SCIENTIFIC REPORT NO. 1

SYNOPTIC CLIMATOLOGY OF THE ARIZONA SUMMER MONSOON

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by
Reid A. Dryson and William P. Lowry

V. E. Suomi

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ABSTRACT

Using the percent of climatological stations reporting rain as a measure of the raininess of a particular day in Arizona, a large increase in rainfall within a few days is found to occur about July 1 in most Arizona summers. By means of flow charts, upper air sequences, mean soundings, and diurnal temperature ranges, this increase is shown to be the result of a rather sharp transition from one dominant air mass to another over the state. The occurrence appears to be related to index, and a hemispherical singularity also appears to be related to the phenomenon.
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I. INTRODUCTION

A. THE WEATHER SINGULARITY

Considerable time and effort have been spent on the controversy surrounding the concept of weather "singularities." Little space will be spent here reviewing details of the matter. However, since the work described in this report is concerned basically with the singularity idea, the author's working definition of a singularity should be given in the beginning:

"A weather singularity is a strong tendency for the recurrence of a particular weather pattern or sequence of weather patterns at very nearly the same date each year."

For many years these recurrences were noted in the records of single parameters at single stations or at stations in a small area.\(^{(1,2)}\) Later, as observations became more numerous and were extended into the upper air, it became more and more apparent that these recurrences were actually rather widespread and were local manifestations of large scale weather patterns. When the concept was examined carefully by statisticians, they frequently reported that singularities were not statistically significant.\(^{(3)}\) One of the most potent arguments in this denial of singularities was the fact that even the most pronounced occurred in only 50 or 60 percent of the years. However, once the problem was approached with the idea that there might be several basic types of behavior represented in annual weather records, and that some years are basically different from others, investigations began to untangle the confused picture and working hypotheses (as exemplified by the above definition) emerged.\(^{(4)}\)
B. THE "ENERGY LEVEL" CONCEPT

Perhaps the most useful concept in the study of singularities is what might be called the "energy levels of the atmosphere". If we make the assumption that the atmosphere has preferred stable patterns and distributions, and that at any one time it is either in equilibrium in one pattern or it is in the process of a rapid transition to another pattern, or "energy level", then we have a useful framework in which to examine the concept of singularity. Indeed, the stable patterns themselves during the times they are appropriate are singularities, as are the transition periods when they are appropriate. In the light of this idea of energy level, the major question seems not to be "Are there singularities?", but rather "When can we say each of the stable patterns and transitions is 'appropriate'?" Answering this question appears to be possible once an "energy budget calendar" is developed. Such a calendar would have a time scale whose reference points, instead of being determined by the solar angle, are occurrences of great physical or thermodynamic significance. As an example, the first widespread snowfall over the Canadian Plains might change the albedo and radiative aspect of a huge area. This would be of great thermodynamic significance. The date of this first snowfall might be almost certain to fall in November, say, but within that restriction the date might be random. Once the snow cover has been laid down, however, the formation of a cold air mass and a subsequent cold outbreak into midlatitudes would become almost a certainty. Yet, without the snow cover, the formation of such a cold air mass would probably be greatly retarded. It may be that the lag time of the first cold outbreak after the first snow cover is quite fixed, in which case the first snowfall would have established one of the reference points, or "dates", on the energy
budget calendar. As a point of interest, this particular occurrence, that of the first cold outbreak, has been proposed as a singularity, (6) and the rudiments of the idea of "energy levels" were included in the proposal in the form of a suggested analog between the containment and release of cold air and the operation of an electrical condenser.

Going back to the question of when certain patterns are appropriate, we hypothesize that there are preferred patterns and their associated weather elements, but that the reference impulses or "triggers" may be considered as random. The behavior of the atmosphere may be thought of as multi-stable, or "flipping" from one situation to the next, rather than the smooth sinusoidal process thought to be the case during most of the development of climatic theory. There is, finally, a further complicating factor; and, paradoxically, this is essentially a smooth sinusoidal process: the annual variation of the supply of solar energy at the outer limits of the atmosphere.

Applying this annual variation of energy supply to the previous case of the snowfall followed by the cold outbreak, let us assume that the time for the first snowfall is approaching...at least according to the calendar on the wall. This implies that the stable pattern existing now is becoming "inappropriate", or unstable, with respect to the existing input and distribution of solar energy. If our snowfall occurs before the degree of instability has become very great, the transition may involve smaller magnitudes of energy redistribution than if the snowfall comes later when the instability has become greater. Since the time occurrence of the trigger is hypothetically random within certain bounds, the resulting intensity of the readjustment processes is thus also variable within certain limits.
C. SINGULARITIES IN A MULTI-STABLE ATMOSPHERE

We now have pictured a multi-stable atmosphere with randomly timed triggers, and the form and sequence of the changes dictated by the input of solar energy and its subsequent distribution. It appears that if we consider only the stable patterns, transitions, and their sequences, all of the resulting weather is composed of singularities according to the definition we have given. According to our hypothesis, the probability of a certain pattern in the time during which it is appropriate must be quite high, as is the occurrence of a transition at about the time it may be expected. This makes each element, and the sequence of elements, a singularity in the simplified picture. It may seem odd to think of the whole year as made up of one singularity after another, but this is probably because the climatic phenomena which have been thought of as something special, and have been given names (e.g. "January Thaw, (7) Altweibersommer, etc.) are the ones which are, or have been, economically or physiologically important. A case in point is a recently analyzed singularity which is manifested by a sharp increase in the probability of snow in the American Midwest in October. (8) The singularity is shown to have recurred for many years, but since it was apparently not of great personal importance to many people, it went unnoticed and unnamed. The whole year might well be made up of "strong tendencies for recurrence" which are masked by their variability of intensity and are, therefore, not thought of as singularities.

II. THE ARIZONA SUMMER MONSOON

A. A PROBLEM EMERGES

In handling data collected for an entirely different study, it was
TWO DAY RUNNING MEAN LATITUDE OF EASTERN PACIFIC ANTICYCLONE — TWO SERIES, TWO DEFINITIONS

(1919-1939)

(‘33-‘38 ‘49-‘52)
noted by Bryson that over a period of twenty years the mean latitude of the center of the Eastern Pacific Anticyclone changed rather markedly in a few days from about 34° to about 40° North. (Fig. 1). In this instance only those days were counted when there were no fronts drawn on the map within ten degrees of latitude or longitude of the 'H' marking the center of the system. The latitude of the center was chosen as that at which the crossbar on the 'H' was drawn. 

To check the validity and reliability of this observation, the author made an independent tabulation of the latitude of the same system, using different criteria for inclusion: that the cell should have at least a ten millibar pressure increase within a closed isobar having the same general shape postulated by Starr(11) (Fig. 2.) for subtropical anticyclones. The latitude of the crossbar of the 'H' was used in this case also, and eleven years were analyzed, seven of which were included in the twenty years used by Bryson. The results showed a definite, though smaller, change from about 38° to about 41° North in mid-July. Although not particularly strong corroboration, the results taken together suggested that there might be a rapid, large-scale change in the General Circulation taking place most years in early July. This hint was strengthened by two other observations: 1) a time graph of the mean daily values of the surface subtropical index (20-35° North) for ten years showed a decided change during late June and early July (Fig. 3), and 2) the reported change in Arizona from extreme drought in June to a rainfall maximum in July. (12) (Fig. 4) These elements seemed to pinpoint in time and space an occurrence which might be described in detail in local terms and yet throw light on hemispherical changes at the same time.
FIGURE 5.
B. ARIZONA'S JUNE AND JULY RAININESS

Since the raininess which occurs during July in Arizona is reported to be of the air mass shower type, it was decided to examine the nature and distribution of precipitation in Arizona from 1 June to 15 July, using as a measure of raininess of a day the percent of climatological stations in the state which reported at least a trace of precipitation on that day. Accordingly, these percentages were tabulated and put on IBM punched cards for each of the 45 days of each year from 1930 to 1954. This data served as the basic information on raininess, and the percentage will hereafter be called the "Raininess Index."

1. Mean Raininess for 25 years. The mean daily values of Raininess Index for 25 years show a sharp increase, as expected, during the first week in July. (Fig. 5) Plots for individual years showed, however, a much sharper increase in rainfall than that of the mean (Fig. 6).

![Figure 6. Raininess Index for individual years.](image)

2. Raininess changes with zonal index. To discover possible differences in the variability of the Raininess Index with varying conditions of hemispheric circulation behavior, the June mean of zonal westerly index (35° to 55° North) was determined for two ten-year periods of the twenty-five.
FIGURE 7.
The daily mean of Raininess Index was plotted for the ten years of the high index half and for the ten years of the low index half of the record. (Fig. 7).

In the high index curve, sharp peaks of raininess appear in early June, a very distinct dry period during the period 25 June to 26 June, and a large, rapid increase in raininess just after 1 July. The low index curve shows low, rounded maxima during early June with a gradual increase in raininess into July, and only a slight rate of increase after 1 July. Thus, some sort of difference in regime appears to exist between high index Junes and low index Junes.

C. AIR MASS CHARACTERISTICS FOR JUNE AND JULY

1. Mean Soundings at Phoenix. The next step was a check of the report of "the first penetration into Arizona of the deep tropical air masses from the Gulf of Mexico" (Jurwitz op. cit.) between 26 June and 4 July. This suggested that the sharp change in raininess in individual years might be explained by a coincident sharp change of air mass over the area. Accordingly, mean soundings were calculated for Phoenix for the same period 1 June to 15 July and for the five years for which sounding data were available: 1946, 1947, 1949, 1950, 1951. Four groupings of the data were suggested by Jurwitz's article (Jurwitz op. cit.) and by an examination of the raininess means: 1-15 June, 16-24 June, 25-30 June, and 1-15 July. The mean soundings and their limits of variability at each level bring out the following points: (Fig. 8)

1) The dry bulb soundings remain quite uniform, the whole column of air from 850 to 500 millibars warming together through the entire 45-day sample period.

2) The mean dew point soundings for the first two periods (1-24 June) also show an expected uniform increase, but
MEAN SOUNDERGINGS AT PHOENIX FOR 5 YEARS
(1946, 7, 9, 50, 51)

1-15 JUNE
16-24 JUNE
25-30 JUNE
1-15 JULY

TEMPERATURE

DEWPOINT

FIGURE 8
a) the variability of the dewpoint (shaded areas) at any one level during each of these two periods is very large, and

b) the sounding for the third period, shown to be a dry period by examination of rainfall at the surface, was somewhat drier at 850 and 700 millibars. Finally,

3) The sounding for the last period (1-15 July) although very similar to the others in dry bulb temperature, had distinctly higher dewpoints and an extremely limited variability at all levels, despite the contributions of dates ranging over a half month.

2. Max-min temperatures as air mass labels. A further check on the idea of a dry air mass during the last six days of June followed by a uniformly moist air mass during the first six days of July was devised. A scattergram was constructed for Phoenix, Maximum Temperature as abscissa and Minimum Temperature as ordinate (Fig. 9): thus each day would determine one point on the graph. The periods 25-30 June and 1-6 July at Phoenix were plotted on one scattergram for the years 1930-35 (known to be years of low hemispheric zonal index) and on another for the years 1949-54 (known to be high index years.) In each of the plots the mean maxima for the two periods were almost identical, while the mean minima were as much as 5.5° F. different, that of the July period being warmer. In addition, when a method of unpaired replicates as a test of the significance of difference of two populations was applied (13), the maximum temperatures of the 25-30 June period were found to be not significantly different (at the 5% level) from the 1-6 July maxima in both high and low index groups. Whereas, the minima of the 25-30 June period were found to be significantly different (at the 1% level) from the 1-6 July minima in both high and low index groups.

The fact that the minima were in general higher just after 1 July in the twelve years examined, while the maxima remained essentially the same, could be explained in general by the appearance of a moist air mass over Phoenix and a resulting change in nocturnal radiative balance, the more consistently
dry air for the period being in high index years.

3. 700 millibar humidity fluctuations and the Raininess Index. But is Phoenix typical of the entire state in this respect? It might be that the city is so located physically as to favor cloud cover development in the immediate area. To answer the question, time series of the relative humidity at 700 millibars over Phoenix and the statewide Raininess Index were plotted together to see whether or not there was a connection between moisture over one station and rainfall over the entire state. (Fig. 10). The results show qualitatively that during most of June the correlation of 700 millibar Relative Humidity at Phoenix and Raininess Index is much lower than in July, when, for example, an increase in 700 millibar Relative Humidity to about 60% over Phoenix is almost always concurrent with an increase of Raininess to about 60% over the state.

It should be pointed out that wherever the radiosonde code reports a relative humidity measurement as "99" or "Missing", an "M" is plotted on the graph. It is very probable that the data were missing because of the failure of the Lithium Chloride strip at low absolute humidities rather than a general failure of the radiosonde. Therefore, wherever an "M" appears, the relative humidity graph shows values below 10%. During each of the five years for which radiosonde data were available there was a distinct dry period between 25 June and 30 June as shown by both variables of the graph.

In general, therefore, the plot shows that high relative humidity over Phoenix is associated with high Raininess Index, the agreement being better in July than in June.

4. Are the rains local or general? Ten days of the period 1-23 June were chosen for analysis, representing nine years and selected so that all classes of raininess were almost equally represented (Table I). The same was done
700mb RELATIVE HUMIDITY AT PHOENIX compared with ARIZONA RAININESS INDEX

1946

1947

1949

1950

1951

FIGURE 10.
for twelve days in the period 1-15 July and representing eight years (Table II.)
For each of these twenty-two days a map of Arizona was drawn showing areal distri-
bution of rainfall amounts for the day by placing the amount at the map
location of the reporting station. Then for each map a tabulation was made,
counting the number of cases in each of fourteen categories; seven amount

<table>
<thead>
<tr>
<th>TABLE I.</th>
<th>TABLE II.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-23 June</td>
<td>1-15 July</td>
</tr>
<tr>
<td>Selection of days for a study of areal distribution of rainfall amounts</td>
<td>Selection of days for a study of areal distribution of rainfall amounts</td>
</tr>
<tr>
<td>Raininess Index</td>
<td>Raininess Index</td>
</tr>
<tr>
<td>.10- .19</td>
<td>.10- .19</td>
</tr>
<tr>
<td>.20- .29</td>
<td>.20- .29</td>
</tr>
<tr>
<td>.30- .39</td>
<td>.30- .39</td>
</tr>
<tr>
<td>.40- .49</td>
<td>.40- .49</td>
</tr>
<tr>
<td>.50 &amp; up</td>
<td>.50 &amp; up</td>
</tr>
<tr>
<td>Number of Cases</td>
<td>Number of Cases</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Years Represented</td>
<td>Years Represented</td>
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</table>

<table>
<thead>
<tr>
<th>TABLE III.</th>
<th>TABLE IV.a.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean number of stations reporting rainfall amounts for ten selected days during 1-23 June and twelve selected days during 1-15 July</td>
<td>Weighted mean ratios of Northern-Southern Rainfall distribution in Arizona for 1-23 June and 1-15 July</td>
</tr>
<tr>
<td>Rainfall amount</td>
<td>Trace</td>
</tr>
<tr>
<td>North June</td>
<td>56</td>
</tr>
<tr>
<td>South June</td>
<td>67</td>
</tr>
<tr>
<td>Ratio N/S June</td>
<td>.84</td>
</tr>
<tr>
<td>North July</td>
<td>75</td>
</tr>
<tr>
<td>South July</td>
<td>78</td>
</tr>
<tr>
<td>Ratio N/S July</td>
<td>.96</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE IV.a.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weighted mean ratios of Northern-Southern Rainfall distribution in Arizona for 1-23 June and 1-15 July</td>
</tr>
<tr>
<td>June 1-23 Amounts</td>
</tr>
<tr>
<td>Total cases N&amp;S, $T_j$</td>
</tr>
<tr>
<td>Ratio N/S, $R_j$</td>
</tr>
<tr>
<td>Weight: $T_j/17$, $W_j$</td>
</tr>
<tr>
<td>Weight x Ratio: $W_jR_j$</td>
</tr>
<tr>
<td>$\sum W_jR_j/\sum W_j = .76$, weighted mean ratio N/S, June</td>
</tr>
</tbody>
</table>
TABLE IV.b

<table>
<thead>
<tr>
<th>July 1-15 Amounts</th>
<th>Trace</th>
<th>.01-.09</th>
<th>.10-.19</th>
<th>.20-.29</th>
<th>.30-.39</th>
<th>.40-.49</th>
<th>.50 &amp; up</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total cases N/S, T_i</td>
<td>153</td>
<td>192</td>
<td>91</td>
<td>46</td>
<td>29</td>
<td>10</td>
<td>45</td>
</tr>
<tr>
<td>Ratio N/S, R_i</td>
<td>.96</td>
<td>1.31</td>
<td>1.17</td>
<td>1.09</td>
<td>1.64</td>
<td>1.00</td>
<td>1.05</td>
</tr>
<tr>
<td>Weight: T_i/10: W_i</td>
<td>15.3</td>
<td>19.2</td>
<td>9.6</td>
<td>4.6</td>
<td>2.9</td>
<td>1.0</td>
<td>4.5</td>
</tr>
<tr>
<td>Weight x Ratio: W_i R_i</td>
<td>14.69</td>
<td>25.15</td>
<td>10.65</td>
<td>5.01</td>
<td>4.76</td>
<td>1.00</td>
<td>4.73</td>
</tr>
</tbody>
</table>

\[ \frac{\sum W_i R_i}{\sum W_i} = 1.17, \text{ weighted mean ratio N/S, July} \]

class intervals in the northern half of the state, and seven in the southern half.
The mean results of these tabulations appear in Table III. The dividing line
between north and south was taken as the 34th North parallel, which is also a
dividing line used in climatological records by the U.S. Weather Bureau.

To obtain a ratio of northern rainfall to southern rainfall weighted accord-
ing to the number of cases in each amount class, the following scheme was used:

\[
\text{TOTAL CASES IN AMOUNT CLASS } i = T_i
\]
\[
\text{LEAST NUMBER OF CASES IN ONE CLASS } (L = 17 \text{ FOR JUNE AND 10 FOR JULY}) = L
\]
\[
\text{RATIO N/S FOR CLASS } i \text{ (FROM TABLE III.) } = R_i
\]
\[
\text{WEIGHTING FACTOR } = \frac{T_i}{L} = W_i
\]
\[
\text{FINAL WEIGHTED MEAN RATIO } = \frac{\sum W_i R_i}{\sum W_i}
\]

The results appear in Table IVa and IVb, and show the following:

1) In June the rainfall in the northern half of Arizona is 78% that of the
   southern half.

2) In July the rainfall in the northern half of Arizona is 117% that of the
   southern half.

Reasoning qualitatively from the fact that northern Arizona is of consid-
erably greater elevation on the whole than southern Arizona, one might expect more
rain to reach the ground with a shorter fall through dry air in the north than in
the south in any period during which a uniformly precipitating air mass lay over
the state. This is the case in July, but not in June, in agreement with the tentative conclusion of an air mass change about 1 July.

5. Summary. Summarizing the evidence given in establishing a change in air mass we find the following:

1) A decided increase in Raininess Index occurs in the first few days of July on a 25-year mean;

2) Mean soundings show a relatively dry and highly variable air mass over Phoenix during all of June, followed by a decidedly moist and quite uniform air mass over Phoenix in the first half of July;

3) During twelve years the mean daily temperature minima at Phoenix during the last six days of June were significantly lower than those for the first six days of July, while the mean daily maxima were not significantly different for the two periods;

4) The correlation of Raininess Index to the 700 millibar Relative Humidity over Phoenix is apparently lower during the period 1-24 June than from 25-30 June when both variables represent a dry spell, and during the first two weeks of July when both raininess statewide and Relative Humidity locally rise and fall together;

5) During the period 1-23 June the northern half of Arizona receives about 20% less rainfall than the southern half, whereas from 1-15 July the northern half of the state receives more by about 20%.

D. HOW DOES THE AIR MASS CHANGE TAKE PLACE?

If there is a change of dominant air mass over Arizona about 1 July, how does this change take place? What is the mechanism of the change?

1. Mean flow charts for June and July. A first step in answering these questions is an analysis of mean flow charts for June and July over the Southwest. (Fig. 11). These charts make several pertinent points:

1) At 2000 meters in June there is evidence of weak divergence over Arizona,
with a strong flow over the state from off the coast of Southern California;

2) At 5000 meters in June there is an anticyclonic system centered over the Mexican Highlands with strong west-southwesterly flow over the state which has nearly zero divergence;

3) At 2000 meters in July there is marked convergence just over the eastern border of Arizona, with a strong flow from over the Gulf of Mexico now reaching and diverting the Pacific flow over the state;

4) At 5000 meters in July the reason for the change at lower levels is apparent at once; the high level anticyclone has moved northward so that Arizona is now under a weak southeasterly current instead of a strong westerly flow.

These results are very interesting and give a rather clear picture of Arizona's relationship to the seasonal poleward movement of an upper anticyclonic pattern, or cell, which explains in a general way the shift from one rainfall regime to another. But this analysis gives very little information about the details of the mechanism or the timing involved in the change.

2. The mean 500-millibar map series. By using 500 millibar heights on a diamond-shaped grid for the entire northern hemisphere for five years, which were available on IBM punched cards, maps for each third day from 3 June to 21 June were computed and drawn, then daily from 21 June to 30 June, then again every third day until 15 July for the area 20° - 60° N and 85° - 155° W. In general terms, the map series shows the following sequence of events: (Fig. 12)

1) Early in June there is a uniform, moderate zonal flow across the entire area from the east central Pacific into the Mississippi Valley, with a low center north of the 50th parallel over the Canadian Arctic. This pattern remains essentially unchanged through 12 June.

2) On the 15 June map there appears a weak jet, or contour packing, over the Oregon coast and into the Rocky Mountain area at about 45° N, the remainder
of the features being unchanged.

3) The jet over Oregon intensifies slowly through 19 June, but remains a feature superimposed on the original pattern of 3 June. The 500 millibar surface has now become a complex of north-south contours just to the lee of the Rockies, combined with the general east-west trend of the contours elsewhere on the map. The pattern gives the appearance of a huge high-altitude standing wave over the High Plains of the central United States.

4) During the period 20-24 June there appears over the northern California coast a high center which intensifies and forces the jet pattern off to the northeast until the map in general appears quite distorted and lacks the simple unity of the early June maps.

5) On 25 June the map appears quite different from the day before; it is now similar to one of the early June maps with the whole pattern shifted about ten degrees north. On 3 June there was a very flat surface south of 30° with a uniform, moderate slope to the north. On 25 June the northern edge of the flat area now lies at about 40° N, and the northern slope is uniform and gentle.

6) From 25 June until 15 July, the end of the series, the map remains quite uniform with moderate zonal flow and relatively little distortion. A suggestion of a slight north-south trough appears over the west coast early in July and is maintained until the end of the series.

In all, this series gives the appearance of a segment of the atmosphere going from one stable "energy level" into an unstable pattern; and then into another stable form with a rapid transition, or "flip", occurring on 24-25 June. There is little doubt that, with the exception of this change of pattern, the maps form smoothly changing and apparently continuous series.

So far the search for details as to mechanism and timing has brought out a broad-scale change of flow pattern as a suggestion of mechanism, and an apparently discontinuous time series of maps suggesting a timetable. All this
has been done "in the mean", however, and there remains a need for looking closely at individual years, or case histories.

3. Case histories examined. Again, the only five years for which complete upper air data were available were examined in some detail with constant notice being taken of the record of Raininess Index for that year, and of the generalized outline of the mechanics and timing just noted. The notes assembled on each case history appear in Appendix A, while here we shall simply outline the sequence of events which seems to take place, either clearly in some years or in a more rudimentary fashion in other years, at the 500 millibar level. The patterns described by the daily maps do not agree in details with the mean maps for 500 millibars. The precise reason for this is not now clear. However, the generalized sequence of daily synoptic climatology for the area shows the following (Fig. 13):

1) From 1 June to 15 June a broad, flat subtropical high pressure belt is south of 25° with a semi-permanent trough making a southward bulge in the northern boundary of the belt at the longitude of Arizona. This boundary is just about at the 19,200 foot contour, for to the north of this line the surface slopes away sharply at about 100 feet per 200 miles into the trough.

2) Sometime between 15 and 20 June this trough begins to intensify and to take on a northeast-to-southwest orientation just to the west of Arizona. This change brings about a southwesterly flow aloft over Arizona replacing the northwesterly flow of the earlier period. Throughout both these periods the whole state has been north of the "jet", or greatest concentration of contours just at the edge of the flat high belt. There is a marked north-south gradient of sea surface temperature in June off the California coast, (Fig. 14) and this southwesterly flow from over warm water continues for three or four days, bringing especially heavy rains for a day or two when the upper trough is deep and of
500mb SYNOPSIS CLIMATOLOGY OF THE ARIZONA SUMMER MONSOON

FIGURE 13.
Figure 14. Sea surface temperature off California in June.

great north-south extent. The largest Raininess Index during the 25 years of record assembled for this study was 85%, and occurred at this stage of the process when a deep tropical cyclone off the southwestern Mexican coast was aligned with the long, deep upper trough. This combination of trough and cyclone occurs in about 20% of the years and produces a sharp one- or two-day peak of raininess about 20 June.

3) The upper trough west of Arizona fills between 20 June and 24 June, in the generalized sequence, and the pattern returns for a time to the early June pattern with a weak trough over Arizona and a broad flat high belt to the south with northwest winds over the state.

4) In a two day period from 25-26 June the northwestern corner of the Bermuda High breaks off into a small high cell bounded by the 19,400 foot contour. This cell moves northwesterly over Arizona, and concurrently the "jet" moves rapidly northward to about 45° in the longitude of Arizona, while the trough reforms over the southeastern United States. Arizona now lies for a time in a region of strong subsidence which produces the distinct dry spell previously noted during the period 25-30 June.

5) Just as rapidly as this high cell appeared in the Southwest, it moves to the northeast about 1 July, and the upper trough reforms again, somewhat
weakened, off the California coast just to the west of Arizona. The whole state
is now under a deep, gentle flow from the Gulf of Mexico on the southwest side of
the westward extension of the Bermuda High. Widespread rains over the area now
begin to fall and persist for several weeks.

E. THE SUMMER MONSOON

To the extent that there has been a rather sharp change of dominant air mass
and seasonal wind direction in Arizona with general rains following the change,
one might say that the area had come under the influence of a "monsoon".

1. The occurrence or non-occurrence problem. Once we have called this
sequence of events a "monsoon" and have implied that it is seasonal, or singular,
in nature, we ought to be able to say in which years it occurred and in which
years not. As with most phenomena which have varying degrees of intensity, this
is sometimes not an easy thing to say, even when the definition of occurrence
is left entirely up to the investigator.

The problem of setting up occurrence - non occurrence criteria in this case
amounted to examining concurrent aerological and raininess information for five
years, then reconstructing an aerological history of twenty other years for which
essentially only raininess information was available.

2. Rainy days and rainy spells. To begin with, it had to be decided what
constituted a rainy day and what constituted a rainy spell. The three-day and
five-day running means of Raininess Index had been computed and punched on the
IBM cards containing the basic information on raininess. The top deciles of
daily raininess, three-day raininess, and five-day raininess for the twenty-
five years of the 45 day period were sorted out and tabulated chronologically
within each year. In this way one could see readily when each year's share of
the top deciles occurred, if there was a share.

3. "Aerological History" criteria. How did the synoptic patterns behave
during these rainy spells and dry spells? Of the five years for which the daily
500 millibar synoptic charts were available, it was decided that two years,
(1949 and 1950), exhibited almost exact replicas of the generalized synoptic sequence; two years (1946 and 1947) had all the elements present but with long, rather than abrupt, periods of transition; and one year (1951) had slow transitions in addition to different timing from the others. In this last case a rudimentary monsoon could be seen to begin just at the end of the sample period; i.e. 15 July. Noting that the heaviest and most general rains over the state occurred when the transitions were short and distinct, and that even slow transitions with less subsequent raininess were timed very nearly the same as in the generalized case, criteria could be set up so as to include factors of magnitude of raininess and accuracy of timing. It is, of course, not surprising that the features of the generalized case appear in most of the five years, since their records determined these features; but it appears to the writer significant that in four of the five years the timing of the events was quite uniform.

The criteria based on the reconstruction of an aerological history, as previously mentioned, were these: the monsoon was said to have occurred in those years when:

1) At least four consecutive days of the period 30 June to 10 July were in the top decile of five-day rainy spells,

2) At least three of these four were also in the top decile of three-day and one-day rainy spells, and

3) At least one of the four days had a Raininess Index of greater than 55%.

The twenty-five years were thus divided as follows: eight clearly had a monsoon, twelve clearly had none, and five were technically without a monsoon but had to be considered individually for one reason or another. Of these five, three were placed with the twelve without a monsoon because, although raininess was nearly sufficient for qualification, the Raininess Index curve showed only a single peak just before 30 June suggesting the intensified pre-
monsoon trough of Part 2 in the general case, and no subsequent monsoon. The
other two of the five years were counted as having had a monsoon for reasons of
very slight timing errors, the raininess being quite sufficient to qualify.
The final count was ten years, or 40%, with a monsoon (Table Va).

<table>
<thead>
<tr>
<th>Clearly with Monsoon</th>
<th>Conditionally with Monsoon</th>
<th>Conditionally without Monsoon</th>
<th>Clearly without Monsoon</th>
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Number of Cases 8 2 3 12

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<th>TABLE V.b</th>
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<td>List of years having Monsoon under &quot;Local Subjective&quot; Criteria</td>
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<tr>
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<td>1939</td>
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Number of Cases 19 6
4. "Local Subjective" Criteria. When compared with the average frequency (71.5%) of the 22 European singularities counted by Brooks (op.cit.), the 40% hardly seemed satisfactory. In addition, when the question of monsoon occurrence as viewed by Arizona residents ("Local Subjective" Criteria) was suggested, it seemed that a loosening of the criteria might be in order. A second set of criteria resulted: the monsoon was said to have occurred in those years when at least two consecutive days of the period 30 June to 10 July were in the top 15% of rainy days (i.e. with Raininess Index greater than 30%). This division set aside 19 years, or 76%, as being monsoon years (Table V). This was quite close to the 71.5% of Brooks.

III. ARIZONA'S SUMMER RAIN AS SEEN BY OTHER AUTHORS

A. TEXT BOOKS

Many standard climatology textbooks mention a seasonal maximum of rainfall in Arizona during July and the dearth of rain during June. ([14] p. 200, [15] p. 342, [16] p. 377, [17] p. 172, [18] p. 772) Of these most mention generally that this summer rain is "of the showery type" as opposed to frontal rain. Only two (Blair and Climate and Man) mention a "deep, moist current from the southeast moving up-slope into the interior" (Climate and Man) as additional explanation. None mentions the fact that late June is very dry while early July is very rainy by local standards, suggesting the presence of some agent which does not change smoothly as the season progresses.

B. THE MOIST TONGUE OVER THE SOUTHWEST

Wexler and Namias (19) show by means of isentropic charts that a deep, curving moist tongue appears to invade the Southwest during August. Since the tongue appears on mean maps for August, they make the statement that "this is a normal state of affairs for summer". Later Namias extended the observation by
constructing mean maps for July and August of 1934–39; and once again the moist tongue appeared quite clearly over the Southwest. Wexler (21) suggests that the anti-cyclonic eddy aloft over southwestern United States, which appeared previously on the mean flow charts in this study, is a result of downstream disturbances from a standing wave in the westerlies over the west coast and the western mountains. Because of a marked temperature contrast from land to sea here a concentration of solenoids is found, and a cyclonic torque is exerted on the northwesterly flow off the coast to produce the standing wave. The complete picture of the circumpolar eddies given in Wexler’s report (21 p. 15) shows a mean upper trough just west of the California coast, the moist and dry tongues intertwining in the large eddy over the Great Plains, and the parallel paths of dry air to the north and the moist air to the south between trough and eddy.

On page 13 of the report we find an explanation of our findings that the northern half of the state has only about 80% of the June rainfall of the southern half: "As the currents (the moist and the dry) move to the northeast, mixing occurs between the moist and the dry air, but near the origin of their first contact in central Arizona it is nearly always possible to detect a sharp dividing line between showers in the east and few or no showers in the west." If the dividing line were drawn southwest to northeast, the orientation of the "jet" described in the generalized mechanism, the two findings about shower and no-shower areas would be at once reconciled.

Aside from the several articles by Wexler, Namias, and Jurwitz (op. cit.) very little has been written in detail about the early summer rainfall regime of the American southwest. Perhaps now a synthesis of these works with the present findings can be made, and future work suggested.
IV. SUMMARY AND SYNTHESIS

A. SUGGESTED MECHANISM OF THE MONSOON

It seems fairly certain that during July and August there is a tongue of warm, moist air entering the United States over the Rio Grande country and reaching well into the Great Plains. On page 14 of Wexler's report (21) he states "Sometimes the western eddy over the United States (of which this moist tongue is part) moves west of its normal position causing rains in western Arizona and southern California." According to Blair (pp. 170-175 op. cit.) Brownsville and Monterrey, Mexico, have rainfall maxima in June and September; El Paso in July; and Yuma and Mazatlan in August. Considering the longitudes and topographic positions of these stations, it seems plausible that the moist tongue might move inland from the Gulf of Mexico in June, move westward (in the mean) as far as Arizona in August, then return to the east during September. Since the mean positions of the tongue as described by Wexler and Namias include no information about June and September, there is here no contradiction of fact by theory.

In June, according to our deductions, the moist tongue is too far east to bring rain to the Arizona area. The trough over the west coast is quite pronounced and in fact intensifies with increasing solenoid concentration as the Great Basin area heats up under clear skies, long days, and dry winds. This concentration anchors the trough to its coastal position, and the downstream perturbation of the induced standing wave over the western mountains finds a stable position just east of the large mountain mass.

As June progresses the pattern in the area covered by the analysis of mean 500 millibar charts becomes more and more unstable. Perhaps increasing east-west temperature gradients locally over longitudinal coastlines around the hemisphere, combined with the classical picture of a tendency for a smooth northward
movement of tropical temperatures in most areas, explains the increasing instability. The circumpolar vortex is trying to shrink, but horizontal s池oidal cells in midlatitudes resist the shrinkage locally. Trusting the previous analysis, we see that about 25 June the strain is relieved. At this time both subtropical zonal index (20-35°) and polar zonal index (55-70°) mean curves show a marked change for the entire northern hemisphere. (Fig. 15.) Some sort of realignment or readjustment must have taken place.

The detailed picture in the southwestern United States seems to show a movement of moisture and raininess into the Great Basin area at this time. This would act as an agent to reduce the continental temperatures in the area and cause a reduced land-sea contrast and a filling of the upper trough. Such local details might offer explanations of the mechanisms of hemispheric readjustment during the "singular" periods of transition hypothesized in the "energy level" concept.

B. RECOMMENDATIONS FOR FUTURE WORK

Probably the most fruitful methods for further investigations of this sort, based on the "energy level" idea, would involve the study of means based on the "energy budget calendar". If one could state objectively that a certain sharp readjustment occurred on, say, "D-Day"... a date variable on the standard calendar and fixed on the "energy budget calendar"...then an examination of mean D-3, D-2, D-1, D+1, etc. maps would be likely to show details of the reason for increasing instability just before the readjustment. In our case of the Arizona Monsoon, for example, such "D-Day" means might show that the moist tongue was to the east of the Rockies on D-1, and west of the Rockies and Mexican highlands on D+1. Such a local "trigger" might well cause a hemisphere-wide change. On the other hand, a similar occurrence elsewhere in the hemisphere might be the impetus and actually cause the changes in the Southwest rather than the other
way around.

The picture of a multi-stable atmosphere with locally induced triggering mechanisms might well allow careful analysis in a relatively small area to permit much improved hemisphere-wide forecasts in the medium-range field. The better understanding of such a picture would certainly clarify the meanings of many observations of the General Circulation, and thus tend to improve long range forecasting as well.

V. CONCLUSIONS

1) The state of Arizona experiences a large increase in rainfall within a few days about 1 July in most years. The percent of climatological stations reporting precipitation may be used as a useful index of raininess in this connection.

2) Mean soundings and max-min temperature scattergrams for Phoenix, data on areal distributions of precipitation over the state, upper level relative humidity fluctuations, and mean flow charts combine to show that the increase in rainfall is due to a rather sharp change from one dominant air mass to another near the end of June.

3) Mean 500 millibar maps of the area show a change from a smooth, organized pattern in early June to an increasingly distorted pattern about 24 June. This map series then shows an abrupt return to a smooth pattern within a few days after 25 June, with a continuation of this situation into mid-July.

4) Detailed inspection of 500 millibar maps for individual years reveals that all years examined in which a definite increase in rainfall occurred had a general sequence of events in common during June and July. The individual years of which the generalized sequence is a composite make it clear that
individual elements of the sequence appear in varying degrees of magnitude and timing accuracy.

5) Time variations of the 10-year mean subtropical zonal index and the 10-year daily mean polar zonal index exhibit a marked change in late June. The former shows an increase in the strength of the Easterlies between 20° and 35° North, while the latter shows an increase in westerly strength between 55° and 70° North around the entire Northern Hemisphere.

6) The mean daily values of Arizona Raininess Index for ten years of high index for June show several distinct peaks of raininess during June, followed by an extreme dry period between 25 June and 28 June and an extremely rapid increase in raininess during the first few days of July. The same data for ten low zonal index Junes show the June peaks to be quite variable, and the increase in raininess to be more gradual into July. This suggests a system involving more dependable timing of sequence elements during high index years.

7) The phenomena and mechanisms outlined in this report are shown to be elements in agreement with an "energy level" and "energy budget calendar" concept proposed for the General Circulation.

8) Modifications of the techniques reported and further investigations of this nature are outlined in the belief that the general method demonstrated holds great promise for increasing understanding of the General Circulation and improving the accuracy of medium- and long-range forecasts.
REFERENCES


(2) Buchan, A.: "Interruptions in the regular rise and fall of temperature in the course of the year, as shown by observations made in Scotland during the past ten years, 1857-1866"; J. Scot. Met. Soc., v.2, New Series 1867-69: Pt. I: 4-15; Pt. II 41-50; Pt. III 107-112 (1869)


(9) U.S. Weather Bureau: "Daily Series, Synoptic Weather Maps, Northern Hemisphere Sea Level and 500 Millibar Charts with Synoptic Data Tabulations"; various years.


APPENDIX A

Short notes on the behavior of elements on 500 millibar maps of individual years.

1946: July 2-3  No rapid movement of high and jet
           July 4     Long but weak upper trough, rudimentary monsoon
           July 11-14 No 500 millibar situation dictating rainfall - surface shows
                             series of trailing fronts from jet lows on Canadian border

1947: June 10  Flat pressure gradient aloft beginning 16th - long upper
                    trough just to west on 18th - pressure low, pattern transitional
           June 21    Between troughs
           July 1     Weak ridge forms over Arizona - 192 contour moves out
           July 4-5   194 contour moves NE slightly
           July 6-7   Good trough settles over state
           July 10    194 moving SW again - trough far west
           July 15    Good trough - high moves NE again

1949: June 8-11 Surface occluded fronts
           June 12-15 Southward movement of jet with strong NW winds over state
           June 16-19 Upper trough deepens to west with strong SW winds over state
           June 28    On NE side of high with NW winds
           June 28-July 2 Rapid movement of jet North
           July 8     Transitional pattern preceded on 6th by jet return over area
           July 11-12 Pattern indeterminate - jet to north again - upper cold
                              trough out

1950: June 22  Upper trough moved into flat ridge. At surface secondary
                    wave NW Arizona formed and dissipated
           June 24-26 Gulf High moves over Arizona rapidly
(1950):  July 3-4  High moves NE
          July 7  Upper trough forms and brings jet back to region
          July 11  Westerly flow over state

1951:  June 16-20  Steady pumping from SW for 4 days
       June 21-30  1192 contour south of state
       July 1  Rudimentary high dominating state
       July 5-6  Moderate pumping from SW
       July 7-10  High dominating
       July 11  Pressure gradient flattens
       July 12  Trajectory over Mexican Highlands
       July 13  Trajectory east of mountains
       July 11-14  High moves out with jet to north