Cyclones and the Atmospheric Water Cycle
A Survey of Research Objectives

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ABSTRACT

This report summarizes research focused on the problem of the water balance and precipitation regimes of extratropical and tropical cyclones. The study centers on the treatment of the cyclone in a moving reference frame so that the system is isolated from the larger scale atmospheric motion field. The extratropical cyclone analysis is based on the evaluation of the net inflow and change of storage of water vapor in the atmospheric volume encompassing the storm. The analysis leads to an estimate of precipitation, neglecting ground evaporation, which is compared to the observed precipitation. The observed precipitation following the moving storm center is obtained from hourly precipitation data. The precipitation regime that evolves is one of highly localized precipitation, even in winter time extratropical cyclones, with the precipitation areas moving within the frame of reference. An analysis of the distribution of precipitation in space and time for raingauges moving through the storm system is presented for both summer and winter cases. Finally, the rule of condensate formation is determined from the mass inflow within the cyclone system. The cyclones are shown to be an efficient system in converting condensate to precipitation (85% efficient). The distribution of condensate as a function of cloud temperature leads to the conclusion that the cyclone could be modified by cloud seeding. The tropical cyclone studies are summarized in a steady-state storm model for southeast Asia. The precipitation yield following the moving tropical storm system is determined. In addition, the computed mass curve for ground stations is evaluated as a function of station location with respect to the storm track.

CYCLONES AND THE ATMOSPHERIC WATER CYCLE

A Question on the General Circulation

On the average, the pole-to-equator temperature difference is about 60°C in winter and 30°C in summer in the lower atmosphere. We know that a sizeable fraction of this difference, as much as half or even more, becomes concentrated from time to time in middle latitudes. There the combination of a high level of potential energy derived from the raised position of the polar cold air relative to the tropical warm air and a coincident maximum kinetic energy in jet streams can lead to instabilities upsetting the balanced state of flow; e.g., give rise to the birth of great energy releasing cyclones.

The existence of the average pole-to-equator temperature difference is usually accepted as a consequence of differential heating between high and low latitudes. In a very broad sense this is of course true. Yet some of the details are of considerable interest. The differential heating is found only when the system earth plus atmosphere is considered. In the atmosphere alone, the flux of the long wave radiation to space is larger in the tropics than in high latitudes. The total north-south temperature difference would decrease by about 0.5°C/day if long wave radiation was the only active agent. Since the short wave radiation absorbed in the lower troposphere is a small factor, transfer of latent and sensible heat from the surface must sustain the almost invariant temperatures in low latitudes. Of these two processes, latent heat exchange is the largest, certainly in the tropics. The latent heat becomes available to the atmosphere as sensible heat only when condensation has occurred and when the condensation product falls back onto the earth as precipitation.

From statistics prepared in various parts of the world we find uniformly that a few synoptic disturbances are responsible for the greatest fraction of precipitation. Even in a basin as extensive as that of the Upper Colorado River (100,000 sq. mi.) 25 percent of the disturbances, or six storms in an average year, produce half of the annual precipitation (Fig. 1). The single largest storm is responsible for 10-20 percent (Fig. 2). In smaller areas, illustrated for the Kenya Highlands in Fig. 1, the statistic is even more extreme. There, 13 percent of the disturbances, or ten storms per ten years on the average, contribute half of the precipitation. Failure of a single one of these storms to appear in a given year can cause a serious dislocation of the water budget and of many aspects of life. These few precipitation systems play a major role in the maintenance of the observed global atmospheric structure. We can almost say that, on its warm side, the pole-equator temperature gradient is maintained or enhanced through a number of point rather than area sources of energy.

The Water Budget in Cyclones

Aware of the role of atmospheric storms in shaping weather and climate over sea and land through the condensation-precipitation process, various U.S. Government Agencies have sponsored research about the atmospheric water cycle at the Department of Atmospheric Science, Colorado State University. Both extratropical and tropical weather disturbances have been, and are being, explored. A convenient and indeed necessary starting point is the determination of the water budget with respect to these systems.

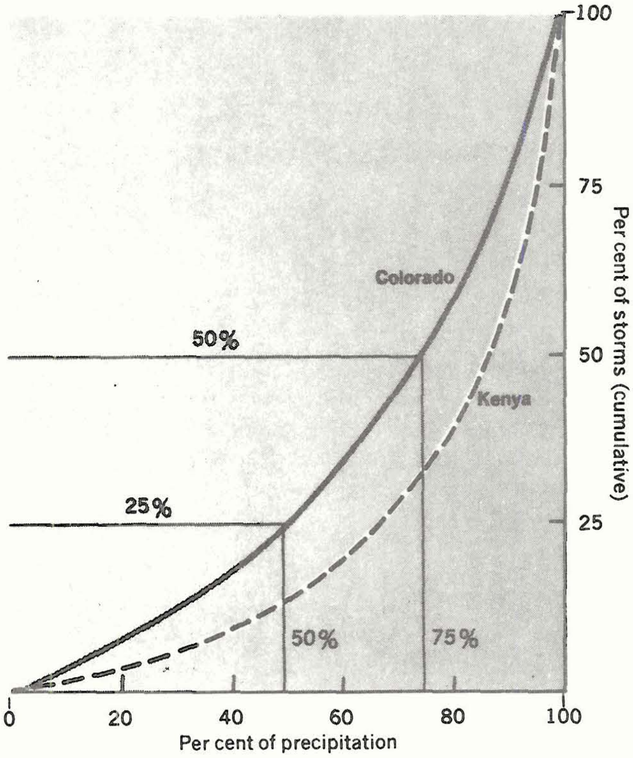

Fig. 1 Percent contribution to annual precipitation made by rainstorms in the Upper Colorado River Basin, 1930-1960. The storm episodes, numbering about 25 per year on the average, are ordered according to their water yield, from highest to lowest rank. White curve gives the same information for the Kenya Highlands.

In the past two decades water balance calculations for certain countries or continents have been undertaken by numerous researchers using meteorological upper air soundings of pressure, temperature, humidity and wind. One determines the net flow of moisture in gaseous form across the boundary of the region of interest and also the change

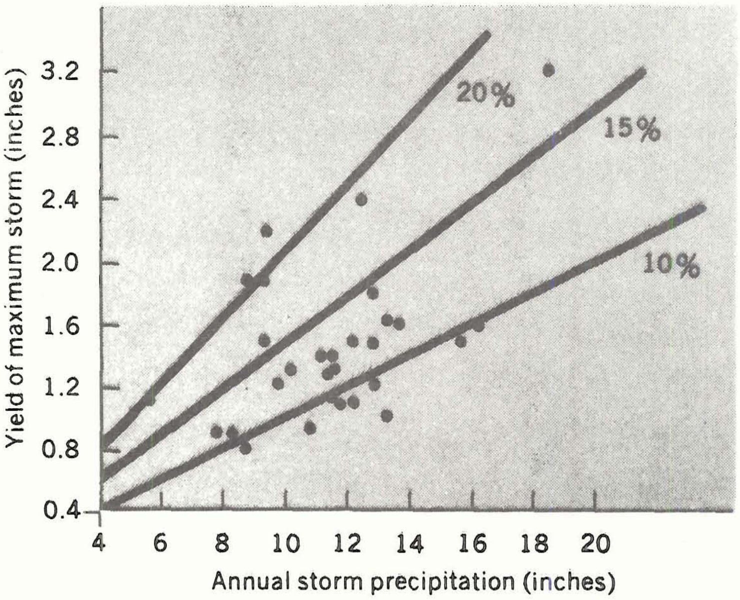

Fig. 2 Scatter diagram of annual storm precipitation against yield of largest storm in each year for the Upper Colorado Basin, 1930-1960. Straight lines give percent contributed by largest storm to annual precipitation.

in local storage in the atmosphere. Usually change in local storage is small when the time unit is the month or the year. But it may be large on individual days, especially when an anticyclone follows a cyclone with drying out of the atmosphere. The sum of inflow or outflow plus storage gives precipitation minus evaporation from the ground ($P-E_{Gr}$). E_{Gr} cannot be measured as yet satisfactorily on a routine basis; it may be estimated, from the radiational heat balance with varying assumptions or instrumentation, for instance a net radiometer over land (Renne, 1970). Assuming this estimate is reasonable, the precipitation can be calculated from the balance requirement and compared with gauge precipitation, given a dense enough network of rainfall stations and not too many complicating topographic features. For a river basin, computed precipitation, or precipitation minus ground evaporation, can be correlated with annual river runoff as done by Rasmussen (1970) for the Upper Colorado (Fig. 3), an area where gauge precipitation seriously underestimates total precipitation since the upper mountain slopes cannot be properly instrumented over such a large area. Alternately, runoff may be computed from $R = P - E_{Gr}$ as done by Renne (1970) for river of eastern Venezuela with the assumption of small net soil moisture storage and underground drainage. Calculated and directly observed runoff may then be compared.

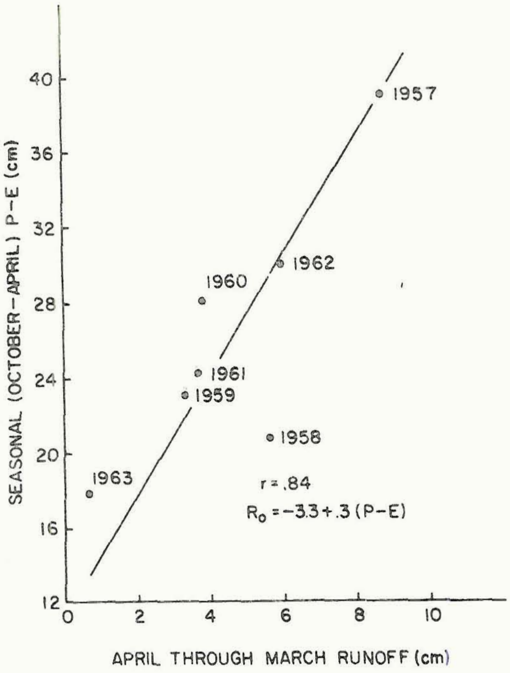

Fig. 3 Seasonal values of $P-E_{Gr}$ (October through April) for the Upper Colorado Basin against April through (following) March runoff at Lee's Ferry at the lower end of the basin. Solid line gives linear regression for the indicated years.

In applying water budget techniques to cyclones we must compute quantities such as wind and precipitation in coordinates moving with the center. For wind, the vector is subtracted from all individual wind observations around a moving boundary; such a boundary is illustrated in Fig. 4 for 18-19 February 1961 in the central United States (Rasmussen, Furman and Riehl, 1970). The wind around the boundary is divided into two terms: the components that flow through the boundary without net divergence or convergence, and the net convergence. The former may be greatly affected by the subtraction of center motion; a fast moving storm may overtake moist air ahead of

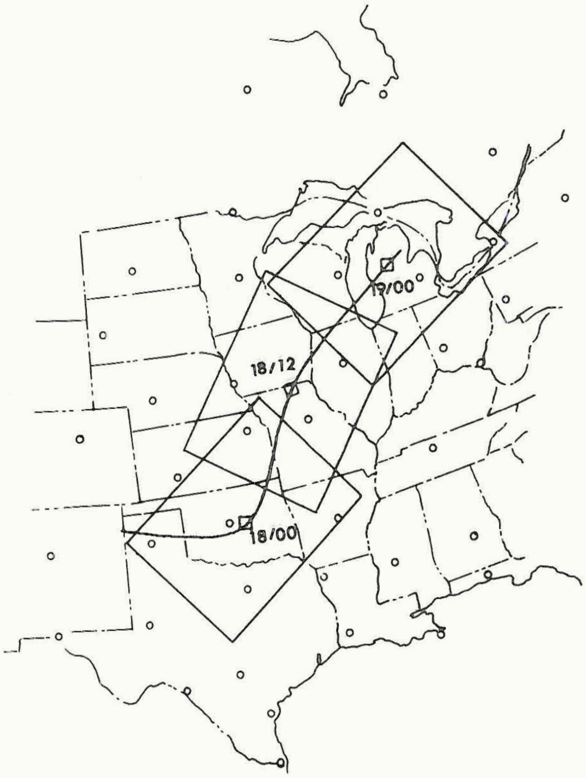

Fig. 4 Track of cyclone center in the Central United States, 18-19 February 1961 and boundary of computation area following center.

the center and leave behind dry air to its rear even though both air masses travel in the same direction as the center. The net convergence remains unchanged in relative coordinates since the storm displacement is a non-divergent vector. It is often a small component, sometimes difficult to determine with accuracy, which has been omitted in many types of calculations but which must be included as a major mechanism for moisture convergence in extratropical and tropical storms (over 80% in the February 1961 storm discussed here). Even for the large Colorado River Basin Rasmussen found that the term could not be arbitrarily excluded as originally planned; it contributed about 50 percent to total precipitation partly in connection with topographic features influencing the flow of air in the lowest atmospheric layers.

In tropical disturbances it is often accurate to say that the steady state assumption is nearly true for periods of one day; further that evaporation from the ground is an order of magnitude less than precipitation and may be omitted within computational limits. Based on these simplifying assumptions Riehl (1965) constructed a model summer disturbance over Southeast Asia. Fig. 5 shows precipitation relative to the moving system. Fig. 6 gives the instantaneous precipitation rate along a line parallel to the direction of storm displacement and passing through the center, as well as the computed accumulation, or mass curve, of water on the ground. In Fig. 7 we see the total effect of the cyclone on ground conditions after, roughly, 60 hours of disturbed weather. It turns out that the model cyclone is by no means extreme. Three to four such storms per month would be needed to account for the average monthly rainfall in the

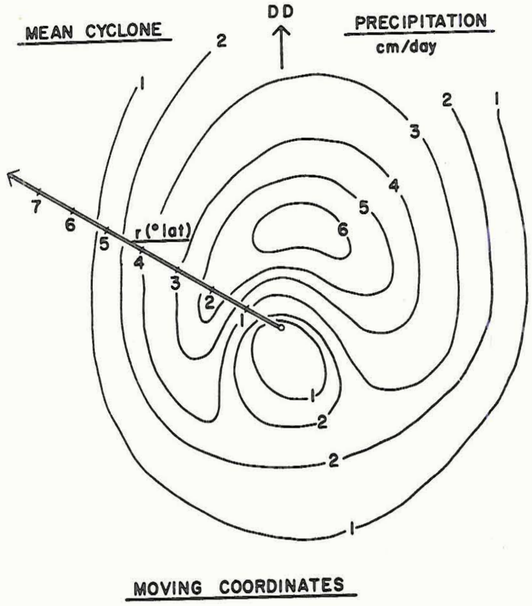

Fig. 5 Computed instantaneous precipitation rate, expressed in cm/day, for summer model storm over Southeast Asia in coordinates fixed relative to the moving center.

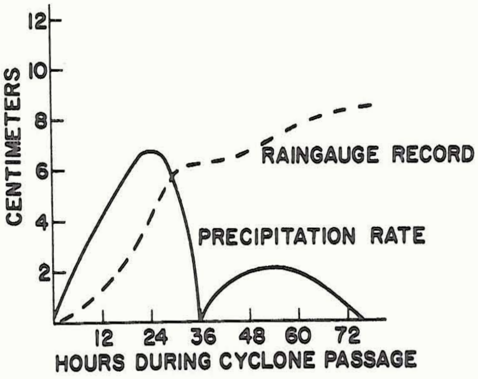

Fig. 6 Profile of instantaneous precipitation rate expressed in cm/day and weighing rain gauge trace computed from Fig. 5 for a gauge on the ground which is passed directly by the center.

Mekong River area during the wet season. In cyclones over the United States, especially in winter, the steady state assumption is not valid for a day or 12 hours even in coordinates moving with the system because of the rapid life cycle of such storms, for example, the water vapor stored in the atmosphere within the boundary depicted in Fig. 4 varied by 40 percent during the 24 hours spanning the three time periods.

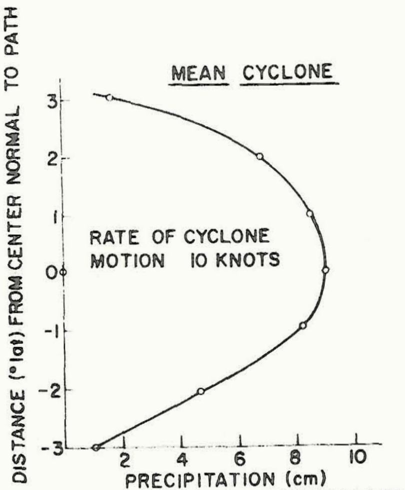

Fig. 7 Accumulation of precipitation on the ground produced by the model cyclone of Fig. 5 along a profile perpendicular to the direction of cyclone motion. Time of accumulation is approximately 2 1/2 days.

In Table I computed precipitation minus evaporation is compared with gauge precipitation (P_{Ga}) for the three computational periods illustrated in Fig. 4. Gauge precipitation in moving coordinates is obtained by letting all stations with hourly precipitation records travel relative to the moving center and thereby assigning nearly

TABLE I

Comparison of water balance results ($P-E_{Gr}$) with gauge precipitation measurements (P_{Ga}) (cm/12 hr), for the three time periods found in Fig. 4.

Date/Time	$P-E_{Gr}$	P_{Ga}
Feb. 18/00Z 1961	1.0	1.0
Feb. 18/12Z 1961	1.1	1.0
Feb. 19/00Z 1961	0.5	0.5

instantaneous precipitation rates in the mobile reference frame. These, for the three periods of Fig. 4, are shown in Fig. 8. A narrow, major band of precipitation is found initially, unlike the 24-hour isohyetal pattern because the smearing effect due to the cyclone travel is eliminated. This narrow band moves forward relative to the cyclone and even exits from the area of computation as occlusion of the warm front takes place. The band shows considerable similarity in pattern with radar PPI displays, satellite photos and some infrared radiation measurements of approximate cloud height from satellites. Our projects are experimenting with direct conversion of satellite observations to rainfall rates, using a series of charts such as Fig. 8 and corresponding information for tropical disturbances.

Table I indicates excellent agreement between $P-E_{Gr}$ and P_{Ga} suggesting that ground evaporation is smaller than precipitation by at least a factor of 10, a reasonable result over the Central United States in winter. Not all computations have yielded such close agreement; however, for nine cases so far analyzed, the average

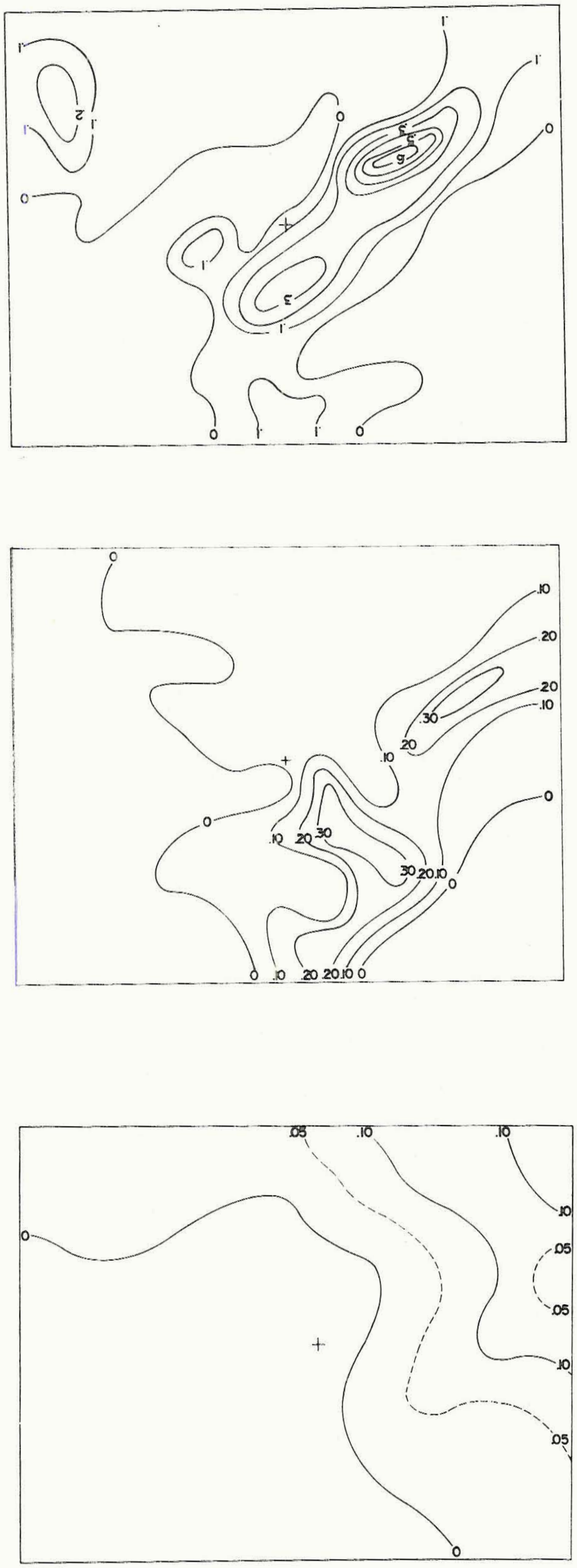

Fig. 8

Precipitation rates (cm/hr) for the three boundaries of Fig. 4. Top: 18 Feb. 1961, 00Z, middle: 18 Feb. 12Z, bottom: 19 Feb. 00Z. These are instantaneous rates in coordinates moving with the center; direction of center displacement is toward the right of the page.

difference between P-E_{Gr} and P_{Ga} was only five percent. Much larger differences are expected in summer when incoming radiation is strong and clouds are mainly cumuli so that even within a cyclone a large fraction of the area receives sunshine. Figs. 9 and 10 compare the fractional area and the time receiving various percentages of 12-hour precipitation in moving coordinates for a winter and a summer case from gauge records. The pattern of Fig. 8 is well sustained: only a small percentage of total area and time is actively producing the bulk of the precipitation. These results are set forth in Table II.

TABLE II

Area and Time percentages required to produce 50, 75, and 100% of the instantaneous total storm precipitation for winter and summer cases.

Percent Precipitation	50		75		100	
	Percent Area	Percent Time	Percent Area	Percent Time	Percent Area	Percent Time
Winter Case	11	29	21	50	65	100
Summer Case	3	5	6	15	40	60

Noteworthy are the smaller area and time percentages responsible for the precipiation in summer due, no doubt, to the exclusively convective character of rainfall. In both systems a large fraction of the area was without any precipitation. For comparison, over Southeast Asia rainfall occurred only 20 percent of the time in monsoon disturbances, and two percent of all hours accounted for half of the precipitation in moving coordinates.

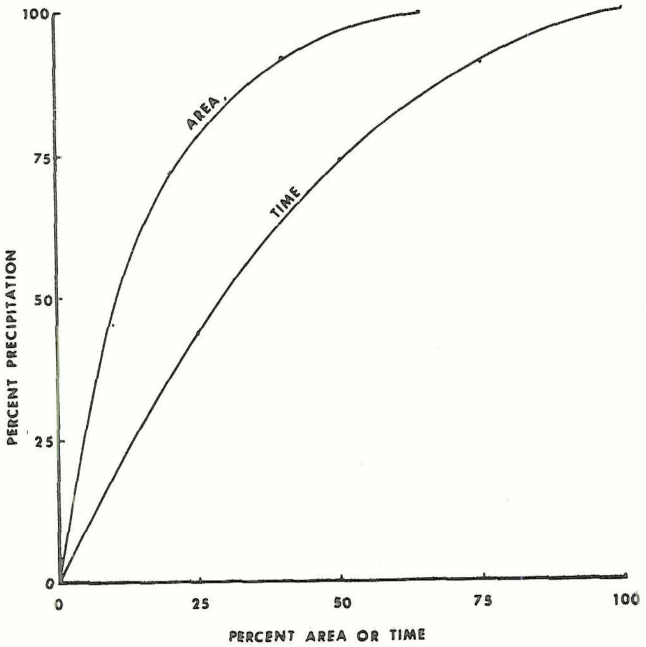

Fig. 9 Precipitation analysis for a cyclone moving northeastward in the Central United States on 26 January 1967. The precipitation is expressed in percent of total precipitation within a box 8° x 12° latitude moving with the surface center for 12 hours. The abscissa gives the accumulative percent of this area and of the time producing this precipitation.

It may be pointed out that the preceding techniques may be used also to compute ground evaporation in clear weather situations, as reported in the literature. We have not applied the method to moving anticyclones, only to fixed coordinates. Rasmussen (1970) solved a special problem for the Colorado River Basin: given clear weather after storm passage, ground evaporation should be highest on the first clear day, since the ground is wet everywhere, and then there should be a decay function as large segments of the ground dry out successively. This postulate could be verified and the decay function established (Fig. 11). Further, the calculation leads to identification of weather patterns particularly conducive to high evaporation and a quantitative estimate of the amount of river runoff lost in such cases, especially in spring (Rasmussen, 1968).

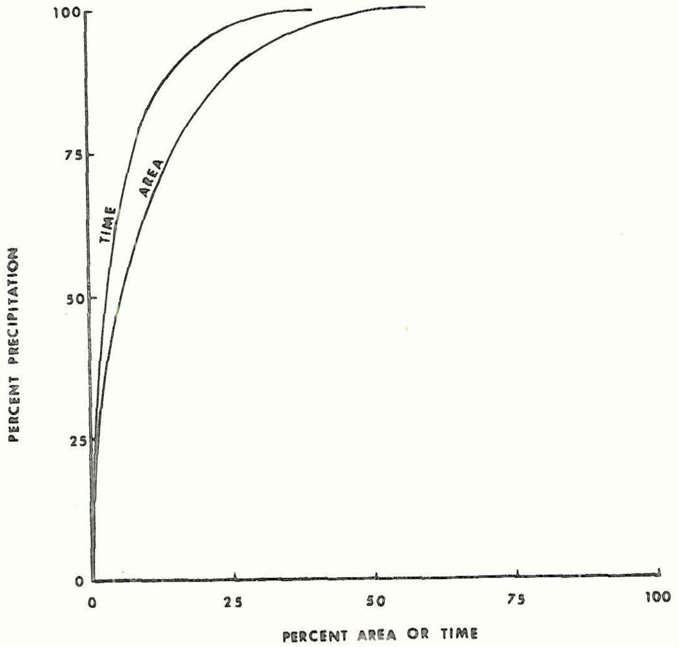

Fig. 10 Precipitation analysis for a stationary area around Oklahoma City but of about the same size as that in Fig. 9, for a 12-hour period centered on 23 July 1966, 1200 GMT. Coordinates as in Fig. 9. Cold front passed during the period.

Conversion of Latent Heat to Kinetic Energy

We saw initially that, in the general circulation sense, condensation heating sustains the pole-to-equator temperature gradient to a large extent. The condensation occurs mainly in a few synoptic disturbances (Fig. 1). Nevertheless, it is often difficult to find an immediate transformation from latent heat to kinetic energy in

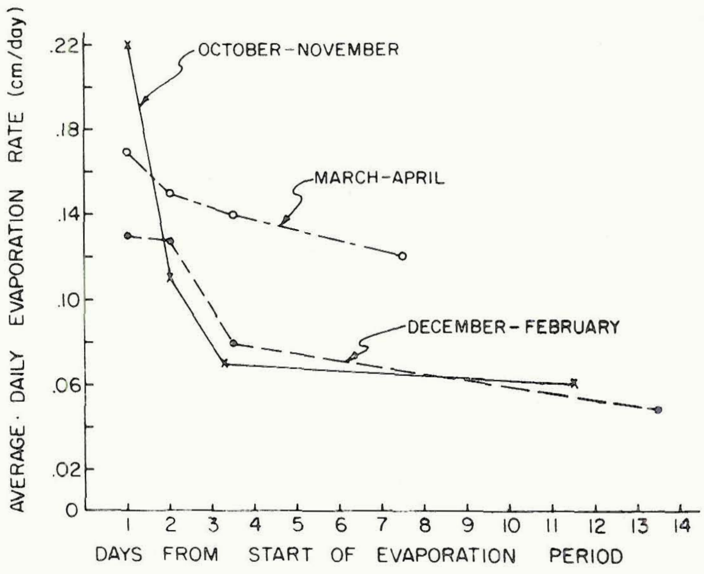

Fig. 11 Decay of evaporation rate with time on clear days following rain episodes in the Upper Colorado Basin.

these storms. An exception is the hurricane where the warm interior is mainly produced by condensation heating. In extratropical storms of winter the vertical stratification is absolutely stable except where thunderstorms break out along fronts, so that vertically rising air would arrive level for level with lower tenperature than previously present. Of course, one must consider the ascent along sloping surfaces, sometimes volumes, of constant equivalent potential temperature (Θ_e) along which the rising motion would take place, given conservation of energy in the ascending air.[1/] Even along these

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[1/] True only for non-turbulent flow without mixing. The fact that Θ_e-tube analysis tends to give good results in extratropical cyclones suggests that mixing is a minor effect there. See Belts (1972) on Θ_e-tubes in tropical convection.

inclined surfaces the condensation would have to produce warming with time in the moving coordinate system, if the temperature gradient across the cyclone and therewith its kinetic energy was to intensify from condensation heating. Some cyclones develop real outflow anticyclones or at least strong anticyclonic bulges of the high-tropospheric flow over them that can be traced to moist ascent of air with high equivalent potential temperature. In Fig. 12 we see that the mass ascent leading to the banded precipitation pattern of Fig. 8 (top) is concentrated along the 315°K equivalent potential isotherm which also outlines the upper flow pattern. This occurred in the Midwest; very

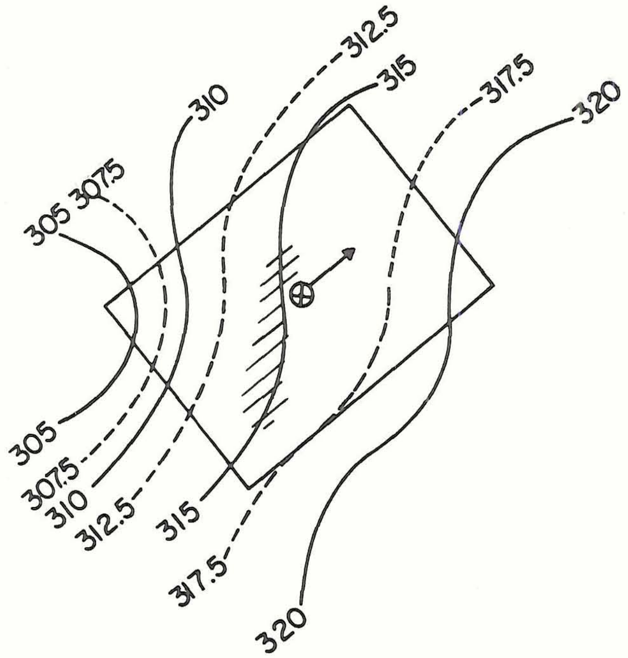

Fig. 12 Field of equivalent potential temperature (°K) at 500 mb, 18 February 1961 (see Fig. 4). Area with heaviest precipitation rate shaded (Fig. 8, top).

sharp upper ridges are sometimes found above incipient east coast secondary cyclones, not always obvious from the synoptic analysis because the upper air data stop so abruptly at the coast. When the event occurs far enough west to be fully visible one has the impression of attempted hurricane formation over land.

Moist-adiabatic ascent, as incorporated into some present-day numerical models, furnishes a substantial advance over earlier dry models in which cooling aloft inevitably followed dry-adiabatic ascent in a stable atmosphere. Yet there is a long way to go before the role of the condensation process in cyclones is completely understood and taken into account. We are computing energy release by considering the vertical mass flux in sheets, rather, tubes, of equivalent potential temperature. By integrating over the cyclone mass a rather complete picture of the energy transformations leading to generation of kinetic energy emerges, including the contribution of latent heat release. The efficiency of this release is very small, on the order of a few percent at most, when production of kinetic energy is expressed in percent of total latent heat release. A different picture results if the portion of latent heat release merely used to hold the atmospheric temperature field in steady state is excluded; we plan to experiment with this type of approach.

One of the interesting results of the computations is the observation that the descent required for the mass in some of the equivalent potential temperature tubes can take place only if evaporation from falling precipitation lowers the temperature inside these tubes; the temperature following the tube then is somewhere between dry and moist adiabatic. It becomes apparent that the moisture cycle within the atmosphere itself requires further refinement of analysis, as briefly introduced below.

Cyclone Modification Potential

In general, a dense network of recording rain gauges will give a reasonably close approximation to storm precipitation. The same cannot be said about the total condensation product except when the cloud bases are only a short distance above the ground. In Colorado, east of the Rockies, where the cloud bases are 7,000 - 10,000 feet above the surface in summer and relative humidity in the atmosphere underneath is low, precipitation at cloud base may be double that recorded in rain gauges, according to a well known hydrologist. This statement is readily believable from moisture balances within the atmosphere. However, such computations yielding the "condensate" -- as contrasted to the "precipitate" -- are difficult to achieve; as yet the sample of cases analyzed can be numbered on the fingers of one hand. We are determining the condensate (C) from the mass flow plus humidity and temperature structure in the tubes of equivalent potential temperature. Then $C-P = E_{Air}$, the "evaporate" within the atmosphere, to be distinguished from the evaporation from the ground (E_{Gr}) discussed earlier. A complete checkout of this statement is a difficult task, at times within the error limits of the observations. Not only must the total moisture budget succeed, but the water to be evaporated must be available where tubes of equivalent potential temperature slope downward. This means upper ascent with condensation above lower descent, such as may happen chiefly to the rear of slow moving cold fronts. There water falling out from an upper tube can drop into and evaporate in a lower one, in polar air. Moisture content of this air will rise with time and temperature is kept down against heating from the ground and from the upper air turbulence. The importance of this evaporation process for cyclones, first noted for waves in the tropical easterlies, is being studied by us. A contribution to cyclone energy may be found from the condensate-evaporate system since it upholds and may increase the temperature gradients in contrast, for instance, to heating of cold air over warm ocean currents which reduces the temperature gradient and thereby acts to decrease cyclone energy.

In Table III we see the results of the internal moisture cycle calculation for the three periods of Fig. 4. Substantial evaporation within the air (40 percent of the condensate) occurred only in the first period when the center was in the south and the principal band of heavy precipitation extended through the center (Fig. 8). The results of the latter periods show practically equal condensation and precipitation rates with differences within the margin of error of the calculations; they may be taken to indicate merely that evaporation within the atmosphere was small.

The energy transformations, as influenced by the condensation-evaporation processes within the atmosphere, also give some information on possible approaches for modification of storms with cloud seeding techniques. In Fig. 13 we see the distribution of condensation product in percent of total condensation as a function of temperature in 10°C class intervals. In the first period nearly all condensation occurred

TABLE III

The totals of units of condensate C, precipitation computed using water balance P, gage precipitation P_{Gr} and evaporation in the air E_{Air} (cm/12 hrs) for the three time periods found in Fig. 4.

Time, February, 1961	C	P	P_{Gr}	E_{Air}
18-0000Z	1.4	1.0	1.0	0.4
18-1200Z	0.9	1.1	1.0	-0.2
19-0000Z	0.6	0.5	0.5	0.1

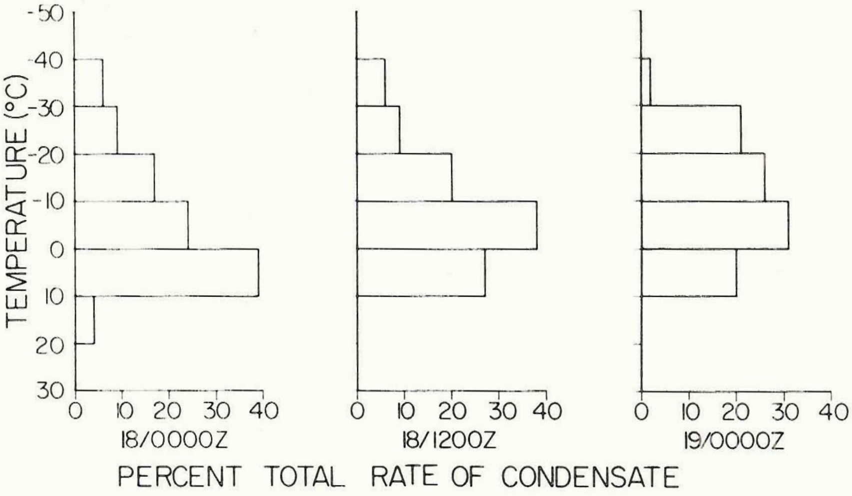

Fig. 13 Percentage of total condensate occurring in 10°C class intervals of cloud temperature, 18-19 February 1961.

at temperatures warmer than -20°C and much of it above freezing. Subsequently, condensation shifted progressively to lower temperatures. If we assume that only freezing nuclei active at -20°C or lower are present and that ice crystals from above do not fall out widely into the narrow main ascending current, then a contribution to the buoyancy of the ascent and to upper warming relative to the cyclone center can be made by introducing freezing nuclei active close to the freezing point. A change may also occur in the total precipitate, if the fall-out pattern is altered.

The scheme of seeding suggested by Fig. 13 is presently seen as the only one that might produce an alteration of cyclone structure. Whether or not it is an important one can be tested with computer modeling of the complex internal moisture transformations in cyclones, given various initial conditions of the ratio P/C under natural conditions.

This ratio can serve as an index describing any internal moisture cycle. At P/C = 0 all condensation products evaporate before reaching the ground as widely found in the trade wind regions. At P/C = 1 all condensate falls out when there is no chance for water to evaporate on the way down, for instance in hurricane cores.

In view of the role of cyclones in the general circulation any modification is potentially a subject of considerable consequences. Our present effort is directed toward gathering further information on the frequency distribution of the ratio P/C and therewith the modification potential in storms where little or no sinking of a cold dome takes place in the middle troposphere and where therefore the moisture cycle must be mainly responsible for maintanence and deepening of the storm system.

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