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Trends, periodicities and ENSO relationships of the annual precipitation over the contiguous United States and Southern Canada

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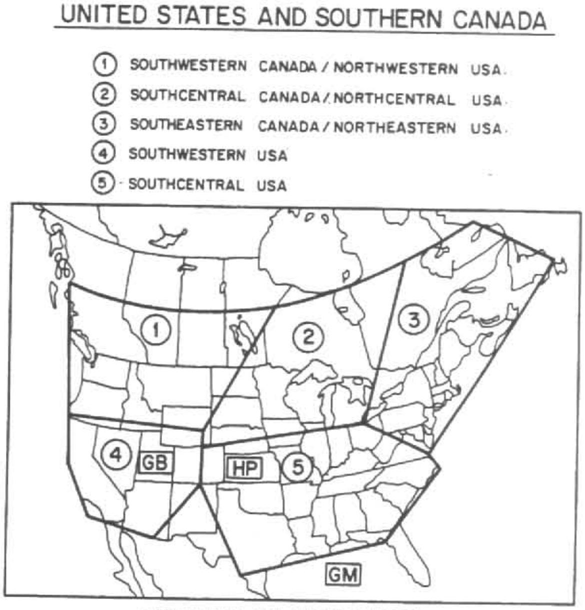
सार - संयुक्त राज्य अमरीका और दक्षिणी कैनेडा (55°उ. के दक्षिण में) के पाँच समरूपी क्षेत्रों की वार्षिक वर्षा की मात्रा के आकलनों से संबंधित ग्रोइसमन और ईस्टरलिंग (1994, a, b) के सौ वर्षों (1891से 1990) के आकलनों की इन्हीं क्षेत्रों में वर्षा की प्रवृत्तियों, आवर्तिताओं और एनसों संबंधों के संदर्भ में जाँच की गई है। सौ वर्षों की इस अवधि में किसी भी क्षेत्र में इन प्रवृत्तियों में उतार - चढाव एक समान नहीं पाए गए हैं। 1891 से 1930 तक की अवधि में इनकी प्रवृत्ति अद्योमुखी अथवा नगण्य थी। तदुपरांत, चक्रीय परिवर्तनों की प्रधानता के कारण प्रवृत्तियाँ अधिकतर उर्ध्वमुखी थीं। अनुक्रम विश्लेषण से क्यू.बी.ओ. और क्यू.टी. ओ. क्षेत्रों (2-3 वर्ष और 3-4 वर्ष) में उल्लेखनीय आवर्तिताओं का तथा उच्चतर आवर्तिताओं का भी पता चलता है जिनमें से कुछ सभी क्षेत्रों में एक जैसी पाई गई है। यह एक जैसी प्रवृत्तियाँ समूचे क्षेत्र में कई बार देखी गई हैं। एनसो संबंधों का अध्ययन करने के लिए एलनिनों की घटनाओं के सूक्ष्म वर्गीकरण का उपयोग किया गया है। प्रत्येक वर्ष की जाँच यह पता लगाने के लिए की गई कि क्या उस वर्ष एलनिनों (ई.एन.) का प्रभाव था और/अथवा दक्षिणी दोलन इंडैक्स, एस. ओ. आई. न्यूनतम (एस.ओ.) था और/ अथवा भूमध्यरेखीय पूर्वी प्रशांत महासागर का समुद्र सतह तापमान एस.एस.टी. उष्ण (डब्ल्यू) या शीत (सी) था। कई वर्ष ई.एन.एस.ओ.डब्ल्यू. वाले वर्ष थे, जिन्हें आगे दो उपसमूहों में विभाजित किया गया, नामतः असंदिग्ध (सुस्पष्ट) ई.एन.एस.ओ.डब्ल्यू. वर्ष जिसमें एलनिनों विद्यमान होता है और जिसमें कलैंडर वर्ष (मई-अगस्त) के मध्य में एस.ओ. आई. न्यूनतम और एस.एस.टी. अधिकतम होते हैं तथा संदिग्ध ई.एन.एस.ओ. डब्ल्यू., वर्ष जिसमें एलनिनों विद्यमान तो होता है किन्तु उसमें एस.ओ. आई. न्यूनतम और एस.एस.टी. अधिकतम कलैंडर वर्ष के मध्य में न होकर वर्ष के पहले अथवा अंतिम भाग में होते हैं। अन्य एलनिनों घटनाएं ई.एन.एस.ओ., ई.एन.डब्ल्यू., ई.एन.सी., ई.एन. प्रकार की पाई गई हैं। अखिल भारतीय ग्रीष्मकालीन मानसून वर्ष में असंदिग्ध ई.एन.एस.ओ.डब्ल्यू. सूखे से अत्याधिक प्रभावित रहे हैं। मैक्सिको की खाड़ी वाले क्षेत्रों और कुछ अन्य भागों को छोडकर संयुक्त राज्य अमरीका और कैनेडा में वर्षा के संबंध एलनिनों के साथ अधिक स्पष्ट नहीं है। इन क्षेत्रों में अधिकतम वर्षा असंदिग्ध ई.एन.एस.ओ.डब्ल्यू. से संबद्ध पाई गई है।

ABSTRACT. The century-long (1891-1990) time series of Groisman and Easterling (1994a,b) representing estimates of annual precipitation amounts over five homogeneous regions of the United States and Southern Canada (south of 55° N) were examined for trends, periodicities and ENSO relationships. The trends were not uniformly up or down during the 100-year interval, for any region. From 1891 to about 1930, the trends were downward or negligible. Thereafter, the trends were mostly upward, with cyclic variations superposed. A spectral analysis revealed significant periodicities in the QBO and QTO regions (2-3 years and 3-4 years) as also higher periodicities, some common to all regions and hence seen in the series for the entire region. To study the ENSO relationship, a finer classification of El Niño events was used. Each year was examined to check whether it had an El Niño (EN) and/or a Southern Oscillation Index SOI minimum (SO) and/or warm (W) or cold (C) equatorial eastern Pacific sea surface temperatures SST. Several years were ENSOW, which were further subdivided into two groups *viz.* Unambiguous ENSOW where El Niño existed and SOI minima and SST maxima were in the middle of the calendar year (May-Aug.), and, Ambiguous ENSOW where El Niño existed but the SOI minima and SST maxima were in the early or late part of the calendar year, not in the middle. Other El Niño events were of the type ENSO, ENW, ENC, EN. For the All India summer monsoon rainfall, Unambiguous ENSOW were overwhelmingly associated with droughts. For the rainfall in USA and Canada, relationships were not clear-cut except in the Gulf-Mexico region and some other parts. For these regions, excess rains were associated better with the Unambiguous ENSOW.

Key words – ENSO, QBO, QTO, SOI, Decadal trends of precipitation.

1. Introduction

The annual precipitation in different parts of the United States of America and Canada is highly variable. Groisman and Easterling (1994a,b) have produced century-long time series of unbiased estimates of the annual precipitation amount over the United States and Southern Canada (south of 55° N). The data used are records from a 593-station subset of the United States Historical Climatology Network (Karl *et al.*, 1990) and



ROPELEWSKI AND HALPERT (1986)
GB = GREAT BASIN, HP = HIGH PLAINS, GM = GULF-MEXICO

Fig. 1. Map of the United States and Southern Canada showing five homogeneous regions (1) Southwestern Canada/Northwestern USA, (2) Southcentral Canada/Northcentral USA, (3) Southeastern Canada/Northeastern USA, (4) Southwestern USA, (5) Southcentral USA. Regions used by Ropelewski and Halpert (1986) are marked as GB (Great Basin), HP (High Plains), GM (Gulf-Mexico)

1380 Canadian stations. Area averaging of annual precipitation over the U.S. and Canadian regions was performed separately for each country. Using the results of a principal component analysis of runoff data for the United States (Lins, 1985), five homogeneous regions were identified *viz.* Southwestern Canada/Northwestern United States, Southcentral Canada/Northcentral United States, Southeastern Canada/Northeastern United States, Southwestern United States and Southcentral United States (Fig. 1) and their separate time series were obtained. Groisman and Easterling (1994a,b) presented results of trend studies (percentage change per 100 years) and found statistically significant relationships with global surface air temperature series for all regions and with Southern Oscillation Index for the Southwestern USA. The main objective of the present study is threefold: (*i*) estimating long-term trends, if there are any, in the Groisman and Easterling (1994a,b) series, (*ii*) obtain periodicities, if there are any, by the sophisticated method MESA (Maximum Entropy Spectral Analysis) and (*iii*) to check whether excess rains and droughts have any relationship with the ENSO phenomenon, in particular with a finer classification of El Niño years.

2. Trends

Fig. 2 shows a plot of the annual precipitation values for the five subdivisions *viz.* (a) SW-Canada/NW-USA, (b) SC-Canada/NC-USA, (c) SE-Canada/NE-USA, (d) SW-USA, (e) SC-USA as also for the average for the entire region (f) Canada-USA, for the period 1891-1990. The numbers represent years of positive/negative rainfall extremes. The superposed thick lines represent 11-year running means. The following may be noted:

(*i*) There are no uniform upward or downward trends, for any region. Thus, trend estimates per 100 years as a whole would not be very meaningful.

(*ii*) From 1891 to about 1930, the trend is downward for region (a), negligible for (b,c,e) and cyclic for (d). For the whole region (f), the trend is negligible.

(*iii*) For 1930 onwards, the trend is upward for regions (a,b,c) and negligible for (d,e), with cyclic variations superposed in some cases.

Table 1 gives the decadal trends (percentage change per 10 years) for the 5 regions and for the whole region, for 1891-1935 (first 45 years) and 1936-1990 (last 55 years) separately.

Groisman and Easterling (1994a,b) have mentioned that the precipitation series are well correlated with global and hemispheric temperatures. In Fig. 2, the bottommost plot (dashed line) shows the global surface temperature (Vinnikov *et al.*, 1990). The scale is on the right. A general similarity is seen between the temperature and the entire region precipitation changes, but details are not matching. For example, during 1891-1930, the temperature was rising but the precipitation was constant.

3. Periodicities

The annual values shown in Fig. 2 have considerable year-to-year variations, some of which are quasi-biennial. To decipher the periodicities involved, a power spectrum analysis was conducted, by using MESA (Maximum Entropy Spectral Analysis, Ulrych and Bishop, 1975), which detects periodicities much more accurately than the conventional BT method (Blackman and Tukey, 1958). Similar to the parameter lag m in BT, MESA has a parameter called LPEF (Length of the Prediction Error Filter), which can be chosen. With low LPEF, only low periodicities are resolved. Larger LPEF resolve larger

TABLE 1

Decadal trends (percentage change per 10 years) for 1891-1935 and 1936-1990, obtained by a regression analysis of the annual precipitation values

Decadal trends		(Percentage change/10 years)	
		1891-1935 (45 years)	1936-1990 (55 years)
Region 1	SW-Canada / NW-USA	-(2.37 ± 0.86)	+(1.44 ± 0.70)
Region 2	SC-Canada / NC-USA	-(0.44 ± 0.69)	+(1.10 ± 0.65)
Region 3	SE-Canada / NE-USA	-(1.19 ± 0.65)	+(1.73 ± 0.55)
Region 4	SW-USA	-(2.04 ± 1.74)	-(0.01 ± 1.65)
Region 5	SC-USA	+(0.83 ± 1.04)	+(1.10 ± 0.90)
Region 6	Canada-USA(WHOLE)	-(0.74 ± 0.56)	+(1.21 ± 0.48)

periodicities, even those approaching the data length, but the errors are larger and, low periodicities show peak splitting. An LPEF of ~50% of the data length is generally adequate and was used in the present analysis.

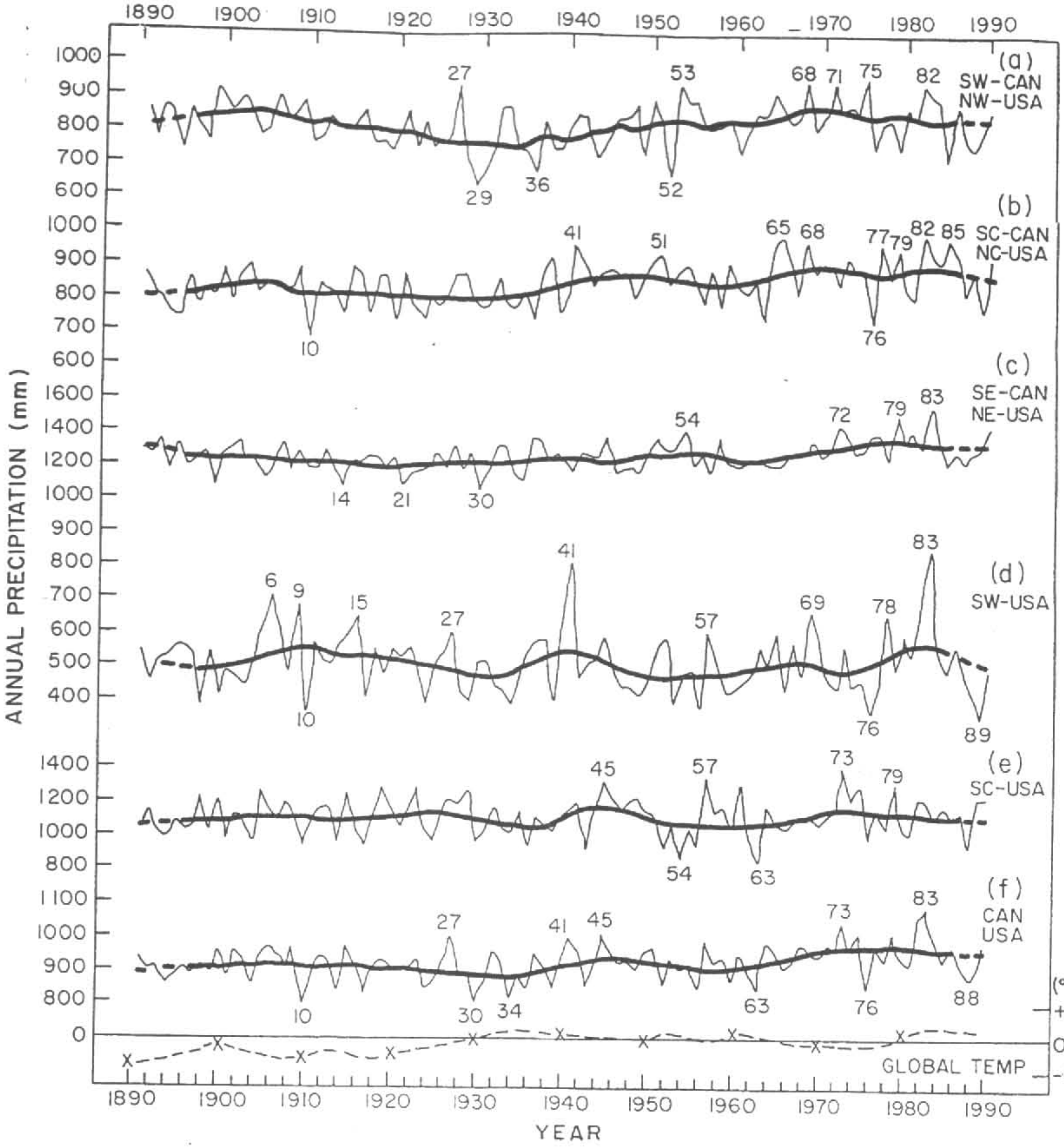
MESA has a drawback *viz*., the power estimates are not reliable (Kane and Trivedi, 1982). Hence, MESA was used only to identify the possible periodicities T_k, which were then used in the expression:

$$f(t) = A_0 + \sum_{k=1}^{n}\left[a_k \mathrm{Sin}\left(2\pi t / T_k\right) + b_k \mathrm{Cos}\left(2\pi t / T_k\right)\right] + E$$

$$= A_0 + \sum_{k=1}^{n} r_k \mathrm{Sin}\left(2\pi t / T_k + \phi_k\right) + E \qquad (1)$$

where $f(t)$ is the observed series and E the error factor. A Multiple Regression Analysis (MRA, Bevington, 1969) was then carried out to obtain the best estimates of A_o, (a_k, b_k) and their standard errors, by a least-square fit. From these, r_k and their standard error σ (common for all r_k in this methodology) can be calculated and any r_k exceeding 2σ would be significant at a 95% (a priori) confidence level.

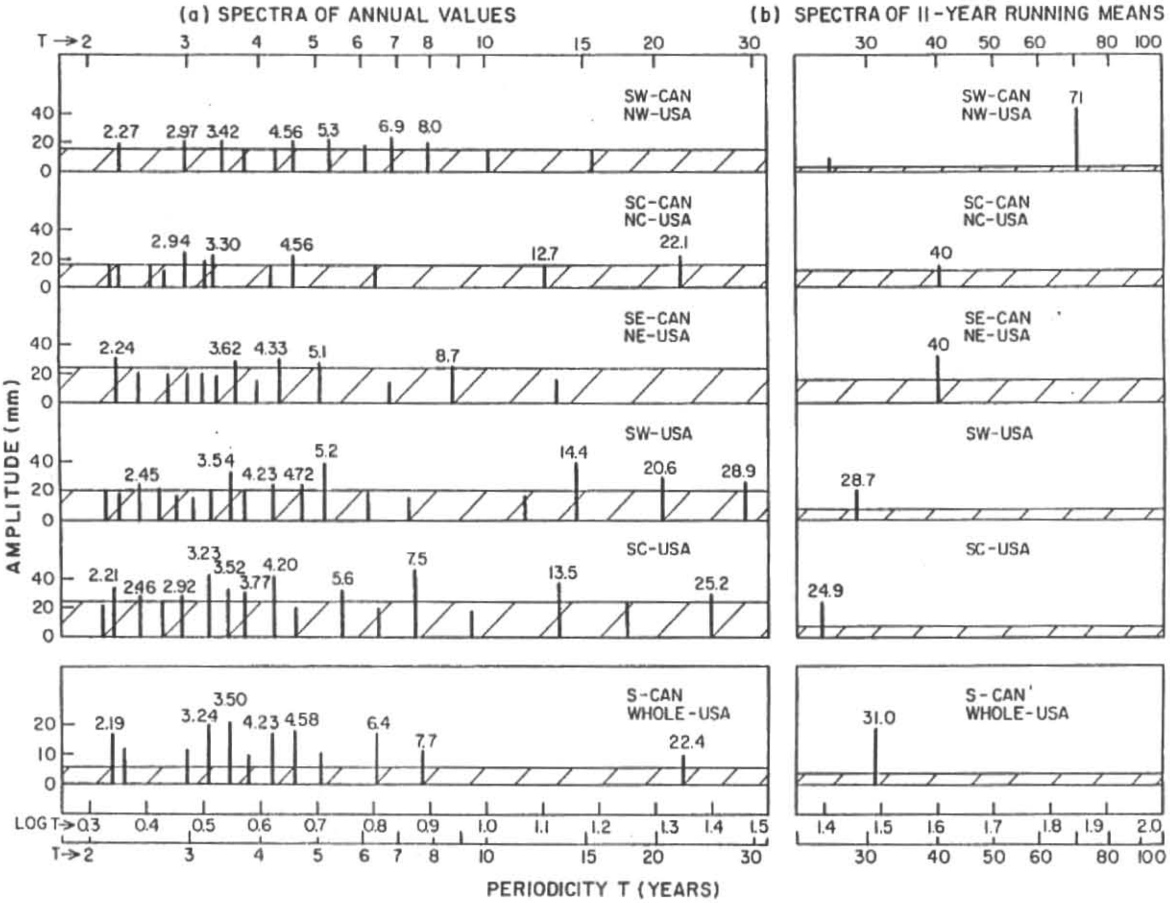
Fig. 3 shows the amplitudes of the various periodicities detected by MESA in the time series shown in Fig. 2. Fig. 3(a) refers to the analysis of the annual values. The hatched portion marks the 2σ limit and, as can be seen, some periodicities stand out above this limit, in all the regions. There are peaks in the QBO region (2-3 years) in all the regions, reflecting the almost alternate year ups and downs in the plots in Fig. 2. The number of peaks is large, indicating possible randomness or transient nature, but this need not be necessarily so. Though peaks are observed in a large range (2-70 years), many are based on physical mechanisms. There are peaks in the QTO region (3-4 years) and larger periodicities also, some common to more than one region and hence, reflected in the series of the entire region (bottom plot). The QBO and QTO peaks could be related to the ENSO (El Niño/Southern Oscillation) phenomenon. This is discussed later in detail. Curiously, there are no peaks near sunspot cycle (11 years), though peaks in the 12-14 year range are seen, some very prominent. It may be noted that the rainfall in NE Brazil also has a periodicity near 13 years, significantly different from the sunspot cycle (Kane and Trivedi, 1988). In the sixth (bottom) plot for whole of USA and south Canada, there is a significant peak at 22.4 years, similar to the 22-year Hale magnetic solar cycle earlier reported by Roberts (1975) for droughts in Nebraska and by Siscoe (1978) for the area extent of droughts in western USA. MESA is very accurate for peak detection and this peak is certainly different from the 18.6 year lunar M_n signal suggested by Currie (1981). There are still higher periodicities; but these can be studied better in the 11-year running mean series spectra shown in Fig. 3(b). The first plot for SW-Canada/NW-USA region shows a 71 years periodicity. However, this may not be reliable as only one cycle is involved in the 100-year data and also, long-term trends could be reflected as false large periodicities. The second and third plots show significant peaks at 40 years and the fourth and fifth plots show peaks



Figs. 2(a-f). Annual precipitation (mm) for (a) SW-CAN/NW-USA, (b) SC-CAN/NC-USA, (c) SE-CAN/NE-USA, (d) SW-USA, (e) SC-USA and (f) entire region CAN-USA. The dashed plot at the bottom shows global surface temperatures (Vinnikov *et al.*, 1990). The numbers on the plots indicate years when excess rainfall extremes occurred

in the range 24-28 years. The whole region spectra show a significant peak at 31 years. In Fig. 2(f) for whole region, the thick line shows broad peaks around 1915, 1946, 1977 and it is tempting to expect excess rains around year 2008, in a gross way (11-year average, 31 years ahead of 1977).

How stable are these periodicities? To check this, the 100-year data series for the whole region [Fig. 2(f)] was divided into 3 parts of 33, 33 and 34 years (1891-1923, 1924-1956, 1957-1990) and each part was subjected to MESA. Fig. 4 shows the results. The top plot is the same



Figs. 3(a&b). Amplitudes of the periodicities (in years, indicated by numbers on each plot) detected by a Maximum Entropy Spectral Analysis of the various precipitation series, using (a) Annual values and (b) 11-year running means. The hatched portions indicate the 2σ limits

as the bottom plot of Fig. 3(a). In the plots for 1891-1923, 1924-1956 and 1957-1990, periodicities at 2.14-2.21 years (QBO) and 3.17-3.23 years (QTO) are common to the three periods and should be considered as stable. Two atmospheric parameters *viz.*, stratospheric low latitude zonal winds and the ENSO indices are known to have QBO and/or QTO. The bottom part of Fig. 4 shows the spectra for the 50 hPa zonal wind for the recent 40 years. The wind has one prominent peak at 2.35 years, a smaller (half size) peak at 2.68 years and still smaller peaks at 2.12 and 3.0 years. Only one of these (the small 2.12 year peak) matches with the precipitation peak. Thus, by and large, the stratospheric zonal winds are not associated with the precipitation. The next two plots are for the Southern Oscillation Index represented by Tahiti minus Darwin mean sea-level atmospheric pressure difference (T-D) (Meteorological Data Reports) and the equatorial eastern Pacific sea-surface temperature SST (for 50 hPa wind, T-D and SST, data available at the website of NOAA, Boulder, Colorado). These two have very similar spectra as expected (both are representative of the ENSO phenomenon), with a most prominent peak at 4.8 years, a subsidiary peak near 3.5 years, and smaller peaks in the QBO region as also higher periodicities. Some of these match with some peaks in the precipitation spectra, indicating some ENSO relationship. However, this is studied in detail in the next section.

4. ENSO relationship with a finer classification

Various studies (Ropelewski and Halpert, 1986; Redmond and Cayan, 1994) mention that ENSO events are

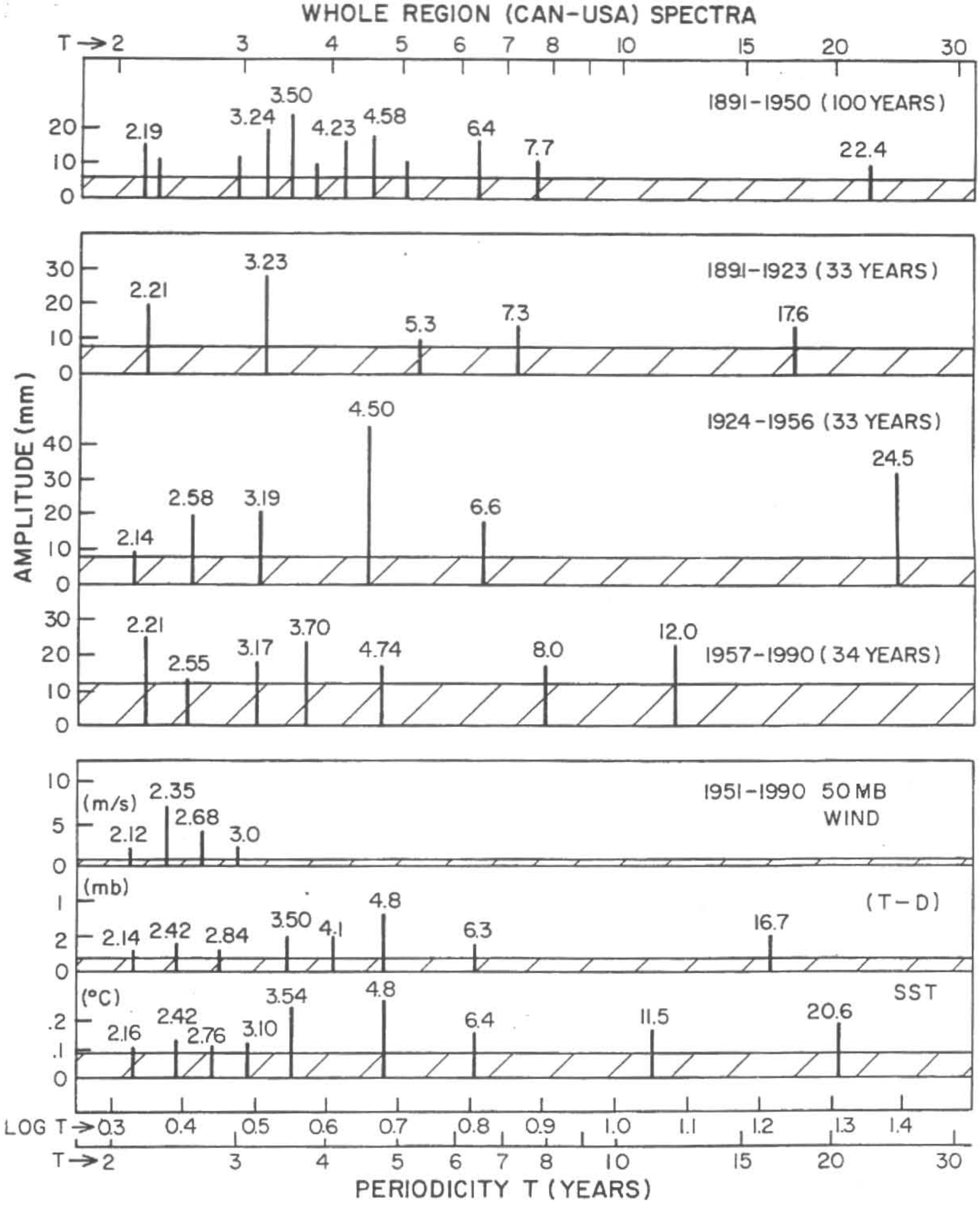


Fig. 4. Amplitudes of the periodicities (in years, indicated by numbers on each plot) detected by a Maximum Entropy Spectral Analysis of the whole region (CAN-USA) precipitation series for 1891-1990 (100 years) (top plot) and for 1891-1923 (33 years), 1924-1956 (33 years), 1957-1990 (33 years). The bottom part shows spectra for the 50 hPa equatorial zonal wind, for the Southern Oscillation Index represented by Tahiti *minus* Darwin sea-level atmospheric pressure difference (T-D) and for the equatorial eastern Pacific sea-surface temperature SST. The hatched portions represent the 2σ limits

TABLE 2

Rainfall status during El Niño years of the types (a) Unambiguous ENSOW, (b) Ambiguous ENSOW, (c) Other types of El Niños. S (strong), M (moderate), W (weak) indicate the strengths of the El Niños involved. I and II indicate first and second years of double events (El Niños in two consecutive years). Columns represent rainfall deviations at (1) SW-CAN/NW-USA, (2) SC-CAN/NC-USA, (3) SE-CAN/NE-USA, (4) SW-USA, (5) SC-USA, (6) Whole region, CAN-USA; Regions used by Ropelewski and Halpert (1986), (7) Great Basin GB, (8) High Plains HP, (9) Gulf-Mexico GM; and (10) All India summer monsoon rainfall (Parthasarathy *et al.*, 1992). The symbols + and - indicate positive and negative deviations within 0 and σ, while triangles (positive) and circles (negative) represent deviations exceeding σ

(a) Unambiguous ENSOW

	(1) SW CAN NW USA	(2) SC CAN NC USA	(3) SE CAN NE USA	(4) SW USA	(5) SC USA	(6) ALL CAN USA		(7) GB	(8) HP	(9) GM	(10) ALL IND
M 1896	+	+	-	+	-	+		+	+		-
S 1899	Δ	-	O	+	-	-		-	+		O
M 1902	+	+	Δ	-	+	+		+	Δ		-
M 1905	-	+	O	Δ	Δ	+		Δ	+		O
S 1911	-	+	-	-	-	-		-	+		O
S 1918 I	-	+	+	+	-	+		-	Δ		O
M 1930 I	O	-	O	+	O	O	+	+	+		-
S 1941 II	Δ	Δ	O	Δ	+	Δ	Δ	Δ	Δ		O
M 1951	-	Δ	Δ	+	+	Δ	+	+	-		O
S 1957 I	-	+	O	Δ	Δ	Δ	Δ	Δ	Δ		-
M 1965	+	Δ	-	+	-	+	Δ	Δ	+		O
S 1972 I	+	-	Δ	-	-	-	+	+	Δ		O
M 1976	O	O	+	O	O	O	+	-	+		+
S 1982 I	Δ	Δ	-	Δ	+	Δ	Δ				O
M 1987	O	O	O	-	+	O					O
Positive/ Total	0.5	0.7	0.3	0.7	0.5	0.6	1.0	0.7	0.9		0.9
Negative/Total	0.5	0.3	0.7	0.3	0.5	0.4	0.0	0.3	0.1		0.1

(b) Ambiguous ENSOW

	(1) SW CAN NW USA	(2) SC CAN NC USA	(3) SE CAN NE USA	(4) SW USA	(5) SC USA	(6) ALL CAN USA		(7) GB	(8) HP	(9) GM	(10) ALL IND
M 1914	-	O	O	+	O	O		+	Δ		+
M 1919 II	-	+	+	-	Δ	+		-	+		+
M 1923	+	O	-	-	Δ	+	Δ	Δ	+		-
M 1925 I	+	-	Δ	-	O	-	Δ	-	Δ		-
M 1926 II	+	-	+	+	+	+	-	-	-		+
M 1931 II	-	-	-	+	-	-	O	-	+		+
S 1940 I	+	O	-	Δ	+	+	+	O	+		-
W 1948	Δ	O	O	-	+	-	-	-	+		+
M 1953	Δ	+	+	O	-	+	O	O	-		+
S 1958 II	-	O	Δ	+	+	+	-	+	+		+
W 1963	+	O	-	+	O	O	Δ	-	+		+
W 1969	O	-	+	Δ	-	-	+	Δ	+		-
S 1983 II	Δ	+	Δ	Δ	+	Δ	Δ				Δ
Positive/Total	0.6	0.2	0.5	0.6	0.5	0.5	0.5	0.3	0.8		0.7
Negative/Total	0.4	0.8	0.5	0.4	0.5	0.5	0.5	0.7	0.2		0.3

TABLE 2 (*Contd.*)

(c) Other El Niños

	(1) SW CAN NW USA	(2) SC CAN NC USA	(3) SE CAN NE USA	(4) SW USA	(5) SC USA	(6) ALL CAN USA		(7) GB	(8) HP	(9) GM	(10) ALL IND
ENSO S 1891	+	Δ	-	+	+	+		+	-		-
EN M 1897	-	-	-	+	-	-		+	O		+
ENSO S 1900	+	Δ	+	O	+	+		Δ	+		+
ENC M 1907	-	-	Δ	+	+	+		-	+		-
ENSO S 1912	+	+	Δ	-	+	+		-	+		-
ENC S 1917	-	O	+	O	O	O		O	O		Δ
EN S 1932	Δ	+	Δ	-	+	Δ	-	+	+		-
EN M 1939	-	O	+	O	-	O	+	O	-		-
EN M 1943	O	-	+	-	O	O	-	O	+		+
ENC S 1973	+	+	+	+	Δ	Δ	-	+	-		+
Positive/Total	0.5	0.5	0.8	0.4	0.6	0.6	0.2	0.5	0.5		0.5
Negative/Total	0.5	0.5	0.2	0.6	0.4	0.4	0.8	0.5	0.5		0.5

associated with discrete precipitation patterns in particular regions of the United States. However, not all ENSO events show similar effects. Recently, a finer classification of ENSO events has been proposed which seems to show improved relationships with droughts in India and Australia (Kane, 1997; Kane 1998). The precipitation records of the five regions will be examined now to see if any improved relationships can be obtained.

The term ENSO is used nowadays for the general phenomenon of the Walker circulation. However, in the classification here, its components EN, SO are used in their literal sense. Thus, every year was examined to check whether it had an El Niño EN (as listed in Quinn *et al.*, 1978, 1987), and/or Southern Oscillation Index SOI minimum (SO) and/or warm (W) or cold (C) equatorial eastern Pacific sea surface temperatures (SST). Several years had ENSOW *i.e.*, El Niño existed and SOI had minima and Pacific SST were warm. These were subdivided into two groups *viz.*, Unambiguous ENSOW where El Niño existed and the SOI minima and SST maxima were in the middle of the calendar year (May-Aug) and, Ambiguous ENSOW where El Niño existed, but the SOI minima and SST maxima were in the early or later part of the calendar year, not in the middle. Besides these, there were other years having El Niño of the type ENSO (*i.e.*, SOI minima existed but SST was neither warm nor cold, just normal), ENW, ENC (*i.e.*, SOI minima did not exist but SST was warm W or cold C) or just EN (*i.e.*, only El Niño, no SOI minima, no SST maxima or minima). Many other years did not have an El Niño and are not considered here.

In Fig. 2, the thick lines show some long-term trends. If the yearly values are expressed as deviations from a general mean for the 100 years, values near 1930 would be mostly negative and, for the El Niños which occurred in this period, the association would seem to be with droughts. (Incidentally, for India and South Asia, Kripalani and Kulkarni (1997a,b) have shown that the impact of El Niño on rainfall variability is more severe during the below normal epochs). Hence, for studying short-term effects like those of El Niños, the long-term trends, whatever these are, need to be removed. In Fig. 2, the thick lines represent such long-term trends and these were subtracted from the annual values. The residual series were normalized *i.e.*, expressed as fractions of the standard deviation of the residual series. Positive and negative deviations within 0 to σ were designated as + and −, while those exceeding σ were designated as triangles (positive, floods) and circles (negative, droughts).

Table 2 shows the rainfall status of the five regional series for (a) Unambiguous ENSOW years, (b) Ambiguous ENSOW years and (c) Years of other types of El Niños (ENSO, ENW, ENC, EN). The symbols S (strong), M (moderate), W (weak) indicate the strength of the El Niño involved. The columns 1-5 show the rainfall status for the five divisions and column 6 represents the whole region. For United States, Ropelewski and Halpert (1986) reported good ENSO relationship for some regions. Their data for Great Basin (GB), High Plains (HP) and Gulf and Mexican region (GM), marked in Fig. 1, are represented by columns 7, 8, 9 in Table 2. India is far away from USA and no teleconnections are expected. But the finer classification of El Niños mentioned above gave good results for All India Summer Monsoon Rainfall (AISMR, Parthasarathy *et al.*, 1992). Hence, in Table 2, results for AISMR are also given, in column 10, just for comparison. The following may be noted:

(*i*) For the 15 Unambiguous ENSOW years [Table 2(a)], AISMR shows negative deviations for 14 events, a very good association with droughts. The bottom rows of Table 2(a) show the fractions of positive and negative deviations. For AISMR, the fractions are (1/15)=0.1 for the positive deviations and (14/15)=0.9 for the negative deviations. For the Great Basin (GB) and Gulf-Mexico (GM) regions of Ropelewski and Halpert (1986), the fractions are 1.0, 0.9 for the positive deviations and 0.0, 0.1 for the negative deviations, indicating an overwhelming association with excess rains. However, for the HP region, the fraction for positive deviations is 0.7, indicating a bias for excess rains but not overwhelming. For the regions 1-5, only regions 2 and 4 show a bias (0.7) for excess rain. Regions 1 and 5 show no bias (0.5) while region 3 shows a bias for negative deviations (negative fraction 0.7). Thus, different parts of Canada-USA react differently (including no clear reaction) to this type of ENSO. Ropelewski and Halpert (1986) had noted this fact, mentioning that the High Plains precipitation did not have a very good relationship with ENSO events.

(*ii*) Table 2(b) refers to Ambiguous ENSOW. Here, AISMR shows mixed results, in fact, slightly opposite results, *viz.* a slight bias for excess rains (positive fraction 0.7). Among the El Niño events, some are double events *i.e.*, occurring in two successive years. Theses are marked as I and II in Table 2 and, most of the second years appear as ambiguous events and gave excess rains (instead of droughts) for AISMR. For the series of Ropelewski and Halpert (1986), mixed results are seen. Thus, Gulf-Mexico GM shows a bias for positive deviations (0.8), indicating that this region shows similar results (excess rains) for both, Unambiguous as well as Ambiguous ENSOW. On the other hand, region Great Basin (GB) now shows no bias (0.5), while region High Plains (HP) shows bias for droughts (negative fraction 0.7). In regions 1-5, region 2 shows a bias for droughts (negative fraction 0.8), while other regions show fractions 0.4-0.6, *i.e.*, mixed results. Thus, except for Gulf-Mexico region, the ENSO association is not satisfactory.

(*iii*) Table 2(c) refers to other types of El Niños. From the 10 events, 3 are ENSO, 4 are EN and 3 are ENC. For AISMR, the results are mixed, 5 positive and 5 negative deviations, with no bias for any type. For the ROHA series, GM and HP showed mixed results (fractions 0.5), while GB had limited data (4 events only) and showed 3 negatives. Among the regions 1-5, only region 3 (eastern region) showed a bias for positive deviations. (For the Unambiguous ENSOW, this region had showed a bias for negative deviations, and for Ambiguous ENSOW, mixed results). Thus, these types of El Niño also give unsatisfactory results.

Summarising, the ENSO relationships with precipitation in the regions of contiguous United States and Southern Canada considered here are mostly weak, except in the Gulf-Mexico region and some smaller areas like the Great Basin. Among the El Niños, the Unambiguous ENSOW type shows the best association with excess rains in these areas, while for the All India summer monsoon rainfall, such events show a very good association with droughts.

5. Conclusions

Using the precipitation data (annual values) for the five homogeneous regions of contiguous United States and Southern Canada given by Groisman and Easterling (1994a,b), the trends, spectral characteristics and ENSO relationships were studied in detail, for the period 1891-1990. The trends were not uniformly upward or downward for the 100-year interval, for any region. From 1891 to about 1930, the trends were downward or negligible. From 1930 onwards, the trends were mostly upward, with cyclic changes superposed. A power spectrum analysis revealed significant periodicities in the QBO/QTO regions (Quasi-biennial and Quasi-triennial oscillations, 2-3 and 3-4 years) as also higher periodicities, not all similar in the five regions. A finer classification of El Niño events had earlier shown that events of the Unambiguous ENSOW type (years when El Niño existed and the Southern Oscillation Index minima and equatorial eastern Pacific sea-surface temperature maxima occurred in the middle of the calendar year, May-August) had a very good association with droughts in India and Australia. For the USA and Canadian regions considered here, the ENSO relationship was not very strong except in the Gulf-Mexico region and some other parts. For these parts, the relationship was better for the Unambiguous ENSOW.

Since the smaller regions selected by Ropelewski and Halpert (1986) show better associations, we suspect that the 5 regions considered here are too broad and probably not all homogeneous. An analysis for smaller regions is in progress and results will be reported soon. Another possible source of discrepancy is the time intervals. For the data of the five divisions, we have used annual (January-December) values, while Ropelewski and Halpert (1986) mention that the ENSO relation for Gulf-Mexico region is seen for October (0) to March (+) season. However, for Great Basin and High Plains, the season they used is April (0) to October (0), which should not be very different from the annual values used in this study.

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