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Growing season moisture deficits across the northeastern United States

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ABSTRACT: Growing season moisture deficit is evaluated for the northeastern United States for the period 1895 through 1996. Moisture deficit values are calculated using the Thornthwaite/Mather water budget analysis technique. This technique allows for the estimation of soil moisture parameters using only mean monthly temperature and monthly precipitation values. Thus, soil moisture estimates can be derived for periods extending back to the nineteenth century with the use of climate division data. For the northeastern United States taken as a whole, growing season moisture deficit values show no evidence of a consistent long-term trend over the period 1895 through 1996. However, the entire region has been subject to decadal-scale variations in moisture deficit, the most pronounced being an anomalous moist period that extended from the late 1960s through the 1980s. A regionalization of growing season moisture deficit indicates the existence of 3 spatially distinct regions across the northeastern United States. One region extends along the Atlantic Coast from the Chesapeake Bay, north to the coast of Massachusetts and inland to the higher terrain of the Catskill and Pocono Mountains. A second region includes most of northern New England and northeastern New York, while a third region encompasses southwestern New York, western Pennsylvania and West Virginia. Each region has diverse time series of moisture deficit values for the period of record. Severe moisture deficit growing seasons are more strongly associated with negative precipitation anomalies than with positive temperature anomalies in the Northeast. The negative precipitation anomalies are associated with a decrease in both the frequency and intensity of precipitation, which occurs in conjunction with a decrease in the frequency of convective rainfall events. Consistent upper-tropospheric flow patterns are associated with the driest and wettest growing seasons.

KEY WORDS: Soil moisture · Northeastern United States · Climate change

1. INTRODUCTION

In many areas of the world where extensive irrigation is not possible or practical, the lack of sufficient water in the root zone of the soil can cause great societal disruption, especially to agricultural concerns. Even in areas like the northeastern United States, where mean monthly precipitation is relatively large and consistent throughout the annual cycle, precipitation variability on diverse time-scales characterizes the climate system. Because of its large urban centers, the northeastern United States is usually not associated with extensive agricultural activity or a great sensitivity to soil moisture variability and drought. However, much of the land surface in the area from West Virginia north through Maine is utilized for agricultural and forest productivity. Although the agricultural sector of the economy is small in comparison to the total economy of the region (EPA 1997), it is still very important, especially in rural areas. Moreover, the large urban centers in the region require large amounts of fresh water for consumption and sanitation needs. Therefore, the northeastern United States is a water sensitive region, and its hydroclimatology merits detailed investigation, specifically in relationship to drought.

Drought is defined in many different ways. A relatively short-term shortage of precipitation or large

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increase in evapotranspiration can cause a loss of water within the soil, making water unavailable for use by both natural and cultivated vegetation. Such a situation is commonly termed an agricultural or soil moisture drought. A significant decrease from normal precipitation totals over a wide area for an extended time is often described as a meteorological drought. A hydrologic drought is commonly more widespread and protracted than a meteorological drought and can last for more than a year. Hydrologic droughts affect the terrestrial portion of the hydrologic cycle, causing low stream flows, reduction in well levels, and the loss of water from lakes and reservoirs.

Soil moisture or agricultural droughts generally occur before the onset of either meteorological or hydrological droughts. As stated above, they can result from a short-term (several days to several weeks) shortage of precipitation, an increase in evapotranspiration or both factors working in concert. Soil moisture droughts are often regionally specific and can be dependent upon soil type and/or the type of vegetation present. This is especially true during the growing season, with the prevalence of scattered mesoscale, convective precipitation. Thus, it is possible for a given area to have an above normal annual or seasonal precipitation total and still have experienced a period of severe soil moisture shortage during some portion of the annual cycle.

Potential natural and human-induced climate changes have raised concerns about the supply of fresh water for human use and for natural and agricultural ecosystems across the earth. These concerns are relevant in the northeastern United States, an area especially prone to flooding (Yarnal et al. 1997, Leathers et al. 1998), and an area that regularly experiences soil moisture, meteorological, and hydrological droughts (Fieldhouse & Palmer 1965, Dickerson & Dethier 1970).

Surprisingly, little research has been done on soil moisture droughts in the northeastern United States. Fieldhouse & Palmer (1965) used the Palmer Drought Severity Index (PDSI; very similar to the Thornthwaite/Mather water budget technique) to study agricultural drought in the northeastern United States during the period 1929 through 1963. They calculated PDSI values for each of the 54 climate divisions for each month during the year and identified ‘drought durations’ over the period of record. They did not discuss the spatial nature of these drought periods in any way and they did not look at their findings in the context of potential climate changes. Dickerson & Dethier (1970) used the PDSI values to calculate drought frequency and drought return periods for individual climate divisions during the period 1929 through 1967. Again, this research was done for each climate division, with no mention of the spatial nature or long-term variability of drought periods.

This research examines the interannual variability of moisture deficit values during the growing season (May through September), the portion of the annual cycle during which natural and cultivated plant life are most susceptible to moisture induced stress. Thus, we will concentrate primarily on agricultural droughts, which are the result of insufficient soil moisture. To accomplish this goal, a 102 yr time series of growing season (May through September) moisture deficit values is constructed for the northeastern United States using the Thornthwaite/Mather water budget technique (Thornthwaite & Mather 1955). Moisture deficit values represent the difference between the climatic demand for water (potential evapotranspiration) and the actual use of precipitation and soil moisture (actual evapotranspiration) by the vegetation. Thus, when the climatic demand for water by vegetation is greater than the combination of water available as precipitation or as soil moisture, a moisture deficit exists. A regionalization of the northeastern United States is performed based upon the interannual variability of growing season moisture deficit values. The association between moisture deficit values and diverse meteorological variables is also investigated. These variables include monthly temperature and precipitation data, daily precipitation frequency data, thunderstorm frequency and duration information for the northeast region, and 30 kPa geopotential height data.

A discussion of the data utilized in the research and a brief introduction to the Thornthwaite/Mather water budget technique is given in the next section. In Section 3, results of the study are presented. Finally, a summary and concluding remarks are given in Section 4.

2. DATA AND METHODOLOGY

This research utilizes the climatic water budget technique developed by Thornthwaite & Mather (1955). Moisture deficit values are derived on monthly timescales for the northeastern United States. For this study, the northeastern United States will be defined as the area located southward of Maine through West Virginia, Maryland and Delaware (Fig. 1).

The climatic water budget methodology is a mass conservation technique that balances estimated inputs of water (precipitation) with water outputs (evaporation and plant transpiration; evapotranspiration). Water input is estimated using monthly precipitation data, a commonly measured climatic variable. Water outputs (evapotranspiration) are more difficult to estimate. A variety of different methodologies have been devised to estimate the evapotranspiration that takes place from a point source or a homogeneous region

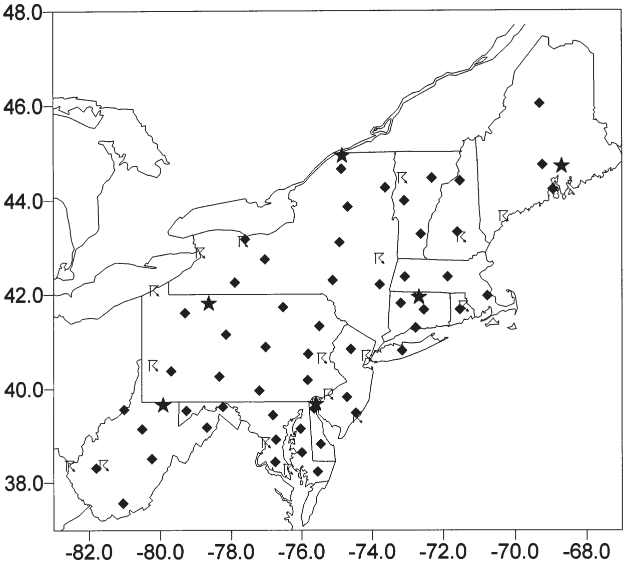


Fig. 1. Distribution of data types used in the study. (◆) Center position of climate divisions with monthly temperature and precipitation data; (⚑) stations with thunderstorm frequency and duration data; (★) stations used in the daily precipitation frequency and intensity analysis

(Mather 1978). Techniques include mass transport, aerodynamic, eddy correlation, and empirical methods (see Mather 1978 for a discussion of each). The climatic water budget is an empirical technique that uses observed data to derive formulae that relate meteorological conditions to evaporation data from irrigation plots and diverse watersheds. Evapotranspiration is estimated using monthly temperature, solar angle, and day length in the Thornthwaite/Mather scheme.

Many other methods for estimating evapotranspiration have been developed since the introduction of the Thornthwaite/Mather technique (1955). The majority of these other techniques require more complete data, such as wind speed, solar radiation and vapor pressure gradients, and many require such information with daily or even hourly temporal resolution. Although several techniques have been shown to produce more accurate evapotranspiration estimates on daily or weekly time-scales (Eagleman 1976), no technique has been shown to improve upon that of Thornthwaite & Mather (1955) at monthly or seasonal temporal resolutions. Since the climatic water budget technique requires only monthly values for temperature and precipitation (solar angle and day-length values are dependent only on latitude and timing within the annual cycle), soil moisture values can be calculated far into the past using very common and easily attainable records. Therefore, the climatic water budget technique is uniquely valuable in historical studies where the availability of data is limited.

Currently, the most widely used index for monitoring drought across the United States is the PDSI (Palmer 1965, Alley 1984). This method is very similar to the Thornthwaite/Mather water budget technique in that it is a mass conservation methodology where water inputs are compared to water outputs. The utility of the PDSI has been investigated quite extensively by a number of authors (i.e. Dickerson & Dethier 1970, Alley 1984, Karl 1986). For this study, the findings of Karl (1986) are the most significant. He found that the PDSI tends to respond slowly to short-term (months or a few months) changes in the precipitation regime. Thus, a month of extremely dry conditions with high temperatures, which would likely result in great deficits of soil moisture for vegetation, may not be identified as readily using the PDSI. Moreover, the PDSI is a moisture index that gives no clear quantitative value for the magnitude of a drought situation. The Thornthwaite/Mather technique used in this research responds immediately to a month with very dry or very wet conditions, and provides a quantitative measure of the amount of water that was deficient. In this regard it is more closely related to the Palmer Z-Index, advocated by Karl (1986) for short-term drought monitoring.

In this study, monthly temperature and precipitation data are utilized from the climate division data set available from the National Climatic Data Center (NCDC; NOAA 1983a,b). To complete the water budget calculations, the latitude and date are needed to derive the day length and solar angle. In addition, the water holding capacity of the soil within each climate division is required. The geographic center of each climate division is taken as the latitude, while the midpoint of each month is utilized as the date. The water holding capacity of the soil, for each climate division in the northeastern region, is estimated by Main (1979) to be 150 mm. Although this water holding capacity may be somewhat high for previously glaciated regions and coastal locations with sandy soils, it represents an integrated value that is appropriate for entire climatic divisions. Temperature and precipitation data for the 54 climate divisions that are encompassed by the study region are collected for the period 1895 through 1996. In addition, precipitation frequency information for several stations across the region is derived from the United States NCDC records of Surface Airways observations. Thunderstorm beginning and ending time data are obtained from the NCDC TD-9945 data set (Changery 1981). Composite 30 kPa geopotential height maps are derived from the National Center for Environmental Prediction reanalysis data set. These data are used to show gross jet stream variations between periods of high and low moisture deficit across the Northeast. The same data set is used for the calculation of the Summer Synoptic Drought Index (SSDI) defined later in this paper.

The climate division data are utilized to calculate complete water budgets for each climate division for the period of record (1895 through 1996). For this research, growing season moisture deficit values are obtained by accumulating monthly moisture deficit values for the entire growing season, defined as the period May through September. Note that the water budget variables are calculated for all months, and that the months May through September are subsequently used to obtain an accumulated growing season value. Therefore, any shortfall of soil moisture that occurs before the start of the growing season is accounted for in this analysis. Although the accumulation procedure effectively 'masks' month-to-month variability in deficit values, the object of this investigation is the study of complete growing season deficit variability. The resulting accumulated moisture deficit value provides an excellent estimate of the relative moisture deficit of the soils during the growing season from one year to the next.

To determine if distinct regions of moisture deficit are found within the northeastern United States, a principal components analysis (PCA) of growing season moisture deficit values is performed. The unrotated PCA utilizes a 54-climate-division by 102-growing-season data matrix. Five major modes of variability, accounting for 77% of the variation in the data matrix, are isolated by the PCA. The number of principal components retained for analysis is based on an inspection of the scree slope (Cattell 1966). The component loadings for each climate division are obtained by calculating the correlation between each division and the individual components identified in the PCA. It is assumed that grid-points in close geographic proximity would have similar component loadings. Thus, Ward's and average-linkage clustering procedures are used to aggregate grid-points with similar component loadings into coherent geographical regions (Kalkstein et al. 1987). A 3-cluster solution is chosen that minimizes within-group variation, while maximizing the variation between groups. The 3-cluster solution is identical for both methodologies, suggesting that the regionalization solution is robust, and not dependent upon the clustering method that is utilized. In addition, the number of principal components retained for the clustering procedure is varied between 4 and 6 to test for any sensitivity in the results due to the number of components retained from the PCA (Fovell & Fovell 1993). No appreciable differences are found in the final 3-cluster solution when the number of input components was varied over this range. These 3 regions are discussed in detail in subsequent sections.

3. RESULTS

Accumulated growing season moisture deficit values are calculated for each climate division for each season during the period 1895 through 1996. Since each cli-

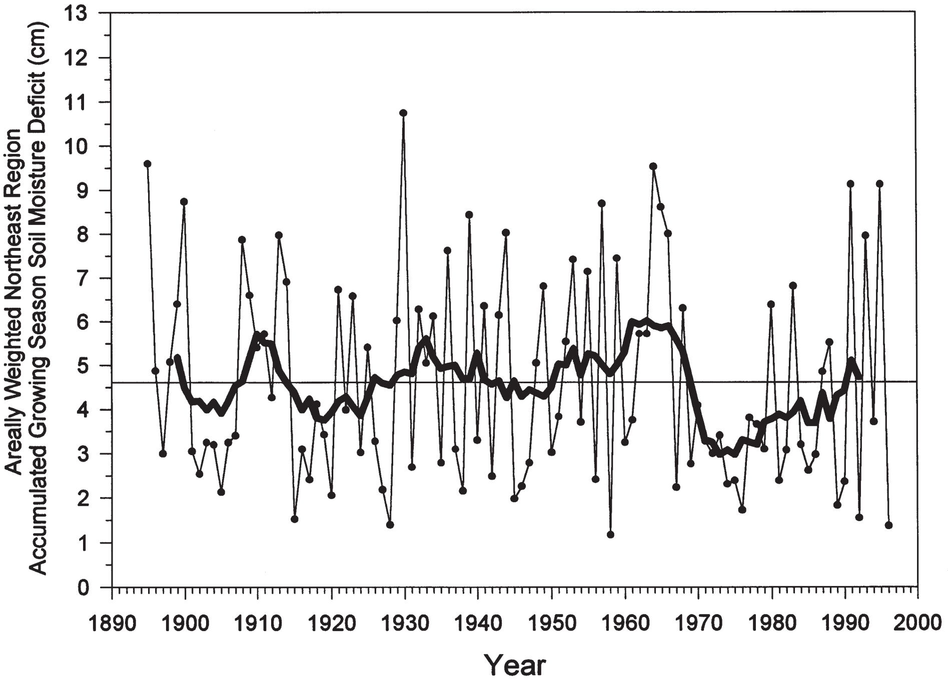


Fig. 2. Areally weighted Northeast region accumulated growing season moisture deficit for the period 1895 through 1996. Heavy line: 10 yr running mean smoothing of data; horizontal line: mean value for period

mate division differs in size, the 54 values for each season are areally weighted and then averaged to produce a time series of regional moisture deficit values for the period of record (Fig. 2). The heavy line in the figure represents a 10 yr moving average of moisture deficit values.

The time series indicates that no long-term trends in growing season moisture deficit values are apparent over the last century, at least when the entire region is combined as a whole. Instead, decadal-scale variations in moisture deficit are found throughout the record. Particularly dry conditions (large moisture deficit values) are found during the early 1910s and again during the 1960s. A very wet period (low moisture deficit values) is found near the end of the record from approximately 1970 through the early 1990s. In addition, the interannual variability is quite large during the 1990s. Thus, the region currently seems to be in transition away from a period of anomalous soil moisture abundance that has been prevalent for the last 2 decades.

The spatial distribution of growing season moisture deficit values, averaged for the period 1895 through 1996, is shown in Fig. 3a. Note that the mid-points of the climate divisions are utilized for the purpose of producing the spatial representations of deficit in the following figures. Although this methodology may produce imprecise maps of deficit in areas where the climate divisions are large, in the northeastern United States the vast majority of climate divisions are small, reducing any biases. The largest values are found along the coastal areas from Massachusetts south through Maryland and Delaware. Here, accumulated deficit values each season are between 5.0 and 6.5 cm. A corridor of similarly large values is also apparent from the Chesapeake Bay, northward to Lake Ontario. Values decrease to less than 4.0 cm across the majority of northern New York, Vermont, New Hampshire and Maine. Average values are also smaller west of the Appalachian Mountains across southwestern New York, western Pennsylvania and West Virginia (5.0 cm or less). As an example of the large interannual variability across this region, the spatial distribution of accumulated moisture deficit values are mapped for the seasons with the largest (extreme dryness; 1930) and smallest (extreme wetness; 1958) accumulated moisture deficit values (Fig. 3b,c).

During the regionally driest growing season of 1930, the southern portion of the Northeast was extremely dry, with deficit values exceeding 22.0 cm across portions of Maryland and Pennsylvania (Fig. 3b). However, during this same season, deficit values across

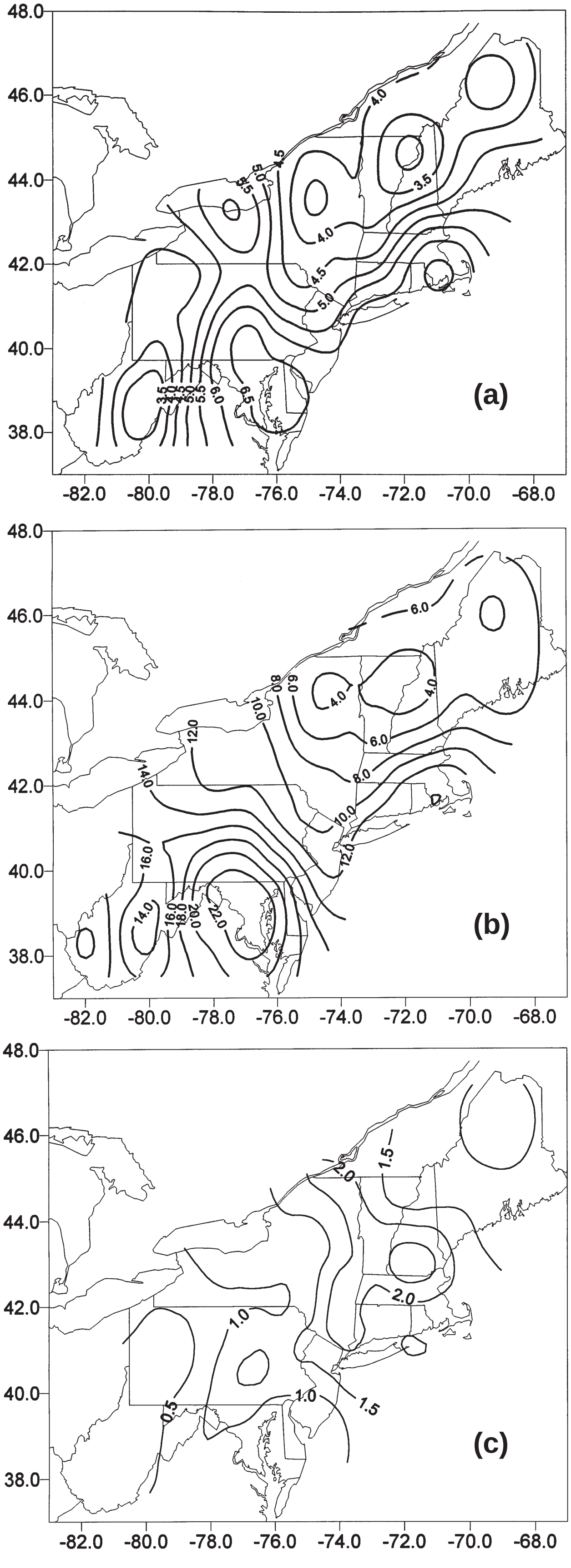


Fig. 3. Accumulated growing season moisture deficit (a) average for all seasons, 1895 through 1996, (b) for 1930 and (c) for 1958

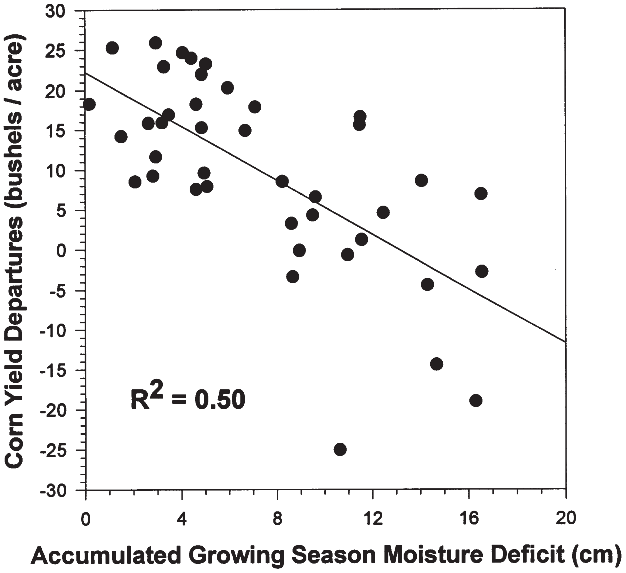


Fig. 4. Scatterplot showing the relationship between Pennsylvania corn yield and Pennsylvania growing season moisture deficit for the period 1955 through 1996

northeastern New York, Vermont and New Hampshire were as low as 4.0 cm, showing the large intra-regional variability possible within a given season. Accumulated growing season moisture deficit values were very small across the entire region during the wettest year of 1958, with little intra-regional variability (Fig. 3c). It is important to note the large differences in moisture deficit values between 1930 and 1958 and the effects that the moisture regime of these seasons would likely have had on natural and human systems such as agriculture and water resources.

As an example of the importance of moisture deficit to agricultural concerns in the region, Fig. 4 shows the relationship between growing season moisture deficit values and corn yield across the state of Pennsylvania for the period 1955 through 1996. Corn yield values are given as departures from a linear trend line fit to the corn yield data. Inspection of Fig. 4 indicates that growing season moisture deficit values are strongly related to corn yields across the state ($R^2 = 0.50$). This strong relationship is especially impressive given the large area covered by the state, and the likelihood of substantial intra-state variability in moisture conditions. Similar moisture deficit/crop yield relationships are found for diverse crops throughout the northeastern region.

3.1. Regionalization

The regionalization procedure, discussed above, was applied to the data, resulting in the delineation of 3 distinct, coherent regions of growing season moisture deficit variation (Fig. 5). Region 1 lies along the coastal plain and piedmont from southern New England, south through New Jersey, Delaware and Maryland. It also encompasses areas of higher terrain such as the Pocono Mountains of Pennsylvania and the Catskill Mountains of New York. Region 2 is contained mainly across northern New England and northeastern New York, while Region 3 covers western New York, western Pennsylvania and West Virginia, generally within or to the west of the Appalachian Mountain chain.

Time series of areally weighted growing season moisture deficit values for the diverse regions are given in Fig. 6. A heavy line represents the 10 yr moving average of moisture deficit values, showing decadal-scale variations in moisture availability across the northeastern United States. Fig. 6 indicates important distinctions in the temporal variation of available moisture. Region 1 shows consistent decadal-scale moisture deficit values over the period of record (Fig. 6a). Similar to the Northeast as a whole, dry growing seasons were common during the early 1910s and again in the 1960s, while anomalous moist periods are apparent from the late 1910s through the 1920s and again from the 1970s through the early 1980s. Interannual variability is quite large as it is across the region as a whole.

Region 2 is characterized by 3 periods of moisture deficit values over the period of record (Fig. 6b). From 1895 through 1930, moisture deficit values were generally below the long-term mean (wetter than average), except for a brief period centered around 1910.

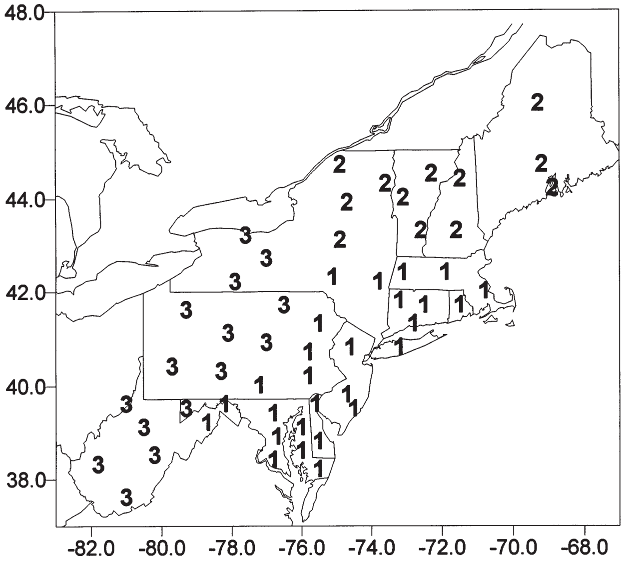


Fig. 5. Regions identified by the combined principal components and cluster analyses

Table 1. Deficit, precipitation and temperature departures associated with seasons +1.0 standard deviation above the 102 yr mean deficit. Standardized departures are given in parentheses. Values are reported for the entire Northeast and each region

	Northeast	Region 1	Region 2	Region 3
Deficit (cm)	3.87 (1.65)	5.38 (1.59)	2.72 (1.52)	5.63 (1.81)
Precipitation (cm)	–8.44 (–1.28)	–11.09 (–1.25)	–7.80 (–1.13)	–10.96 (–1.38)
Temperature (°C)	+0.54 (+0.87)	+0.42 (+0.70)	+0.44 (0.72)	+0.81 (1.01)
No. of seasons	18	20	20	14

After 1930, a dry period was predominant across this region, reaching a peak at about 1950 and continuing until approximately 1970. Since that time, the region has returned to a more moist state, but not as moist as the early portion of the record. Again, no long-term trends are evident over the century.

Region 3 clearly displays a downward trend in growing season moisture deficit values over the period of record (an increase in soil moisture; Fig. 6c). Superimposed upon this long-term trend are decadal variations that indicate a drying of the region centered around 1910, in the 1930s and in the early 1960s. During the 1970s and early 1980s the region experienced a string of moist years that had been unprecedented in the previous century. A return to dryer conditions occurs near the end of the record.

3.2. Relationships between temperature, precipitation and soil moisture

To document the nature of precipitation and temperature anomalies during severe moisture deficit growing seasons, all seasons with moisture deficit departures greater than or equal to +1.0 standard deviation, during the period 1895 through 1996, are used in a compositing analysis. Table 1 shows the precipitation and temperature anomalies (based upon the 102 yr mean) for the Northeast as a whole and for each region previously identified. For the entire Northeast, deficit values are nearly 4 cm greater than normal during the driest seasons. During these same years, precipitation is more than 8 cm below the mean and seasonal temperatures are slightly elevated (+0.54°C). A regional analysis indicates that Region 1 has a large moisture deficit anomaly (+5.38 cm) and the largest precipitation deficit (–11.09 cm) but the smallest temperature anomaly (+0.42°C) of any of the 3 regions during severe moisture deficit seasons. Soil moisture anomalies are relatively small, as are precipitation anomalies during severely dry periods across Region 2; and temperature anomalies are again less than 0.5°C above the long-term mean. Region 3 temperature anomalies are nearly twice that of the other regions during severely dry periods (0.81°C). This region also has large precipitation departures (–10.96 cm) during the driest years. Thus, across the entire Northeast, and for each region separately, seasons with intense moisture deficits are associated with large precipitation deficits. Only small temperature anomalies (that would lead to an increase in evapotranspiration) are found during the intense moisture deficit seasons.

Table 2. Explained variance (R^2) between precipitation, temperature and deficit calculated for the period 1895 through 1996. Deficit/precipitation and deficit/temperature R^2 values are significant at the 95% level

	Deficit/ precipitation	Deficit/ temperature	Temperature/ precipitation
Northeast	0.72	0.27	0.05
Region 1	0.69	0.19	0.02
Region 2	0.63	0.21	0.03
Region 3	0.70	0.39	0.13

The relative importance of precipitation and temperature to growing season moisture deficit values is quantified by using linear regression techniques. Table 2 shows the explained variance values (R^2) calculated by regressing moisture deficit values against precipitation and temperature for the entire northeastern United States and for each region for the complete period of record. Results indicate that deficit values are most strongly associated with precipitation anomalies for the entire Northeast and for each region. Much weaker relationships are found between deficit values and temperature anomalies (Table 2). It is interesting to note that Region 3 has by far the strongest connection to temperature of any of the 3 regions. Thus, severe moisture deficit values are more closely tied to temperature and hence evapotranspiration in this region of the Northeast when compared with the other regions. Temperature and precipitation are poorly related to one another across each region, indicating that the explained variances they contribute to the moisture deficit variability are nearly independent of one another.

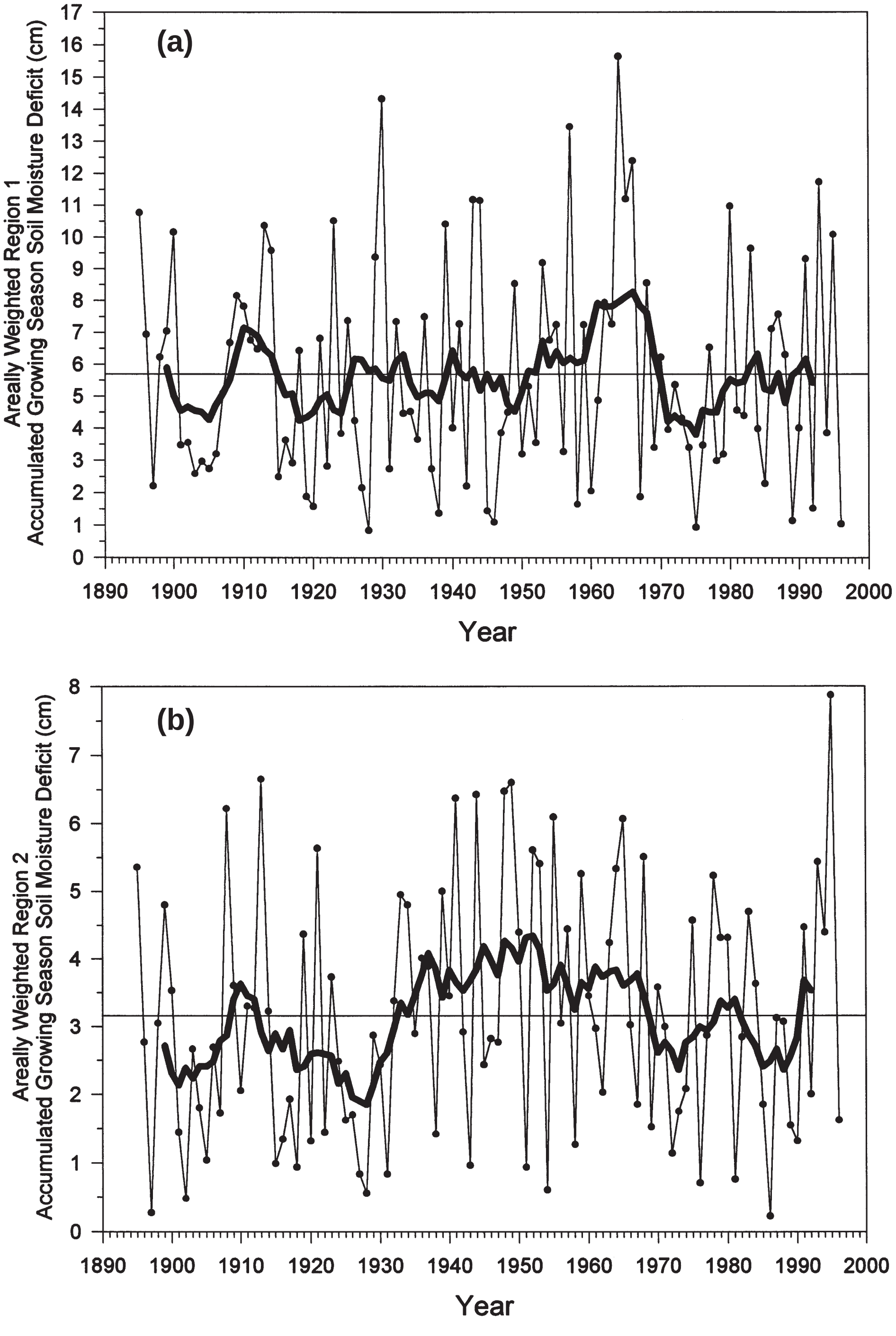
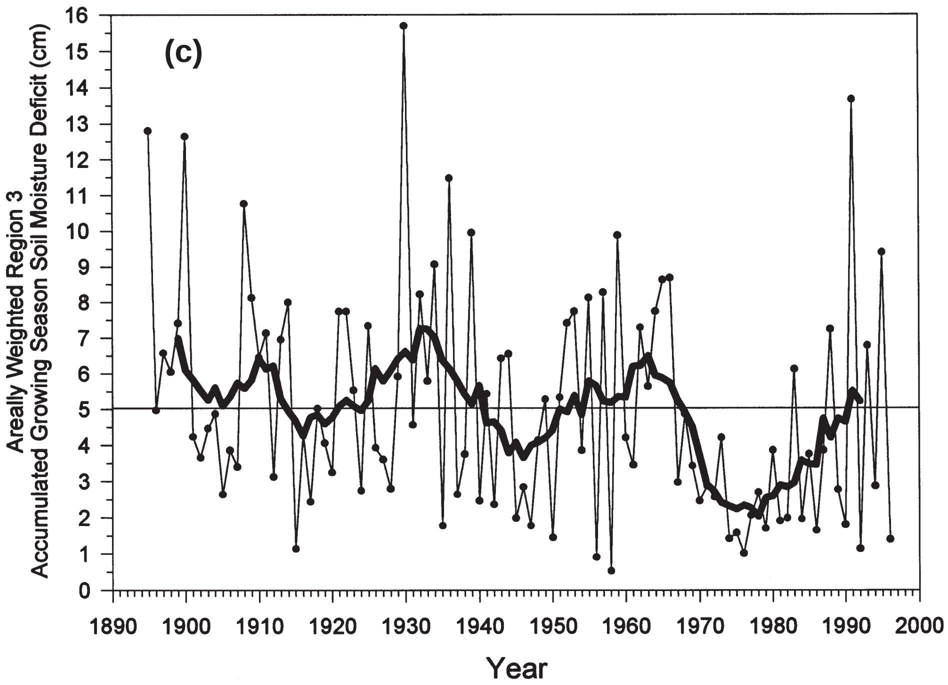


Fig. 6. (Above and facing page.) Areally weighted accumulated growing season moisture deficit (cm) for (a) Region 1, (b) Region 2, and (c) Region 3. Heavy line: 10 yr running mean smoothing of data; horizontal line: mean value for period

3.3. Precipitation frequency and intensity

Daily precipitation data are collected for 2 stations within each soil moisture region to ascertain the association of precipitation frequency and precipitation intensity with severe moisture deficit. The stations are chosen to represent as diverse geographic areas of the individual regions as possible. Mean precipitation frequency and intensity are calculated for each region for the 5 driest seasons during the period 1950 through 1995 and for the remaining 41 seasons. The 5 driest seasons were chosen because they represent



the driest 10% of the distribution during this time period. Precipitation frequency is defined as the total number of days during the seasons with measurable precipitation. Precipitation intensity is calculated by summing the precipitation total for each precipitation day during the growing season and dividing by the number of days with precipitation. Thus, precipitation intensity is a daily intensity measure. To ascertain whether the difference in means is statistically significant, the Student's *t*-test is utilized. In Region 1, Hartford, CT, has a statistically significant difference in means between dry years and others for both precipitation frequency and intensity (Table 3). During dry seasons, there are less days on which precipitation occurs and less precipitation each day. The situation is the same for Wilmington, DE, except that the intensity difference is not statistically significant. Similarly, Region 3 is characterized by relatively large decreases in precipitation frequency and intensity during severe moisture deficit seasons as evidenced by data from Bradford, PA, and Morgantown, WV (Table 3). In each case, precipitation frequency and intensity are significantly lower during seasons with large moisture deficit values. In Region 2, there is little change in the precipitation frequency at either Bangor, ME, or Messena, NY, during dry seasons when compared to the means of the other 41 seasons. Although intensity changes are relatively large, neither site is characterized by statistically significant differences between the 5 driest years and all others.

Table 3. Precipitation frequency, intensity and explained variance (R^2) between deficit and seasonal precipitation frequency and precipitation intensity. *Difference in means between extremely dry seasons and other seasons is significant at the 95% confidence level using a Student's *t*-test

	Frequency (d)		Intensity (cm d^{-1})		R^2	
	Dry	Other	Dry	Other	Frequency	Intensity
Region 1						
Hartford, CT	45.0	53.0*	0.71	0.97*	0.36	0.12
Wilmington, DE	40.0	48.0*	0.91	1.04	0.43	0.13
Region 2						
Bangor, ME	55.0	54.0	0.61	0.81	0.15	0.18
Messena, NY	64.0	61.0	0.73	0.89	0.35	0.02
Region 3						
Bradford, PA	52.0	62.0*	0.66	0.91*	0.38	0.27
Morgantown, WV	47.0	57.0*	0.66	0.88*	0.54	0.14

Using linear regression analysis, growing season moisture deficit values are regressed against seasonal precipitation frequency and intensity. The analysis indicates that the precipitation frequency explains more variation in moisture deficit than precipitation intensity at all stations except for Bangor, ME (Table 3). In fact, in most cases the amount of variation explained by frequency is more than twice the amount explained by the intensity. It is also important to note that precipitation frequency and intensity are very weakly associated with each other at all stations.

Taken as a whole, this analysis indicates that severe growing season moisture deficits in the northeastern United States are associated with both a decrease in precipitation frequency and a decrease in the daily intensity of precipitation. However, the decrease in the number of days with precipitation appears to be the major forcing mechanism for dryer than normal conditions.

3.4. Thunderstorm frequency and duration

Since the majority of precipitation that falls during the growing season is a result of convective activity (Throp & Scott 1982), it is hypothesized that severe growing season moisture deficits may be associated with the number and duration of convective events as represented by thunderstorms. To test this hypothesis, the thunderstorm beginning and ending time data set is utilized (TD-9945; Changery 1981, Changnon 1988a,b). The thunderstorm beginning and ending time data set lists all thunderstorms and their beginning and ending times for 17 stations across the Northeast for the period 1948 through 1977 (shown as thunderstorm symbols in Fig. 1). The average number of thunderstorm events and the average thunderstorm duration are calculated for the 5 driest and wettest growing seasons during the period 1948 through 1977. The 5 driest and wettest seasons are chosen so as to maximize any signal present in the thunderstorm data. Changnon (1988a) cautions users of this data set that audibility, the actual ability to hear the thunder from a distant storm, changes depending upon the geographic location. In this study, temporal periods from consistent geographic regions are compared so that the audibility problem should not be a major source of error.

For the Northeast as a whole, Table 4 shows that, on average, 3 less thunderstorms occur at each station during dry seasons compared to wet seasons. However, there is less than a 1 min difference in duration between thunderstorms during the 5 wettest and driest seasons. On a regional basis, only Region 1 shows a strong relationship between thunderstorm frequency and soil moisture conditions. In Region 1, dry seasons are characterized by approximately 9 less thunderstorm events per season than wet years. Once again, thunderstorm duration is similar between the wettest and driest seasons. This relationship is reversed in Region 2. Across northern New England, dry seasons average 11 more thunderstorm events per season when compared to wet seasons. Although this relationship merits further investigation, it may be an artifact of the small sample size available for thunderstorm data across this region (only 3 stations available for this area). It may also indicate that the total growing season precipitation across Region 3 is less dependent upon variations in convective activity and more dependent upon the placement of storm tracks, especially in the early and late portions of the growing season. Dry seasons average 3 less thunderstorm events in Region 3, while thunderstorms are 4 min shorter, when compared to wet seasons.

Table 4. Thunderstorm frequency and duration for the 5 largest (driest) and smallest (wettest) deficit growing seasons during the period in which thunderstorm data were available (1948 through 1977)

	5 dry seasons	5 wet seasons
Northeast		
No. of events	47.4	50.4
Duration (min)	47.9	47.8
Region 1		
No. of events	38.7	47.3
Duration (min)	47.9	49.3
Region 2		
No. of events	42.5	31.0
Duration (min)	48.7	46.4
Region 3		
No. of events	62.7	65.9
Duration (min)	44.9	48.7

Thus, the analysis indicates that there is a general reduction of thunderstorm frequency in the Northeast during dry seasons, especially across the coastal sections of the region, where the reduction is as great as 17%. However, across the northern portions of the region an increase of thunderstorm frequency is noted during dry seasons, a relationship that needs further investigation. No strong relationships between thunderstorm duration and soil moisture are apparent in any region or for the Northeast as a whole.

3.5. Large-scale atmospheric patterns associated with moisture deficits

Although much of the rainfall that occurs across the northeastern United States is a result of mesoscale convective events, it is still likely that large-scale atmos-

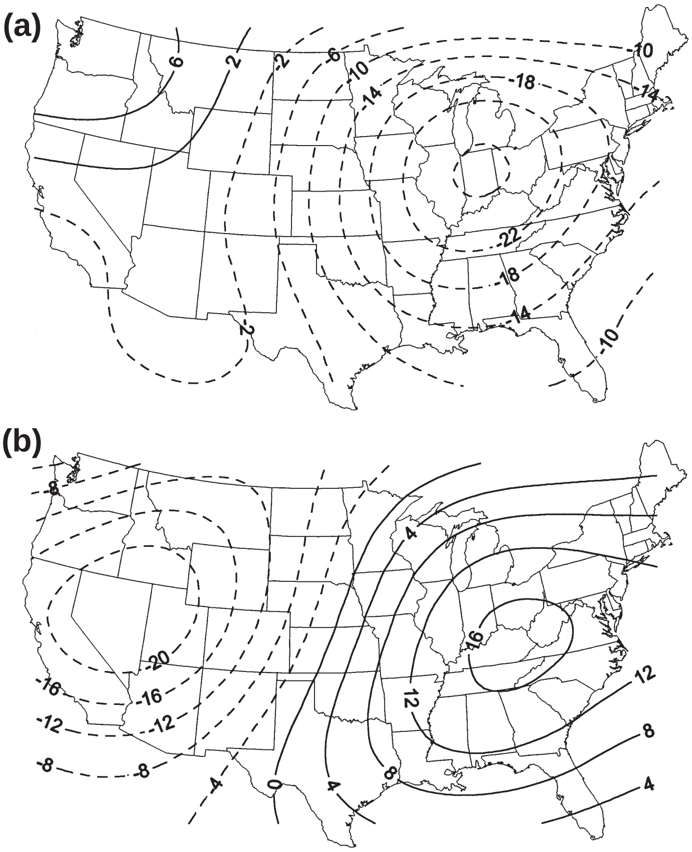


Fig. 7. 30 kPa geopotential height anomalies for (a) the 5 wettest growing seasons and (b) the 5 driest growing seasons during the period 1960 through 1996

pheric circulation patterns play a role in the maintenance of the driest and wettest growing seasons. To evaluate this hypothesis, the 5 seasons with the largest (driest) and the 5 with the smallest (wettest) growing season moisture deficit values are used to produce composites of the jet stream level atmospheric circulation for each extreme. National Center for Environmental Prediction (NCEP) re-analysis data for the period 1960 through 1996 is used in the compositing analysis.

Fig. 7a shows the 30 kPa geopotential height anomalies present during the 5 smallest moisture deficit growing seasons (the wettest seasons) during the period. The composite indicates the presence of enhanced ridging of the jet stream across the western United States and substantial troughing in the eastern one-third of the country. The anomalous troughing places the Northeast in the area of the ascending branch of the upper-level flow (in an anomaly sense), a preferred region for precipitation. During large moisture deficit seasons (dry seasons) the pattern is reversed, with an anomalous trough in the western United States and ridging in the east (Fig. 7b). The eastern ridge keeps the Northeast under the descending branch of the jet stream (in an anomaly sense), a region that is not conducive for the formation of precipitation.

The NCEP data are also used to derive a circulation index based upon 30 kPa geopotential height anomalies found in the western (42° N, 118° W) and the eastern (42° N, 80° W) portions of the United States. The Summer Synoptic Drought Index (SSDI) is calculated by taking the difference between the eastern United States and western United States geopotential height anomalies. A large positive index value is associated with anomalous ridging in the east and troughing in the west, while a large negative index value results from the opposite pattern (troughing in the east, ridging in the west). SSDI values are regressed against moisture deficit values for the region for the period 1960 through 1996. Fig. 8 is a scatterplot showing the relationship between regional moisture deficit values and the SSDI. A strong relationship exists between the simple synoptic index and moisture deficits across the region ($R^2 = 0.30$). However, a group of ‘outlier’ seasons dramatically decreases the strength of the relationship. If the 1966, 1975, 1978, 1986 and 1989 seasons are removed from the analysis, the explained variance value (R^2) increases to 0.63. The reason for the anomalous character of these years is currently under study.

4. DISCUSSION AND CONCLUSIONS

The availability of soil moisture to both cultivated and naturally occurring plant life is of great importance in the northeastern United States. Changes in soil moisture characteristics could greatly impact both agricultural and economic concerns across the region. In this study, growing season moisture deficit values were calculated for the period 1895 through 1996 using the technique developed by Thornthwaite & Mather (1955). This technique allows for the calculation of long time series of soil moisture parameters because of the limited data inputs needed for the soil moisture model (only monthly temperature and precipitation are needed). This analysis yielded several major finds including:

(1) For the Northeast as a whole, growing season moisture deficit values have shown no consistent long-term trend. However, the entire region has been subject to decadal-scale variations in soil moisture between very dry and moist periods, the most pronounced was an anomalous moist period that extended from the late 1960s through the 1980s.

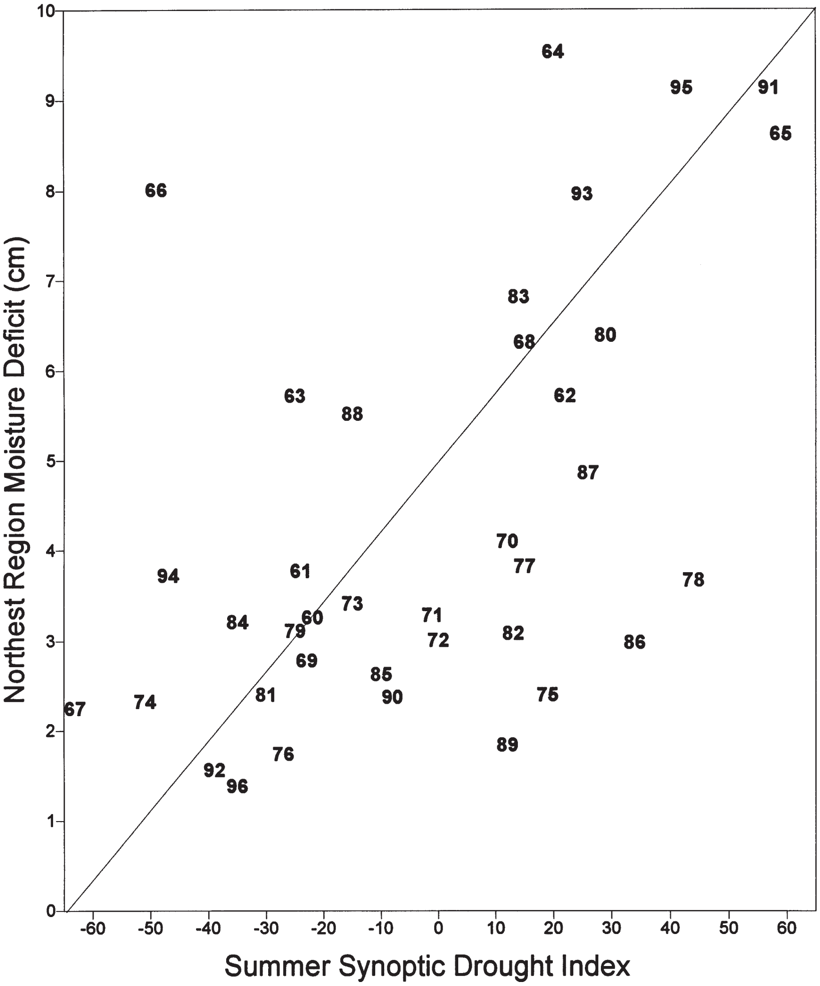


Fig. 8. Scatterplot showing the relationship between northeastern United States growing season moisture deficit and the Summer Synoptic Drought Index for the period 1960 through 1996. Numbers indicate the year of the observation

(2) A regionalization of the growing season moisture deficit values indicates the existence of 3 distinct regions of soil moisture variation across the Northeast. These include a region that extends along the Atlantic Coast from the tidewater area north to the coast of Massachusetts and inland to the higher terrain of the Pocono, Catskill and Berkshire Mountains (Region 1). A second homogeneous region includes most of northern New England and northeastern New York (Region 2), while a third includes southwestern New York, western Pennsylvania and West Virginia (Region 3). All 3 regions evidence very different time series of moisture deficit, with large decadal-scale variations found in each record. A strong trend toward more moist conditions during the growing season is apparent in Region 3.

(3) Severe moisture deficit seasons are more strongly associated with negative precipitation anomalies than with positive temperature anomalies (increased values of evapotranspiration) across the Northeast. The negative precipitation anomalies are associated with a decrease in both precipitation frequency and intensity across Regions 1 and 3; this decrease occurs in conjunction with a decrease in the number of thunderstorm events in these areas. Very dry seasons across Region 2 show no strong association with precipitation frequency, intensity or thunderstorm events.

(4) Growing seasons with large moisture deficit values (dry seasons) are associated with anomalous troughing of the jet stream circulation in the western United States and eastern ridging of the jet. Wet seasons (small moisture deficits) are associated with the opposite pattern, anomalous ridging in the western United States and troughing in the east. A simple synoptic index, the Summer Synoptic Drought Index, is able to explain substantial amounts of the variation of seasonal moisture deficits during the period 1960 through 1996.

A pilot investigation done in connection with this work indicates that the frequency of tropical disturbances in the North Atlantic Basin has no strong association with growing season deficit values across the

Northeast. Although this topic needs more thorough investigation, it is likely that the relatively low frequency of tropical events in this area and the fact that such events typically occur only in the last one-third of the growing season limit the influence of such disturbances on deficit values.

Studies such as this investigation provide valuable 'baseline' information to planners and climatologists interested in potential changes in soil moisture variability associated with human-induced and natural climatic variations. Before an assessment of the potential impacts of climate change can be complete, it is important to understand the long-term relationships between various portions of the climate system and soil moisture. In future studies we plan to investigate the processes involved in severe soil moisture droughts by using detailed case studies with more complete meteorological, agricultural, societal and forestry data. Moreover, recent work by the authors indicates that the meteorological character of soil moisture drought may be changing over time in the Northeast to a more temperature-dependent regime. This possibility will also be investigated in future work.

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