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A NUMERICAL MODEL OF THE GREAT PLAINS
SQUALL LINE THUNDERSTORM

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Carl E. Hane

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GREAT PLAINS SQUALL LINE THUNDERSTORM

Carl E. Hane

National Center for Atmospheric Research*
Boulder, Colorado 80302

1. INTRODUCTION

The squall line thunderstorm of the Great Plains possesses several outstanding characteristics which warrant much investigation and explanation. For one, the squall line thunderstorm is very persistent in the sense that the individual thunderstorm either lasts a long time or creates conditions necessary for redevelopment following its dissipation. Secondly it exists in an environment characterized by strong vertical shear of the horizontal wind and pronounced dryness in middle levels. That the thunderstorm should exist under such conditions, at first glance, seems paradoxical.

However, in the last twenty-five years or so, certain ideas have been expressed to attempt to explain this apparent paradox. Newton (1950) suggested that the interaction of the strong up- and downdrafts with the environment tends to favor a downshear propagation of the system. He also reasoned that the strong shear allows for the relative inflow of potentially warm air in low levels and potentially cold air in middle levels, favorable for the maintenance of updrafts and downdrafts respectively.

Another important point is that regarding the shape of the updraft within the mature cloud Bates (1961), Browning and Ludlam (1962), and Newton (1963) have all noted that it is quite likely that the main updraft in large storms is inclined in an upshear direction through an appreciable depth of the cloud. Fig. 1 is a schematic drawing which combines and summarizes this idea and the earlier idea concerning the strong shear. Here, the two-dimensional air flow within a traveling convective storm is shown with the downdraft within the cloud coexisting just upshear from the upshear tilting updraft. Such an arrangement of updraft and downdraft allows the rain to fall from the updraft, relieving the updraft of this regarding force, and allows the rain to fall into a region which is most favorable for the production of negative buoyancy through evaporation. Because of the strong shear, the updraft is continually replenished by the incoming warm moist low-level air, and the downdraft con-

tinually sustained by the dry middle-level air overtaking the system. The downward transport of horizontal momentum by the downdraft leads to a convergent area in low levels on the downshear side of the system, resulting in maintenance of the existing updraft or generation of a new one. Thus, the system is able to convert the potential energy of its environment into the kinetic energy which is necessary for its maintenance, an idea first stated by Normand (1946).

Fig. 1. Schematic representation of the motion field within a middle-latitude cumulonimbus in wind shear (after Ludlam, 1961).

The testing of the above-mentioned ideas awaits the analysis of observations taken within squall line thunderstorms. In the meantime, a reasonable approach seems to be to use the data which is available in the immediate surroundings of such storms in specifying initial and boundary conditions for the numerical modeling of such systems. The numerical modeling of both dry and moist convection has been carried out since the early dry thermal experiments of Malkus and Witt (1959). Moisture was introduced a few years later by Ogura (1963), but these early models were beset

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with numerical difficulties which were not overcome until the mid-60's. The work of Kessler, Newburg, Peteris, and Wickham (1961-1964) in the area of microphysics of cloud and rain led to the inclusion of liquid water in these models in the late 1960's and early 1970's by Arnason, Greenfield, and Newburg (1968), Orville and Liu (1969), Murray (1970), and Takeda (1971). Srivastava (1967) had earlier included explicit treatment of cloud and rain in a one-dimensional experiment. Other one-dimensional experiments, including those of Squires and Turner (1962), Simpson and Wiggert (1969), Weinstein (1970), Ogura and Takahashi (1971), and Danielsen, Bleck, and Morris (1972) have included consideration of the ice phase in their calculations.

Attempts in the past aimed specifically at numerically modelling the squall line have been very few. Early attempts by Sasaki (1959) and also by Ogura and Charney (1962) did not explicitly treat the individual clouds and their internal circulations, but dealt with the problem on a much larger scale. More recently, Takeda has modeled what he calls a "long lasting cloud," which resembles the squall line thunderstorm in that it is persistent, but occurs under wind shear conditions unlike those found in squall line situations. More recently, Schlesinger (1972) and Hane (1972) have treated the squall line specifically, and on the cloud scale.

2. THE MODEL

The model to be presented here is two-dimensional, variations along the line being neglected. The figures which will be presented showing the model results will therefore be vertical cross-sections through the squall line. The consequences of imposing this two-dimensional restriction will be discussed in the result section.

To initiate the calculations, a disturbance is superimposed upon an environment possessing the characteristics noted in the introduction, and the appropriate physical equations are integrated numerically to study the time evolution of the system. It is the goal here that the model simulate the observed long-lasting character of the squall line through either (a) the attainment of a quasi-steady cooperative updraft-downdraft system continuously interacting with its environment, or (b) a succession of developments, each containing the ingredients necessary for redevelopment following dissipation. In addition, the effect of vertical shear of the environmental wind will be studied by variation of the shear from one experiment to another.

In the model certain physical processes and characteristics are included, while others are not. Included are: (1) the condensation and evaporation processes and their associated temperature changes, (2) liquid water "in bulk" assuming a Marshall-Palmer (1948) distribution of drop sizes, (3) the fallout of rain including variable terminal fall speeds, and (4) turbulent mixing by scales of motion not resolvable by the 400-meter grid. Not included are: (1) the ice phase, (2) horizontal and time changes in air density, (3) radiational effects, and (4) the exchange of heat, moisture, and momentum between the air and the earth's surface.

The basic model equations include time-dependent equations for the vorticity, temperature, and for the mixing ratios of water vapor, cloudwater, and rainwater. The other basic equation relates the vorticity to the stream function. The vorticity equation may be shown (Hane, 1972) to be:

$$\begin{aligned} \frac{\partial \eta}{\partial t} = & -u \frac{\partial \eta}{\partial x} - w \frac{\partial \eta}{\partial z} - \eta D_v - \frac{g}{T_v} \frac{\partial T_v}{\partial x} \\ & + g \frac{\partial}{\partial x} (q_k + q_c) + c_M \left\{ \frac{\partial}{\partial z} \left[\left| \frac{\partial w}{\partial x} \right| (u'' - u) \right] \right. \\ & \left. - \frac{\partial}{\partial x} \left[\left| \frac{\partial w}{\partial x} \right| (w'' - w) \right] \right\} + \frac{\partial}{\partial x} \left[v_x \frac{\partial \eta}{\partial x} \right] \\ & + \frac{\partial}{\partial z} \left[v_z \frac{\partial \eta}{\partial z} \right] \end{aligned} \quad (1)$$

where the vorticity $\eta = \partial u / \partial z - \partial w / \partial x$, u is the horizontal wind speed, w the vertical wind speed, $D_v = \partial u / \partial x + \partial w / \partial z$, T_v is the virtual temperature, q_k the rainwater mixing ratio, q_c the cloudwater mixing ratio, c_M the turbulent mixing coefficient, u'' and w'' time invariant vertical distributions of the horizontal and vertical motion, respectively, characteristic of the environment, and v_x and v_z the time-space dependent horizontal and vertical eddy viscosity coefficients. For a discussion of these coefficients see Hane (1972). The equation of continuity takes the following form:

$$\frac{\partial}{\partial x} (\rho u) + \frac{\partial}{\partial z} (\rho w) = 0, \quad (2)$$

where ρ is air density. A stream function may thus be defined

$$\rho u = \frac{\partial \psi}{\partial z} \quad \text{and} \quad \rho w = - \frac{\partial \psi}{\partial x}$$

leading to the diagnostic relation between vorticity and stream function:

$$\nabla^2 \psi - \frac{1}{\rho} \frac{\partial \psi}{\partial z} \frac{\partial \rho}{\partial z} = \rho \eta \quad (3)$$

A term containing the horizontal gradient in air density has been neglected here. The first law of thermodynamics has the following form:

$$\begin{aligned} \frac{\partial T}{\partial t} = & -u \frac{\partial T}{\partial x} - w \left[\frac{\partial T}{\partial z} + \Gamma_d \right] + \frac{1}{c_p} \frac{dQ}{dt} \\ & + c_M \left| \frac{\partial w}{\partial x} \right| (T'' - T) + v_\theta \nabla^2 T \end{aligned} \quad (4)$$

where T is the absolute temperature, Γ_d the dry adiabatic lapse rate, $(1/c_p)(dQ/dt)$ the latent heating or cooling rate, T'' the time invariant vertical profile of temperature characteristic of the environment, and v_θ the constant ($500 \text{ m}^2 \text{ sec}^{-1}$) coefficient of thermal eddy diffusion. The equations involving the moisture are three in number.

$$\begin{aligned} \frac{\partial q_v}{\partial t} = & -u \frac{\partial q_v}{\partial x} - w \frac{\partial q_v}{\partial z} + c_M \left| \frac{\partial w}{\partial x} \right| (q_v'' - q_v) \\ & + v_\theta \nabla^2 q_v + \text{evaporation} - \text{condensation} \end{aligned} \quad (5)$$

$$\frac{\partial q_c}{\partial t} = -u \frac{\partial q_c}{\partial x} - w \frac{\partial q_c}{\partial z} + c_M \left| \frac{\partial w}{\partial x} \right| (q_c'' - q_c) \\ + v_\theta \nabla^2 q_c - \text{autoconversion} - \text{accretion} \\ - \text{evaporation} + \text{condensation.} \quad (6)$$

$$\frac{\partial q_l}{\partial t} = -u \frac{\partial q_l}{\partial x} - w \frac{\partial q_l}{\partial z} + \frac{\partial}{\partial z} (q_l v_T) + \frac{q_l v_T}{\rho} \frac{\partial \rho}{\partial z} \\ + \text{autoconversion} + \text{accretion} \\ - \text{evaporation.} \quad (7)$$

Here, q_v is the water vapor mixing ratio and q_v'' and q_c'' are time invariant vertical profiles of the water vapor and cloudwater mixing ratios, respectively, characteristic of the environment. The turbulent mixing term, appearing in all the time-dependent equations except Eq. (7), is discussed at length in Hane (1972), as are the autoconversion, accretion, rainwater fallspeed, and rainfall evaporation expressions which are based upon the work of Kessler, *et al.* (1961-1964).

3. COMPUTATIONAL PROCEDURES, BOUNDARY CONDITIONS, AND INITIAL CONDITIONS

The time integration scheme used is a predictor-corrector scheme, which means that Eqs. (1), (3), (4), (5), (6), and (7) are solved twice during each time step. The length of each time step is variable, depending upon the magnitude of air motions, but generally lies in the 15-20 sec range. The grid distance is 400 meters in both the horizontal and vertical, while the total domain of integration varies in size from 25.6 km (horizontally) by 12.8 km (vertically) to 38.0 km (horizontally) by 12.8 km. No flow is allowed through the top and bottom boundaries. The flow through the lateral boundaries is fixed with time, and the values of other variables along the lateral boundaries are determined by an inflow-outflow condition at those boundaries. Temperature and water vapor are determined along the lower boundary by setting the anomaly of temperature and of water vapor equal to that at the next higher row of grid points (400 meters).

As was mentioned earlier, the purpose here is to study the structure and tendency for self-maintenance of the squall line thunderstorm. The problem of squall line development is another question and is not considered here. With this in mind, the form and intensity of the initial perturbation is not important, as long as it does not influence the structure of the system at later times. Various initial perturbations were tried with the result that there was a tendency toward convergence upon a common solution after an amount of time which increased as a function of the initial difference between perturbations. In the cases reported upon here, the initial perturbation is a well-developed thunderstorm-like circulation. Other cases have been tried beginning with a "dry line" type situation, where a low-level convergent zone is superimposed upon a low-level horizontal moisture gradient. In the latter case the same basic structure is ar-

rived at after two to three hours as was arrived at after a few minutes in the former case. This being the case, only the initial environmental profiles and not the initial perturbations will be shown here.

Figure 2 shows the environmental temperature and moisture profiles which were used in all the experiments to be described. The environment is quite unstable with a sharp drop in the moisture profile between 600 and 500 mb. The sounding is typical of observed soundings taken prior to squall line passage. Figure 3 shows the profiles of the environmental wind used in each experiment. The curves plotted show wind speeds relative to the earth, although the winds used in the computations are those relative to the moving disturbance. The numbers in parentheses next to each curve denote the approximate rate of motion (m sec^{-1}) of the system in each case. In practice each of these speeds is determined by finding that speed which, when subtracted from the air motion relative to the earth, renders the disturbance stationary with respect to the side boundaries throughout the period of the disturbance's existence. The wind profiles in the "moderate" and "strong" cases are within the range of those observed in nature in squall line situations, although cases with much stronger shear are not uncommon.

Fig. 2. Initial vertical distribution of environmental temperature (solid) and environmental dew point (dash-dotted).

A more detailed discussion of computational procedures, model boundary conditions, and initial conditions (excluding the "dry line" case) is included in Hane (1972).

4. RESULTS OF COMPUTATIONS

Table 1 summarizes the experiments which were run using the various environmental wind profiles. Two of the experiments (R6 and R7) were run on a larger grid for a longer period of time using the same shear distributions as were used in shorter experiments (R1 and R2, respectively).

Fig. 3. The vertical distribution of the horizontal environmental wind used in the model experiments. R1-moderate shear (solid); R2-strong shear (long-dashed); R3-weak shear (dash-dotted); R4-mixed shear (short-dashed); R5-no shear (dotted).

TABLE 1. Summary of the model experiments.

Number	Title	c	Grid
R1	Moderate Shear	10	65x33
R2	Strong Shear	19	65x33
R3	Weak Shear	7	65x33
R4	Mixed Shear	16	65x33
R5	"No" Shear	0	65x33
R6	Moderate Shear	10	96x33
R7	Strong Shear	19	96x33

All the experiments reported upon here were begun with a well-developed circulation as the initial perturbation. For that reason the most intense stage of the convective circulation is reached rather quickly. The results of Experiment R1 after about 5 minutes of integration will be described in some detail here in order that various features in the results to be presented at other times will be better understood. Fig. 4 shows the results of R1 at 5.6 min. and includes the two-dimensional fields of stream function, rainwater mixing ratio, temperature anomaly, and vertical motion. The rainwater distribution and the cloudwater outline are superimposed upon the stream function field in the top section of this figure and in each of the other cases that will be shown. The motion field at this time shows the coexistence of updraft and downdraft; the updraft exhibits an upshear tilt and the downdraft originates in middle levels located for the most part beneath the updraft. There is relative inflow from the left-hand side at middle levels, a portion of which enters into the downdraft circulation. The downdraft, upon reaching the ground,

spreads both forward and to the rear. The cloud outline shows a tilted structure also, with new development of cloud occurring on the lower right (downshear) side. The outline of the cloud on the left side follows the line of no vertical motion between the updraft and the downdraft. The upper portion of the cloud is spreading in the horizontal, mainly in the downshear direction. The rainwater pattern shows an increasing accumulation of liquid water along the left hand edge of the updraft (max. value greater than 7 g kg^{-1}). This location is favored because of production of rainwater from cloudwater in the updraft and a combination of advection by the tilted updraft with the fall of raindrops relative to the air which contains them. Rainwater reaches the ground at this time, but not in great amounts.

Fig. 4 Results of Experiment R1 at 5.6 minutes. Upper: solid lines are stream function ($10^3 \text{ kg m}^{-1} \text{ sec}^{-1}$); dashed lines are rainwater mixing ratio (g kg^{-1}); scalloped lines are cloud outline. Middle: temperature anomaly ($^{\circ}\text{K}$). Lower: vertical wind speed (m sec^{-1}).

The temperature anomaly pattern at this time shows a warm region with a maximum slightly greater than 7°C located along the axis of the updraft, due to condensational heating in the updraft. A relatively cool area exists just to the left of the warm area, extending upward from a cold region at the ground (greater than -6°C anomaly). This relatively cool region results from evaporation of rain in the downdraft. To the left of this a warm region (max. 3°C anomaly) exists, resulting from dry adiabatic warming in descending air with little or no rain in it. To the right of the updraft is a slightly cool region resulting from dry adiabatic cooling in upward moving air containing little or no condensate.

The vertical motion pattern shows the maximum upward motion to be more than 22 m sec^{-1} located at about 7 km height. The downward maximum is slightly greater than 10 m sec^{-1} located at about 3 km height. There are regions of downward "compensation" outside the cloud, located on

the right in the upper troposphere and on the left, merging with the rain-augmented downdraft, between the cloud and the left boundary.

The results of Experiment R1 are shown at 16.3 min. in Fig. 5. The most apparent change here is the lessened intensity and lack of organization in the system. At least three reasons may be given for this change in shape and intensity, and all are related to the two-dimensional constraint imposed in this model.

1) The air in the downdraft upon reaching the ground must spread either forward or to the rear, whereas in nature it can and does spread to some extent into the third dimension. Since the updraft originates at the micro-cold front at the leading edge of this cold downdraft air, the lower updraft undergoes an excessive downshear displacement. This means that in order for the updraft to maintain itself at its original intensity, it must regenerate in middle levels on its right hand side. This regeneration is prevented because

2) The downward motion in middle levels to the right of the original cloud is advecting dry air into the updraft. This downward motion is more intense than it would be in nature where some of the "compensation" takes place out of the plane of this model.

3) The strong relative left-to-right flow in upper levels must take part in the in-cloud circulation in this two-dimensional case, whereas in nature a great deal of the air must go around the cloud, since the precipitation-filled cloud must to some extent act as an obstacle to the flow (cf. Fankhauser, 1971). Thus the strong horizontal winds aloft in this two-dimensional case tend to bend the updraft in a downshear sense in upper levels, and some rain tends to fall on the right hand side of the cloud. This creates additional difficulty for the regeneration process to occur continuously in that vicinity.

Fig. 5. Same as Fig. 4 but for Experiment R1 at 16.3 minutes.

Figure 6 shows the time variation of maximum updraft speed, maximum downdraft speed, and maximum rainwater mixing ratio for Experiment R6 which is an extension of Experiment R1. During the 20-30 minute period following initiation, the flow (not shown) is quite simple. It is characterized by the forced ascent of air over the cold "dome" near the surface with essentially undisturbed conditions (little or no vertical motion) above 5 km. It is seen from Fig. 6, however, that significant redevelopments do occur centered at about 42, 59, and 104 minutes. Fig. 7 shows the variable fields at approximately 42 minutes. The structure of the motion, thermal, and rainwater fields at this time is basically the same as that shown in Fig. 4. This is also true of the developments at 59 and 104 minutes. Thus, in this two-dimensional treatment of the problem, the longevity of the system is not due to a quasi-steady state condition, but to the apparent continuous band structure of the convection, persistent because of an aperiodic regeneration.

Fig. 6. For Experiment R6(R1), the variation with time of the magnitude of the maximum upward motion (solid), maximum downward motion (dashed), and maximum rainwater mixing ratio (dash-dotted).

Referring again to Fig. 6, in the case of each development the maximum upward motion is followed by a maximum in rainwater mixing ratio and then by a maximum in downdraft speed. The interpretation here is that rain continues to be produced in the updraft even though the speed is decreasing. At the same time the rain is falling and does so at a greater rate (relative to the earth) as the updraft speed decreases. The two effects (production and falling) result in a maximum in rainwater mixing ratio which lags the maximum upward motion by about two minutes in each case. As the rain falls, the downdraft speed increases due to negative buoyancy resulting from evaporational cooling and due to the weight of the rain. Thus the maximum downdraft speed lags the maximum rainwater mixing ratio by about three minutes and the maximum updraft speed by about

Fig. 7 Same as Fig. 4 but for Experiment R1 at 41.9 minutes.

five minutes in each case. It should also be noted that there are actually two maxima in the downdraft speed (temporal maxima) during each development. First, the increase in maximum updraft speed and vertical development of the updraft is accompanied by an increase in maximum downdraft speed purely through mass compensation. This downward compensation decreases in maximum value as it spreads over a larger area during the time that the updraft is at its maximum intensity. This is followed by the concentration of this downward motion over a smaller area (in the rain area) and an increase in maximum value as rain produced in the updraft falls on the upshear side of the cloud.

The results of Experiments R3, R4, and R5 will not be shown here because they include environmental wind shears unlike those characteristic of squall line situations. However, a brief description of each will now be given. In the weak shear experiment (R3), a loss of intensity and organization occurs rather quickly in that (a) the upward motion area is narrower because of the weaker relative low-level inflow and (b) a separation of the updraft occurs more dramatically than in the moderate-shear case because of the more rapid left-to-right movement of the surface cold air relative to the mid-level updraft. Experiment R4, where the wind shear is very strong in the lowest 3 km and very weak and of the opposite sign above that level, was run in an attempt to see the effect of not having strong winds in upper levels, which in a two-dimensional experiment, have an exaggerated effect upon the upper parts of convective clouds. The result was that the upshear tilting updraft had a longer lifetime than in other experiments, and that the downdraft was considerably stronger because the rain had fallen in the same area for a long time. Experiment R5 was run with no environmental wind shear. This development most closely resembles the latter two-thirds of the life cycle of an "air mass" cumulonimbus as described by Byers and

Braham (1949). The motion is primarily upward in a non-tilting updraft in the early stages with a large accumulation of liquid water, followed by the development of a strong downdraft and the dissipation of the updraft as the rain falls out.

Experiment R2 differs from R1 in that the vertical shear of the horizontal wind is stronger in the mean than in R1, and much stronger below 3 km (see Fig. 3). The results of Experiment R2 at about 5 min. are shown in Fig. 8. The updraft shows a slight upshear tilt, but not so pronounced as in R1 (cf. Fig. 4). More rain is present ($> 9 \text{ g kg}^{-1}$) than in Experiment R1 at this time because of the stronger ($> 28 \text{ m sec}^{-1}$) and broader updraft and additional condensation. This rain, because of the more vertical updraft, remains suspended in the updraft to a greater extent than in R1 and as a result does not maintain so strong a downdraft during much of its early history. Once again downward "compensation" is fairly strong ($> 4 \text{ m sec}^{-1}$) to the right of the updraft in upper levels in the anvil outflow.

Fig. 8 Same as Fig. 4 but for Experiment R2 at 5.0 minutes.

The time evolution of this experiment is shown in Fig. 9. Once again, following the loss of organization and intensity of the first development, redevelopment occurs at aperiodic intervals (38 and 54 min.). A comparison of the time evolution of Experiments R6 and R7 (Figs. 6 & 9) reveals that the timing of the developments is nearly the same, except that the development at 95-100 min. is not present in the strong shear case due to problems along the right lateral boundary from 83 minutes on. The maximum upward motion during developments appears to be about the same on the average; however, the developments in the strong shear case are longer lasting and include broader updraft regions (as revealed by an examination of the two-dimensional fields of vertical wind speed during individual developments). As a result more rain is produced and falls to the ground in the stronger shear developments. This increased intensity with increased

wind shear is evidently due to the increased relative inflow of warm moist air in low levels that accompanies the increased horizontal system speed. Since the downshear tilting of the updraft in upper levels is due to the inclusion of strong horizontal winds from the environment, the artificial effect of the two-dimensional constraint here is to prevent a strong updraft from penetrating to high levels. The stronger development at 5 minutes in Experiment R7 occurs because the time is not sufficient for the shear to affect the structure as it does in the developments at 38 and 54 minutes. Fig. 9 also reveals that during the period of the two developments occurring between 32 and 67 minutes, the maximum rainwater mixing ratio does not decrease below 5 g/kg. If such a storm were viewed by PPI radar it would be assumed that a single development of long duration had occurred.

Fig. 9 Same as Fig. 6 but for Experiment R7 (R2). The arrow denotes the time when the maximum upward motion shifts to near the boundary.

Comparisons will now be made between model calculations and natural observations. Rainfall amounts resulting from individual model clouds passing over fixed points on the ground are approximately 0.40 inches. Horizontal wind speeds near the ground in the cold outflow behind the micro-cold front are in the 20-25 m/sec range (these should be compared with sustained winds rather than short-lived gusts which cannot be resolved with a 400 meter grid). Radar reflectivities calculated from model rainwater mixing ratios compare favorably with those measured in nature. An attempt is also made to compare the vertical temperature structure within the cold "dome" with that in a natural situation. For details of how these figures used for comparison were arrived at, see Hane (1972). Fig. 10 shows that within the cold "dome" which exists as a result of the convection, model calculations agree with observed measurements between the surface and about 1.5 km, but the observed case shows a greater total decrease in temperature (2° to 3°C

colder) between 2 and 3 km. The warmer temperatures above 1.5 km in the model calculations probably result from the moderate downward motion and adiabatic warming in middle-level dry air to the left of the cloud and rain area. This downward motion may not be so strong at this location in nature. Differences might also result from particular conditions in the observed case which was chosen.

Fig. 10 Temperature anomaly within the cold dome for Experiment R6 at 28.9 minutes (solid) and for an observed case of May 29, 1968 in Oklahoma (dashed).

5. CONCLUSIONS

Four points are worthy of note. (1) The basic structure of the in-cloud circulations arrived at in this model agrees quite well with the basic structure hypothesized in qualitative physical models in the past. (2) The effect of strong vertical shear is to increase the intensity and longevity of cloud circulations, but at the same time there is an artificial shearing off of cloud tops because of the imposed two-dimensionality. (3) The results of the calculations point to three specific areas where the third dimension is important in the squall line thunderstorm circulation. Experimentation in the future should therefore be carried out taking into account effects of the third dimension. (4) From the fact that the squall line in this model undergoes regeneration (at irregular intervals), it is inferred that once initiated such a system is self-maintaining as long as it remains within a convectively unstable air mass whose motion is characterized by moderate to strong vertical shear.

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REFERENCES

- Árnason, G., R. S. Greenfield, and E. A. Newburg, 1968: A numerical experiment in dry and moist convection including the rain stage. J. Atmos. Sci., 25, 404-415.
- Bates, F. C., 1961: The Great Plains squall line thunderstorm - A model. Ph.D. Thesis, St. Louis University.
- Browning, K. A., and F. H. Ludlam, 1962: Air flow in convective storms. Quart. J. Roy. Meteor. Soc., 88, 117-135.
- Byers, H. R., and R. R. Braham, 1949: The Thunderstorm. Washington, D.C., U.S. Govt. Printing Office, 287 pp.
- Danielsen, E. F., R. Bleck, and D. A. Morris, 1972: Hail growth by stochastic collection in a cumulus model. J. Atmos. Sci., 29, 135-155.
- Fankhauser, J. C., 1971: Thunderstorm-environment interaction determined from aircraft and radar observations. Mon. Wea. Rev., 99, 171-192.
- Hane, C. E., 1972: Squall line structure and maintenance: numerical experimentation. Report No. 72-5, Florida State University, Grants E22-19-71(G) and E22-58-69(G) from NOAA, 190 pp.
- Kessler, E., E. Newburg, P. Feteris, and G. Wickham, 1961-1964: Relationships between tropical precipitation and kinematic cloud models. Reports 1-5, Travelers Research Center, Contract DA36-039 SC 89099.
- Ludlam, F. H., 1961: The hailstorm. Weather, 16, 152-162.
- Malkus, J. S., and G. Witt, 1959: The evolution of a convective element: a numerical calculation. The Atmosphere and the Sea in Motion. Ed. B. Bolin, New York, Rockefeller Institute Press, 425-439.
- Marshall, J. S., and W. McK. Palmer, 1948: The distribution of raindrops with size. J. Meteor., 5, 165-166.
- Murray, F. W., 1970: Numerical models of a tropical cumulus cloud with bilateral and axial symmetry. Mon. Wea. Rev., 98, 14-28.
- Newton, C. W., 1950: Structure and mechanism of the prefrontal squall line. J. Meteor., 7, 210-222.
- _____, 1963: Dynamics of severe convective storms. Meteorological Monographs, 5, 33-58.
- Normand, Sir Charles, 1946: Energy in the atmosphere. Quart. J. Roy. Meteor. Soc., 72, 145-167.
- Ogura, Y., and J. G. Charney, 1962: A numerical model of thermal convection in the atmosphere. Proc. International Symposium on Numerical Weather Prediction, Met. Soc. of Japan, Tokyo, Japan, 431-451.
- _____, 1963: The evolution of a moist convective element in a shallow, conditionally unstable atmosphere: a numerical calculation. J. Atmos. Sci., 20, 407-424.
- _____, and T. Takahashi, 1971: Numerical simulation of the life cycle of a thunderstorm cell. Mon. Wea. Rev., 99, 895-911.
- Orville, H. D., and J. Y. Liu, 1969: Numerical modeling of precipitation and cloud shadow effects on mountain-induced cumuli. J. Atmos. Sci., 26, 1283-1298.
- Sasaki, Y., 1959: A numerical experiment for squall line formation. J. Meteor., 16, 347-353.
- Schlesinger, R. E., 1972: A numerical model of deep moist convection: the influence of ambient conditions and internal physical mechanisms. Studies of the Atmosphere Using Aerospace Probing/Annual Report-1971: Vol. 1, The University of Wisconsin, Grant E-230-68-(G) from ESSA.
- Simpson, J., and V. Wiggert, 1969: Models of precipitating cumulus towers. Mon. Wea. Rev., 97, 471-489.
- Squires, P., and J. S. Turner, 1962: An entraining jet model for cumulonimbus updraughts. Tellus, 14, 422-434.
- Srivastava, R. C., 1967: A study of the effect of precipitation on cumulus dynamics. J. Atmos. Sci., 24, 36-45.
- Takeda, T., 1971: Numerical simulation of a precipitating convective cloud: The formation of a 'long-lasting' cloud. J. Atmos. Sci., 28, 350-376.
- Weinstein, A. I., 1970: A numerical model of cumulus dynamics and microphysics. J. Atmos. Sci., 27, 246-255.