CLIMATIC TRENDS OF TEMPERATURE AND PRECIPITATION

in the

CONTINENTAL UNITED STATES

by

Dr. Hurd C. Willett
Massachusetts Institute of Technology

I. Introductory Remarks

The analysis of climatic trends in the United States which is reported briefly in this paper was initiated as part of a study of long-term solar-weather relationships. This investigation is supported almost 100% by the joint Weather Bureau - M. I. T. Extended Forecasting Project. Because of unavoidable delay in the completion of the solar phase of this study, the following discussion is concerned only with the climatic data, without reference to the accompanying state of solar activity.

The period covered by the study extends for the most part from 1899 - 1956, inclusive, to coincide with the Weather Bureau northern hemisphere historical map series, which will be used to study parallel changes of the pattern of the general circulation of the northern hemisphere. The data that are discussed in the following pages are derived almost entirely from the Climatological Data of the U. S. Weather Bureau.

The primary purpose of this climatic study is to obtain an integrated picture of climatic trends over the entire country. Only a limited amount of sectional breakdown of the picture is attempted, in the section between the continental divide and the Mississippi River, where the cyclical pattern of drought has been of critical importance.

II. Outline of Statistical Procedures

The nationwide trend of each of the two weather elements, temperature and precipitation, is obtained in the following manner:

1. The seasonal departures from normal of each element for the period 1899-1956 inclusive, are computed from the mean monthly departures for each of the 44 climatological sections into which the country is divided in the Weather Bureau climatological data.

2. For each climatological section the seasonal temperature departures are expressed as ratios to the standard deviation of the mean temperature for each season, and the seasonal precipitation departures as percentages of the

mean for each season.

3. The seasonal departures of temperature and precipitation expressed in this manner for each climatological section are then multiplied by a constant factor which expresses the ratio of the area of the section to the total area of the country.

4. The sectional seasonal departures of temperature and precipitation weighted by sectional area are then added for the entire country to give a mean seasonal departure for the country expressed as the average of the standard deviation ratios of all 44 sections, weighted by area. Annual mean sectional and nationwide departures are obtained by averaging the four calendar seasonal departures, for the years beginning with December instead of January.

5. Annual and seasonal mean nationwide cumulative trend curves of temperature and of precipitation are obtained by adding for successive years the annual and seasonal (for each calendar season separately) nationwide departures. The annual and four seasonal nationwide cumulative trend curves for temperature are given by the uppermost curve in Figs. 1 - 5. The corresponding curves for precipitation are given by the uppermost curve in Figs. 6 - 10.

Shifting of the centers of annual or calendar seasonal areas of positive and of negative nationwide departures of temperature and of precipitation is computed as follows:-

1. The weighted (by area) sectional seasonal departures of temperatures and of precipitation (as computed under (3) above) are multiplied in turn by each of two factors. One of these factors gives the north (+) or south (-) distance in degrees of latitude of the center of the respective sectional area from the areal center of the continental United States (approximately 39° N and 99° W). The other factor gives the distance in kilometers east (+) or west (-) of the center of the respective sectional area from the meridian of the areal center of the United States.

2. The products obtained with each coordinate factor in (1) are summed separately for the positive and for the negative sectional seasonal departures of each element. The four sums thus obtained for each element for each calendar season give the latitudinal (in degrees) and the longitudinal (in kilometers) displacement from the geographical center of the nation of 39° N and 99° W, of the areal center of gravity of the total nationwide negative anomaly, and of the total nationwide positive anomaly, of the respective element for the respective season. Annual mean latitudinal and longitudinal displacements of the weighted center of the areas of total negative and of total positive anomaly of temperature and of precipitation are obtained for the December - November calendar years by averaging the four seasonal values.

3. Annual and seasonal mean nationwide cumulative trend curves of the latitude and of the longitude of the weighted centers of the areas of total negative and those of total positive departure of temperature and of precipitation are obtained by

adding for successive years the annual and the seasonal (for each calendar season separately) displacements of the centers of the nationwide anomaly areas as computed under (2) above. The annual and four seasonal trend curves for the latitude and longitude of the weighted centers of the nationwide areas of temperature surplus are represented by the two middle curves in Figs. 1 - 5, those of the areas of temperature deficit by the two curves at the bottom of Figs. 1 - 5. The corresponding annual and seasonal trend curves for the weighted centers of the nationwide areas of precipitation surplus and deficit are represented similarly by the middle and bottom curves, respectively- in Figs. 6 - 10.

To obtain a crude latitudinal breakdown of climatic trends in the critical area between the continental divide and the Mississippi valley an entirely different procedure was followed. It was decided to compare trends in three widely separated zonal belts, each belt to be represented by the records of three or four weather stations of long standing. To represent the northern strip in the Canadian wheat belt north of the border four stations were selected, Edmonton and Calgary, Alberta, Prince Albert, Saskatchewan, and Winnipeg, Manitoba. To represent a narrow belt at Mid-latitudes in the United States, three stations were selected, Denver, Colorado; North Platte, Nebraska and Omaha, Nebraska. To represent a narrow belt in the southernmost latitudes of the United States, four stations were selected, Yuma, Arizona and El Paso, Abilene and Galveston, Texas.

Each of these three groups of stations was treated as a climatological unit or section, as follows:

1. The monthly departures of temperature at each station in the group are averaged to give seasonal departures which in turn are averaged to give the seasonal departure of the group. Standard deviations are then computed for each of the three groups of stations for each calendar season, and the individual seasonal departures of each group are expressed as ratios to the corresponding seasonal standard deviations.

2. The four celandar seasonal departure - deviation ratios for each group for each year are averaged to give an annual mean ratio for the December - November years.

3. Annual and calendar season cumulative trend curves of temperature are computed for each group of stations by adding the annual and seasonal (for each calendar season separately) departure - deviation ratio values for the successive years. These temperature trend curves are plotted in Figs 11 - 15 for the three zones arranged by decreasing latitude from the top to bottom of each figure.

4. The monthly departures from normal of the total precipitation at each station in each group are summed to give total seasonal departures from normal of precipitation by individual stations. These seasonal station departures from

normal are expressed as percentages of the station normal, and then averaged for the stations in each group to give seasonal group percentage departures from normal.

5. The four calendar seasonal percentage departures from normal for each group are averaged to give a December - November annual mean percentage departure of the group.

6. Annual and calendar season cumulative trend curves of precipitation are computed for each group of stations by adding the annual and seasonal (for each calendar season separately) percentage departures for the successive years. These precipitation trend curves are plotted in Fig. 16 - 20 exactly as the corresponding temperature trend curves are plotted Figs. 11 - 15.

III. Temperature Trends in the United States

The following features of interest concerning the over-all trend of temperature in the continental United States (exclusive of Alaska) may be noted in Figs. 1 - 5.

1. We note in Fig. 1 that in considering annual means for the country as a whole during the past 58 years a rather simple temperature trend pattern emerges. An outstandingly cold decade from 1910 - 1920 (down 3-1/2 standard deviations) and a warm decade from 1930 - 1940 (up three standard deviations) comprise the only really abnormal periods. For the remainder of the time the country as a whole averaged very close to the long-term normal. It might be noted that a gain of one standard deviation in one year (which was exceeded in 1934) requires an average nation-wide warmth equivalent to that of all 44 climatological sections during each season of that year being warm by an amount slightly in excess of that which occurs for each season in one year out of six.

2. No significant trends appear in the cumulative trend curves of the position of the centers of the weighted annual mean centers of surplus or deficit of temperature. In other words, there was no persistent latitudinal or longitudinal displacement of annual mean positive or negative temperature anomalies from the areal center of gravity of the country.

3. When we look at the pattern of behavior of the seasonal temperature anomalies we note that something of the annual mean pattern is to be seen in each of the four seasons, although with some substantial variation.

4. During the winter season, the cold decade of the teens was strongly pronounced, but above normal conditions have tended to prevail from 1920 to the present, with no outstandingly warm decade during the thirties. During this season the weighted areas of positive temperature anomaly show little consistent pattern of displacement, whereas the weighted areas of deficit show a tendency to shift along a NW - SE axis (opposition in the slope of the two coordinate trend curves).

5. During the spring season the cold decade of the teens and the warm decade of the thirties stand out clearly from the remaining period as they did on the annual means, but with slightly smaller average departure (slope of the trend curve). There is again a slight suggestion of a NW - SE oriented axis of shift of the weighted deficit centers.

6. The summer season is notable primarily for the fact that its temperature trends are much stronger than those of any other season, a fact that is obscured by the usual presentation of departures from normal in degrees, because deviations about the mean trend to be significantly less than during the other seasons, particularly winter. Most noteworthy is the fact that during the warm decade of the thirties, the summer averaged twice as warm as during any other season, or during the year as a whole, and that whereas the cold decade of the teens is as cold as it was during any other season, the previous decade was equally cold, which was not at all true of any other season. To be noted also is the warmth of the peak drought summers of 1934 and 1936, each averaging close to two standard deviations above normal for the 44 climatological districts, weighted by area.

7. Another striking feature of the summer season (Fig. 4) is the highly combined consistent opposition, both latitudinally and longitudinally, of the locations of the centers of the weighted areas of surplus and deficit of temperature. Such consistent opposition is not characteristic of any other season. Most noticeable is the poleward displacement of the surplus anomaly center during the very warm decade.

8. By and large the cumulative trend curves of the autumn season are weak like those of the spring season, perhaps even weaker, although the same warm decade and cold decade are clearly recognizable. During this season the cold decade is more pronounced than the warm decade, like winter and spring. Nothing worthy of note suggests itself concerning positional trends during the autumn season.

IV. Precipitation Trends in the United States.

A number of interesting features concerning the over-all trend of precipitation in the continental United States may be noted in Figs. 6 - 10, as follows:-

1. We note in Fig. 6 that the annual means of precipitation during recent years show much stronger cumulative trends than do those of temperature. In earlier years a wet period from 1904 - 1916 ushered in the cold decade of the teens, and markedly dry conditions prevailed during the warm decade of the thirties. However, whereas there appears little cumulative trend of temperature since 1940, the decade of the forties was as wet as any earlier decade, while following 1950 the cumulative trend turned more sharply downward than during any earlier period. This downward trend probably continued even more sharply through 1956, but has been very strongly reversed since then.

2. Several features may be noted in the cumulative trend curves of the coordinates of the weighted surplus and deficit centers of precipitation. During the early wet and progressively cooler period ending in 1916 there was a tendency for deficit centers to favor the southern part of the courtry, whereas during and preceding the dry period of the thirties was a tendency for the surplus centers to favor the southern part of the country. During the recent short and very dry period, there is a pronounced tendency for deficits to occur in the south, surpluses in the north.

3. The seasonal cumulative trend of precipitation show much stronger deviations from the annual mean trend curves than do those of temperature from the annual mean trend of temperature.

4. The winter season contributes very strongly, about 50% of the total, to the annual cumulative surplus of precipitation from 1904 - 1916. On the other hand, the principal winter deficit accumulated from 1917 - 1930, and not at all during the drought decade of the thirties, while the sharply dry period since 1950 is reflected only weakly in the winter trend curve. There was also little contribution to the wet decade of the forties.

5. Most noteworthy in the winter coordinate trend curves is the tendency during the dry periods following 1916 and again following 1950 for the latitude of the weighted surplus and deficit centers to show opposite displacements, during the earlier drought period surplus centers tended to be equatorward, deficit centers poleward of the geographical center, while during the recent drought this opposition was sharply reversed in sense.

6. The spring season contributed only slightly to the wet period from 1904 - 1918, and that contribution was made entirely from 1905 - 1908, well before the cold decade started. On the other hand, the spring season contributed strongly to the drought decade of the thirties and to the wet decade of the forties, but only slightly to the recent dry period.

7. The spring trend curves of the coordinates of the weighted surplus and deficit centers also reflect weakly the same tendency since 1916 for opposite latitudinal displacement of the surplus and deficit centers that is indicated by the winter season.

8. The summer season contributes strongly to all features of the annual cumulative precipitation trend except to the drought following 1950, which scarcely shows at all. It contributes most strongly to the drought of the thirties, as it did also, to the warmth of that decade. This contrast reflects the fact that the extreme summer weather patterns of the thirties tended to be nation-wide (strongly zonal) in character, whereas those of the fifties were strongly cellular, with strong compensating intersectional contrasts.

9. Summer trend curves of the coordinates of the weighted surplus and deficit centers show a slight consistent trend for both positive and negative anomalies to be centered west of the geographical center, i.e., for percentage de-

partures of precipitation to be greater in the west than in the east, and for some slight degree of opposition in the latitudinal displacement of the centers of positive and of negative anomaly. The first of these two effects could not exist if the departures were expressed in standard deviations like the temperature instead of in percentages. In that case all of the cumulative trend curves must end close to the axis (cf. Figs. 1 - 5 with Figs. 6 - 10).

10. The autumn season is in outstanding contrast to the winter season in that the large nationwide trends of precipitation occur after 1925, whereas in the winter season they occurred previous to 1925. During the earlier period is to be noted the normality of the years 1904 - 1916, in contrast to extreme wetness during the winter season. On the other hand, there is a period of extreme wetness just previous to 1930 which does not appear at all in the annual means or during any other season. The drought of the thirties is strongly reflected in the autumn trend curve, as is the wetness of the forties, and particularly the drought following 1950.

11. The only noteworthy feature of the autumn trend curves of the weighted surplus and deficit centers is the slight tendency during most of the period for both positive and negative anomalies to be centered south of the geographical center, thus indicating a tendency during this season for the largest percentage fluctuations of precipitation to occur in the southern part of the country, as during the summer they do in the western.

In conclusion it may be said about the nationwide trend of temperature and precipitation that:-

(a) There exists a consistent long-term cycle of temperature, perhaps about 80 years in length, such that cooler temperatures tended to prevail previous to the twenties, warmer since, a cycle which is contributed to in varying amount by each of the calendar seasons, most strongly by summer.

(b) There exists no corresponding long-term cycle of precipitation. Such fluctuations as exist are shorter and irregular in period, and highly erratic as to their comparative behavior during the different calendar seasons.

V. Latitudinal Breakdown of Temperature Trends in the Western Plains

Figures 11 - 15 contain the same cumulative trend curves of standard deviation of temperature for each of the three east - west station sections east of the Divide that are contained in the top curves of Figs. 1 - 5 for the nation as a whole. The vertical scale is reduced to half of that in Figs. 1 - 5, because the standard deviations apply to single sectional groups of stations instead of being averaged for a number of sectional groups of stations, hence run considerably larger. The three short heavy lines appearing under each cumulative trend curve (four under the bottom curve) in all five figures, indicate, from left to right, the five-year stretch of maximum annual mean coldness during the early cold period, the five-year stretch of lowest level (turn from cold to warm) of the annual mean trend curves, and the comparatively recent five-year stretch of maximum annual mean warmth (two periods for the southern stations.)

The following facts of interest may be noted concerning the long-term temperature trends in America between the Continental Divide and the 95th Meridian:

1. The annual mean temperatures of all three sections, Fig. 11, show the same long-term cyclical trend as that of the nationwide mean temperature, but the greater extension of the record to earlier years in this sectional analysis indicates that the length of the full cycle is almost certainly 80 - 90 years as surmised from the nationwide data.

2. Certainly in this west - central portion of the continent, and probably in the country as a whole, the coldness of the twenty years previous to 1900 was much more pronounced than that of the 1910 - 1920 decade. The latter cold period does not appear at all in the Canadian section, and only weakly in the two United States sections. This agrees with Brückner's early analysis, which indicates that in most sections of the northern hemisphere a minimum of temperature was reached in the 1880 - 1890 decade. Likewise, the pentad of maximum warmth does not adhere too closely to the nationwide warm decade of the thirties, but starts with 1919 in the Canadian section, with 1930 in the mid section, and in 1933 and again in 1950 in the southern section.

3. By far the largest amplitude of the cumulative trend cycle, i.e., the greatest year-to-year consistency of the cyclical fluctuation, is manifest in the curve of the southern section. Note, for instance, that for the 20-year period 1880 - 1899 inclusive, every single year in that section was colder than normal, while for the period since 1932 temperatures have been almost equally consistently warm.

4. The pentads of maximum coldness, those of change of trend, and those of maximum warmth all show a consistent, if somewhat irregular, lag in years as one progresses from higher to lower latitudes.

5. Surprisingly enough the temperature trends of the winter season, Fig. 12, are weaker and more erratic than those of the annual means in all three sections, but particularly so in the southern section where the annual mean trends are outstandingly consistent. By and large the winter cumulative trend curves manifest the essential long-term features of the annual mean curves, but at least four of the 10 significant pentad periods of the annual means are not at all reflected in the winter season curves.

6. Except perhaps in the southern section, the cumulative trend curves of temperature for the spring season (Fig. 13) are even weaker and more erratic than those of the winter season, corresponding exactly in this respect to the cumulatime trend curve of spring season temperature for the country as a whole. Not

half of the 10 strong pentad periods of the annual mean curves are significantly reflected in the curves for the spring season, which is the weakest of the four seasons trendwise for both sectional and nationwide mean temperatures.

7. The summer sectional trend curves of temperature (Fig. 14), for all three sections, like the nationwide curve, are much the strongest and most regular of those of any season. Likewise, all 10 of the strong pentad periods are significantly reflected in the trend curves for this season. We might note that during this season the warm decade of the thirties is strongly reflected in all three sections (including the Canadian), as is the recent warm decade in the southern section. However, it is clear again here that the cold decade of the teens is practically non-existent in comparison with the coldness approximately from 1880 - 1908. Note again the amazing uniformity of the temperature cycle in the southern section, where every summer from 1880 - 1900 inclusive, was significantly colder than normal, and only one summer from 1924 - 1957 was colder than normal.

8. The sectional cumulative trend curves of temperature for the autumn season (Fig. 15) are notably weaker and less consistent than those of the summer season, but in general appear to be stronger than those of any other season except summer. Particularly the southern section retains a close similarity during this season to the annual mean, and to the summer season in a less extreme degree. The warm decades of the thirties and of the last ten years are well reflected in the two American sections, but not in the Canadian.

In summary, the outstanding features to be remarked on these west-central sectional trend curves of temperature are the following:

1. A clear cyclical trend in temperature of some 80 - 90 years in period, which can be seen for all four seasons and all sections, and which is generally strongest in summer, second strongest in autumn and weakest in spring.

2. A definite tendency for the changes to occur at some years lag in lower latitudes. The coldest weather in all sections occurred previous to 1900, but the warmest weather occurred between 1912 - 1944 in the northern section, 1930 - 1948 in the middle section, and 1933 - 1957 in the southern section.

3. Both the annual and the seasonal trends are stronger and more consistent in the southern than in the middle and northern sections.

VI. Latitudinal Breakdown of Precipitation Trends in the Western Plains

Figures 16 - 20 contain the same cumulative trend curves of percentage departures of precipitation for each of the three east - west station sections east of the Divide that are contained in the top curves of Fig. 6 - 10 for the nation as a whole. In comparison with the temperature curves, the precipitation curves show the same variable complexity and lack of consistency between the seasonal and annual mean curves that was shown by the nationwide trend curves of precipitation compared with those of temperature. Attention is called to the fact that in Figs. 17 - 20 the vertical scale of the trend curves (seasonal) is reduced to half of that of Fig. 16 (annual). No similar scale reduction is made in plotting any of the other seasonal curves. The following items may be noted:-

1. In the annual mean curves (Fig. 16) the outstanding periods to be noted, for which the strongest pentads again are underlined to follow the intersectional continuity, are the following:

   a. A wet period before 1890 which is not reflected in the northern section due to shortness of the record.

   b. A following dry period which falls mostly in the decade of the nineties.

   c. A rather sharp reaction to a wet period which is terminated in all sections by 1915.

   d. A strong dry period in the middle section centered on the warm decade of the thirties (the dust bowl decade) which is reflected only very weakly in the northern and southern sections.

   e. A strong dry period culminating in 1956 in the southern section which is very slightly reflected in the middle section and to some extent reversed on the northern.

2. Again there is some evidence, in the strongest pentads of these periods, for the weather in the south to lag after that in the north, but this relationship is less clear than it is in the corresponding trend curves of temperature.

3. Particularly since 1915 there have occurred marked divergences in the cumulative trend pattern for the three sections, as follows:

   a. In the northern section, trends have been notably weak, but tending to be wet since 1931, particularly during the last five years.

   b. In the middle section, the trend was strongly dry from 1919 to 1940. since then moderately wet except for the last five years.

   c. In the southern section the trend was predominantly wet through 1945, since then extremely dry, particularly during the last five years. The only previous prolonged drought period in the south was during the nineties, on record in some places as rivalling the recent drought in severity, but certainly not in the average of this section.

4. Figure 17 shows that the sectional winter season cumulative trend curves,

like the corresponding temperature curves are characterized by more erratically variable trends than are the annual mean curves, and by little correspondence in detail, as indicated by a failure of most of the strong annual pentad periods to be significantly reflected in this season.

5. Particularly noteworthy deviations of the winter season trend curves of precipitation from the annual curves are perhaps the early drought period (previous to 1905) in the Canadian and the southern sections, and the disappearance of the wet trend in the southern section from 1905 to 1945.

6. In general the cumulative sectional trend curves of precipitation for the spring season (Fig. 18) bear a closer resemblance to the annual mean curves than do those of the winter season, but there does occur considerable deviation in detail, as shown by the failure of a number of the outstanding pentad periods to be significantly reflected. Along with the deviations of the seasonal trend curves from the annual mean curves there goes also a decrease of any consistent lag relationship from northern to southern sections.

7. The cumulative trend curves of precipitation for the summer season (Fig. 19) look more like the annual mean curves for the two northern sections than do those of any other season, but that definitely is not true of the southern section. The majority of the outstanding pentad periods are reasonably reflected in the curves for this season.

8. The cumulative trend curves of precipitation for the autumn season (Fig. 20) deviate rather widely from the annual mean curves for the two northern sections, but for the southern section the autumn curve resembles the annual mean much more closely than does that of any other season. Particularly to be noted about the autumn season is the relative wetness of the drought decade of the thirties, which is reflected only in the middle section, and that to a very slight degree.

In summary, the outstanding features to be remarked on these west - central sectional trend curves of precipitation are the following:

1. Compared to the corresponding curves of temperature, the same lack of any clear overall cyclical trend of precipitation that was noted in the comparison of the nationwide trend curves of precipitation with those of temperature.

2. Likewise, as correspondingly large deviations of the seasonal trend curves of precipitation from the annual mean trend curves as were found for the deviations of the nationwide seasonal trend curves from the annual mean curve.

3. Some evidence, particularly in the annual means, of a lag towards lower latitudes of characteristic features of the cumulative trend curves, but the evidence is less clear than it is in the cumulative trend curves of temperature.

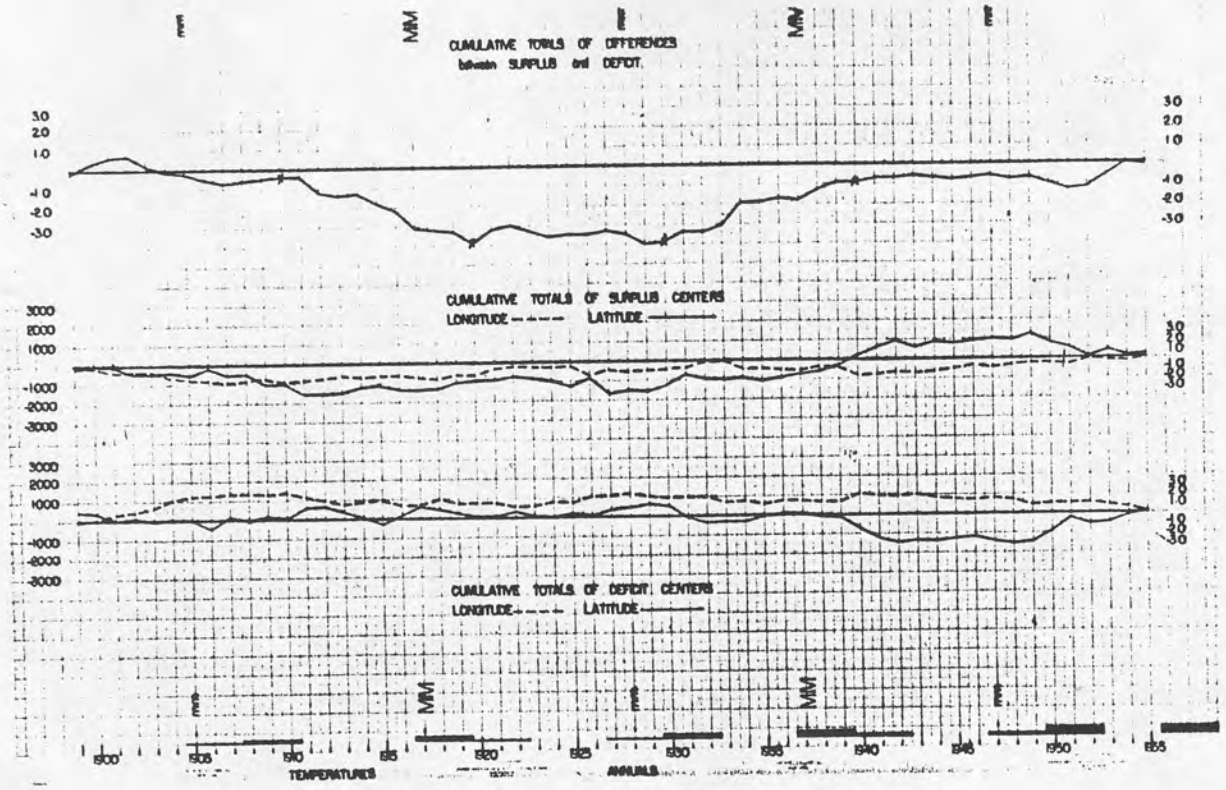

Figure 1

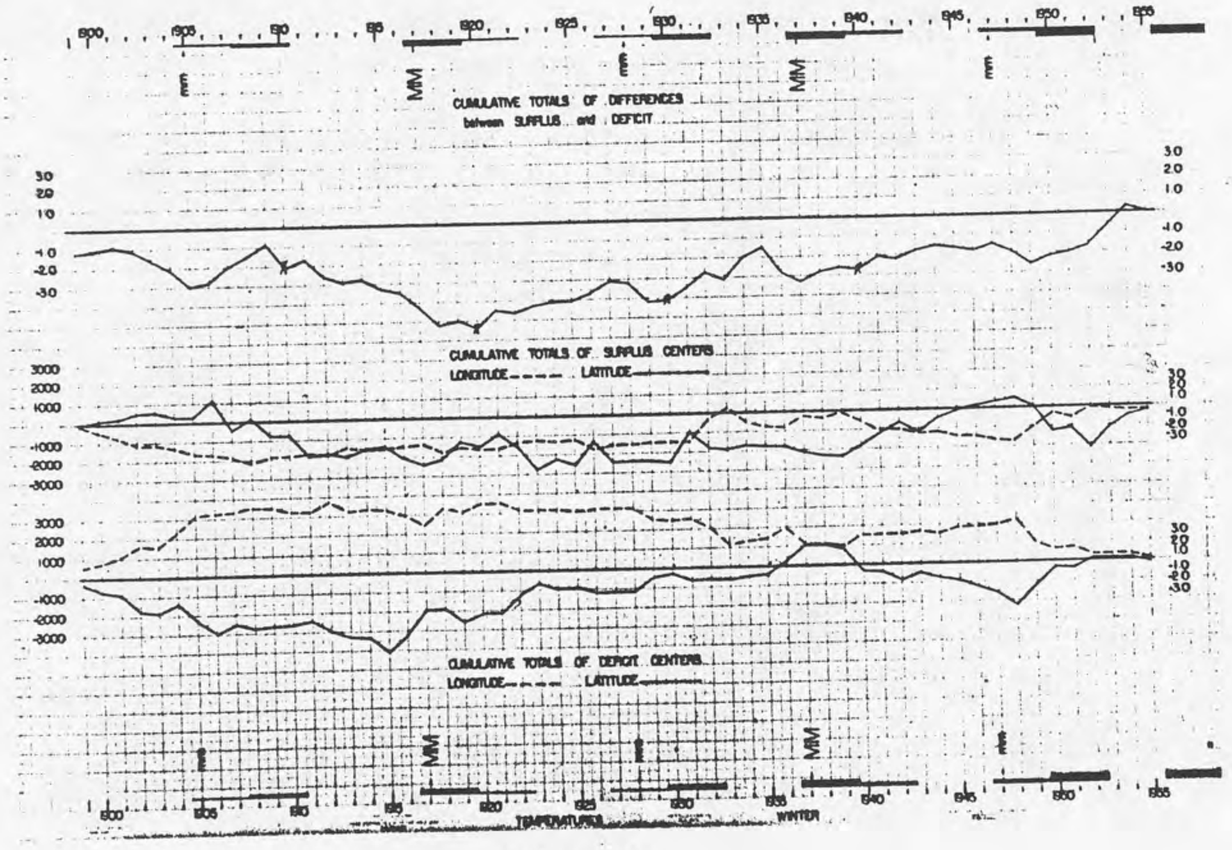

Figure 2

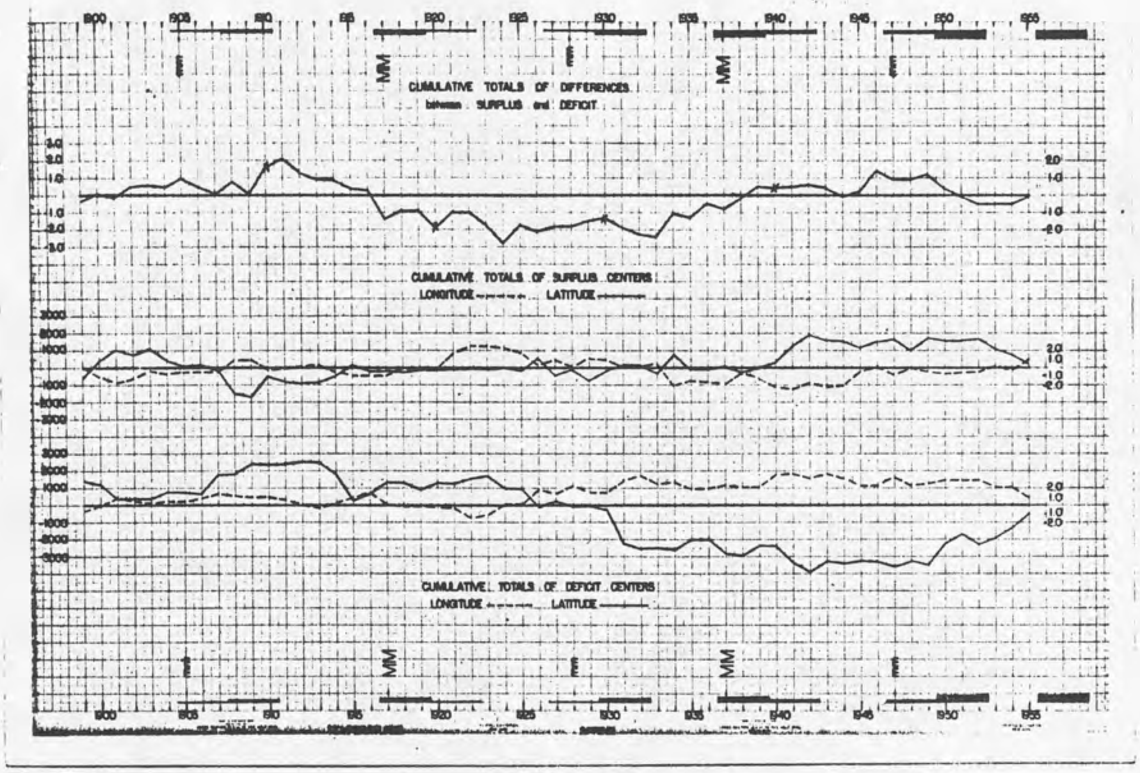

Figure 3

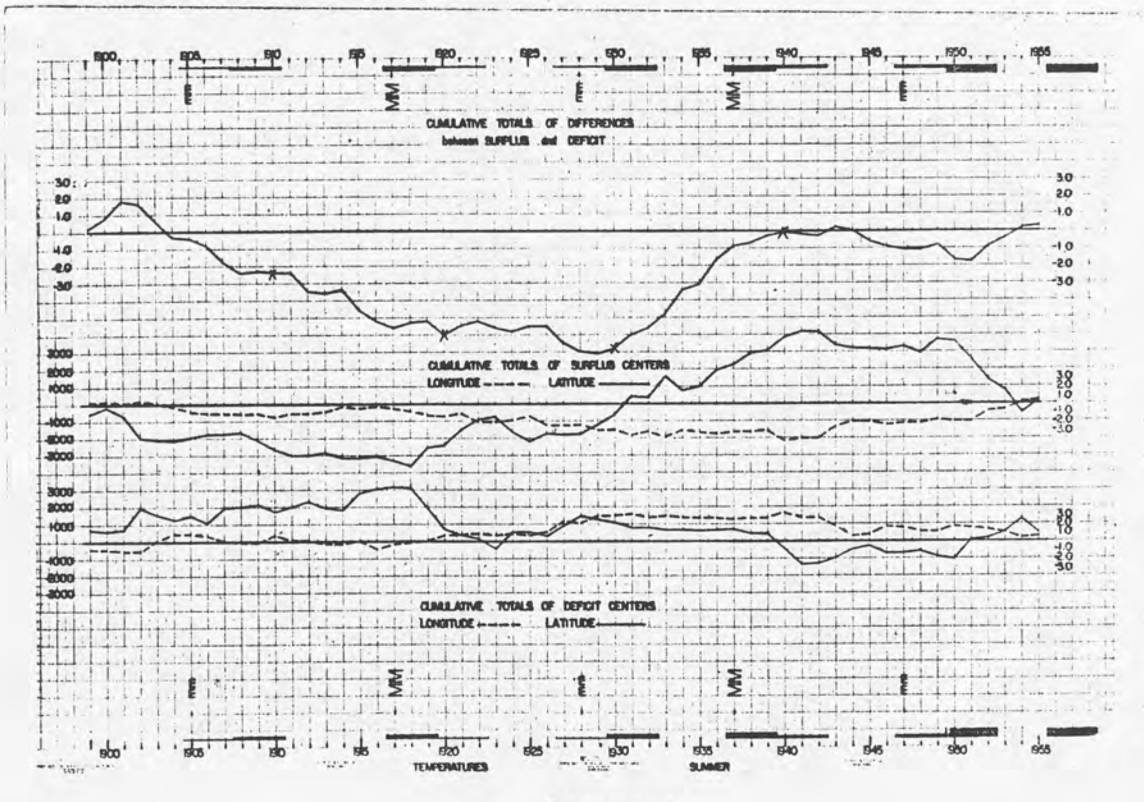

Figure 4

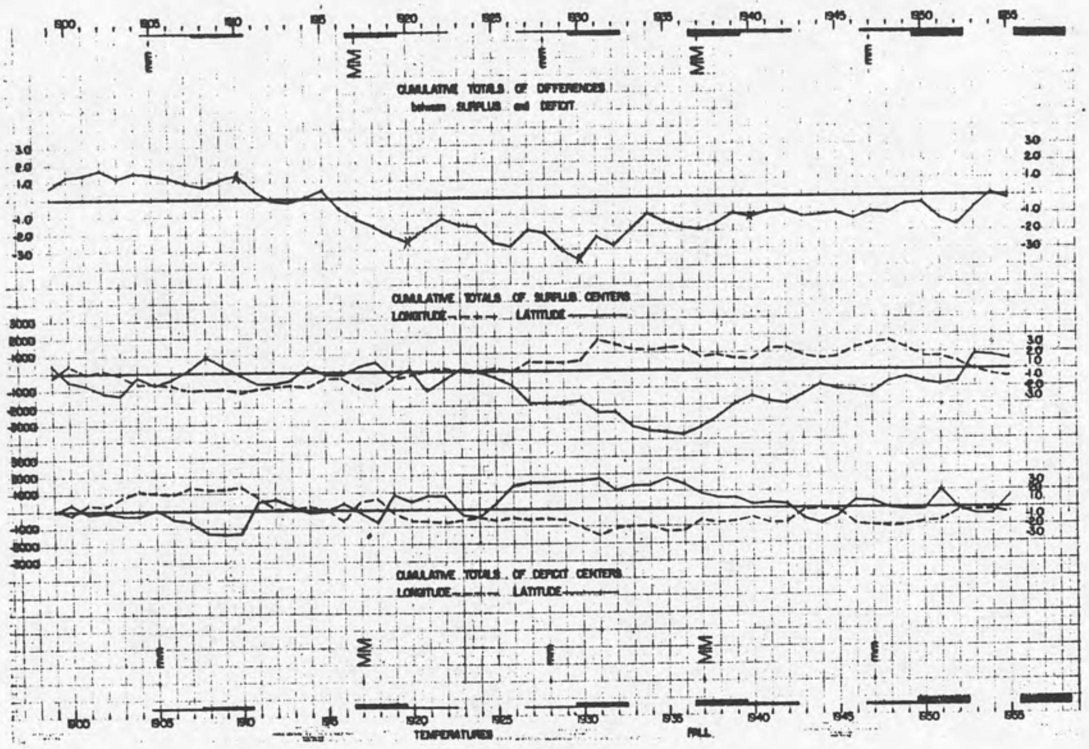

Figure 5

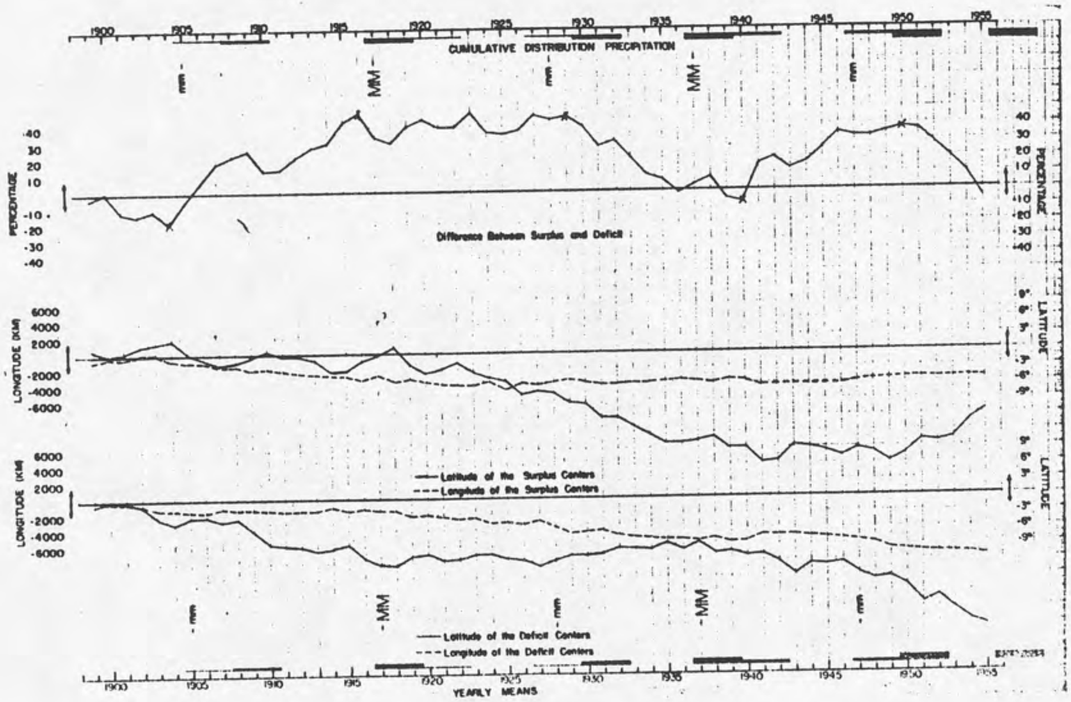

Figure 6

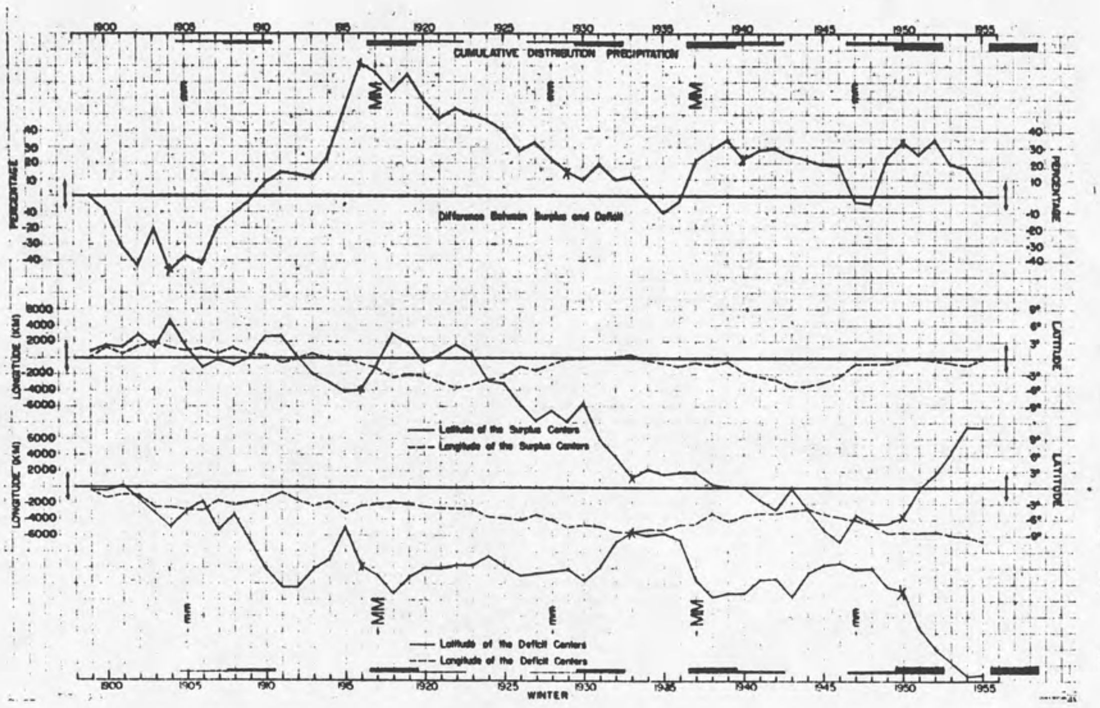

Figure 7

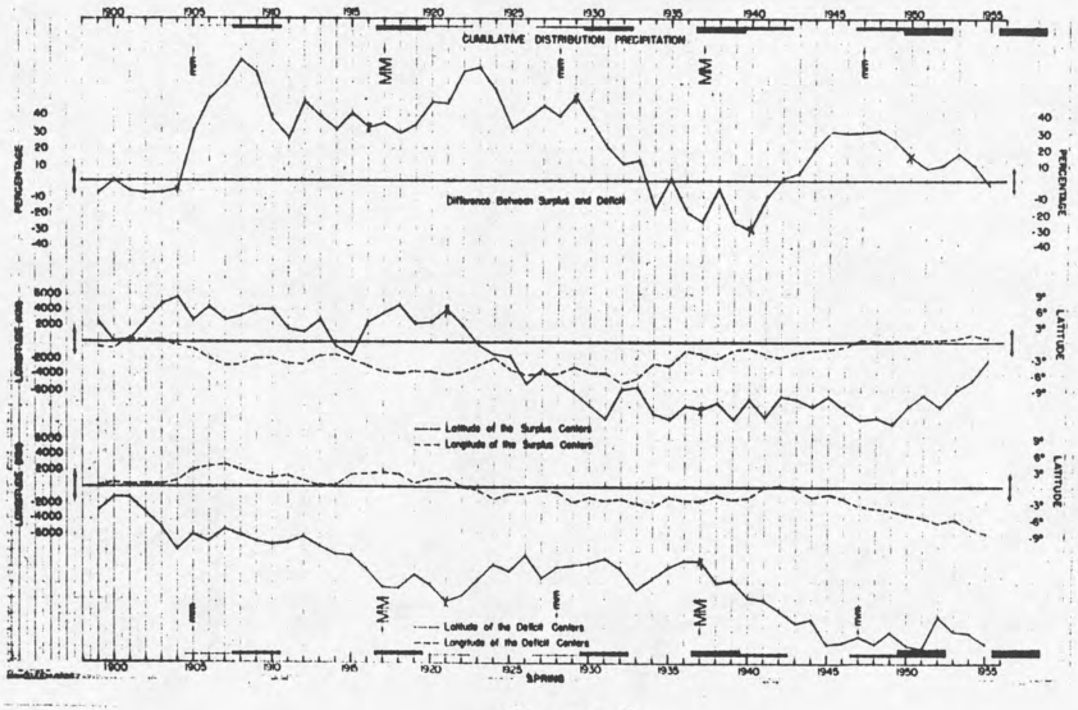

Figure 8

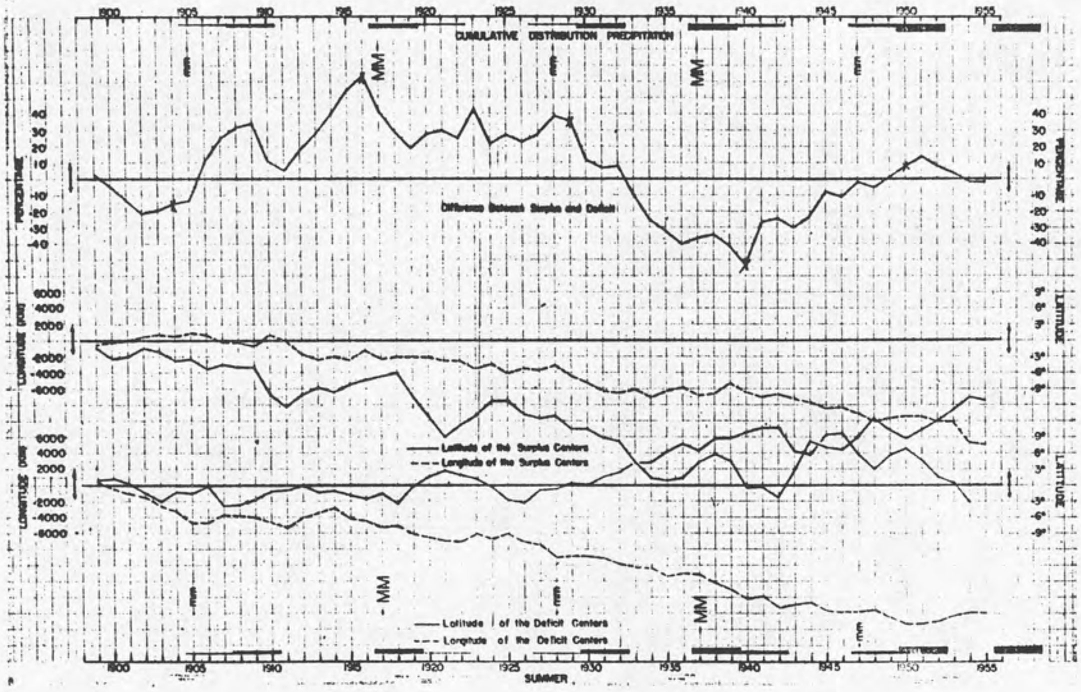

Figure 9

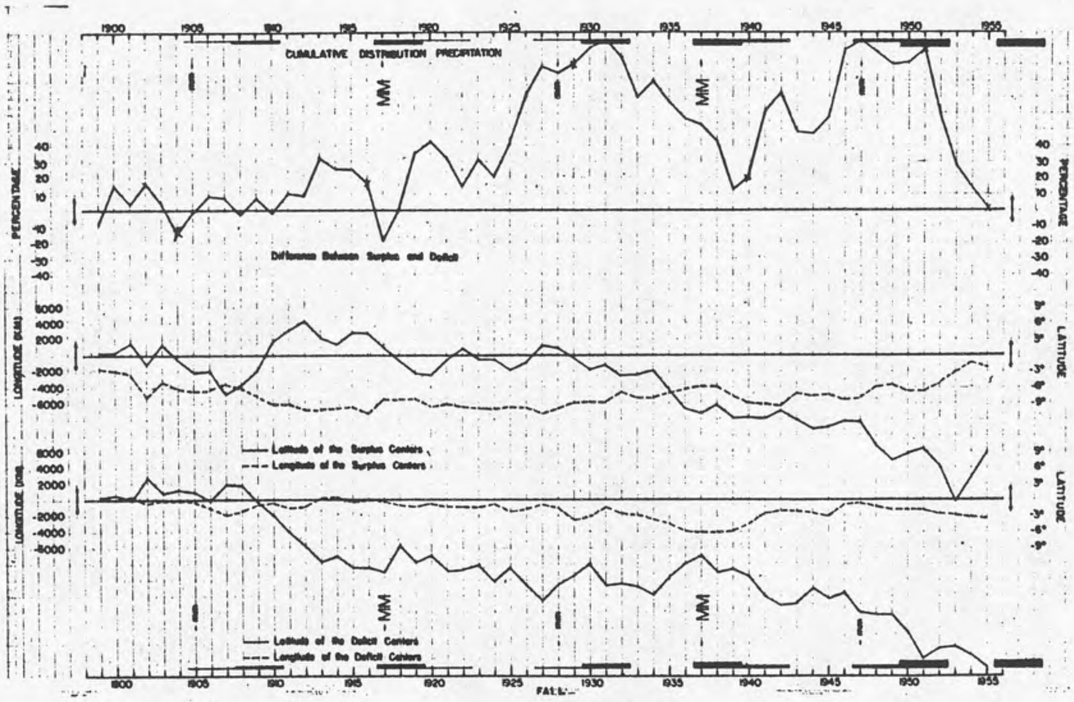

Figure 10

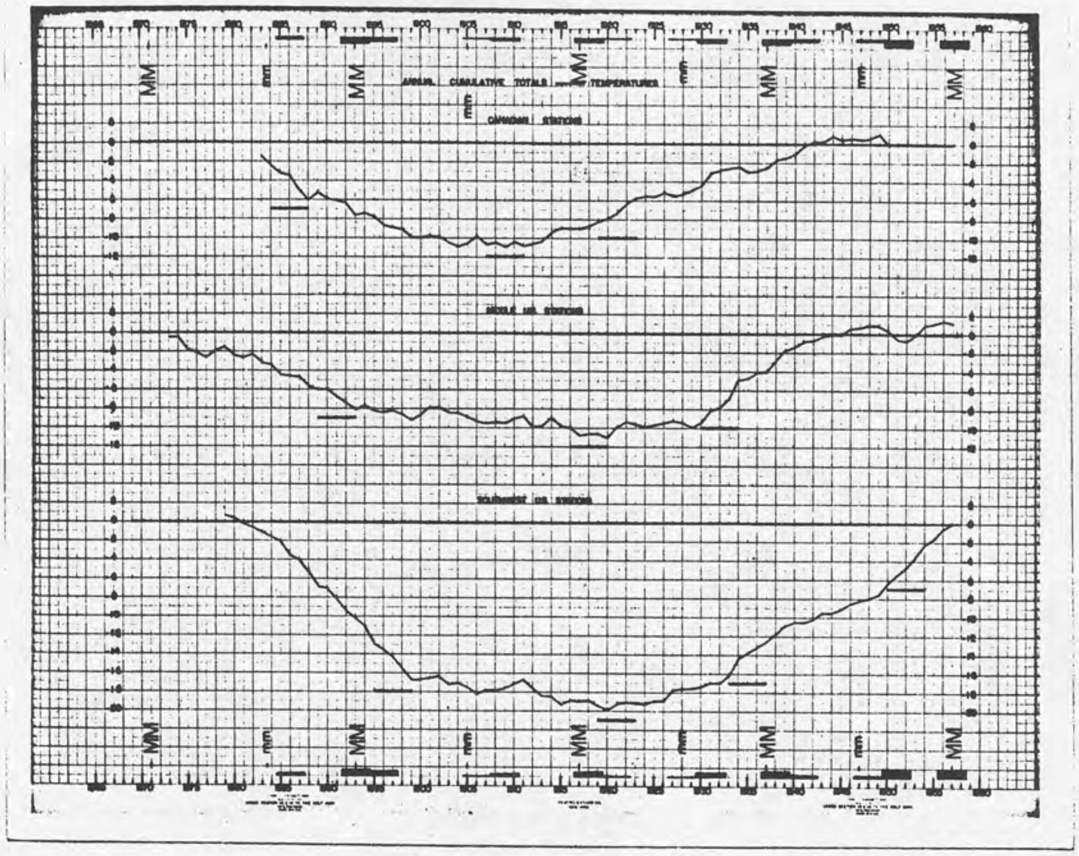

Figure 11

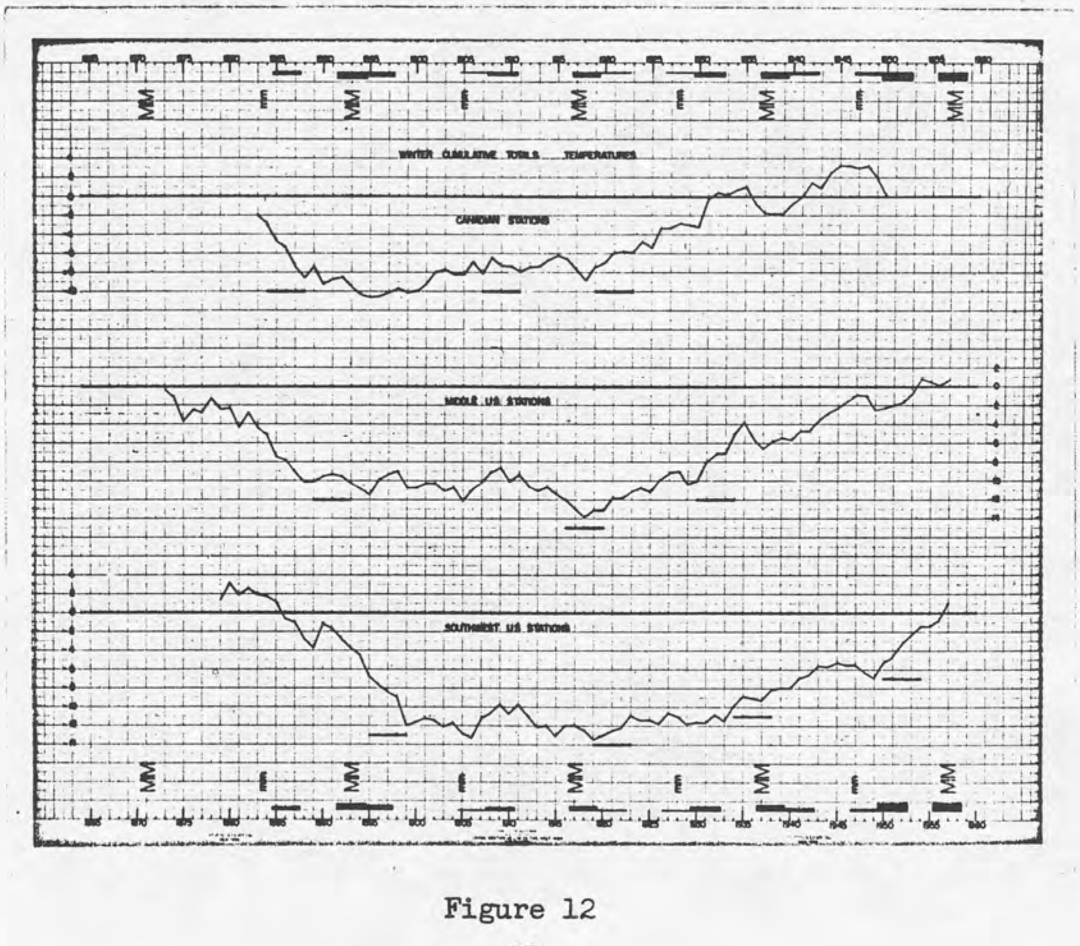

Figure 12

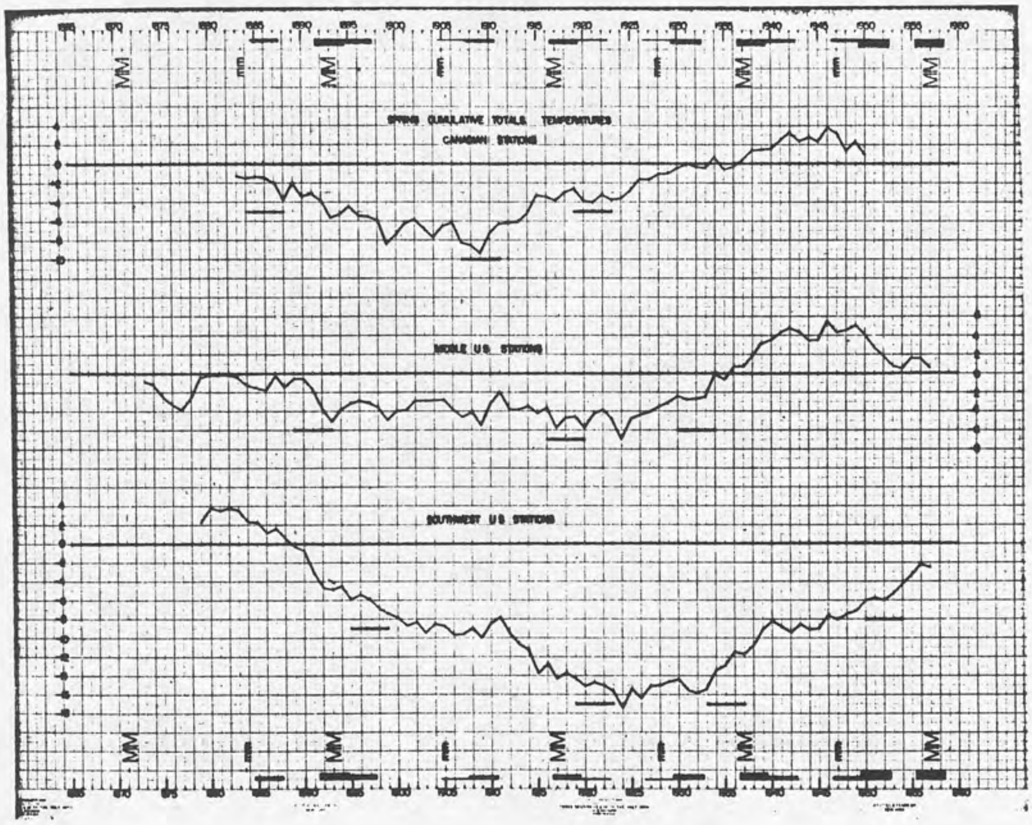

Figure 13

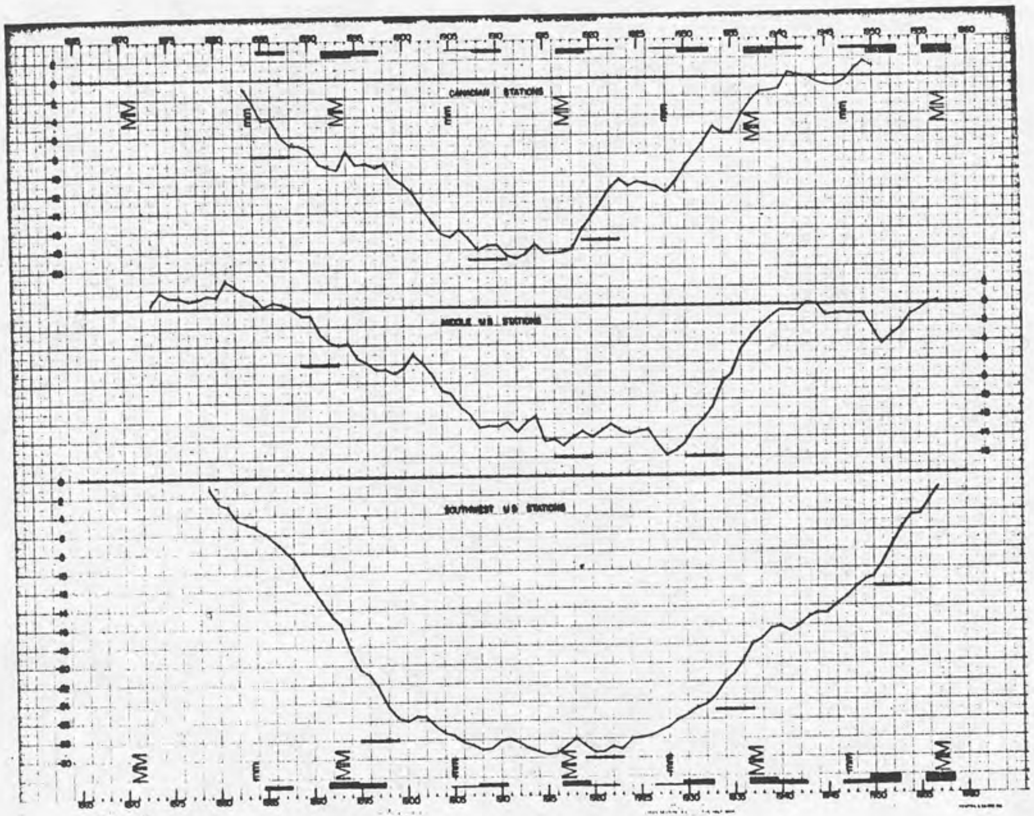

Figure 14

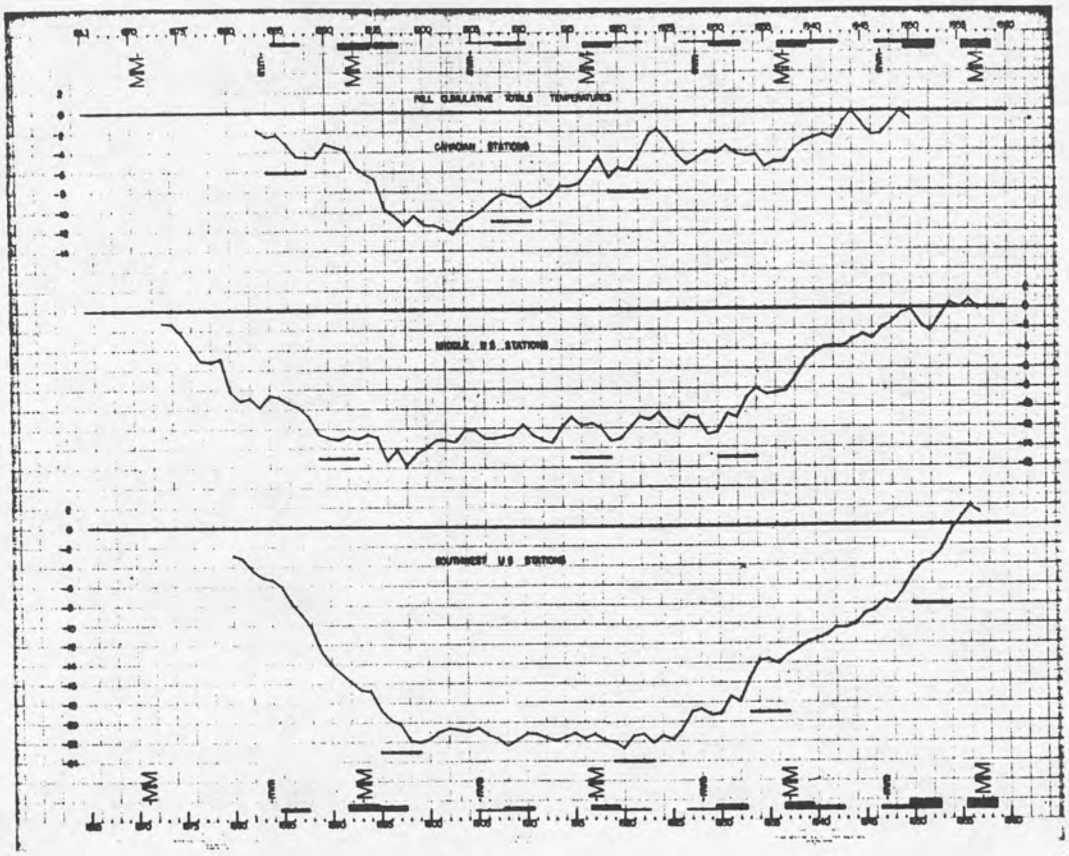

Figure 15

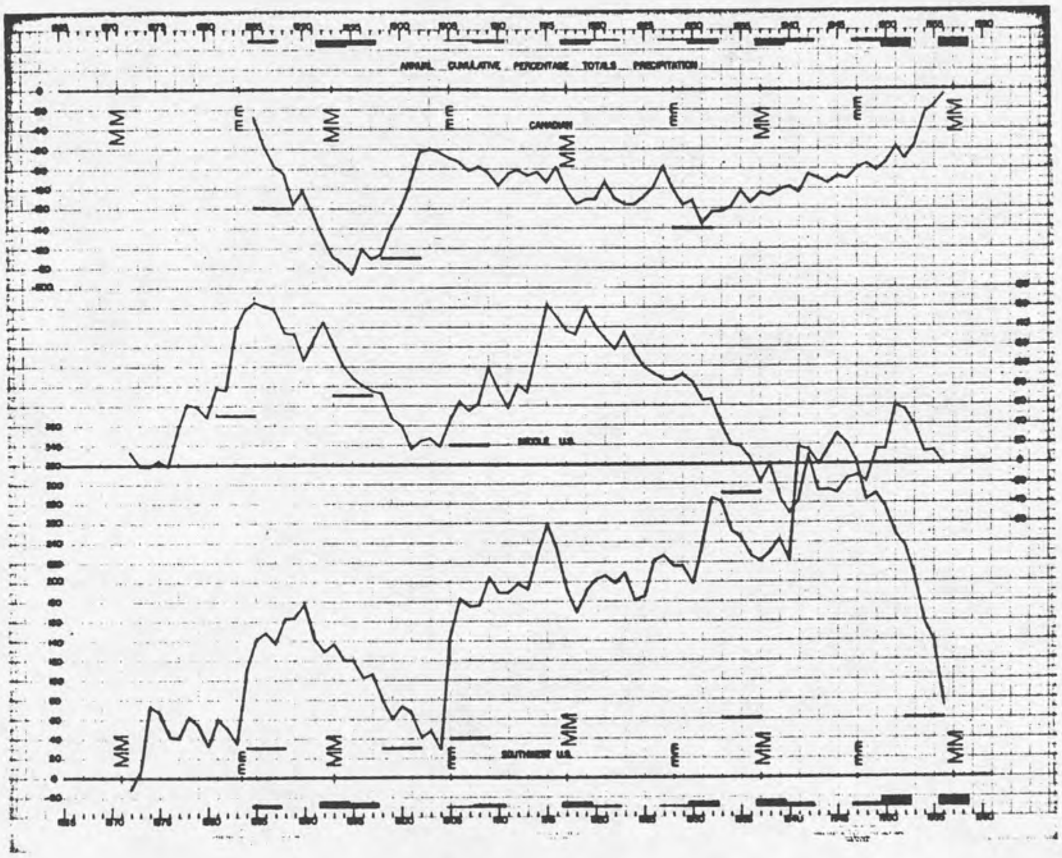

Figure 16

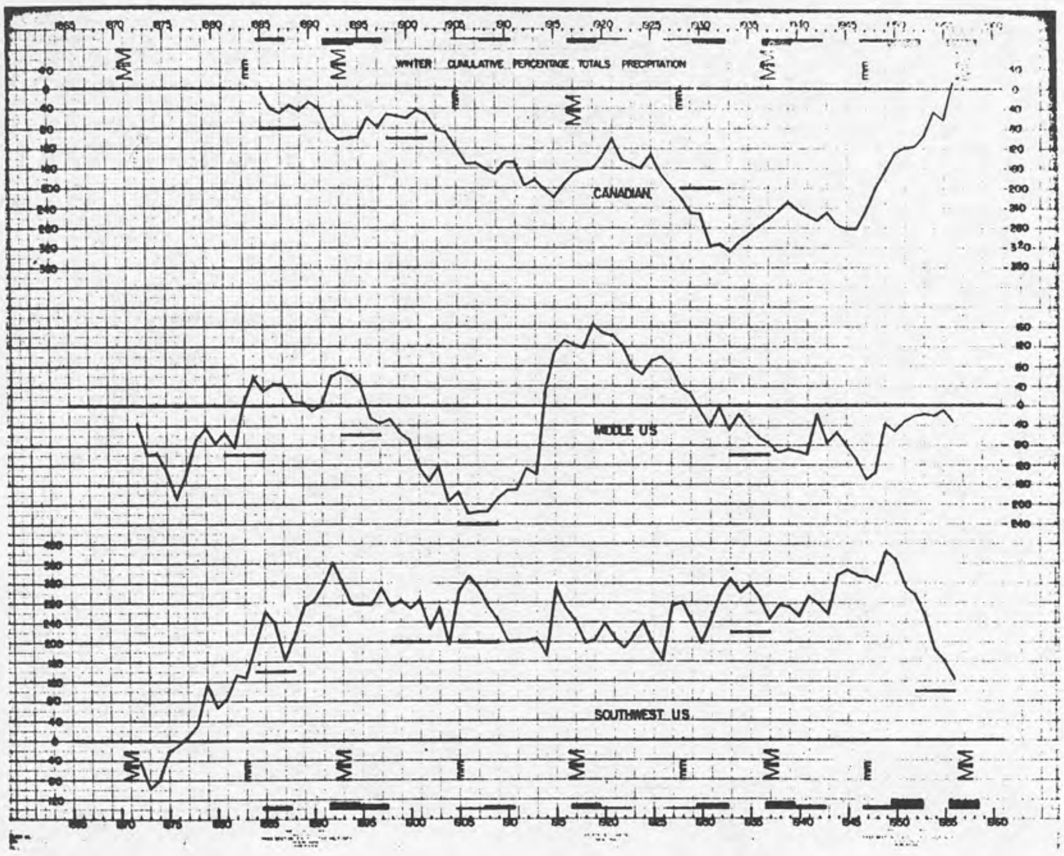

Figure 17

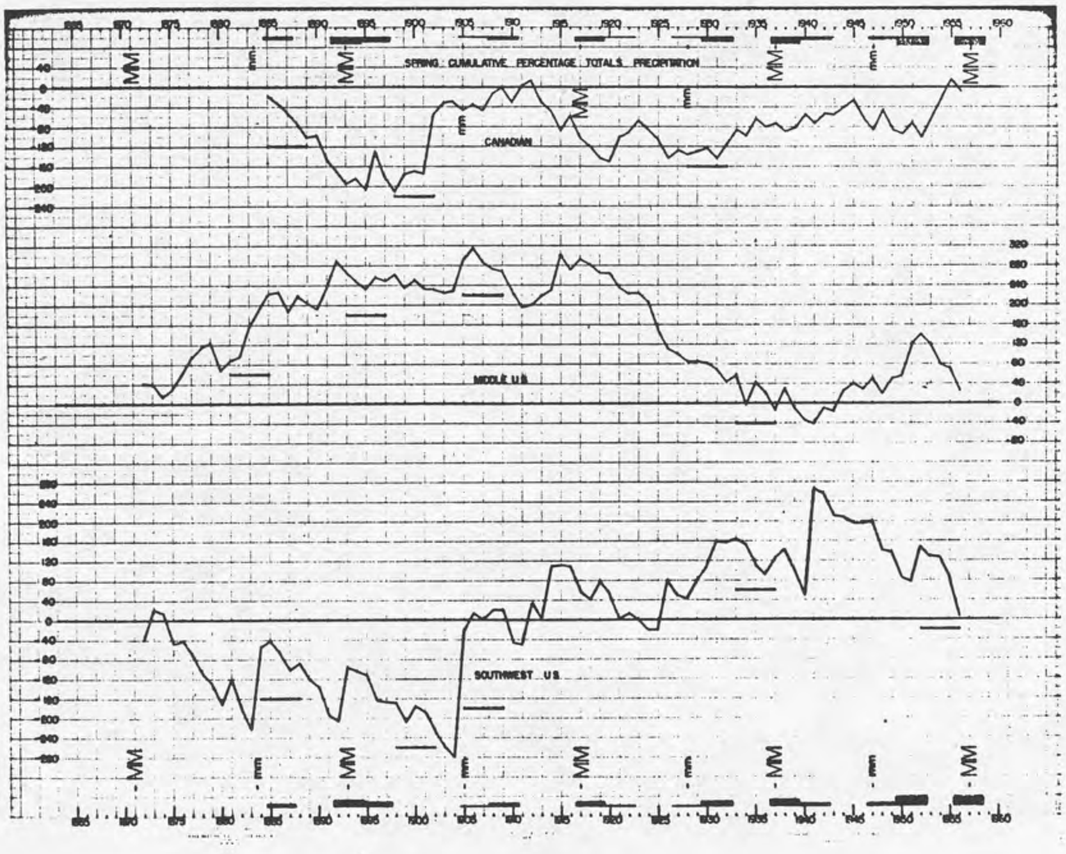

Figure 18

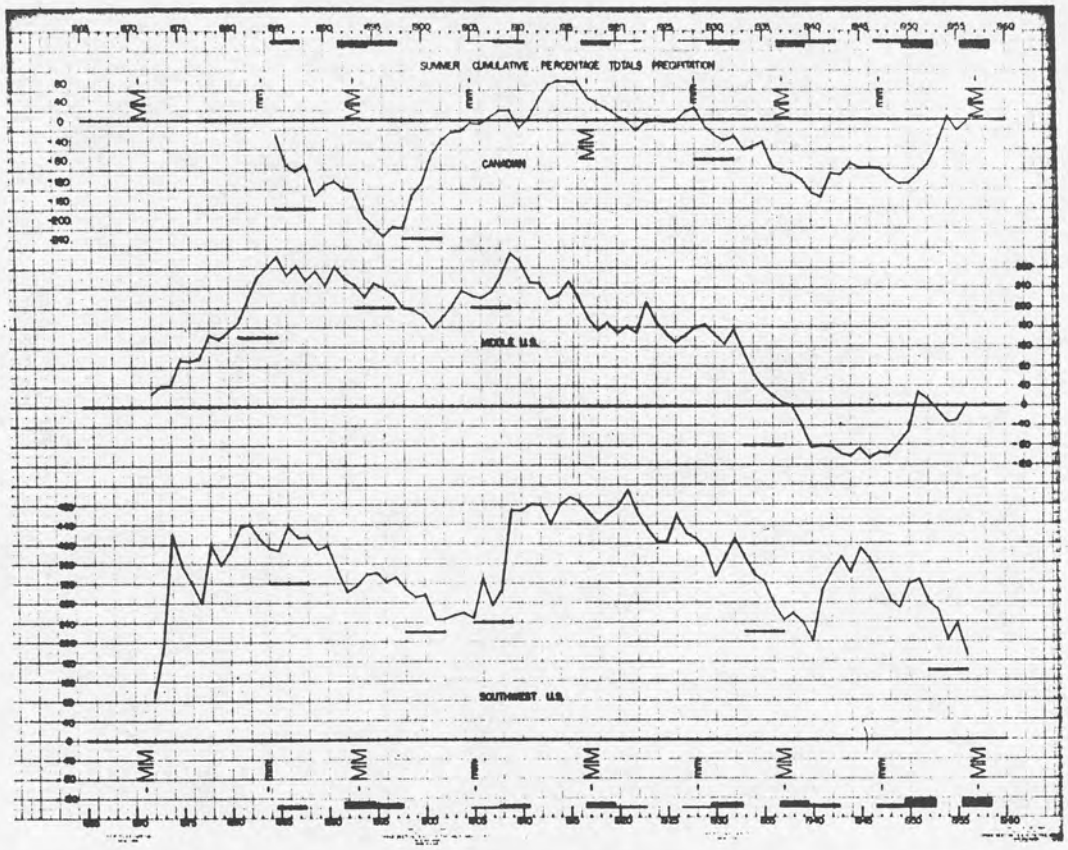

Figure 19

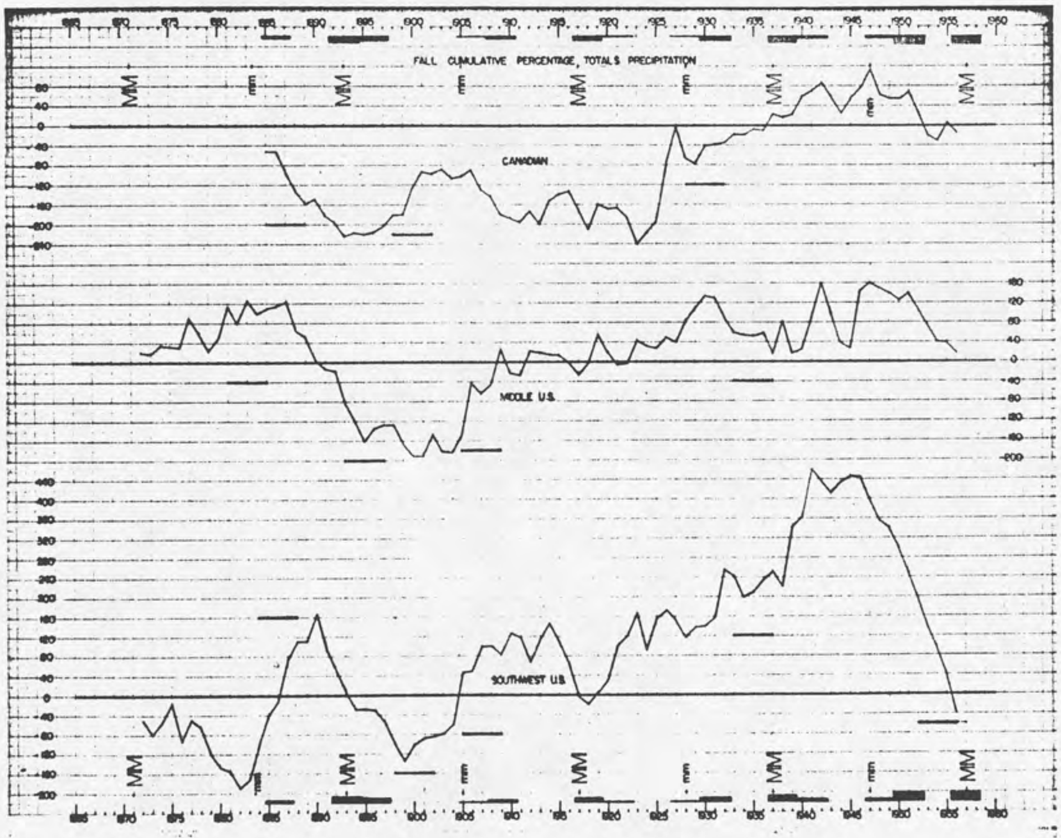

Figure 20