NOTES AND CORRESPONDENCE

Comparison between the Droughts of the 1930s and the 1980s in the Southern Prairies of Canada

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ABSTRACT

The drought decades of the 1930s and 1980s in the southern prairies of Canada were compared using Palmer's drought severity index (PDSI). Nine of the 11 yr from 1929 to 1939 inclusive were drought years compared to 6 of 11 from 1979 to 1989. The longest runs were 4 yr for the 1930s and three for the 1980s. Although the territorial size under mild to extreme drought was 16% larger in the 1930s than in the 1980s, the area impacted by extreme drought was 10% more during the 1980s. In the 1930s, PDSI averaged −1.39 in dry years compared to −1.33 in the 1980s; the most severe drought (average PDSI −3.18) occurred in the 1980s. Recovery in the 1980s averaged 1.20 PDSI units yr^{-1} compared to 1.02 units in the 1930s. Spatially, the pattern of drought intensity was patchy in the 1930s but zoned in the 1980s. A southwest–northeast-running ''moist plume'' coupled with regular storm activity point to one possible cause of drought in the 1930s, namely, a southerly displacement of the Alberta storm track from its normal path, possibly passing through the chinook corridor. The absence of a plume and a diminished strength of west winds suggest that many of the droughts of the 1980s might have been linked to the numerous blocking highs observed during that decade.

1. Introduction

Drought is endemic to Canada's southern prairies. Almost every decade since records began in the seventeenth century has featured at least one drought year. Three decades, 1910–20, 1930–39, and 1980–89, however, stand out as dry because at least half their length was drought stricken. The earliest of these decades is not well documented largely because human impacts were limited due to sparse population. The later two are distinguished for different reasons. The 1930s were notorious for the ''dust bowl,'' the combination of heat, water deficits, and dust storms that wasted soil and agricultural resources and, in the process, threatened the survival of the southern prairies as a viable economic community. The 1980s drought coincided with increasing alarm over global warming. The combination of rising temperature and near-normal to deficient precipitation pressed home the concern being raised by environmentalists that we are on the threshold of a major change in climate (Hansen 1988). The motives for interest in the two drought decades may be different, but did drought features change significantly over the two decades? This paper compares the two droughts in terms of intensity, duration, spatial expression, and recovery patterns. Based on these comparisons, theories are advanced concerning possible causation during each decade. Climate, climate change, and variability will continue to feature prominently as environmental issues during the next several years. Because the past is often a good analog of the future, lessons learned from the two historical drought decades should provide useful insight into managing similar events in the future. For example, the large human and ecological costs of the droughts of the 1930s did not repeat during the 1980s because, some would argue, the lessons of the 1930s were used to advantage.

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2. Background

When the southern Canadian prairies were first explored during the 1850s, Captain John Palliser, the expedition's leader, was not optimistic about the settlement potential of the roughly triangular region that now bears his name (Fig. 1), due mainly to the drought that prevailed in that area during his visit (Nkemdirim 1991). Subsequent recovery from drought, political necessity, the building of a transcontinental railway, innovations in agriculture including development of new strains of wheat that thrive and mature in a short growing season, summer fallow, and improved markets for farm products

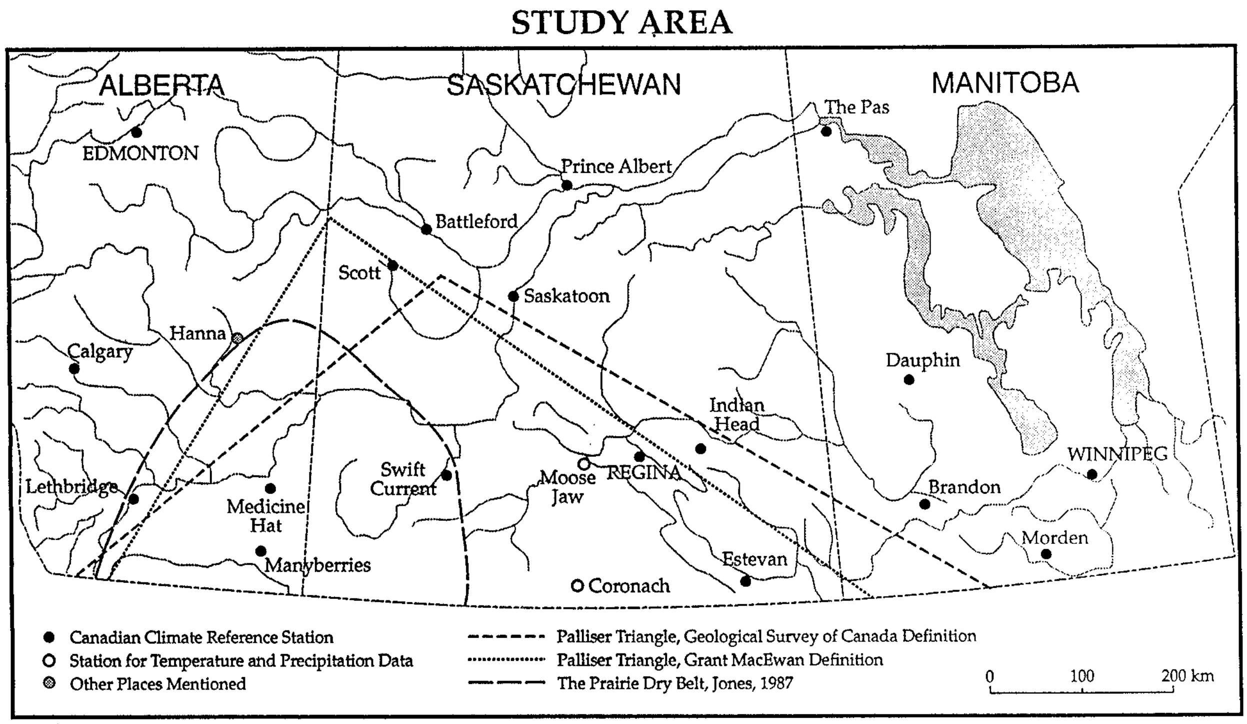

FIG. 1. The study area.

enabled communities to flourish in the region. The settlements were well tested by the return of drought, briefly in the 1920s and more rigorously in the 1930s.

Three successive crop failures in 1929, 1930, and 1931, with yields of 70–150 kg ha^{-1}, were attributed to lack of timely rainfall. The next two years both began with optimism and good crops but turned into economic disasters. In 1932, falling grain prices did not cover the cost of harvesting, and in 1933, great sun-blocking clouds of grasshoppers stripped the land of all growing things. The year 1934 was one of the driest on record to that point, and vast clouds of dust accompanied the continent-wide drought. In 1935 rust fungus decimated the wheat crop, and an outbreak of equine encephalitis, spread by mosquitoes that hatched during the moist spring, killed many of the remaining hunger-weakened working horses. Abundant spring moisture due to record snowfall in the winter of 1935/36 gave way to new drought and heat records in the summer of 1936 throughout the North American plains. The dry spring of 1937 introduced the driest summer yet in the southern Canadian prairies, and the combination of even more intense heat waves, dust storms, and grasshopper plagues left the region devoid of greenery (Gray 1967).

During the 1980s, particularly 1988, local newspapers throughout the prairies dealt extensively with disturbing "trends" in the region's climate. Farmers complained about drought conditions. Comparisons were made between the warm and dry weather of the 1980s and that of the 1930s. The distinguishing feature of the precipitation climate of the decade was the dry winters and springs. Average winter precipitation hovered between 30% and 35% below normal in many parts. In 1988, winter snowfall averaged 43% of normal; in 1989, 46%. In 1981, 1983, 1984, 1985, and 1986, it ranged from 73% to 68% of normal. Environment Canada (1998) reports a continuation of this drier winter trend, noting that 7 of the last 10 winters, and 15 of the last 20, received less than normal precipitation. As was the case in the 1930s, some of the drier summers, notably 1987 and 1988 (the 10th driest year of the century), featured heat waves. Partly on account of poor winter and spring precipitation, soil moisture levels measured well below field capacity leading into the summer. In 1988, for example, soil moisture at Calgary in May through August averaged 8% below field capacity. Sloughs and other types of wetland dried. Municipalities experienced historical peaks of water demand.

Several of the dry years of the 1980s coincided with exceptionally intense El Niño–Southern Oscillation (ENSO; Smit 1989). But unlike the 1930s, some crops were produced and although precipitation was deficient, the environmental, social, and economic disasters that marked the earlier decade were largely absent. Measures adopted during the 1980s to guard against wind erosion of the top soil, including new tillage techniques, stubble mulching, irrigation, and wind shelter belts, were factors that ensured that many of the socio-economic setbacks of the 1930s did not repeat. Crop insurance and government subsidies were helpful (see Jones 1987; Jones 1988).

Dey (1982) studied droughts on the Canadian prairies and noted a significant correlation between drought and strong anticyclonic patterns forced by midtropospheric ridging. Bonsal et al. (1993) linked the anomalous North Pacific sea surface temperature (SST) and corresponding midtropospheric anomalies to extended droughts in the same area. Guezen and Raddatz (1988a) studied the 1988 prairie drought, pointing to similarities between the event and those of the 1930s. Wheaton and Arthur (1989) also showed similarities between 1988 and 1936 in terms of dust storm frequency, anticyclonic activity, and possible northward displacement of the jet stream. Lang and Jones (1988) and Guezen and Raddatz (1988b) also compared the dry spells of the 1930s and 1980s. They found that while the droughts of 1987–88 were more widespread than those of 1937–38, the actual cumulative precipitation deficit did not suggest which drought was more intense. Lang and Jones (1988) hypothesized that the reason the 1930s were perceived as climatologically worse than the 1980s was due to unsuitable farming practices.

Although individual years or sequence of years within this century's two major drought decades have been studied, those works appear to have been limited to separately analyzing precipitation and temperature conditions; other components of the water balance, for example, atmospheric demand and soil moisture recharge, which are also factors in the droughts, have received little attention. Numerical experiments have simulated some of the feedbacks that intensified the droughts of the 1980s (Oglesby and Erickson 1989; Yeh et al. 1984), but to our knowledge those results have not been applied simultaneously to the 1930s and the 1980s to search out differences in drought patterns. In this paper, the objectives stated above are pursued through use of the Palmer drought severity index (PDSI) and various modifications proposed by Karl (1983), Alley (1984), and Karl and Knight (1985). In a subsequent paper, the energy feedbacks due to soil moisture change and dust loading and their roles as drought drives are examined.

a. Choice of a drought index

Subrahmanyan (1967) reviewed several definitions and indices used for quantifying droughts, many of them discipline or practice specific. These include precipitation droughts (Cole 1933), climatological droughts (Hoyt 1936), and agricultural droughts (van Bavel 1953). In general, precipitation droughts concern consecutive days of rainlessness; climatological droughts are defined by shortfalls in precipitation relative to a climatological normal; and agricultural drought definitions consider soil moisture and its adequacy for crop development. Landsberg (1960) argued that drought was biological rather than climatic and should therefore be defined separately for each plant species. However, to be both flexible while being useful, it is necessary to define a drought in such a manner that any index arising from that definition crosses discipline boundaries. Definition of a drought as a prolonged period in which water supply in inadequate to satisfy established uses (Linsley et al. 1975; Dracup et al. 1980) seems, at least at a conceptual level, to meet this need because it can include both supply (e.g., precipitation, runoff) and demand (e.g., soil moisture recharge, evapotranspiration) terms and, by implication, the difference between them. An index designed to measure the balance between supply and demand while crossing discipline boundaries should meet the following criteria.

- The sense of drought conveyed by the index converges at discipline boundaries.
- Drought severity as measured by the index reflects both magnitude and duration.
- The index enables comparisons of drought severity over time and space.
- Construction of the index includes a procedure for identifying the beginning and end of both a drought and a wet period.
- The index is capable of differentiating between aridity and drought, as well as between climatically driven normal dry seasons and drought seasons.

The Thornthwaite moisture index (Ogallo 1989), the Budyko–Lettau dryness ratio ''D'' (Hare 1977), the Priestley Taylor α (Hare 1977), and the crop moisture index (Jones 1988) are examples of drought indices that may be used on a monthly time frame to represent drought severity as lack of supply. The Bhalme Mooley Drought Index (BMD) (Olipado and Hare 1986) has a recursive term to take into account drought duration and persistence, and is normalized with respect to long-term precipitation variability. However, none of them satisfies all the conditions specified above.

The PDSI, developed by Palmer as a meteorological drought index (Palmer 1965), does meet the above expectations. While the index is meteorological in nature, its backbone is a thorough hydrological accounting. The calculations are made from numerous but simple equations, using as major inputs four easily obtainable site-specific data, namely, precipitation, precipitation normals, mean temperature, and available soil moisture capacity. A full treatment of the PDSI, including modifications by Alley (1984), is covered in Weber and Nkemdirim (1994, 1998). The 1994 paper includes software for computing the index and mapping its spatial patterns.

b. Construction of the index

The PSDI is determined through a detailed water budget accounting for a specific station for a specific time. To do this, the soil is divided into two layers, an upper and a lower layer. Twenty-five millimeters of water are stored in the upper layer. This water is lost at the po-

TABLE 1. Summary of water budget calculations.

Variable	Description (calculation)
j	As subscript, refers to month number, $j = 1$ *to* 12
i	As subscript, refers to year number, $i = 1$ *to* n
AWC_u	Available water capacity of the underlying layer, $AWC_u = AWC - 25$ mm
Prec	Precipitation in mm. Refers to total for the month
PE	Potential evapotranspiration, calculated from Thornthwaite's equation; *otherwise,* $S_u = MAX[(Prec\ PES_s)(S'_u/AWC, S'_u)]$
S_s	Amount of available moisture in the surface soil layer, $S_s = S'_s + S_s$
S_u	Amount of available moisture in the underlying soil layer, $S_u = S'_u + S_u$
PR	Potential recharge, the amount of moisture required to bring the soil to field capacity, $PR = AWC - (S'_s + S'_u)$
R	Recharge, the net gain in soil moisture during the month (positive or 0), $R = MAX\ (S_s = S_u, 0)$
PL	Potential loss of moisture, from both layers, $PL = MIN(PE, S'_S) + \{PE - [MIN(PE, S'_s)(S'_u/AWC)]\}$
L	Net loss of soil moisture during the month, $L = ABS[MIN(S_s + S_u, 0)]$
ET	Computed actual evapotranspiration for the month, $ET = MIN[PE, Prec + ABS\ (S_s) + ABS\ (S_u)]$
RO	Computed runoff, $RO = MAX(Prec\ PES_s\ S_u, 0)$
PRO	Potential runoff, PRO = AWC PR

tential evapotranspiration rate until depleted. Thereafter, water is removed from the lower layer at a decreasing rate dependent on the amount of moisture in storage. When recovery from drought starts, recharge begins with the upper soil layer until field capacity is attained. Thereafter, recharge of the lower layer begins. No runoff occurs until both layers reach field capacity.

The concept of drought is based on a comparison between the water balance of the target period and the water balance that would have been climatically appropriate for the conditions (CAFEC) of the time and place being examined. Through this comparison, the amount of precipitation necessary in a month to maintain "normal" evapotranspiration, runoff, and soil moisture storage considering antecedent moisture conditions is determined. This is the moisture anomaly index.

Palmer divided the index into four broad categories. He assigned a value of −1.0 as the boundary marking the start of mild drought, −2.0 separating mild and moderate drought, −3.0 separating moderate to severe drought, and −4.0 separating severe and extreme drought.

After reconciling for the effect of intense short period deficits as opposed to less intense but longer ones, Palmer obtained an expression for drought (and wetness) severity. This index ranges from greater than +4.0 (very much wetter than normal) to smaller than −4.0 (extreme drought) with values from +0.49 to −0.49 constituting a near-normal class.

The algorithm calculates Palmer's hydrological drought index (PHDI) in which the beginning and ending times of dry and wet spells are determined by hydrology. It computes the "true" meteorological drought

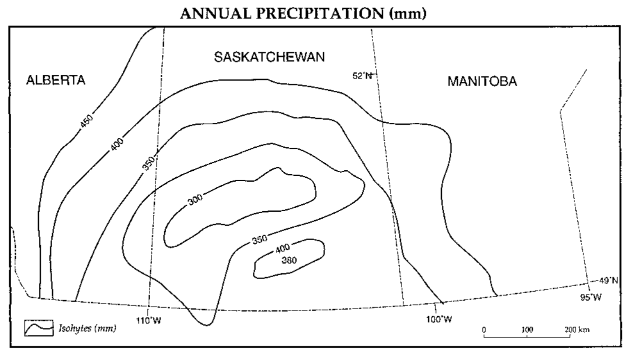

FIG. 2. Mean annual precipitation within the study area.

index (PDSI) through several subroutines sequenced to accommodate (i) the probability that a drought or wet spell has ended, (ii) the probability that a wet spell has begun, and (iii) the probability that a drought has begun.

Table 1 contains the key variables included in the compilation. The constants utilized are

$$\alpha_j = \overline{ET}_j/\overline{PE}_j \quad \text{if } \overline{PE}_j > 0,$$

$$\alpha_j = 1 \quad \text{otherwise},$$

$$\beta_j = \overline{R}_j/\overline{PR}_j \quad \text{if } \overline{PR}_j > 0,$$

$$\beta_j = 0 \quad \text{otherwise},$$

$$\gamma_j = \overline{RO}_j/\overline{PRO}_j \quad \text{if } \overline{PRO}_j > 0,$$

$$\gamma_j = 0 \quad \text{otherwise},$$

$$\sigma_j = \overline{L}_j/\overline{PL}_j \quad \text{if } \overline{PL}_j > 0,$$

$$\sigma_j = 0 \quad \text{otherwise}.$$

These constants are used to compute the quantities CAFEC precipitation $\acute{P}$,

$$\acute{P}_{i,j} = \alpha_j PE_{i,j} + \beta_j PR_{i,j} + \gamma_j PRO_{i,j} - \sigma_j PL_{i,j};$$

the moisture deficit for a specific site in year i and month j,

$$d_{i,j} = Prec_{i,j} - \acute{P}_{i,j};$$

the moisture anomaly index for the site in year i and month j by

$$Z_{i,j} = d_{i,j}k_j,$$

where k_j is the ratio of mean moisture demand to mean supply,

$$k_j = (\overline{PE}_j + \overline{R}_j)/(\overline{Prec}_j + \overline{L}_j),$$

and the moisture anomalies normalized with respect to time and place Z_{ij} from

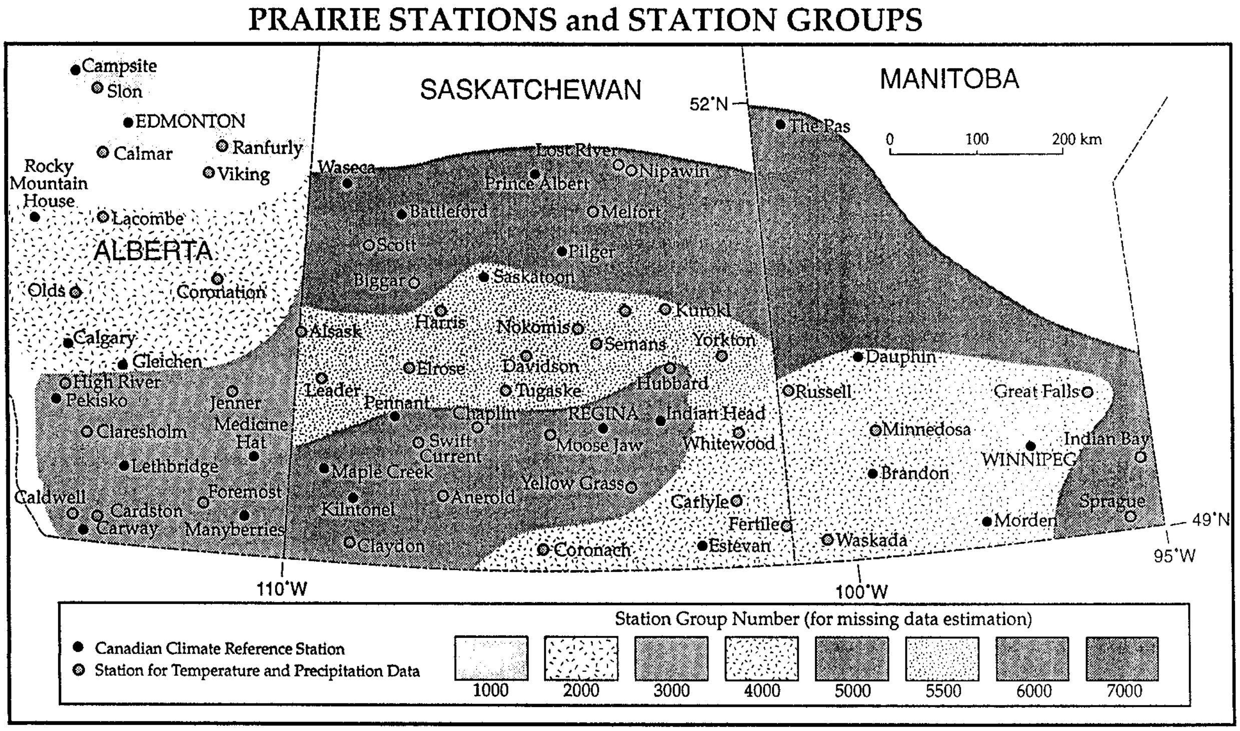

FIG. 3. Station groups. Stations within each group are meteorologically homogeneous.

$$Z_{i,j} = k_j d_{i,j},$$

$$k_j = \frac{17.67}{\sum_{1}^{12} \overline{D}K'} K',$$

$$K_j' = 1.5 \log_{10}[(S_j + 2.8)/D_j] + 0.50,$$

$$D_j = \frac{1}{n} \sum_{i=1}^{n} |d_{ij}|.$$

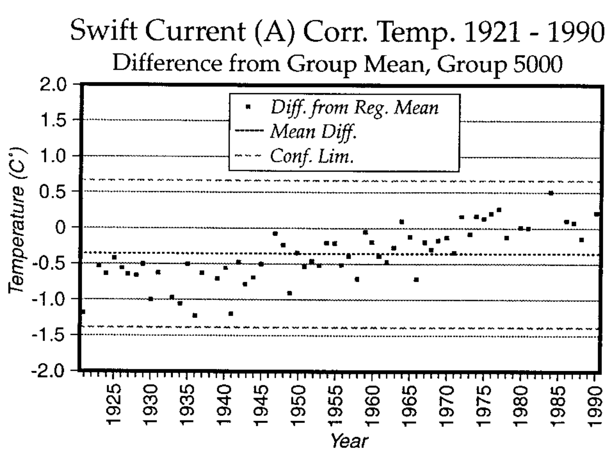

FIG. 4. Homogeneity test for mean temperature for Swift Current, Saskatchewan. The confidence interval shown is 99%.

The limitations of the PDSI, particularly with respect to its many assumptions, have been detailed by Karl (1983), Alley (1984), and Weber and Nkemdirim (1998), among others. Karl (1983), for example, studied the sensitivity of the PDSI to the available water capacity (AWC) factor and found that an increase in AWC tends to increase the length of the drought explaining that "an area with a large capacity for storing water is rather sensitive to prolonged dry spells since it has developed an ecosystem which has almost always had dependable water supply." Weber and Nkemdirim (1998) confirmed this tendency with data from Regina, Saskatchewan, especially for multiyear droughts. They found, however, that for shorter duration events, in the order of one year or less, variations in PDSI calculated with different values of AWC were not statistically significant. Alley (1984) noted the subjectivity of the Palmer approach in assigning drought conditions and, by inference, the length of a drought. His revised scheme (adopted in this study) that relies on specific probability values that a drought has begun or ended produced results that were consistent with other drought indicators (proxies) found in provincial archives such as reports of drier sloughs and wetlands, crop moisture stress, and documented evidence of the beginning and end of wet/dry conditions (Nkemdirim 1991). Weber and Nkemdirim (1998) showed that for droughts one season or more in length, the assumption that no runoff occurs

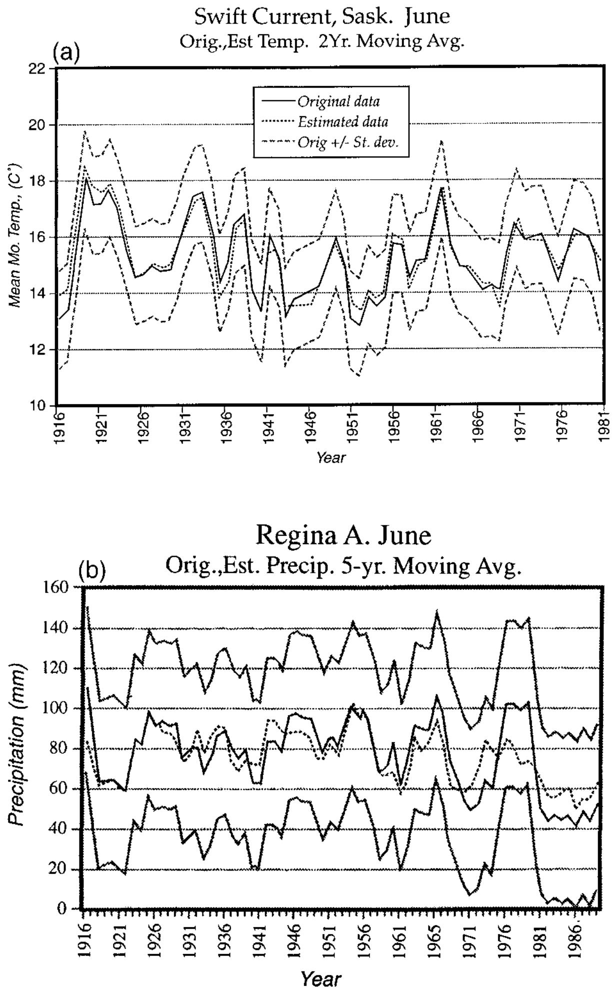

FIG. 5. (a) Synthetic vs measured temperature data for Swift Current, Saskatchewan, for the month of Jun 1916–81. (b) Synthetic vs measured precipitation for Regina, Saskatchewan, for Jun 1916–87. Similar tests for temperature and precipitation were conducted for each month for each station used.

before the two soil layers are filled to capacity was realistic.

Taken as a whole, the PDSI satisfies our requirements for a drought index for comparing drought and wetness over a wide geographical area, especially within a historical context. At a time (the 1930s) when datasets useful for calculating water balance over a sufficient number of stations to enable regional specification were restricted to daily precipitation and temperature, the PDSI provides a robust measure of drought severity and, when applied uniformly over time and space (equal treatment of cases), is a useful tool for comparing the march of drought, its severity, spatial characteristics and patterns, and recovery.

c. Study area

The area covered by this investigation includes parts of the three Canadian prairie provinces, Manitoba, Saskatchewan, and Alberta. It extends from Lake Winnipeg to the east to the Alberta border in the west (Fig. 1). The southern border is the 49th parallel. The northern boundary runs roughly along latitude 54°N. This area includes the Palliser triangle (according to two definitions) and the overlapping Canadian dry belt, which is approximately one-half the size of the triangle. The belt measures about 128 000 km^2.

In general, the region consists of a gently sloping plain, rising from a low 200 m above sea level in the Lake Winnipeg area to more than 1800 m in the foothills of the Rockies west of Calgary. Most of the region is part of the Hudson Bay drainage basin; extreme southwest Alberta and southeast Saskatchewan are within the Mississippi drainage basin. Large sections within the dry belt/Palliser triangle form interior drainage areas; shallow lakes and ponds, known locally as sloughs, dot the landscape. During droughts, many of those ponds, and even the lakes, may dry up completely.

The southern prairie climate is cold snowy continental with cool long summers (Db according to Köppen) punctuated in some places, northeast Saskatchewan, for example, with Dc type (short cool summers). The dry belt ranges from moist steppe (BS) to a cool dry steppe (BW); here moisture is not adequate to support plant growth during the year and agriculture is mostly dependent on irrigation. The average annual precipitation at the core of the dry belt is about 300 mm. Elsewhere, precipitation ranges from 330 mm in the south to 460 mm in the north (Fig. 2). Mean annual temperatures run from 0°C in the northeast of the study area to 5°C in the southwest corner. Aridity is endemic to this region where the ratio of potential evapotranspiration to annual precipitation increases from 120% in the north to 175% in the dry belt to the south.

3. Methodology

a. Data

The monthly meteorological data utilized were obtained from Canada's Atmospheric Environment Service (AES). After careful screening and homogeneity tests were performed separately for temperature and precipitation, the original group of 82 stations was reduced to 57. The stations were subsequently divided into groups such that stations within groups shared more in common than they did with those in adjacent groups, a quality achieved through analyses of correlations and variances. The groups are shown in Fig. 3. Nearest-neighbor statistics confirmed the station spread to be uniform. Some AES estimates of missing data were expunged from the files and new synthetic ones created from the multiple regression fits obtained between each station and the others within the group. Tests with double mass curves showed that the newly created precipitation files were homogeneous while the expunged ones were not. AES estimates missing station data from re-

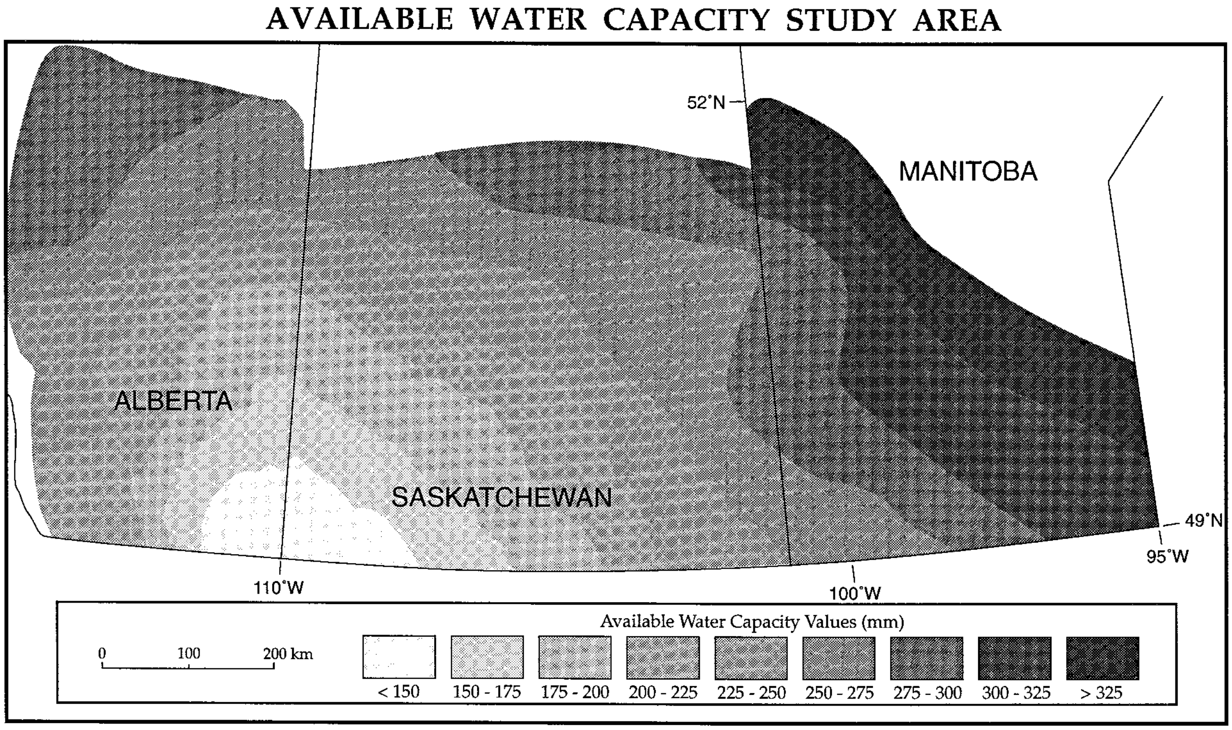

FIG. 6. Distribution of available water capacity within the study area.

cords taken from other stations within the drainage basin to which the station belongs. This approach is usually successful where the basin is meteorologically homogeneous. However, in some cases, the station in question may have greater meteorological commonality with its nearest neighbors outside its basin than with those in its basin. It is on those occasions that our method yielded data that gave us better results. The final list of stations in a group was obtained by testing to ensure that departures of the mean of each stations within a group from the group mean was contained inside the 99% confidence interval (Fig. 4). Those stations that failed the test were discarded. Urban bias was removed from temperature data utilizing methodology recommended by Kukla et al. (1986) that produced results that agreed well with Hengevold's (1991) estimates for Canadian cities. Within groups correlations exceeded 0.95 for temperature, but ranged from 0.75 to 0.90 for precipitation depending on the season. In nearly all cases, for both temperature and precipitation, the estimated data, when compared to the true values, were more conservative and generally closer to the mean than the true value. The standard deviation of the true series was nearly always higher than that of the estimated series and decreased as estimated data were included in the record. Thus, drought events may conceivably be missed due to the inclusion of synthetic data, but droughts would not be recorded when none occurred nor overestimated in severity. These efforts yielded continuous monthly series for the period 1927 through 1990, which overlaps the two drought decades. Comparison between synthetic and true data are shown for temperature and precipitation in Figs. 5a and 5b.

The AWC was estimated for each station based on field survey and previous studies (Jones 1984; Smit 1989). AWC varied from a low 150 mm for the brown soils of southwestern Saskatchewan and southeastern Alberta to a high of just over 300 mm in the thick black soils northeast of Yorkton, Saskatchewan (Fig. 6).

b. Calculation of the Palmer drought index

A program, PDSI94, was written and used to calculate monthly values of the Palmer drought index, the first step in building the comparison between the two drought decades (Weber and Nkemdirim 1994). The program is modular and works through several subroutines and functions specifically designed to utilize mean monthly temperature, precipitation, and available water to compute the variables described in Table 1. The subroutine "WaterBud" keeps a running account of moisture input, moisture demand, and moisture surplus. Calculations are done for each of the three layers—the ground surface, the upper soil layer consisting of the top 25 mm, and the underlying soil layer to a depth determined as the AWC. Palmer's constants, α, β, γ, and δ, defining the site-specific CAFEC hydrological parameters, were calculated for each month and for each station.

PDSI was computed for each station for 1927 through 1996. A series of maps were created using IDRISI, a geographic information system program. The ''usual'' climate was estimated, and the drought index shows, spatially, comparable values of the departure of the moisture conditions from the normal. The maps presented are mean annual values.

4. Results

a. Climatic capability

The climatic capabilities of the region expressed in terms of Palmer's α, β, γ, and δ for four stations chosen to represent the north (Edmonton), the west (Calgary), the dry belt (Swift Current), and the east (Regina) are provided in Table 2. The ratio of actual to potential evaporation (α) averages 85% annually in the study area. However, in the critical growing season (May–September) it drops to 75%. The ratios of recharge to recharge potential, runoff to runoff potential, and moisture loss to moisture loss potential are all low.

In general, stations near the northern boundary are less stressed than those in the south. The stress factors are most pronounced in the dry belt, where α averages 80% annually and 67% in the growing season. The west and the east fall between northern and southern values. Note the increase in variability with decreasing ratios.

These ratios and variabilities point to a region that is climatically water stressed, a stress that is aggravated by a drought, even one of modest intensity (Jones 1987). Recent evidence suggests that water shortage may be growing. A study of trends in streamflow revealed statistically highly significant declines in major river basins in the region (Yulianti and Burn 1998), which the authors attribute to rising temperature (Environment Canada 1998). This decline is occurring at time when *annual* precipitation is near normal and is consistent with the thesis advanced by Nkemdirim and Purves (1994) that projected decrements of up to 30% in Canada's dry belt if temperature increased in the range indicated by general circulation models for an equilibrium 2 $\times$ CO_2 climate, even when a possible increase of 10% in precipitation is factored in.

b. Mean PDSI and variability

The mean annual PDSI and standard deviations for the region based on the areally weighted average for the eight subregional groupings is provided in Table 3. 1929 and 1979 are included, thereby stretching the decade to 11 yr. The spatial distribution of PDSI are shown in Fig. 7 for the 1930s and Fig. 8 for the 1980s. The remarks included in Table 3 summarize observations drawn from both the table and the figures.

Over the 22 yr represented in this study, 15 were dry and 6 were ''wet.'' There were nine drought years in the 1930s and six in the 1980s. The mean annual PDSI

TABLE 2. PDSI constants for Calgary, Edmonton, Regina, and Swift Current.

Month		α	β	γ	δ
Calgary					
Jan	1	1.0000	0.0969	0.0059	0.0000
Feb	2	1.0000	0.1100	0.0108	0.7464
Mar	3	1.0000	0.1519	0.0210	0.1318
Apr	4	0.9531	0.1091	0.0182	0.4140
May	5	0.8917	0.0549	0.0056	0.4306
Jun	6	0.8654	0.0996	0.0100	0.3117
Jul	7	0.7802	0.0133	0.0150	0.5100
Aug	8	0.6961	0.0189	0.0179	0.5098
Sep	9	0.7021	0.0517	0.0126	0.4789
Oct	10	0.6996	0.0261	0.0087	0.5349
Nov	11	0.8304	0.0774	0.0105	0.5446
Dec	12	1.0000	0.0823	0.0128	0.0000
Year		0.86822	0.0669	0.0124	0.385
Std. dev.		01.25	0.045	0.048	0.232
Edmonton					
Jan	1	1.0000	0.2044	0.0098	0.0000
Feb	2	1.0000	0.1866	0.0096	0.0000
Mar	3	1.0000	0.2244	0.0138	0.1273
Apr	4	0.9754	0.0823	0.0205	0.4772
May	5	0.9104	0.0245	0.0036	0.4599
Jun	6	0.8843	0.0760	0.0013	0.3371
Jul	7	0.8835	0.0590	0.0022	0.3439
Aug	8	0.8371	0.0305	0.0026	0.4151
Sep	9	0.7681	0.0327	0.0000	0.4929
Oct	10	0.7853	0.0349	0.0000	0.5119
Nov	11	0.8859	0.1176	0.0000	0.1759
Dec	12	1.0000	0.1706	0.0000	0.0000
Year		0.0108	0.103	0.0053	0.278
Std. dev.		0.085	0.078	0.007	0.2056
Regina					
Jan	1	1.0000	0.1109	0.0159	0.0000
Feb	2	1.0000	0.1117	0.0080	0.0000
Mar	3	1.0000	0.1536	0.0178	0.0000
Apr	4	0.9618	0.0714	0.0091	0.4615
May	5	0.8440	0.0389	0.0010	0.5095
Jun	6	0.7926	0.0645	0.0005	0.3557
Jul	7	0.6834	0.0055	0.0000	0.5691
Aug	8	0.5641	0.0041	0.0000	0.6095
Sep	9	0.5904	0.0225	0.0001	0.4861
Oct	10	0.6719	0.0434	0.0004	0.4158
Nov	11	1.0000	0.0939	0.0006	0.0000
Dec	12	1.0000	0.0972	0.0037	0.0000
Year		0.841	0.068	0.0048	0.284
Std. dev.		0.175	0.047	0.006	0.258
Swift Current					
Jan	1	1.0000	0.1738	0.0185	0.0000
Feb	2	1.0000	0.1653	0.0090	0.0000
Mar	3	1.0000	0.2074	0.0265	0.1724
Apr	4	0.9443	0.1139	0.0247	0.4642
May	5	0.8347	0.0542	0.0167	0.5279
Jun	6	0.8065	0.0711	0.0104	0.3957
Jul	7	0.6535	0.0070	0.0000	0.6004
Aug	8	0.5364	0.0043	0.0000	0.5863
Sep	9	0.5516	0.0245	0.0000	0.5496
Oct	10	0.6380	0.0324	0.0000	0.4900
Nov	11	0.8400	0.1058	0.0000	0.5871
Dec	12	1.0000	0.1455	0.0000	0.0000
Year		0.815	0.092	0.0088	0.364
Std. dev.		0.182	0.069	0.0104	0.268

TABLE 3. Comparative data for drought from 1929 to 1989.

Year	Mean PDSI	Standard deviation	Remarks
1929	−1.14	1.37	• 545 km² as extreme drought in northeastern Manitoba • most areas show moderate drought to near-normal conditions
1930	−1.28	1.73	• 500 km² as extreme drought in three separate areas • most areas show moderate drought to near-normal conditions
1931	−2.51	1.36	• 3500 km² showing extreme drought in four major areas, the largest in south-central Saskatchewan • northern areas near normal
1932	−1.26	1.58	• 2700 km² as extreme drought in south-central Saskatchewan and Manitoba, west-central Alberta • grasshopper plague
1933	0.21	1.02	• only 220 km² showing moderate drought (PDSI < -2.0): patches in Saskatchewan • grasshopper plague returns
1934	−0.54	1.61	• 325 km² as extreme drought, in southeastern Saskatchewan, southern Manitoba: part of major drought to south • major dust storms, grasshoppers
1935	0.65	1.57	• 650 km² moderate drought (PDSI ≤ -2.0 in southwestern Saskatchewan, southeastern Manitoba • rust fungus attacked wheat crop
1936	−0.35	1.48	• record cold winter followed by record hot summer • more than 5000 km² moderate to extreme drought, most severe in southern Alberta, northern Saskatchewan: part of major drought to the south • zone of moisture through central part of the study area
1937	−2.54	1.94	• 5400 km² of extreme drought (PDSI < -4.0), with more than seven centers—two major ones in southwestern and northeastern Saskatchewan • major dust and alkali storms, grasshoppers, cattle feed crisis • rains began mid-July
1938	−1.51	2.26	• recovery started, but still 1800 km² extreme drought, with three widespread centers • moisture zone shows mean storm track
1939	−1.65	1.98	• 2000 km² of extreme drought, with centers in northwestern Alberta, southwestern Manitoba • moisture zone shows mean storm track
1979	0.22	1.42	• normal to moist conditions: 1325 km² of moderate drought in central Saskatchewan • last of 30 generally moist, cool years
1980	−1.83	1.33	• 17 500 km² moderate to extreme drought throughout eastern Saskatchewan
1981	−1.62	1.45	• 1250 km² of extreme drought: southeastern Saskatchewan, southwestern Manitoba • alternating zones of moisture, drought oriented north–south
1982	0.14	1.50	• near-normal conditions prevalent • southeastern Saskatchewan, southwestern Manitoba slow to recover; 1400 km² moderate to severe drought
1983	0.07	1.12	• near-normal conditions prevalent—wet zone in central Saskatchewan, 1500 km² moderate drought in southeastern Saskatchewan, southwestern Manitoba, southwestern Alberta
1984	−0.62	1.20	• 6500 km² moderate to extreme drought in southern Saskatchewan, southwestern Manitoba, southwestern Alberta; pattern from 1983 spread
1985	1.21	1.36	• only 285 km² moderate drought, mostly in southern Saskatchewan • northern section of study area wet
1986	1.72	1.48	• entire area shows normal to extreme wet spell PDSI values • full recovery
1987	−0.65	1.30	• 2300 km² moderate to severe drought, mainly where 1986 was least wet
1988	−3.20	1.20	• 10 500 km² as extreme drought, across the southern prairies • part of continental drought • single driest year within the two decades
1989	−2.57	1.63	• still 6600 km² of extreme drought in Manitoba, eastern Saskatchewan • recovery faster in the western areas

for the 1930s was −1.1; in the 1980s it was −0.5. This statistically significant difference indicates that when the two decades are compared as wholes, the 1930s were definitely drier; the 1980s barely qualify as a drought decade. However, when wet years are excluded, the PDSI averaged −1.39 for the 1930s and −1.34 for the 1980s. This difference, which was not statistically significant, suggests that when droughts actually occurred, they were, on average, equally severe in both decades. Three of the top-ranked five dry events occurred in the 1930s compared to two in the 1980s. The top-ranked drought event (−3.18), however, occurred in 1988; the second ranked (−2.38) in 1931. There were two 4-yr runs of drought in the 1930s. The longest run in the 1980s was the 3-yr run from 1987 to 1989 inclusive. During their longest runs, the 1930s averaged −1.59 compared to −2.04 for the 1980s. Based on the decadal average, the droughts rank in the mild to moderate category. However, among subregions, in most of the dry years, values in excess of −5 (extreme drought) were common (Figs. 7 and 8). In the 1988 event (Fig. 8) as well as in other years, several areas experienced values greater than −6. Drought intensity varied areally from year to year (Table 3). The standard deviation over the decades was 1.62 and 1.36 PDSI units for the 1930s and 1980s, respectively. When only dry years are considered, the values are 1.70 and 1.36, respectively. This statistically significant difference in variability suggests that the spatial pattern of drought severity in the southern prairies of Canada was more uniform in the 1980s than it was in the 1930s. We use the term ''zoned'' to describe a tendency for large contiguous areas to experience similar drought conditions (the 1980s) and ''patchy'' to describe a pattern in which intensities differ significantly over relatively short distances (the 1930s). This is illustrated in Fig. 9, where the variability associated with the events of the 1980s almost consistently lies below those of the 1930s. Figure 9 also reveals some consistency in patterns of variability in relation to the PDSI. Even though there is only one point for each decade in PDSI −2.5, variability at that level is less than 1.5 PDSI units. Thus for very severe droughts, the spatial pattern tends to be ''uniform.'' For droughts in the −0.5 to −2 PDSI range, variability tends to increase with drought severity irrespective of decade. Conversely, for wet events (PDSI ≥ 0) variability tends to increase with increasing wetness. This implies that when recovery occurs it tends to be more local than regional in character, driven perhaps not by the spatial distribution of precipitation, but by local recharge controls, soils, for example.

1) Spatial patterns

The difference in mean variability appears to be reflected in the spatial pattern of drought severity index. While in the 1930s, spatial distribution of PDSI was patchlike especially with respect to the severely impacted areas, in the 1980s, there were usually well marked, fairly extensive, and continuous drought zones (Figs. 7 and 8). Because of this, spatial patterns of the 1980s are better defined than those of the 1930s. In 1980, 1981, and 1989, the moist and dry zones were differentiated from east to west; in 1983, 1984, and 1988 the zones ran south to north.

Such a structure was not evident in the 1930s. Rather each subregion appears to have its own drought cell where intensities decrease from the center outward. 1929, 1930, 1937, 1938, and 1939 exemplify this cell-like pattern. Greater continuity (zonal structure) is seen in the remaining years especially those characterized by less severe drought (average −1 to −2). The one consistent pattern that is discernible for the 1930s is a southwest to northeast oriented plume of relatively moist conditions flanked on both sides by cells of moderate to extreme drought.

2) Areal comparisons

Figure 10 shows the percent of area in the study region falling within each PDSI classification, where class 1 is the lowest at <-5.0 and 12 is the highest at $>+5$. While the 1980s had, on average, slightly more area in the most extreme drought category, the total percentage of area in classifications up to class 6 (PDSI $<$ 0) was greater during the 1930s. If the total area under moderate to extreme drought (mean annual PDSI < -2.0) is considered, the mean for the 11 years representing the 1930s is about 112 700 km^2. The corresponding value for the 1980s is 95 200 km^2, a difference of almost 16%.

The size of the largest contiguous area with PDSI $<$ −2.0 was also determined for each year of the two decades. The ratio of the area of the largest contiguous dry zone to the total dry area was also calculated. The results are plotted in Fig. 11. If the exceptionally wet year of 1986 is ignored, then generally the higher values occurred during the 1980s, showing that the events of the 1980s more frequently consisted of fewer but larger zones than those observed during the 1930s. This is consistent with the spatial pattern discussed above.

c. Temporal comparison and recovery

The time series of the weighted areal mean PDSI for the two decades are plotted in Fig. 12. The slightly greater mean drought severity of the 1929–39 series discussed earlier is confirmed. The two series are, however, similar in terms of progression into drought and through recovery. The smaller of the two drought climaxes occurred one to two years into the decade. Recovery was interrupted by a return to mild drought conditions. Recovery peaked around the seventh year of the decade but was quickly followed by a steep decline into the major climax. Each decade ended with a trend toward a recovery. The signature of the two drought decades may be summarized as follows: a first half marked

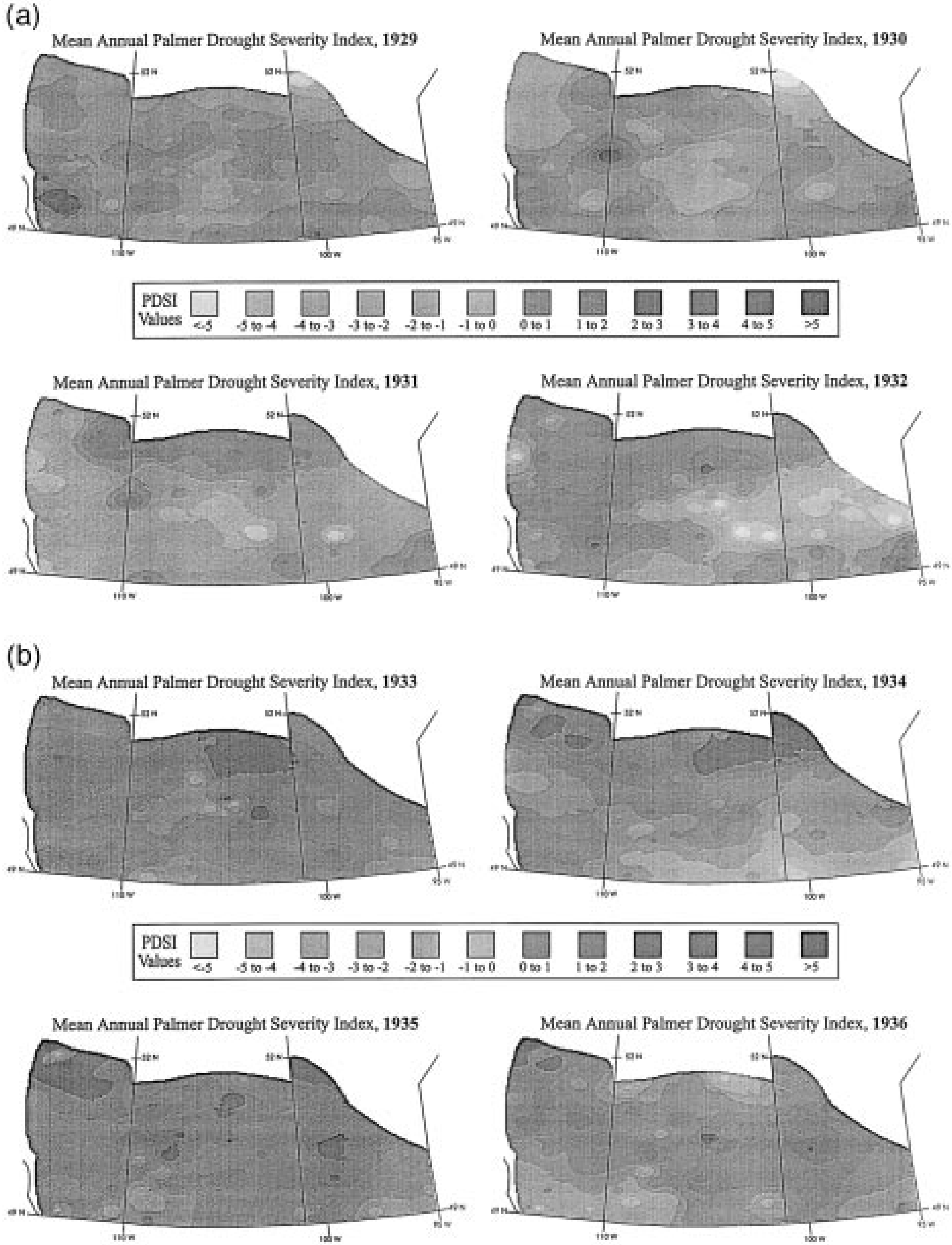

FIG. 7. Spatial distribution of drought intensities during the 1930s.

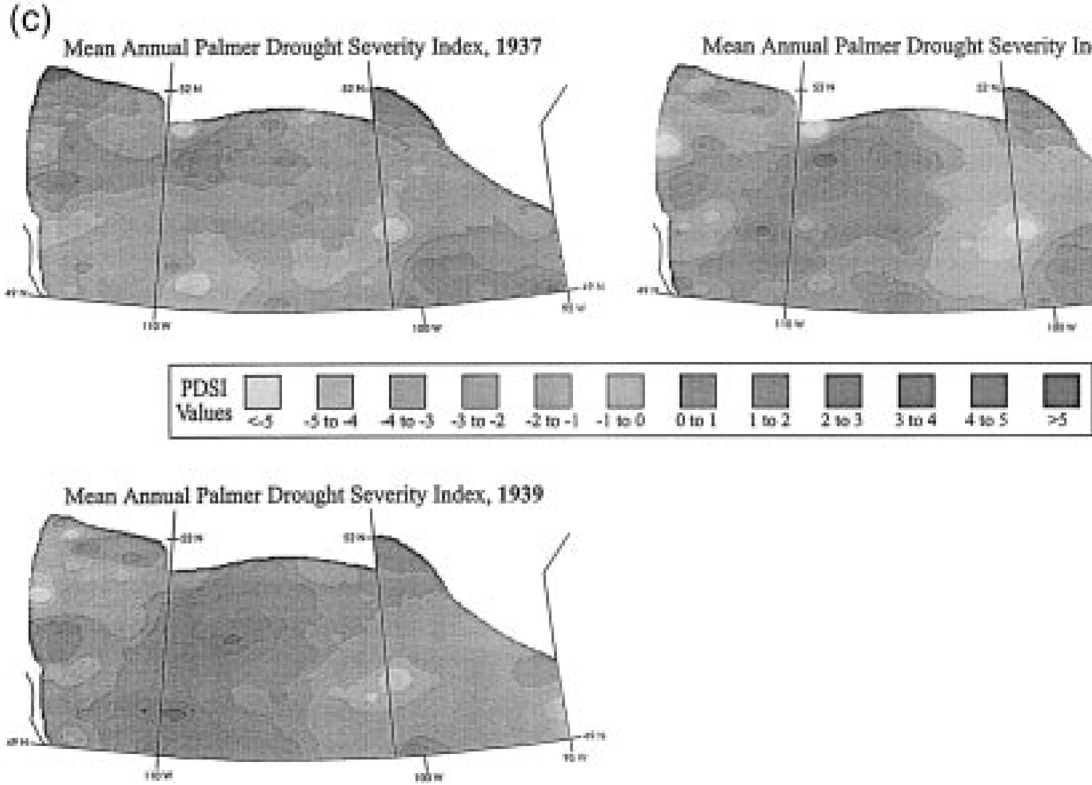

FIG. 7. (*Continued*)

by relatively less intense drought, followed by a modest recovery near the middle of the decade, and ending with a run of droughts of greater severity than those experienced in the first half.

But there are also dissimilarities. The slopes of the time series, that is, the rate of progression into droughts and out of them, are different during the two decades. In the 1930s drift into drought was slower and drawn out (the loss of PDSI units averaged 0.90 units yr^{-1}). Recovery was also weaker than the 1980s. The average gain during the recovery phase was 1.02 units yr^{-1}. Compare these numbers against 1.76 units yr^{-1} loss (drought phase) and 1.20 units yr^{-1} gain (recovery phase) during the 1980s, which suggest that the plunge into drought conditions was steep in the 1980s but recovery was also faster and stronger.

SUMMARY

The numbers and descriptions suggest that although droughts were more frequent and persistent in the 1930s, individual events were generally less severe than those of the 1980s. The 1930s events covered more territory when all droughts are included; however, when the severest events are considered, the droughts of the 1980s were areally more extensive. Whereas the pattern of severity was patchlike during the 1930s, large continuous drought zones marked the events of the 1980s. Variability of intensity over space was significantly (α = 0.05) lower in the 1980s than the 1930s, thus the drought experience was more uniform in the latter decade than the former. Both decades enjoyed a recovery from drought conditions around the midpoint of their respective decades, but the decade with the more intense events (the 1980s) experienced a much stronger recovery. However, this did not compromise the severity of the second half-drought of the 1980s, suggesting that without the generous recovery, the second series of runs would have been much worse.

5. Discussion

Related atmospheric conditions

The droughts of the 1930s and 1980s were not unique to the southern prairies. The events were part of a larger North American phenomenon occurring especially in the American great plains and the west. The prairie drought is a northern extension of the continental drought and consequently it is discussed within that context. To understand the anomalies in circulation that may have caused the droughts, one must first consider the normal circulation patterns that prevail in the region.

The Polar maritime air (mP) from the Pacific source region splits into two on the north coast of British Columbia. One prong travels southward along the Pacific

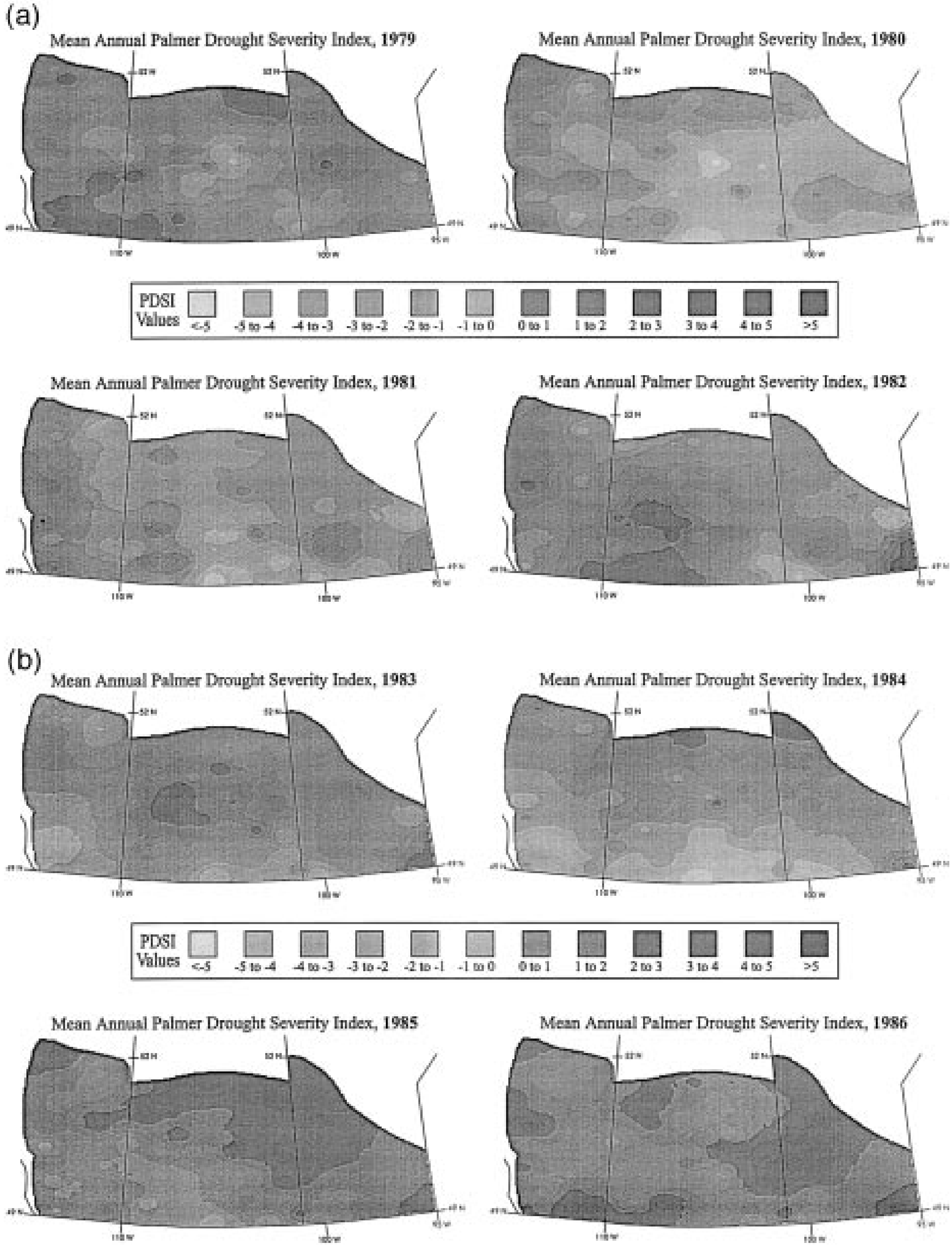

FIG. 8. Spatial distribution of drought intensities during the 1980s.

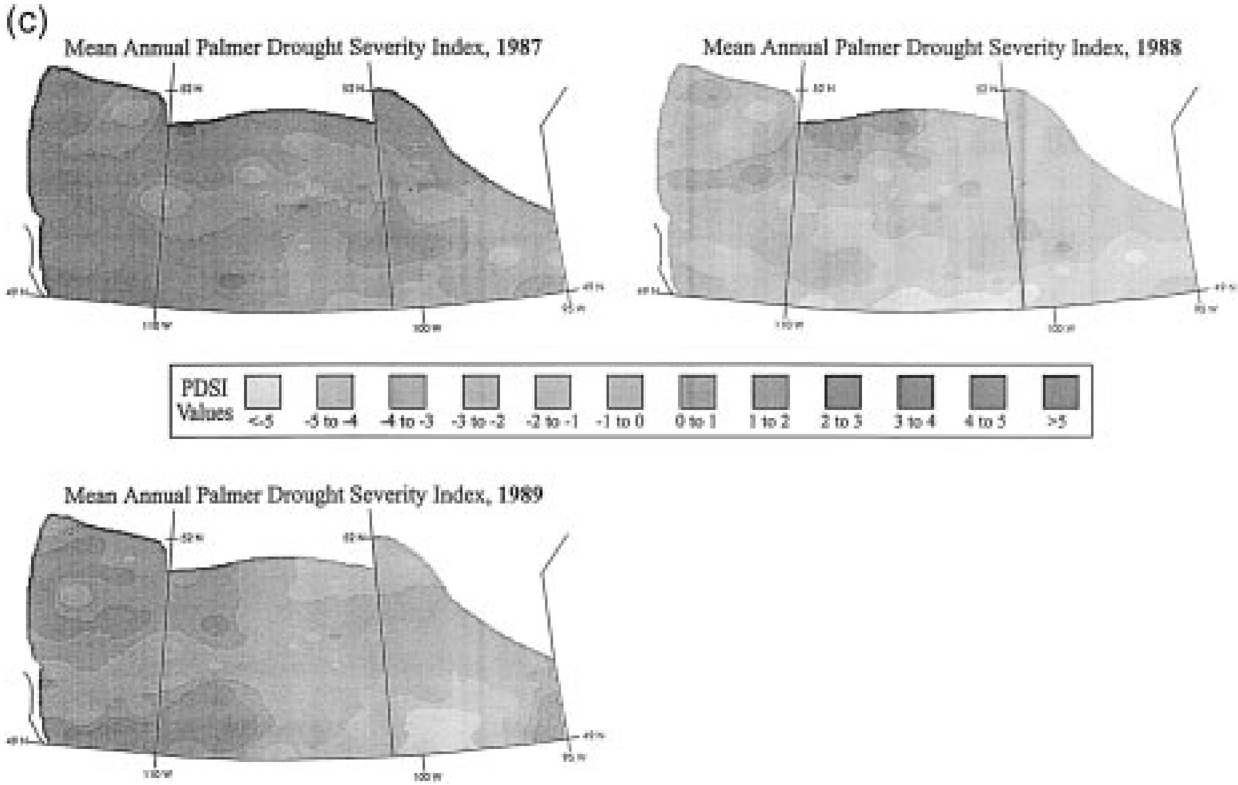

FIG. 8. (*Continued*)

coast and the other enters Canada via the Rockies, moving southward along the east side and through the Peace River basin where the Alberta storm track originates. It is this penetration that provides a high frequency of maritime air along the 55th parallel and the precipitation maximum experienced near the northern boundary of the study area. The dry belt and the Palliser triangle to the south lie between the northern and southern prongs of this Pacific air stream. Because of its position north of the jet stream, it is an area of inflow along the left side of the jet. This inflow leads to subsidence aloft, which is probably associated with the decrease in precipitation, during the summer, north of the jet stream to about 51°N. Sea level pressure charts show a low frequency of cyclones and a high frequency of anticyclones in this area (Riehl 1948). Additionally, perturbations of

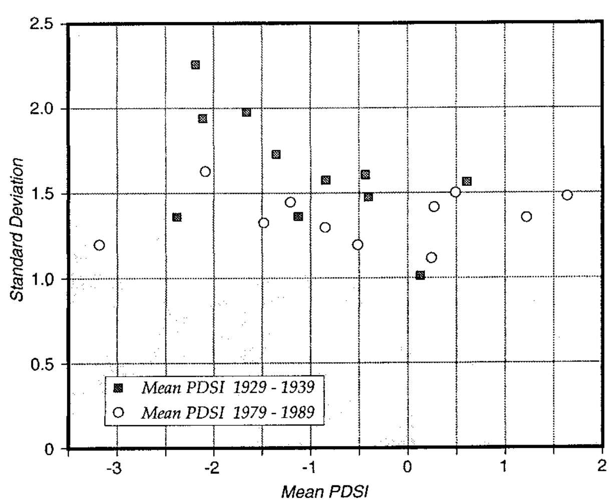

FIG. 9. Relationship between mean areal drought intensity and spatial variability of intensities. Values on the vertical axis are areally weighted standard deviation of intensity.

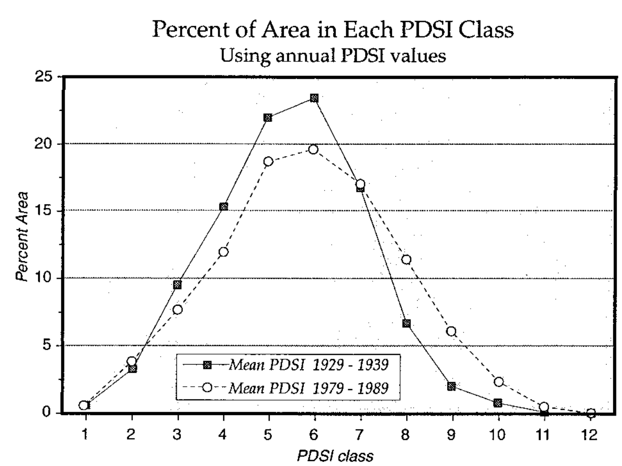

FIG. 10. Proportion (%) of study area under each PDSI class. Class 1 is PDSI ≤ -5.0, class 6 is PDSI $= 0$, and class 12 is PDSI $\geq +5.0$.

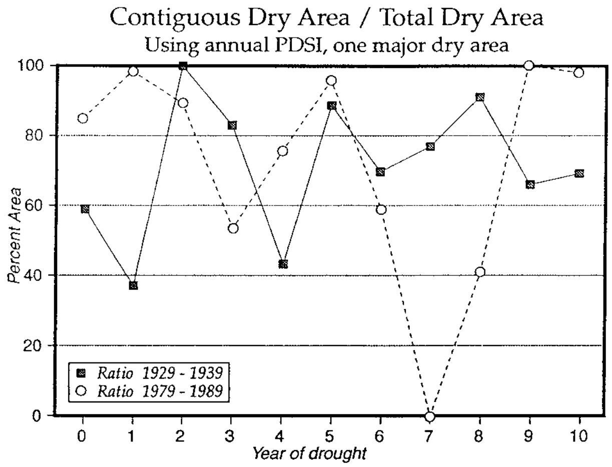

FIG. 11. Proportional area of the largest contiguous zone with PDSI < -2.0 during the two drought decades. Year 0 begins the decade; year 10 ends it. For convenience, a decade in this study spans 11 yr.

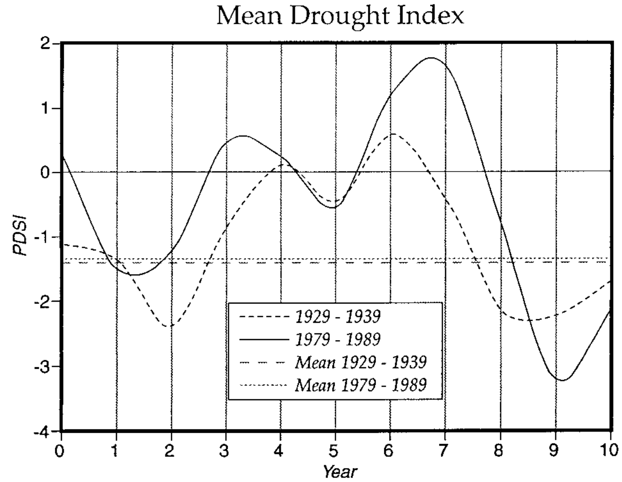

FIG. 12. Time series of weighted mean areal PDSI for each drought decade. Year 0 begins the decade; year 10 ends it.

the westerlies result in the formation of two anticyclonic rotations leeward of the Rocky mountains; one of these sustains a dry current of air directly over the dry belt. Borchert (1953) showed by means of streamlines of resultant airflow at the geostrophic wind level that dry continental air dominates the area bounded by the Alberta storm track and the 100th meridian and the U.S. border in July. Longley (1972) has shown that precipitation in this region is not only deficient but also some of the most variable in Canada in both wet and dry years.

Because the study region is precariously wedged between two zones, one with reliable precipitation to the north, and the other a drier and less reliable precipitation zone to the south, any significant shift in atmospheric circulation patterns can bring it either into a moister regime or a drier one. A lack of reliable midtropospheric geopotential height maps for this region during the 1930s forces us to speculate on the possible atmospheric circulation impacting it during that time based on the drought–wetness patterns contained in the PDSI maps for drought years. Firstly, considering the years 1933 through 1935 when the average PDSI was positive or mildly negative, the broad pattern of wetness are consistent with normal zonal patterns of precipitation shown in Fig. 2. The wet region to the north reflected the mean position of the Alberta storm track. However, during drought years, the wet zone appears to curve southwest (from Alberta) to northeast (into Manitoba), flanked on both sides by drier conditions. This appears to suggest a southerly shift of northern storm track and to be consistent with the hypothesis of a southward displacement of the midlatitude storm tracks associated with an expansion of the circumpolar vortex, the development of large amplitude quasi-stationary long waves in the westerlies, and the contraction equatorward of the meridional circulation in the Tropics (Barry and Chorley 1976). Reduced precipitation along the wet zone further suggests that the cyclones did not carry significant amounts of moisture into the region. This may be due to passage through the "chinook corridor" where considerable dewatering of storms occurs on the windward side of the mountain, leaving them water deficient through their remaining course across the continent (Nkemdirim 1996). The area of low precipitation normally found south of the storm tracks shifted farther south and exacerbated dryness in the area. The fact that strong winds, and frequently dust storms, were the signature of the drought of the 1930s (Berton 1991) is consistent with the theory that storm passage was frequent but the storms themselves were poorly organized, hence the patchlike pattern of moisture deficiency.

The absence of wet plumes from the drought patterns of the 1980s suggests that the main drives for its events may have been different from those that operated in the 1930s. The maps of drought years (Fig. 8) show zonal continuity with drought intensifying generally from north to south, paralleling the area's normal spatial precipitation pattern. This could indicate that cause did not differentiate as areally as it did in the 1930s. Large parts of the region may have been blocked out from precipitation-bearing storms by strong highs positioned over the region leaving subregions to survive on precipitation generated from local sources, hence the moister regime in the north where the boreal forest and lakes could supply the moisture for limited local precipitation.

These speculations are justified by Figs. 13 and 14. The mean surface pressure map for DJF for 1979–89 (Fig. 13) shows that the study region was dominated by a high pressure ridge extending from above the Arctic circle to below the 49th parallel, far south of its normal northern limit just below the circle. Figure 14 is a composite diagram constructed from surface and midtropospheric weather maps during the droughts of 1987–89. The key feature is a well-developed ridge lying over

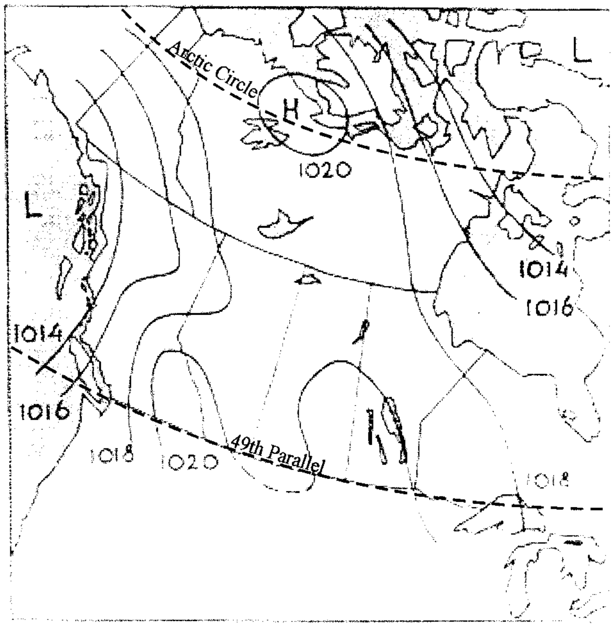

FIG. 13. Mean sea level pressure for Dec–Feb 1979–89.

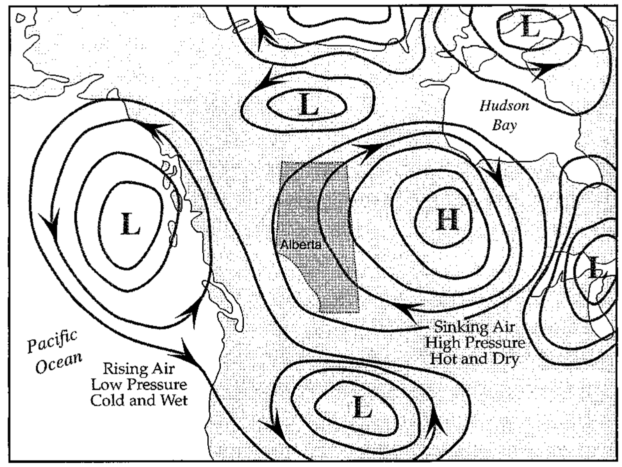

FIG. 14. Composite surface and midtropospheric pressure pattern associated with droughts in the 1980s.

the region ''trapped'' by four low pressure cells. An overlay of Fig. 14 on the 1988 and 1989 maps of Fig. 8 demonstrates a striking correlation between the atmospheric patterns illustrated in Fig. 14 and the spatial pattern of many of the droughts. This may also help explain the difference in windiness between the 1930s and the 1980s. Smit and Nkemdirim (1990) noted that west winds in this region were 2 m s^{-1} weaker than normal during the 1980s.

6. Conclusions

The 1930s and 1980s were drought decades. In both decades mean annual temperature was above normal. The 1980s were the warmest decade this century in the study area; the 1930s were the second warmest. However, while the winters of the 1930s were slightly wetter than normal, winter and spring precipitation was below average in the 1980s. Both decades experienced dry summers.

The following details emerge from analyses of the two droughts. Droughts were more frequent in the 1930s and runs of drought years were longer than those of the 1980s. For the decade as a whole, the 1930s were drier. However, when only the severest drought years are considered, those years were drier in the 1980s than the 1930s. During the longest runs, PDSI averaged −2.04 from 1987 through 1989 compared to −1.59 from 1936 through 1939. The worst event occurred in 1988, when PDSI averaged −3.18. While droughts in the low to moderate category covered a wider area in the 1930s, those in the moderate to extreme category were more expansive in the 1980s. The spatial distribution of drought severity was quiltlike during the 1930s, with patches occurring on both sides of a plume of relatively wet corridor. In the 1980s, a zoned pattern characterized the spatial distribution; the wet corridor of the earlier decade was mostly absent.

We conclude from the PDSI patterns that the drought dynamics were different. In the 1930s, it appears that the normal storm track was displaced south from its Peace River district position to the chinook corridor. Although the storms were there, they carried little moisture into the study area and hence the drought. In the 1980s, a series of stable highs blocked out storms, thus creating a regional drought whose pattern reflected the normal precipitation distribution in the area.

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