8.13 A CLIMATOLOGICAL ASSESSMENT OF MAJOR 20TH CENTURY DROUGHT IN SOUTHERN ONTARIO, CANADA

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1. INTRODUCTION

Drought conditions experienced over southern Ontario from mid-1997 through 1999 heightened concerns with many municipalities and provincial conservation authorities over the future of regional water resources. The issue was of particular significance to the Grand River Basin in southern Ontario which supplies water to a population of over 800,000. Water management authorities questioned if the ongoing drought conditions were more serious than those experienced in southern Ontario during the 1930s and early 1960s. This drought study was subsequently undertaken to address these concerns. The results of the study provide an assessment of the severity of the drought of the late 1990s relative to other significant 20th century regional droughts. The study also examines the possible connections of climate variability cycles to droughts in southern Ontario. This paper presents a summary of the results from the complete drought study report (Klaassen, 2000).

2. DEFINING DROUGHT

The term drought has always been difficult to define. Although there is no one universal definition of drought, the one aspect that is common to all definitions is the lack of moisture. Three basic types of drought can be defined, which may occur either separately or simultaneously. ***Meteorological drought*** is defined in terms of a significant precipitation departure from normal over a prolonged period. ***Agricultural droughts*** link the characteristics of meteorological droughts to the impacts on livestock and crop growth. Meteorological and agricultural droughts are normally of a shorter duration than ***hydrological drought***, which occurs when the effects of precipitation deficiencies have a serious impact on regional water resources. As a longer period of time is required before these effects are observed, a hydrological drought also normally lags the occurrence of meteorological and agricultural droughts.

This study was concerned with those years in the 1930s, 1960s and late 1990s that were identified by the Grand River Conservation Authority as having had serious impacts on the water resources of the Grand River Basin.

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3. OVERVIEW OF THE 1930S, 1960S and 1990S DROUGHTS

The term “Dirty Thirties” is often used to describe the widespread drought conditions that afflicted large areas of the United States and Canada during the 1930s. Southern Ontario was one of the regions that was hard hit by the dry 1930s. Although the majority of the years during the decade observed drought conditions, 1933, 1934 and 1936 were considered to be the most devastating for agricultural crop losses. This was particularly true in 1936 when the deadliest heat wave in southern Ontario’s history was recorded. Mid-July temperatures soared to the 40ºC mark in several locations, setting maximum temperature records that remain unbroken through 2001. It was reported that more than 550 deaths were directly attributed to the heat. Agricultural production was reduced by 25 percent as crops wilted and fruit literally baked on the trees in the Niagara Peninsula.

Although of a shorter duration, drought experienced in the 1960s in southern Ontario also seriously impacted water resources. This was especially true in 1963 and 1964. When wells in farming communities dried up, tank cars and trucks were used to supplement water supply for human and livestock use. Crops suffered, with soybean and corn production drastically cut. In the spring and autumn, 1964, Great Lakes water levels fell to extreme lows. The economic impact from this alone was estimated to exceed $100 million, with the majority of the losses sustained by the shipping industry.

Above-normal temperatures made weather headlines over southern Ontario during 1998 and 1999. These warm temperatures were part of a national, as well as global, warming trend, where the 1990s was the warmest decade and 1998 the warmest year since reliable instrumental records commenced in 1861. In contrast to the above-normal temperatures, however, precipitation over southern Ontario was well-below normal in 1998 and 1999. The consequences of these temperature and precipitation trends had a tremendous impact on southern Ontario water resources. By the end of 1999, water levels in all of the Great Lakes had fallen below the 80-year average. By the summer of 1999, groundwater levels in the Grand River Basin had dropped to their lowest values since at least the 1930s.

4. THE DROUGHT ANALYSES

One of the purposes of this study was to assess the relative severity of the late 1990s drought in comparison to other significant 20th century droughts over southern Ontario. Thus, several methods were used to compare the 1997-1999 moisture conditions over southern Ontario to historical moisture conditions over the region in the past century. Daily climate data for stations within, and just outside, the Grand River Basin boundaries was used in the analyses. Seasonal and annual precipitation and temperature departures from normal were computed at each of these stations. Similarly, calculations of the cumulative precipitation index (CPI) were made and a water budget model was run for each analysis station over the years that included the drought periods.

Finally, a separate analysis was performed for major 20th century El Niño/La Niña and North Atlantic Oscillation years to determine if a link could be established between these major atmospheric-oceanic circulations and significant drought years.

4.1 DATA SOURCES/ANALYSIS STATIONS

The climate data used in the drought analyses was extracted from Environment Canada's National Climate Data Archive. It included all available daily mean, maximum and minimum temperature, precipitation, rain and snow data for stations within, and just outside, the Grand River Basin boundaries for the period September, 1909 to August, 1999. However, due to the length of record being analysed, more than one station often had to represent the analysed site, or supplement missing data from the main analysis station. Short term data gaps were also filled by subjectively assessing information from nearby supplementary climate stations. A map showing the location of the main climate stations that were used in the data analyses is given in Figure 1. From these stations, 9 analysis stations were identified.

With the exception of the water budget model results, all analysis years that are referred to in this paper are for the hydrological year September to August. For example, the year 1998 refers to September, 1997 to August, 1998 inclusive. The water budget model runs on a standard "January-December" year.

4.2 CLIMATIC DEPARTURES FROM NORMAL

Annual and seasonal temperature and precipitation departures from 1961-1990 normal were calculated for nine analysis stations for the hydrological drought years. The years included in this analysis and in the remainder of the study are: 1930-1939, 1961-1966 and 1997-1999.

A sample graphic of annual precipitation and mean temperature departure from normal at Brantford during the analysis years is provided in Figure 2.

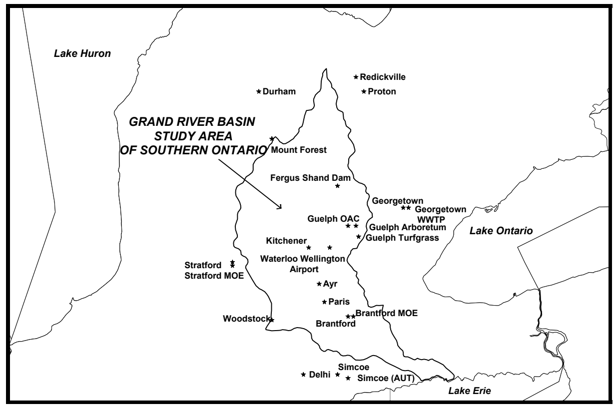

Figure 1. Location of main climate stations used in the drought analyses. The stations are near and within the Grand River Basin in southern Ontario.

From this analysis, it was determined that it is difficult to find specific and consistent seasonal predictors for significant drought years. Although drought years are normally characterized by below-normal annual precipitation, seasonal precipitation may be significantly above normal. For example, 1964 summer precipitation was above normal in the basin, while some stations reported record or near-record winter snowfalls in the early 1930s. Although annual mean temperatures are usually above normal during a significant drought year, below-normal values also occur. For example, cooler-than-normal annual mean temperatures were reported at all stations during the serious drought year 1963, with the majority of stations also reporting below-normal temperatures during each of the individual seasons. Numerous occurrences of major one-day rainfall events (i.e. exceeding 40 mm) were found in the station records during the significant drought years. However, the bulk of this precipitation would likely be lost as runoff, especially if the rainfall was observed over a relatively short period, and thus would do little to alleviate the ongoing drought conditions.

4.3 CUMULATIVE PRECIPITATION INDEX CALCULATIONS

Drought indicators are one means that are commonly used to quantify or rank drought conditions. The Palmer meteorological and hydrological drought indices are two of the best known and widely used indices that are routinely calculated in the United States and in parts of Canada. The cumulative precipitation index (CPI) is another index, which is simple and reliable, and requires only the input of precipitation data. It is often calculated on a regular basis for use by water supply managers and it was the index chosen for this study. Under non-drought conditions, the CPI compares an 8-week accumulation of daily precipitation values with normal totals for the same period. The resulting ratio is expressed as a percentage. If the percentage is 60 percent or greater, the CPI calculations continue, with the first week dropped from the calculations and a

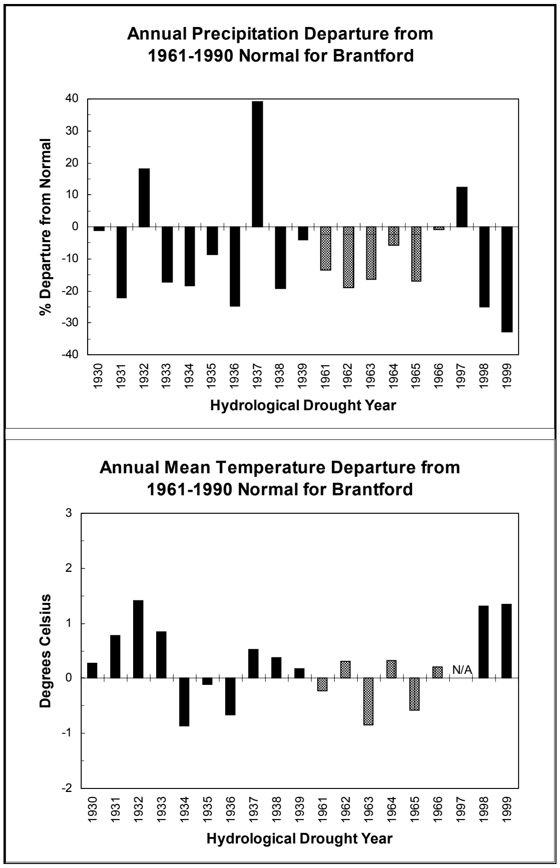

Figure 2. Annual precipitation and mean temperature departures from 1961-19990 normal at Brantford during analysis years of the 1930s, 1960s and 1990s.

new week added. If it is below 60 percent, the original period is not removed from the calculations and the computations continue until the 60 percent threshold is once again exceeded or drought conditions are considered to be ending. The Ontario Ministry of Natural Resources uses a modified version of the CPI as a precipitation indicator for low water conditions, calculating weekly, monthly, 3-monthly and 18-monthly precipitation departures from normal in determining Level 1, 2 or 3 drought/low water level advisory conditions for the province of Ontario.

Cumulative precipitation computations were performed for nine analysis stations for the significant hydrological drought years during the 1930s, 1960s and late 1990s. The weekly station normals were calculated using all available data during the station analysis years. Periods of a minimum of 17 weeks for which the CPI values were at or below 60 percent (drought warning level) were tabulated. All of the prolonged drought periods spanned part or entire summer seasons, and occurred primarily during the early years of the 1930s, 1998 and 1999. Cumulative precipitation calculations for Brantford are displayed graphically in Figure 3 for several drought years during the 1930s, 1960s and late 1990s.

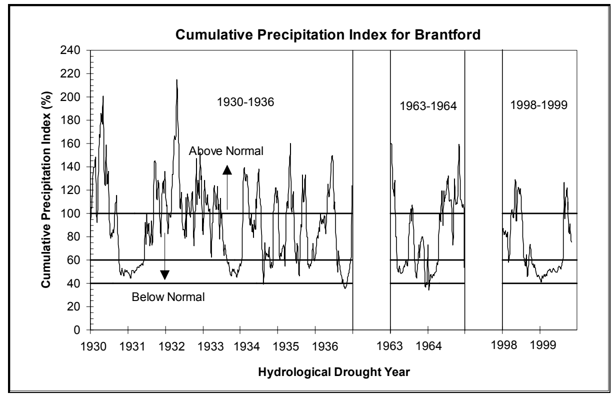

Figure 3. Cumulative Precipitation Index computations for Brantford for significant 20th century hydrological drought years.

4.4 WATER BUDGET CALCULATIONS

Water budget model results were also used to help simulate the moisture conditions over southern Ontario during the significant 20th century hydrological drought years. The water budget procedure used in the calculations is a modified Thornthwaite and Mather (1955) approach, with an additional snowmelt model added. The model, which has been used by the Canadian Climate Centre, is described by Johnstone and Louie (1984). The meteorological input data to the model consists of daily values of mean temperature and total precipitation. The only additional input parameters required are station latitude, as well as an estimate of the station's soil water holding capacity.

For each model year run, the monthly components of the water budget are output, based on the accumulated daily computations during the period. The monthly water budget components include:

- temperature
- precipitation
- rain*
- snow*
- snow melt
- potential evapotranspiration
- actual evapotranspiration
- moisture surplus
- moisture deficit
- soil moisture storage

As missing data is more frequent prior to 1920, the water budget model in this study was run for all available years from 1920-1999. In particular, annual station water budgets were produced for each of the significant

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* Total monthly rainfall (snowfall) is computed from the daily rainfall (snowfall) values. The daily precipitation is considered to be rain (snow) if the mean daily temperature is above -1°C (less than or equal to -1°C).

drought years. The results were subjectively compared to MacIver and Whitewood's (1992) long-term station water budget normals that were calculated from the same water budget model using all available data for the period 1968-1988. Based on the water budget results, serious drought conditions were determined to have occurred at the stations in 1930, 1933, 1934, 1936, 1963, 1998 and 1999. In general, the highest annual station water deficits were observed in 1998, with those from 1930, 1933, 1934 and 1936 closely rivaling these values. Figure 4 graphically displays Stratford's annual station water deficits for the period of record from 1916-1999, illustrating that the highest model water deficits occurred during 1998.

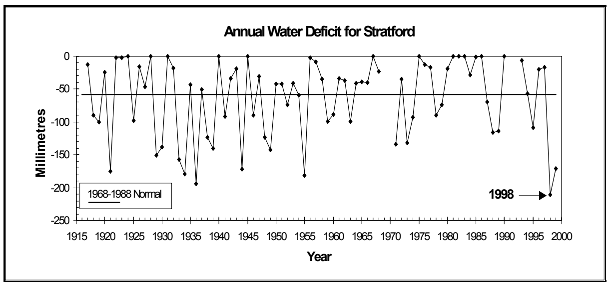

Figure 4. Annual water deficit values for Stratford in the 20th century, as computed from the water budget model used in the study.

4.5 El Niño/La Niña and Drought

Scientists studying El Niños and La Niñas have linked these climate variability cycles to various global severe weather events, especially in the Tropics. El Niños, for example, have been linked to the occurrence of severe drought conditions in Australia, Africa and Indonesia, while drought is often experienced during La Niña years over the mid-western United States.

Given the importance of the potential link between El Niño/La Niña and drought, an analysis of the southern Ontario hydrological drought period temperature and precipitation records was undertaken for significant ENSO years for the period 1910-1999. Strong to moderate ENSO events during this period were identified and are listed in Table 1. Events prior to 1950 were based on the Southern Oscillation Index (SOI) remaining in the lower 25 percent (El Niño) or upper 25 percent (La Niña) of the distribution for five months or longer (Shabbar et al., 1996; Rasmusson, 1984; Ropelewski and Jones, 1987). ENSO events since the start of 1950 were compiled using a classification that is based on tropical Pacific sea surface temperatures and provided on the National Oceanic and Atmospheric Administration (NOAA) website: *http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.html* .

Seven hydrological drought years are identified from the table; four are classified as El Niño events

El Niño Years	La Niña Years
1911 - 1912	1916 - 1917
1914 - 1915	1924 - 1925
1918 - 1919	1928 - 1929
1923 -1924	**1938 - 1939**
1925 - 1926	1950 - 1951
1930 - 1931	1954 - 1955
1932 - 1933	1955 - 1956
1939 - 1940	**1964 - 1965**
1941 - 1942	1970 - 1971
1951 - 1952	1973 - 1974
1953 - 1954	1975 - 1976
1957 - 1958	1988 - 1989
1965 - 1966	1995 - 1996
1969 - 1970	**1998 - 1999**
1972 - 1973	
1976 - 1977	
1982 - 1983	
1986 - 1987	
1991 - 1992	
1994 - 1995	
1997 - 1998	

Table 1. Years of onset of strong or moderate El Niño and La Niña events from 1910-1999. Corresponding hydrological drought years in southern Ontario are in bold print.

while the remaining three are listed as major La Niña events.The information in Table 1 would suggest that there is no clear connection between ENSO and hydrological drought years in southern Ontario. However, it does not rule out that a link could exist between ENSO events and below-normal annual and/or seasonal precipitation, or above-normal annual and/or seasonal mean temperatures. To investigate this possibility, an annual and seasonal analysis of precipitation and mean temperature data was performed for the nine analysis stations for the period 1910-1999. The analysis was repeated on data for only the 1970-1999 period, as ENSO events have become stronger and more frequent since the 1970s. Averages of the climate data were calculated for each station for all years during the respective analysis periods and these values were considered to be the "normal" for this analysis. Calculations of departure from normal were made for the major El Niño and La Niña years, as listed in Table 1, as well as for the remaining "neutral" years, or years that were classified as non-major ENSO events. Extreme events, such as droughts, are concerned with the amount by which the precipitation and temperature actually deviate from annual and seasonal normals. Therefore, an additional distribution analysis was performed on the data. Precipitation was classified into twenty-three categories: ranging from 100 percent below normal to 100 percent above normal at 10 percent intervals, with an additional above-normal category for values equaling or exceeding 110 percent. The zero-percent distribution included precipitation less than 10 percent from the period normal. Similarly, mean temperatures were placed into eleven classes, from 5°C below normal to 5°C above normal. The zero-degree distribution included mean temperature departures less than 1°C from the period normal.

Several interesting observations were made from the ENSO analyses. At all stations, it was determined that El Niño winters have been warmer than normal for the 1910-1999 analysis period, as well as the recent 1970-1999 period. Since 1970, El Niño winters have been drier, as well as warmer, than normal. El Niño summers since 1970 have been warmer than normal. The distribution analyses revealed that since 1970, La Niña years are more likely to represent the extreme below-normal values of the annual precipitation distributions, while El Niño and neutral years dominate the extreme above-normal values. Depending on the season, the distribution of seasonal precipitation extremes varies between El Niño, La Niña and non-ENSO years. However, since 1970, if annual precipitation departs from normal by more than 10 percent, it is most likely to be below normal, i.e. a "drier" year. As the majority of the ENSO results are seasonal, no definitive statement can be made on how an El Niño/La Niña event would impact on an entire drought year.

4.6 North Atlantic Oscillation and Drought

The North Atlantic Oscillation or NAO is another important climate teleconnection pattern. Strong positive values of the NAO index have, for example, been linked to lower-than-normal precipitation across southern and central Europe. Could there be a link to drought in southern Ontario?

As for ENSO years, an analysis of hydrological drought period temperature and precipitation records was undertaken for significant NAO years within the periods 1910-1999 and 1970-1999. Years that exhibited winters (December-March) with higher (+) and lower-than-normal (–) NAO index were identified and are listed in Table 2. For years up to 1984, the NAO classifications of Rogers (1984) were used. Significant NAO years after 1984 were determined from the NOAA website for teleconnection indices: *http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.html* .

Eleven hydrological drought years can be identified from the table; five are classified as +NAO index events while the remaining six are listed as having a –NAO index.

The information in Table 2 would suggest that there is no clear relationship between NAO and hydrological drought years in southern Ontario. However, it does not rule out that a link could exist between NAO events and below-normal annual and/or seasonal precipitation, or above-normal annual and/or seasonal mean temperatures. To investigate this possibility, the same annual and seasonal computational procedures that were used for the ENSO analyses (see section 4.5) were repeated for the NAO computations, with NAO

+ NAO Winter Index Years	**– NAO Winter Index Years**
1910	1912
1915 and 1916	1917 and 1918
1920	1926
1922 and 1923	1929
1925	**1932**
1928	**1936**
1930 and 1931	1940 and 1941
1934	**1947**
1937	1955 and 1956
1943 and 1944	1959 and 1960
1949	**1963 through 1966**
1952	1968 and 1969
1954	1977 through 1979
1957	1987
1961	1996
1973 through 1976	
1981	
1983 and 1984	
1988 through 1995	
1999	

Table 2. Years with winters of high NAO (+) and low NAO (–) indices from 1910-1999, where winter is defined as Dec-Mar and 1998, for example, is Dec 1998-Mar 1999. Corresponding hydrological drought years in southern Ontario are in bold print.

years classified as high (+), low (–) or neutral (non-trends were identified in the 1970-1999 data subset.The most important of these included the observation that winter precipitation has been below normal at the majority of these stations during low NAO index years since 1970, while summer mean temperatures have been above normal at all stations in recent high NAO index years. From the distribution analysis results, it was determined that winter precipitation has been more likely to be 10 percent or more below normal, rather than above normal, during low NAO index years since 1970. However, the findings could not be used to support a definitive link between the NAO and southern Ontario hydrological drought years.

5. CONCLUSIONS

Although drought is a recurring phenomenon in nature, not all droughts are of the same intensity and duration. In the 20th century, the droughts of the 1930s, 1960s and the late 1990s had a serious impact on water resources in southern Ontario.

From water budget model results and cumulative precipitation index calculations, this study concluded that 1998 drought conditions in the Grand River Basin had indeed rivalled those of even the driest years during the 1930s or 1960s. The most serious drought years were determined to be 1930, 1933, 1934, 1936, 1963, 1998 and 1999.

The analyses also determined that it is difficult to find specific and consistent seasonal predictors for significant drought years. Although summer temperatures were found to be usually warmer than normal, the remaining seasonal mean temperatures showed considerable variability both above and below normal. Although droughts are normally characterized by below-normal annual precipitation, seasonal precipitation can vary from significantly below to above normal. In addition, major one-day rainfall events have also been recorded during significant drought years.

The study also examined the possible links between climate variability cycles, such as ENSO and NAO, and the drought years of the 1930s, 1960s and 1990s. Although some interesting seasonal observations were made with the ENSO and NAO analyses, especially in the recent decades since 1970, no definitive statement could be made linking these atmospheric-oceanic circulations to significant drought years.

When the 20th century drought study was concluded in February, 2000, drought conditions were continuing over southern Ontario. The question of when the drought would end over the region was finally answered in May, 2000 when heavy rainfalls arrived in southern Ontario. The above-normal rainfall continued through the summer of 2000, and flooding, rather than drought, became a concern to municipalities, conservation authorities and farmers. Then during the summer of 2001, serious drought conditions abruptly returned to much of southern Ontario, as well as central and northeastern parts of the province. Ironically, the conditions of the summers from 1997-2001 have been analogous in many ways to those experienced during the 1930s, when a respite from several years of drought was experienced during the wet summer of 1937, but then serious drought conditions returned in 1938.

Climate change scenarios from Global Climate Models (GCMs) suggest that southern Ontario may experience more frequent and more intense droughts during the 21st century. Studies of past drought will hopefully provide climate researchers with a better understanding of drought and its impacts, as they continue to work towards finding reliable predictors to use in long-range drought forecasting.

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