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CONTENTS



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THE TREE-RING BULLETIN

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Tree-Ring Laboratory
University of Arizona
Tucson, Arizona

# DENDROCLIMATIC HISTORIES IN THE BRYCE CANYON AREA, UTAH*

EDMUND SCHULMAN

This report presents an eight-hundred-year index of fluctuations in winter rainfall and in river flow for the area of Bryce Canyon National Park. As in other papers in this series, the principal objective is the setting up in quantitative form of a master chronology having the greatest possible fidelity to seasonal rainfall and related variables, for use in studies of climatic change and in archaeological dating.

With regard to climatic studies, this paper represents merely a progress report. It is the writer's view that the importance of the objective and the presence of serious uncertainties in the climatic significance of even the most sensitive index of growth from any one locality makes highly desirable a body of ring chronologies representing various species and many widely separated areas. The complete analysis of the Bryce Canyon data in terms of climate is therefore postponed; special emphasis is here given to the problem of refinement of the indices.

## COLLECTIONS

Increment borings obtained in 1941 and on several later field trips have shown this area to be one of the very richest sources of dendroclimatic records in western North America. Open stands of over-age conifers, eking out a scant livelihood on rocky slopes, are developed on a relatively vast area of some thousands of square miles in central south Utah. The ring chronologies in the several sampled localities in and near Bryce Canyon, reported here, represent only a minute fraction of the potentially fruitful collection sites of this region, though, as will be evident, the sampled trees provide a good first approximation to the rainfall chronology of the entire area.

The three principal sampling areas were in Bryce Canyon near Bryce Point (37°36′ N, 112°09′ W), along Tropic Canyon, about five miles northeast, and in Red Canyon, fourteen miles northwest. The spectacular columnar erosion of the soft, pervious Eocene limestone, so familiar to thousands of visitors to Bryce Canyon, is to be found, in modified form, in the other canyons also.

Douglas fir (*Pseudotsuga taxifolia*) is the generally dominant conifer in the "breaks," interspersed in varying proportions with, or occasionally entirely replaced by, limber pine (*Pinus flexilis*), pinyon pine (*P. edulis*), and scopulorum and other junipers (*Juniperus* spp.). A few Colorado blue spruce (*Picea pungens*) were sampled in Red Canyon. In the rolling

*Seventh report on chronologies in the Pueblo area; previous reports in this Bulletin, 12(3) et seq. Mr. Charles W. Ferguson, Jr., assisted greatly in the field and laboratory. The cooperation of Bryce Park personnel in the field studies is gratefully acknowledged.

country just north of the National Park scopulorum juniper reaches magnificent stem diameters of three feet or more, but sampling showed that the very favorable soil moisture conditions as compared with hillside sites result in fast growth, relatively young trees, and complacent ring records.

During the latest visit to this area, in September, 1950, an especially large number of cores were obtained in Tropic Canyon in order to study possible differences in climatic chronology in young as compared with over-age trees.

Experience has amply shown that in drought conifers of western North America one well selected core from each of a number of different trees provides an average growth index little different from that when many radii are used. In these collections, therefore, the widest possible sampling of the various sites was made, only one core being generally obtained from each selected tree.

Sampled trees were grouped according to location, species, and age as noted in Table 1. The innermost ring on the core is in most cases within two or three decades of the birth year of the tree, the cores being taken at the lowest level of the stem above the root flares and usually including the pith or its adjacent rings. Occasional borings which failed, owing to center rot or other reasons, to reach the heart of the tree are noted in the table by beginning dates enclosed in parentheses.

Table 1. Sampled Trees in the Bryce Canyon Area

| Group No. | Canyon Site | Species | Cores Begin | | | | | |
|---|---|---|---|---|---|---|---|---|
| 1 | Red and Bryce | Douglas fir | 1618, | 1629, | 1658, | 1665 | | |
| 2 | Tropic and Red | Douglas fir | 1366, | 1393, | 1436, | 1456, | 1477 | |
| 3 | Tropic | Pond. Pine | 1332, | 1334, | 1395 | | | |
| 4 | Bryce and Tropic | Douglas fir | 1114, | 1267, | 1284, | 1309 | | |
| 5 | Tropic | Douglas fir | 1502, | 1509, | 1663, | 1700, | (1660), | (1679) |
| 6 | Tropic | Douglas fir | 1416, | 1420, | 1451, | 1455, | 1469, | (1613) |
| 7 | Tropic | Pond. Pine | 1431, | 1460, | 1520, | 1618, | 1633 | |
| 8 | Tropic | Pond. Pine | 1356, | 1375, | 1445, | 1458, | 1469 | |
| 9 | Red* | Pond. Pine | 1444, | 1525, | 1581, | 1581 | | |
| 10 | Red | Douglas fir | 1588, | 1624, | 1742 | | | |
| 11 | Red | Blue Spruce | 1664, | 1678, | 1688, | 1729, | (1730) | |

*Two ponderosa pines from a stand 18 miles south-southwest of Red Canyon included in this group.

Twelve Douglas firs and ten ponderosa pines from a homogeneous site in Tropic Canyon were each grouped, for sub-group correlations discussed below, in two sets of relatively fast and slow growth, based on the average growth rate of the interval 1750-1850. In a general way the two sets with slower growth, groups 6 and 8, represent older trees, as shown in the table.

## EXAMPLES OF EXTREME LONGEVITY

So many conifers in the six-hundred-year age class have been found throughout the Rocky Mountains in recent years that only trees well over this age merit, in general, special mention. One of the more noteworthy is No. 1161, the Bryce Point Douglas fir, which with only a handful of other trees of comparable age extends the published index[1] of the flow of the Colorado River for 150 years preceding A.D. 1400.

When first sampled in 1942 this tree, a typical drought conifer, about two feet in stem diameter and twenty-five feet high,[2] showed only scattered

[1] E. Schulman, Tree-Ring Hydrology of the Colorado River Basin, *Univ. Arizona Bulletin* 16(4), 1945.

[2] Estimated as 15 feet in the frontispiece title of the cited reference. This striking tree grows just above and about halfway along the short trail from the car parking lot to the lookout platform at Bryce Point.

small living branches in a generally dead crown; only two or three were alive in 1945 and none by 1950. Cores showed that the fir had begun life about A.D. 1250.

Some interesting features of the growth of this tree during its final decades are illustrated in Figure 1. Its growth is compared with that of three other very old but still hale Douglas firs of the area, whose average ring-width approximated its own during recent centuries. The extreme excess in growth during 1928 follows an injury which, as all cores showed, had occurred well along in June, shortly after cambial growth began; the compression wood laid down during the favorable growth years 1932 and 1933 is no doubt related to this injury. The relative percentages in Figure 1 would appear to indicate that the final growth decline towards death may have begun in the 1920's.

Whether the surge in growth for some decades preceding the final decline depends upon a locally favored root or whether it has some relation to the tree's death might perhaps be determined by complete sectioning of the snag.

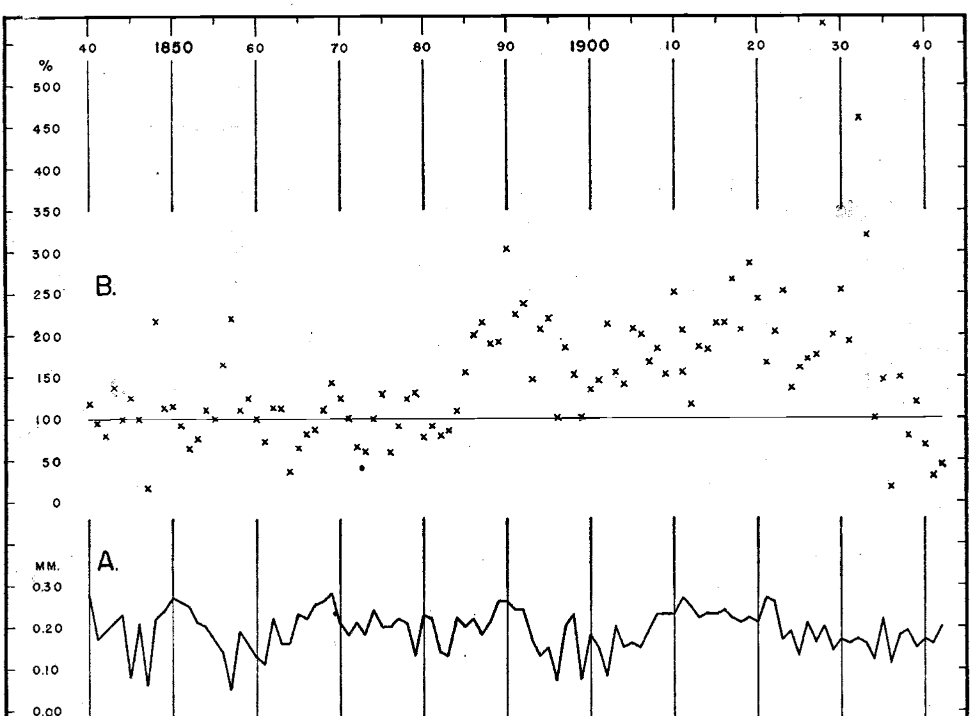


Fig. 1. A: The average growth of Douglas fir trees nos. 3178, 1189, and 3145.
B: The relative growth of tree no. 1161 in per cent of the mean of curve A.

In Tropic Canyon are found the oldest specimens of ponderosa pine thus far sampled in the Rocky Mountains. Numerous pines only twenty to twenty-five inches in stem diameter but yielding five to six centuries of climatic history exist here, often in quite pure groves. The oldest pine, a stunted and gnarled but still vigorous specimen, showed some eight hundred years on a core which failed to reach the rotted center; however, this tree is of interest only as an indicator of the maximum possible age for ponderosa pine, since, characteristically unlike Douglas fir under extreme stress, its chronology is unreadable.

Nearby grew tree No. 3145, a Douglas fir, which yielded an eight-inch core with 837 years of excellent chronology; this tree thus provides one of the longest continuous records for this species in the Rocky Mountains.

## THE CHRONOLOGY AND ITS REFINEMENT

One of the most important properties of ring chronologies of climate is their susceptibility to refinement. Ring indices may be revised by the use of climatically more sensitive, longer, and more widely representative individual records, in some areas leading to a much greater fidelity to the fluctuations in the most significant climatic element controlling growth. When an objective in dendroclimatic studies is the construction of an index of the absolute values of seasonal rainfall of the past, year by year for many centuries, a reduction of even a few per cent in the random fluctuations in such an index is obviously of the first importance. In this section the capacity for improvement of data in the Bryce Canyon area is considered in some detail.

The analysis of ring records in chronology conifers from suitable sites in the Bryce Canyon area is relatively simple, for very good crossdating character is generally present, false rings are almost nonexistent, and locally absent rings are relatively uncommon even in the oldest trees.

*Growth curves.* Four of the longest individual growth records, all Douglas firs, are plotted in Figure 2. Since each curve represents only one core from each tree, that is, one radius, the occasional nonclimatic surge or depression in mean growth rate to be noted here and there is probably exaggerated, though the existence of such abnormal departures in even the best dendroclimatic records emphasizes the danger in relying on just one or even several cores for climatic studies. It is nevertheless obvious in the diagram that the general characteristic of these individual tree records is parallelism in chronology.

Cancellation of much of the random element in individual tree growth whenever a few trees are averaged is illustrated in the group curves of Figure 2. It may be noted here that in averaging the growth of the four old Douglas firs, to obtain group curve No. 4, the injury repair growth for 1928 in tree No. 1161 was omitted; the excessive growth of 1932 and 1933 in this tree, mentioned above, was allowed to enter the averages unchanged.

Inspection of this figure fails to show any striking differences in chronology that are related to age or species differences apart from the usual age trends. However, a more quantitative study of possible differences, developed below, leads to somewhat different conclusions.

A considerable set of cores obtained in September, 1950, for this study of the details of chronology variation is reduced to growth curves in Figure 3. The composition of these groups is shown in Table 1.

*Tests for improvement in chronology.* To examine the various ring chronologies quantitatively, a procedure is used which may be called "Master Fifty-Year Correlation." The Mesa Verde ring chronology in Douglas fir,[3] representative to greater or less degree of the entire Southwest, is selected as a base. With it are correlated, for as many fifty-year intervals back from the present as the data permit, the various group chronologies of the Bryce Canyon area. Use of the linear correlation coefficient as a quantitative index of curve similarity is widely familiar; the mean of three or four

[3]Schulman, *Tree-Ring Bulletin* 14(1), 1947.

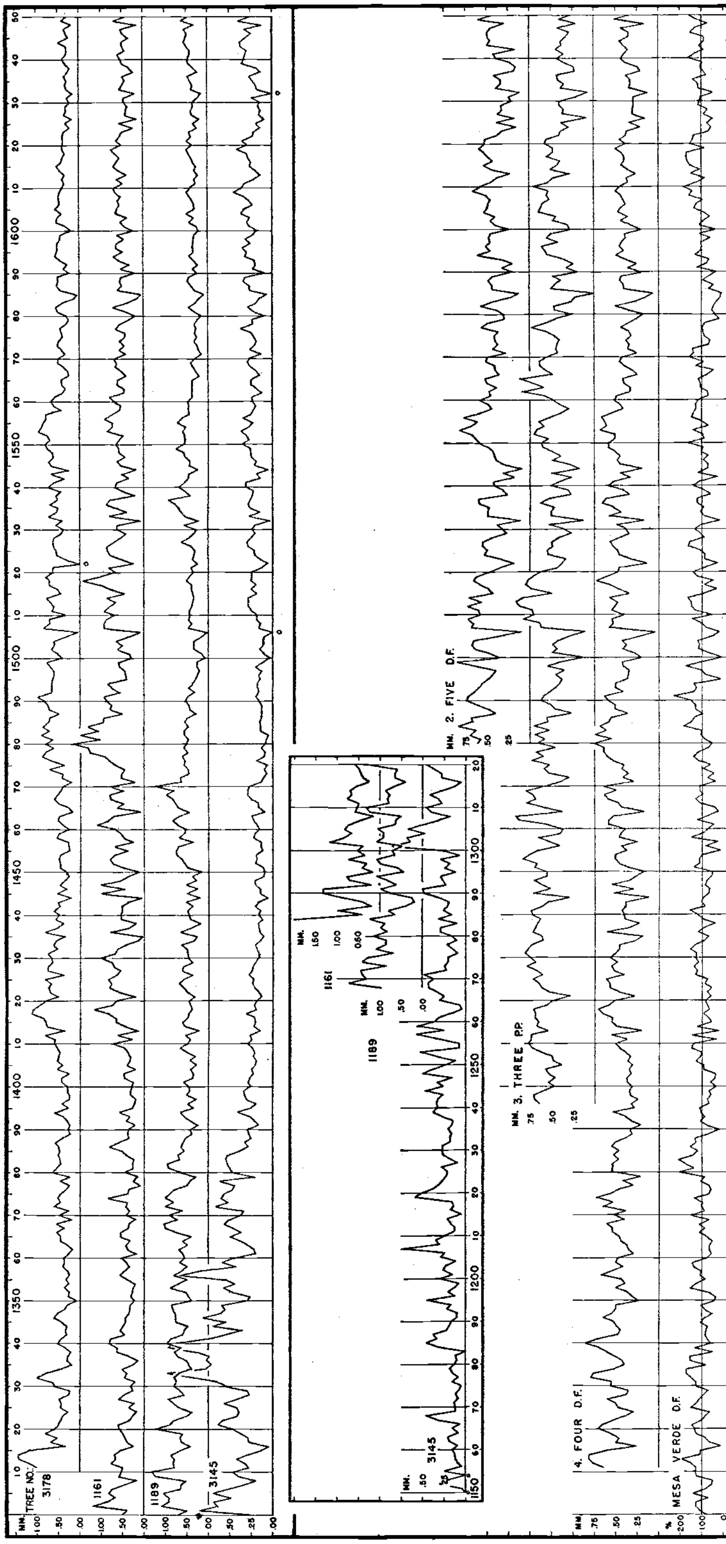


Fig. 2a. Measured ring-growth in the Bryce Canyon area, A.D. 1150-1650. The upper four curves represent the oldest Douglas firs thus far sampled in this area; the insert carries the records back preceding A.D. 1300. Groups of Douglas firs and ponderosa pines in several age classes are averaged to provide unstandardized growth means in the lower part of the figure. The master index in Douglas fir at Mesa Verde is plotted for comparison.

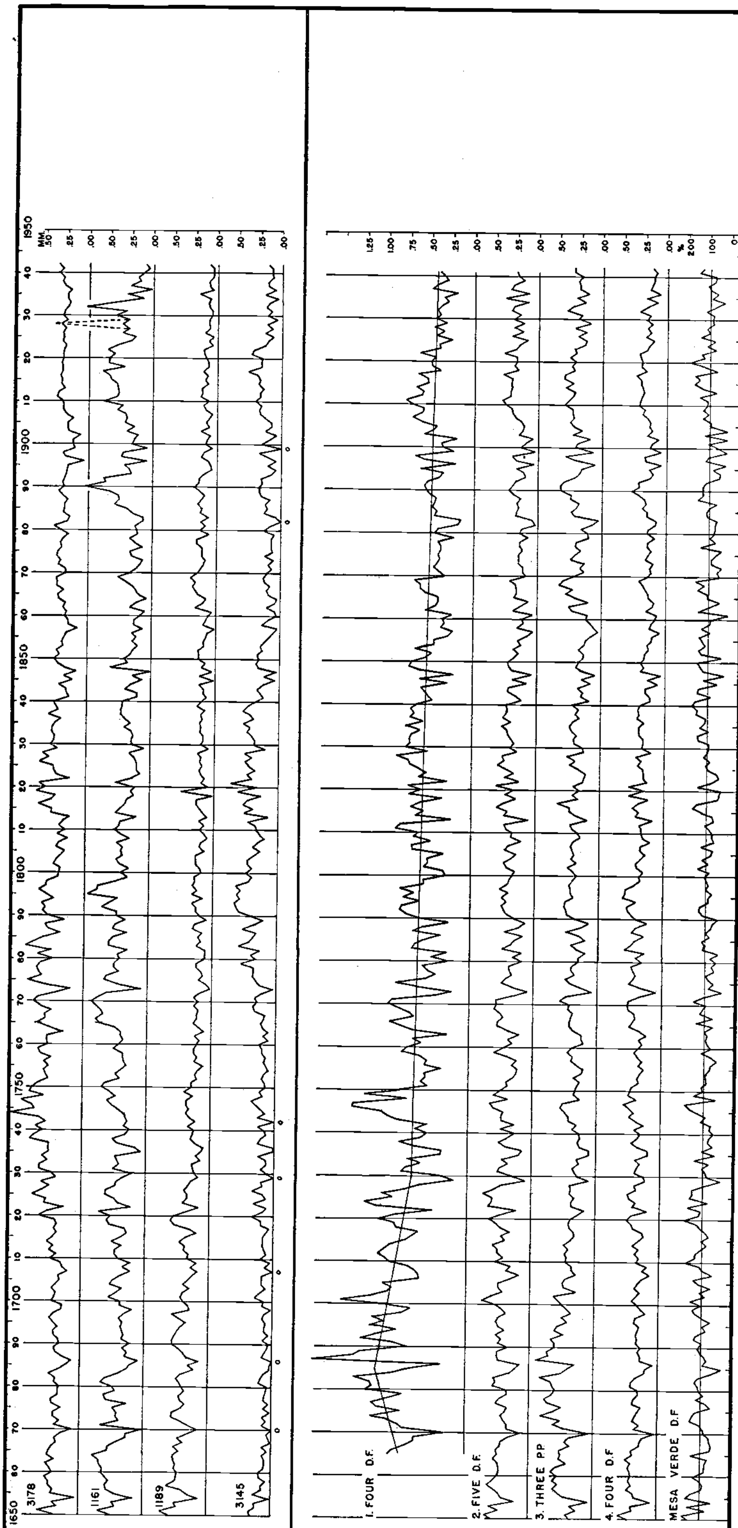


Fig. 2b. Measured ring-growth in the Bryce Canyon area, A.D. 1650-1942.

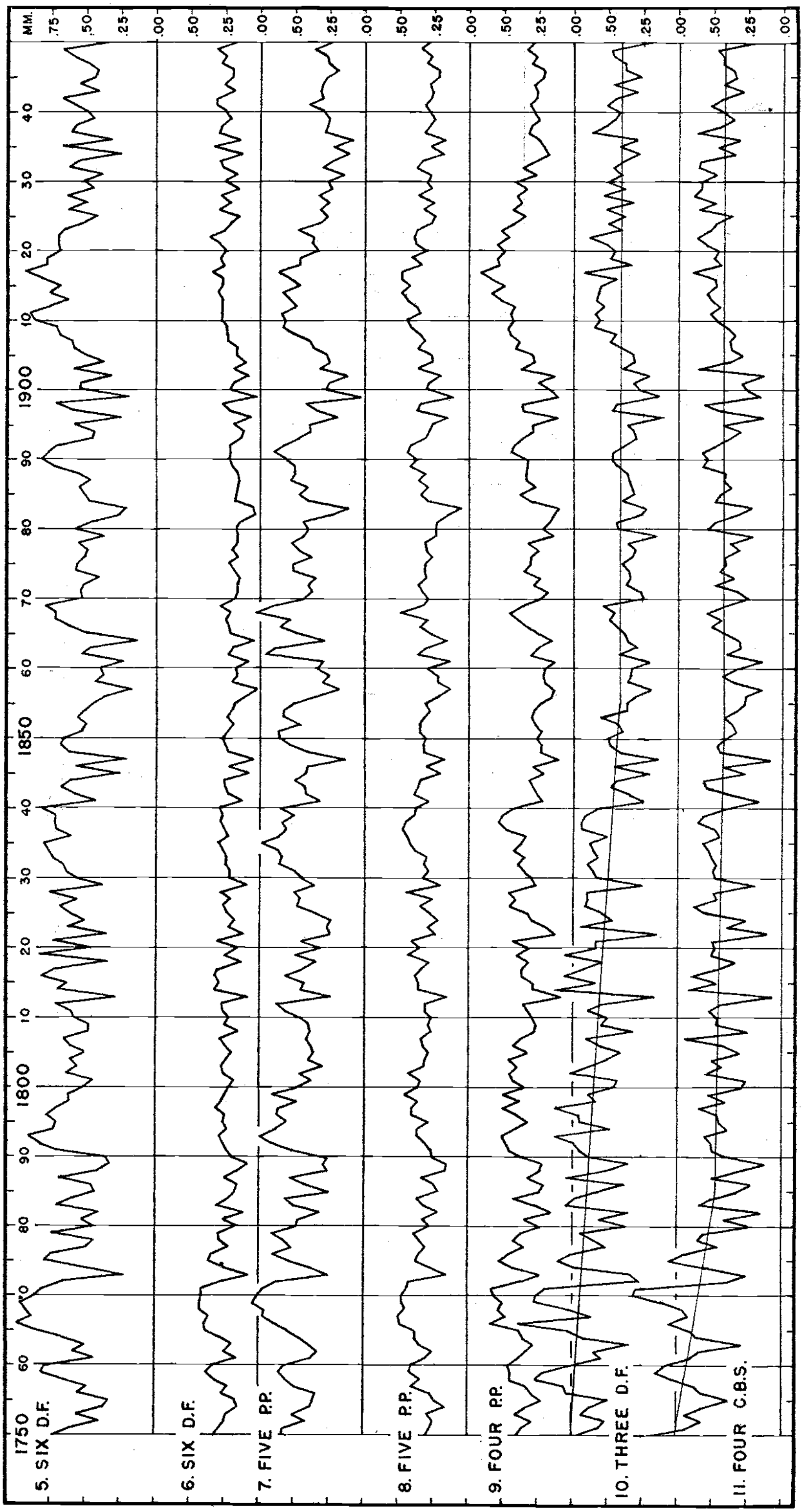


Fig. 3. Mean measured ring-growth of various species in Tropic and Red Canyons, Bryce Canyon area, A.D. 1750-1950.

fifty-year coefficients to a considerable extent removes the instability associated with only one; if good general crossdating in chronology exists between the master area and the area tested, even minor improvements in chronology in the tested area should show up in the coefficients.

The labor in computing correlation coefficients has occasionally led to the use of more simple statistical devices. One of the more common of these is the trend coefficient, which requires merely a count to obtain the percentage of agreements in sign of the successive changes in any two sequences. As a reconnaissance tool, particularly when the magnitude of these changes (the first differences) is taken into account and when the average of a number of such coefficients may be derived, this rapidly obtainable coefficient seems to serve a useful purpose. For more quantitative studies its highly approximate character is a serious defect.

A comparison[4] of the two types of coefficients is afforded in Table 2. The greater sensitivity of the correlation coefficients in this table is striking; for example, in the interval A.D. 750-999 three of the Flagstaff-Mesa Verde fifty-year trend coefficients have the value .66, to which correspond coefficients of correlation of +.29, +.57, and +.59. The latter type of coefficient has therefore been used in this analysis.

Table 2. Comparison of Stability in Correlation Coefficients *vs* Trend Coefficients

| Interval, A.D. | Correlation Coefficient | Trend Coefficient | Correlation Coefficient | Trend Coefficient |
|---|---|---|---|---|
| | *Mesa Verde vs Tsegi* | | *Mesa Verde vs Flagstaff* | |
| 750- 799 | +.33 | .64 | +.29 | .66 |
| 800- 849 | .43 | .62 | .53 | .68 |
| 850- 899 | .35 | .60 | .57 | .66 |
| 900- 949 | .58 | .64 | .57 | .64 |
| 950- 999 | .83 | .78 | .59 | .66 |
| 1000-1049 | .65 | .72 | .55 | .66 |
| 1050-1099 | .68 | .76 | .56 | .82 |
| 1100-1149 | .65 | .76 | .52 | .58 |
| 1150-1199 | .65 | .80 | .66 | .82 |
| 1200-1249 | .78 | .78 | .56 | .76 |
| 1250-1299 | .60 | .76 | .53 | .76 |
| 1300-1349 | .69 | .66 | .64 | .62 |
| 1350-1399 | .77 | .72 | .46 | .56 |
| 1400-1449 | .70 | .90 | .17 | .62 |
| 1450-1499 | .83 | .78 | .36 | .70 |
| 1500-1549 | .82 | .78 | .54 | .68 |
| 1550-1599 | .56 | .70 | .41 | .64 |
| 1600-1649 | .64 | .64 | .52 | .62 |
| 1650-1699 | .61 | .68 | .29 | .48 |
| 1700-1749 | .76 | .74 | .62 | .76 |
| 1750-1799 | .68 | .72 | .48 | .66 |
| 1800-1849 | .74 | .72 | .53 | .76 |
| 1850-1899 | .76 | .70 | .51 | .66 |
| 1900-1946 | .72 | .76 | .... | .... |
| Means: | | | | |
| 750- 999 | +.504 | .656 | +.510 | .660 |
| 1000-1249 | .682 | .764 | .570 | .728 |
| 1250-1499 | .718 | .764 | .432 | .652 |
| 1500-1749 | .678 | .708 | .476 | .636 |
| 1750- | .725 | .725 | .507 | .693 |
| Grand Mean: | | | | |
| 750- | .659 | .723 | .498 | .672 |

[4]Data compared with the Bryce series have been published as follows: Mesa Verde—*Tree-Ring Bulletin* 14(1), 1947; Tsegi—*Idem* 14(3), 1948; Flagstaff—*Idem* 14(2), 1948; Southern California—Tree-Ring Hydrology in Southern California, *Univ. Arizona Bulletin* 18(3), 1947.

*Correlations with neighboring areas.* Since the age trend during the last two centuries in most of the group curves in Figures 2 and 3 is negligible for this correlation study, the unmodified group means of the ring measurements have been used in computing the coefficients, except for groups 10 and 11, which were first standardized.

Table 3. Correlation Coefficients of Bryce Canyon Chronologies Compared with Neighboring Areas

| Bryce Group | No. Trees | Average Age, Approx. | Species | 1750-99 | 1800-49 | 1850-99 | 1900-49 | Mean |
|---|---|---|---|---|---|---|---|---|
| | | | *Vs Mesa Verde Douglas Fir* | | | | | |
| 5 | 6 | 375 | DF | +.55 | +.64 | +.54 | +.68 | +.60 |
| 6 | 6 | 525 | DF | .46 | .58 | .47 | .65 | .54 |
| 5+6 | 12 | 450 | DF | .53 | .58 | .65 | .70 | .615 |
| 7 | 5 | 440 | PP | .42 | .59 | .53 | .57 | .53 |
| 8 | 5 | 550 | PP | .40 | .50 | .46 | .58 | .485 |
| 7+8 | 10 | 495 | PP | .44 | .58 | .49 | .59 | .525 |
| 9 | 4 | 440 | PP | .51 | .42 | .44 | .66 | .51 |
| 10 | 3 | 325 | DF | .47 | .34 | .62 | .65 | .52 |
| 11 | 4 | 300 | CBS | .51 | .46 | .44 | .48 | .47 |
| 1[a] | 4 | 325 | DF | .56 | .41 | .54 | .56* | .52* |
| 4[b] | 4 | 725 | DF | .48 | .42 | .56 | .62* | .52* |
| | | | *Vs Northeast Utah Douglas Fir* | | | | | |
| 4[c] | 4 | 725 | DF | .45 | .53 | .46 | .57* | .50* |
| 5+6 | 12 | 450 | DF | .53 | .65 | .58 | .68* | .61* |
| | | | *Vs Southern California Bigcone Spruce* | | | | | |
| 5+6 | 12 | 450 | DF | .44 | .44 | .59 | .48* | .49* |
| 7+8 | 10 | 495 | PP | .41 | .47 | .70 | .41* | .50* |

*End date of compared series in early or middle 1940's.
[a]1700-49, +.53.
[b]1650-99, +.41; 1700-49, +.60.
[c]1650-99, +.27; 1700-49, +.71.

The coefficients in Table 3 may be considered as indicating that in the Bryce Canyon area (a) no radical change in climatic sensitivity of chronology trees seems to appear with increasing age, although more extensive testing may confirm the more vigorous trees to be slightly more reliable sources of chronology; (b) the elimination of random fluctuations is significantly greater in groups based on six Douglas firs as against groups with only three or four, and a group based on ten or more trees is desirable;[5] and (c) the chronology in ponderosa pine appears to be systematically more variant than in Douglas fir as compared with Mesa Verde Douglas fir. The last result is in contrast to the equally good correlation of both species at Bryce with the bigcone spruce index in Southern California and the slightly better interregional correlations in pine reported earlier, in the Southern California study;[4] this inconsistency points up the need for testing the foregoing properties in many localities before safe generalizations may be made.

*Construction of mean growth curves.* To reduce the growth records of trees of differing ages to a standard form it has for many years been customary to "standardize" the series in individual trees or small groups of even-aged trees by fitting trend lines and computing percentage departures of growth from such lines. This procedure has the desired result of largely eliminating the effect of differing absolute growth rates.

[5]The effects of nonclimatic surges or depressions in growth of long period are likely to be missed when the correlated interval is as short as fifty years. The larger group would seem to be particularly desirable when the objective is an index of the absolute values of past rainfall.

In refining tree growth data to obtain more faithful absolute values of past rainfall and river flow, one of the approximations inherent in standardizing, the "end effect," may be minimized, given a sufficient number of long records. The "end effect," applied to tree-ring series, is the uncertainty in the exact position of the fitted trend or standardizing line, which might be raised or lowered on the curve were more data available at either limit of the ring series. Thus, in averaging standardized individual growth curves of various lengths to get a group mean, or various group means for a regional mean, the run of values of the resultant index may be too high or too low near the end points of the component series by some undetermined amount. Though this error is likely to be small, it introduces a serious uncertainty in interpretation of long-term fluctuations in growth as a climatic index. This effect has been long recognized as particularly important in the early portions of growth curves where the age trend is usually pronounced. Douglass, for example, used a "merging" process[6] to spread such discontinuities in the averages over a number of years, a process he found to be entirely satisfactory for general cycle studies.

The need for controlling the "end effect" is partly responsible for the writer's extended field search during the past decade for specially long-lived trees.

The following procedure is being used in a new program now under way of refinement and extension of dendroclimatic indices in the Colorado River basin and elsewhere. In any area, the individual series of growth measurements are subdivided into two or more sets, e.g., young, mature, and overage trees, and the original ring measures averaged with the earliest common year as beginning date; no change is made in the raw data other than the application of a simple factor, as x2 or x½, to *all* values in some occasional series showing particularly fast or slow growth. Unstandardized mean curves from various localities are then similarly averaged into regional means. In this way, unmodified indices of various lengths become available from which conclusions representing a consensus of climatic indications may be derived. Standardized values of such unmodified indices, which may be necessary for certain comparative studies, may easily be interpreted in terms of the original ring measurements.

In view of the considerable number of standardized ring indices now available in tabular form in this Bulletin, it seems desirable to publish some extended series of unmodified ring measurements of Southwestern trees. The data in Table 4 represent only a part of the Bryce Canyon records now measured but include the longest series in Douglas fir and ponderosa pine and the most inclusive averages for these species in the shorter series. No weighting of any individual series was necessary in any of these groups. The tabulated data are plotted as follows: 4A—Figure 1; 4B—group 4, Figure 1; 4C—group 3, Figure 1; 4D—mean of groups 5 and 6, Figure 2; 4E—mean of groups 7 and 8, Figure 2.

## GROWTH, RAINFALL, AND RUNOFF

Although complete analysis of the climatic significance of the indices reported in this Bulletin is being postponed until the construction of master Southwestern ring data is essentially complete, some critical relationships in these Bryce Canyon data are presented here.

Numerous test studies have shown that the growth of drought conifers in the Colorado River basin in general shows the highest correlation with total rainfall during October-June. Undoubtedly, the various factors disturbing any simple rainfall-growth or runoff-growth relationship result in considerable variation in the true effective interval from year to year; nor can

[6]Douglass, *Carnegie Inst. Wash. Pub.* 289, III, 1936, p. 27.

Table 4A. Ring-Widths of Tree No. 3145, Douglas Fir, Bryce Canyon Area. Unit .01 mm.

| A.D. | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1150 | 00 | 04 | 30 | 21 | 00 | 22 | 05 | 10 | 11 | 12 |
| 1160 | 15 | 09 | 19 | 20 | 08 | 15 | 06 | 33 | 47 | 11 |
| 1170 | 12 | 13 | 08 | 11 | 07 | 05 | 15 | 08 | 15 | 18 |
| 1180 | 13 | 10 | 11 | 00 | 31 | 45 | 33 | 37 | 21 | 19 |
| 1190 | 16 | 10 | 10 | 21 | 17 | 45 | 12 | 20 | 12 | 08 |
| 1200 | 30 | 15 | 25 | 23 | 11 | 28 | 24 | 75 | 30 | 35 |
| 1210 | 24 | 13 | 13 | 17 | 21 | 05 | 17 | 13 | 15 | 59 |
| 1220 | 51 | 37 | 30 | 26 | 22 | 21 | 28 | 09 | 18 | 26 |
| 1230 | 27 | 27 | 17 | 17 | 16 | 19 | 15 | 14 | 27 | 37 |
| 1240 | 32 | 33 | 32 | 26 | 47 | 26 | 33 | 15 | 50 | 38 |
| 1250 | 23 | 11 | 33 | 53 | 07 | 08 | 31 | 57 | 25 | 57 |
| 1260 | 36 | 31 | 16 | 04 | 07 | 30 | 25 | 33 | 43 | 44 |
| 1270 | 37 | 49 | 22 | 24 | 20 | 20 | 09 | 15 | 21 | 10 |
| 1280 | 15 | 29 | 29 | 10 | 32 | 16 | 26 | 21 | 19 | 30 |
| 1290 | 49 | 50 | 23 | 26 | 29 | 11 | 24 | 18 | 29 | 06 |
| 1300 | 26 | 86 | 64 | 69 | 48 | 68 | 52 | 33 | 18 | 40 |
| 1310 | 46 | 28 | 32 | 42 | 29 | 13 | 05 | 28 | 29 | 37 |
| 1320 | 45 | 63 | 58 | 41 | 39 | 41 | 56 | 40 | 27 | 29 |
| 1330 | 54 | 64 | 92 | 123 | 78 | 72 | 77 | 74 | 88 | 123 |
| 1340 | 113 | 76 | 56 | 35 | 69 | 54 | 81 | 60 | 55 | 59 |

Table 4B. Mean Ring-Widths of Four Old Douglas Firs in the Bryce Canyon Area. Unit .01 mm.

| A.D. | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1310 | .... | 64 | 77 | 82 | 82 | 63 | 26 | 50 | 47 | 56 |
| 1320 | 71 | 66 | 54 | 40 | 30 | 48 | 51 | 60 | 38 | 36 |
| 1330 | 56 | 56 | 79 | 77 | 53 | 40 | 43 | 52 | 62 | 70 |
| 1340 | 85 | 72 | 48 | 45 | 49 | 53 | 65 | 56 | 51 | 51 |
| 1350 | 24 | 32 | 38 | 51 | 40 | 43 | 68 | 54 | 42 | 51 |
| 1360 | 48 | 30 | 36 | 37 | 44 | 47 | 55 | 55 | 62 | 40 |
| 1370 | 54 | 38 | 66 | 54 | 74 | 57 | 48 | 31 | 43 | 22 |
| 1380 | 56 | 55 | 55 | 48 | 54 | 48 | 56 | 52 | 39 | 32 |
| 1390 | 34 | 22 | 33 | 39 | 55 | 29 | 33 | 26 | 34 | 34 |
| 1400 | 32 | 38 | 38 | 33 | 35 | 32 | 37 | 34 | 39 | 47 |
| 1410 | 52 | 38 | 56 | 21 | 50 | 56 | 55 | 67 | 71 | 58 |
| 1420 | 52 | 28 | 47 | 58 | 58 | 61 | 41 | 53 | 56 | 49 |
| 1430 | 57 | 51 | 46 | 46 | 28 | 19 | 60 | 35 | 23 | 40 |
| 1440 | 41 | 43 | 39 | 39 | 12 | 53 | 29 | 55 | 34 | 27 |
| 1450 | 17 | 37 | 47 | 51 | 51 | 38 | 44 | 25 | 47 | 44 |
| 1460 | 40 | 59 | 59 | 54 | 18 | 44 | 47 | 60 | 64 | 50 |
| 1470 | 64 | 28 | 42 | 36 | 43 | 41 | 54 | 61 | 65 | 65 |
| 1480 | 76 | 55 | 75 | 61 | 69 | 59 | 57 | 36 | 52 | 52 |
| 1490 | 59 | 64 | 42 | 51 | 51 | 37 | 36 | 35 | 42 | 43 |
| 1500 | 20 | 28 | 43 | 38 | 43 | 22 | 04 | 59 | 54 | 55 |
| 1510 | 41 | 56 | 52 | 49 | 57 | 36 | 48 | 57 | 73 | 61 |
| 1520 | 48 | 47 | 14 | 34 | 47 | 49 | 54 | 58 | 46 | 35 |
| 1530 | 39 | 50 | 18 | 59 | 44 | 53 | 66 | 62 | 34 | 42 |
| 1540 | 59 | 53 | 33 | 45 | 18 | 45 | 48 | 45 | 50 | 58 |
| 1550 | 58 | 51 | 51 | 68 | 60 | 63 | 66 | 54 | 41 | 44 |
| 1560 | 51 | 49 | 33 | 33 | 40 | 41 | 25 | 30 | 39 | 45 |
| 1570 | 43 | 26 | 36 | 34 | 38 | 32 | 34 | 44 | 35 | 26 |
| 1580 | 18 | 36 | 50 | 30 | 15 | 06 | 40 | 41 | 45 | 44 |
| 1590 | 19 | 36 | 25 | 38 | 49 | 40 | 45 | 43 | 38 | 39 |
| 1600 | 20 | 31 | 44 | 36 | 47 | 44 | 38 | 41 | 43 | 50 |
| 1610 | 45 | 35 | 37 | 26 | 36 | 43 | 40 | 40 | 43 | 50 |
| 1620 | 38 | 45 | 38 | 37 | 20 | 34 | 15 | 30 | 30 | 29 |
| 1630 | 29 | 29 | 12 | 34 | 33 | 33 | 38 | 21 | 25 | 39 |
| 1640 | 43 | 40 | 36 | 41 | 45 | 35 | 35 | 44 | 16 | 52 |
| 1650 | 34 | 45 | 28 | 31 | 07 | 27 | 28 | 35 | 30 | 33 |
| 1660 | 32 | 32 | 34 | 32 | 37 | 29 | 31 | 22 | 21 | 18 |
| 1670 | 05 | 28 | 22 | 29 | 26 | 24 | 20 | 30 | 28 | 23 |
| 1680 | 24 | 32 | 31 | 26 | 16 | 15 | 07 | 21 | 21 | 24 |

| A.D. | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1690 | 21 | 26 | 25 | 26 | 24 | 23 | 28 | 27 | 15 | 21 |
| 1700 | 25 | 31 | 27 | 22 | 28 | 25 | 21 | 11 | 19 | 14 |
| 1710 | 26 | 24 | 28 | 25 | 31 | 25 | 18 | 20 | 31 | 33 |
| 1720 | 38 | 33 | 14 | 32 | 28 | 36 | 37 | 28 | 30 | 17 |
| 1730 | 19 | 30 | 28 | 24 | 29 | 14 | 15 | 27 | 34 | 27 |
| 1740 | 24 | 31 | 20 | 29 | 37 | 32 | 37 | 43 | 29 | 38 |
| 1750 | 36 | 34 | 26 | 28 | 25 | 21 | 26 | 23 | 28 | 32 |
| 1760 | 27 | 23 | 27 | 18 | 26 | 38 | 34 | 32 | 33 | 39 |
| 1770 | 40 | 39 | 27 | 07 | 26 | 39 | 34 | 31 | 34 | 37 |
| 1780 | 25 | 32 | 22 | 44 | 37 | 33 | 22 | 36 | 32 | 18 |
| 1790 | 31 | 37 | 41 | 42 | 32 | 47 | 44 | 44 | 34 | 27 |
| 1800 | 28 | 24 | 31 | 32 | 27 | 22 | 27 | 27 | 16 | 24 |
| 1810 | 26 | 26 | 28 | 13 | 33 | 30 | 36 | 31 | 18 | 41 |
| 1820 | 24 | 41 | 20 | 24 | 24 | 25 | 31 | 27 | 33 | 16 |
| 1830 | 26 | 25 | 25 | 29 | 30 | 30 | 25 | 32 | 30 | 31 |
| 1840 | 29 | 17 | 18 | 23 | 23 | 09 | 21 | 05 | 29 | 25 |
| 1850 | 28 | 25 | 24 | 20 | 21 | 17 | 16 | 07 | 19 | 17 |
| 1860 | 13 | 11 | 23 | 16 | 14 | 21 | 21 | 24 | 27 | 31 |
| 1870 | 22 | 18 | 19 | 16 | 24 | 22 | 18 | 22 | 22 | 14 |
| 1880 | 22 | 21 | 13 | 12 | 23 | 23 | 28 | 24 | 26 | 32 |
| 1890 | 40 | 32 | 33 | 19 | 16 | 20 | 07 | 24 | 26 | 07 |
| 1900 | 19 | 17 | 10 | 23 | 17 | 20 | 19 | 22 | 28 | 26 |
| 1910 | 32 | 31 | 29 | 27 | 28 | 30 | 31 | 36 | 24 | 30 |
| 1920 | 29 | 31 | 33 | 24 | 21 | 16 | 25 | 19 | 24 | 18 |
| 1930 | 24 | 20 | 33 | 25 | 12 | 25 | 09 | 20 | 18 | 16 |
| 1940 | 16 | 13 | 17 | | | | | | | |

Table 4C. Mean Ring-Widths of Three Old Ponderosa Pines in the Bryce Canyon Area. Unit .01 mm.

| A.D. | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1390 | .... | .... | .... | .... | .... | .... | 65 | 70 | 72 | 60 |
| 1400 | 48 | 55 | 47 | 54 | 57 | 39 | 49 | 50 | 64 | 74 |
| 1410 | 78 | 75 | 75 | 55 | 68 | 66 | 69 | 69 | 71 | 56 |
| 1420 | 50 | 28 | 54 | 62 | 65 | 72 | 61 | 68 | 79 | 69 |
| 1430 | 75 | 81 | 78 | 74 | 60 | 62 | 72 | 69 | 67 | 63 |
| 1440 | 72 | 74 | 61 | 55 | 29 | 72 | 52 | 63 | 70 | 56 |
| 1450 | 56 | 70 | 68 | 84 | 77 | 66 | 41 | 54 | 66 | 40 |
| 1460 | 38 | 56 | 88 | 92 | 38 | 60 | 80 | 69 | 72 | 79 |
| 1470 | 58 | 40 | 30 | 54 | 59 | 53 | 74 | 60 | 69 | 46 |
| 1480 | 67 | 59 | 70 | 53 | 71 | 55 | 56 | 27 | 47 | 52 |
| 1490 | 63 | 60 | 53 | 46 | 41 | 39 | 46 | 36 | 55 | 41 |
| 1500 | 14 | 49 | 44 | 49 | 44 | 29 | 11 | 63 | 64 | 83 |
| 1510 | 72 | 74 | 88 | 92 | 84 | 50 | 75 | 80 | 79 | 72 |
| 1520 | 63 | 44 | 39 | 34 | 55 | 56 | 50 | 51 | 42 | 28 |
| 1530 | 37 | 54 | 13 | 51 | 51 | 48 | 63 | 54 | 27 | 30 |
| 1540 | 51 | 41 | 26 | 50 | 17 | 28 | 49 | 39 | 48 | 60 |
| 1550 | 62 | 54 | 70 | 68 | 58 | 65 | 52 | 39 | 30 | 39 |
| 1560 | 48 | 58 | 84 | 59 | 72 | 86 | 48 | 57 | 63 | 64 |
| 1570 | 57 | 42 | 44 | 43 | 41 | 47 | 56 | 74 | 57 | 46 |
| 1580 | 26 | 46 | 47 | 27 | 23 | 01 | 50 | 46 | 39 | 49 |
| 1590 | 20 | 32 | 24 | 35 | 55 | 57 | 61 | 42 | 55 | 51 |
| 1600 | 28 | 30 | 48 | 44 | 64 | 62 | 60 | 52 | 55 | 53 |
| 1610 | 70 | 53 | 48 | 29 | 51 | 43 | 39 | 55 | 48 | 48 |
| 1620 | 57 | 56 | 40 | 39 | 30 | 38 | 08 | 37 | 35 | 40 |
| 1630 | 40 | 21 | 07 | 39 | 35 | 42 | 43 | 22 | 23 | 35 |
| 1640 | 43 | 36 | 44 | 38 | 39 | 33 | 29 | 43 | 21 | 41 |
| 1650 | 27 | 31 | 20 | 27 | 05 | 34 | 41 | 47 | 41 | 47 |
| 1660 | 42 | 49 | 44 | 31 | 40 | 38 | 39 | 27 | 33 | 27 |
| 1670 | 04 | 36 | 47 | 38 | 62 | 47 | 37 | 54 | 57 | 48 |
| 1680 | 45 | 48 | 50 | 63 | 37 | 31 | 22 | 68 | 53 | 55 |
| 1690 | 46 | 46 | 50 | 35 | 46 | 43 | 32 | 38 | 27 | 32 |
| 1700 | 38 | 42 | 47 | 21 | 36 | 37 | 34 | 22 | 27 | 27 |
| 1710 | 34 | 33 | 35 | 31 | 36 | 29 | 24 | 25 | 30 | 31 |
| 1720 | 29 | 20 | 13 | 28 | 28 | 25 | 30 | 29 | 30 | 03 |
| 1730 | 22 | 25 | 26 | 20 | 23 | 08 | 08 | 19 | 21 | 19 |
| 1740 | 20 | 28 | 23 | 33 | 33 | 37 | 42 | 40 | 19 | 26 |
| 1750 | 25 | 23 | 20 | 26 | 18 | 17 | 24 | 30 | 29 | 35 |
| 1760 | 30 | 16 | 19 | 19 | 29 | 33 | 33 | 32 | 29 | 34 |

| A.D. | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1770 | 33 | 44 | 37 | 07 | 21 | 33 | 38 | 27 | 31 | 31 |
| 1780 | 23 | 23 | 15 | 26 | 32 | 15 | 22 | 38 | 20 | 11 |
| 1790 | 29 | 37 | 38 | 40 | 39 | 30 | 33 | 33 | 34 | 30 |
| 1800 | 26 | 30 | 36 | 27 | 33 | 29 | 31 | 33 | 31 | 22 |
| 1810 | 25 | 32 | 34 | 14 | 27 | 35 | 35 | 49 | 25 | 32 |
| 1820 | 24 | 31 | 20 | 18 | 17 | 25 | 35 | 29 | 38 | 19 |
| 1830 | 21 | 30 | 31 | 28 | 34 | 36 | 33 | 25 | 29 | 26 |
| 1840 | 32 | 14 | 23 | 21 | 27 | 13 | 22 | 07 | 23 | 29 |
| 1850 | 26 | 21 | 21 | 26 | 20 | 18 | 13 | 04 | 09 | 13 |
| 1860 | 18 | 17 | 35 | 38 | 15 | 32 | 42 | 34 | 50 | 45 |
| 1870 | 33 | 21 | 26 | 20 | 37 | 32 | 25 | 31 | 30 | 16 |
| 1880 | 17 | 25 | 12 | 05 | 33 | 36 | 30 | 27 | 37 | 36 |
| 1890 | 48 | 49 | 46 | 31 | 26 | 24 | 08 | 33 | 43 | 10 |
| 1900 | 32 | 29 | 15 | 35 | 24 | 34 | 38 | 33 | 35 | 35 |
| 1910 | 44 | 39 | 34 | 32 | 43 | 34 | 45 | 44 | 33 | 36 |
| 1920 | 31 | 38 | 31 | 33 | 21 | 19 | 29 | 19 | 32 | 14 |
| 1930 | 29 | 25 | 42 | 36 | 21 | 31 | 17 | 27 | 27 | 28 |
| 1940 | 24 | 33 | 33 | .... | .... | .... | .... | .... | .... | .... |

Table 4D. Mean Ring-Widths of Twelve Mature Douglas Firs in Tropic Canyon, Bryce Canyon Area. Unit .01 mm.

| A.D. | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1750 | 51 | 44 | 31 | 39 | 25 | 24 | 40 | 35 | 48 | 59 |
| 1760 | 55 | 29 | 42 | 34 | 47 | 62 | 68 | 62 | 67 | 69 |
| 1770 | 63 | 60 | 47 | 14 | 39 | 57 | 54 | 35 | 35 | 51 |
| 1780 | 30 | 39 | 20 | 51 | 40 | 30 | 31 | 47 | 28 | 20 |
| 1790 | 27 | 47 | 54 | 59 | 48 | 48 | 51 | 51 | 44 | 43 |
| 1800 | 36 | 31 | 45 | 41 | 42 | 35 | 43 | 46 | 31 | 46 |
| 1810 | 40 | 43 | 47 | 18 | 51 | 46 | 57 | 51 | 23 | 54 |
| 1820 | 30 | 52 | 23 | 42 | 34 | 42 | 47 | 38 | 52 | 24 |
| 1830 | 40 | 43 | 45 | 49 | 52 | 54 | 42 | 48 | 50 | 49 |
| 1840 | 55 | 28 | 41 | 46 | 43 | 17 | 40 | 12 | 43 | 47 |
| 1850 | 46 | 38 | 34 | 39 | 35 | 31 | 23 | 09 | 32 | 27 |
| 1860 | 28 | 15 | 38 | 33 | 08 | 36 | 42 | 48 | 46 | 54 |
| 1870 | 40 | 35 | 34 | 28 | 37 | 39 | 33 | 34 | 35 | 26 |
| 1880 | 37 | 29 | 14 | 12 | 33 | 34 | 35 | 31 | 35 | 47 |
| 1890 | 52 | 49 | 46 | 29 | 28 | 38 | 15 | 40 | 49 | 10 |
| 1900 | 37 | 36 | 19 | 38 | 23 | 34 | 37 | 41 | 46 | 47 |
| 1910 | 57 | 59 | 51 | 45 | 53 | 48 | 54 | 64 | 52 | 53 |
| 1920 | 47 | 49 | 53 | 45 | 36 | 28 | 46 | 35 | 46 | 30 |
| 1930 | 38 | 27 | 45 | 42 | 19 | 50 | 23 | 45 | 43 | 33 |
| 1940 | 37 | 44 | 49 | 30 | 40 | 32 | 31 | 38 | 42 | 49 |
| 1950 | 25 | | | | | | | | | |

Table 4E. Mean Ring-Widths of Ten Mature or Old Ponderosa Pines in Tropic Canyon, Bryce Canyon Area. Unit .01 mm.

| A.D. | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1750 | 44 | 43 | 33 | 40 | 27 | 29 | 32 | 45 | 45 | 50 |
| 1760 | 48 | 34 | 29 | 37 | 42 | 46 | 57 | 61 | 58 | 63 |
| 1770 | 62 | 56 | 52 | 19 | 32 | 45 | 50 | 42 | 45 | 52 |
| 1780 | 37 | 39 | 27 | 41 | 47 | 23 | 33 | 44 | 21 | 22 |
| 1790 | 36 | 40 | 49 | 56 | 50 | 42 | 51 | 51 | 42 | 55 |
| 1800 | 42 | 36 | 44 | 31 | 35 | 33 | 36 | 37 | 33 | 35 |
| 1810 | 36 | 44 | 47 | 20 | 40 | 40 | 47 | 39 | 31 | 46 |
| 1820 | 32 | 43 | 25 | 28 | 23 | 32 | 42 | 36 | 48 | 27 |
| 1830 | 39 | 40 | 46 | 45 | 50 | 58 | 52 | 51 | 52 | 45 |
| 1840 | 49 | 30 | 41 | 40 | 43 | 32 | 36 | 15 | 36 | 44 |
| 1850 | 47 | 49 | 40 | 45 | 43 | 41 | 28 | 15 | 26 | 24 |
| 1860 | 32 | 21 | 53 | 47 | 22 | 38 | 47 | 41 | 63 | 49 |
| 1870 | 37 | 35 | 38 | 33 | 41 | 41 | 32 | 39 | 42 | 34 |
| 1880 | 32 | 33 | 19 | 08 | 35 | 40 | 35 | 44 | 41 | 46 |
| 1890 | 47 | 54 | 49 | 39 | 34 | 33 | 17 | 36 | 38 | 07 |
| 1900 | 29 | 27 | 16 | 34 | 25 | 27 | 36 | 36 | 43 | 49 |
| 1910 | 51 | 47 | 43 | 49 | 53 | 44 | 51 | 54 | 40 | 43 |
| 1920 | 32 | 37 | 37 | 43 | 30 | 26 | 32 | 26 | 34 | 26 |
| 1930 | 28 | 21 | 34 | 29 | 15 | 25 | 13 | 30 | 27 | 25 |
| 1940 | 29 | 35 | 28 | 28 | 29 | 24 | 20 | 28 | 27 | 35 |
| 1950 | 26 | | | | | | | | | |

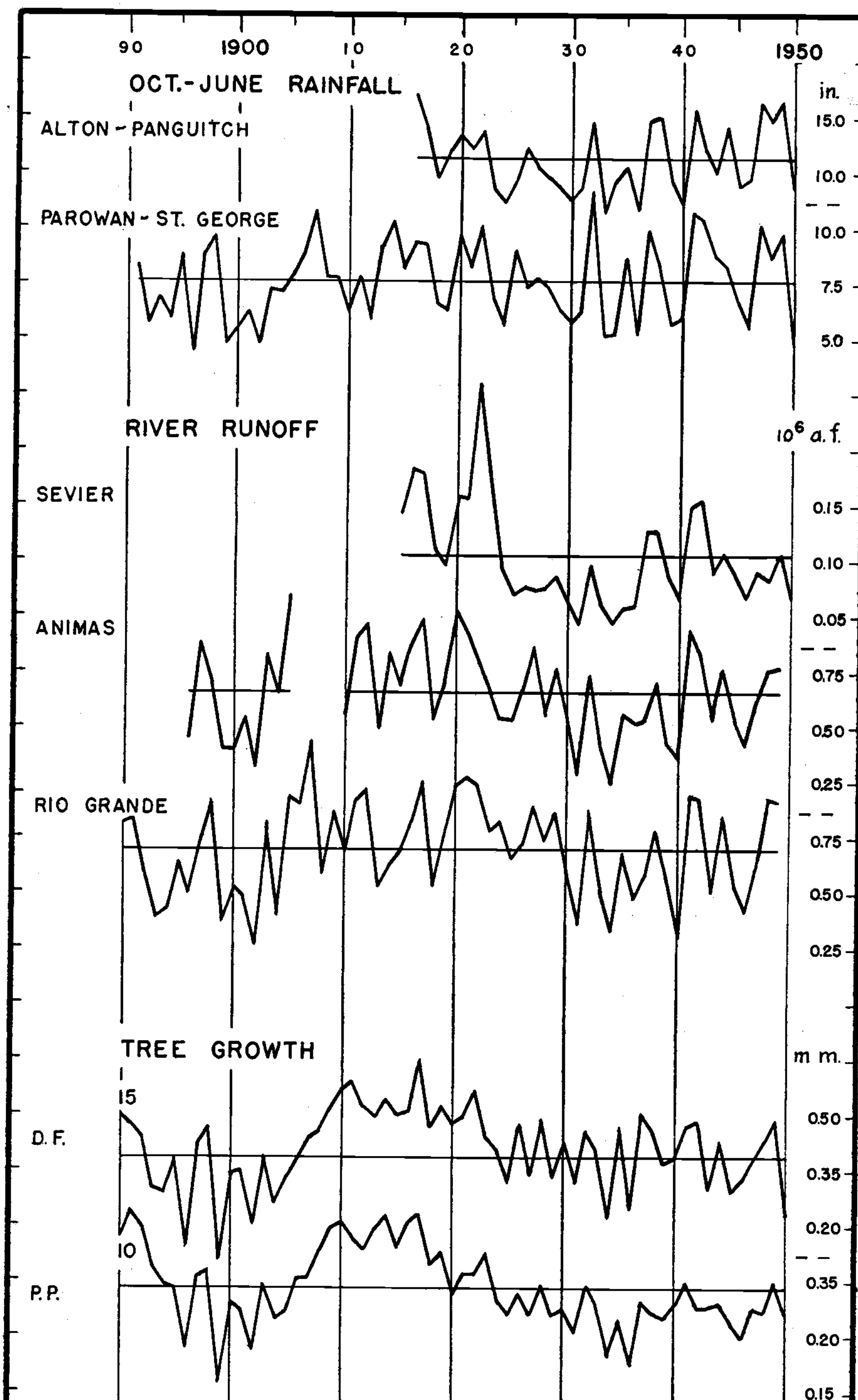


Fig. 4. Comparative fluctuations in rainfall, runoff, and growth.

such factors as the varying distribution of storms during the interval October-June be represented in any simple sum. With regard to the spotty summer rains it seems evident now that almost no effect is present in chronologies based on sensitive ring-growth in the northerly portions of this basin and very little in the southerly portions.

Some growth-climate relationships are illustrated in Figure 4. The two longest rain gauge records[7] in the general neighborhood of Bryce Canyon, Parowan and St. George, are averaged to provide the principal rain index. Since these stations are, however, some sixty and eighty-five miles westward and in another drainage area, a control index, short but based on two nearby stations, is provided in the Alton-Panguitch curve. The two curves show only minor differences, possibly random in the main.

Representative of a much larger area are the river flow data, plotted in the figure for the water-year ending September 30.[8] The flow of the Sevier River, which heads in the Bryce Park area, has been continuously measured only since 1914-15; the headwaters record near Kingston, Utah, plotted in the figure, shows some of the flash-flood characteristics which disturb the growth-runoff relationships in the Gila-Salt basin of southern Arizona. The Animas River at Durango and the Upper Rio Grande at Del Norte, some 250 or more miles to the east, have more stable flows averaging over five times that of the Sevier and provide much longer series of data. Though some differences in rainfall chronology undoubtedly exist across this considerable distance, the observation that on the whole all these areas lie in the same storm belt permits some useful comparisons.

It is evident in Figure 4 that Bryce Canyon growth shows considerable relation to both rainfall and river flow. The correlation coefficients collected in Table 5 emphasize, however, a curious aspect of these relationships. The growth indices seem to bear a decidedly lower relation to local winter rainfall than to that at Durango some 250 miles to the east! That the latter relation is highly significant is borne out by the very good relation between Bryce growth and river flow of the Upper Rio Grande. The relatively low correlations of Bryce growth with local rainfall are not improved when the correlated series are smoothed (a simple three-term running mean was used); in contrast, pronounced improvement in the correlations with rainfall and runoff in southwestern Colorado results after such smoothing. Inspection of Figure 4 in the light of these relations suggests that the Parowan-St. George rainfall record, though long, may represent too low an average winter rainfall to give a true picture of the general trend in this element during the recent past. This trend, closely similar in the Upper Rio Grande flow, Durango winter rainfall, and Bryce growth, exerts a controlling effect on the size of the coefficients.

Table 5. Bryce Tree Growth Correlated with Rainfall and Runoff

| | Interval | Douglas Fir, 15 trees[1] | Ponderosa Pine 10 trees[2] |
|---|---|---|---|
| Parowan-St. George Oct.-June rainfall | 1891-1950 | +.54 | +.38 |
| Same, smoothed | 1891-1950 | .54 | .33 |
| Durango, Colorado, Oct.-June rainfall | 1895-1949 | .60 | .53 |
| Same, smoothed | 1895-1949 | .69 | .66 |
| Rio Grande water-year runoff | 1890-1949 | .65 | .42 |
| Same, smoothed | 1890-1949 | .75 | .52 |

[1]Groups 5+6+10.
[2]Groups 7+8.

[7]U.S. Weather Bureau Climatological Data.
[8]U.S. Geological Survey Water-Supply Papers.