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A Cumulus Convection Model Applied to Thunderstorm Rainfall in Arid Regions

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14. ABSTRACT
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FOREWORD

This Research Note is a preliminary report of research findings resulting from a 3-year (1968-1971) contract with the University of California, Davis. The research project is concerned with "Methods of Estimation of Runoff From Arid and Semiarid Climate Watersheds". The estimation of runoff in arid climates is one of the more difficult problems encountered in hydrology, because runoff-producing precipitation events are usually of a thunderstorm type and possess characteristics of great time and space variability whose definition is filled with uncertainty. There are also unique problems connected with predicting the runoff response of dryland watersheds to thunderstorm precipitation.

The research conducted thus far has been focused in the following areas:

a. A study of storm patterns and investigation of a thunderstorm model to be used in connection with runoff prediction.

b. Development of theory for the characterization of thunderstorm statistics in an effort to establish criteria for frequency prediction of runoff producing thunderstorms over watersheds.

c. Development of a hydrologic system model based on recent investigations, among which is the procedure utilizing the kinematic wave theory.

This report is concerned with the first of the objectives listed above. It is planned to publish reports in connection with other aspects of the project.

The principal investigators who have conducted the research are Dr. J. Amorocho, Dr. L. Borgman, and Mr. D. Morgan. Dr. Amorocho is the project leader and has primary responsibility for formulation of the hydrological models. Dr. Borgman has been in charge of the statistical analyses and Mr. Morgan has been responsible for meteorological aspects of thunderstorm analysis.

RESEARCH NOTE NO. 1

A CUMULUS CONVECTION MODEL APPLIED TO THUNDERSTORM RAINFALL IN ARID REGIONS

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ABSTRACT

Rainfall estimates from a computer model for cumulus convection were compared to measured precipitation. The estimates of amount and duration of rainfall compared favorably with data from dense rain gage networks in Arizona and New Mexico for most of the thunderstorm cases examined. Systematic differences are attributed to the inability of the model to replicate complex atmospheric processes completely, nonrepresentativeness of input data, and to difficulties in assessing fully the ground truth precipitation.

A CUMULUS CONVECTION MODEL APPLIED TO THUNDERSTORM RAINFALL IN ARID REGIONS

D. L. Morgan

Introduction

In the arid and semiarid regions of the western United States flash flooding occasionally results from concentrations of runoff from intense convective rainfall over watersheds in the mountainous areas. Damage can be severe when communities built on the normally dry outwash areas adjacent to these watersheds are suddenly deluged with torrents of debris-laden water debouching from the nearby mountains.

Such communities develop adequate protection from infrequent flash flooding by building water-slowing and retaining structures along the washes which drain the mountain watersheds. Optimum design of such structures for both safety and economy depends on information of two types: watershed response to intense-spotty precipitation, and the frequency, magnitude, and areal distribution of convective rainfall.

Unusually heavy amounts of precipitation occur generally in association with complex atmospheric conditions which exaggerate the more common desert thunderstorm in size and duration. As a first step to understanding the more complex situation this paper offers the following approach. In order to estimate runoff, characteristics of the watershed under consideration and the time and space distribution of rainfall over it must be known. It would be desirable to have a storm model which, using input of individual convective cell rainfall amount and duration, could describe the time and space evolution of a precipitation field based on the statistically determined frequency and distribution of a series of such convective cells. Such a convection model could be used to give an estimate of convective cell rainfall amount and duration based on an atmospheric sounding of temperature, moisture, and winds above a watershed plus information on the dimensions of expected clouds. A detailed description of a parameterized cumulus convection model and the results of testing this model for the more typical semiarid-region conditions follows general discussions of thunderstorms and of convective storm modeling.

Thunderstorms

Thunderstorms and their associated convective rainfall differ from region to region. It is important in applying convection models to have a clear picture of these differences and in particular to understand semiarid region or desert thunderstorms, since these are the types of storms usually associated with flash flooding.

One of the earliest studies documenting thunderstorm genesis, evolution, and structure is by Byers and Braham (1949). Their information, based on observations made in Ohio and Florida, is representative of air-mass thunderstorms in the humid eastern United States, although in Ohio many thunderstorms are associated with squall lines or organized weather systems. This classic work describes the life-cycle of a thunderstorm cell. The cell is a subunit of the larger thunderstorm, which is usually made up of a cluster of individual cells in various stages of development. The average life of one such cell was found to be about 20 minutes from the beginning of the mature stage, when precipitation begins falling from the cloud, until the heavy rainfall ceases and the cell enters the dissipating stage. Such mature cells were found to average 6 miles in diameter, with the normal base and top of the cells (clouds) at 5,000 and 20,000 feet above sea level, respectively.

In the Great Plains area, giant thunderstorms frequently produce devastating hail and severe weather, including tornadoes. As a result of public interest, a great deal of research has been focused on these super storms during the past two decades. The bulk of recent literature on thunderstorms deals with this extreme type of thunderstorm, reflecting the concentration of research.

These giant thunderstorms are produced by a combination of solar heating of the air near the surface and synoptic disturbances traveling the westerly flow aloft. Well organized systems of these thunderstorms sometimes form rather suddenly, as in a case examined by Kessler (1970), in which a line of such storms 250 miles long suddenly came into being. These giant thunderstorms contain super-cells, according to Fujita and Byers (1962), considerably larger than cells described in the classic work referenced above. These larger-diametered super-cells have bases at about the same level as thunderstorms in the humid east, but they may reach heights over 60,000 feet above sea level, for radar echo observations show (Long, 1966) they penetrate well into the tropopause.

Some of these giant thunderstorms, associated with squall lines, attain an apparent steady-state condition lasting for hours (Newton, 1966), in contrast to the normal 20-minute life-cycle of the humid-region thunderstorm cells. Once formed, the Great Plains thunderstorm usually travels under the influence of the movement of the initiating synoptic disturbance, with the formation of new cells to the right of the major thunderstorm. This is because a supply of warm, moist air feeds the storm from the southeast quadrant (Newton and Fankhauser, 1964). These storms frequently become large enough to develop local circulations of their own, which affect the flow in which they are embedded, causing irregular and unpredictable movement (Fujita and Grandosa, 1968).

Contrasting the arid-semiarid thunderstorms of the western United States with the thunderstorms of the humid east and the giant thunderstorms of the Great Plains, we find some similarities, although major differences become apparent.

Thunderstorms of the summertime arid-semiarid region are usually of the air-mass type, forming as a result of the intense surface heating. Mountain masses, an inherent part of the southwest, assist in the formation of thunderstorms through both high-elevation heating and orographic uplift. Satellite pictures of large cumulonimbi forming over the western United States clearly show the association of these thunderstorm clouds with mountain masses as their source regions (Fugita, 1967). These thunderstorms usually drift slowly along with the weak flow that feeds moisture into the arid regions. On occasion thunderstorm activity becomes widespread and intense as organized disturbances in the weak flow aloft move through the area, adding increased instability to the atmosphere, augmenting the heating and lifting processes commonly present.

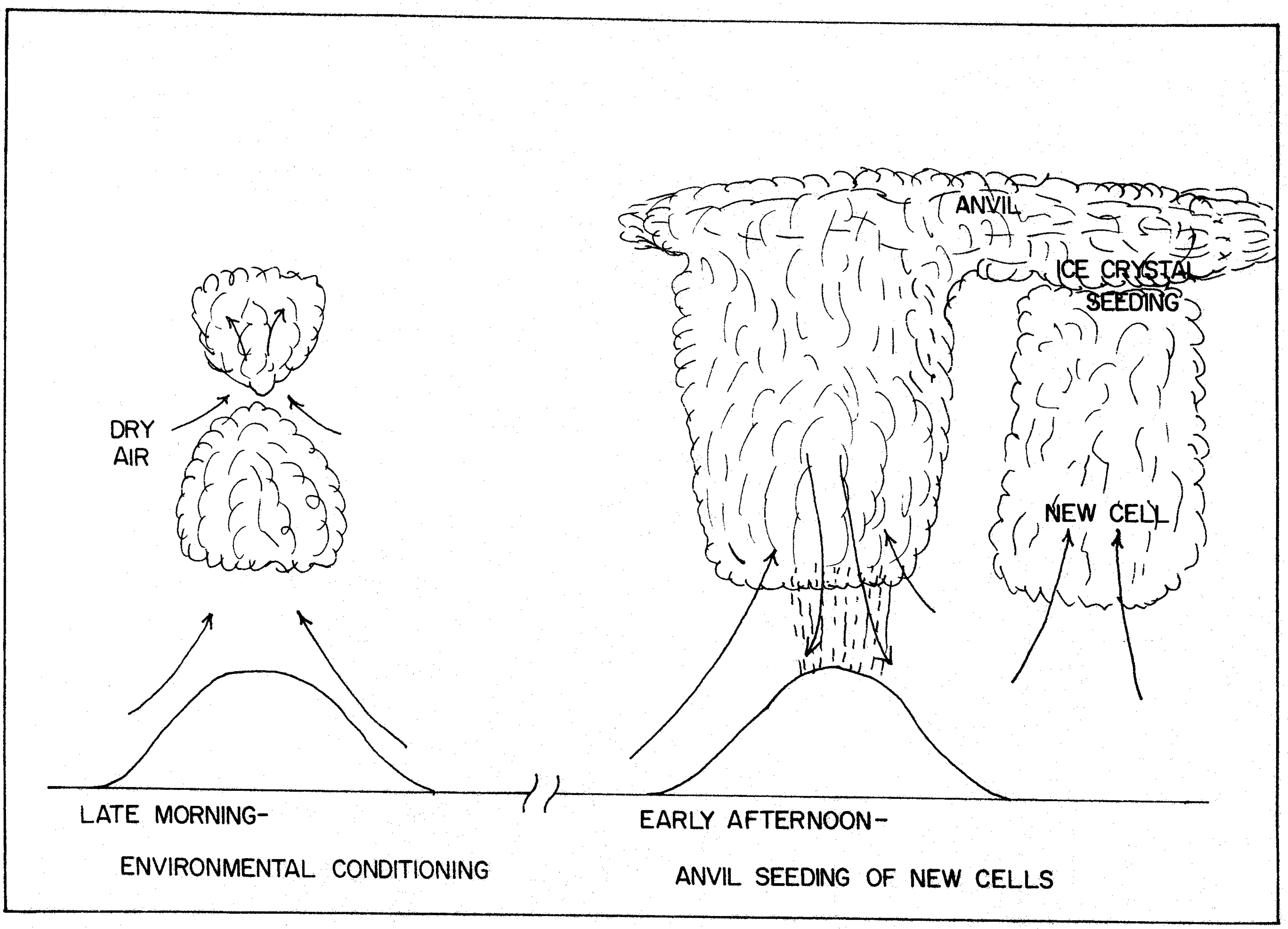
Figure 1 depicts a typical sequence of thunderstorm activity in the arid regions, including some special features as observed near Flagstaff, Arizona, by Davis, Kelly, Weinstein, and Nicholson (1969), during intensive studies of desert thunderstorms. This diurnal sequence is as follows:

-The day dawns clear, surface heating begins, and cumulus clouds start to form over the mountains. The timing depends, among other meteorological factors, on the amount of moisture present in the air.

-These cumulus clouds grow and dissipate again and again as successively rising bubbles and plumes of moist air are mixed into the dry air aloft. This "conditioning" of the drier upper-air with the addition of convected moisture from below,reaches a state where larger clouds are no longer eroded away. These clouds now reach heights where temperatures are cold enough for natural ice crystals to form. The growing cumulus glaciates, and rain begins to fall from the cloud, now entering the mature stage of a thunderstorm cell.

-The upper portions of these clouds become ice-crystal anvils, which drift away from the mother cloud with the winds aloft. These long-persisting anvil cirrus clouds act to seed younger growing cumulus below them. Thus, these younger-developing cumuli are accelerated into the mature stage, and rain begins to fall from them.

-As the day wears on, the collection of cool air, having been generated by the cold downdrafts of sequentially maturing thunderstorm cells, acts as a mesoscale cold front triggering the formation of new clouds in an expanding area centered on the point of the earliest-maturing thunderstorm cells (Fujita, Styber, and Brown, 1962).


DRY AIR
ANVIL
ICE CRYSTAL SEEDING
NEW CELL
LATE MORNING-
ENVIRONMENTAL CONDITIONING
EARLY AFTERNOON-
ANVIL SEEDING OF NEW CELLS

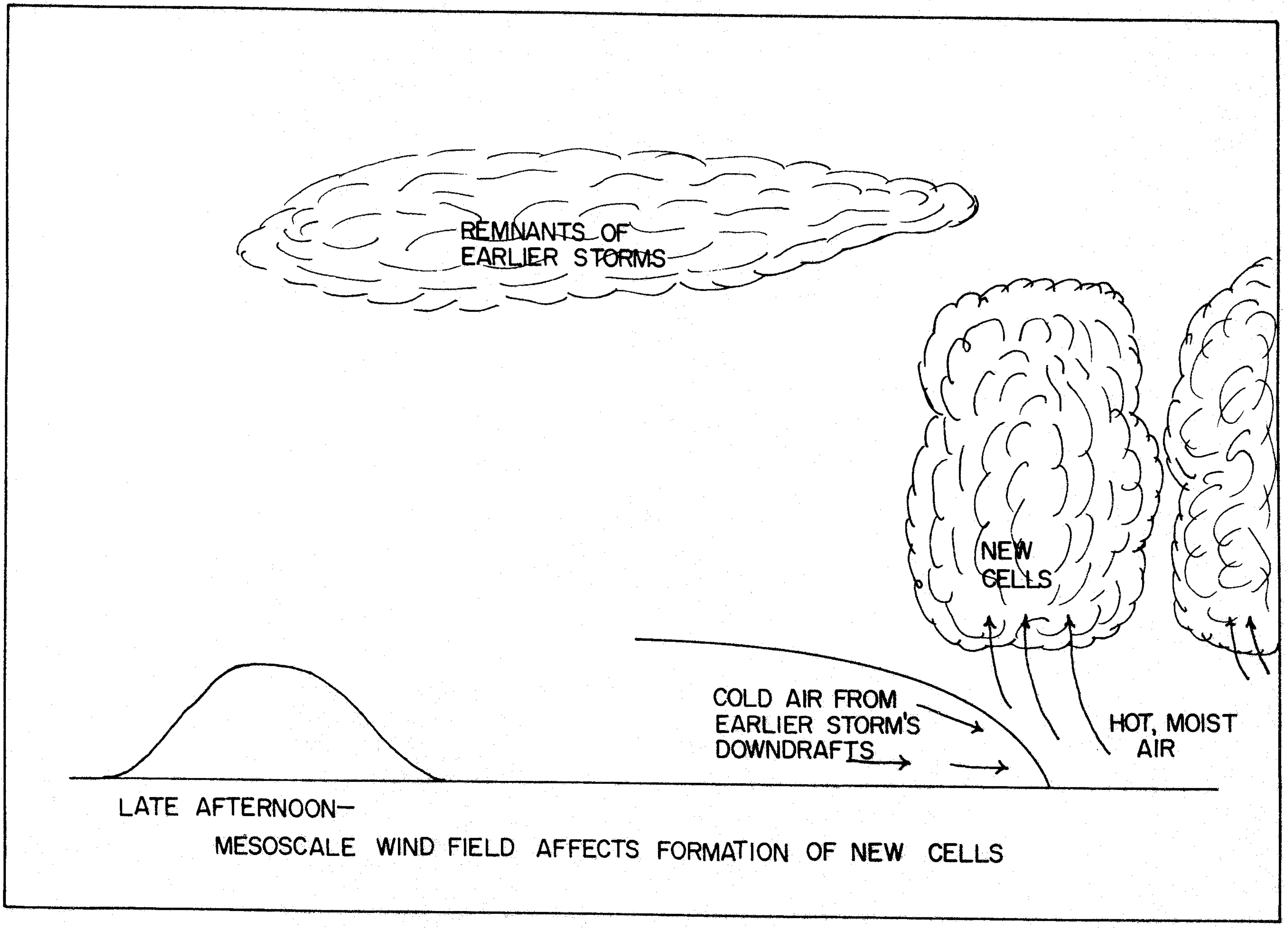


FIG. 1 HYPOTHETICAL SEQUENCE OF THUNDERSTORM DEVELOPMENT IN THE ARID AND SEMI-ARID REGIONS OF THE WEST.

As stated by Battan (1966), convective clouds in Arizona, representing a part of the arid-semiarid west, differ in many respects from those normally observed over the more humid regions of the world. In arid regions, cloud bases are generally higher, in many cases measuring 10,000 to 14,000 feet above sea level (Davis, Kelly, Weinstein, and Nicholson, 1969). Fujita, Styber, and Brown (1962) found an average height of summer cumulus cloud bases to be near 12,000 feet. The average height of thunderstorm cell tops in Arizona was found by Davis, Kelly, Weinstein, and Nicholson (1969) to be over 37,500 feet. Battan (1966) points out that in addition to their higher bases and tops, Arizona thunderstorm cells must reach greater altitudes than their humid-area counterparts before precipitation is produced naturally. An average 5-mile diameter was indicated for individual thunderstorm cells in the Flagstaff area by radar echo and cloud data of Davis, Kelly, Weinstein, and Nicholson (1969) and in cellular isohyetal patterns of rainfall presented by Fujita, Styber, and Brown (1962).

Convective Storm Modeling

Before the first quantitative model of a thunderstorm described by Byers and Braham (1949) in the Thunderstorm Project, many scientists were fascinated by this dramatic atmospheric phenomenon. Resulting from this fascination, attempts were made to create descriptive models which depict the thunderstorm. Over six different models appeared in the literature during the early 1900's. Ludlam (1963) gives an excellent account of these early descriptive models.

A few years after the classic work on thunderstorms by Byers and Braham (1949), two additional quantitative models appeared in the literature, one by Wichmann (based on observations of cumulonimbi by sailplane pilots over Germany) and one by Faust, who applied the findings of the Thunderstorm Project to a model developed by Koschmieder some ten years earlier.

Interest in the severe storms of the Great Plains increased during the 1950's, and data from these hail-producing giant cumulonimbi became available for analysis. Separately, four quantitative models of these giant convective storms were developed by four researchers, Fulks, Newton, Dessens, and Ludlam. Culminating these efforts were a Meteorological Monograph with sections on the dynamics of severe convective storms by Ludlam (1963) and Newton (1963), and a Cambridge Press publication by P. Squires (1962) on the dynamics of clouds.

The stage was almost set for the development of a numerical model of a convective storm. Second- and third-generation digital computers appeared on the scene during the 1960's, and research in cloud and precipitation physics produced the needed elements for such a model. Braham (1968) describes the extreme complications of combining knowledge from cloud dynamics with that from the microphysics of clouds in order to produce a realistic model of a precipitation-producing convective storm.

At the initiation of this project, in 1968, the writer, after surveying current literature, wrote to the leading researchers in the relatively new fields of cloud dynamics and precipitation physics in order to assess the current state-of-the-art in numerical modeling of convective storms. Three numerical models were discovered, all of them in relatively early stages of development.

The first, a computerized model for precipitating cumulus towers, was developed by Simpson and Wiggart (1968). This model combined work of many researchers over several decades, as diagramed in Figure 2. The model had been used successfully in working with tropical cumuli over warm ocean areas.

The second computer model, developed by Liu and Orville (1968), describes the growth and development of cumulus over idealized mountains. Again, this model incorporates research results of many scientists over a long period, as represented in Figure 3. This complex model requires a computer with a large core memory for its processing.

The third, a parameterized numerical model of cumulus convection, was developed by Weinstein and Davis (1968) at Pennsylvania State University. This model had been simplified slightly and then used operationally in the Flagstaff, Arizona, summer thunderstorm study described by Weinstein and MacCready (1969).

Because of its operational level of development and application to the more simple arid-region convective storms, the Weinstein-Davis Model was selected for further study and testing in conjunction with this project.

The Weinstein-Davis Model of Cumulus Convection

The model, described in general terms by Weinstein and MacCready (1969), is a steady-state Lagrangian solution of the equations used by Davis (1965), along with the cloud microphysics parameterization developed by Kessler, Feteris, Newberg, and Wickham (1962-1964). The thermodynamic and dynamic calculations are numerical analogs of the classical parcel method with entrainment. The equations that are used are a version of the first law of thermodynamics and the vertical equation of motion. The entrainment concepts of Strommel (1947) are included in the calculations in a manner similar to that employed by Simpson, Simpson, Andrews, and Eaton (1965).

The cloud microphysics calculations partition the liquid water in the updraft into cloud water, Q_c (liquid water contained in small droplets), and hydrometeor water, Q_h (liquid water contained in precipitation-size droplets). Cloud

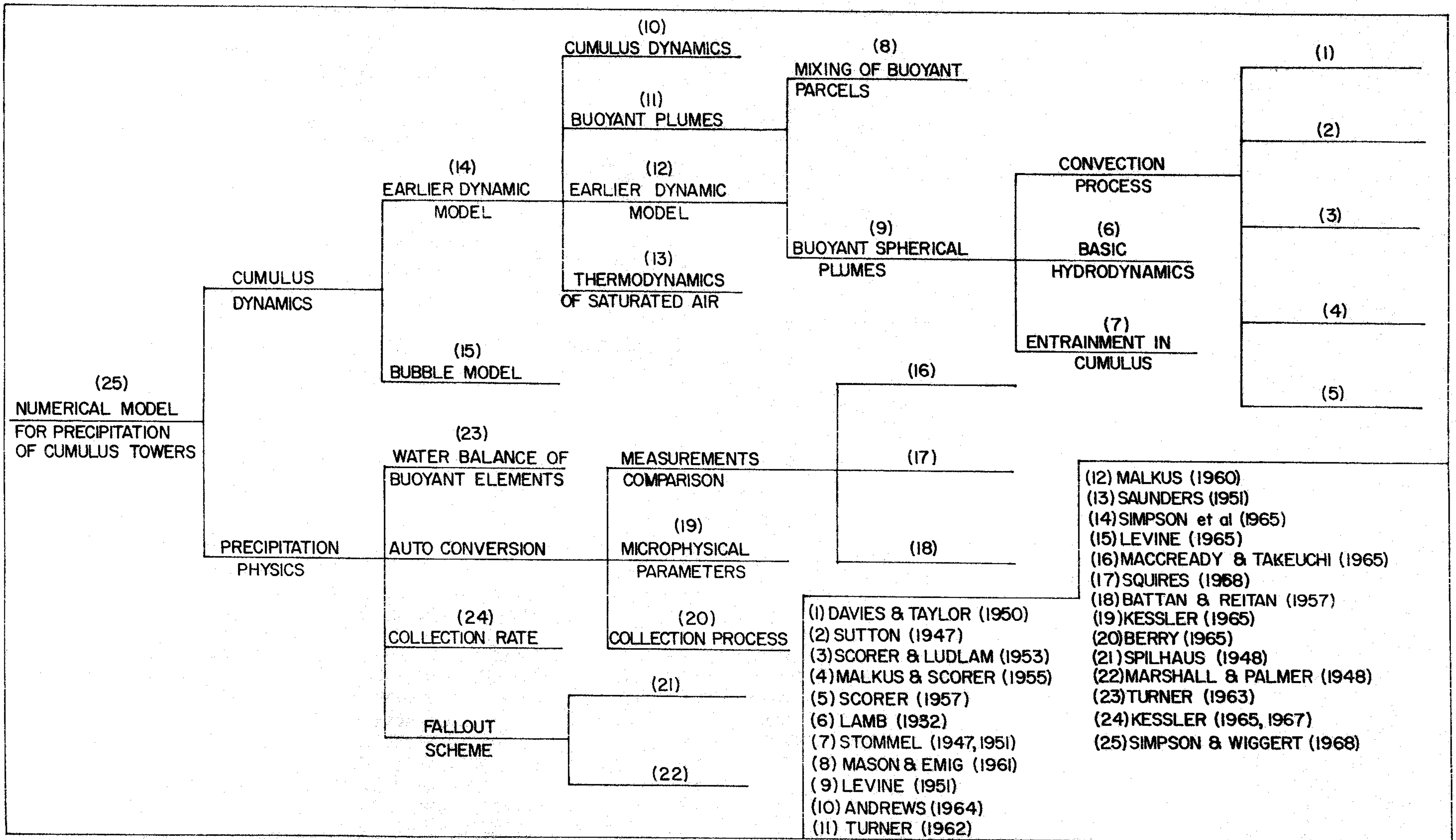


FIG. 2 FLOW OF RESEARCH BLENDING INTO A NUMERICAL MODEL FOR PRECIPITATING CUMULUS TOWERS DEVELOPED BY J. SIMPSON AND V. WIGGERT

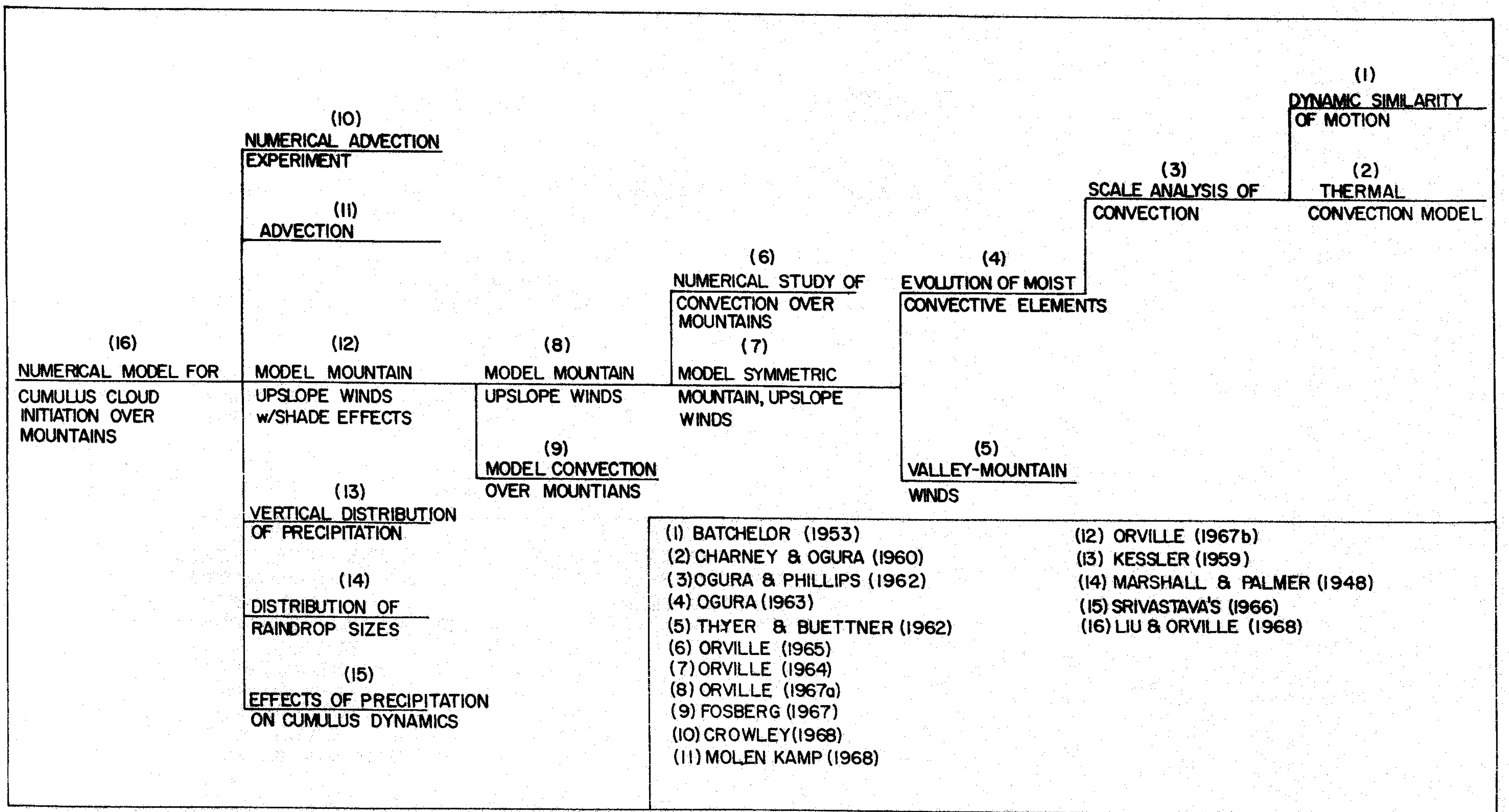


FIG. 3 FLOW OF RESEARCH RESULTS BLENDING INTO A NUMERICAL MODEL FOR CUMULUS CLOUD INITIATION OVER MOUNTAINS BY J.Y. LIU AND H.D. ORVILLE

water is produced directly from condensation and is transformed into hydrometeor water via conversion and collection. As these processes continue, hydrometeor water accumulates in the computer-generated cloud, and the final output of the program is accomplished by allowing all of the hydrometeor water to fall to the base of the cloud constituting the total rainfall. The time which it takes for the hydrometeor water to accumulate at the base of the cloud is the duration of the rainfall. A complete description of the Weinstein-Davis model is given by Weinstein (1968).

A schematic representation of this cumulus convection model is shown in Figure 4, with the inputs on the left-hand side. The inputs consist of cloud parameters and an atmospheric sounding, that is, pressure, temperature, relative humidity, and wind speed--all as functions of height-above-the-surface. The cloud parameters are discussed in detail below. Program calculations shown in the center column include first, the interpolation of the sounding into increments for detailed processing, layer by layer; second, the thermodynamics, including the section that calculates the latent heat conversion into kinetic energy; third, the cloud microphysics; and fourth, the cloud dynamics--all of which feed into the output calculations, listed on the right-hand side of the figure. The key outputs, with regard to this particular project, are the rainfall amount, in inches, and the duration, in minutes. Also of interest are the cloud dimensions, that is, the height of the cloud, the radius of the cloud updraft, and the area of updraft within the cloud compared with that of sinking air outside of the cloud mass. Other outputs include profiles of various elements within the cloud mass.

Figure 5 shows some of the input cloud parameters, identified by (I) after the item. The variable input parameters, in addition to changing environmental soundings, are the height of the cloud base above sea level, the updraft radius, the proportion of mixing of environmental air with cloud air along the edges of the cloud, the temperature of ice nucleation, and certain options as to buoyancy, shear, the thickness of the layer for the calculation base, and the level within the cloud at which the calculations should begin. Key output items, also shown in Figure 5 and identified by (O) after the item, are the rainfall amount and duration, the updraft area, and the height of the cloud top--all of which can be confirmed by independent measurements in the field. Given an environmental sounding with knowledge about the cloud-base height and cell diameter, the opportunity is available to develop an estimate of expected rainfall amount and duration which in turn can be used as input to a storm model for generating an idealized precipitation field over a watershed.

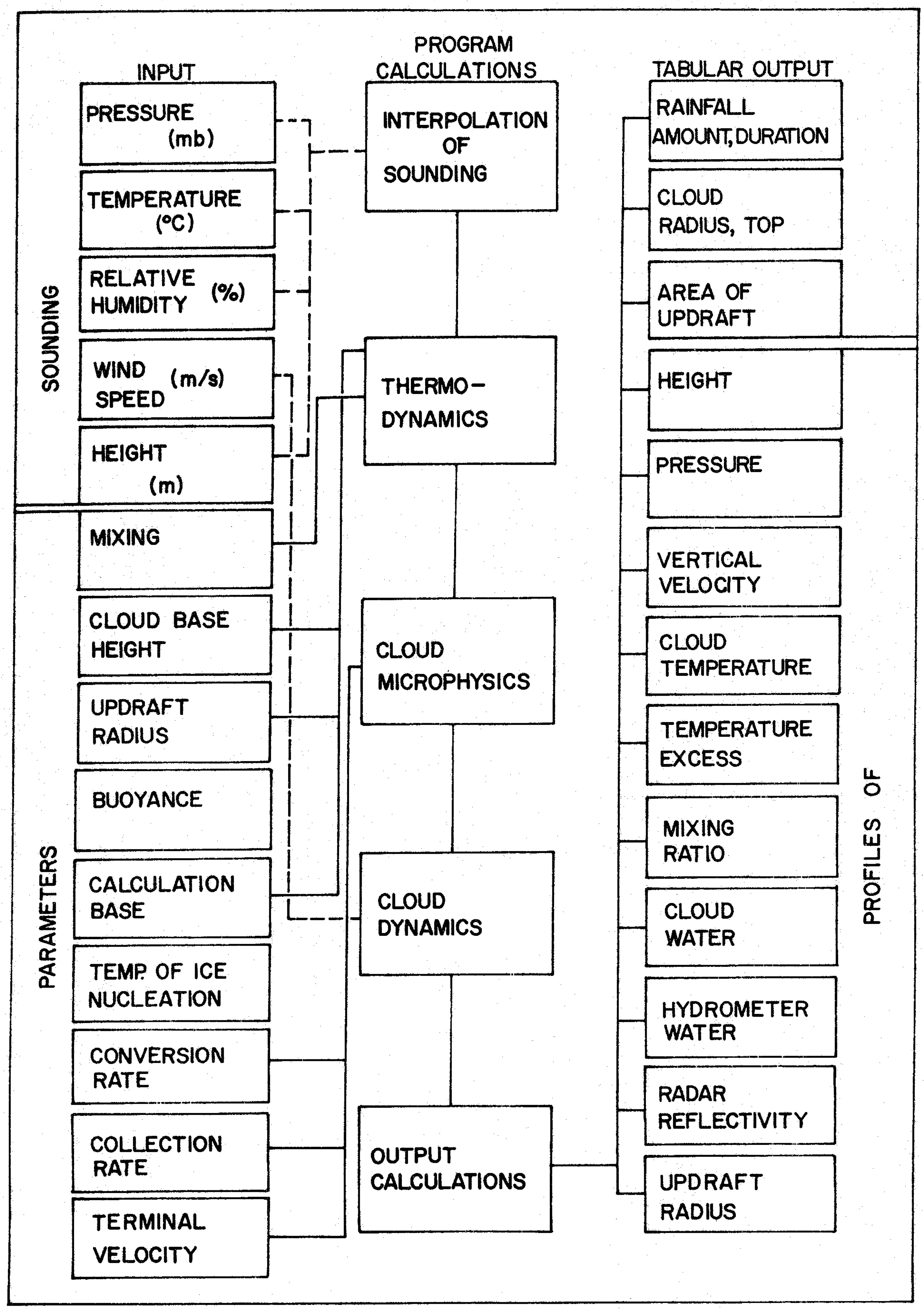


FIG.4 SCHEMATIC OF CUMULUS CONVECTION NUMERICAL MODEL

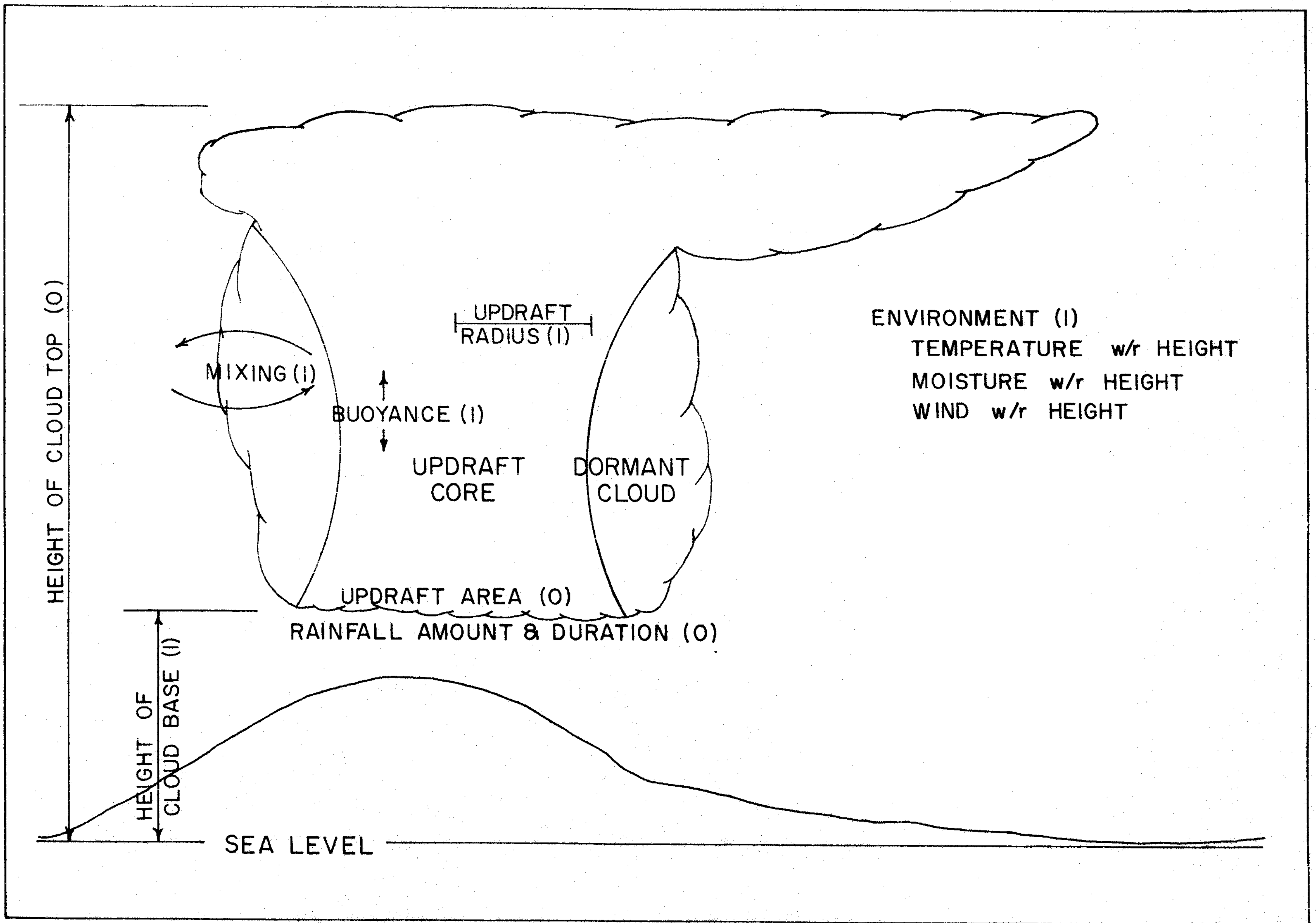


FIG. 5 CLOUD INPUT AND OUTPUT PARAMETERS FOR THE CUMULUS CONVECTION MODEL

Results of Testing the Model

A listing of the computer program for this parameterized cumulus model was obtained from Dr. Weinstein, currently employed at the Meteorological Research Inc. in Altadena, California. His computer program was adapted by A. Michael Brown for use on the IBM 7044 located at Davis, California. A test of the model was made using data from the Flagstaff project, gathered on the 10th of August 1967. Having been convinced that the model was working properly, a series of tests on data gathered from various locations in the Southwest was begun.

To facilitate testing of various data with the model, a form was made up to aid in keeping track of the selected options and values of the parameters used as input to the model. For a particular test case, the options and values for the parameters were coupled with a synchronous atmospheric sounding from the nearest reporting location and were fed into the computer.

Storms which had occurred over the Walnut Gulch Watershed, near Tombstone in southeastern Arizona, and over a watershed near the Alamagordo Reservoir in eastern New Mexico were of particular interest. Some detailed rainfall data were available for these two watersheds through the Southwest Watershed Research Center of the Agricultural Research Service, located in Tucson, Arizona, an agency operating dense rain gage networks on both the Walnut Gulch and Alamagordo Creek Watersheds. Selected rainfall data from dense rain gage networks located on the Los Angeles County Flood Control District watersheds and the San Dimas Forest and Range Experiment Station Watersheds were also available.

Table 1 contains the output from the Weinstein-Davis convection model, giving values of the amount of rainfall in inches and the duration of rainfall in minutes in the columns following the location and date of various storm cases. Numbers in the Remarks column refer to values of the cloud base height and updraft radius used for the case being considered. In the columns on the right-hand side of the table, listed under measured rainfall, is a column indicating the type of thunderstorm activity, either of single thunderstorm cell or continuing thunderstorm development with cell after cell forming and traveling over the watershed. The next column shows the number of gages used in averaging the measured rainfall, with the average value shown in the next column and the average duration in the following column. The last two columns show the amount of precipitation and duration of that precipitation as measured by the gage showing the highest value for the particular storm cell. A word should be said here on the method of averaging the precipitation for a particular storm case. For the single-thunderstorm-cell event over the watershed, a five-mile-diameter area, centered on the maximum cell activity, was

TABLE 1. RAINFALL AMOUNT AND DURATION PREDICTED BY THE WEINSTEIN-DAVIS CONVECTION MODEL AND MEASURED RAINFALL FROM DENSE RAINGAGE NETWORKS.

Location	Date	Predicted rainfall			Measured rainfall					
		Convection model					Averaged		Highest	
		Amount (in)	Duration (min)	Remarks	Type	Number Gages	Amount (in)	Duration (min)	Amount (in)	Duration (min)
Walnut Gulch Watershed, Arizona										
	22 July 1964	1.36	31.7	1	Single	28	1.13	31.0	2.06	30
	31 July 1964	1.24	27.4	1	Continuing	17	.18	25	.90	15
	8 Sept 1964	.90	23.6	1	Single	20	.80	56.8	1.31	35
	11 Sept 1964	1.17	28.1	1	Continuing	19	.73	30	1.36	25
	7 July 1967	.45	16.3	1	Single	25	.39	31.2	.69	15
	10 Sept 1967	.98	27.7	1	Continuing	12	.94	25	1.47	25
Alamagordo Watershed, New Mexico										
	27 July 1965	.87	28.6	2	Continuing	13	.29	35	.61	15
	17 Aug. 1966	.57	22.1	2	Single	14	.46	44.1	.97	20
Los Angeles County Flood Control District Watershed, California										
	3 Mar. 1943	.00	0	1	Continuing	4	1.21	28.5	1.52	30
	3 Mar. 1943	.06	10.5	3	Continuing	4	1.21	28.5	1.52	30
	18 Nov. 1967	.10	10.2	3	Continuing	4	1.13	25	1.70	30
San Dimas Watershed, California										
	28 April 1948	.49	23.6	1	Continuing	5	.28	25	2.50	360

Remarks:

1 Calculated for a cloud base height of 3,000 m above MSL and an updraft radius of 4.0 km.

2 Calculated for a cloud base height of 3,500 m above MSL and an updraft radius of 2.0 km.

3 Calculated for a cloud base height of 2,000 m above MSL and an updraft radius of 4.0 km.

determined from isohyetal maps. See Figure 6. This area was used as a window through which were selected rain gage amounts to be used in the average. For cases where continuing thunderstorm cell activity occurred during the period, an individual cell was selected using a five-minute series of isohyetal maps. The center of cell activity was identified, using a five-mile-diameter area, and gages were selected to be included in the averaging. The duration for the data to be included in the averaging was based on the life-span of the selected cell.

Table 1 shows that in general the averaged measured amounts and duration of rainfall were quite comparable to the values predicted by the Weinstein-Davis convection model, especially for the Walnut Gulch watershed. In light of the many things that could cause differences between the measured precipitation and the model calculations, it is encouraging to see such close agreement between the estimates from the model and the observations.

Some of the causes of differences between the measured precipitation and the model calculations of rainfall are inherent in the model, while other differences can be attributed to the selection of input data. Some parts of the model are not completely refined, as fully admitted by the authors. A great deal more can be done in refining and developing the model further as new research produces better relationships for the dynamics of convection and for the physics of the precipitation processes. One of the current weaknesses of the model is that the rainfall is predicted at the base of the cloud. Evaporation of rain in the sub-cloud air is therefore not considered, and this is reflected in the generally smaller amounts of measured rainfall compared to the predicted amounts for the cases shown in Table 1. Davis, Kelly, Weinstein, and Nicholson (1969) suggest evaporation below the cloud base and storage of water in the anvils of deep cumuli as reasons for differences between predicted and measured rainfall in their tests of the convection model on thunderstorms in southern Arizona.

Looking at the input data used for the model, the atmospheric sounding is a key item. Since soundings are taken regularly only at rather widely scattered locations, the nearest sounding station was selected for each watershed area as follows: Tucson, Arizona, 60 miles northwest of the Walnut Gulch watershed; Albuquerque, New Mexico, 140 miles west of the Alamagordo watershed; and San Diego, California, 120 miles south of the Los Angeles County Flood Control District watersheds and the San Dimas watersheds. A second relevant point is that the morning sounding was used while most of the thunderstorms occurred in the afternoon. Synoptic weather systems over the southwestern United States are very weak and sluggish, containing light winds at most levels during the summer months

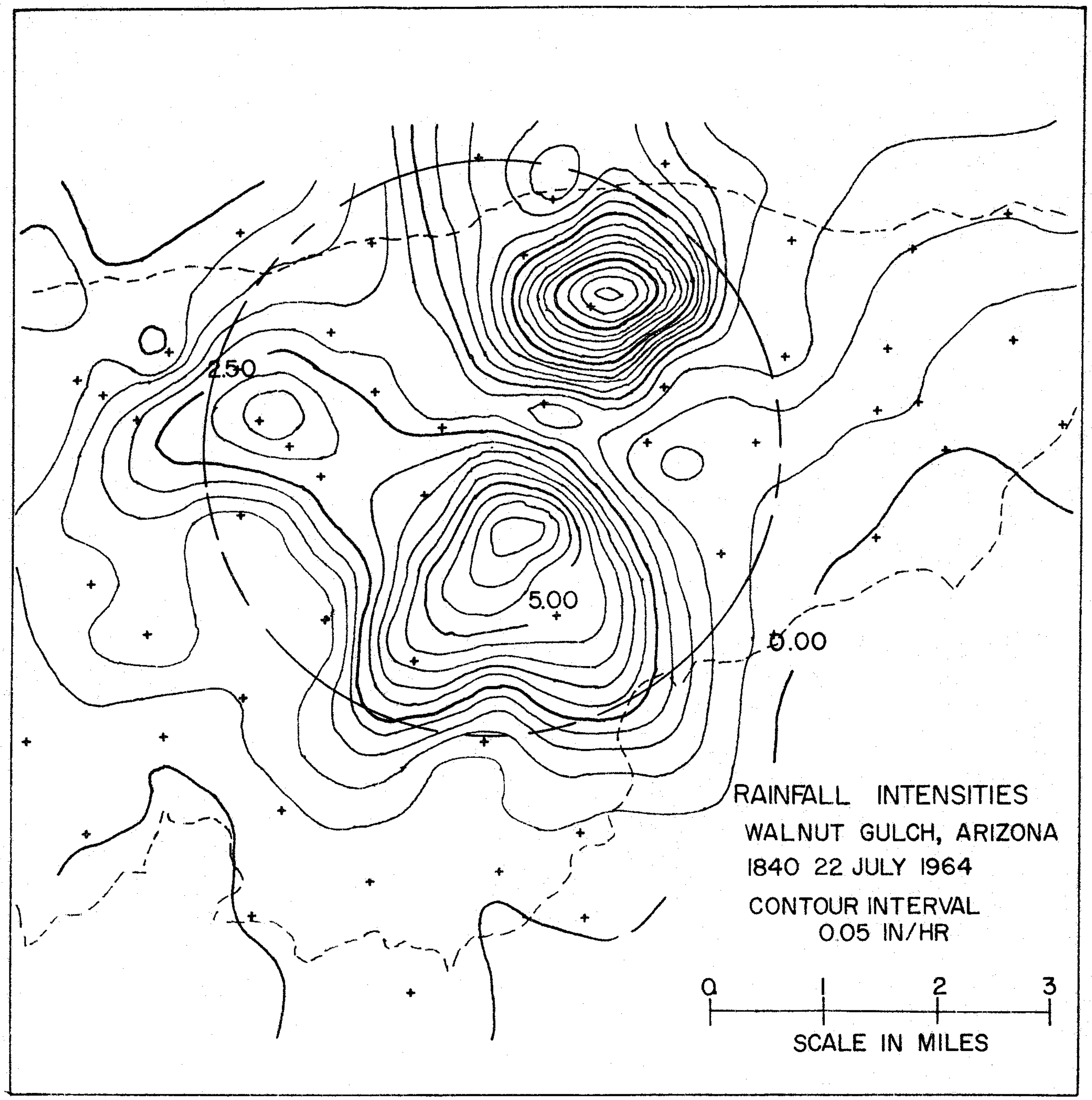


Figure 6. A typical isohyetal map showing three centers of active rainfall circumscribed by the 5-mile diameter "window" - dashed line circle- within which individual rain gage data were selected for comparison with the convective model results.

as shown in Figures 7 and 8. Thus, the Tucson soundings are very likely good representations for the Walnut Gulch watershed storms, since Tucson is relatively close and the cases are for summertime storms. The relatively good agreement between predicted and measured values for the Walnut Gulch storms bears this out. The Albuquerque soundings were perhaps less representative of the conditions over the Alamagordo watershed, as reflected in the results of the model compared to the measured data. The San Diego soundings were not representative of conditions over the watersheds in the Los Angeles area due to both distance and time factors. The three storm cases occurred during the spring and fall, when synoptic weather systems are well developed and move rather rapidly. Thus, it is not surprising that the model results are far from agreement with the measured data. An alternative to the use of the nearest single sounding would be to construct the best hypothetical sounding, making use of all relevant available data in both time and space as suggested by J. T. Tiedel in personal correspondence.

Another source of differences between the measured and predicted precipitation amounts and durations can be found in the values used for the cloud parameters and in the options selected as input data for the various cases. The mixing (entrainment) rate was selected to be .15/R, as used by Weinstein and Davis successfully in their application of the model to Flagstaff thunderstorms. The letter R represents the updraft radius, which was allowed to vary with height. The option to have the updraft support only cloud water was selected in preference to having the updraft support both cloud water and hydrometeor water. This selection was also based on the experience of Weinstein and Davis. Calculations were made from the cloud base up, as opposed to beginning at the freezing level, and with a thickness of 200 meters for the layers of calculation, again based on the experience of Weinstein and Davis. A temperature of 248°K (-25°C) was used for the temperature of ice nucleation so as to represent natural ice-forming nuclei as being the basis of the precipitation-forming process. Selected values for conversion rate, collection rate, and terminal velocities were all based on the experience of Weinstein and Davis.

The two cloud parameters that were varied in testing the model were the cloud-base height and the updraft radius at the base of the cloud. The cloud-base height for individual storms was based on the convective condensation level, on observation, or on climatology, depending on the particular case being studied. The values selected for the updraft radius were based on observations from both the Flagstaff studies and from the Great Plains storms. There is room for error in these estimates, which, again, could cause the model-predicted values to be different from the ground-measured precipitation.

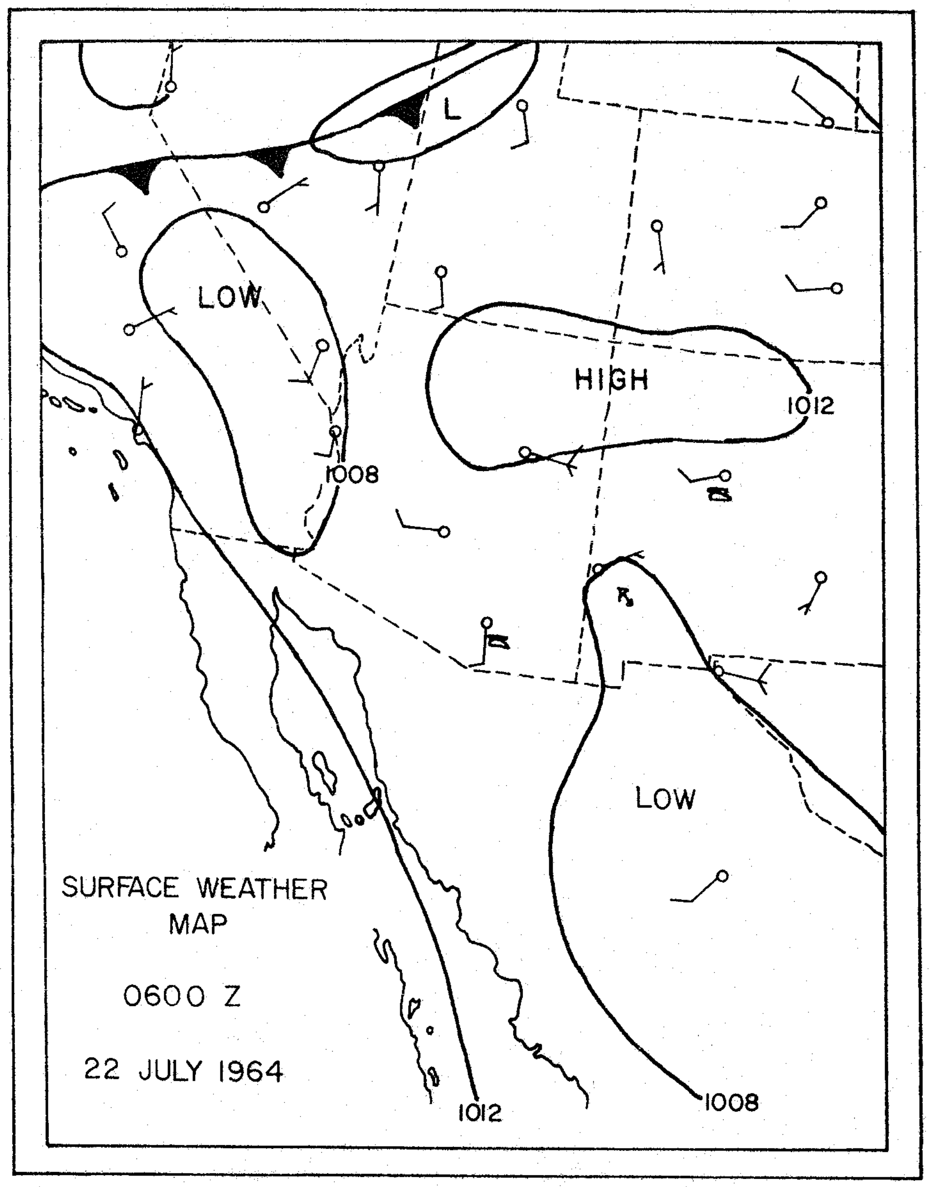


Figure 7. Summertime surface weather map showing weak winds - one full barb on an arrow shaft represents 10 mph winds.

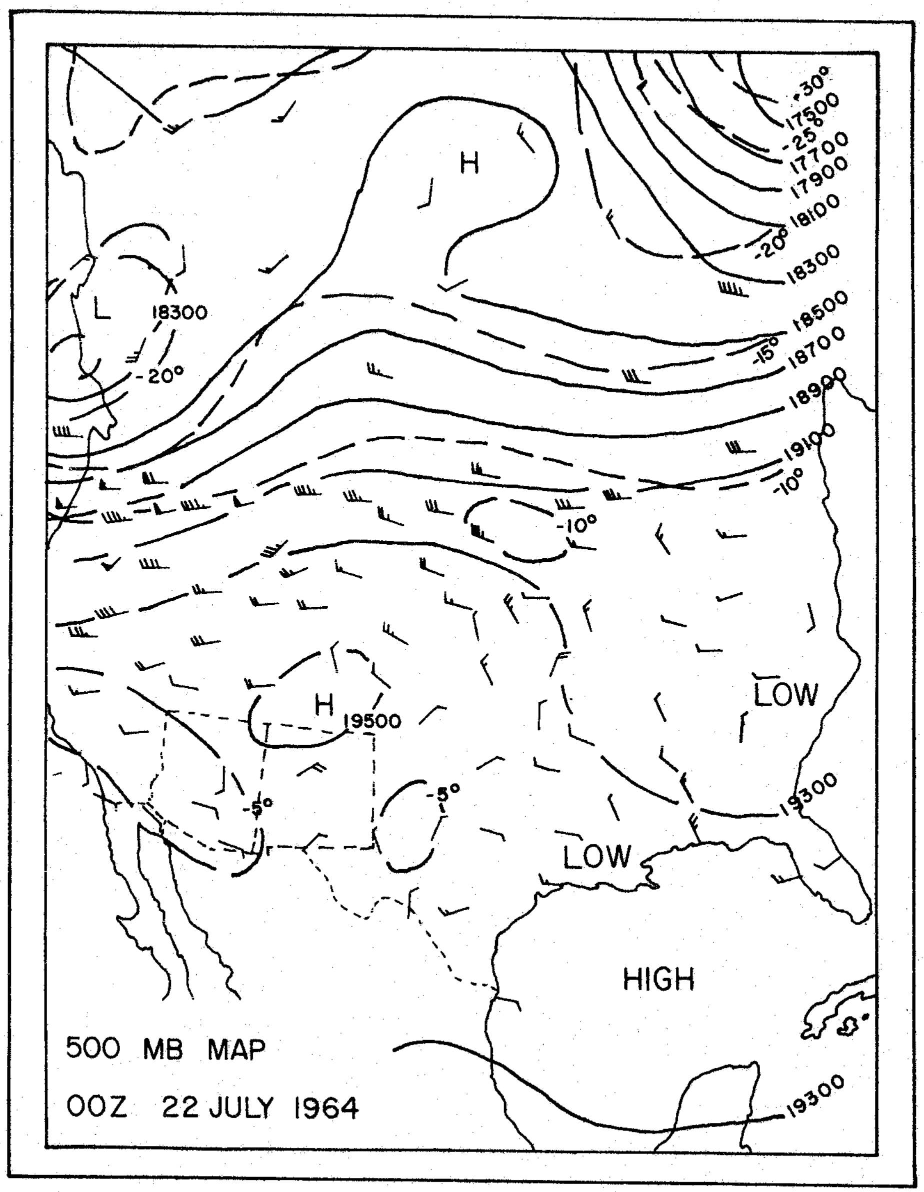


Figure 8. Diffuse temperature and pressure gradients and weak winds at 500 mb (18,000 feet above sea level) typical of summertime conditions over the United States.

A third source of possible differences could be in the measured precipitation; that is, the average rainfall over a 5-mile-diameter area may not accurately reflect the real total rainfall from a particular thunderstorm cell. Movement of the cell during the 20 or 30 minutes of its activity, very light rain on the edges of the cell, or gage distribution being such that no gages were present in the heaviest area of rainfall, could cause underestimates of the real precipitation. In the case of continuing thunderstorm cell development over a watershed, weaknesses lie in the difficulty of selecting a single cell that is not overlapped by a later-forming cell and in estimating the duration of the selected cell.

Considering the multitude of things which can cause the model-predicted values to differ from the measured values of rainfall, it is very encouraging to note how close the predicted values from the model of both rainfall amount and duration agree with the measured values for many cases, especially in the summer season. Similar results were found in tests made by Davis, Kelly,Weinstein, and Nicholson (1969) using the model to test seeding effectiveness on thunderstorms in southern Arizona. Encouraged by the reasonable results from the model, some additional experiments with the model were tried. First, thunderstorm development over the Sierra Nevada mountains of California was examined. The Las Vegas, Nevada, early morning sounding, being observed upstream of the Sierra Nevadas, was used, giving the following results. Table 2 shows the predicted values for July 22, 1969, an average day with thunderstorms, and for the special case of July 31, 1969, when flash flooding was reported in the Owens Lake area on the east side of the Sierra Nevada. The model predicts a 0.82 inch rainfall for the average day and 1.34 inches for the flash-flooding case. It was decided to take a look at the climatological atmospheric conditions for the Southwest in July and August and process these conditions through the model. It was also decided to take a look at an extreme summer case for the desert Southwest, where the possibility of flash flooding might be realized. The extreme case is one where a great deal of moisture is present in a rather unstable atmosphere. This occurs occasionally when very humid air is brought into the Southwest by a dying tropical storm. The model predicted values for single cell thunderstorms that appeared reasonable when compared with those that might be expected for climatologically average days in the Southwest and also for the extreme case.

To put the Southwest arid-semiarid general thunderstorm types in perspective, it was decided to run a Great Plains severe-weather sounding through the model. The results are shown near the bottom of Table 2, where 2.87 inches of rainfall in 36.9 minutes is indicated. The verification data on this particular Great

TABLE 2. RAINFALL AMOUNT AND DURATION PREDICTED BY THE WEINSTEIN-DAVIS CONVECTION MODEL.

Location	Date	Predicted rainfall convection model			Comments
		Amount (in)	Duration (min)	Remarks	
Sierra Nevada Mountains, California					
	22 July 1969	.82	28.5	1	Day with thunderstorms over mountains
	31 July 1969	1.34	32.7	1	Flash flooding reported near Owens Lake
Southwest: New Mexico-Arizona-California-Nevada-Utah					
	Climatological	1.22	30.7	1	
	July & Aug.	.68	23.6	2	
	Extreme-summer (moist)	1.47	33.1	3	Tropical air mass
Great Plains area					
	Severe weather Spring	2.87	36.9	4	Three-inch hail reported

Remarks:

1 Calculated for a cloud base height of 3,000 m above MSL and an updraft radius of 4.0 km.

2 Calculated for a cloud base height of 3,800 m above MSL and an updraft radius of 4.0 km.

3 Calculated for a cloud base height of 2,500 m above MSL and an updraft radius of 4.0 km.

4 Calculated for a cloud base height of 1,100 m above MSL and an updraft radius of 4.0 km.

Plains severe-weather case was the report of 3-inch hail falling from a storm that occurred in the atmosphere represented by the sounding used here. This demonstrates the completely different nature of the intense Midwest superstorm when compared to the arid-semiarid thunderstorm, using the simplified single-cell approach.

Conclusions

The Weinstein-Davis model, as tested on rainfall data from dense rain gage networks located in both Arizona and New Mexico, is a useful tool for making estimates of typical maximum expected rainfall amounts from single-cell arid and semiarid region thunderstorms during the summer months.

A possible use of this convection model would be to examine the climatological values of tropopause height, temperature and moisture distribution, and other key parameters for different regions, as suggested by L. R. Beard in a personal conversation early in the project. This information could be fed through the model, generating expected precipitation amounts and durations based on the climatological values for each set of parameters particular to various regions in the arid and semiarid west. It should be possible to determine sets of extreme atmospheric conditions which might be expected for a particular region and to determine the resulting extreme single-cell precipitation amount and duration through use of the convection model. These most extreme values could be fed into a storm model producing an extreme type storm configuration, repeating these single-cell estimates in time and space over a watershed area. A watershed model using this storm configuration could then be used to estimate values of extreme runoff as a first approximation of the complexly produced flash-flood flow.

It would be of interest to test the Weinstein-Davis model further. However, no more information is yet available from the dense networks located in the arid-semiarid west. However, as new data become available, testing of this model could continue.

Another interesting direction to pursue would be to conduct a thorough sensitivity test of the model. This author conducted, in part, such a test to see just which input elements had the greatest effect on the output of the model. Of the input elements tested, the sounding configuration, the height of the cloud base, and the updraft radius appeared to be the most effective. Concentration on these sensitive inputs could help in looking for data that would be needed to use this model in a regular operational type of program. A more thorough sensitivity check could also lead to a deeper understanding of the model itself and where possible improvements might be made as new data and research results become available.

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