An Areal and Temporal Analysis of Precipitation in the Northeastern United States[1]

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ABSTRACT

Harmonic analysis, an objective method of analyzing precipitation seasonality, is applied to 1941–70 monthly precipitation normals for nearly 200 stations in the northeastern United States. Our analysis presents distribution of the annual precipitation as the sum of six different sine curves (harmonics). The first three harmonics account for most of the variance in the original precipitation distribution in this area. Maps are presented of percent variance reduction and phase angle, and possible meteorological factors responsible for the observed patterns are suggested. In addition, the results are compared to previous applications of harmonic analysis to monthly precipitation normals during 1921–50 and 1931–60. The greatest difference appears as a substantial increase in the third harmonic in the coastal region from Maryland to Massachusetts. Variance reductions as high as 73% occurred in the center of this area, compared to a maximum value of only 46% for the 1931–60 normal period. Several possible reasons for this phenomenon are discussed.

1. Introduction

Precipitation seasonality is of interest because of its importance to agriculturalists and others concerned with water supply. Seasonal patterns also reflect changes in the global circulation such as shifts in storm tracks and air mass dominance. Studies of precipitation seasonality may provide an insight into atmospheric circulation changes. When different periods of record are considered, studies of seasonality may even provide information on climatic change.

In this study, harmonic analysis of monthly precipitation is used to investigate precipitation seasonality in the northeastern United States and its changes through time.

2. Literature review

Bar graphs have been a commonly used method of illustrating precipitation seasonality but there are many difficulties in their use. These include subjectivity in station selection and poor representation of precipitation regime areal extent and transition zones.

A more objective and thorough approach to describing precipitation seasonality is harmonic analysis. This method is based on the fact that any curve (such as precipitation plotted against time) can be represented as the sum of a series of different sine curves. Twelve monthly values (such as monthly means of precipitation) can be adequately represented by six sine curves of frequencies 1–6 (Panofsky and Brier, 1958). To obtain the best fit to the curve of original data, two properties of each curve can be altered: the ordinate value and the abscissa value. The shift in the ordinate is called the amplitude of the curve, while the shift along the abscissa is the phase angle. These two values objectively describe each curve or harmonic (Horn and Bryson, 1960) and can be used to construct isopleth maps which are much more easily interpreted than those using discrete bar graphs. A disadvantage to this method is that the amplitude and phase angle values must be presented separately.

The curve with frequency 1, that is, with one maximum and one minimum, is the first harmonic. This describes the annual variation in the original precipitation curve. Its amplitude indicates the difference between the annual precipitation maximum and minimum. The phase angle represents the time of year when the maximum occurs. The curve with frequency 2, or the second harmonic, has two maxima and minima, and describes any semiannual variation in the original curve. The remaining harmonics, frequencies 3–6, describe variations of 4, 3, 2.4 and 2 months, respectively (Horn and Bryson, 1960). Figs. 1 and 2 illustrate New Brunswick's annual precipitation curve using the 1931–70 normal values and their component harmonics, with only the first four harmonics shown.

The amplitude of any harmonic indicates its importance to the description of the original curve. Those

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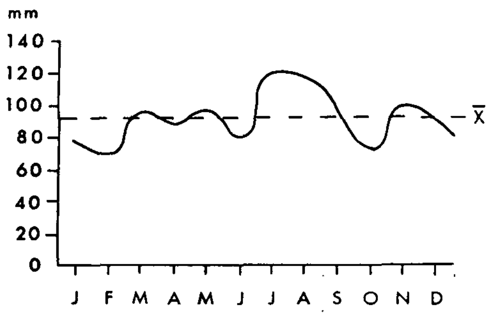

FIG. 1. Curve of monthly mean precipitation at New Brunswick, New Jersey (1941–70 normals).

harmonics that fit the curve most closely have the highest amplitude values. Harmonics that fit less well have smaller amplitudes. If one harmonic happens to fit the curve perfectly, the amplitudes of all the others is zero (Shulman and Leblang, 1974). The amplitudes can also be used to compute the percentage of variance in the original curve that each harmonic accounts for. This is a better estimate of the relative importance of the harmonics obtained for different stations, since it is not affected by variations in total rainfall received.

Horn and Bryson (1960) investigated temporal precipitation patterns in the United States, using normals for the period 1921–50. In the Northeast they found the first harmonic to be the most important, but considered it large enough to be significant only in interior New England because of the small size of all the amplitude terms. The interior tended to have a late July peak, while along the coast the time of precipitation maximum shifted to winter. A discontinuity in phase angle was also noted in the vicinity of the Great Lakes. To their north and west the seasonal precipitation maximum occurred in summer, but southeast of the Lakes the peak shifted to late autumn.

In two areas of the northeastern United States the amplitude of the second harmonic exceeded that of the first. One was located along the southern New Jersey shore, the other in northern New York along the St. Lawrence River. Higher harmonics were deemed unnecessary to the explanation of precipitation patterns in the area.

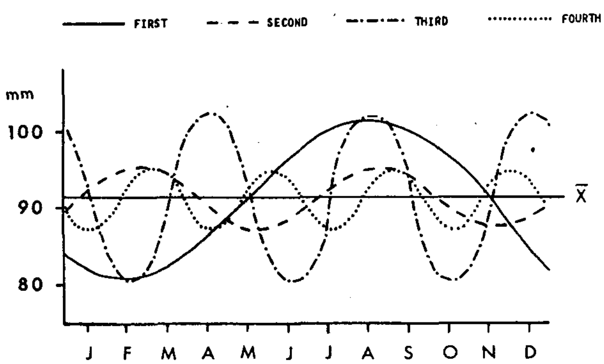

FIG. 2. First four harmonics of monthly mean precipitation at New Brunswick, New Jersey (1941–70 normals).

A more intensive study by Shulman and Leblang (1974) analyzed precipitation at 36 stations in and around New Jersey, using 1931–60 normals. This gave a more detailed evaluation of precipitation seasonality than the earlier study of Horn and Bryson (1960), which used ~20 stations for the entire northeastern region. Their rather similar results showed that the first harmonic had greatest importance inland and diminished toward the coast. The phase angle correspondingly shifted from July to September. Shulman and Leblang attributed this pattern to a peak of summer thunderstorms in the interior, and the influence of heavy tropical storm precipitation along the coast in late summer and early fall. The weakening of the first harmonic toward the coast was due to the substantial winter precipitation this area also receives from extratropical storms. This produced a corresponding increase in the second harmonic's importance.

The purpose of this study is to extend this more detailed type of analysis to the entire northeastern United States. The results may then be compared to the earlier studies in terms of both station network density and period of record.

3. Methodology

For this study the northeastern United States includes the states of Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, Connecticut, New York, New Jersey, Pennsylvania, Delaware, Maryland and West Virginia. This region has quite an even annual precipitation regime due to the year-round convergence of storm tracks over the northeastern United States. A slight summer precipitation maximum due to convective activity is present over most of the region, especially in the western interior far from stabilizing marine influences (Rumney, 1968).

Monthly mean precipitation values for nearly 200 stations were obtained from *Monthly Normals of Temperature, Precipitation and Heating and Cooling Degree Days: 1941–1970* (U. S. Department of Commerce, 1973), published for each of the states. Data from several stations in Ohio and Virginia were also used to guide mapping near the borders of the study area. In this study normals from first-order stations are arithmetic means adjusted for changes of location and exposure. Normals for cooperative stations are simple arithmetic means, but are calculated only for those stations not experiencing significant changes in location. A significant change is said to have occurred if the observation site is moved over 5 mi horizontally or 100 ft vertically during the period of record (U. S. Department of Commerce, 1973). Since months are not of equal lengths, the monthly normals must be adjusted to represent exactly $\frac{1}{12}$ of a year or 30.44 days (Horn and Bryson, 1960).

Panofsky and Brier (1958) state that, for 12 monthly means, the annual mean, five sine terms and six cosine terms will describe the six harmonics. The complete series can be represented by

$$X=\bar{X}+\sum_{i=1}^{i=N/2}\left[A_i\sin\left(\frac{360}{P}it\right)+B_i\cos\left(\frac{360}{P}it\right)\right],\quad (1)$$

where $\bar{x}$ represents the annual mean, N is the number of observations, i the number of the harmonic, P the total period covered by the harmonic (in this case, 12 months) and t the phase angle. The coefficients A and B can be calculated from

$$A_i=\frac{2}{N}\sum\left[X\sin\left(\frac{360}{P}it\right)\right],\quad (2)$$

$$B_i=\frac{2}{N}\sum\left[X\cos\left(\frac{360}{P}it\right)\right].\quad (3)$$

For simplicity the sine and cosine terms can be combined into one term for each harmonic, given by

$$C_i\cos\left[\frac{360}{P}i(t-t_i)\right].\quad (4)$$

Equations for C_i and t_i are given below:

$$C_i=(A_i^2+B_i^2)^{\frac{1}{2}},\quad (5)$$

$$t_i=\frac{P}{360_i}\arcsin(A_i/C_i).\quad (6)$$

Here C_i is the amplitude of the ith harmonic, and t_i is its phase angle (Panofsky and Brier, 1958). This gives the phase angle in degrees, but the displacement along the x axis may also be indicated by time of year. Here the origin (0=0°) has been chosen as 15 December. The 12 months can be indicated every 30°. Therefore, 15 January (30°) is indicated by 1, 15 February (60°) as 2, and so on. When phase angle values are isoplethed, the isochrones may converge on a point or a line. These nodal points or lines occur where phase angle values are changing rapidly with distance, and are useful in distinguishing boundaries between different precipitation regimes.

The first few harmonics may describe the precipitation curve adequately and make further computation unnecessary. The variance reduced by the ith harmonic is given by $C_i^2/2s^2$, except for the last harmonic, which is C_i^2. Here s is the standard deviation. The variances for each harmonic may be summed to obtain the total variance accounted for, since all harmonics are independent and orthogonal (Panofsky and Brier, 1958). As mentioned before, the variance reduction may be used as a "standardized" indicator of the importance of a harmonic in place of the amplitude.

A WATFIV FORTRAN program (Leblang, 1974, private communication) was used to perform the above calculations on the Rutgers University IBM 370 computer.

4. Results

The first three harmonics (Figs. 3–8) represent most of the physical factors responsible for the observed patterns. The fourth, fifth and sixth harmonics generally accounted for very little of the total variance and are not illustrated.

a. *First harmonic*

Considering the first harmonic, several areas of dominance stand out. In inland areas, this harmonic generally accounts for 60–80% of the total variance (Fig. 3). Phase angles in this area range from 5 to 7, or from mid-May to mid-July (Fig. 4). This suggests a continental-type regime where spring and early summer heating triggers an annual peak of convective precipitation (Rumney, 1968). The phase angles increase toward the north, indicating the progressively later arrival of spring and the subsequent precipitation maximum.

A second area of first harmonic dominance lines along the northern New England coast. Variance reductions here generally range from 40–60%. Phase angles vary from around 11 (mid-November) slightly inland, to 12 or nearly 1 (mid-December into January) near the coast. In this section of the Northeast, cool ocean water in-

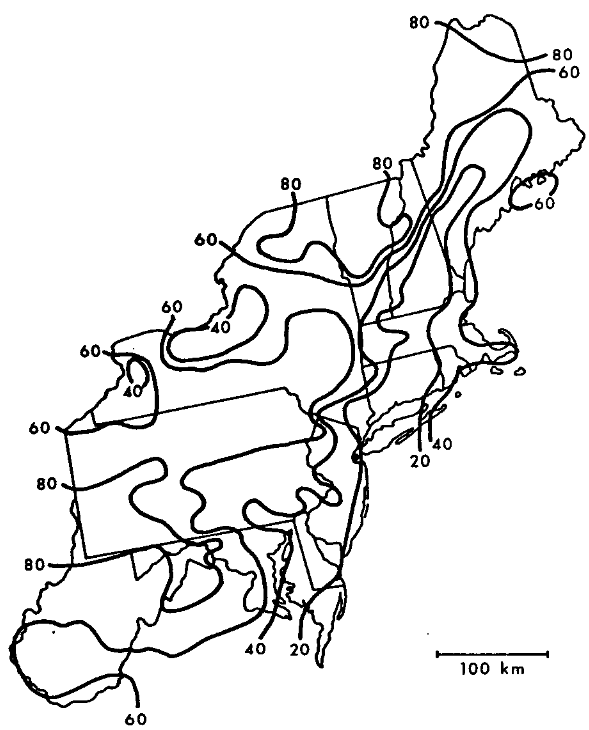

FIG. 3. Percent of total variance accounted for by the first harmonic.

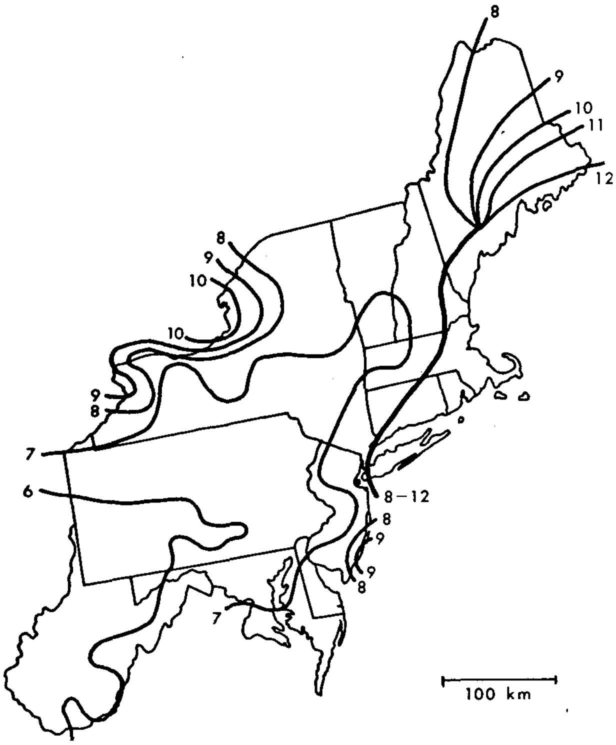

FIG. 4. Phase angle of the first harmonic (January 15 = 1).

hibits convective precipitation in summer. However, there is extensive cyclonic activity during late fall and early winter, leading to a small precipitation peak.

Between the inland summer maximum and the coastal winter maximum, in central New England, there is a region of much lower first harmonic values (<20%). This appears to be a transition zone, where overlap of the two types produces a more even precipitation curve in which higher harmonics predominate. Higher elevations in this area may also contribute to a more even regime through orographic effects.

Three other areas of relatively low first-harmonic importance appear. One is located on the New Jersey coast, and can be attributed to the influence of coastal extratropical storms in winter countering the normal warm-season peak. The other two areas of low-variance reduction (<60%) are located to the south and east of Lakes Erie and Ontario. Here, as in coastal New England, cooler water reduces convective precipitation in summer. In autumn and early winter, cold continental polar and arctic air moving over the still-warm lakes produces snow showers on the southeast shores. Even before temperatures are low enough to produce snow, in early fall, there is an annual thunderstorm and hail peak due to lake-induced instability (Changnon and Jones, 1972). Thus, the lake modification reduces the importance of the first harmonic (warm-season peak) that normally would be quite dominant inland.

b. Second harmonic

Considering the second harmonic (Fig. 5), it is evident that it generally accounts for much less of the total variance than the first. Except for southern Maryland, the variance values never exceed 50%.

Areas where the second harmonic is of greatest importance (20–30% variance reduced) are central New England, the Great Lakes and New Jersey coastal areas, discussed previously, where combinations of two or more precipitation-causing factors create more even annual curves. Phase angles in central New England run from 5 to 5.5, equivalent to mid- to late-May and mid- to late-November peaks. This corresponds to the inland spring and coastal early winter maxima (Fig. 6). Near the lakes the phase angles run from 4 to 5, or mid-April to mid-May and mid-October to mid-November. This indicates the influence of the fall lake-induced precipitation on the continental late spring–early summer maximum regime.

The very high values of variance in southern Maryland and the somewhat lower ones along the New Jersey coast are both related to the combination of winter extratropical and summer tropical storms. Phase angles range from around 1.5–2, or from early to mid-February and early to mid-August, supporting this relationship.

Over the rest of the Northeast, second-harmonic variances generally do not exceed 20%. An interesting feature of the phase angle map (Fig. 6) is the marked discontinuity in the southern part of the study area shown by the 4–12 nodal line. Peak precipitation times

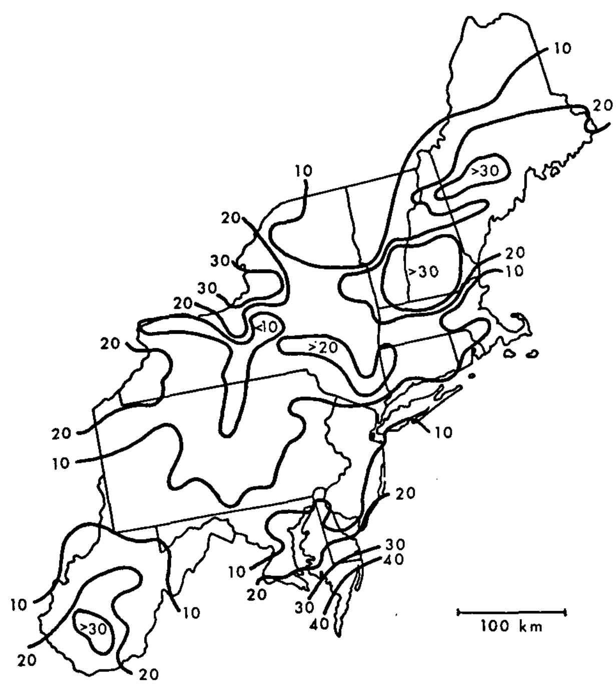

FIG. 5. Percent of total variance accounted for by the second harmonic.

shift from mainly late spring–late fall in the north to late winter–late summer to the south.

c. Third harmonic

The third harmonic maps (Figs. 7 and 8) reveal a striking pattern. An extensive area of high variance values lies along the mid-Atlantic coast, centered on New York City and extending ~45 km on either sides of a line from Kingston, Rhode Island, to Wilmington, Delaware. Variance reductions as high as 71% (Scarsdale, New York) and 73% (Mineola, New York) occur near its center. Phase angles in the area of high variance values run from about 3.4 to 3.7. This indicates precipitation peaks in late March to early April, late July to early August, and late November to early December.

Elsewhere, variance reductions for this harmonic are extremely low, usually under 10%. Exceptions to this are the previously mentioned areas of more even precipitation regimes in central New England and the Great Lakes, but even here the values do not exceed 30%.

5. Discussion of results

A comparison of these results with those obtained by Horn and Bryson (1960) and Shulman and Leblang (1974) reveals relatively minor differences in results for the first and second harmonics. The basic pattern is similar except that Horn and Bryson do not show the decreased importance of the first harmonic in the central New England area. In fact, they cite this area as the only section of the northeast where the first harmonic is significantly more important than the others.

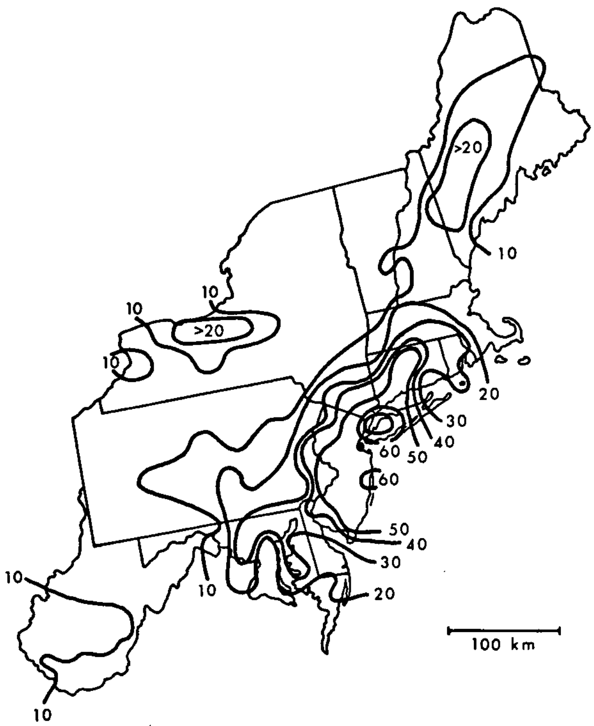

FIG. 7. Percent of total variance accounted for by the third harmonic.

There is a striking difference, however, in results obtained for the third harmonic. Neither of the two previous studies shows such a large area of high variance values along the mid-Atlantic coast. The highest individual variance reduction obtained by Shulman and Leblang was only 46%. The amount of variance reduction attributable to the first harmonic appears to have decreased accordingly, as did that of the second harmonic, but to a lesser extent. Phase-angle values in this area are similar for all three studies, seemingly indicating an intensification of an existing pattern rather than a shift to a new one.

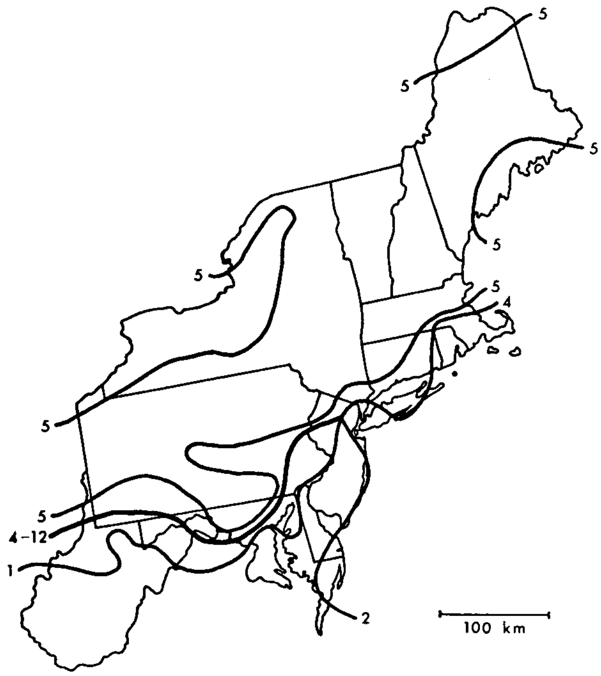

FIG. 6. Phase angle of the second harmonic (January 15 = 1).

SYNOPTIC CLIMATOLOGY

To investigate any changes in precipitation climate that may have resulted from changes in atmospheric circulation, a synoptic analysis was carried out on a 5% random sample of days drawn from nonoverlapping decades of the present normal period (1941–70) and that used by Shulman and Leblang (1931–60). Use of the nonoverlapping decades would show any climatic differences between the two periods much more clearly than if the entire periods had been compared. The two decades of identical data would have yielded redundant results that would have tended to obscure any changes.

Frequencies of air mass occurrences, surface-flow type and frontal passages were then determined from *Daily Synoptic Charts: Historical Series* for the 1931–40

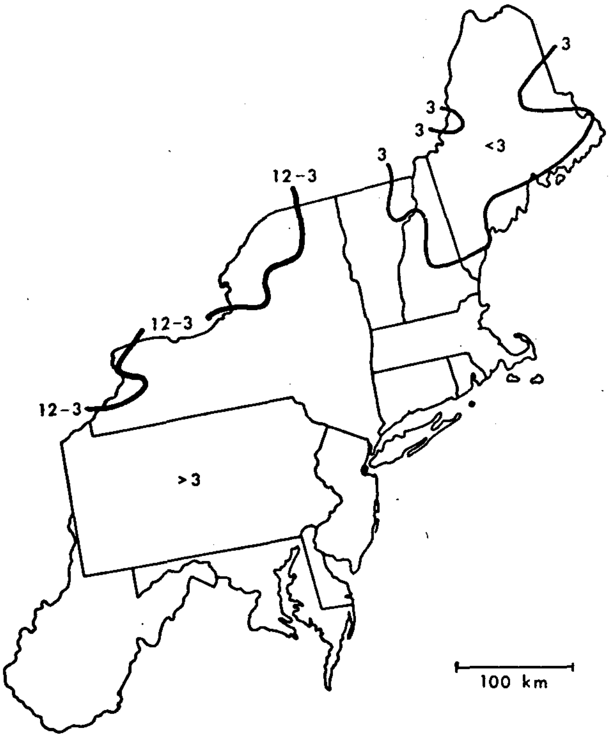

FIG. 8. Phase angle of the third harmonic (January 15 = 1).

decade, and from the *Daily Weather Map* series for the 1961–70 decade. Air masses were divided into continental polar (cP), maritime polar (mP), maritime tropical (mT) and a "modified" type, on the basis of their trajectories and observed local temperature, dew point and wind speed and direction. The "modified" air mass consisted either of mP air from the Pacific or slow-moving cP air, both with a trajectory from west to east across most of the continent and consequent modification. Flow patterns were divided into anticyclonic, cyclonic and straight types according to surface isobar configuration. Frontal passages across the area were recorded as analyzed on the maps. Frequencies for all three features were determined for a rectangular region 45 km either side of a line from Kingston, Rhode Island to Wilmington, Delaware. Fronts were recorded as having passed if they were any place in the rectangle at the time of the map.

The frequencies of these synoptic features in each decade were then compared, using the chi-square test. Results are shown in Table 1. The analysis of air masses shows an increase in the percentage frequencies of cP and "modified" air masses. Frequencies of mT and mP air showed decreases. A chi-square value of 17.04 indicates this change is significant at the 0.001 level. Comparison of different flow patterns shows a decrease in the percentage frequency of cyclonic flow and increases in the frequencies of anticyclonic and neutral flows. A chi-square value of 8.71 indicates the difference in frequencies is significant at the 0.02 level.

Analysis of frontal type frequencies shows the percentage of cold fronts to be nearly the same in both decades, 50.0 and 47.8%, respectively. The percentage frequency of warm fronts and occluded fronts both decreased. Especially notable is the increase in frequency of stationary fronts from 3.1 to 21.7%. The chi-square value for this synoptic feature is 15.45, significant at the 0.01 level.

Frequency changes in all three synoptic features were significant at least at the 0.02 level. This suggests that some change in climatic patterns has occurred. Some meteorological situations that may be related to this phenomenon can be suggested.

A significant meteorological event that occurred during the 1961–70 decade was a shift in the upper air pattern associated with the northeastern drought. Namias (1966) found the drought to be associated with an abnormally strong upper air trough off the northeast coast. This caused storms to move quickly offshore to intensify at sea, reducing precipitation over land. The trough also caused a more frequent occurrence of cP air masses in the region. This agrees with the results in Table 1, as well as with an earlier study of drought-air mass relationships (Horowitz and Shulman, 1967). Namias also hypothesized that abnormally cold water offshore, besides helping to maintain the trough, also tended to stabilize surface air. This reduced convective precipitation ahead of cold fronts and from air mass thunderstorms.

Inhibition of frontal precipitation would be most significant in spring and summer when the trough was best developed (Namias, 1966). It is possible that such a reduction in precipitation might result in a more uniform precipitation regime, since summer is normally

TABLE 1. Chi-square comparison of air mass, flow type and frontal passage frequencies (F) between 1931–40 and 1961–70 using 5% random sample.

	1931–40		1961–70	
Air masses	F	Percent	F	Percent
cP	65	38.9	78	46.4
Modified cP	31	18.6	44	26.2
mT	40	24.0	25	14.9
mP	31	18.6	21	12.5
$\chi^2 = 17.04$ (significant at 0.001 level)				
Flow types				
Cyclonic	80	47.9	63	37.5
Anticyclonic	60	35.9	68	40.5
Neutral	27	16.2	38	22.6
$\chi^2 = 8.71$ (significant at 0.02 level)				
Fronts				
Cold fronts	16	50.0	11	47.8
Warm fronts	12	37.5	6	26.1
Stationary fronts	1	3.1	5	21.7
Occluded fronts	3	9.4	1	4.3
$\chi^2 = 15.47$ (significant at 0.01 level)				

the time of peak precipitation inland. These changes might allow the third harmonic to provide the best fit to the new annual precipitation curve. It is interesting to speculate as to whether these drought-related phenomena could alter the precipitation pattern for an entire normal period.

The coincidence of the area of increased third harmonic importance with the urbanized area stretching from Washington, to Boston leads to a consideration of possible urban influences on precipitation. Several factors have been cited as possible causes of increased precipitation over cities: increased turbulence, increased heating from combustion and other sources, and increases in condensation and freezing nuclei (Oke, 1974). Some statistical evidence has been presented supporting the claim that urbanization enhances precipitation, but this does not relate directly to an increase in the third harmonic's importance. Urban influences on precipitation would have to peak during certain times of the year, masking or smoothing the expected annual precipitation profile. They could not simply increase the probability of precipitation at all times. That would leave the original pattern amplified but unchanged. These results suggest that more work is required if a definite explanation for this change in temporal precipitation pattern is to be found.

6. Conclusions

Monthly precipitation normals for over 200 stations were subjected to harmonic analysis. This procedure mathematically breaks down the annual precipitation curve into its component sine curves or harmonics. For twelve monthly values, six harmonics of frequencies 1–6 are obtained. The amplitude and phase angle, or the importance of each harmonic and the time of year it peaks, respectively, can then be used to analyze a location's precipitation seasonality.

The first, second and third harmonics proved sufficient to account for most of the variance in this area. Mapping of the results revealed the first harmonic as the most important component in the interior, usually with an early summer peak. This was related to a maximum of convective precipitation in a continental-type precipitation regime. The first harmonic was also important along the northern coast of New England, with an early winter maximum attributable to increased cyclonic activity. The importance of the first harmonic decreased and that of the second harmonic increased in areas affected by two precipitation-causing mechanisms. This included central New England, where the interior summer maximum bordered on the coastal winter maximum, and along the southeastern shores of the Great Lakes, where there was an interior summer maximum combined with a lake-induced late fall maximum.

Results obtained for the first two harmonics were similar to those presented in previous studies using earlier data, but those for the third harmonic showed a definite change in pattern. A large area of very high variance reductions (over 70% in its center) appeared on the mid-Atlantic coast centered on New York City. Neither such high variance reductions or such a coherent pattern had been found in previous analyses.

A statistical comparison of air mass, flow and frontal passage-type frequencies indicated significant changes in all three between 1931-40 and 1961–70. It was suggested that conditions associated with the northeastern drought of the 1960's (storms intensifying at sea rather than over land, in particular) might have influenced the annual distribution of precipitation enough to produce the observed changes in third harmonic importance. Urban influences on precipitation may also have been a factor, but would have had to produce a differential effect during different times of year to smooth out the annual curve. No definite conclusions could be drawn as to causation, and additional research is suggested.

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