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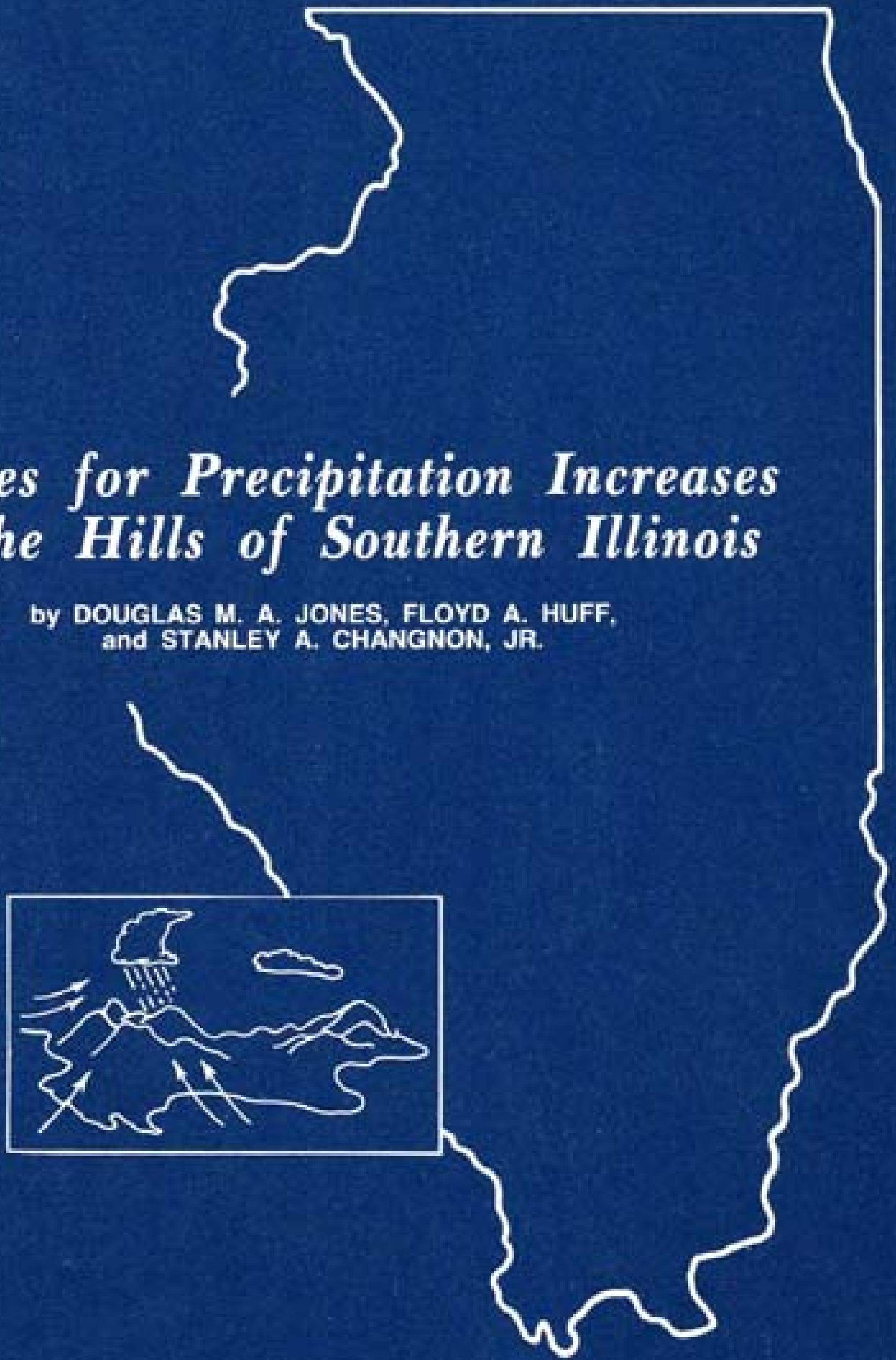
REPORT OF INVESTIGATION 75

STATE OF ILLINOIS

DEPARTMENT OF REGISTRATION AND EDUCATION



Causes for Precipitation Increases in the Hills of Southern Illinois

by DOUGLAS M. A. JONES, FLOYD A. HUFF,
and STANLEY A. CHANGNON, JR.

ILLINOIS STATE WATER SURVEY

URBANA

1974

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Title: Causes for Precipitation Increases in the Hills of Southern Illinois.

Abstract: Studies involving precipitation in Illinois have shown the presence of 10 to 15 percent more precipitation in the average annual precipitation pattern in the Shawnee Hills area of southern Illinois than in nearby flatlands. Three methods differing in scale and time were used to delineate the hill anomaly and to determine the reasons for it. First, a series of climatic studies of precipitation distribution considering daily, monthly, and seasonal data for comparison of hill and flatland stations were performed during 1960-1963. Next, a 5-year project involving analysis of data from a special raingage network on the basis of individual rain periods, months, and seasons during 1965-1969 was planned to define the areal extent of the hill high. Finally, the results of these two studies were used to design a 1-month field study involving a weather radar, 3 cloud cameras, 5 weather (temperature-humidity) stations, 1 pilot balloon site, and aircraft sampling flights. Results of the three major studies show that the hill enhancement of precipitation is the addition of moisture due to greater evapotranspiration from the forested hills and the convergent wind field created over the western hills caused by the configuration of the hills and valleys.

Reference: Jones, Douglas M. A., Floyd A. Huff, and Stanley A. Changnon, Jr. Causes for Precipitation Increases in the Hills of Southern Illinois. Illinois State Water Survey, Urbana, Report of Investigation 75, 1974.

Indexing Terms: Cloud condensation nuclei, convection, diurnal differences, hill effect, Illinois, precipitation, radar echoes, wind.

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DEAN BARRINGER, Ph.D., Director

STATE WATER SURVEY DIVISION
WILLIAM C. ACKERMANN, D.Sc, Chief

URBANA
1974

Printed by authority of the Stale of Illinois—Ch. 127, IRS, Par. 58.29
(5-74-2000)

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Causes for Precipitation Increases in the Hills of Southern Illinois

by Douglas M. A. Jones, Floyd A. Huff, and Stanley A. Changnon, Jr.

ABSTRACT

More precipitation falls on the western Shawnee Hills of southern Illinois than falls on the flatlands both north and south of the hills. Three methods differing in scale and time have been used to delineate the hill anomaly and to determine the reasons for it.

Average monthly precipitation values were studied in a series of climatic investigations. The effect of the hills was found to be most pronounced during the warm season of the year when showers and thunderstorms are the major source of precipitation.

A 5-year study involving a dense recording raingage and wind recording network installed in the hills began in 1965 to better define the hill area maximum. The results from this network data also showed that the hill-related increases apparendy came through enhancement of heavy showers associated with squall-line and cold frontal conditions.

An intensive field study in July 1970 used the recording raingage and wind network, a hygrothermograph network, meteorological radar, and a meteorologically instrumented aircraft. The 1-month study occurred in an abnormally dry period, and because of this most of the rain was from air mass showers, not frontal storms. These air mass showers were found to be enhanced partially by the moisture derived from the forested hills under low wind conditions. In addition, the low speed winds from the south were found to be directed by the valleys within the hills so as to develop a convergent pattern above the hills where the atmosphere was convectively unstable.

The explanation of the hill enhancement of precipitation is the addition of moisture due to greater evapotranspiration from the forested hills and the convergent wind field created over the western hills caused by the configuration of the hills and valleys.

INTRODUCTION

Climatological studies of the precipitation of Illinois have shown the presence of increased precipitation in the average annual and seasonal precipitation patterns in a hill area of southern Illinois (Water for Illinois—A Plan for Action, 1967). This hill high was not as well defined geographically by the existing climatic stations as might be desired, but the few stations in the hills had 10 to 15 percent more precipitation on the average than did stations located in the lower and flatter lands to the north and south of the hills.

If the increase is real, its causes are important and challenging questions to be answered from a view to increasing our knowledge of atmospheric processes and their interaction with the biosphere and hence the water resources of southern Illinois (Roberts et al., 1962).

If the rain increase is topographically related, it represents a sizeable rainfall change with a minor elevation change, a heretofore unsuspected phenomenon. The hill area has a mean elevation that averages only 400 feet higher than the surrounding flatlands. However, the southern edge of the hills, part of which is at right angles to the prevailing low-level southerly winds, rises abruptly (300 to 500 feet within a distance of 2000 feet) from very level flatlands, and this conceivably could produce localized vertical motions and convergence.

Another possibility for the increase in rainfall over the hills relates to land use differences, since the hills are largely in forest and the flatlands in row crops. These land use differences could 1) affect the turbulence of the lower levels, 2) account for spatial differences in humidity due to differences in evapotranspiration, 3) lead to different natural amounts of cloud and ice nuclei released to the atmosphere, and 4) result in a difference in the partitioning of solar energy impinging upon the different surfaces.

Scope of Project

To obtain answers to the questions of reality, dimensions, and causes of the rainfall anomaly, the Illinois State Water Survey pursued three sequential avenues of investigation. First, a series of climatic studies of precipitation distribution were performed during 1960-1963. These initially considered daily, monthly, and seasonal data for comparison of hill and flatland stations. These initial climatic studies tended to confirm the reality of the hill high, and to reveal that it was a warm season phenomenon.

Subsequently, a 5-year project was planned to better define the areal extent of the hill high. This project involved facility support from the National Science Foundation to purchase 44 recording raingages and 5 recording windsets. This equipment was installed and operated in a dense network (Shawnee Network) during 1965-1969. Analyses of these data, on the basis of individual rain periods, months, and seasons did describe the dimensions of the rainfall high in the hills and the rather exact placement of the maximum rainfall area within a portion of the hills.

Finally, these results and those from the climatic studies were used to design a 1-month field study involving a weather radar, 3 cloud cameras, 5 weather (temperature-humidity) stations, 1 pilot balloon site, and aircraft sampling flights.

Unfortunately, the extensive 1-month effort in the field sampled a very dry period in the hills, and hence very few desired data on rain days were collected. This necessitated further analyses of certain climatic data and that from the 5-year operation of the dense rain-wind network in order to 1) evaluate the meager results from the 1-month field effort, and 2) understand better the possible causes involved in the increase over the hills.

This report is divided into three sections. The first presents various climatic data and results considered relevant to 1) establishing the reality of the hill rainfall high, 2) suggesting the processes involved in the rain increase, and 3) verifying whether the dry 1-month sample should exhibit rain increases.

The second section is based on the 1965-1969 network data for summer. On the basis of rainfall patterns, each rainfall period (storm) was classified as 1) a potential hill-effect storm (maximization in hills), 2) a potential no-effect storm (maximization in flatlands), or 3) an indeterminate storm (major centers in both hills and flatlands). Then analyses were performed with respect to seasonal rainfall patterns; synoptic storm types; rain types; mean values of rainfall volume, duration, and rate in the hill, flatland, and indeterminate storms; the frequency distributions of mean and maximum rainfall in the topographically grouped storms; and the distribution of heavy storm rainfalls. These analyses, although based on a semisubjective definition of hill-effect storms, provided useful information in verifying the presence of a hill-effect mechanism and in defining the meteorological factors most strongly related to the apparent hill-effect.

The third section of the report presents results from the 1-month field project conducted during July 1970. A few of the individual rain periods are discussed, and various other results from the data as partitioned on either a regional (hill vs flatland) basis or on a time (cloud vs no-cloud) basis are included.

Background

The fact that mountains significantly affect the weather on and around them has been thoroughly documented (Fujita et al., 1962). In recent years it has been shown that orographic features of much lesser heights are effective in modifying the temperature regimes about them, and in altering the precipitation regimes to a degree unexpected heretofore (Bergeron, 1968). However, the 'Project Plevius' studies of Bergeron were concerned primarily with precipitation enhancement by forest-crowned hillocks with maximum height of 200 feet during stable rains. Bergeron has explained the hill enhancement as being caused by the increase in size of raindrops falling from altostratus clouds and dropping through cumulus 'feeder' clouds generated orographically by the gentle uplift in airflow over the hillocks. The hillocks receive more precipitation under these conditions than do the surrounding lowlands.

During convective rains no hillock-associated pattern has been established, although Bergeron hypothesizes that it is present and would thus be expected to appear in the average pattern from a large number of convective storms.

A difference in the flora on the Cypress Hills of Manitoba, Canada, has been used to explain and to estimate an annual precipitation of 20 inches compared with 13 inches at Medicine Hat which has a different flora at 1800 feet lower altitude and 35 miles distance (Holmes, 1969). In addition, the Cypress Hills (width 15 miles, length 150 miles) lay orthogonal to the prevailing westerly winds. Holmes has stated, "Further, the effects of the hills can be measured in the atmosphere to a considerable height above the summit."

Climatic records reveal that the Shawnee Hills of southern Illinois, with a mean height above the bordering Ohio and Mississippi Rivers of 310 feet, have a climate different from the surrounding lower and flatter lands, as evidenced by higher valley winds and typical hill and valley temperature contrasts. For this hill and flatland area, a difference in flora cannot be used to indicate an increase in precipitation, since both hills and lowlands receive more than enough precipitation to support dense forest cover of both conifers and hardwoods. However, land use and flora differences between the two areas (crops in flatlands, forests in the hills) lead to regional differences in evapotranspiration that might help explain a rainfall difference.

Acknowledgments

This work was performed under the general guidance of Dr. William C. Ackermann, Chief of the Illinois State Water Survey. Dr. Ackermann greatly encouraged the study of the hill effects.

The 1-month field project and related analyses were a joint effort of the state of Illinois and the National

Science Foundation, under grant GA-19494 awarded to D. M. A. Jones. Those involved in the field effort under Jones' direction included Neil G. Towery, Meteorologist; Robert Terry, Radar Technician; and Joseph Scott and James Dyer, Meteorological Aides. They were ably assisted by Eugene Mueller and Donald Staggs in the radar installation and testing. The willingness of the field group to work long hours throughout July 1970 materially aided the project. Mr. Towery, with the assistance of Wilma O'Brien and Patricia Coughlin, processed much of the field data. We are also indebted to Thomas Henderson and Donald Duckering of Atmospherics Incorporated for their interpretation of the flight data and perceptive observations during the 1970 flight program.

The National Science Foundation also awarded a facilities grant (GP-2896) in 1964 to S.A. Changnon, Jr., to purchase 44 recording raingages and 5 recording wind instruments to instrument the western Shawnee Hills area. Operations of this network were state-supported and under the direction of Mr. Changnon. The raingages were installed by James A. Harry and Mr. Jones, and Levi M. Frost served faithfully for 5 years in operating and maintaining these instruments. Routine data processing was performed by Oscar Anderson and Edna Anderson. Further interpretative analysis of the network data was performed by Elmer Schlessman. The useful advice and direct contributions from Richard Semonin, Bernice Ackerman, Griffith Morgan, Jr., and Robert Beebe are greatly appreciated. Thanks are expressed also to Mrs. Patricia A. Motherway who edited the final manuscript. Illustrations were prepared by John Brother, Jr., William Motherway, Jr., and Linda Riggin, all of the Graphic Arts Section.

RESULTS OF CLIMATIC STUDIES

Thirty-year normal annual precipitation amounts for the period from 1931 through 1960 were determined for the U.S. Weather Bureau (now National Weather Service) Cooperative Climatological Stations of Anna, New Burnside-Creal Springs, Carbondale, Brookport, Jackson, and Cape Girardeau, and for the National Weather Service First Order Station at Cairo. These stations are shown on the average annual precipitation map of figure 1. This map shows that the two hill stations (Anna and New Burnside-Creal Springs) have larger mean annual precipitation amounts than the flatland stations around them. In particular, Anna had 10 percent more annual precipitation than Cape Girardeau and 7 percent more than Cairo, both located in the Mississippi River Valley portion of the flatlands to the south.

Also shown in figure 1 is a generalization of the 500 foot mean sea level contour to indicate the outline of the hills. The 500-foot contour was chosen because most of the surrounding area is less than 500-feet msl, and the hills rise abruptly above the lowlands through this level. The highest point in southern Illinois is 1030 feet msl in the western hills near Cobden.

The cooperative stations were divided into two groups, hill stations and flatland stations. Group aver-

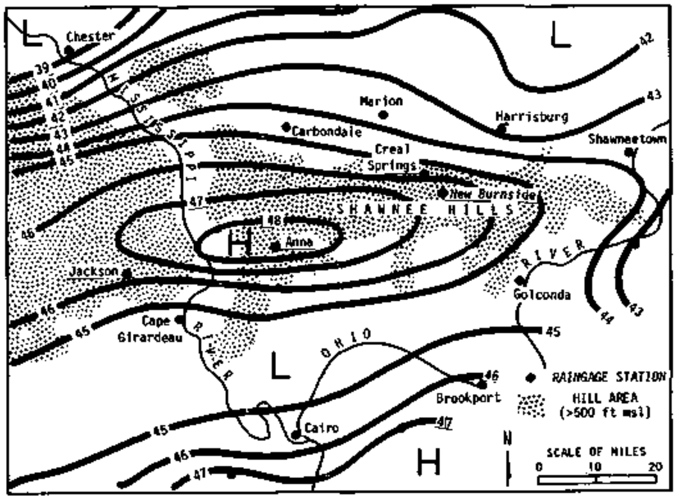


Figure 1. Average annual precipitation, inches, 1931-1960

Table 1. Comparison of Mean Monthly, Seasonal, and Annual Precipitation (Inches) for Hill and Flatland Areas, 1931-1960

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	Winter (Dec-Feb)	Spring (Mar-May)	Summer (Jun-Aug)	Fall (Sep-Oct)
Hill stations*	4.24	3.53	4.74	4.72	5.00	4.29	3.29	3.85	3.57	3.16	3.91	3.43	47.69	11.20	14.45	11.42	10.63
Flatland stations**	4.45	3.56	4.70	4.22	4.39	3.91	4.12	3.45	3.45	2.91	3.73	3.37	45.29	11.38	13.31	10.48	10.09
Percent difference hill-flatlands/flatlands	−4.7	−0.8	+0.8	+11.8	+13.9	+9.7	+5.4	+11.6	+3.5	+8.6	+4.8	+1.8	+5.3	−1.6	+8.6	+9.0	+5.4

**Hill stations were Anna and New Burnside-Creal Springs*

***Flatland stations were Cape Girardeau, Cairo, Brookport, and Carbondale* ages of monthly, seasonal, and annual precipitation are presented in table 1. The average of the hill stations is the higher on an annual basis, but the hill excess does not exist in winter. The hill excess is most pronounced in the spring and summer seasons, and this suggests that the hill-effect is most active in convective precipitation since 50 to 90 percent of spring and summer precipitation in this area is related to thunderstorms (Changnon, 1957).

Since the historical differences might be caused by errors in precipitation measurement rather than differences in orography and land use, an investigation of the quality of the historical records was performed. However, the pattern coherence with the highest average rainfall in the hills and the lowest in the flatlands suggested accurate records.

Annual Rainfall and Station Evaluation

The histories of the particular climatic precipitation-measuring stations including their physical sites, instrumentation, and the observer changes were pertinent to this entire climatic study. Reliance must be placed upon lengthy records free of bias to determine whether the hills influence precipitation processes (and hence precipitation patterns), or whether the increase was due to observational-instrumental errors. The excess of precipitation in the hills, as compared with more southerly and lower-level stations, was first noted in a study of long-term rcords (Page, 1949). It is conceivable that a 10 percent difference between nearby stations might be generated through the years by slight differences in exposure. Seven stations within and around the hills of southern Illinois have been in existence from 1931 through 1960, the interval used by the National Weather Service to determine the normals listed in table 1, and their histories were carefully examined.

Cape Girardeau. This station in Missouri was at the same site from 1 November 1904 until 1 February 1969 when the station was moved south of the city to the city airport. During the time that the station was within the city (elevation 345 feet msl), the station instrument readings were recorded by three members of the same family with a single individual taking the responsibility from 1932 until the city station was closed in 1969. Thus, this station apparently had a homogeneous record.

Brookport. The U. S. Army Corps of Engineers installed a precinitation-measuring station on this site during the construction of Lock and Dam No. 52 on the Ohio River at Brookport, Illinois (elevation 330 feet msl). The recording of precipitation data began in November 1928 and has been continuous since under the supervision of several lockmasters. The record is considered to be homogeneous.

New Burnside. This station began continuous operation in February 1895 with the precipitation gage at one location (elevation 560 feet msl) from August 1911 through 20 November 1964. The gage was serviced by the same person from 22 May 1914 through 20 November 1964. Since an attempt to find another observer for the gage site failed, the station was moved 4 miles in 1964 to the nearby town of Creal Springs (elevation 495 feet msl). After September 1968 the station was combined with an existing station known as Marion 4 NNE (elevation 477 feet msl). The precipitation records for the period when the station was in the hill area (at New Burnside and at Creal Springs) are considered to be homogeneous. The move to Marion 4 NNE, in the flatlands north of the hills, resulted in a noticeable change toward decreased precipitation, as would be expected (see figure 1).

Jackson. There has been a precipitation-measuring station in and around Jackson, Missouri, since 31 January 1879. Although there have been several observers and several sites since 1930, the changes were not reflected in a double-mass curve analysis (Kohler, 1949) in which the average of the three previously identified homogeneous-record stations was used for comparison. Its elevation has been about 450 feet msl.

Anna. Figure 1 reveals that the hill station at Anna (elevation 645 feet msl) recorded more precipitation during 1931-1960 than any other nearby station. A double-mass curve evaluation for this station is shown in figure 2. Four stations, Cape Girardeau, Jackson, Brookport, and New Burnside, were used to develop areal climatological means for each year against which the records for Anna and the other regional stations were compared by double-mass analyses.

The curve for Anna in figure 2 has several slope changes occurring with changes in locations. The slope of the curve is constant (1:1) from 1931 through 1938, and again from 1945 through 1956. The precipitation at Anna increased relative to the regional average between 1939 and 1945, corresponding to an observer and site shift in 1939. A relative precipitation change at Anna continued after a site change in 1956 but it appears to have stabilized at a slope, and on a projection of the accumulation curve, the same as that from 1931 through 1938. Thus, the mean annual precipitation computed for the period 1931 through 1967 (to take advantage of the New Burnside-Creal Springs records) has been used without adjustment. It will be noted that the climatological normal mean for 1931-1960 is larger than the 1931-1967 mean because of the slope changes.

Carbondale. The station at Carbondale has had a history similar to the station history at Anna. This station on the north side of the hills is at an elevation of 380 feet msl. A double-mass curve analysis (not shown) revealed that the slope changes were not pronounced and that the 37-year values were acceptable.

Cairo. The last station carefully evaluated is the first-order station of the National Weather Service at Cairo (elevation 315 feet msl). As with many of the first-order stations, the precipitation records have been obtained from sites that were selected more for observer convenience than for proper exposure. Precipitation records have been collected at Cairo since 1 June 1871, but the instrument was on a building roof at heights 50 to 79 feet above ground from its installation until 31 May 1942. Then the gage was moved to the standard 3-foot height for U. S. gages. This drastic site change in 1942 is obvious in the double-mass curve for Cairo in figure 2. The tendency for raindrops to be blown away from a gage exposed to the wind is well known (Jevons, 1861), and apparently is the reason for lesser rainfall at the exposed elevated gage in Cairo.

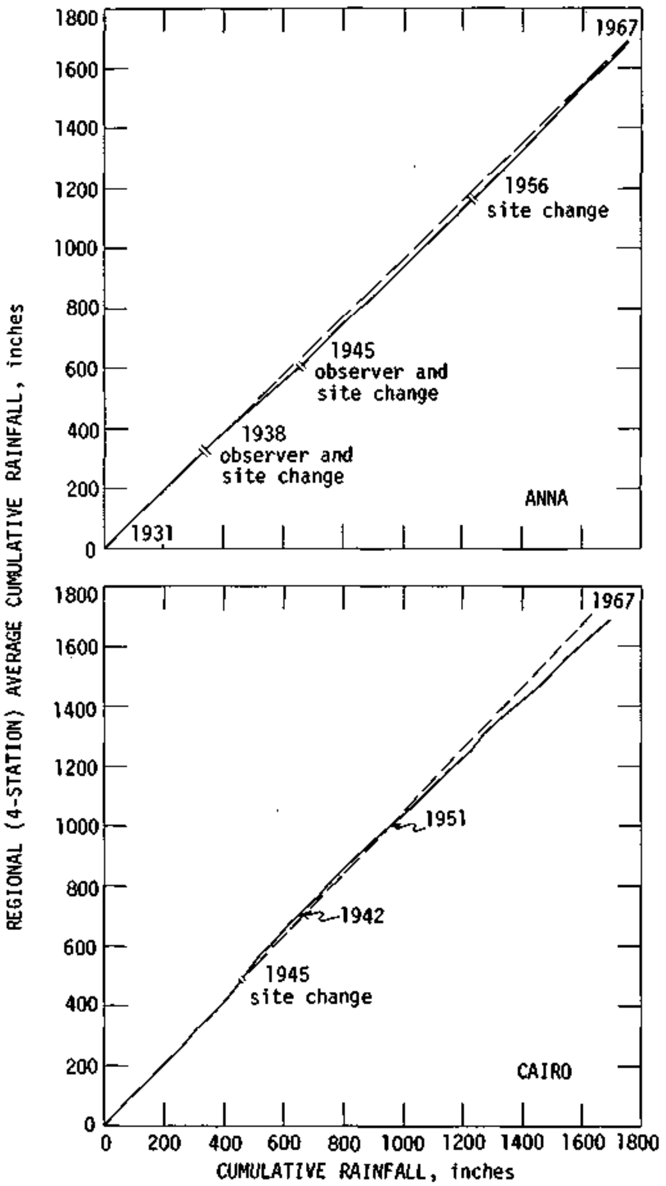


Figure 2. Double-mass curves of annual precipitation for Anna and Cairo and their regional stations

A reason for the further decrease in relative precipitation catch between 1942 and 1946 cannot be found in the history of the station, but the increased precipitation from 1946 through 1967 is considered to be the true tendency. A regression equation between the average 4-station annual precipitation and the Cairo annual precipitation for the years of 1946-1967 has been developed:

$$\text{Cairo} = 3.667 + 0.987\ (\text{mean})$$

If the 4-station mean annual precipitation of 45.56 inches is applied in this equation, the Cairo mean annual precipitation is found to be 48.63 inches rather than 46.10 inches, the National Weather Service normal.

Other Stations. The greatest number of precipitation-reporting stations in and about the Shawnee Hills existed during the 17 years from 1951 through 1967. Stations were installed in Illinois at Glendale and Grand Tower in 1940, at Marion in 1942, and at Cobden and Makanda in 1951. Double-mass curve analyses of these stations indicated that the records were all reliable. Station means were calculated for 1931-1967 by regression analysis similar to that performed for Cairo. The resulting 'adjusted' mean annual precipitation for the region is shown in figure 3.

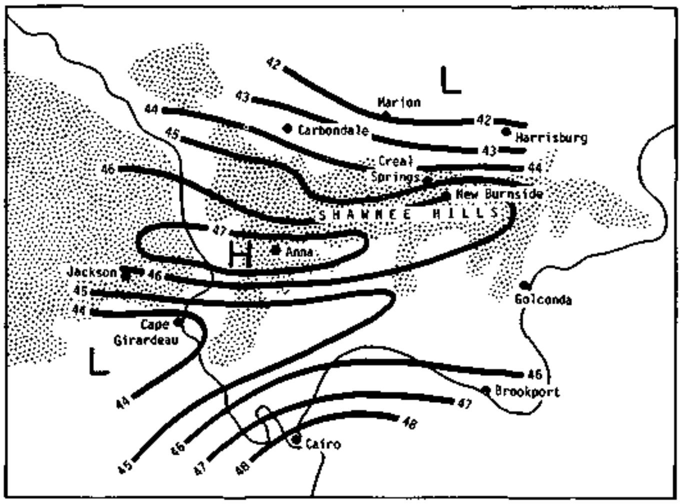


Figure 3. Adjusted average annual precipitation, inches, 1931-1967

Figure 3 reveals that Cairo and Anna have had the highest precipitation totals in the study area and that there is a sharp decrease in precipitation just north of the hills. It is unfortunate that there were no climatological stations between Cairo and Anna to delineate better the pattern of average rainfall between the two sites. The pattern shown on figure 3 indicates that there is a decrease in annual precipitation north of Cairo and an increase farther north over the hills.

Although the adjusted 37-year pattern is not as strong in its indication of a hill-related increase in rainfall as the 30-year normals, the increase is still present and apparently real. Since July was a prime month of apparent hill-effect and the month chosen for the detailed field study, the July (1931-1967) values at Cairo and Anna were adjusted and used with all other station data to derive 'correct' averages. These were used to develop the pattern shown in figure 4. The high exists over the hills with maximum rainfall (4.25 inches) at Makanda.

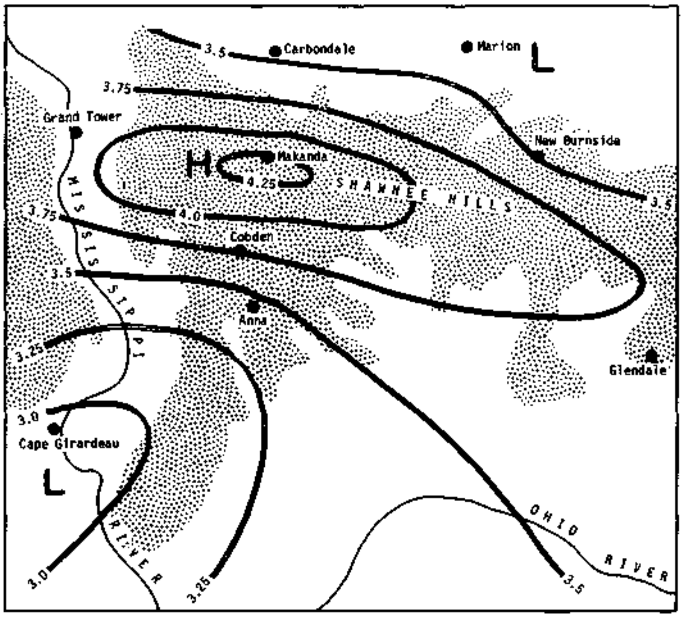


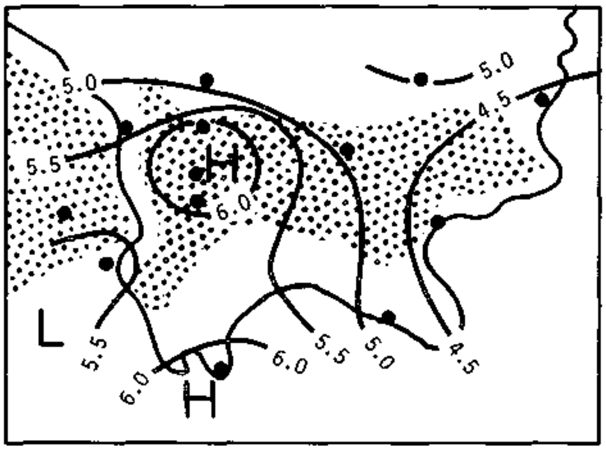
Figure 4. Adjusted average July rainfall, inches, 1931-1970

Summer Rainfall and Related Winds

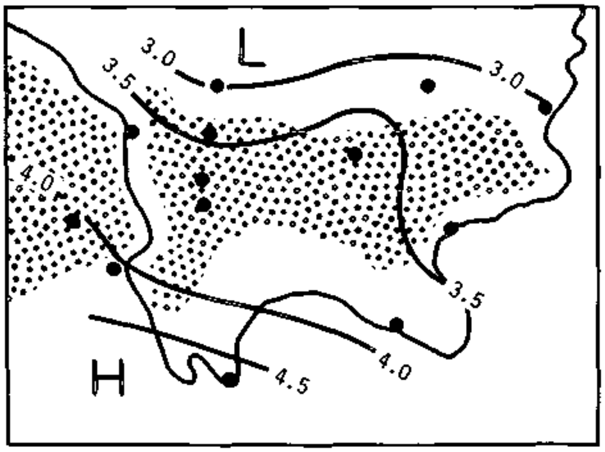
The seasonal analyses of precipitation in the Shawnee Hills clearly revealed that the precipitation center in the hills maximized during the summer (June-August). Thus, other climatic analyses of the summer rainfall, and that of each of the summer months, were pursued. Regional daily rainfall and wind data for 1960-1964 were studied to gain a better understanding of the possible causes of the hill maximization in the summer, and particularly of the possible influence of the south-facing steep hill slopes on airflow and the production of turbulence.

For each date of rain at all 12 stations in and around the hill area (figure 1), the daily amounts were listed for each station. These amounts were sorted according to the prevailing surface wind flow recorded at the Cairo station. Directions were sorted according to the 8 principal directions of the compass. Total rainfall at each of the 12 stations for each of the 8 wind directions was totaled for the 5-year period. Then 8 precipitation maps were plotted and isohyetal patterns constructed. Although not sophisticated, this effort was expected to yield gross estimates of the wind flow regime when rainfall maximization occurred within the hills.

Essentially, three types of wind-rain patterns were found. One type was a gradual north-to-south increase in precipitation with little if any apparent local increase within the hills. This pattern was present most frequently when prevailing winds were from the north, northwest, or southeast. A second type of pattern was classed as 'indeterminate' with no major highs or lows, as defined by two or more stations. The indeterminate patterns were found to dominate with winds from the northeast, east, and west. The third and most interesting pattern showed a distinct isolated maximum at the hill stations, and this was found with southerly and southwesterly flows. Interestingly, the rainfall pattern for the southerly flow showed a maximization in the Anna-Cobden area (southern section of the hills), whereas the maximization with southwesterly flow was found at Grand Tower and Makanda (both in the more northerly portion of the hill area).



a. SOUTH AND SOUTHWEST WINDS
ON RAIN DAYS



b. WINDS FROM WEST, NORTHWEST, NORTH,
NORTHEAST, EAST OR SOUTHEAST
ON RAIN DAYS

Figure 5. Average summer rainfall, inches, 1960-1964, for different directions of low-level winds on rain days

The rainfall values for the south and southwesterly flow days were grouped and used to develop the summer average pattern for 1960-1964 shown in figure 5. The pattern shows a distinct maximum over the hills with lesser rainfall to the north, east, and southwest.

Another high existed at Cairo for this 5-year period. The average summer rainfall pattern when winds came from all the other 6 directions is also shown on figure 5, and a general decrease from south to north is clearly evident.

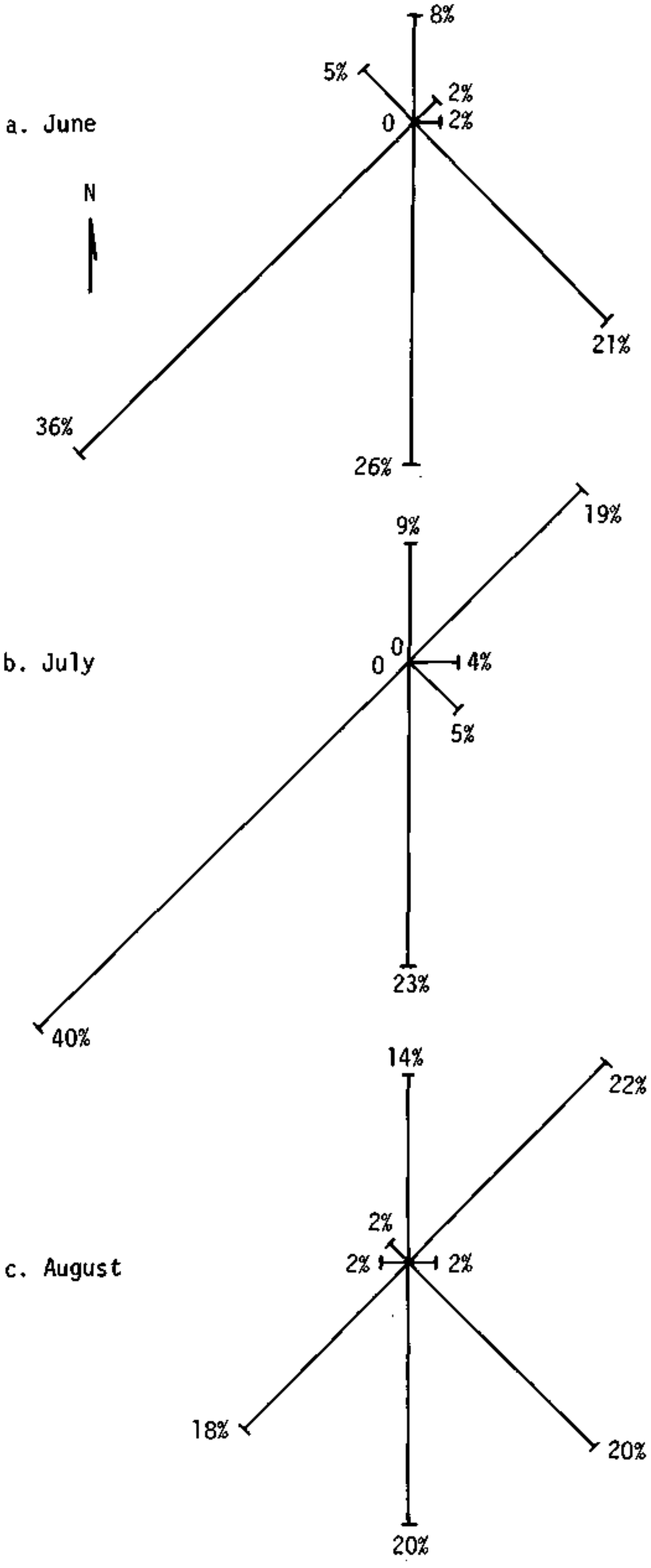


Figure 6. Monthly rain day wind roses at Cairo, 1960-1964 (frequency in each direction expressed as a percent of total rain days)

Figure 6 depicts the monthly wind roses from prevailing winds on rain days at Cairo for 1960-1964. These wind roses show the predominance of rain days when southwesterly and southerly surface flows exist. These diagrams reveal that more than 60 percent of all rain days in June and July come with southwesterly or southerly flow, with only a minor number of rain days occurring from the other directions. In August, wind flow on rain days is not so dominated by the southwest and southerly flow, and comparison of these results with those in figure 5 suggests that the hill-effects would be most pronounced in June and July.

Results from this study certainly suggest that forces leading to the hill increases exist primarily on days with low-level wind flow from the south and southwest. These results could be indicative of two conditions. First, wind flow from those directions is typical of the days when isolated, unstable air mass (disorganized) showers and thunderstorms occur and when cold fronts and prefrontal squall lines approach. The results may indicate that hill increases are most prevalent only under such conditions. Secondly, the results may indicate that the abruptness and configuration of the west-east oriented edge along the southern hill border may indeed interact with winds normal to this axis, thus producing increased turbulence in the lower atmosphere that in turn aids local convection. Low-level heating of the air over the nearby lowlands would tend to be destabilized in passing over the hills.

Comparison of Daily Rainfall Values

Information on possible hill-effect was sought in a climatic study of daily rainfall data. To this end, daily rainfall values for Anna, in the hill area, and for Cape Girardeau, which is located 20 miles southwest of Anna and in the flatlands, were analyzed. The climatological normal annual precipitation difference between the two stations for the 1931-1960 period is 4.7 inches. In order to compare the two stations, the daily rainfall amounts for the 10-year period 1950-1959 were listed and analyzed in various ways.

The rainfall values for these two stations are representative of the orographic areas in which they are situated and differences between them should be indicative of any hill-effect in the daily rainfall magnitudes. This particular study was pursued to compare the historical daily rainfall values so as to 1) investigate whether one station had more rain days, 2) how often one exceeded the other, and 3) the magnitude of the difference between their daily values.

The 10-year frequency of daily rainfalls of the two stations are listed in table 2. This shows that Cape Girardeau (CGI) which had 36 inches less rainfall in the 10-year period than Anna, actually had 19 more rain days. This represents a rain-day increase of nearly 10 percent over the Anna value. However, the rain-day frequencies for the different rain intensity classes in table 2 show that the greater frequency at CGI came on days with very light rainfall, less than 0.1 inch. This may result from the Anna observer failing to measure some exceptionally light rainfalls or it may be a real difference. For the rainfall amounts between 0.10 and 0.24 inches there is no difference, but in the moderate to heavy classes, 0.25 inch up to 1.0 inch, the Anna frequencies are distinctly greater. There is essentially no difference in the very heavy daily rainfalls (greater than 1 inch).

Table 2. Frequency of Daily Rainfall Amounts at Anna (Hill) and Cape Girardeau (Flatland), 1950-1959

	Number of days in rainfall intensity classes (*inches*)					
	0.01-0.09	0.10-0.24	0.25-0.5	0.51-1.0	> 1.0	Total
Anna	147	14	18	12	13	204
Cape Girardeau	173	14	14	8	14	223
Difference	−26	0	+4	+4	−1	−19

A more meaningful comparison of the daily rainfall values involved classifying each rain day according to which station had the higher value and then determining the numerical difference between the two values. As shown in table 3, Anna had 137 daily rainfall values that were greater than those at CGI. Comparisons based on rain at one station and none at the other were performed to obtain potential indications of rainfall initiation differences. On 50 percent of the 137 days when Anna exceeded CGI (68 days), there was no measurable rain at CGI (table 3). However, on 56 percent of the days when CGI had a value exceeding the Anna value, there was no rainfall at Anna.

Table 3. Comparison of Summer Daily Rainfalls at Anna and Cape Girardeau According to Higher Value

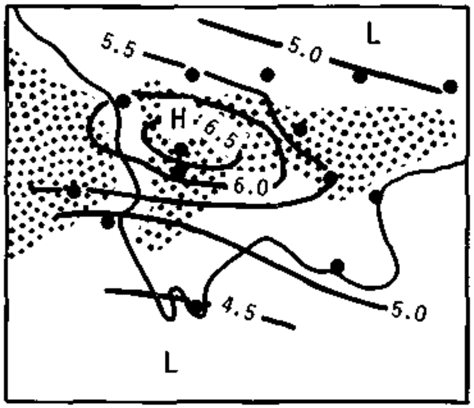
	Number of rain days	Percent of days with zero rainfall at low station	Percent of days when difference ≥0.2 inch
Anna value > CGI value	137	50	64
CGI value > Anna value	153	56	37

The numerical differences in the values for the two stations were also determined. The percent of the total number of rain days when the difference between the two values equaled or exceeded 0.2 inch is shown in table 3. On 64 percent of the 137 days when the Anna value exceeded the CGI value, the difference in their values was >. 0.2 inch, whereas only 37 percent of the days when the CGI value was highest had differences of 0.2 inch or more.

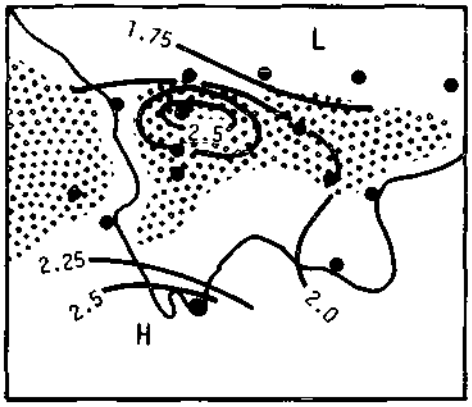
The various analyses and comparisons of the Anna and Cape Girardeau daily rainfall data suggest that the higher rainfall in the hills is not due to the localized initiation of rain over the hills nor to many days when the hill stations have slightly more rainfall by enhancement. Rather it is due to a considerable enhancement of rainfall on a few rain days.

Climatic Patterns of July Rainfall

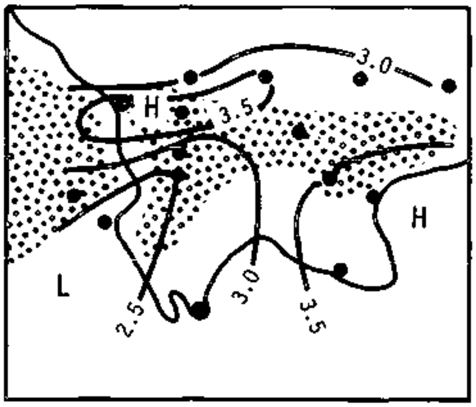
Examination of average rainfall patterns by seasons in the various climatic studies showed that summer was the primary season for increased precipitation over the Shawnee Hills. Inasmuch as the 1-month field project in 1970 occurred in July, it was important to assess the rainfall climate of July. Inspection of the average monthly rainfall patterns revealed that the localized hill maximum was pronounced in July. Furthermore, examination of the wind analyses (figures 5 and 6) revealed that hill-effects occurred primarily with southerly and southwesterly low-level flows and that these flows were frequently experienced in July.



a. WET



b. DRY



c. NEAR NORMAL

Figure 7. Average July rainfall patterns, inches, for the 10 wettest, 10 driest, and 10 near normal Julys in the study area, 1941-1970

The July rainfall data were studied in two ways. First, the July values for the 1941-1970 period were investigated to ascertain the various isohyetal patterns likely to occur in dry, near normal, and wet Julys. Secondly, time trends in the July rainfall for the 1951-1970 period were determined to examine for regional anomalies in the data.

For each July the 1941-1970 rainfall data at the 12 stations in the area were averaged to determine an areal mean value. These 30 mean rainfall values were ranked so that the 10 wettest, 10 driest, and remaining 10 near normal Julys were identified. For each of these classes, the average values were determined and plotted on separate maps. The resulting patterns are shown in figure 7.

The pattern based on wet Julys revealed a very distinct isolated hill maxima with the maximum point value occurring at Cobden. The pattern for the 10 near-normal rainfall Julys was quite different. Much of the hill area had low rainfall, although a small high existed across the northern edge of the hills with the maximum at Makanda. The pattern for the 10 driest Julys also did not exhibit much regional variability although there was a minor maximum in the northern portion of the Shawnee Hills where Makanda had an average of 2.51 inches. However, Cairo had the highest point average in the dry Julys.

This analysis indicated that extensive data collection and study for either dry or near normal rainfall in July would be informative but not as revealing as that for a wet July when greater data and information would be available. These data also showed that the maximization of precipitation in the hills is a function of the frequency and magnitude of rainfall, a conclusion also suggested by the daily rainfall comparisons of Anna and Cape Girardeau. The hill area maximum is somewhat farther south during wet Julys than it is in the drier and more normal Julys. Whether these differences are due to different hill-related mechanisms or to differences in storm motions and predominant synoptic storm types during wet, moderate, and dry Julys cannot be established from the climatic studies.

To examine further the historical July rainfall values, the July values for 1951-1970 from 11 stations in and around the hill area were studied for changes with time and regional continuity. The values at each station were individually regressed against time to determine the slope values (coefficients) in the regression equation of time against July rainfall. These slope values were plotted on a base map and the resulting patterns (figure 8) reflect a trend surface that can be used for identifying stations with unusual trends. All stations had slight negative trends during the 20-year period used in this analysis. The stations with the least negative trends included Cobden, New Burnside, Cape Girardeau, and Grand Tower. Only one of the individual trend values suggests a unique or questionable trend for the July rainfalls. This was Cairo which had a much greater negative value (-0.079) than the others in the area. The reduction in slope is also apparent in the annual precipitation at Cairo after 1950 *(see figure 2).*

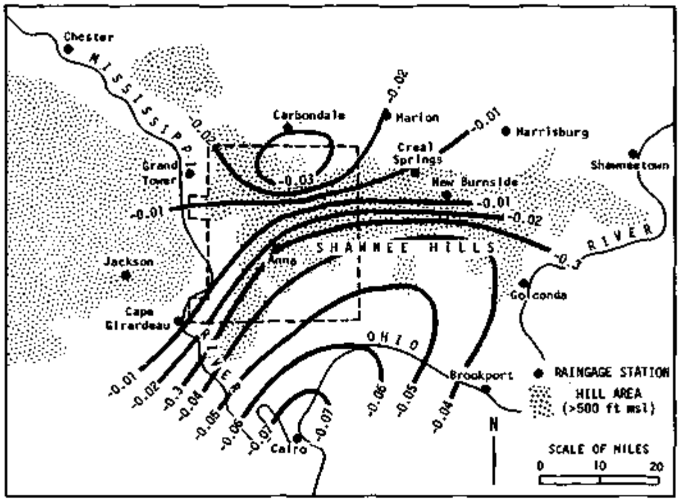


Figure 8. Trend of July rainfall, 1951-1970

SHAWNEE NETWORK RAINFALL ANALYSES, 1965-1969

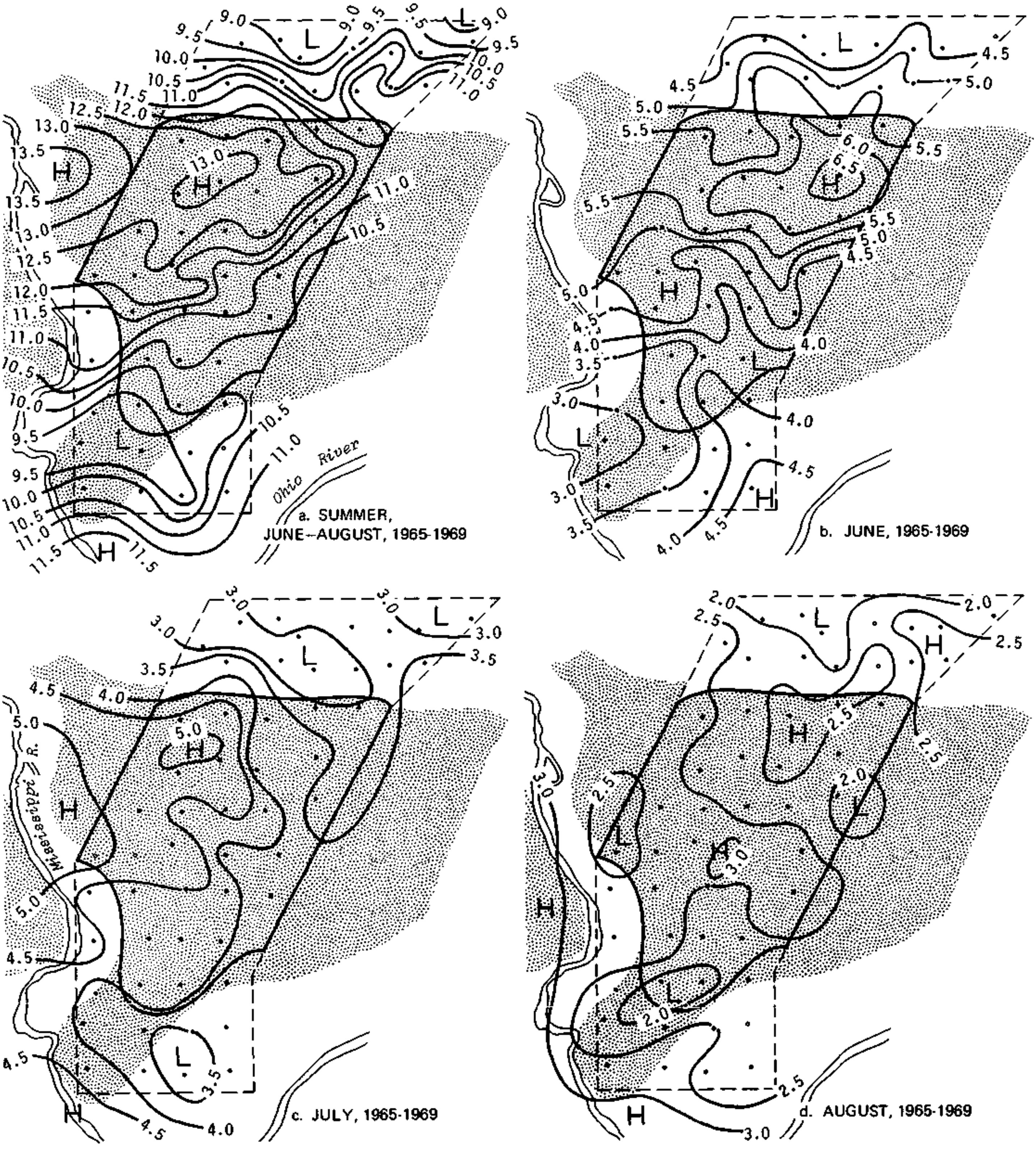
A detailed analysis of summer rainfall (June-August) during the 1965-1969 period, as obtained from the dense Shawnee Network of weighing-bucket raingages, was made in an effort to gather additional evidence pertaining to the potential hill-effect on rainfall in the Anna region of southern Illinois. Individual monthly and seasonal maps of total rainfall were constructed for each of the five years. From these, average and total rainfall by monthly and seasonal periods for the 5 years were determined and mapped.

Several types of statistical analyses were performed on the data after the Shawnee Network was divided into two general areas, the hills and flatlands. The defined hill area consisted of 31 raingages in approximately 440 square miles, and the flatland area had 28 gages in 427 square miles surrounding the hill region. However, only the analyses most useful in providing information on the possible hill-effect will be discussed in this section.

A hill-effect storm was defined as one in which the three highest rainfall amounts occurred in the hill area. Similarly, the flatland storms were those in which the three heaviest rainfalls were observed in the flatland region. Storms were classed as indeterminate if the three heaviest rainfall amounts were divided between the hill and flatland areas.

Summer Isohyetal Patterns

Figure 9a shows the average summer (June-August) rainfall for the 1965-1969 period on the Shawnee Network. A pronounced high in the summer rainfall pattern extends W-E across the hill area. However, the heaviest rainfall (13.59 inches) was recorded at Grand Tower on the Mississippi just west of the hill region boundary.



a. SUMMER, JUNE–AUGUST, 1965-1969

b. JUNE, 1965-1969

c. JULY, 1965-1969

d. AUGUST, 1965-1969

Figure 9. Five-year mean rainfall, inches, for summer, June, July, and August, 1985-1969

Reference to normal summer rainfall maps for Missouri and Illinois indicated the Grand Tower high was an isolated peak in the general climatic pattern. Further investigation showed that the Grand Tower station is located in the vicinity of an isolated 600-foot hill having a crest extending about 2 miles in a N-S orientation. Therefore, this station can really be considered representative of a hill-effect region rather than a flatland observation site. In view of the above circumstances, the departure of the major high in figure 9a from the regional climatic pattern can be considered evidence in support of a hill-effect on the summer rainfall in the study region.

Examination of summer rainfall patterns in the 5 individual years showed the 1969 pattern corresponding most closely to the 5-year mean pattern. Over most of the network, summer rainfall was above normal in 1969 and much above normal in the hill area. Summer 1967 also had a pattern which was quite similar to the 5-year mean, but this was a year when the rainfall was below normal over most of the network. Summer 1965 showed a secondary high across the hills, but the primary maximum was in the western and southern flatland areas. The summer patterns for 1966 and 1968 had little resemblance to the 5-year mean. Thus, 2 of the 5 years had similar high rainfall ridges across the hill area and a third year had a secondary maximum in this region. On the basis of this 5-year sampling period, consistency in the summer rainfall pattern was not outstanding. Results suggest that the hill high was the result of more frequent peaking in the hills east of Grand Tower than in any other specific area in the study region.

June Isohyetal Patterns

The major W-E hill high for summer shown in figure 9a is present also on the average June rainfall map for 1965-1969 (figure 9b). The peak rainfall has shifted eastward from Grand Tower to the east side of the network in the hill region. A secondary high is located near Anna. However, reference to maps for each June did not indicate consistency in the location of the 5-year mean pattern. Only in 1969 did the individual monthly pattern correspond closely with the 5-year average, and because of the unusually heavy rainfall in June 1969, this month exerted a major influence on the characteristics of the June 5-year mean. For example, at station 10 where the 5-year June mean maximized, 50 percent of the 1965-1969 total rainfall occurred in 1969. The June 1969 rainfall at station 10 contributed 26 percent of the total 5-year summer rainfall, so that this month also exerted considerable control over the average summer pattern.

Further investigation revealed a total of 14 network storms in June 1969, but most of the monthly rainfall in the W-E high region occurred in three heavy storms on the 12th, 22nd, and 30th. In the other four years, 1965-1968, the maximum rainfall was not located in the W-E high region. In these years, the maximum occurred in the flatlands, although in two years, 1966 and 1967, the maxima were located just north of the hill region and could have been influenced by the hills. June 1966 and 1967 were relatively dry over most of the network.

Although the June 1965-1969 mean pattern shows a definite hill high, evidence in support of any pronounced hill-effect high for June is weak because of the pattern dependence on the heavy rainfall of June 1969. However, at this point the 1969 pattern does suggest the possibility that the hill-effect may be most pronounced in heavy rainstorms, and that the long-term high at Anna could be the result of enhancement of such storms.

July Isohyetal Patterns

Figure 9c shows the average July isohyetal pattern for 1965-1969. The peak rainfall occurred in the western part of the hill area, but the high is not nearly so pronounced as in the 5-year summer and June means discussed previously. For individual years, the peak July rainfall was found in the hill area in 1965, 1967, and 1968. These were years in which most of the sampling area experienced near normal to above normal monthly totals. In 1969 July rainfall was much above normal but the peak rainfall occurred in the southern flatlands. Thus, there appears to be no outstanding relationship between occurrence of the hill high and total monthly rainfall.

August Isohyetal Patterns

The 5-year mean rainfall pattern for August 1965-1969 (figure 9d) does not show a hill pattern similar to those for June, July, and total summer rainfall. There are two isolated highs in the hill area, but these are offset by highs NE and SW-S of the hill area. However, the peak monthly rainfall occurred in the hill area in 1965, 1967, and 1969, and in 1968 the high was located near the northern border of the hill area. Thus, the peak monthly rainfall occurred more consistently in the hill area in August than in June and July during the 1965-1969 period.

The absence of a well-defined hill-area high appears to be the result of the more random location of the August peak rainfall from year to year. This suggests that the hill-effect storms of June and July tend to be more consistent spatially in their occurrence compared with those of August. In turn, this could be related to differences in synoptic conditions associated with hill-effect storms in late summer, particularly with respect to the wind field as pointed out earlier (figures 5 and 6). However, in the interpretation of the 1965-1969 results, it must be recognized that this period showed some departures from the long-term climatology of the area.

Distribution of Synoptic Weather Types with Network Storms

An investigation was made to determine whether hill-effect storms tend to be associated more frequently with any particular synoptic storm situation in comparison with the flatland and indeterminate storm groups. The 1965-1969 storms were classified into four basic synoptic types: frontal storms, air mass (nonfrontal) storms, low center passages, and squall lines. The frontal storms were grouped further into cold, warm, static, and occluded types. Classification was made from published maps of the National Weather Service.

Cold front precipitation was defined as that occurring from 100 miles in advance of the front until ending of rainfall with the frontal passage. Pre-cold-front squall lines included those occurring in the warm air mass approximately 100 to 300 miles in advance of the front and were considered to be indirectly associated with cold fronts. Rainfall associated with warm and occluded fronts included that occurring with the approach and passage of the fronts and, depending upon the synoptic situation, could include precipitation up to 200 or 300 miles in advance of the front. Static front precipitation was defined as that occurring from stagnating fronts south of the area of interest, and was usually associated with a stagnating cold front within 50 to 100 miles. Low center passages were defined as closed pressure centers passing through or near the area of interest, and could be accompanied by frontal passages associated with the low center. Air mass storms included rainfall occurring in both warm air masses in the absence of fronts and cold air mass instability showers occurring well after the passage of the cold front, and often associated with the passage of a trough aloft.

Table 4. Distribution of Network Summer Storms by Synoptic Type

Synoptic storm type	Hill-effect storms		Flatland storms		Indeterminate storms	
	Number	Percent	Number	Percent	Number	Percent
Air mass	17	29	18	31	28	32
Low center	2	3	2	4	4	5
Cold front	20	35	17	29	23	26
Static front	11	19	14	24	25	28
Warm front	1	2	2	4	1	1
Occluded front	2	3	2	4	1	1
Squall line	5	9	2	4	6	7
Total	58	100	57	100	88	100
All fronts plus squall lines	39	68	37	65	56	63

Table 4 shows the number of cases and percentage frequency for each synoptic type in the hill, flatland, and indeterminate categories. Most storms during the sampling period were air mass, cold front, and static front types. These three synoptic types accounted for 83 to 86 percent of the three topographic classes of storms. The percentage frequencies show cold fronts most prominent with the hill-effect storms. Air mass and static front storms were found more often in the flatland and indeterminate categories. In cold frontal situations, hill-effect storms occur 6 to 9 percent more often than do the flatland and indeterminate storms.

Overall, there is some evidence that the hill-effect occurs most frequently with cold front systems. However, the percentage frequency of these systems is not sufficiently greater than air mass storms to eliminate the possibility that it merely reflects a sampling vagary in the 5-year period.

Next, the mean and median rainfall amounts were determined for each major synoptic type in the storms centered in the hills or flatlands. Means and medians were determined for the entire network and for the subareas enclosing the hill and flatland regions. Calculations were made for cold fronts, static fronts, air mass storms, and cold fronts plus prefrontal squall lines. Results are summarized in table 5.

Table 5. Distribution of Storm Rainfall by Synoptic Type

Storm center location	Storm rainfall (*inches*) for given synoptic type					
	Network		Hills only		Flatlands only	
	Mean	Median	Mean	Median	Mean	Median
Cold front						
Hills	0.49	0.12	0.59	0.16	0.37	0.06
Flatlands	0.25	0.07	0.21	0.08	0.30	0.09
Static front						
Hills	0.18	0.07	0.22	0.08	0.12	0.03
Flatlands	0.18	0.05	0.12	0.01	0.25	0.07
Air mass storm						
Hills	0.09	0.03	0.12	0.04	0.05	trace
Flatlands	0.04	0.02	0.02	trace	0.07	0.03
Cold fronts plus squall lines						
Hills	0.55	0.15	0.68	0.20	0.37	0.08
Flatlands	0.25	0.09	0.20	0.08	0.31	0.09

Tabulations for the entire network show that cold fronts and cold fronts plus squall lines produced the most rainfall per storm. Smallest average and median amounts were associated with air mass storms. In all synoptic types, the hill-centered storms had larger means and medians than the flatland-centered storms. This provides evidence of a hill intensification mechanism in the sampling area.

The underlined values in the 'hills only' columns are hill-area means and medians for storms centered in the hill regions. Similarly, the underlined numbers in the 'flatlands only' columns are flatland means and medians for those storms centered in the flatlands. The other numbers show the flatland means and medians in hill-centered storms and, conversely, the hill means and medians in the flatland-centered storms.

The statistics in the 'hills only' and 'flatlands only' categories lead to the same conclusions regarding a hill intensification mechanism. Comparing the underlined values in these columns, the hill-area values exceed the flatland values in each case, except for the means in static fronts. In the most intense synoptic type (cold fronts plus squall lines) the hill-flatland ratio of means for the underlined values is 1.84 and the ratio of medians is 2.22. Thus, hill-centered storms tend to produce much more intense rainfall in the hill area than flatland-centered storms do in the flatland region.

Further analyses showed that cold fronts and the cold front-squall line combination not only had the highest means and medians but were the major producers of total rainfall in both the hill and flatland regions. Thus, in hill-centered storms, 47 percent of the hill-area rainfall was associated with cold fronts and 68 percent with cold fronts plus squall lines. In flatland-centered storms, 50 percent of the flatland-area rainfall occurred with cold fronts and 62 percent with cold fronts plus squall lines. Thus, both areas received the majority of their rainfall from the same sources. This similarity again points to hill intensification of storms as the major cause of the observed hill high for the 1965-1969 period (figure 9a), which was discerned also in the long-term climatic data for southern Illinois.

Storm Rainfall Means, Durations, and Rates

Analyses were made to determine possible differences among hill-effect, flatland, and indeterminate storms with respect to storm mean rainfall, average storm duration, and average storm rainfall rate on the Shawnee Network. Results are summarized in table 6. Network rainfall averaged highest (0.35 inch) among the 58 hill-effect storms, and was much higher in the hill storms than in those centered in the flatlands (0.16 inch). This relatively large difference in magnitude among storms centered in the hills and flatlands provides strong evidence of a hill intensification factor.

Table 6. Averages of Three Basic Storm Parameters in Network Summer Storms

Storm parameter	Hill	Flatland	Indeterminate
Mean rainfall (*inches*)	0.35	0.16	0.30
Duration (*hours*)	2.5	2.6	3.3
Rainfall rate (*inches/hour*)	0.14	0.06	0.09

No major difference between the hill and flatland storms is shown by average storm duration in table 6, but average rainfall rate is more than twice as great in the hill storms. Thus, the difference in network mean rainfall is the result of greater rainfall rates in the hill-effect storms. Average storm duration is substantially greater in the indeterminate storms compared with the hill and flatland storms. This indicates a greater frequency of larger storm systems in this storm category. The fact that the indeterminate storms had storm maxima divided between hill and flatland stations provides indirect evidence that any hill-effect is less pronounced or nonexistent in the larger, longer duration storms.

Distribution of Rain Types in Network Storms

Table 7 shows the percentage frequency of major rainfall types in the three topographic classifications of network storms. In those storms in which more than one rainfall type was observed, the storm was assigned to the predominating type.

Table 7. Percentage Frequency of Rain Types in Network Summer Storms

Rain type	Hill	Flatland	Indeterminate
Thunderstorms	52	39	58
Rainshowers	24	43	16
Thunderstorms with hail	21	4	12
Other types	3	14	14

Comparing hill and flatland storms immediately reveals major differences. The predominant rain type in the hill storms was thunderstorms, whereas rainshowers occurred most frequently in flatland storms. Furthermore, severe weather (thunderstorms accompanied by hail) occurred much more often in the hill storms. Rainfall rates were greater in thunderstorm rainfall than in rainshowers, on the average. Thus, the rain type frequency differences between hill and flatland storms given in table 7 support and help explain the differences in mean rainfall and average rainfall rate shown in table 6. That is, both tables provide evidence of an intensification of convective storms in the hill region.

The rain type distributions for indeterminate storms show thunderstorms dominating and a substantial percentage of hail events, similar to the hill-effect storms. As pointed out in the discussion of table 6 these tend to be larger, longer duration storms with maximization divided between hill and flatland areas. Thus, predominance of thunderstorms in summer rainfall is a logical expectation in these storm events.

Frequency Distribution of Areal Mean Rainfall

Further comparison of storm mean rainfall distributions in the hill, flatland, and indeterminate groupings was made through development of frequency distributions for each storm type. Thus, the 58 storms in which there was a potential hill-effect (highest three rain amounts in the hills) were ranked from high to low mean rainfall, and probability curves were derived from the ranked data. Results of this analysis, obtained from the curves derived for each storm type, are summarized in table 8. Network mean rainfalls are shown for selected probabilities.

Comparison of the hill-effect and flatland values in table 8 illustrates the tendency for more intense storms to be centered over the hills. Thus, the

1965-1969 data indicate that 1 storm in 20 (a 5 percent probability) centered in the hills will have a network mean of 1.72 inches or more, compared with 0.85 inch for the equivalent flatland frequency. The skewness of the storm rainfall distribution is well illustrated by comparing the network means of table 6 and the network medians (50 percent probability values) in table 8.

Table 8. Frequency Distribution of Network Storm Mean Rainfall in Hill and Flatland Storms

	Network mean (inches) equaled or exceeded	
Probability (%)	Hill centered	Flatland centered
5	1.72	0.85
10	1.14	0.55
20	0.59	0.27
30	0.33	0.15
40	0.19	0.09
50	0.12	0.05

Possibly a better method of comparing the storm intensity regimes in the hill and flatland areas is to develop frequency distributions of the hill-area only and flatland-area only mean rainfall as opposed to the entire network mean rainfall used in deriving table 8. The results summarized in table 9 further strengthen the evidence that the hills tend to intensify the storm rainfall under certain synoptic conditions.

Table 9. Frequency Distribution of Storm Mean Rainfall within Hill Area Only in Hill-Centered Storms and within Flatland Area Only in Flatland-Centered Storms

	Areal mean (inches) equaled or exceeded	
Probability (%)	Hill centered	Flatland centered
5	2.10	0.94
10	1.35	0.65
20	0.67	0.37
30	0.37	0.21
40	0.22	0.13
50	0.13	0.08

Frequency Distribution of Storm Maximum Rainfall

Frequency distributions of network maximum rainfall were developed for hill-centered and flatland-centered storms following the same procedure used in the network mean rainfall analyses. The results summarized in table 10 provide additional support for storm intensification in the hill region. Table 10 indicates that 1 storm in 20 (5 percent probability) of those centered in the hill region will have a maximum rainfall of 4.05 inches or more. The same probability value for flatland-centered storms is 2.70 inches. A substantial difference is found throughout the range of probability values shown in table 10, and at the median (50 percent probability) the hill-centered maximum (0.66 inch) is 28 percent greater than the flatland value (0.47 inch).

Table 10. Frequency Distribution of Network Storm Maximum Rainfall in Hill and Flatland Storms

	Network mean (inches) equaled or exceeded	
Probability (%)	Hill centered	Flatland centered
5	4.05	2.70
10	2.80	2.15
20	1.80	1.55
30	1.28	1.10
40	0.94	0.74
50	0.66	0.47

Spatial Pattern of Maximum Rainfall Occurrences

The frequency of occurrence of maximum storm rainfall at each gage was determined for all storms combined during the 1965-1969 sampling period. The total number for each gage was then plotted on the network base map to determine whether storms tended to maximize in a particular region. This analysis revealed no trend for storms to maximize in the hill region more frequently than in the flatlands. The storm maximum was recorded in the hill area in 49 percent of the storms and in the flatlands in 51 percent of the cases. Thus, it is apparent that the hill maximization in the total rainfall pattern is related to greater intensity in hill-effect storms rather than more frequent centering of storms in the hill region.

Distribution of Heavy Rainstorms

Since climatic studies described earlier in this report indicated the hill high was associated with heavy rain events, the Shawnee Network data for 1965-1969 were analyzed for the frequency of storms in which rainfall equaled or exceeded 1 and 2 inches. The results summarized in figure 10 provide support for dependence of the hill high on the distribution of heavy rainstorms. The 1-inch map shows an area of maximum frequency extending W-E across the hill region in the same general area as the total rainfall high for summer shown in figure 9a. A second high frequency area of smaller extent is located near Anna where the presence of the hill high was originally discerned in the long-term climatic statistics.

The >. 2-inch map in figure 10 also shows the major area of high frequency in the hill region. The most outstanding peak in this pattern is again oriented W-E but lies a little south of the total rainfall high of figure 9a. A secondary high is located in the NW part of the hill area, and there is a small peak in the pattern in the flatland area just SW of the hill region. In general, the 2-inch pattern also supports the strong relationship between the frequency of heavy rainstorms and the seasonal high in the rainfall pattern. Average frequency of 2-inch storms in the hill area (figure 10) was 4.3 per gage compared with 2.3 per gage in the flatland area. This indicates nearly double the probability of a 2-inch storm occurring in the hills than in the flatlands.

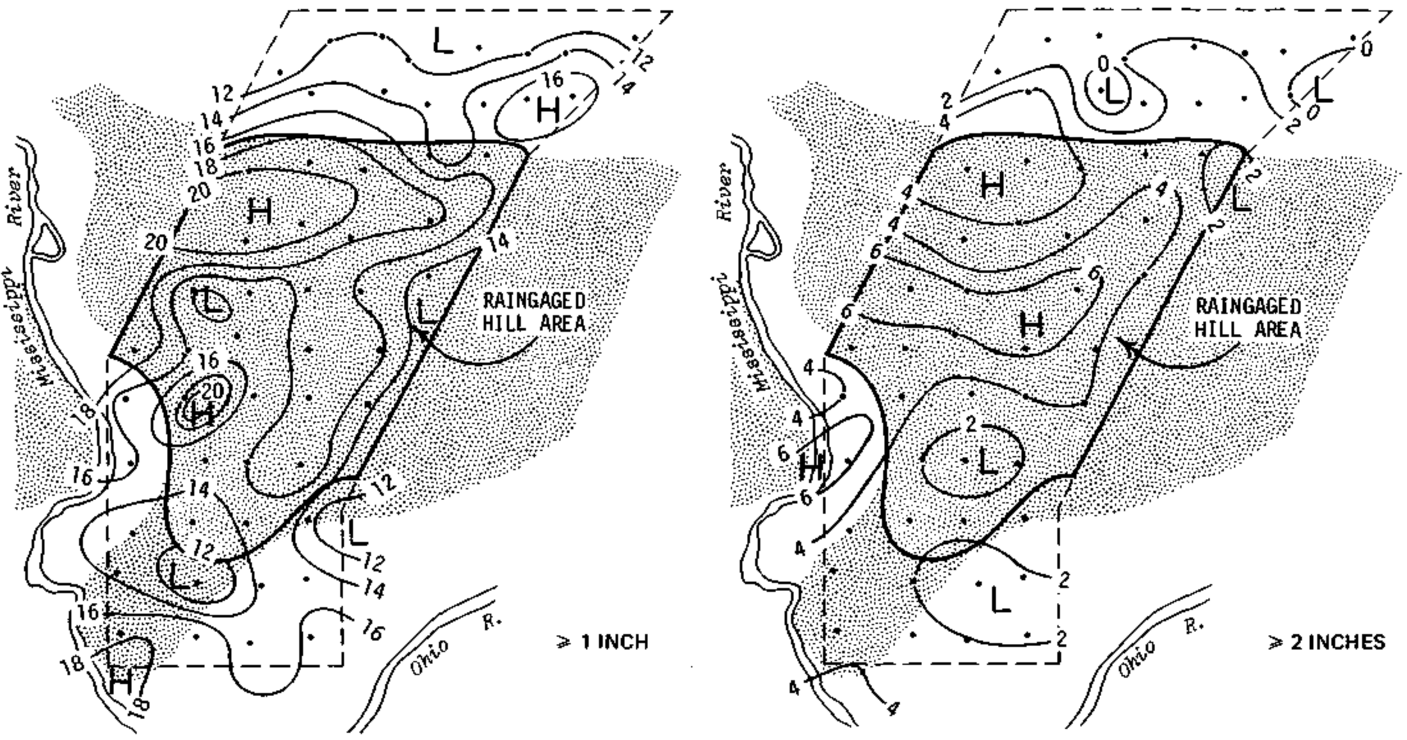


Figure 10. Number of times storm rainfall was 2.1.0 and >2.0 inches during June-August, 1965-1969

Low-Level Wind Flow prior to and during Rainstorms

A 6-hour period (prior to and during rainstorms) during which at least 4 of the 5 wind-recording stations were producing good records was selected for analysis of the low-level wind flow patterns. The wind velocities were plotted on base maps, and the resulting patterns of streamlines were classified as nondivergent (straight-line), divergent, or convergent. These patterns were then paired with the categories of areal maximization of precipitation as shown in table 11. This table shows only the rainstorms associated with cold fronts and squall lines during 1965 and 1966. When there was convergence over the hills, there was never a flatland maximum of precipitation. When there was divergent flow over the hills, there was only one case of a hill maximum.

The wind field pattern typical before the onset of air mass showers was for SE or SSE winds of low speed. This low wind speed permitted the winds to blow up the valleys to the south of Anna converging upon the plateau. In contrast, the winds preceding squall line and cold frontal rains typically blew from the S or SW at a more moderate speed. These winds were found to be from the SW over the flatlands south of the hills, SSW in the Mississippi River Valley west of the hills, and southerly over the hills themselves. This pattern is convergent and appears to be caused by the steep hills bordering the floodplain of the Mississippi River and the valleys in the hills.

Table 11. Occurrences of Windflow Patterns Six Hours prior to and during Cold Frontal and Squall Line Rains

	Hill rain maximum	Flatland rain maximum	Indeterminate rain maximum
Convergent	5	0	5
Divergent	1	4	1
Nondivergent	2	2	4
Inadequate wind data	2	2	2
Total	10	8	12

ONE-MONTH INTENSIVE FIELD INVESTIGATION

The enhancement of precipitation by the hills may be the result of one or more physical causes: 1) increased surface roughness (Bergeron, 1968; Anderssen, 1963); 2) higher level heat source (MacCready, 1955); 3) south-facing hill slopes (Braham and Draginis, 1960; Ranft and Kilburn, 1969); 4) increased moisture supply from increased evapotranspiration (Jones, 1966); and 5) added cloud or ice nuclei from local man-made or floral sources.

Bergeron and Anderssen studied the increased precipitation in a concentrated precipitation gage network in southern Sweden. They found that gages located on small wooded hillocks received more precipitation than did gages on the surrounding treeless plains.

The Swedish Hills are not as high as the Shawnee Hills and the enhancement in Sweden has been observed only during stable rains. The Shawnee Hills were found to enhance precipitation totals predominantly during the summer in moderate convective showers. However, there are similarities in the fact that both locations show the enhancement in wooded hills surrounded by lower flatlands.

It is possible that the Shawnee Hills increase convective precipitation through dynamic processes started by the additional heat and resultant convective overturning associated with the south-facing slopes and higher terrain. These factors have been discussed for isolated mountain slopes by MacCready (1955) and Braham and Draginis (1960). The difference in scale between mountains of 5000 feet above the surrounding terrain which they analyzed and the Shawnee Hills 400 feet above surrounding terrain would seem to preclude the high-level heating as a significant factor in the enhancement. However, the isolation of many showers over the area during summer air mass (nonfrontal) shower days lends credence to these possible factors.

The possibility exists that the hills receive more rain because they evapotranspire more moisture into the layers of air immediately above the terrain. It has been shown by Jones (1966) that evapotranspiration is higher in these hills than in other parts of Illinois north or south of the hills. This may be due to the greater plant-leaf surfaces available for transpiration from the trees in the hills compared with those offered by the crops in the surrounding flat farm lands; or it may be because the added precipitation in the hills leads to an excess available for evapotranspiration. The humidity measurements were designed to answer the question of additional humidity, but would not necessarily define the source.

A similar project in hills that are considerably higher than the Shawnee Hills is being performed by the Canadian Department of Transport in the Cypress Hills area in Manitoba (Holmes, 1969). Differences between the Cypress Hills climate and that of the surrounding prairie are being studied in an attempt to document a rainfall difference. The Cypress Hills, which are 150 miles east-west in length and 15 miles wide, rise approximately 2000 feet above the environs.

The Canadians have not emphasized the enhancement of precipitation since the enhancement is only obvious in the different flora of the hills and the plains. It is estimated that the average annual precipitation is 20 inches for Cypress Hills and that 13 inches is the long-term annual average at Medicine Hat 35 miles northwest. Colton (1958) found that the San Francisco Peaks in northern Arizona, which rise to 8000 feet above the nearby desert, caused a maximum of 7.45 inches of summertime precipitation which may be compared with 2.50 inches over the Painted Desert to the east of the Peaks. The average summer rainfall in the Shawnee Hills is 11.6 inches compared with 9.7 inches in the flatlands to the south and 10.9 inches in the flatlands to the north.

The primary objective of the intensive 1-month field project in the hills and ensuing analysis was to determine the causes of the enhancement of the precipitation over the hills. To establish the causative factors for the hill increases, the following hypotheses were explored:

1) The hill-effect rain increases may result from clouds that develop over the upwind flatlands, either in a random or selective spatial pattern with a few clouds intensifying as they move over the hills, or the observed 'hill-effect' may really be a statistical coincidence resulting from a preferred breeding area in the upwind flatlands.
2) The effect may be caused by clouds developing along the edges of the hills and remaining in a quasi-stationary position as they develop.
3) The clouds may develop in a preferential upwind breeding area and precipitation from them may be initiated or intensified by hill-effects as they move across the uplands.
4) The hill-effect rains may tend to form in clusters with one or two becoming predominant, or they may result from very isolated cloud developments.
5) An increase in active cloud and/or freezing nuclei from a source localized in the hills may be causing an enhancement of precipitation. Schnell (1972) has shown that the forests of the west, through the release of terpenes, add useful quantities of freezing nuclei. Samples of forest litter from the western Shawnee Hills were supplied to Schnell for his analysis, and he found that this litter could be active as freezing nuclei (personal communication, 1972).

instrumentation and Operations

This project involved, in addition to the existing raingage and wind set network, additional surface instrumentation, upper air wind measurements, and low-level aircraft flights. Five Cotton Region Weather Shelters housing hygrothermographs were installed in a rhombic pattern centered on Anna (figure 11). An anemograph also was located at each shelter site.

The raingage network of 1965-1969 was rearranged into an approximate rectangle (figure 11) on the basis of information gained during the previous 5 years of network operation. It was particularly desired to obtain data in the Pine Hills area along the western edge of the network where a high in precipitation values had frequently been found in 1965-1969. All the surface weather instrumentation was operated continuously during July 1970.

It was anticipated that answers to the basic problems and questions would be provided largely by analyses of cloud and radar echo histories recorded by cloud cameras and a radar set installed for the field project. However, the radar became the primary tool employed in this analysis since the cloud photographic data were not of sufficient value to justify the data reduction task.

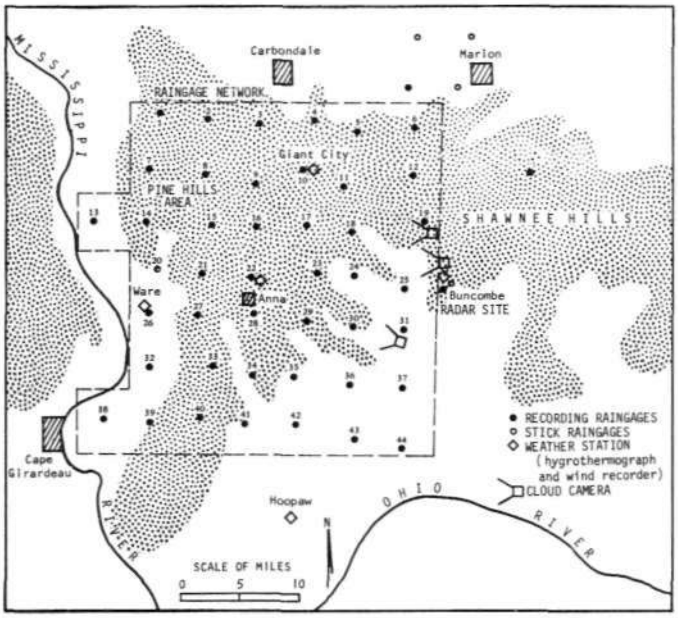


Figure 11. Instrument sites in July 1970

Other measurements were employed in efforts to define the relative importance of such hill-effect factors as terrain roughness, differential heating of slopes, and increased evapotranspiration in the initiation and or intensification of convective clouds and precipitation. A series of measurements was needed in the hill region to establish 1) the horizontal and vertical wind fields and associated convergence or divergence, and 2) the moisture profiles in the lower layers (below 5000 feet). The primary means for collecting these data was by aircraft which made horizontal measurements of temperature and moisture to define the distribution of unstable air and sources of moist air in the mornings before clouds formed. Many low-level horizontal soundings prior to cloud formation allowed mapping of the spatial patterns of temperature and moisture and updraft areas. Other measurements of low-level wind motions and trajectories were obtained by the daily use of pibal measurements and zero-lift balloon trajectories.

A trailer-mounted 3-cm (M-33) radar capable of tracking and plotting the position (height, range, and azimuth) of a tracked object was installed in June 1970 (figure 12) and was operated between 0900 and 1900 CDT on each day in July. The location was chosen to optimize scanning of the hills to the west and north and flatlands to the south (figure 11). The PPI was routinely photographed to record the position and movement of precipitation echoes detected by the radar within 60 nautical miles. The tracking and plotting capabilities of the radar were employed for the determination of upper air winds and the tracking of zero-lift balloons. Vertical growth rates of precipitation, as represented by echo height change, were monitored by the reading of tilt angles from the radar. This was done to determine whether echo growth rates over the hills might be different from the rates of nonhill echoes. Sheltered time-lapse cloud cameras were installed at 3 sites (figures 11 and 12).

Figure 12. Buncombe radar site with wind set tower and cloud camera shelter (foreground)

Attempts were made to track ground-released helium-filled zero-lift balloons by radar, theodolites, and by automobile to determine the structure of the convection in passing from the flat terrain into the hills. Seven balloons were released in the southern flatlands near Cape Girardeau, and all were tracked along the Mississippi River Valley into the Pine Hills. Tracking was done on 17, 19, 24, 25, 27, 28, 29, and 30 July. Although the balloons were obviously following local air currents in both the horizontal and vertical, those that reached the hills skirted along the rim of the hills without rising above them. Balloons released directly within the hills could be tracked for only short distances because of obscuration behind intervening ground objects, usually trees. Attempts to track target-equipped zero-lift balloons with the radar were limited to release points within the range of the radar's optical periscope, found to be approximately only 4 miles in the haze characteristic of the region in a dry July. The results from the zero-lift balloon experiments were considered inconclusive other than the indication that the low-level horizontal winds tend to follow the valleys.

An Aztec aircraft (figure 13) was leased and flown with an on-board meteorologist on days when convective activity was expected. The number of operational flights as roundtrips from Marion Airport was 1 on 23

Figure 13. Project aircraft

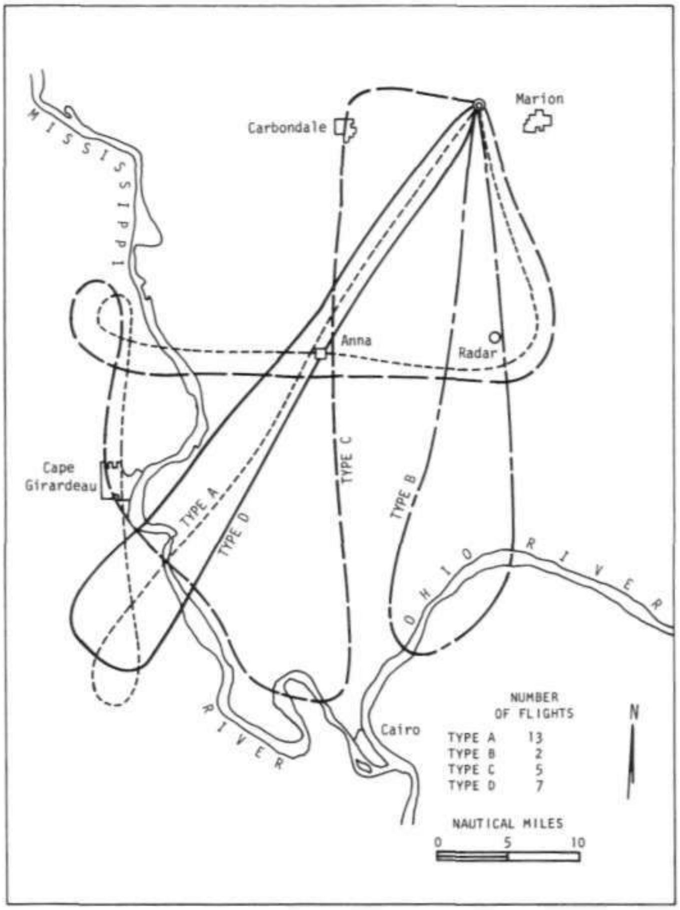


Figure 14. Types of flight tracks

days and 2 on 2 days. Four calibration test flights were performed. This aircraft was instrumented with Mee dry bulb and wet-bulb depression instruments, both recording their data on a dual-channel strip chart running at 3 inches per minute. Manual readings of a Gardner condensation nuclei counter and an MRI freezing nuclei cold-box were made at frequent intervals on each flight. Regional cloud coverage and cloud base heights were estimated routinely, and photographs were taken of selected clouds. Flights were 1 of 4 possible types shown in figure 14. The flight pattern chosen was generally across the hills and parallel or perpendicular to the low-level wind flow. Height on most flights was constant at about 1500 feet msl (800 to 1100 feet above ground). Vertical soundings to flight height were made on all flights, and on 3 days soundings were made between 5000 and 7500 feet msl.

Precipitation in July 1970

Precipitation fell on some part of the Shawnee Network on 11 days during July 1970. On only four of those days did rainfall cover the entire network. The July rainfall at Anna was 1.21 inches which is 35 percent of normal and the third lowest July total since 1931. Only one station in the dense network had above-normal rainfall, and that was gage 38 near Cape Girardeau (figure 11). However, the Cape Girardeau raingage station, located 8 miles to the southwest of gage 38, received far below normal rainfall.

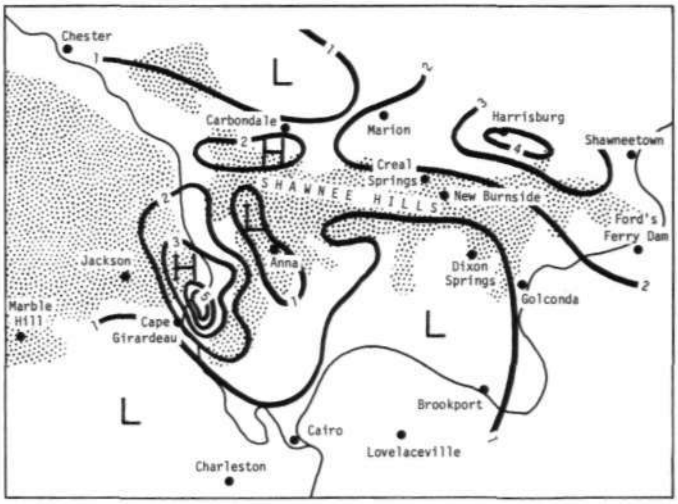


Figure 15. Total rainfall, inches, for July 1970

Only a minor hill increase is apparent in the total monthly precipitation pattern (figure 15). The pattern is not unlike the average pattern for dry Julys shown in figure 7. This meant that July 1970 was a typical dry July in the study area, and that only minor, if any, rain increases in the hill area could be expected. Thus, it was not an optimum sample for study of the causes for hill-area enhancement of rain.

The July 1970 showers tended to be heavy only in small areas, and were mostly of the air mass type (nonfrontal). In general, moisture was adequate near the surface, but was generally not adequate through a sufficiently deep atmospheric layer to permit the formation of widespread thundershowers in the absence of the lifting associated with a frontal discontinuity.

The mean large-scale circulation over North America in July 1970 closely resembled the normal conditions. The average 700 mb height over southern Illinois was less than 1 decameter difference from the mean. However, somewhat above average mean heights over the Northern Plains and western United States provided frequent northwesterly flow aloft over southern Illinois during the first three weeks of July. The four resulting cold frontal passages did not stagnate (a condition favorable for convective precipitation), but moved rapidly through the area followed by dry, more stable air.

The last week in July was highlighted by tropical storm Becky's northward incursion across the Florida Panhandle into Indiana. Although moisture associated with Becky resulted in heavy rainfall in the southeastern United States, its effect on the mid-latitude circulation resulted again in northerly flow and a cooler, undisturbed air mass over southern Illinois. The pattern of the national percentage of normal precipitation for July showed an area of less than one-half the normal precipitation extending from southern Illinois into a region of extreme drought in Oklahoma and Texas.

Following is a discussion of the more relevant rain periods in July 1970.

3 July. The first rain of July 1970 occurred on the 3rd and was one of the heaviest of the month. The heaviest rain in the hills fell between Carbondale and Grand Tower (figure 16). The isohyetal pattern suggests that this rain was enhanced by the presence of the hills. There were two rain periods for the day. The first, between 0845 and 1210 CDT, was prefrontal and maximized in the northwest corner of the dense network. The second period began at 1535 CDT and accompanied a cold-frontal passage. This rain maximized in both the northwest and the southwest corners of the dense raingage network. Low-level winds preceding both storm periods were from southerly quadrants.

An aircraft flight between 1326 and 1415 CDT followed flight pattern type A (figure 14). Temperatures over the northern hills were 1.5 to 4.5 F higher than those over the flatlands north or south of the hills. No comparable dew point increase over the hills was noted, but there was a north-to-south decrease in dew points of 5 F. The aircraft temperature data suggest the possibility of enhancement of convective activity over the hills on the afternoon of 3 July. Surface dry bulb and dew point temperatures during the morning and afternoon showed consistently lower values over the hills. On the basis of a convective cloud cover definition developed to class days as to possible hill-effects *(see table 14 in a later section),* the afternoon of the 3rd was classed as a no-hill-effect condition.

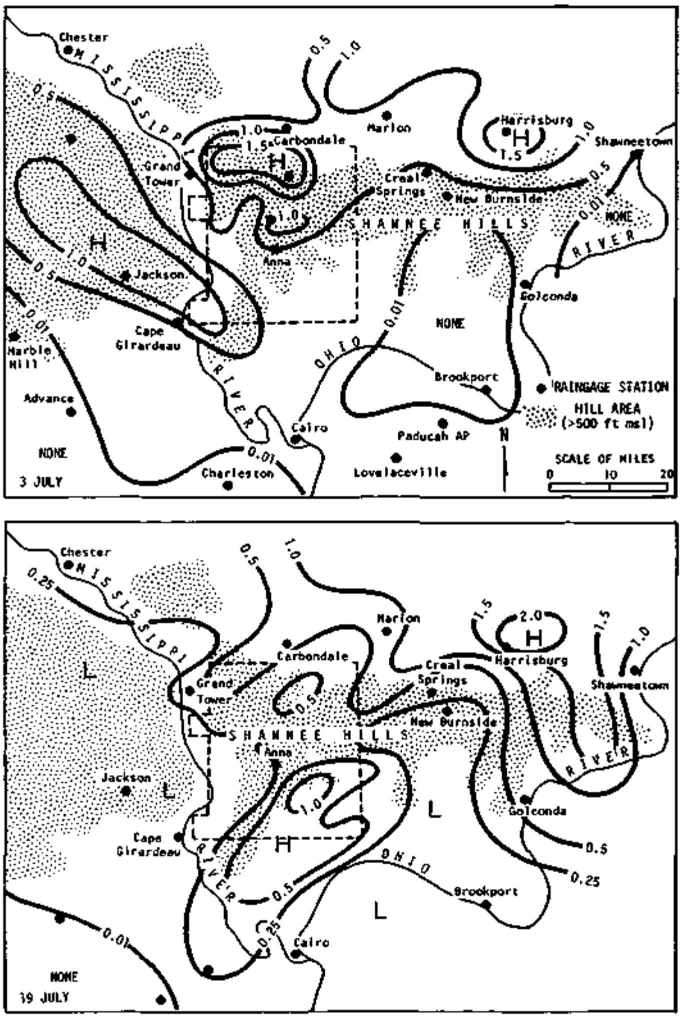


Figure 16. Rainfall, inches, on 3 July and 19 July 1970

19 July. Thundershowers occurred in two periods during the day of 19 July. Minor rains had occurred on the network on 8 and 15 July. The first period of rain on 19 July was from 0730 to 1130 CDT, and the second from 2140 to 2400 CDT. Synoptic analysis shows that the morning showers were prefrontal, but that the evening showers immediately preceded the passage of a cold front through the region. The combined rainfall from the two periods are depicted in figure 16. The heaviest rains were north and east of the hills, and the pattern is indicative of potential hill-effects. In fact, this storm is included to illustrate a rainfall incident when effects were apparent in the morning period but not in the evening storm.

All during the night of 18-19 July, dry bulb and dew point temperatures over the hills (Anna and Buncombe, figure 11), were higher than those in the southern flatlands (Hoopaw). Winds were light (6 mph) and southeasterly until 0700 CDT and convergence was indicated in the surface flow in the western hills. The flow changed to SSW and was more laminar after 0800 CDT. Pibal observations at Buncombe show that at 0800 CDT the wind was from the SW from near the surface to 12,000 feet. The morning rain pattern (figure 17) suggests cell development and maximization over the hills. The first shower of the morning developed over the hills and all cells moved from the SW.

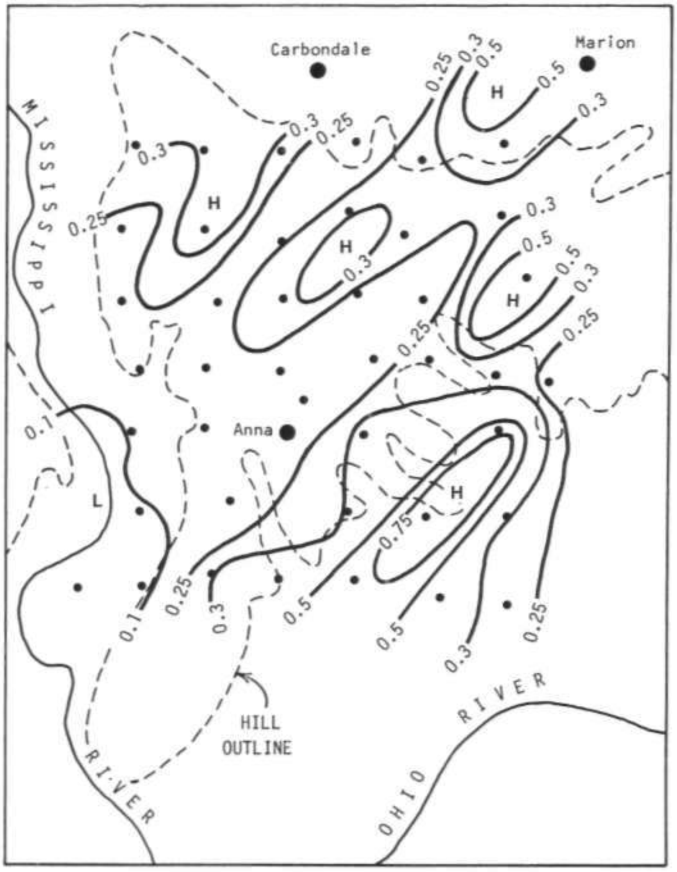


Figure 17. Rainfall, inches, between 0730 and 0950 CDT on 19 July 1970

A radar-tracked balloon released at 2000 CDT (1 hour before the evening showers reached the network) indicated that the SW flow near the surface turned to WNW above 3000 feet. No convergence existed in the surface wind flow in the evening hours, and surface dry bulb and dew point temperatures in the hills and flatlands were generally similar. The only aircraft flight on 19 July occurred at 1900 CDT. Its measurements showed a remarkably uniform distribution of dry bulb and dew point temperatures across the hills and flatlands, with all dry bulb values near 86 F and all dew point values between 81.5 F and 82.5 F. These uniform conditions across the hills and flatlands prior to the onset of rainfall in the evening suggest the lack of hill-effects.

26 July. Late in the day of 26 July thundershowers developed in the hills and flatlands immediately south of the Shawnee Hills. These showers moved from the SSW and most maximized over the hills. The afternoon clouds over the northern hills are depicted in figure 18. The total rainfall pattern (figure 19) suggests a case of rain enhancement by the Shawnee Hills. The only other areas receiving rain were in the hills of Missouri. The air mass within 800 miles of the hills was uniform and without fronts and the showers were singular to the mT air mass in which they were imbedded.

Figure 18. Afternoon clouds at 1548 CDT on 26 July 1970

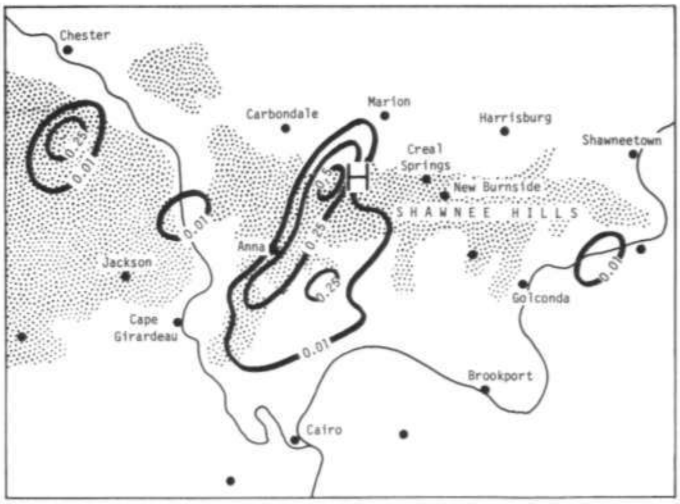


Figure 19. Rainfall, inches, on 26 July 1970

An analysis of the individual raincells in and near the network was pursued largely from the raingage data but with some use of radar data. There were 17 distinct rain cells in the network on the 26th, and their isohyetal patterns appear in figure 20. They are numbered in chronological order, and the isochrones of rain start are also plotted. These isochrones and the cell shapes reveal they all 1) were narrow cells, 2) moved from the SW or SSW, and 3) were not long-lived. Table 12 describes the origin of the 17 cells and their maximization point classified according to 1 of 5 possible locations: river valley, southern flatlands, southern hills, central hills, or northern hills.

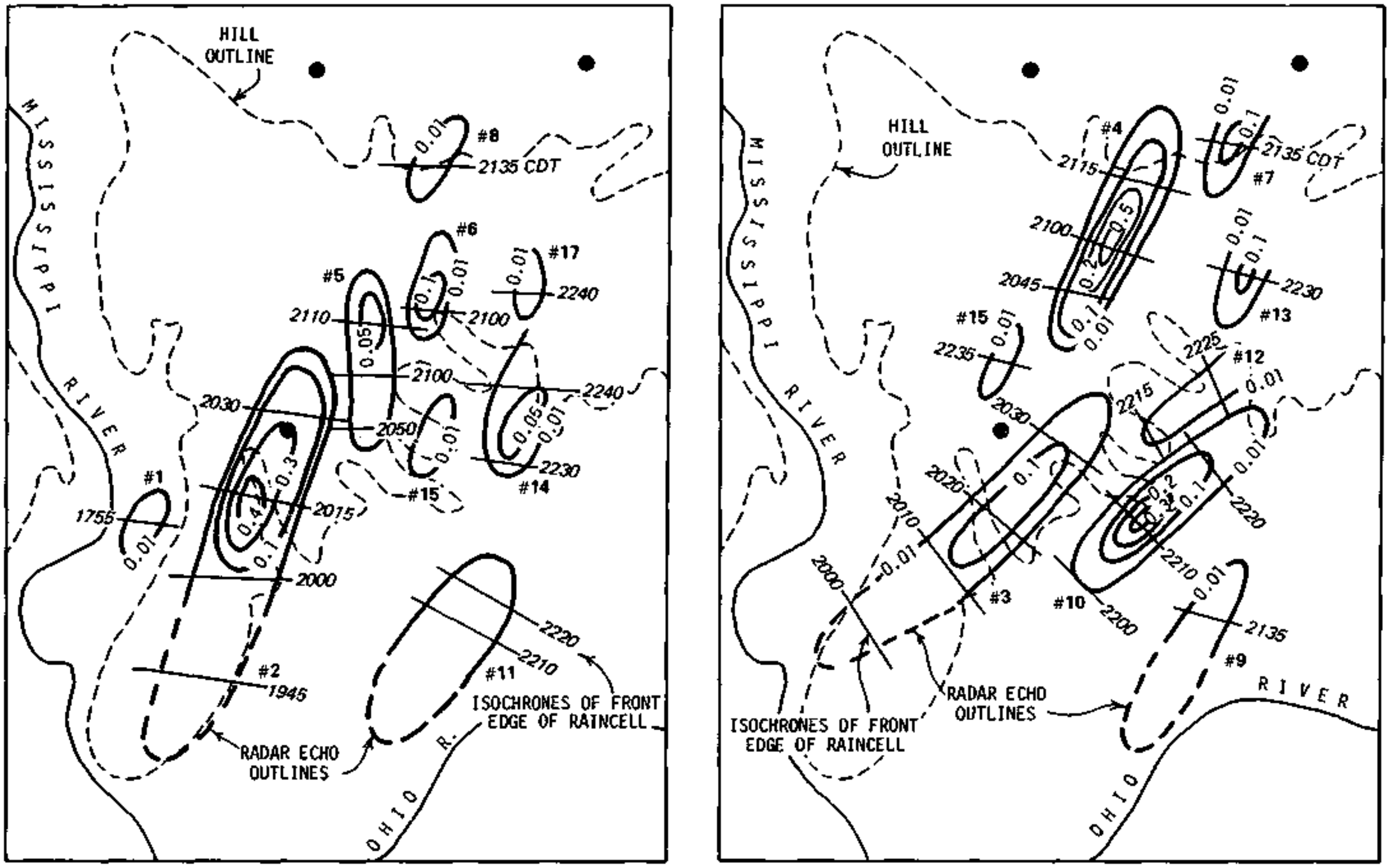


Figure 20. Raincells on 26 July 1970

Table 12. Description of 17 Raincells on 26 July

	Cell times Start	End	Enclosed in rain network	Where initiated	Maximum point rainfall Amount (inches)	Where	Area average rainfall (inches)
1	1754	1805	yes	River valley	trace	River valley	trace
2	1940	2052	no	S. hills	0.42	S. hills	0.18
3	2000	2045	no	S. hills	0.18	S. hills	0.10
4	2043	2122	yes	C. hills	0.57	N. hills	0.28
5	2050	2116	yes	S. hills	0.23	N. hills	0.10
6	2101	2134	yes	C. hills	0.16	C. hills	0.16
7	2132	2205	no	N. hills	0.18	N. hills	0.18
8	2134	2140	yes	N. hills	0.03	N. hills	0.03
9	2137	2155	no	S. flatlands	0.04	S. flatlands	0.04
10	2201	2229	yes	S. flatlands	0.40	S. flatlands	0.16
11	2206	2240	no	S. flatlands	0.06	S. flatlands	0.03
12	2211	2234	no	S. hills	0.01	S. hills	0.01
13	2228	2236	no	C. hills	0.18	C. hills	0.18
14	2231	2254	no	S. hills	0.08	S. hills	0.04
15	2233	2248	yes	C. hills	0.02	S. hills	0.02
16	2238	2253	yes	S. hills	0.01	S. hills	0.01
17	2240	2253	no	C. hills	0.03	C. hills	0.03

Certain results in table 12 are summarized in table 13. These show the development was primarily in the south and central portions of the Shawnee Hills. Their maximization locale was displaced somewhat northward. The heavier rain cells, those with areal means of 0.1 inch, were almost all contained in the hills. The times of their initiations show that the earlier cells, those numbered 2 through 8 all initiated in the hills and generally were the heaviest rain producers. The 3 cells of flatland origin (cells 9, 10, and 11) initiated later. The last six cells of the day were largely light rain producers. Thus, the greatest hill amplification of the rain (both initiation and enhancement) came early in the 3-hour period of showers.

Table 13. Frequency of Raincell Characteristics by Location, 26 July 1970

Location	Number of cells originating	Number of cells based on maximum point rainfall	Number of cells by primary location with average ≥0.1 inch
River valley	1	1	0
Southern flatlands	3	3	1
Southern hills	6	6	2
Central hills	5	3	2
Northern hills	2	4	3

Pibals at rain time indicated the wind field was southwesterly up to 13,000 feet. However, easterly winds had prevailed from the surface to 22,000 feet earlier in the day. Such a change in the wind flow pattern may have been partially responsible for the relatively late outbreak of the thunderstorms; that is, the southwest flow had to become established before moisture and stability criteria were met to permit the formation of thunderstorms in the air mass. The surface winds are also of interest. During the night (25-26 July) they were calm, but from 0700 to 1000 CDT they were very light and variable. From 1100 until 1800 CDT winds in the hills were higher but still in the 3 to 8 mph range. Of added interest is the fact that beginning at 1300 CDT the surface wind directions in the 5-station network indicated low-level convergence over the western hills with SSE flow at Anna and SW flow at Ware from 1500 to 1700 CDT.

About 1115 CDT, the aircraft flew from Marion to Cape Girardeau along what 7 hours later would be the path of the raincells. Dry bulb temperatures averaged about 79.7 F, and the dew point temperatures were about 75.2 F near Cape Girardeau (south) and 78.8 F near Marion (north). The dew point temperatures over the hills were 77 F which was higher than over the southern flatlands. Later, the plane flew north from Cape Girardeau at 1524 CDT. The air temperature at 1500 feet had risen to an average of 84.2 F over the southern flatlands, 85.0 F over the hills, and 86.1 F over the northern flatlands. The dew points had also risen and exhibited the same south-to-north gradient found in the dry bulb values.

Surface temperature and moisture data for 26 July are very informative and support the aircraft findings. A comparison of hill data (Anna) with that from the southern flatland (Hoopaw) reveals that shortly after 0000 CDT on 26 July, the dry bulb and dew point temperatures in the hills exceeded those of the flatlands. This may be due to more rapid cooling at Hoopaw. The hill area values of air temperature and moisture (dew point) remained 1 to 3 F higher than the flatland until the rain began around 2000 CDT. The hill dew point temperatures were 74 to 76 F from 0100 CDT until 2000, and the dry bulb values increased from a low of 75 F at 0600 CDT to a high of 92 F at 1600 CDT. Thus, the hills were relatively warmer and moister for 20 hours preceding the onset of the hill showers. This condition existed at the surface and at 1500 feet msl. Furthermore, the light wind field in the afternoon indicated convergence over the hills.

27 July. Isolated air mass showers occurred on 27 July, as shown in figure 21. There was no indication from the rain pattern that the Shawnee Hills played a part in their formation or intensification, since very little rain fell over the hills and the heaviest rain occurred far to the south in Kentucky. The rain that fell in the Shawnee Hills from two raincells came during the time of maximum solar heating (1400-1500 CDT). However, radar precipitation echoes were evident from as early as 1030 CDT 30 miles to the SSW. The wind field was SW from the surface to at least 22,000 feet, the top of the radar wind sounding.

The surface and aircraft data for 27 July were investigated to study the conditions prior to rain. In general the aircraft-derived patterns of temperature and moisture were similar to those on 26 July, but showed a less pronounced hill-flatland difference. The 27th surface data also were similar with the following exceptions: 1) the hill area dry bulb and dew point values did not exceed the flatland values until after 1000 CDT (much later than on 26 July); 2) the amount they exceeded was less (only 1F); 3) the morning surface winds were stronger on the 27th; and 4) no low-level convergence appeared over the hills until 1400 CDT, and it disappeared by 1500 CDT. Since the synoptic weather conditions on both the 26th and 27th were identical, these noted differences suggest that a) the early morning buildup of moisture over the hills and b) persistent low-level convergence must both exist to get initiation or enhancement of air mass showers in the hills.

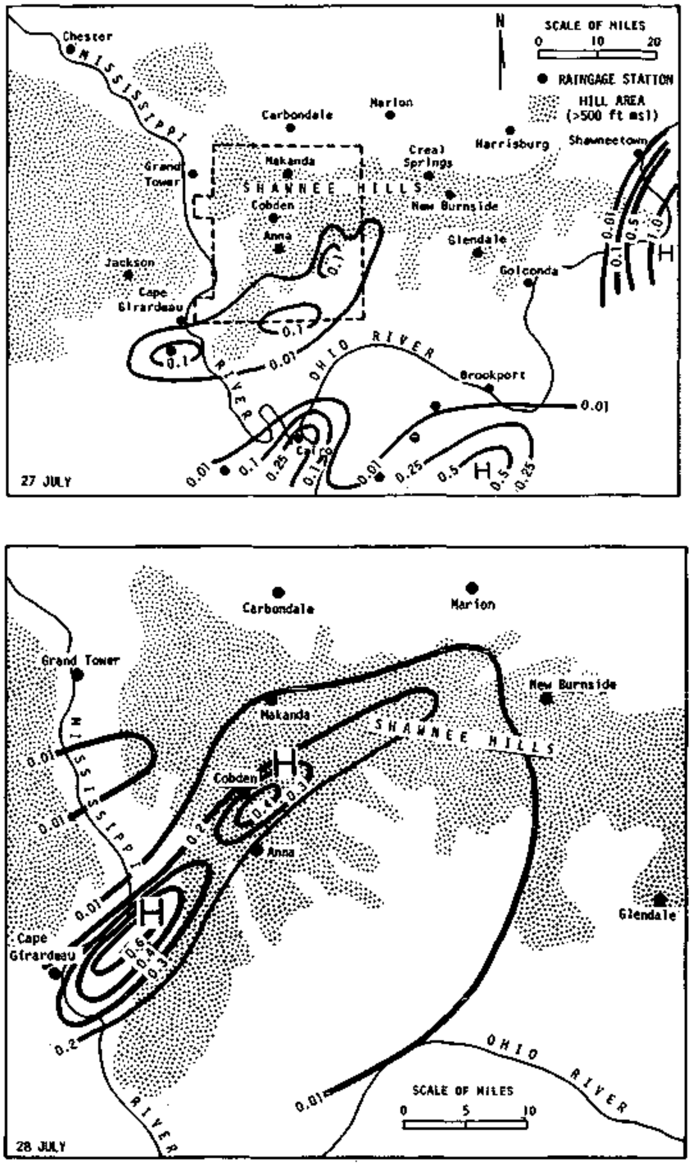


Figure 21. Rainfall, inches, on 27-28 July 1970

28 July. Air mass showers and thunderstorms occurred over the dense raingage network on 28 July. The isohyetal pattern in figure 21 suggests possible enhancement over the hills. However, heavier rains fell 65 miles SSW of the dense network.

Alto-cumulus clouds were present by 0700 CDT with evidence of strong convective growth by 0900

CDT before the radar detection of precipitation. Cumulus clouds apparently influenced by the hills were building so rapidly that pileus was forming above them, although estimated cloud tops were no higher than 4500 feet. Typical clouds on 28 July are shown in figure 22. Attempts to launch and track wind-sounding balloons by both radar and optical theodolite were unsuccessful at that time because low clouds interfered with the optical tracking necessary before electronic tracking could be accomplished. Echo movement of the storms was from the SW and this is reflected in the configuration of the total storm pattern in figure 21. At 0850 CDT the wind was from the SW from the surface up to 12,000 feet where the balloon entered the alto-cumulus deck and backed to the SSW up to the top of the sounding at 24,500 feet.

Figure 22. Clouds over the hills at 1223 CDT on 28 July 1970

Detailed analysis of the radar and raingage data showed two periods of activity. The first activity (and producer of the heaviest network rainfall) was in and south of the hills during 1240-1700 CDT. The second series of shower activity occurred in the 1830-2040 CDT period, but it produced very light amounts (0.1 inch or less).

There were 18 echoes that lasted 20 minutes or more (and were within 60 nautical miles) during the 1200-1700 CDT period. The time and placement of their points of origination and dissipation are plotted on figure 23. The motions were all from SSW (220°) at 15 to 20 mph. Their developments and subsequent motions were concentrated along a SW-NE axis that crossed the network and was the cause of the narrow rain maximum shown on figure 21. Inspection of the location and timing of the echo initiations is relevant. The first 3 echoes (1240, 1300, and 1316 CDT) were in or on the edge of the hills. The next 3 echoes (1320, 1321, and 1341 CDT) developed in the flatlands to the south. A regional breakdown of echo formation shows that 9 echoes formed in the hills (3 in the south, 4 in the central, and 2 in the north), 2 on the edge of the hills, and 7 in the southern flatlands. The heaviest rain-producing cells in the network were those that developed at 1240 CDT (hills), 1300 CDT (edge of hills), and 1321 CDT (flatlands). Obviously, some initiation and intensification of rainfall occurred in the hills.

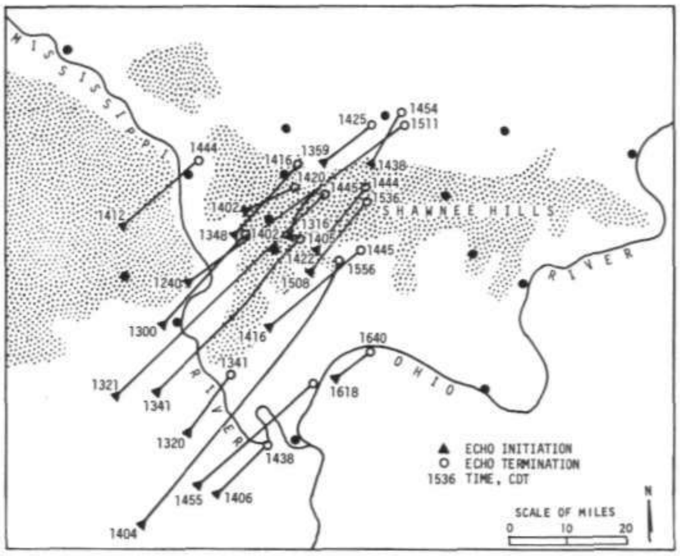


Figure 23. Echo formation and dissipation locations from 1200 to 1700 CDT on 28 July 1970

The surface temperature, moisture, and wind data for 28 July were interesting. The expected (normal) differences existed until 0800 (flatlands warmer and moister). However, at 0800 (and until the rain began in the hills) the hill temperatures were warmer than the flatlands. At 1200 CDT the hill dew point values became higher. Surface winds were calm through the night and until 0700 CDT when light (1 to 2 mph) SE winds began. Wind speeds remained light until rain began at 1300 CDT. Importantly, the Anna and Ware wind directions showed convergence (SW at Ware and S at Anna) from 1100 until rain began at 1300 CDT. Thus, surface weather conditions on 28 July in the hills and southern flatlands were similar to those on the 26 July. That is, 1) the winds were very light with convergent flow developing in the western hills before rain, and 2) the hills became relatively warmer and moister several hours before the rain initiated.

There were two flights on 28 July. The first aircraft flight was made just prior to precipitation initiation, 1151-1245 CDT, and the second flight from 1603 to

1650 CDT. The dry bulb and dew point temperatures on both flights showed the same pattern: north-to-south decreases across the hills with the lowest temperature and moisture values over the flatlands to the south. Dry bulb values were 0.6 to 1.0 F lower over the flatlands, and dew point values were 2 to 4 F lower. Thus, the pattern of warmer and moister air at 1500 feet msl over the hills was comparable to the surface pattern and similar to the conditions on 26 July.

31 July. Precipitation echoes developed in the hills NE of the radar site at 0805 CDT. Except for a 10-minute period about 1120 CDT, precipitation echoes existed within 60 miles in the hills west and/or east of the radar site until radar operations ended at 1708 CDT.

One peculiarity of 31 July was in the movement and propagation of the raincells shown in figure 24. Those in the NW corner of the dense network moved from WSW. The first thunderstorm (cell number 1) developed in the hills west of the network and almost reached the NW corner of the network when it dissipated, and then a new cell (number 2) formed immediately east of the dissipated storm. The new cell moved to the ENE, and another new cell (number 3) downwind of it moved to the east. Cell number 5 developed in the hills along the east edge of the dense network and moved to the ESE. The raincells developed and maximized in the hills and suggested a potential influence from the hills.

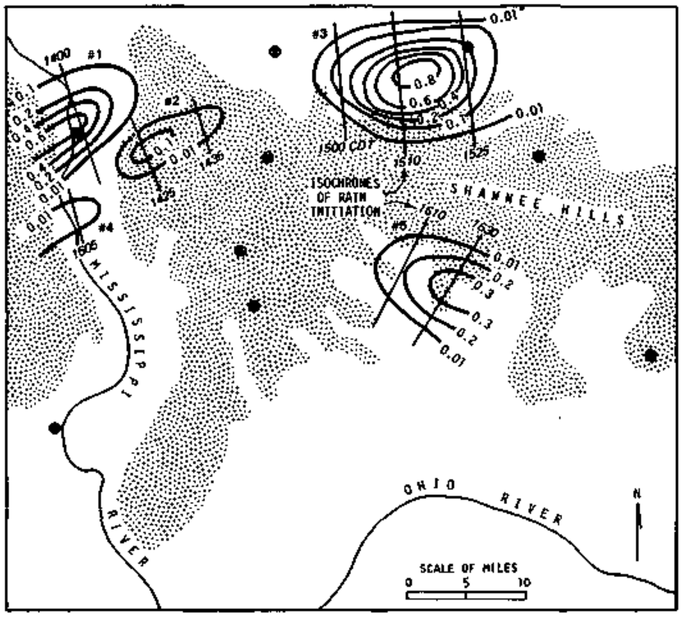


Figure 24. Raincells on 31 July 1970

Inspection of the surface weather patterns in and around the hills on 31 July showed that the hills were cooler and drier than the surrounding flatlands throughout the night. However, by 0700 CDT the hills had become relatively warmer (1 to 3 F), and by 1100 CDT they had become more moist (dew points were 2 to 3 F higher) and averaged 81 F. Surface winds were light at night (2 to 3 mph) and increased only 5 to 8 mph during the day. Surface winds throughout the night were from the SSW in all areas. At 0600 CDT, the direction at Anna was still SW, but those at Buncombe and Ware were SSW or S. This resulted in divergence over the western hills but convergence farther east. This convergent flow between Anna and Buncombe persisted until 1600 CDT when raincells 3 and 5 developed. Unfortunately, the temperature and moisture measurements on the aircraft flight across the hills were faulty. The surface temperature anomaly on 31 July and wind flow characteristics (low speeds with convergence where cells developed or maximized) are similar to those found on other days with apparent hill-effect storms (19, 26, and 28 July).

The wind field with height had become quite confused by 1400 CDT on 31 July with SW winds from the surface up to 5000 feet, W winds from 5000 to 9000 feet, NW to 13,000 feet, N to 23,000 feet, and then W and SW up to 34,000 feet where the tracked balloon burst. This turning with height helps explain the behavior of the precipitation echoes in the afternoon. It appears that the steering level for the storms was increasing in height with time.

Average Surface Air and Dew Point Temperatures for July 1970

The recorded temperature and humidity data at the 5 hygrothermograph stations were summarized for the month of July to derive reference values of temperature and dew point.

Inspection of figure 11 shows that the Hoopaw station was in the flatlands to the south, the Ware station was in the Mississippi Valley (found to be representative of flatland conditions), the Anna station was in the higher hills but near the southern edge, the Buncombe station was also in the southern hills (generally similar to Anna), and the Giant City station was in the more northern section of the hills.

The data for the entire month for each of the 5 locations were used to develop station averages for each 2-hour interval. The average dry bulb temperature curves presented on figure 25 show the normal diurnal variations. Data for the Buncombe station were not plotted because they closely approximated the Anna values of the southern hills. The Ware values in the lower Mississippi River Valley were not plotted since they were closely approximated by those at Hoopaw which is considered to be typical of the flatland temperature regime to the south of the Shawnee Hills.

As would be expected, because of its more southern location and lower elevation, the Hoopaw station has higher average air temperature in all hours. However, some interesting differences exist including the fact that the maximum temperatures occurred later in the flatlands (1600 CDT compared with 1400 CDT in the hills), and that the flatland minimum temperature came later (0600 CDT versus 0400 CDT in the hills). Temperatures in the hills and flatlands were very similar in the 0600 to 0800 CDT period with differences less than 1 F.

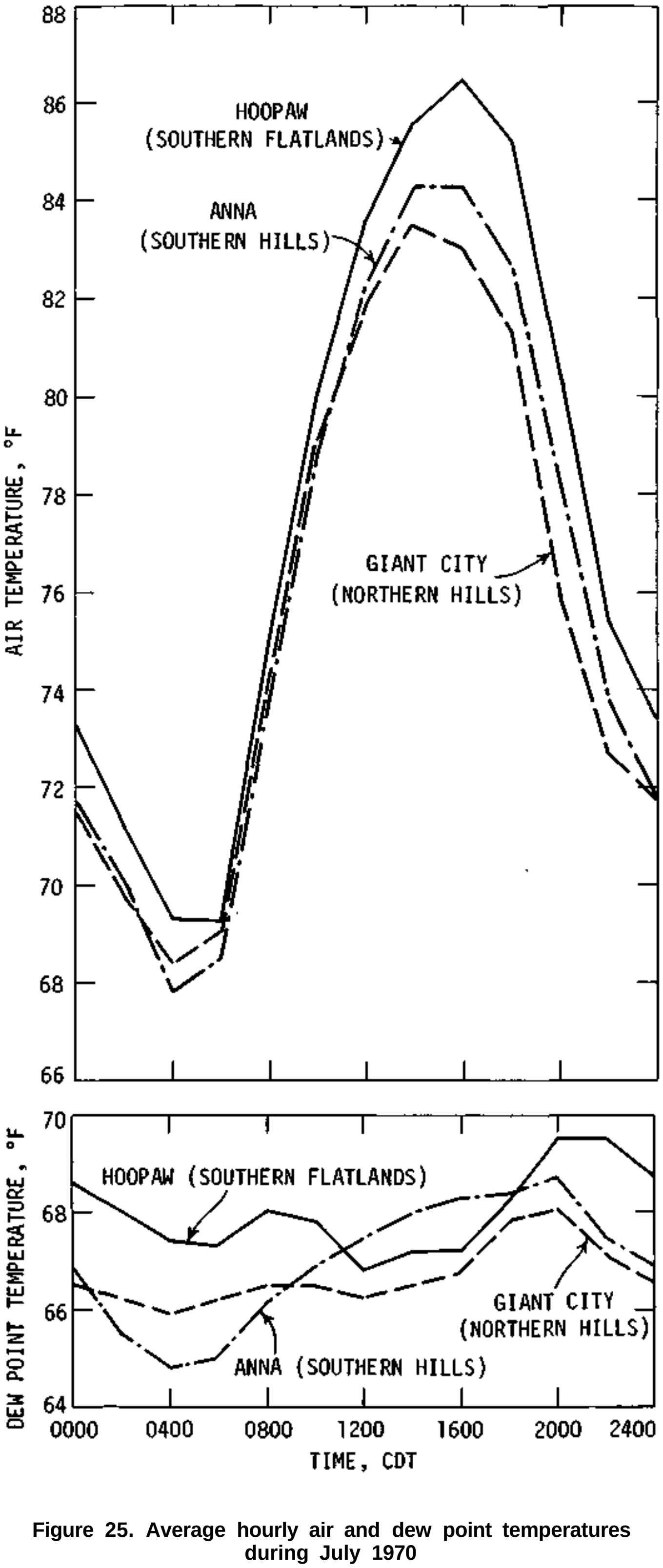


Figure 25. Average hourly air and dew point temperatures during July 1970

Comparison of temperature curves for the two hill stations, one for the northern section and one for the southern section, provides some interesting observations concerning the temperature structure on the hills, at least in July 1970. The station elevations are comparable so differences can only be attributed to slight latitudinal differences or actual differences in the weather regimes in the hills. The Giant City (northern) site was warmer than Anna from 0400 through 1000 CDT, but in the remaining hours Anna was the warmer hill location. In fact, from after 1400 through 2200 CDT the average temperature at Anna remained more than 1 F higher than that at Giant City.

Averages of dew point temperatures also were computed for the 5 hygrothermograph stations, and the 2-hour values for the Hoopaw, Giant City, and Anna stations appear in figure 25. These curves all show that the highest dew point temperatures during the day were achieved during the late afternoon and early evening hours. The southern flatland station had the highest dew point values from 2000 through 1000 CDT (night and early morning), but from 1200 through 1800 CDT, the Anna station, representative of the southern hills, had the highest dew point tempteratures. This suggests that localized moisture sources are present in the hills, particularly in the southern hill area.

The Shawnee Hills are heavily covered by both deciduous and coniferous trees. In contrast, the flatlands are primarily planted to row crops with bare soil between rows. Although the bare soil and row crops will tend to evaporate moisture at potential rates when wetted by recent rains (Yamaoka, 1958), upon drying of the surface the evaporation rate from bare soil decreases. Under these drier conditions the forested hills will evaporate more moisture into the atmosphere and will be a localized moisture source (Kittredge, 1948).

Potential Hill-Effect on Convective Cloud Days

The absence of many precipitation events in July 1970 restricted a meaningful evaluation and comparison of conditions 1) on a regional scale (hills vs flatlands) and their differences on rain days, and 2) on a temporal scale, i.e., rain day conditions (in hills and flatlands) with those on non-rain days. Therefore, another method was sought to define an event or an atmospheric condition in the hills which approximated conditions necessary for convective rainfall, even though the rains did not occur. Obviously, not all of the conditions necessary for rain could be met since rain did not occur. In general, it appeared that the necessary ingredient missing from the convective cloud days was sufficient moisture at mid-levels to sustain the convection through to shower development.

Since the hills are recognized as a unique environment, an atmospheric sounding in the hills would be desirable to determine the stability of the above-hill atmosphere. The closest sounding site was Salem, Illinois, in the much less rugged terrain 65 miles north of the hills. However, convective cloud development, even without rain, is a measure of the convective potential of the atmosphere. Hence, the existence of a moderate degree of convective cloud cover was used for this purpose.

Definitions and Data. Aircraft flights were made each day that had any possibility for the formation of convective clouds. These flights were programmed to be made at or just after the clouds formed in order to sample the currents that were responsible for the formation of the clouds. This was generally between 1100 and 1400 CDT. The observers on the aircraft made an estimate of the sky covered by clouds and the cloud type at 5-minute intervals.

It was found that the storms that precipitated more rain over the hills than over the flatlands were in a southerly air stream. Thus the search for favorable and nonfavorable hill-effect days was restricted to days with southerly flow. The amount of cloud cover is a measure of the instability of the atmosphere. The cloud cover data split into two sets divided near 0.3 of sky coverage. Therefore, the further categorization was made for favorable (unstable) days with cloud cover of 0.3 or more and nonfavorable days with 0.2 or less. There was a total of 7 favorable days and 11 nonfavorable days. An example of clouds on nonfavorable days is shown in figure 26.

Table 14. Favorable and Nonfavorable Cloud Days in July 1970

			Daily winds	
Date	Flight time	Cumulus coverage over hills	Direction	Speed (knots)
		Favorable Days		
7/18	1031-1108 1346-1419	0.3	SW	5
7/24	1553-1703	0.5	S	4
7/25	1239-1351	0.4	S	3
7/26	1059-1135 1520-1556	0.6	S	3
7/27	1241-1342	0.5	SW	4
7/28	1146-1256	0.5	SW	5
7/31	1010-1226	0.6	SW	4
Average		0.5	SW	4.0
		Nonfavorable days		
7/1	1353-1503	0.1	SW	3
7/3	1310-1420	0	S	6
7/7	1032-1142	0.2	SW	4
7/8	1425-1531	0.1	SW	6
7/13	1025-1130	0.2	S	2
7/14	1121-1131	0.1	SW	7
7/15	1104-1140 1430-1456	0.1	SW	7
7/17	1402-1507	0.2	SW	3
7/19	1830-1925	0.1	SW	4
7/29	1334-1437	0.2	SW	8
7/30	1145-1302	0	SW	6
Average		0.1	SW	5.1

Surface and aircraft data were separated and compared on the basis of the data obtained from the favorable days and from the nonfavorable days. Included were comparisons of surface dry bulb and dew point temperatures, low-level (aircraft) dry bulb

Figure 26. Clouds on two nonfavorable days

and dew point temperatures, surface and low-level wind divergence patterns, and the distribution of condensation and freezing nuclei. The days in each sample are listed in table 14. Comparison of the average values of the wind flow for each of the two categories (table 14) shows that there is a prevailing southwesterly wind under both conditions, but that wind speeds on the nonfavorable days were 25 percent greater than those on the favorable days.

Synoptic Weather Conditions. The major features of the macroscale weather patterns on the favorable and nonfavorable days were compared. All of the 7 favorable days were in mT air masses. The nearest major weather disturbances (fronts, squall lines or zones, and mesoscale lows with extensive rain) varied from 300 to 800 miles away from the hills with an average of 656 miles. The description of the favorable days fits that of days when air mass showers might be expected if sufficient moisture had been available. In fact, the National Weather Service forecast the moderate probability of showers and thunderstorms on most days during July 1970.

On nonfavorable days also the Shawnee Hills were frequently in a warm, moist air mass. The average distance from the hills to the nearest major disturbance was 186 miles on nonfavorable days. The significance of the distance of major disturbances is not known.

Condensation Nuclei. The Gardner-type counter in the aircraft was used to collect samples of condensation nuclei at flight level (1500 feet msl) intermittently on all flights. Normally, between 10 and 13 sets of measurements were made at different locations during the typical 60-minute flight. Each set of measurements included 6 pressure values: a minimum, a maximum, and 4 intermediate pressure settings on the Gardner counter.

A median of the maximum pressure values obtained on each flight was determined and used to construct figure 27. Counts were higher in the earlier part of the month when there was less rainfall. However, most daily median values (based on maximum pressure setting) varied between 3000 and 8000 counts.

The aircraft frequently flew over 9 specific locations and nuclei samples were always made at these sites. The median of all the July 1970 maximum values collected over these 9 sites was determined and plotted on figure 28. The values taken over the cities of Cape Girardeau, Anna, and Marion were the three highest, and each city had identifiable particulate sources. The other values for July 1970, both in the flatlands and in the hills, were all between 3500 and 4600, and no marked regional differences are apparent.

The maximum CCN (cloud condensation nuclei) values for the favorable and nonfavorable days were grouped for 7 of these sites, and median values were determined for both classes as shown in figure 28. At all sites except Cape Girardeau, the condensation nuclei on the favorable days were lower than those on the nonfavorable days. This is probably related to the fact that several nonfavorable days occurred in the first half of July when counts were high (figure 27), which is probably related to the greater dryness and dustiness of the early part of the month. On favorable days, the two southern flatland values (3200 and 3500) were not markedly different from the values in the hills away from Anna (2700 and 3100). On nonfavorable days, these two pairs of values were 4400 and 4250 (flatlands) and 4200 and 4500 (hills), again showing no regional difference.

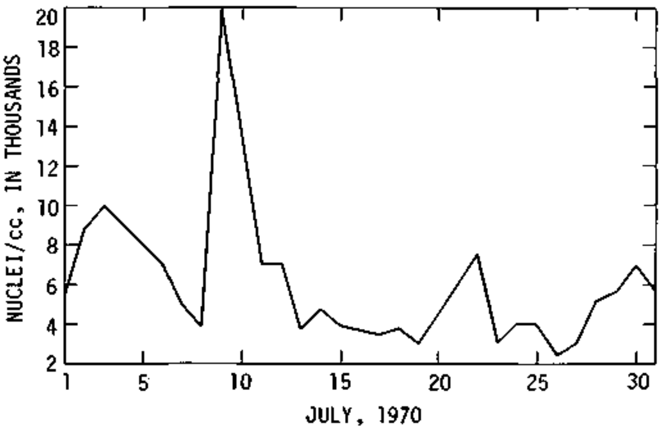
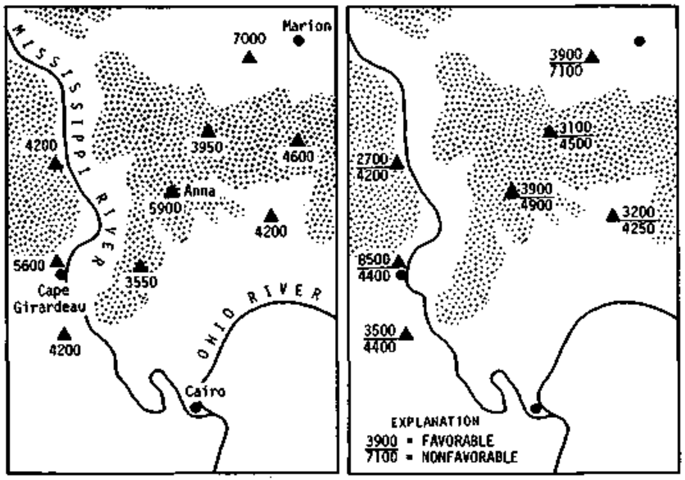


Figure 27. Median values of CCN on each flight in July 1970



MEDIAN POINT VALUES FOR ALL JULY 1970 SAMPLES

MEDIAN POINT VALUES FOR FAVORABLE AND NONFAVORABLE DAYS

Figure 28. Median CCN values at airborne sampling locations

There were generally fewer condensation nuclei on favorable days, and this might be interpreted as indicating a more favorable condition for clouds and rain development (less overseeding). However, the condensation nuclei data do not show a flatland-hill area difference on favorable and nonfavorable days. This does not appear to support an explanation of hill-effect based on localized source of nuclei in the hills.

The Gardner counter observations were further stratified into an upwind flatland area (Cape Girardeau), an over the hills area (Anna), and a downwind flatland area (Marion) on favorable and nonfavorable days.

The average nuclei count was obtained for each of the pressure intervals used. These pressure intervals can loosely be considered as depicting activation supersaturations. Although the meaning of such measurements with regard to cloud nuclei is uncertain, it is clear that the counts obtained at the lowest pressure values approach the cloud nuclei values obtained by the more sophisticated thermal diffusion methods. Increase in the pressure corresponds to the activation of smaller and smaller aerosol particles extending into the Atkin range of sizes.

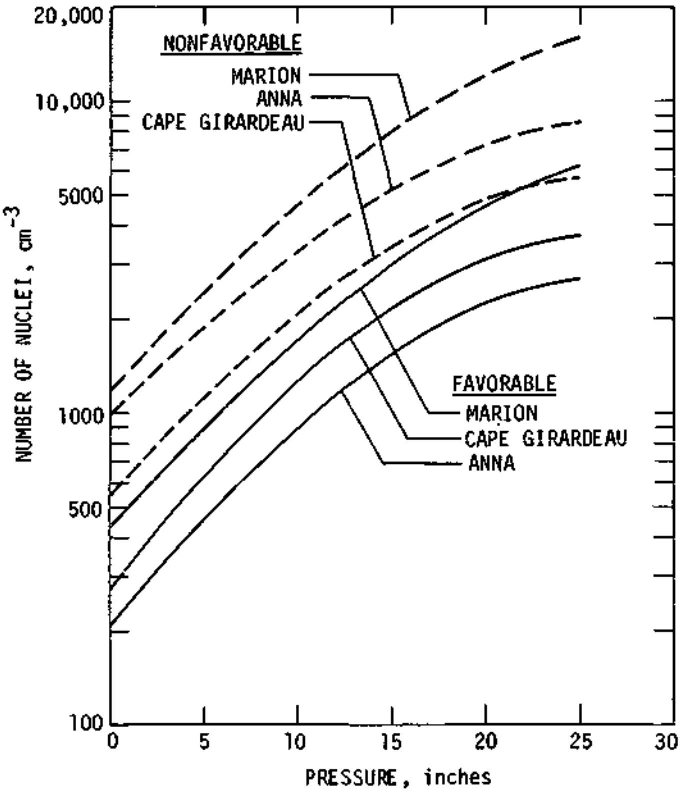


Figure 29. Average CCN counts for various pressure settings at three locations on favorable and nonfavorable days

A striking feature of the distributions shown in figure 29 is the distinct difference between the favorable and nonfavorable data at all pressure levels. As a three-station group, the number concentration of nuclei for the group is considerably greater on the nonfavorable days. In the broad concept of the warm rain process, these data indicate a tendency toward clouds containing a greater number of droplets per unit volume and, hence, a decreasing probability for the warm rain process to be effective. This is an interesting result since all of the data were obtained with southwest flow and the only difference in the synoptic observation is the increase of cumulus activity on the favorable days. It is difficult to explain this observation in terms of the trajectories of the air or local sources of nuclei.

The relative concentrations of nuclei on the nonfavorable days (figure 29) indicate a general increase in the number from the southwest to the northeast. Of course, the relative altitude of the samples above ground decreases along this direction which may indicate a low-level source for nuclei.

The data observed on favorable days show an interesting reversal between Cape Girardeau and Anna. Whereas the count at both stations is less than on the nonfavorable days, a very sharp decrease in the number concentration is noted at Anna. This distribution is definitely favoring the formation of rain through the coalescence process. The results therefore suggest 1) that local sources of CCN are not directly related to the cloud development or extent on favorable days, and 2) that the lower values on favorable days are produced by vertical mixing and by incorporation of CCN in clouds existing on favorable convective days. In other words, the lower CCN values noted on favorable days are a result, not a cause, of the cloud developments over the hills.

Freezing Nuclei. One of the possible causes for the increased precipitation over the Shawnee Hills could be some hill area optimization of the nuclei necessary for the heterogeneous freezing of cloud droplets. Desirable freezing nuclei characteristics are that the nuclei should encourage freezing of the droplets at a relatively warm temperature (as close to 0 C as possible). They also should be able to nucleate sufficient droplets to permit the favored droplets to grow (by vapor deposition, coalescence, and accretion) into efficient precipitation but they should not produce so many nuclei that an excessive number of droplets freeze and insufficient liquid water remains in the cloud to permit any droplet to grow to precipitable size. There were several days in July 1970 when the building cumulus congestus (as shown in figure 30) were not glaciating until their tops had reached the temperature of homogeneous nucleation near —40 C. By the time the cloud had reached this altitude, the opportunity for increased cloud growth had been lost, and the lower cloud evaporated leaving the glaciated anvil as cirrus densus. Little or no precipitation developed from such clouds.

An extra source of freezing nuclei active at relatively warm temperatures was found to exist in the Shawnee Hills. Schnell (1972 a and b) and Schnell and Vali (1972) have shown that decaying vegetation generates a substance, or substances, that exhibits a spectrum of activity as desirable nuclei depending upon the species of vegetation and the stage of the decaying process. A sample of the litter from the heavily forested Shawnee Hills was analyzed by Schnell for nucleating activity. He found it to produce 10^9 nuclei active at —10 C (personal communication, 1972). Since the surrounding flatter terrain is not heavily wooded and litter is not allowed to accumulate on the farmland, more desirable numbers of freezing nuclei should be available to the atmosphere above the forested hills than above the flatlands north or south. A convergence zone active over the hills might lift the nuclei into the clouds that are forming above.

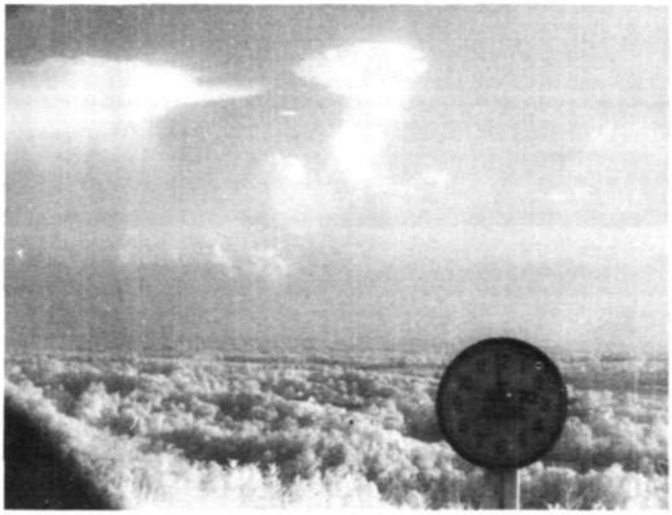


Figure 30. Cumulus cloud, looking southwest of the Buncombe site at 1959 CDT on 8 July 1970 (infrared film)

Freezing nuclei aloft (1500 feet) were measured during the July aircraft flights. Median values were determined at 8 sites in the area for both the favorable days and nonfavorable days, and these values are plotted on figure 31. The nonfavorable values show more areal uniformity with most values of 2 per liter (at —20 C). A higher value exists at Anna and a lower one over the flatlands. The favorable day values were lower than the nonfavorable values at most locales. The highest favorable day values existed at Marion, Anna, and Cape Girardeau.

The freezing nuclei results from the 1500-foot msl level were comparable with those for the airborne condensation nuclei with 1) fewer on favorable days (possibly related to the greater capture in the clouds), 2) little meaningful regional variation, 3) isolated maxima at the larger towns, and 4) no indication that the geographic distribution of freezing nuclei accounts for an enhancement of rainfall in the hills. If the trees and their litter emit a greater frequency of active nuclei in the hills, this frequency was not detected at 800 to 1000 feet above the surface.

The lack of regional differences between hills and flatlands in the condensation and freezing nuclei suggests that local sources or sinks are not sufficient to affect cloud droplet formation. Both nuclei showed significantly lower values, on the average, on favorable days than on nonfavorable days. This difference is attributed to the greater frequency of clouds on favorable days, in that the greater mixing due to overturning (cloud updrafts and resulting subsidence of cleaner air from above) essentially produced a less polluted air at the typical flight level.

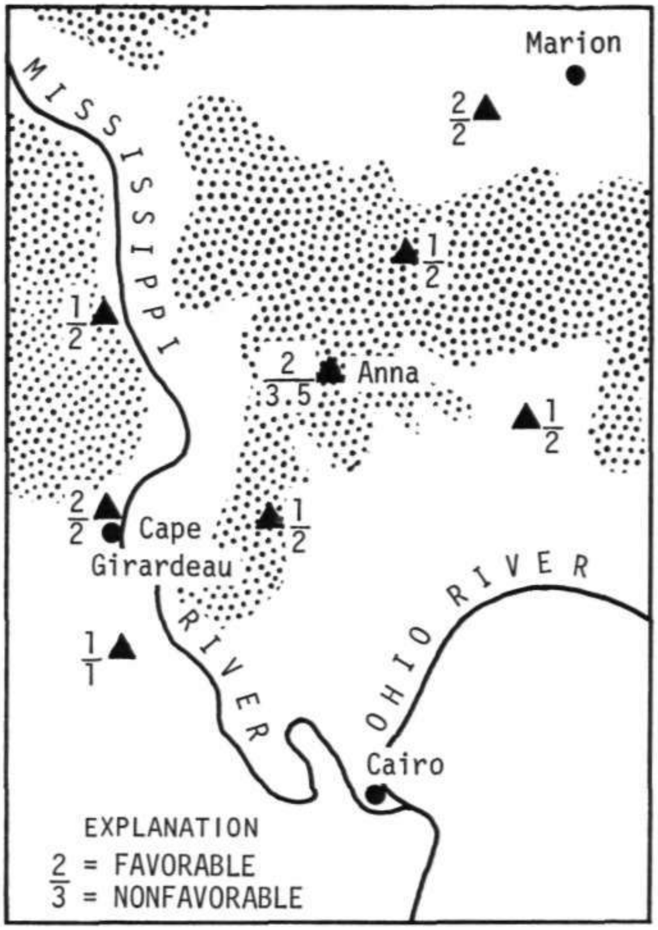


Figure 31. Median freezing nuclei per liter (at -20 C) for favorable and nonfavorable days at airborne sampling locations

Surface Temperature and Moisture Differences. Many possible temperature differences from combinations of data for the 5 hygrothermograph stations were inspected. The results most relevant to ascertaining hill-effects concern the differences in temperatures between the southern hills (Anna) and those from the southern flatlands (Hoopaw). Hourly values for the 7 favorable days at both sites were averaged and the average difference was determined and plotted (figure 32) to illustrate the diurnal variations. On the favorable days the hill area had relatively higher temperatures than the southern flatlands from 0600 through 1600 CDT, averaging more than 1 F higher at 1200 and 1400 CDT. Conversely, on the 11 nonfavorable days (figure 32), the hill temperatures were lower than those in the flatlands in all hours, becoming nearly 4 F, on the average, lower than the flatland temperatures at 1800 CDT.

Comparison of the two 'difference' curves on figure 32 shows that the temperature structure between the southern flatlands and the hills on the favorable days was distinctly different from that on the nonfavorable days, particularly during midday when the hill area is a relative 'hot spot.'

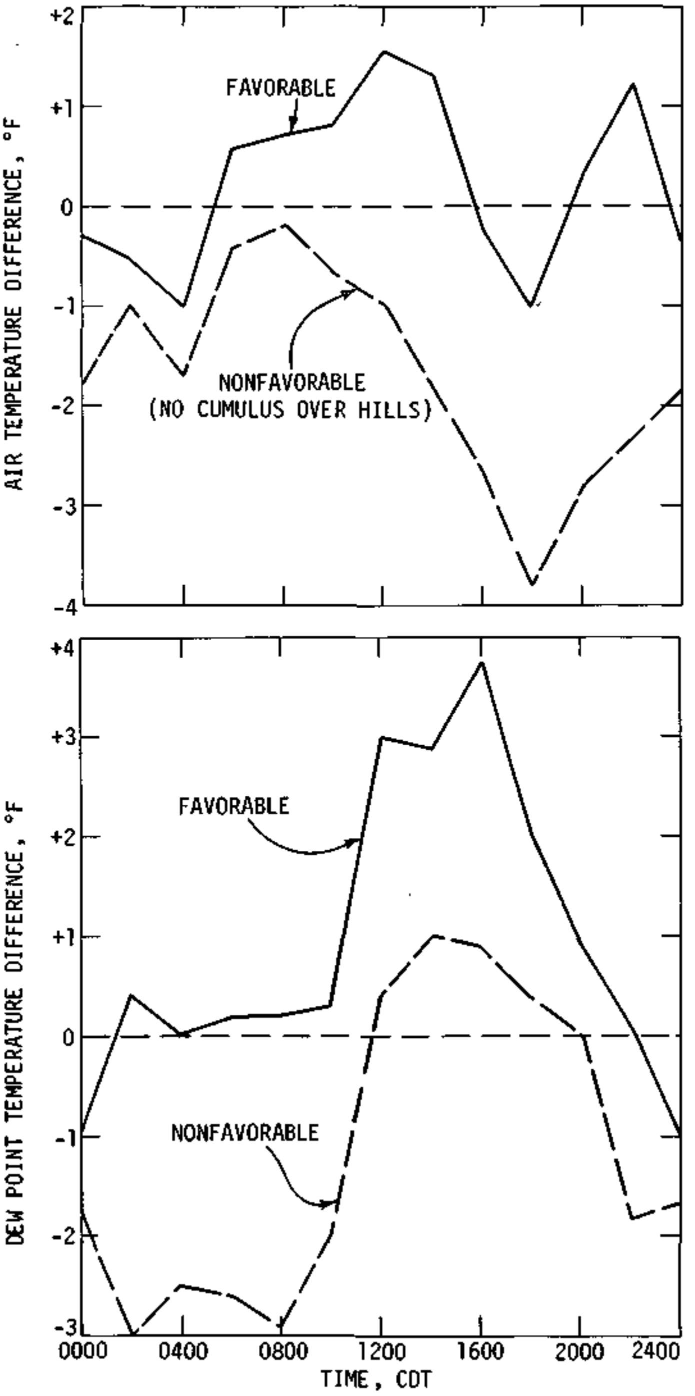


Figure 32. Diurnal differences in air and dew point temperatures between hills (Anna) and southern flatlands (Hoopavv) on favorable and nonfavorable days

Comparison of the regional differences in the dew point temperatures on favorable and nonfavorable days also revealed distinctly different temperature-moisture regimes (figure 32). On the 11 nonfavorable days, the hill dew point values were almost 2 to 3 F below the flatland values from 2200 through 1000 CDT, but were slightly above the flatland values in the 1200 to 1800 CDT period. The curve based on the 7 favorable days had the same general shape as that for the nonfavorable days, suggesting that the rates by which local moisture was being made available to the atmosphere under favorable and nonfavorable conditions were comparable. However, the hill values on favorable days were greater than the flatland values in most hours, becoming markedly so, the difference being greatest during the daylight hours. These results and others in the study of moisture differences between the hills and the flatlands suggest that 1) the favorable days were moister in the hills than were the nonfavorable days, and 2) that this greater moisture was most evident in the early morning nocturnal hours of the favorable days.

The comparisons of the surface moisture and temperatures definitely prove that the hill areas were relatively warmer and moister on days that produced moderate amounts of convective activity than they were on days when little or no convective activity occurred. Why the hills were warmer and moister on the 'favorable' days cannot be explained from these data alone, but these data suggest that additional convective activity over the hills was at least partly rooted to surface conditions. Although the surface temperature and dew point data proved to be very valuable in this study, a major drawback was the lack of recorded temperature data in the flatlands north of the hills.

Low-Level Temperature and Moisture Differences. As with the surface temperature and dew point data, proper interpretation of any low-level flight data anomalies in temperature or dew point over the hill area requires background information. Although various flight tracks were used *(see figure 14),* all flights passed over the flatlands north of the hills, over Anna in the southern hills, and over portions of the flatlands to the south. Since most flights were at 1500 feet msl, comparable average temperature and moisture information could be determined for these three basic locations. Furthermore, averages were determined over the northern and southern portions of the hills (north and south of Anna) on the basis of all values obtained through these two sections.

Table 15. Average Dry Bulb and Dew Point Temperatures at 1500 Feet MSL for 24 Flights on 21 Days in July 1970

	Northern flatlands	Northern hills	Central hills (Anna)	Southern hills	Southern flatlands
Dry bulb (°F)	85.1	84.2	84.0	82.7	84.6
Dew point (°F)	80.2	79.8	79.2	78.2	79.1

Data from the 24 flights on 21 days in July 1970 were used to develoo the average temperature values shown in table 15. The highest average dry bulb temperatures at 1500 feet msl were found over the northern flatlands, and there was a decrease in temperatures over the hill area south of Anna. The change in dry bulb temperatures between the northern flatlands and Anna was not as great as that south of Anna where the southern hill average is markedly less. The dew point temperatures showed less variability in the cross section represented in table 15 than did the dry bulb values. However, for both sets of temperatures, the average low-level values over the hills were lower than those over the flatlands to the north or south of the hills.

Table 16. Average Dry Bulb and Dew Point Temperatures (°F) during Flights on Favorable and Nonfavorable Days in July 1970

	Northern flatlands	Central hills (Anna)	Southern flatlands
Dry bulb			
Favorable (≥ 0.3 cumulus)	84.5	83.5	82.9
Nonfavorable (<0.3 cumulus)	86.3	85.6	86.2
Dew point			
Favorable	80.5	79.6	79.1
Nonfavorable	79.9	79.0	79.2

The low-level (aircraft) dry bulb and dew point data were sorted according to their occurrence on the 7 favorable and 11 nonfavorable days. The results based on averaging the favorable and nonfavorable values over the northern flatlands, central hills, and southern flatlands are listed in table 16. Inspection of the values for the nonfavorable days shows that the hill values are lower than those either north or south. However, the dry bulb and dew point values on favorable days both show north-to-south decreases, or gradients, that are not present on the nonfavorable days. That is, the hill area average temperature at 1500 feet msl is 0.6 F warmer than that over the southern flatlands on favorable days, but the hill values are 0.7 F lower than the southern flatland temperature on nonfavorable days. The July mean values in table 15 indicate there is a slight north-to-south decrease in the dry bulb and wet bulb temperatures in the total July soundings. Thus, the lower southern values found under favorable and nonfavorable cases are not surprising.

Importantly, the dew point temperature results from these low levels reinforced the dry bulb results showing that when cumulus development is slight, the dew point temperature aloft over the hills is low with respect to the flatlands north and south. However, when apparent effects occur (moderate cumulus coverage exists), there is a gradient such that the values of moisture and temperature aloft over the hills exceed those to the south. These data also show that the surface comparisons of southern flatland and hill areas (figure 32) extend at least 1000 feet above the surface by midday.

Thus it appears from the results that higher temperatures and moister air over the hills exist when more convective activity develops (favorable days). Whether this is a cause of the increased convection or an effect from it is not clear. As shown in table 17, favorable days had lower average wind speeds across the area. The fact that the moisture anomaly in the hills on favorable days developed early in the day (figure 32) would suggest that the lower winds on favorable days do not dissipate and diffuse the low-level moisture over the hills. Thus the moisture anomaly appears to be rooted in the nocturnal conditions preceding the favorable day, and this fact necessitates studying the wind field to learn if the winds were low during the preceding night. Obviously, increased moisture over the hills on the favorable days may be considered a factor in the increased convective activity. It becomes important to establish or explain how increased moisture developed over the hills during the early morning hours (figure 32).

Table 17. Pilot Balloon Wind Speeds on Favorable and Nonfavorable Days

	Average speeds (mph) for given height intervals		
	0-400	401-799	800-1165
Favorable	5.7	10.6	12.0
Nonfavorable	10.4	18.1	22.9

Winds on Favorable and Nonfavorable Days. By definition, the regional wind regime on both favorable and nonfavorable days was southerly and one might not expect regional differences in the wind fields based on this singular definition. However, the recorded wind data at the 5 sites in the area were separated by favorable and nonfavorable days and then averaged on an hourly basis. Patterns of prevailing direction and average wind speeds at 2-hour intervals are presented in figure 33 to compare the favorable and nonfavorable data.

Differences at 1000 CDT were not great, showing an anticyclonic deflection of the winds over the hills on both the favorable and nonfavorable days. The flow became southerly again in the northern hill position (Giant City). Wind speeds at all locations were higher at 1000 CDT on the nonfavorable days, averaging 18 percent greater than the speeds on the favorable days. Both types of days showed an amplification of wind speeds at the two southern hill stations (Anna and Buncombe).

The wind regime at 1200 CDT was markedly different from that of 1000 CDT for the favorable days. Inspection of figure 33 reveals an alteration in the flow such that the Anna station has southeasterly flow compared with southwest flow at Buncombe and Ware. This suggests convergent flow in the area north of Ware and Anna, the primary region of rain maximization within the Shawnee Hills. Such a convergence pattern was not present in the nonfavorable pattern at 1200 CDT nor in the nonfavorable patterns in succeeding afternoon hours. These all reflect a cyclonic deflection in the winds as they pass over the hills. The favorable-day wind flow patterns for 1400 and 1600 CDT continue to show this convergence zone in the Anna-Ware area and a divergence zone in the area east of Anna, and west of Buncombe. Also, in the afternoon hours, the wind speeds on the nonfavorable days averaged 20 to 25 percent higher than the speeds on the favorable days.

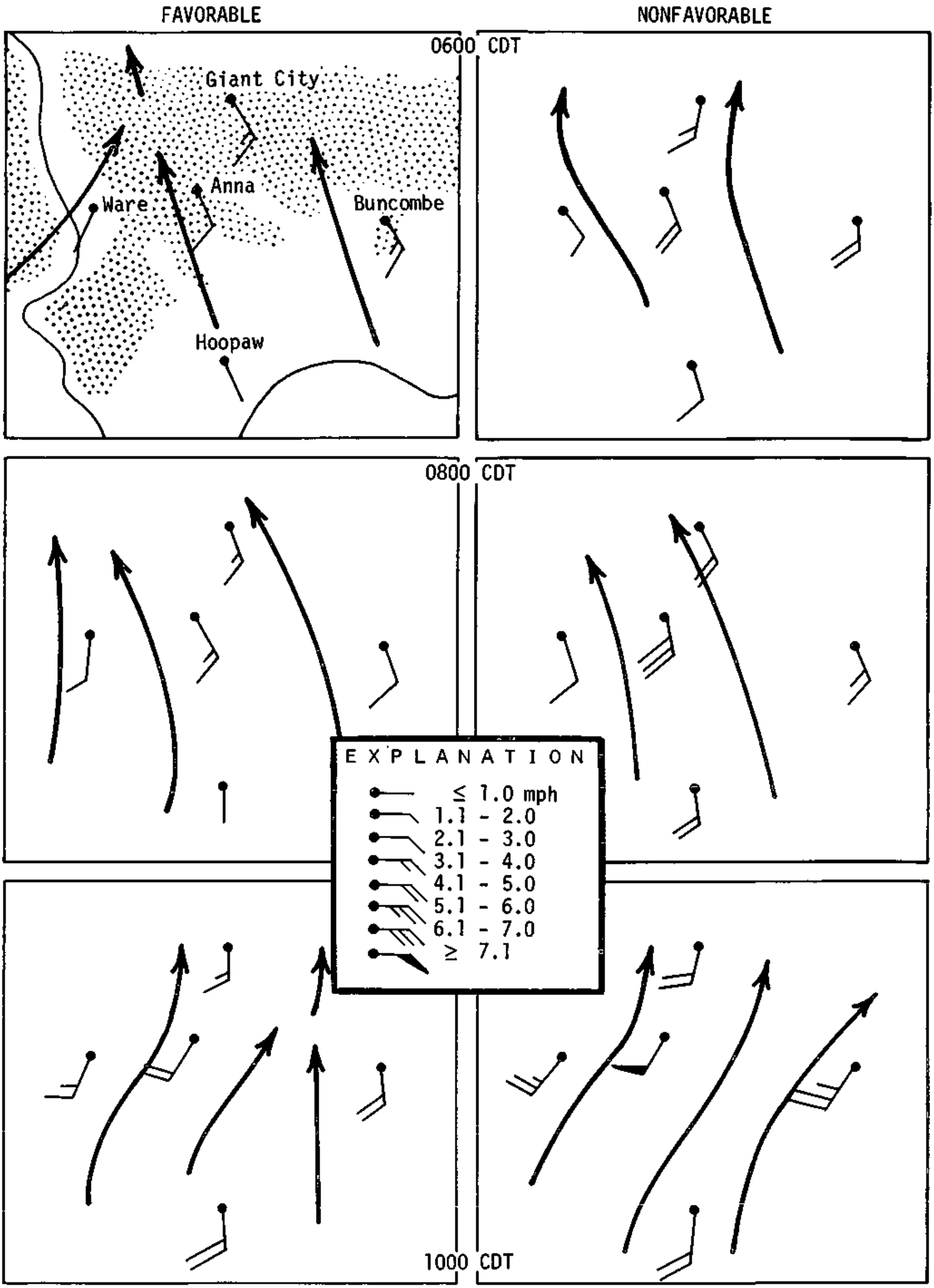


Figure 33. Prevailing winds and average speed, mph, on favorable and nonfavorable days

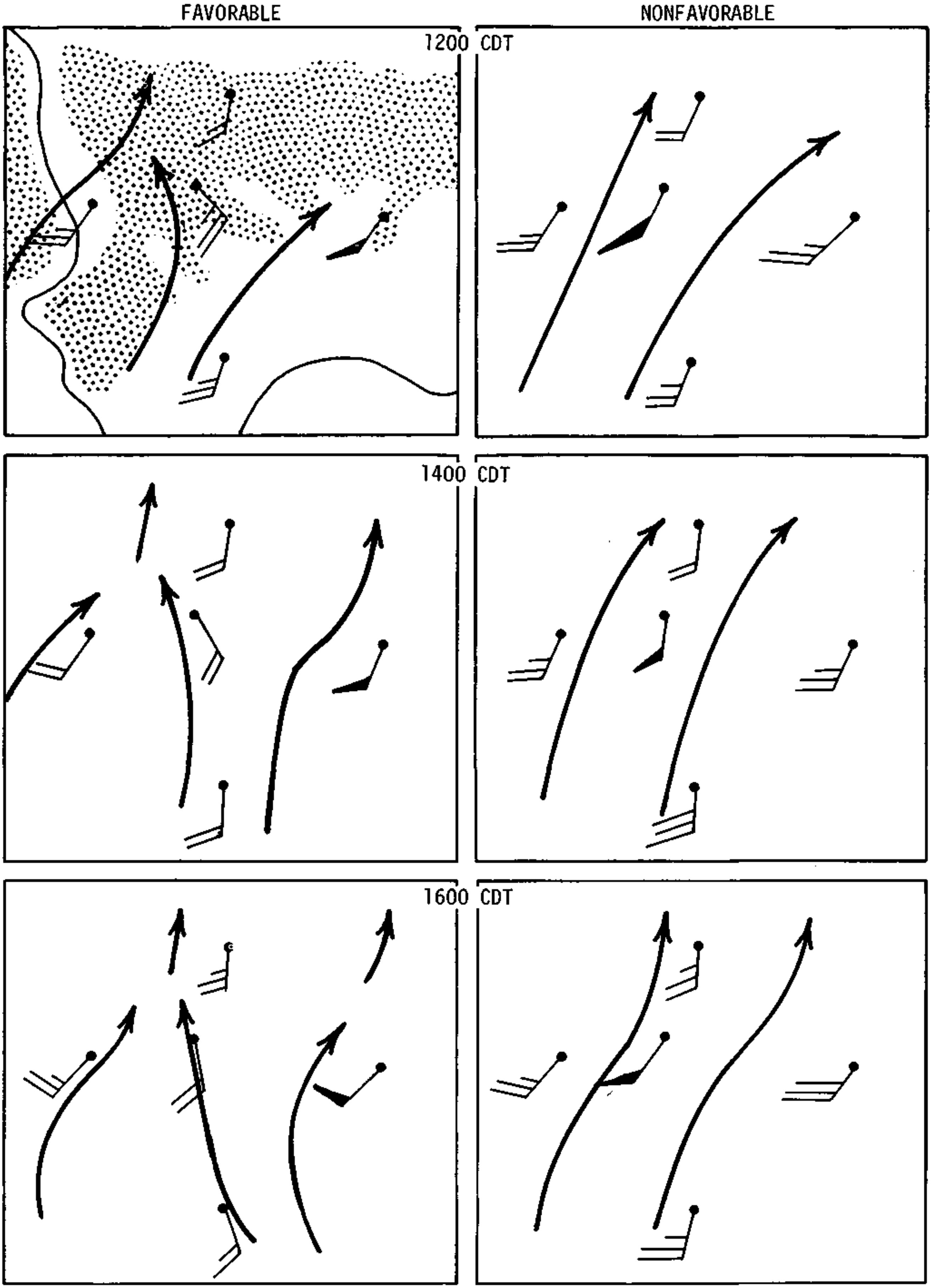


Figure 33. (Concluded)

Comparison of the early morning wind speeds over the hills on the favorable and nonfavorable days revealed that the favorable-day values averaged 50 percent lower. Thus, the wind regimes were much weaker on nights before favorable days than on nights before nonfavorable days.

Data from pibal releases taken at the Buncombe site on most of the favorable and nonfavorable days reinforced these results. Balloon releases were normally made in the morning period (0900-1200 CDT). These values, portrayed in table 17, show the sizeable difference in the wind speeds for three different levels of the lower atmosphere on the favorable and nonfavorable days, and these results substantiate the differences found in the surface wind data.

The analyses of the surface and low-level wind flow data provided two interesting conclusions. First, the wind speeds on the favorable days were 20 to 25 percent lower than those on nonfavorable days during midday, and most importantly were 50 percent or more lower on favorable days during the early morning hours when the hill area moisture increase was noted. The lower wind speeds probably enhance the available moisture in the lower levels in that they do not transport and diffuse this moisture away from the hills.

The second important finding from the wind analyses was the discovery that on the favorable days there was development of convergence in the wind field north of Anna and in the western Shawnee Hills area where the rainfall maximization was greatest. In seeking an explanation for this convergence, it must be remembered that it is partially related to the lower wind speeds that existed on the favorable days and partly due to the local orography. Inspection of the orography *(see figure 11)* reveals that there are two topographic features in the area which may lead to this unique localized convergence. First, the SW-NE trending Mississippi River Valley, at least in the lower half of the hills, would produce a natural flow from SW to NE. This was corroborated by the tracking of constant level balloons in the Mississippi River Valley. These tended to go into the hills in the small SW-NE trending valleys north of Ware, rather than proceeding to the NW along the major river valley. Secondly, a river and several major creek valleys that drain the hills along its southern flank have developed valley systems that have NW-SE orientations (almost at right angles to the Mississippi River Valley), and these valleys are located S and SE of Anna (figure 11). Thus, winds coming up these valleys, aided by upslope motions obviously enhanced in weak wind situations, produce a southeasterly component to the low-level flow through the Anna area, resulting in a convergence of low-level flow in the area north and west of Anna.

This convergence situation plus the additional moisture and heating over the hills are considered to be the prime causes for the increased convective activity over the hills in July 1970. Whether these are the hill-related factors that produce the heavier rainfalls noted in the wet Julys over the hills cannot be specifically stated. However, several of the favorable days (table 14) came in sequential order, suggesting that when synoptic conditions are right to produce additional moisture and hill-related convergence, they may tend to persist for several days. This could result in the self-amplification of rainfall when the wetter conditions exist. That is, given the onset of conditions favorable to hill-effects (additional moisture and low-level convergence), they may tend to persist (or recur) and to reinforce their development from the added hill precipitation and relatively greater potential evapotranspiration in the hills.

Flight Turbulence Results

There were 4 flights (11, 12, 22, and 27 July) of the aircraft when the track types B and C (shown on figure 14) provided an extensive leg over the flatter terrain to the south. A comparison was made of the deviations from smoothed wet-bulb temperature curves above the hills and those above the flatlands in an effort to identify any differences in the roughness and convection.

It was found that there was a regional difference. The data above the hills exhibited greater wet bulb deviations over short-time intervals and the air was thus more turbulent. These deviations were spaced on the average so as to be about 5 seconds from peak to peak (a distance of approximately 1000 feet at the common flight speed of 120 knots) over the hills. Those over the flatland were about 1200 feet apart. In addition, the dew point records from over the hills also exhibited another higher frequency of smaller convective elements on the order of 2 seconds peak to peak, corresponding to a distance of 400 feet. Few or none of the higher order, small turbulent elements were apparent in the dew point records over the flat terrain.

These convective elements are apparendy derived as thermals originating at the surface with the difference in the turbulence between the hills and the flat terrain expressed 1) in the increased mechanical turbulence represented by 2-second length (peak to peak) of oscillations, and 2) in the increased amplitude of the longer wavelength elements at the 5-second peak-to-peak oscillation. This turbulence appears to be caused by greater heating and roughness over the hills. On the average there was no obvious difference in the moisture content of the air over the plains compared with the air over the hills, but on favorable (cumulus) days there was a difference with greater moisture over the hills.

CONCLUSIONS

In general, the results of the three major studies aimed at ascertaining the causes of the enhancement of precipitation over the Shawnee Hills allow the following conclusions.

1) The hill-effect is real. The hill enhancement was first noted in climatic studies in which the long-term normal precipitation for the precipitation stations in Illinois and the surrounding states were compared. The most striking difference in annual precipitation normals was noted between Anna in the hills and Cape Girardeau on the Mississippi River. The addition of the dense network of recording gages to the existing climatological network revealed that the rainfall maximum in the hills occurred somewhat north of Anna on an east-west axis through the northern portion of the hills.

2) Careful study of the limited 1970 rainfall events and the favorable (moderate-to-heavy convective cloud development) and nonfavorable days (little or no convective clouds) from July 1970 has provided indications as to how the hills, on a localized scale, affect convective activity, clouds, and rainfall, at least in a typically dry summer period. The results may or may not be applicable to wet summer periods which have been shown climatologically to have the greatest maximization of rain over the Shawnee Hills.

   Those conditions that appear to have been conducive to increases in clouds and rain over the hills ranged from the synoptic scale down through the microscale as represented by the local temperature, humidity, and wind variation. Initially, the hill-effects occurred only in synoptic weather conditions that were nonfrontal but marginally unstable. Furthermore, the synoptic scale pressure conditions throughout the area were such that steep pressure gradients did not exist. Thus, light winds existed in the lower layers of the atmosphere for 6 to 18 hours before the clouds and/or rain occurred in the hills.
   Given that these synoptic conditions exist, then certain local factors come into play. Apparently through more rapid evapotranspiration from the forests in the hills as compared with the plowed flatlands around them, the lower atmosphere over the hills becomes more moist at night, in the absence of strong winds, than that over the flatlands. Nocturnal cooling occurs more rapidly over the flatlands. Thus, with little or no nocturnal wind or morning air movement, the surface air temperature and moisture content over the hills both become higher than those in the southern flatlands. By midday this temperature-moisture anomaly extends vertically at least 1000 feet above terrain, creating a more unstable low-level air mass over the hills than over the flatlands. Finally, at the time of maximum convective activity (afternoon) the weak to moderate wind field and the unique orography of the western hills interact to produce upslope motions and low-level convergence that together increase the magnitude and frequency of convection and presumably help lift the more unstable moist layer over the hills to the condensation level.

3) The climatological studies revealed that the hill-effect was most active during the heaviest rains, particularly those rains totaling more than 2 inches during the warm season of the year. Thus, the frontally associated and squall-line thunderstorms with southwesterly surface flow contribute most to the anomaly of the hill-effect storms.

4) No significant difference was found in average storm duration between hill-centered and flatland-centered storms. Thunderstorms occurred most often with potential hill-effect storms, whereas rainshowers were most common with the flatland-centered storms. Also, severe weather (thunderstorm accompanied by hail) was much more frequent in the hill-centered storms. Determination of the frequency of storm maximization in the hills and flatlands showed no significant difference, and this fact provides further indication that the hill high in the long-term climatic pattern in the region of the Shawnee Hills is related to storm intensification rather than a more frequent centering of storms in the hills.

5) The cause is not related to nuclei generated locally by the forests since there seems to be no mechanism operative with sufficient frequency to raise the nuclei from the forest floor into the convective systems.

6) The most prominent wind directions prior to and during hill-effect storms are southerly and southwesterly at low levels. At low wind speeds, southerly winds are turned by the Mississippi River Valley into southwesterly, while the creek valleys south and southeast of the highest hills turn the low-level winds so that they blow from the southeast. This flow pattern results in a convergence zone over the highest hills north of Anna and in the enhancement of the showers (usually air mass) associated with these lighter winds.

   Stronger winds are often associated with the southwesterly flow preceding thunderstorm squall lines and the thunderstorms in the proximity of cold fronts. This southwesterly flow is diverted by the Mississippi River Valley into southerly winds north of Cape Girardeau that converge over the western hills into a wind field conducive to upward motion, whereas the wind field over the eastern hills becomes divergent.

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