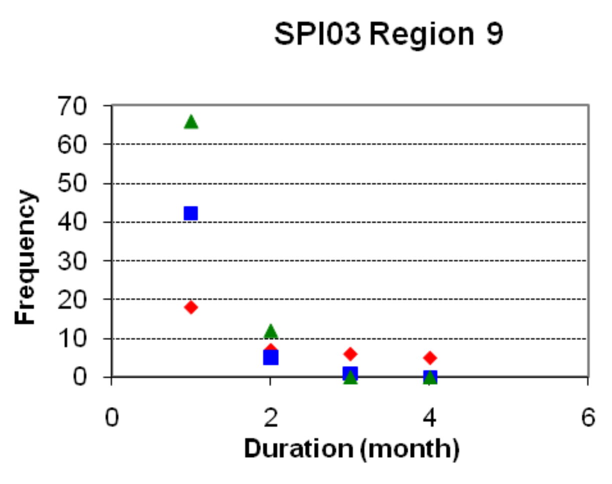
Figure 19(h). Drought frequency based on PHDI, PDSI, SPI01 – 12 for climate division 8.

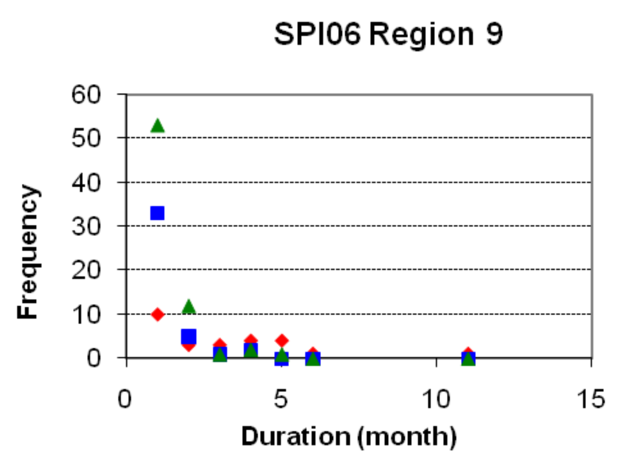

PDSI Region 9


PHDI Region 9


SPI01 Region 9


SPI02 Region 9


SPI03 Region 9


SPI06 Region 9

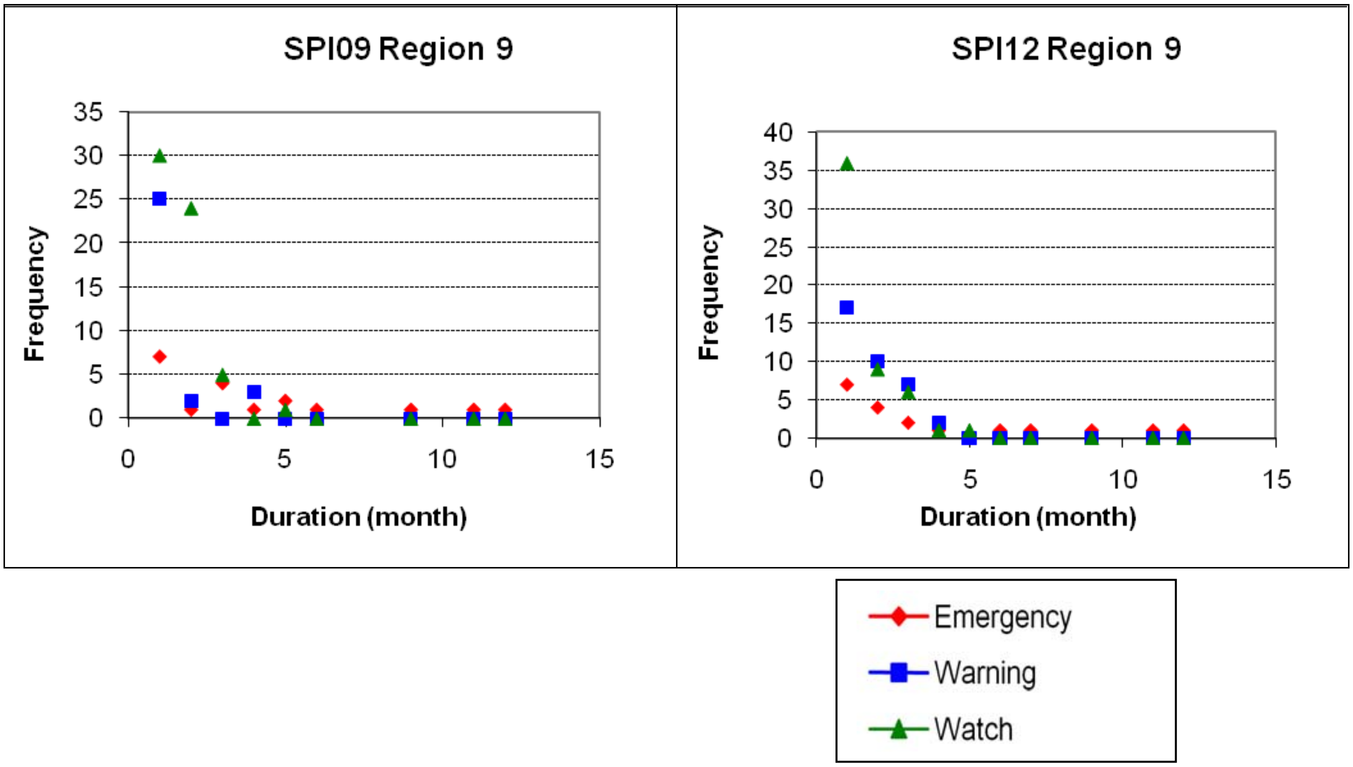
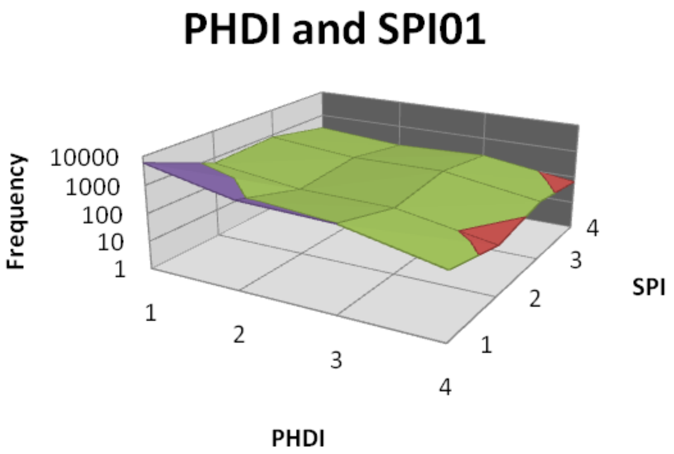
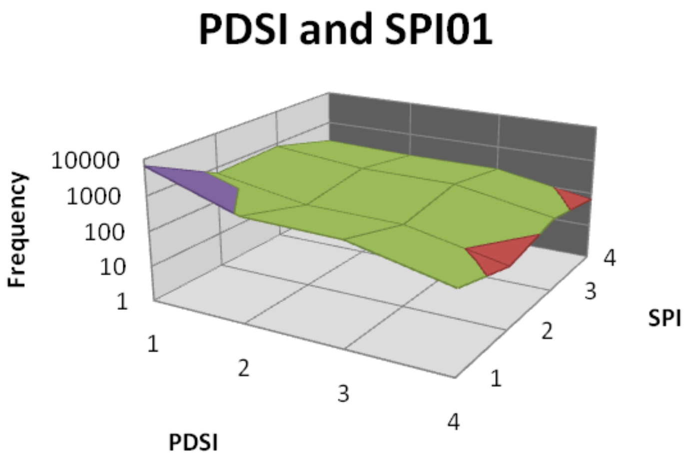
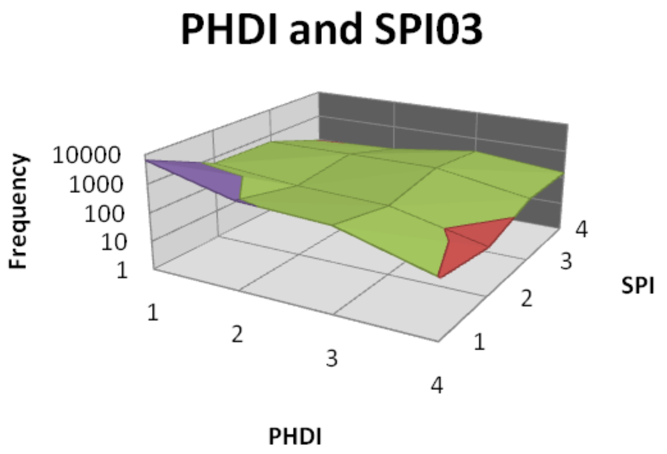
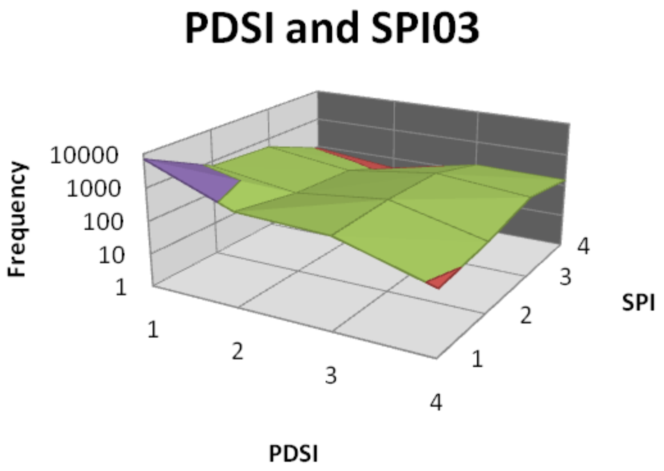


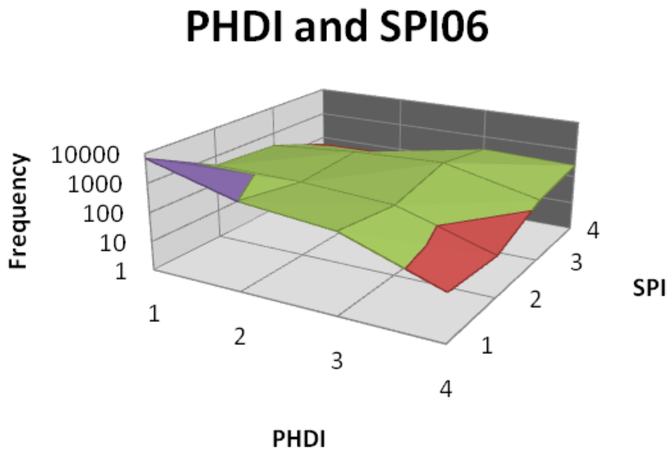
Figure 19(i). Drought frequency based on PHDI, PDSI, SPI01 – 12 for climate division 9.


PHDI and SPI01
Frequency
10000
1000
100
10
1
1
2
3
4
PHDI
1
2
3
4
SPI


PDSI and SPI01
Frequency
10000
1000
100
10
1
1
2
3
4
PDSI
1
2
3
4
SPI


PHDI and SPI03
Frequency
10000
1000
100
10
1
1
2
3
4
PHDI
1
2
3
4
SPI


PDSI and SPI03
Frequency
10000
1000
100
10
1
1
2
3
4
PDSI
1
2
3
4
SPI


PHDI and SPI06
Frequency
10000
1000
100
10
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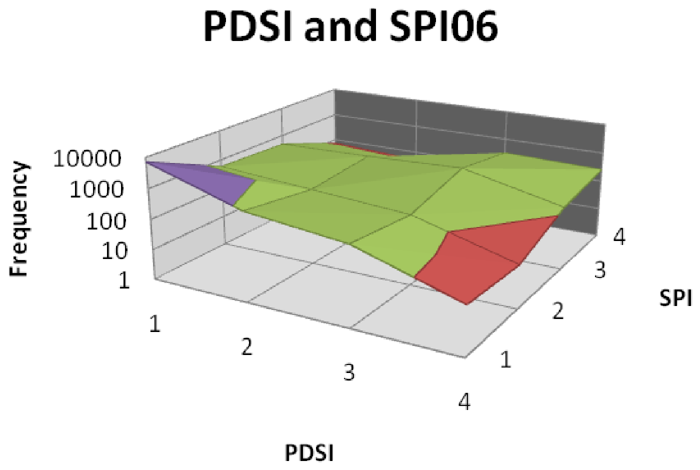
1
2
3
4
PHDI
1
2
3
4
SPI


PDSI and SPI06
Frequency
10000
1000
100
10
1
1
2
3
4
PDSI
1
2
3
4
SPI

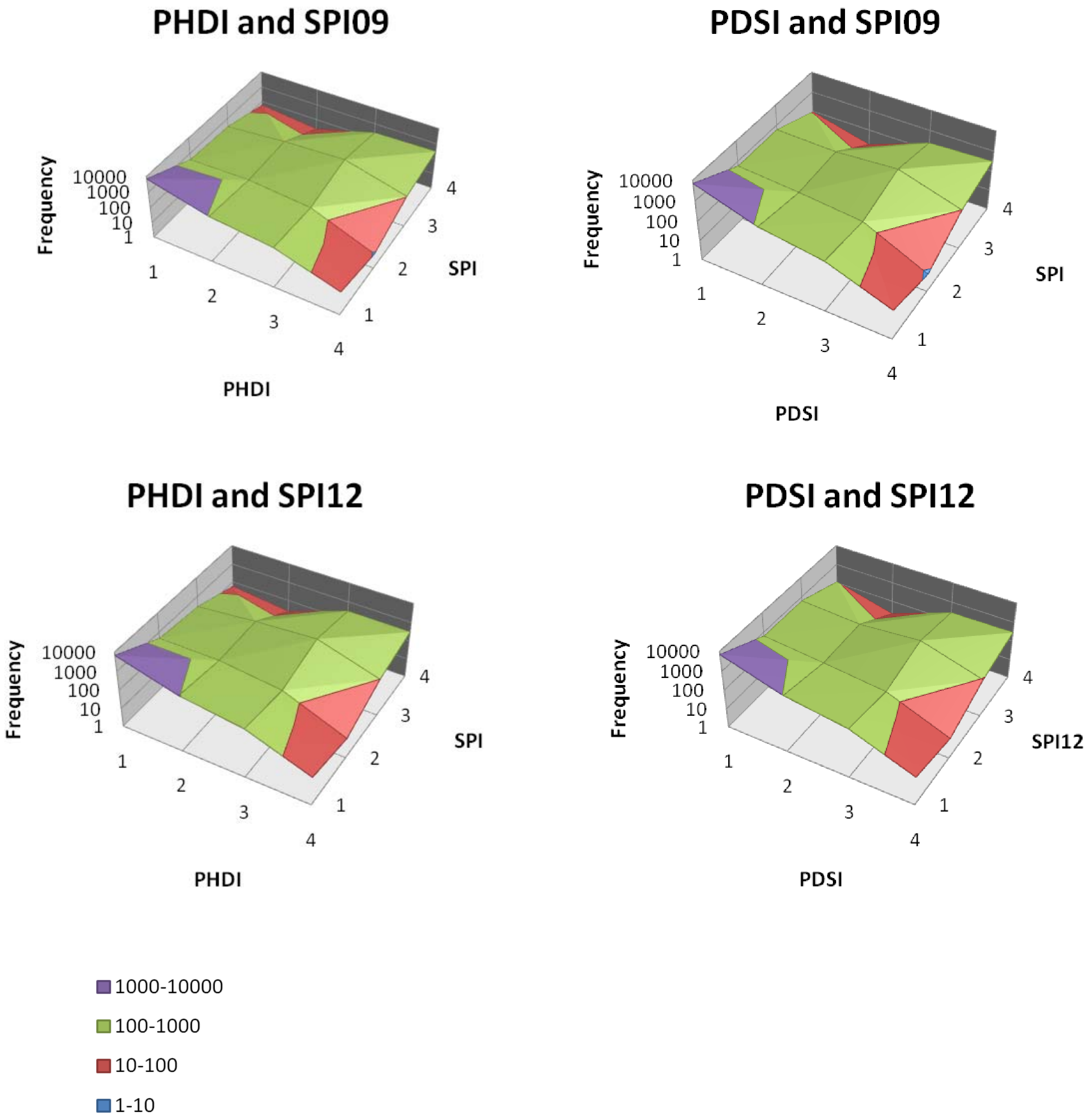


Figure 20. The consistency of indices, PHDI, PDSI, SPI01 – 12 over Indiana State.

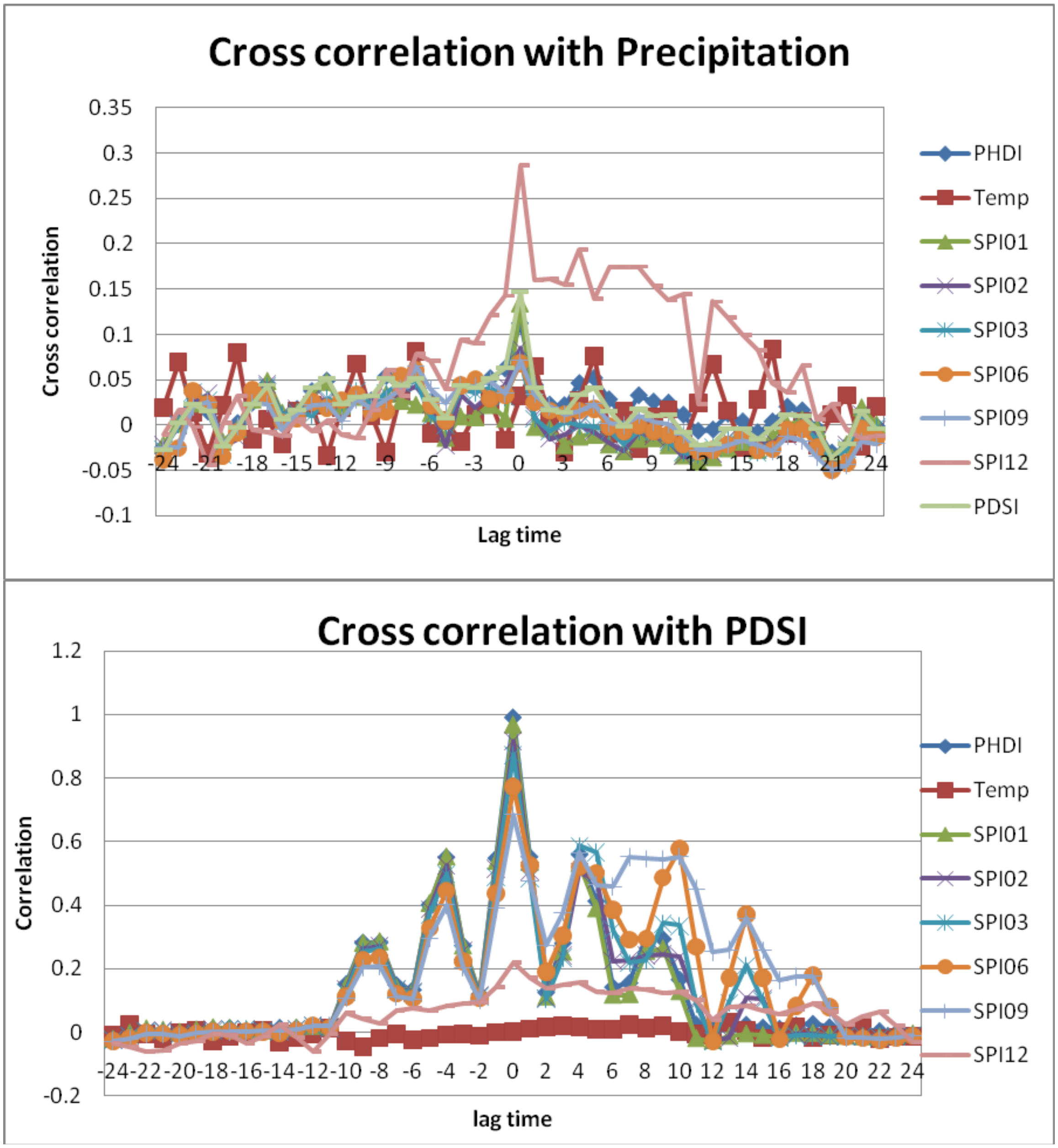


Figure 21. The cross-correlation of drought indices.

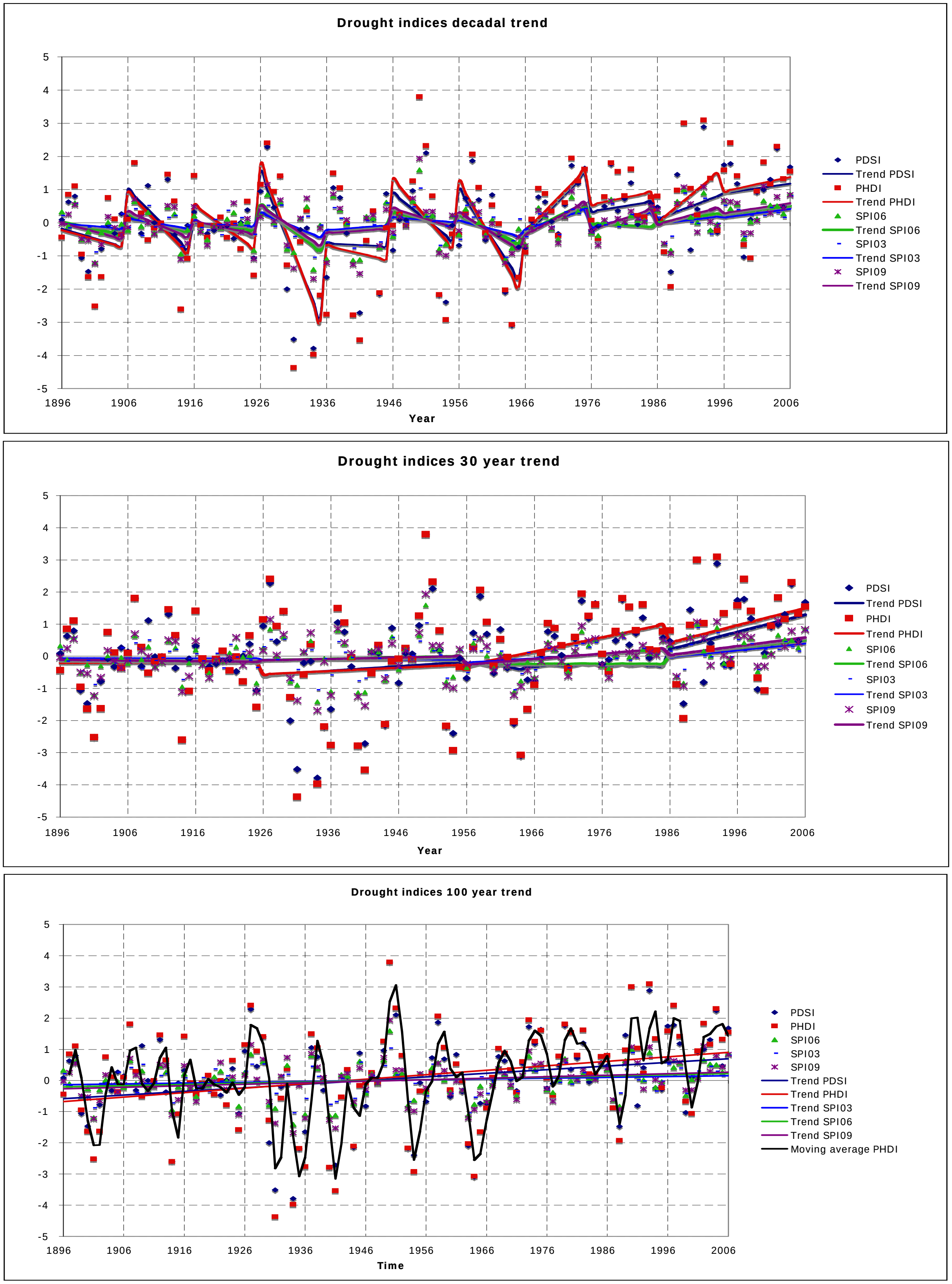
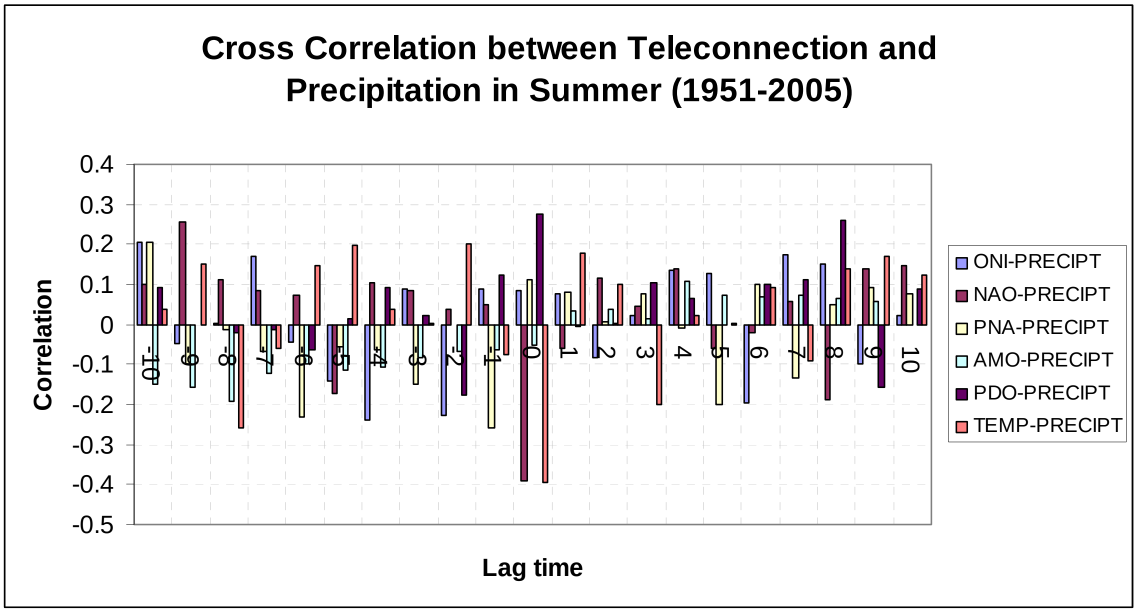


Figure 22. The 10, 30 and 100 year trend of the drought indices, PDSI, PHDI and SPI over Indiana (1896-2006).



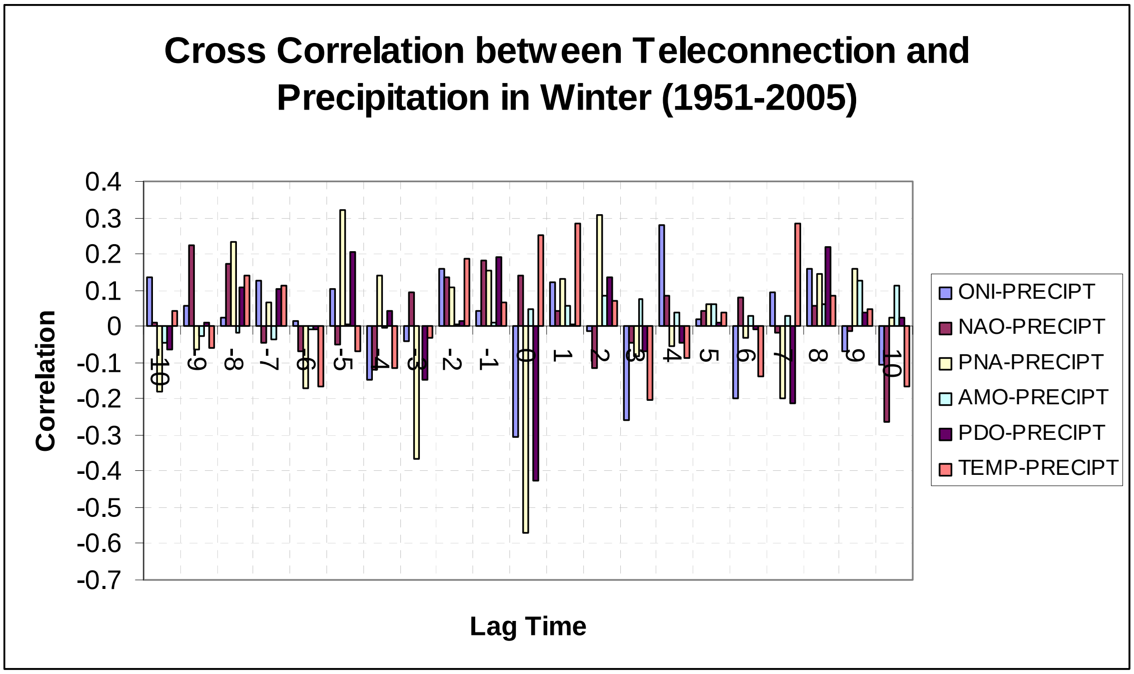


Figure 23. The cross-correlation between tele-connection and precipitation in winter and summer.

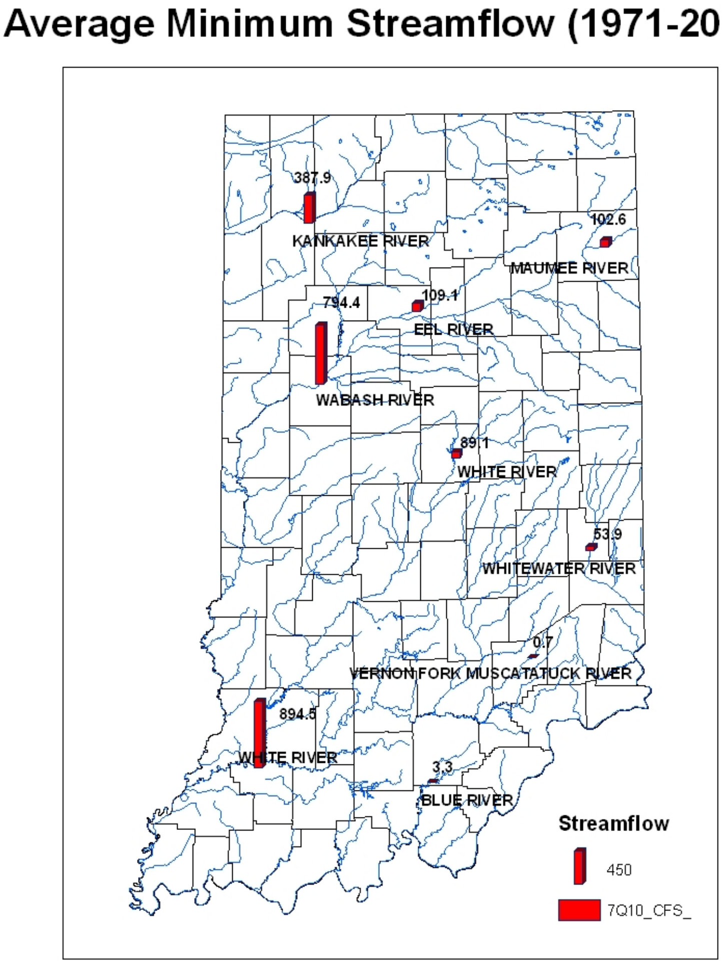

Average Minimum Streamflow (1971-2000)

Figure 24. The locations of stream flow measurements and 10 percentile of 7-day average minimum streamflow.

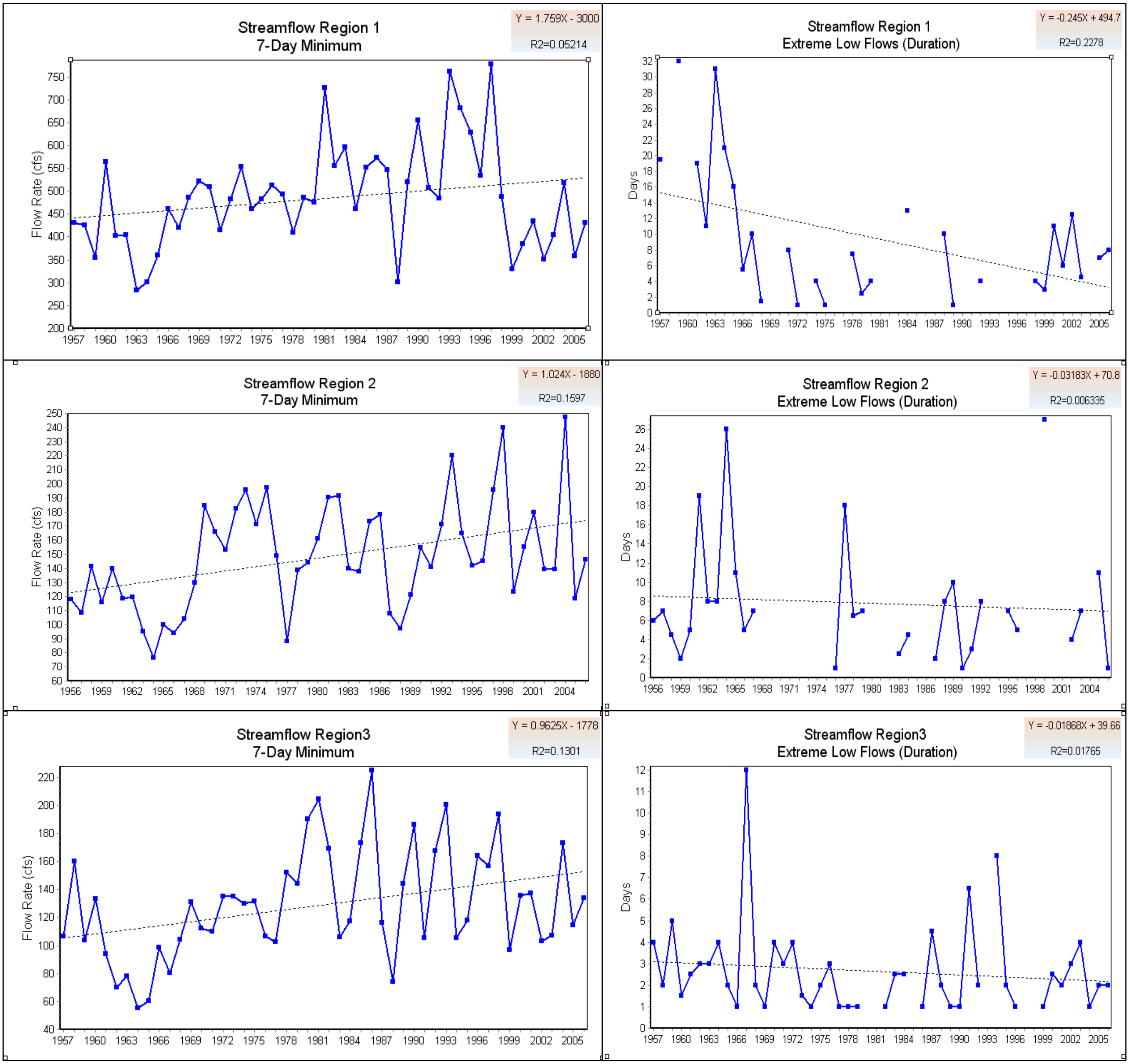


Figure 25(a). 7-day minimum streamflow level and extreme low flows duration in climate division 1,2 and 3.

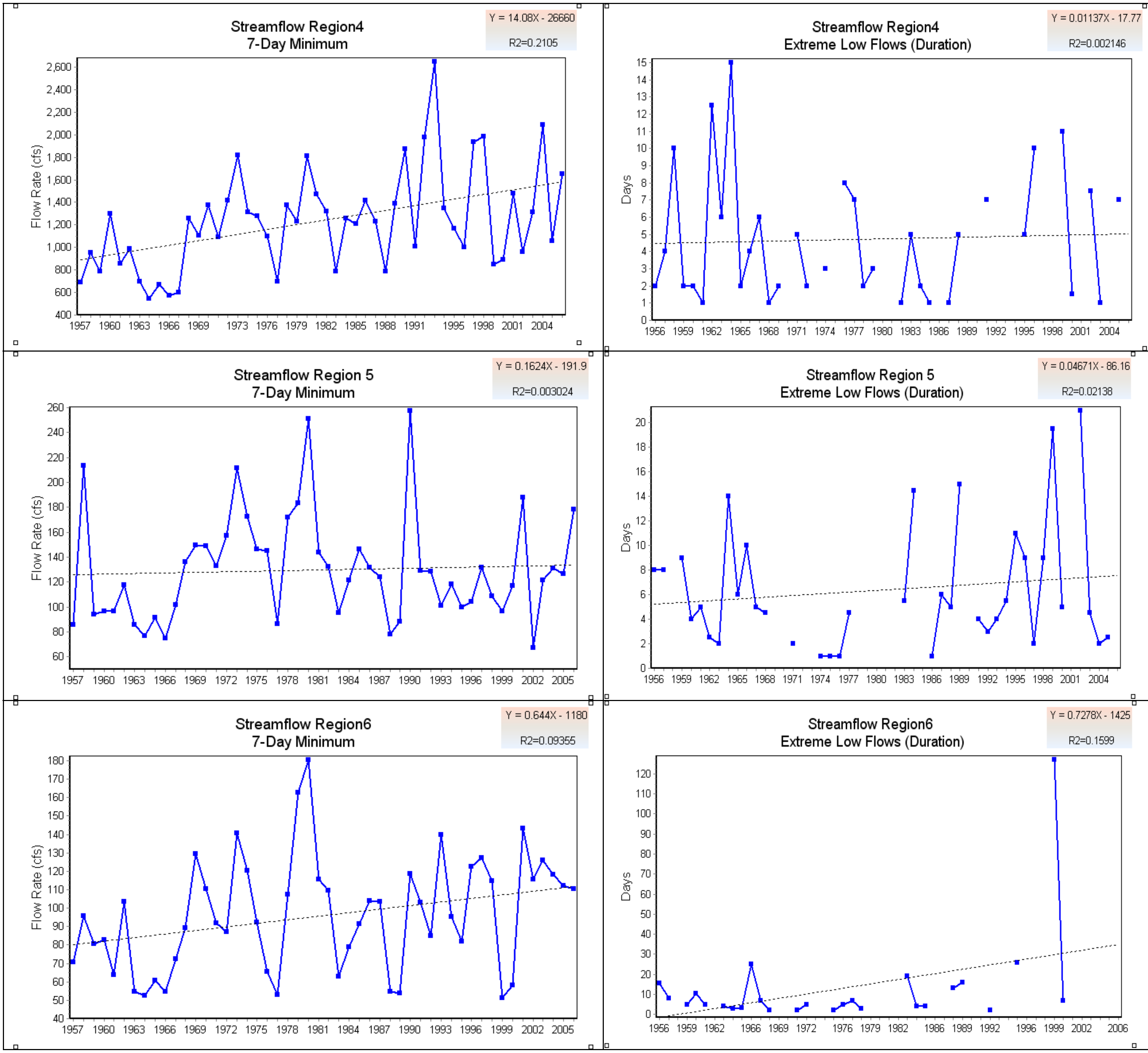
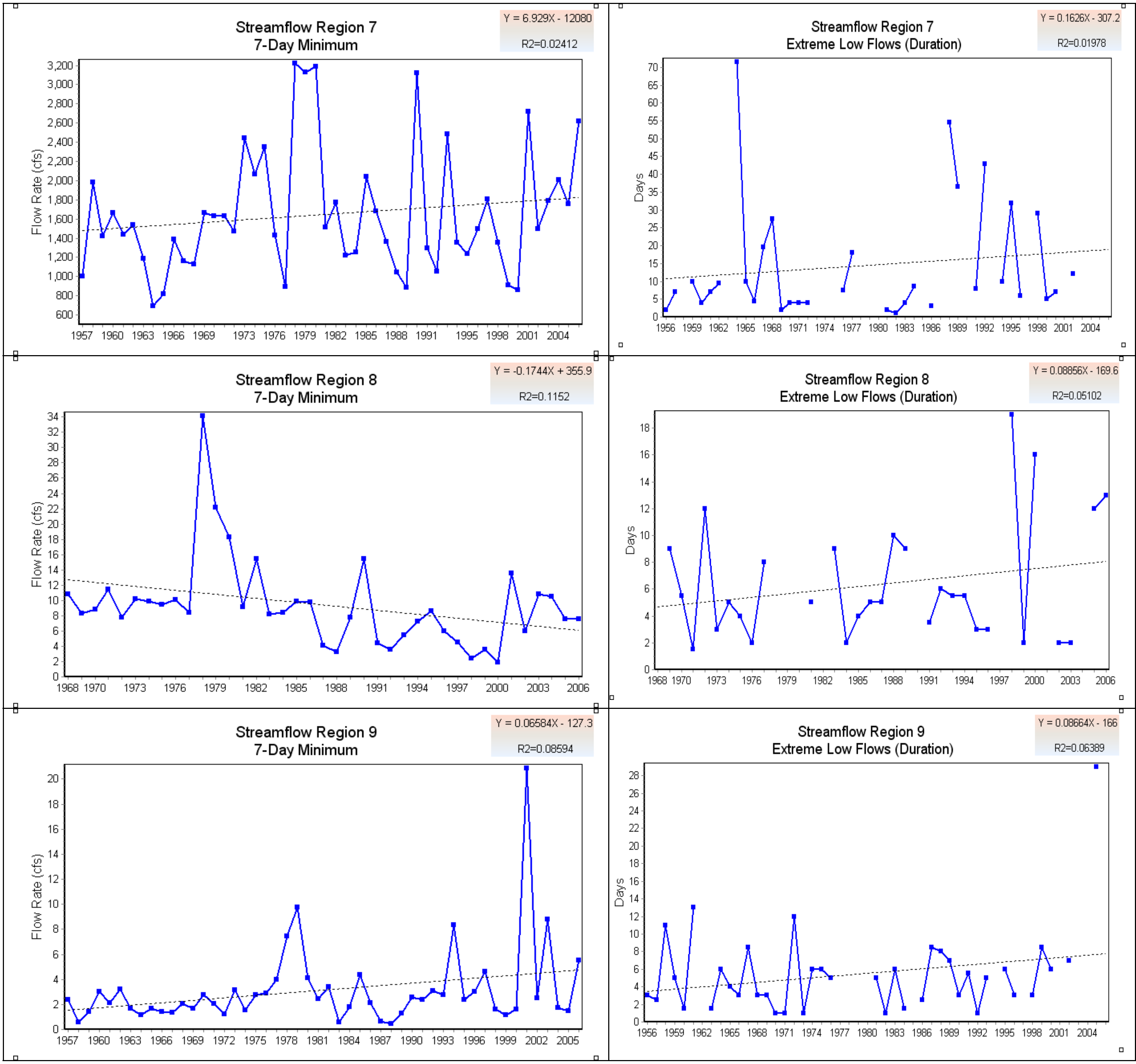


Figure 25(b). 7-day minimum streamflow level and extreme low flows duration in climate division 4, 5 and 6.



Streamflow Region 7
7-Day Minimum

Streamflow Region 7
Extreme Low Flows (Duration)

Streamflow Region 8
7-Day Minimum

Streamflow Region 8
Extreme Low Flows (Duration)

Streamflow Region 9
7-Day Minimum

Streamflow Region 9
Extreme Low Flows (Duration)

Figure 25(c). 7-day minimum streamflow level and extreme low flows duration in climate division 7, 8 and 9.