Contemporary Trends in Drought on the North American Continent

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1. Introduction

The Intergovernmental Panel on Climate Change Third Assessment Report concluded that human activities have had a discernible influence on the earth's climate during the latter half of the 20th century (IPCC, 2001). Among the body of observational evidence used in reaching this conclusion was an increase in global surface temperatures, increases in precipitation over mid- and high-latitude land surfaces, decreasing snow cover extent, retreating glaciers and sea ice, and rising sea levels. There were fewer indications of increases in the frequency or severity of extreme events, but changes including increases in heat waves, severe storms, heavy precipitation events and drought have been found in some parts of the world. Conclusions regarding the variability and change in most extremes, including drought, were less conclusive than those for changes in mean conditions due to a limited number of analytical studies and, in many cases, a lack of sufficient climate data.

Data sufficient for the analysis of drought in North America are more plentiful than in many other regions of the world, and studies have provided valuable information on the changes in drought that occurred during the 20th century. However, additional analyses are now necessary for reaching more definitive conclusions regarding all aspects of changes in the occurrence and severity of drought. By combining existing analyses with new studies, it will be possible to obtain a clearer picture of the effect that associated changes in climate, such as temperature and precipitation, may have had on the incidence and severity of drought. Because climate data are, in many cases, more readily available in North America than in other regions of the world, studies of conditions during the period of instrumental record on this continent may best help enhance the scientific understanding of drought and its relationship to changes in other climate variables.

Drought can be defined in general terms as a "prolonged absence or marked deficiency of precipitation", a "deficiency of precipitation that results in water shortage for some activity or for some group," or a "period of abnormally dry weather sufficiently prolonged for the lack of precipitation to cause a serious hydrological imbalance" (Heim, 2002). While these definitions make it clear that insufficient precipitation is a prerequisite of drought, an increase in precipitation may not necessarily result in fewer droughts or reduced drought severity. In fact, it is possible that the severity or incidence of drought could increase even while precipitation amounts are increasing. Possible scenarios include shifts in precipitation frequency that result in longer periods between precipitation events and succeeding heavier events that result in more runoff with less soil moisture recharge. Some global climate models indicate that increases in temperature can lead to increases in evapotranspiration that amplify naturally occurring episodic dry periods and droughts. Although precipitation may increase in the form of heavier short-lived events, the severity and expanse of droughts may worsen, particularly during the summer season, as warming temperatures and increased evapotranspiration deplete surface and subsurface moisture. Possible impacts include more frequent shifts between wet and dry periods, short-lived but more extreme wet and dry periods, and trends toward more severe drought in areas of the continent that were at one time less susceptible to drought.

Using results from existing studies and analyses of recently developed datasets, we investigate the likelihood that changes in temperature and precipitation that occurred during the 20th century were sufficient to affect the frequency and severity of drought throughout North America. While precipitation generally increased during the 20th century across much of the continent, it was also a period of rapidly increasing temperatures, especially during the latter few

decades. From the mid-1970s through the end of the century, mean annual temperature in the United States, Canada and Mexico increased at rates equal to or greater than 0.3° C/decade. Minimum daily temperatures increased at a faster rate than maximum temperatures, and mean annual temperature increased throughout all regions of the continent.

2. Background

The effect of increasing temperature on water demand is incorporated in the water budget accounting procedures of the Palmer Drought Severity Index (Palmer, 1965) and its derivatives. These indices, along with the Keetch-Byram Drought Index (KBDI) and in situ daily and monthly temperature and precipitation data, are used to assess the trends and variability in drought severity and frequency in North America during the period of greatest instrumental record. The KBDI, unlike the Palmer indices, is calculated on a daily basis.

The severity and extent of drought in the United States were greatest during the Dust Bowl years of the 1930s. Because of the size and severity of the episodic events of that decade, succeeding droughts have typically been compared to conditions in those years, particulary conditions during 1934 and 1936. The decades of the 1950s and 1960s were also characterized by several episodes of widespread severe drought (Karl and Heim, 1990; Dai et al., 1998).

The succeeding decades of the 1970s and 1980s as a whole were unusually wet. Precipitation throughout much of the period was above average across much of the United States. However, severe drought episodes affecting large parts of the country occurred in each of those decades. As recently as the late 1990s and succeeding years, more than one-third of the contiguous United States was in severe to extreme drought. Drought conditions persisted over the South and parts of the East through much of 1998-2002, and drought that began in the West in 1998 has persisted in many areas through the summer of 2003.

Devastating droughts also periodically affected Canada and Mexico during the 20th century. Major droughts occurred on the agricultural prairies of Canada during the 1930s, 1960s, 1980s, and during the first several years of the 21st century. In the 2001-2002 agricultural year, over 65% of the prairie cropland in Canada was affected by moderate, severe, or record drought conditions, according to Agriculture and Agri-food Canada. In Mexico, a prolonged period of drier than normal conditions led to debates about shared water rights on both sides of the Rio Grande (Lawrimore et al., 2002).

3. Observed Trends

Precipitation and drought index time series produced on a quarterly basis for our analysis provide insights into differences in seasonal precipitation and drought. During the latter half of the 20th century, winter precipitation increased in much of the southern tier of the United States, Mexico, much of Alaska and most strongly in northern areas of Canada. In spring, precipitation increased in most areas of the continent. Widespread exceptions include the southeastern and northern plains states of the United States, much of Ontario and Manitoba, and parts of southern Mexico. Summer precipitation trends were more evenly distributed, but increases remained dominant. Trends in the fall were strongly positive throughout much of the eastern two-thirds of the United States. Precipitation also increased throughout large parts of Canada and Alaska, while trends toward drier fall conditions occurred in the extreme western United States, some

areas of southern and western Canada, and much of the southern two-thirds of Mexico. Similar trends in Canada were found by Zhang et al. (2000).

Trends in short-term drought in large part parallel precipitation trends during all seasons. For instance, in winter, trends in the Palmer Z Index indicate increasing severity in the northeastern and northwestern regions of the United States and areas of the western half of Canada, where precipitation decreased. Elsewhere, drought severity generally decreased, consistent with increasing precipitation. Trends during spring were similar to those observed in winter in many areas, but exceptions include the southeastern US, where the trend was toward increasing drought severity and the northeastern US, where the opposite trend occurred. There were fewer clear regional signals during summer, but during fall, strong decreasing trends in drought severity were present in much of the eastern two-thirds of the United States and the eastern half of Canada.

Trends in areal coverage of severe to extreme meteorological drought within each of nine climate regions in the United States were also studied using simple linear regression for the period 1950-2002 (based on the Palmer Drought Severity Index). A trend toward increasing areal expanse of severe to extreme drought in the northern Plains and far western areas of the United States was in contrast to a decrease in the area affected by drought in the southern and eastern half of the country. As shown in Figure 1h, the percent of the Pacific Northwest affected by severe to extreme drought was markedly higher during the last two to three decades of the century than in the preceding 20 years. Severe to extreme drought covered more than 75% of the region during the droughts of 1976-77, 1987-88, 1992, and 2001. Smaller increases occurred in two regions, the West and the West North Central (Figures 1i and 1e, respectively), but trends for all three regions were significant at the 0.05 level, based on the student's t-statistic. Seasonal trends in severe to extreme drought coverage were also positive in these regions.

The droughts of the 1950s and 1960s in the southern and eastern United States were followed by two unusually wet decades, and severe to extreme drought generally occurred in only short episodic events until the late 20th and early 21st century. Although the trend in the Southeast region was near zero (Figure 1d), trends in the remaining five regions indicated a decreasing areal expanse of drought. The largest negative trend was in the Southern region, due in large part to the severe and long-lasting droughts of the 1950s. From 1960 through 2002, there was no statistically significant trend in the areal expanse of drought in this region.

The decreases in the areal extent of drought in regions where precipitation trends were positive indicate that factors such as increases in temperature and evapotranspiration were not large enough to dramatically offset the effects of increases in precipitation. However, severe and extreme episodic droughts occurred in all regions throughout the period of record, even in regions and during decades that were unusually wet. Although trends in the areal extent of drought were positive in only a few regions of the US, the naturally occurring episodic droughts in all regions of the US were possibly made more severe by the recent period of rapidly increasing temperatures.

During the last 25 years of the 20th century, global temperatures increased at an unprecedented rate, approximately three times faster than the century-scale trend of 0.6° C/century years. Annually averaged temperatures increased in all regions of the US, and the increase for the contiguous US as a whole was 0.3° C/decade during that period. Potentially faster rates of evapotranspiration resulting from this increase in baseline surface temperatures could have produced droughts that were more widespread than those that would have occurred if temperatures had not risen. To determine what effect the temperature increases of the past

quarter of a century had on drought severity and extent, monthly divisional temperature data was linearly detrended during the period 1976 – 2002 while monthly precipitation totals were left unchanged. The Palmer Modified Drought Index (PMDI) was then calculated and the area of each region in severe to extreme drought determined for each month throughout the period of record. The resulting values of areal extent were compared with Palmer model results using actual monthly temperatures in order to study the impacts of higher mean temperatures. When detrended, mean temperatures during the summer months of the late 1990s were more than 1.0° C cooler than the actual observed temperatures in some regions, while detrended winter temperatures were as much as 6.0° C cooler.

The effects of the temperature increases of the past 25 years were clearly evident in the resulting analyses. As shown in table 1, model calculations made using detrended temperatures showed a considerable decrease in the percent of each region affected by severe to extreme drought during the period 1998 through 2002. The comparison was performed by averaging the areal coverage across those months in which at least 25% of each region was affected by severe to extreme drought (in the base run). The average areal coverage was then calculated for those same months using results from the Palmer simulation with detrended temperatures. The average areal coverage across the contiguous United States for those months in which at least one-quarter of the country was affected by severe to extreme drought dropped from an average of 28% to 20%.

Droughts in regions of the western United States appear to have been most affected by increasing temperatures. For example, the percent area dropped from 57% to 39% in the Northwest region, while it decreased from 59% to 38% in the Southwest. The average areal extent was also lower in central and eastern regions of the country when detrended temperatures were used. In the Southeast region the average areal extent dropped from 35% to 23%. No change in average areal extent occurred in the West North Central region. This was likely due to relatively small increases in summer and fall temperatures (0.1° and 0.2° C/decade, respectively), and a decreasing trend in spring temperature (-0.3° C/decade) during the 1976-2002 period. Severe to extreme drought was not widespread in the East North Central region between 1998 and 2003 and did not affect at least 25% of the region in any month during those years.

While these results suggest that increasing temperatures have contributed to wider episodic droughts, it is also possible that the observed increases in both temperature and precipitation have increased the likelihood that oscillations between periods of extreme wetness and severe to extreme drought could occur with increasing frequency. To investigate the possibility that this type of trend has already begun to occur, the frequency of short-term extremes was analyzed using the Palmer Z Index. The number of months throughout the year having a Z value greater than 2 or less than -2 (severe to extreme wetness or drought, respectively) were summed within each region of the United States during the period 1950-1974 and likewise from 1975-1999.

Increases in the frequency of occurrence of both wet and dry months from the first to the second half of the 50-year period provide indications that both wet and dry extremes may be increasing in some regions of the United States. There was a 54% increase in the number of severely dry months and a 36% increase in severely wet months in the Southeast. A similar increase of both dry and wet months occurred in the western US as well. The increase in the number of severely dry/severely wet months was 56%/27% in the Northwest region and 104%/20% in the West region. The other six regions of the contiguous US had increases in the

number of severely wet months and either a decrease or no change in the number of severely dry months.

The Keetch-Byram Drought Index (KBDI), an index designed as a measure of meteorological conditions conducive to forest fire development (Keetch and Byram, 1968), was also used to study the change in dryness during the latter half of the 20th century over high latitude regions of the continent. Although factors in addition to soil moisture influence the occurrence and behavior of forest fires, experience has established the close association of difficult fire suppression with cumulative dryness, or drought. The index makes use of daily temperature and precipitation data, and it varies from 0 (no forest fire danger) to 800 (extreme danger).

Indications of increasing summer dryness were found in central Alaska and western Canada. The frequency of summer days with KBDI above 200 and 400 has increased during the past 50 years by 22% and 70%, respectively. In Canada north of 55°N and west of 95°W, the frequency of summer days with KBDI above the non-zero 99th percentile increased two to three-fold in the past 50 years, and the frequency of spring days increased four-fold (Figure 2). Given the lack of widespread decreases in precipitation in these regions during the past 50 years, the increasing dryness is likely due at least in part to the increasing temperatures that have occurred over the same period. Spring and summer mean temperatures in Canada north of 55°N and west of 95°W have risen at a rate near 0.3° C/decade since 1950. Temperatures in central Alaska increased at a rate of 0.2° C/decade in the summer and 0.3° C/decade in the spring.

4. Summary

Our analysis indicates a strong correspondence between trends in precipitation and trends in drought severity and areal expanse during the latter half of the 20th century in North America. Modeled results indicate that the increase in temperature observed during the recent past has worsened the severity of episodic droughts in the United States. However, observational evidence does not suggest that the warming of the 20th century was dramatic enough to completely offset the beneficial effects of increasing trends in precipitation. Drought severity largely decreased in areas of the continent that had increasing precipitation trends while it increased in areas, such as the Pacific Northwest, where precipitation trends were negative. There are indications of increasing frequency in both wet and dry extremes in some regions of the United States, but wider evidence of this was not identified. An increase in spring and summer dryness was found in high latitude regions of the continent.

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Table 1. Average percent of the contiguous United States and each of nine climate regions affected by severe to extreme drought for the months in which the areal extent was at least 25% during the period 1998-2002. (Values are based on computations using the Palmer Modified Drought Index.) Averages were calculated for those same months in the model run containing detrended temperatures. Values in row one were calculated using actual monthly mean temperatures throughout the period of record and values in the second row are based on monthly mean temperatures detrended during the period 1976-2002. Row three contains the number of months when at least 25% of the region was affected by severe to extreme drought from 1998 to 2002 in the base run calculations.

	US	CEN	ENC	NE	NW	SE	SO	SW	WE	WNC
Average % - Model run using Actual Temperature	33	40	-9	42	57	35	36	59	47	38
Average % - Model run using Detrended Temperature	25	29	-9	32	39	23	21	38	34	38
# of months with at least 25% of region in sev/ext drought	10	5	0	6	25	16	10	18	26	28

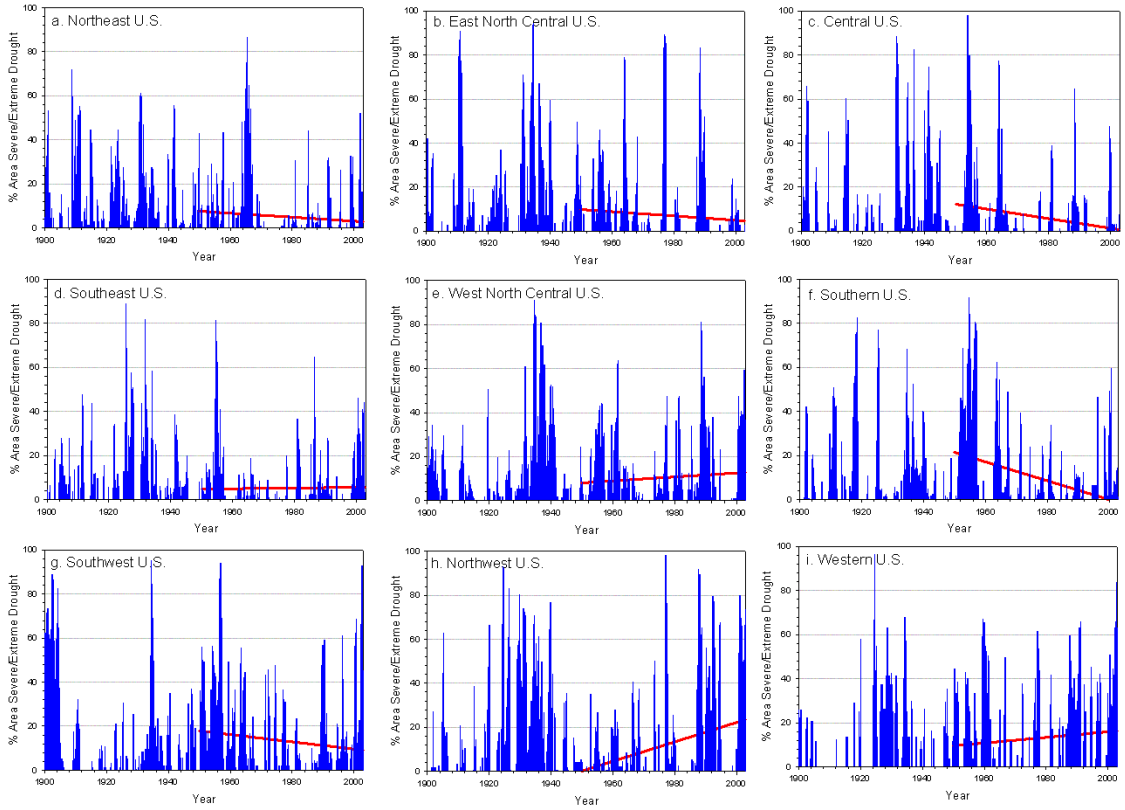
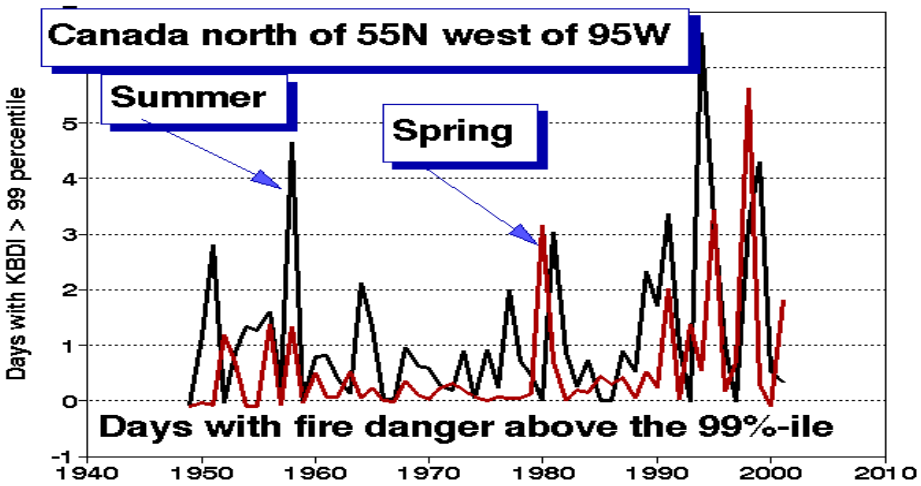


Figure 1. Percent of regional area in severe to extreme drought (based on the Palmer Modified Drought Index) in each month from 1900 through 2002. The linear trend is shown for the period 1950 through 2002 for each of the nine US climate regions; a) Northeast, b) East North Central, c) Central, d) Southeast, e) West North Central, f) Southern, g) Southwest, h) Northwest, i) West.



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