On the Causes of Local Climatic Anomalies, with Special Reference to Precipitation in Washington State

A. B. Pittock

CSIRO Division of Atmospheric Physics, Aspendale 3195 Australia

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ABSTRACT

Topographic effects on climate, and particularly on precipitation, are well known in the literature. Nevertheless their separation on the mesoscale from possible anthropogenic effects has proved difficult. A method based on patterns of correlation between local climate elements and indices of the general circulation, which was developed in a study of Australian rainfall, has been applied to precipitation in the State of Washington and surrounding areas where relief is much greater. Patterns are found which account for the major part of some climatic anomalies discussed in the literature and which have previously been ascribed to anthropogenic effects. The wider implications for the study of urban and other anthropogenic effects is discussed with reference to the La Porte anomaly and METROMEX.

1. Introduction

Topographic effects on climate are well known in the literature. These have been of particular interest to hydrologists concerned with estimating precipitation and runoff in inaccessible or sparsely instrumented mountainous catchments.

There is also widespread interest in possible urban and other anthropogenic effects on local climates (Oke, 1974). Obviously there is a need to separate mesoscale topographic effects from anthropogenic effects, but this has proved difficult. Changes in mesoscale climate patterns with time in situations of possible anthropogenic influence, and differences between weekday and weekend patterns are commonly taken as evidence of anthropogenic effects.

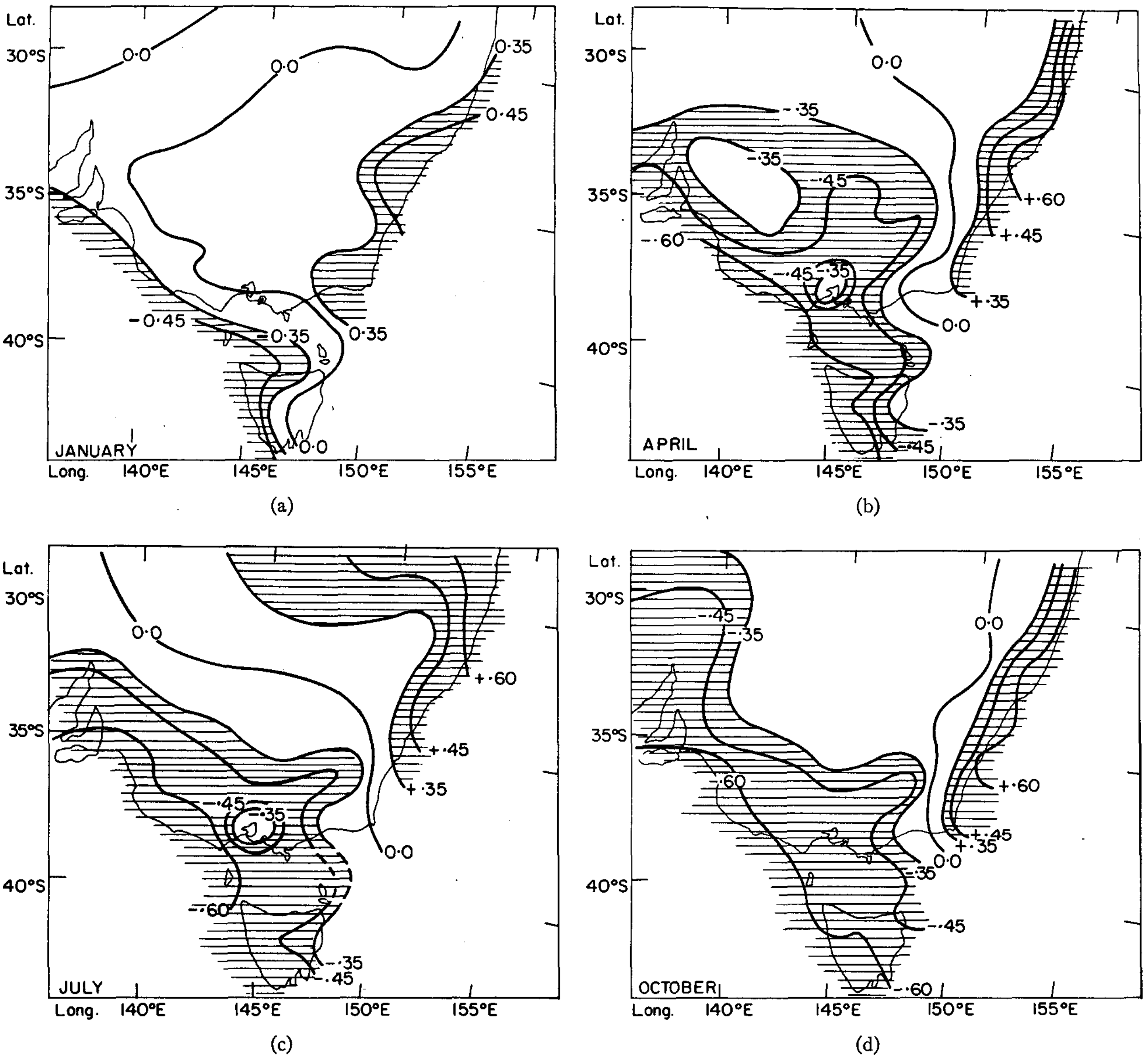
In this paper a method based on patterns of correlation between year-to-year fluctuations in local climatic parameters and indices of the larger scale general circulation is applied to the case of precipitation patterns in the State of Washington and surrounding areas. The results suggest that the major portion of apparent climatic anomalies in this region is explicable in terms of widespread natural climatic variation rather than localized anthropogenic effects. The wider implications for the study of other possible anthropogenic effects is discussed with particular reference to the La Porte anomaly and METROMEX.

2. Topographic effects

The nature, magnitude and mechanisms of topographic effects on climate have been investigated by numerous workers using various statistical techniques, mesoscale synoptic analyses, analytical and numerical models and satellite cloud photographs.

For example, orographic effects have been investigated by Lee (1911), Coote and Cornish (1958), Schermerhorn (1967), Chuan and Lockwood (1974) and Wolfson (1975). Valley effects and topographic convergence are discussed by Wilson and Atwater (1972), Longley (1974) and Huff *et al.* (1975). Sea breeze effects have been observed by Hatcher and Sawyer (1947) and Clarke (1955) among many others, and modeled for example by Estoque (1962), McPherson (1970) and Pielke (1975). Lake effects have been reviewed by Changnon and Jones (1972), and lake breeze convergence documented by Harman and Hehr (1972).

Coote and Cornish (1958) correlated rainfall at 97 stations in South Australia against altitude and position and found the variation of monthly or annual rainfall with altitude to be about 15–30% per 100 m. Bergeron (1961) found rainfall differences in repeated individual widespread rain episodes of a factor of 2 or more over wooded hills only some 50 m above the surrounding plain. Wilson and Atwater (1972) studied rainfall distribution over Connecticut during large-scale stratiform type rainstorms, which they grouped into east-wind and west-wind storms. Despite height differences of only about 150 m, they found maximum rainfall occurred on the windward edges of the hills in each case, with ratios of maximum to minimum rainfall of 2.1 (east winds) and 1.7 (west winds). They concluded that "orographic effects on rainfall, even in regions of small relief, (should) be included in any studies that attempt to evaluate man's intentional or



(a) (b) (c) (d)

FIG. 1. Isopleths of equal correlation coefficient between district mean monthly rainfalls and corresponding monthly mean latitudes of the surface high-pressure belt along the east coast of Australia for January, April, July and October, (a)–(d), respectively. Data are for 1941–70 inclusive. $r=0.35$ is significant at 5% chance probability level and $r=0.45$ at 1% level.

inadvertant modification of precipitation." Huff *et al.* (1975) found that warm season precipitation over forested hills in southern Illinois, only some 120 m above the flatlands to the north and south, was 15% greater, and that this was due to enhancement of heavy showers by topographically induced convergence.

3. Patterns of correlation with the general circulation

Pittock (1973, 1975) has studied spatial patterns of year-to-year variations of rainfall and their relation to variations in the general circulation of the atmosphere in the Australian region. One such pattern, accounting for a major part of the year-to-year variation in annual rainfall in coastal areas of southeastern Australia, is associated with variations in the annual mean latitude L of the surface subtropical high-pressure belt over the east coast of Australia [as defined and tabulated by Pittock (1973)].

The results of such an analysis using monthly district mean rainfall data for 66 standard Bureau of Meteorology rainfall districts in southeastern Australia are presented in Fig. 1.[1] The districts are those shown in Fig. 1 of Pittock (1975). Figs. 1a–d show isopleths

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[1] This is reproduced, with minor amendments, from a paper given at the International Conference on Weather Modification, Canberra, 1971. See Preprints, Amer. Meteor. Soc., pp. 330–338.

of the correlation coefficient r between this rainfall data and corresponding monthly L values [determined from a chain of 11 stations along the east coast of Australia from Cairns (16.9°S) to Cape Bruny (43.5°S), south taken as positive sign] for January, April, July and October, respectively, over the years 1941–70 inclusive; $r=0.35$ is significant at the 5% level of chance probability and $r=0.45$ at the 1% level.

Fig. 2 is a topographic map of the same area. It is clear that the position of the rather low mountainous areas influences the resulting correlation patterns. Positive, or less negative, correlations occur to the east of mountainous areas, while negative, or less positive, correlations occur on the western slopes. This is explicable in terms of coastal and orographic effects, with rain-bearing easterlies and westerlies both being further south when L is large. The seasonal changes in these patterns associated with seasonal variations of the general circulation are also of interest.

A similar analysis based on annual data for 276 individual rainfall stations in an area of much greater relief in and around the State of Washington reveals the broad pattern shown by the coded symbols on the simplified relief map in Fig. 3. Data are again for the 30-year period 1941–70, although missing data at many stations reduced the statistical significance of many of the correlation coefficients. Only stations with at least 20 years of data have been plotted. L values were determined from plots of monthly mean mean sea level pressures versus station latitude, as tabulated in *World Weather Records* and *Monthly Climatic Data for the World*, for 16 stations near the West Coast of North America, ranging from Salina Cruz (16.2°N) to Barrow (71.3°N). The latitude of the maximum of a generally single-peaked smooth curve drawn through these points was taken as L. From the scatter of points and the sharpness of the maxima individual monthly L values are estimated to be accurate on average to about 0.5° of latitude. Annual mean L values are probably accurate to within 0.2°, and are given in Table 1.

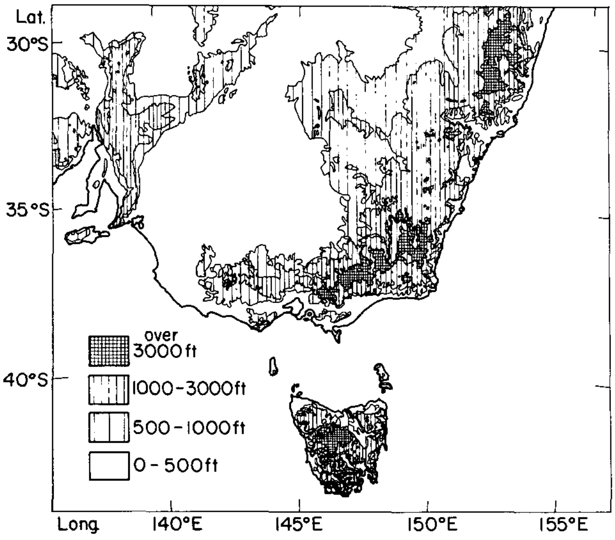

FIG. 2. Topographic map of southeastern Australia. Contours are at 500 ft (~152 m), 1000 ft (~305 m) and 3000 ft (~914 m) as indicated.

TABLE 1. Annual mean latitude L of the MSL maximum pressure along the west coast of North America.

Year	L	Year	L	Year	L
1941	43.5	1951	45.2	1961	43.7
1942	45.1	1952	44.9	1962	42.7
1943	46.2	1953	43.2	1963	42.2
1944	47.0	1954	44.7	1964	42.8
1945	46.0	1955	43.4	1965	44.1
1946	45.0	1956	44.5	1966	43.1
1947	45.4	1957	44.4	1967	43.7
1948	45.3	1958	45.2	1968	41.8
1949	45.6	1959	44.0	1969	43.0
1950	44.2	1960	43.0	1970	43.0
1941–50	45.3_3	1951–60	44.2_5	1961–70	43.0_1

Fig. 4 shows individual correlation coefficients (multiplied by 100 for easier display) for those stations having at least 20 years of data in the Puget Sound area. This is of particular interest because of the mesoscale pattern in this area since the area is subject to appreciable pollution.

Statistically significant negative correlation coefficients between precipitation and L are in evidence for areas on the western slopes of Vancouver Island, the Coast Range, Cascade Range and the Selkirk Mountains of British Columbia. High negative correlations are also evident in the Puget Sound area, probably associated with rainfall penetrating to the northwest across the lowlands south of the Olympic Peninsula (Schermerhorn, 1967; Church, 1974). Higher than average rainfall in this area is normally associated with a ridge located further south than usual. The Columbia Basin area, on the other hand, contains a concentration of stations with much smaller (and hence statistically insignificant) correlations, with a tendency for low positive values. Clearly, any long-term trend in L, as is evident in Table 1, will lead to trends in precipitation which will differ from station to station with larger changes in areas of high correlation.

4. Possible anthropogenic effects in the Washington area

Hobbs *et al.* (1970) compared precipitation and stream flow data in Washington State between the periods 1929–46 and 1947–66. They found mean annual increases which exceeded 30% at some stations, and ascribed these, particularly in the Puget Sound area, to cloud condensation nuclei emitted by paper mills and other pollution sources. Elliott and Ramsey (1970) disputed this supposed causal connection, pointing out that the northwestern United States experienced wide-

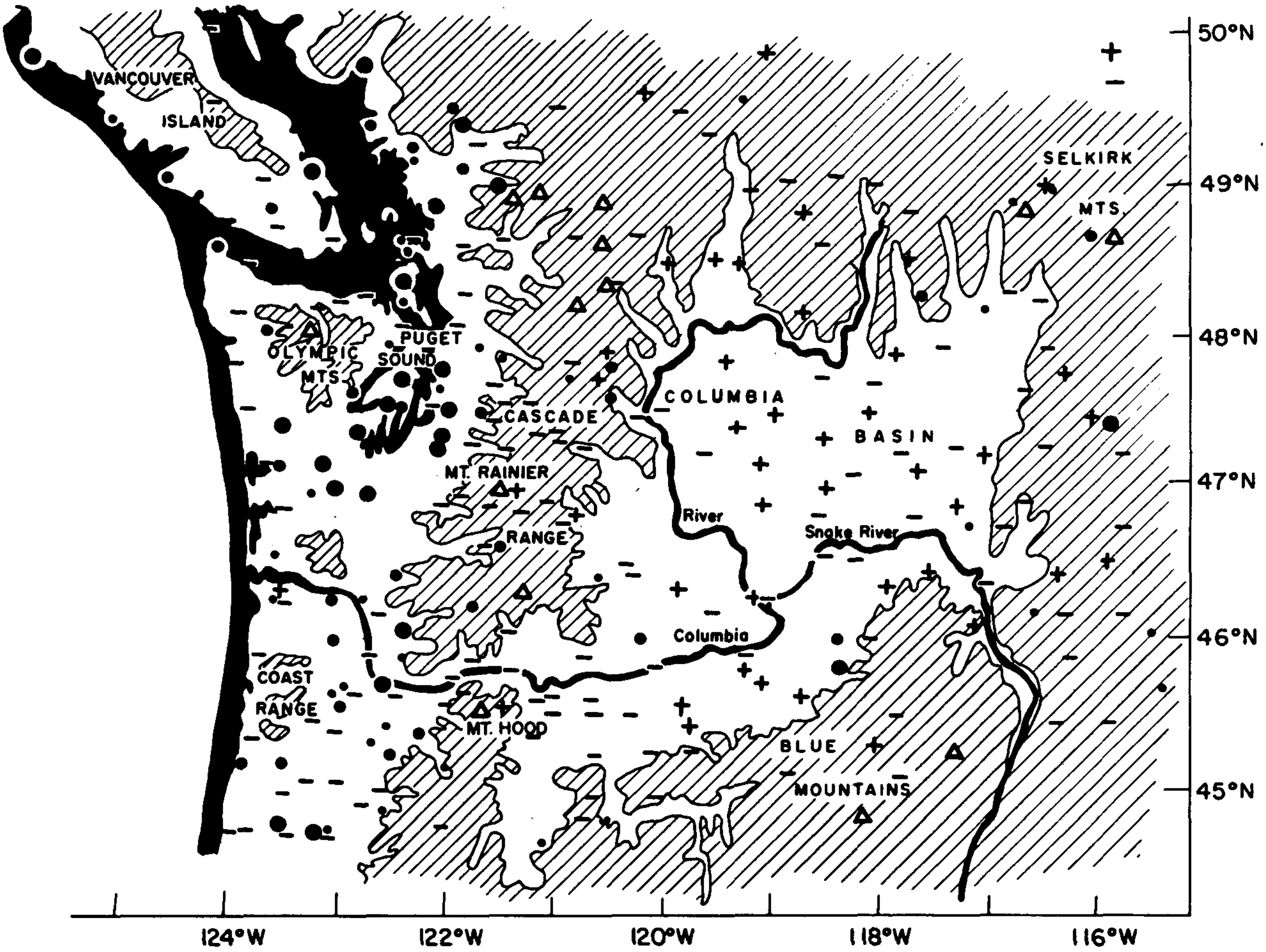

FIG. 3. Station correlations in State of Washington and parts of Oregon, Idaho and British Columbia between annual rainfall and corresponding annual latitude of surface high pressure along West Coast of North America (see Table 1). Data are for years 1941–70. Only stations having at least 20 years of data have been plotted. White areas, 0–1000 m altitude; hatched areas, >1000 m; △ major mountain peaks. Significance levels of correlations: ● 2%, ● 5%, ● 10%—all negative; minus signs (negative), plus signs (positive)—all not significant.

spread drought in the early 1930's. Indeed, longer time series of precipitation in the Puget Sound area (Church, 1974) show a marked decrease in 10-year running mean precipitation from the 1890's to about 1930, followed by an intermittent rise into the 1960's.

From the observed trend in L (from Table 1) and the

TABLE 2. Correlation coefficients r between station annual precipitation and annual L values, data for 1941–70. Numbers refer to points on Fig. 5. All these stations have at least 25 years of data in the 30-year period.

No.	Station	r	No.	Station	r
1	Estevan Point, B. C.	−0.51*	12	Chimicum, Wash.	−0.23
2	Bremerton, Wash.	−0.73*	13	Victoria Gonzales, B. C.	−0.12
3	Brittania Beach, B. C.	−0.53*	14	Chewelah, Wash.	−0.38*
4	River Jordan, B. C.	−0.43*	15	Oroville, Wash.	−0.20
5	Alouette Lake, B. C.	−0.44*	16	Wenatchea, Wash.	−0.03
6	Chemainus, B. C.	−0.54*	17	Kimberley A, B. C.	+0.01
7	Pachena Point, B. C.	−0.37*	18	Princeton A, B. C.	+0.21
8	Vancouver A, B. C.	−0.47*	19	Penticton A, B. C.	+0.31
9	White Rock, B. C.	−0.47*	20	Conconully, Wash.	+0.05
10	Comox A, B. C.	−0.23	21	Irene Mt. Wauconda, Wash	+0.14
11	Coupville, Wash.	−0.48*	22	McCulloch, B. C.	+0.16

* Significant at the 5% level of chance probability or better.

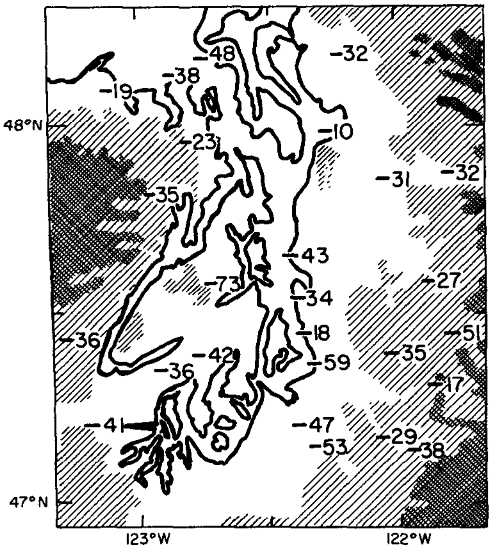

FIG. 4. Station correlation coefficients (×100) in Puget Sound area as in Fig. 3. $r=0.35$ is significant at 5% chance probability level, and $r=0.45$ at 1% level. Hatched area is above 200 m altitude. Cross-hatched area is above 1000 m.

observed year-to-year correlations of precipitation with *L* indicated in Figs. 3 and 4, it is possible to make an estimate of the "expected" change in mean precipitation at each station due to the change in that aspect of the general circulation accounted for by *L*. The residual difference between this predicted change in precipitation and the observed change over the same period is a measure of the possible anthropogenic effect, although changes due to other circulation changes (not accounted for by *L*) and scatter due to statistical sampling and error will also contribute to this residual.

Fig. 5 is a plot of the observed changes in decadal mean precipitation at the various stations indicated in the inset map and which are listed in Table 2, against the "predicted" changes. The predicted change is simply the observed change in *L* multiplied by the individual station regression coefficients of precipitation on *L*. The changes are for the decades (1961–70) minus (1941–50), except that most of the data series used for British Columbia end with 1967 so that seven-year means apply in those cases. The stations plotted are an arbitrary selection over the full range of correlation coefficients of those having at least 25 years of data, out of the total of 276 stations analyzed. These points are to be taken as illustrative in the context of Figs. 3 and 4 which established the spatial coherence of the correlations.

It is clear from Fig. 5 that in this sample the major part of the observed precipitation changes, where these are statistically significant, are as might be expected from the observed change in *L*. Indeed the scatter of

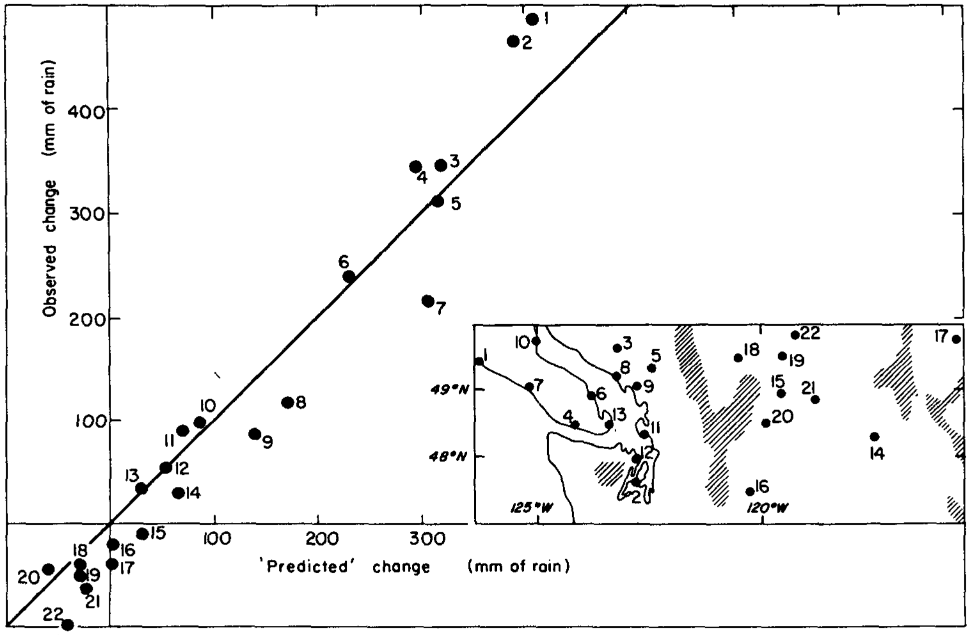

FIG. 5. Plot of the observed changes in decadal mean precipitation at the various stations identified by number in Table 2 and located on the inset map, against the "predicted" changes from the observed change in *L* (Table 1) and the regression of station annual precipitation on *L*. Changes are for the decades (1961–70) minus (1941–50) as far as data allow (see text). Only an arbitrary selection of stations over the full range of correlation coefficients has been plotted. Spatial coherence is indicated in Fig. 3.

the points about the equality line for the statistically significant stations is comparable to the scatter for the stations having nonsignificant correlation coefficients.

Of particular note are the similar observed and predicted rainfall changes at Estevan Point, B. C., and Bremerton, Wash. The former is an exposed pollution-free coastal station, while the latter is in the Puget Sound area where most of the observed changes have previously been ascribed to pollution. Coupville and Chimicum are also in the Puget Sound area, but show little sign of anomalous behavior. Chewelah, Oroville, Wenatchea and Conconully, all of which were taken as "control" stations by Hobbs *et al.* (1970), lie east of the Cascade Range and all except Chewelah have nonsignificant correlations of precipitation with L.

While the existence of some small effect on precipitation due to anthropogenic influences cannot be ruled out, the evidence presented here indicates that the major part of the rainfall changes observed in the Washington area between 1941 and 1970 can be accounted for by a change in the general circulation pattern. Additional evidence for the change in the general circulation may be found in Namias (1972a) who found higher sea surface temperatures off the West Coast and stronger anomalous southwest wind components in the 1958–69 period as compared with 1948–57.

5. Discussion

Although the present study of precipitation in the Washington State area does not cover exactly the same period nor use all the same data as that of Hobbs *et al.* (1970), it does suggest that natural changes in the general circulation, locally enhanced by topography, largely account for changes which have been ascribed to pollution. This suggests the need for a more critical examination of other supposed local anthropogenic effects. The following remarks are meant to point in that direction, but do not pretend to be thorough or conclusive case studies.

The La Porte anomaly was first described by Changnon (1968) who found that during 1951–65 La Porte, Ind., had 31% more annual precipitation, 38% more thunderstorms and 246% more hail days than surrounding stations, and that annual and warm season precipitation varied in close parallel to steel production in the upwind Chicago area. Holzman and Thom (1970) maintained that the anomaly was an artifact of observational error, but later studies (reviewed by Changnon, 1973) of stream flow records, hail insurance and other data supported the reality of the anomaly.

Harman and Elton (1971) have suggested an alternative explanation for the La Porte anomaly in terms of the location of the lake breeze convergence zone in the vicinity of La Porte, and its movement under the influence of changing mean winds. The review of lake effects by Changnon and Jones (1972) indeed shows a precipitation maximum due to lake effects in the vicinity of La Porte, and a more extensive one in Upper Michigan. Harman and Hehr (1972) have documented lake breeze convergence effects in the latter area. Support for a suitable change in prevailing winds comes from Eichenlaub (1971) who showed a lowering of the 700 mb level and movement of the prevailing winds from southwest to west–northwest through the 1940's to 1960's over Grand Rapids, Mich. Wahl (1968) showed that marked changes in summer precipitation in the area around the southern end of Lake Michigan occurred between the 1830's and the 1931–60 period, and suggested a recent reversal which is consistent with the trend at La Porte. Namias (1972b) has documented a deepening of the long-wave trough over eastern North America in the 1960's which is also consistent with this picture.

Subsequent to the initial controversy over La Porte, major effort has gone into METROMEX, a study of urban effects around St. Louis, Mo. (Changnon *et al.*, 1971). Here height differences of the order of 100 m occur within the defined control and major and minor effect areas, in a fairly complex pattern of valleys and hills. Bearing in mind the results quoted earlier from Wilson and Atwater (1972) and Huff *et al.* (1975), such height differences and valley effects may well account for a major part of the observed supposedly urban effects (e.g., Huff and Changnon, 1972; Changnon, 1973). For instance, the increase in summer rainfall ratios in the "major effect" area from the 1940's to the 1960's quoted by Huff and Changnon (1972), could well be related to a shift in prevailing wind direction such as found by Eichenlaub (1971) acting on the topography of the area. The present author would strongly endorse the comment made by Braham *et al.* (1973) that their analysis "tends to support the existence of a precipitation maximum east of St. Louis but it shows that a larger raingage network might show that this precipitation maximum is considerably larger than previously suspected and may be due to a combination of urban and topographic effects."

Day-of-the-week analyses for various urban and rural areas have been contradictory; for example, weekdays have greater rainfall in St. Louis (Changnon, 1973) and greater London (Lawrence, 1971; Nicholson, 1969) but also at nonurban Brighton (Nicholson, 1969), while weekends have greater rainfall at La Porte (Changnon, 1970) and at nonurban Norwich (Norgate, 1974) and Irchester (Carrea, 1975). New York shows no effect according to Shulman and Brotak (1973). The statistical significance of a number of these analyses must be questioned because of a natural tendency for quasi-periodicities of about a week (Kidson, 1925; Hamon, 1962; Brier, 1955; Namias, 1966; and Pittock, 1970).

6. Conclusion

The present analysis for the Washington State area suggests that a profitable approach to the quantification of mesoscale topographic effects in areas of possible anthropogenic influence would be to look for correlation patterns between secular variations in station climatic data and appropriate parameters of the larger scale circulation (e.g., 700 mb wind speed and direction). Secular variations which are not accounted for by trends in such climatic parameters might then reasonably be ascribed to unknown and possibly anthropogenic effects. Certainly much greater attention should be paid to possibly complex interactions between large-scale circulation and local topography.

Natural causes would appear to largely account for a number of supposed anthropogenic effects on precipitation. Anthropogenic effects on local climate (e.g., urban heat islands) undoubtedly exist, but the nature and magnitude of the effects on precipitation are seriously questioned. More rigorous analytical, statistical and quantitative treatment is needed if these effects are to be accurately and confidently assessed.

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