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September 1976 - June 1979

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ABSTRACT

A two-dimensional, time-dependent model has been developed which gives realistic simulations of many severe storm processes — such as heavy rains, hail, and strong winds. The model is a set of partial differential equations describing time changes of momentum, energy, and mass (air and various water substances such as water vapor, cloud liquid, cloud ice, rainwater, and hail). In addition, appropriate boundary and initial conditions (taken from weather sounding data) are imposed on a domain approximately 20 km high by 20 km wide with 200 m grid intervals to complete the model. Modifications have been made to the model which allow additional water vapor and heat to be added at several lower grid points, simulating effluents from a power park.

Cases have been run which depict realistic severe storm situations. One atmospheric sounding has a strong middle-level inversion which tends to inhibit the first convective clouds but gives rise later to a severe storm with hail and heavy rains. One other sounding is taken from a day in which a severe storm occurred in the Miami area. A third sounding depicts atmospheric conditions in which severe storms formed in the vicinity of Huron, South Dakota.

The results indicate that a power park emitting 80% latent heat and 20% sensible heat has little effect on the simulated storm. A case with 100% sensible heat emission leads to a much different solution, with the simulated storm reduced in severity and the rain and hail redistributed. A case in which water vapor is accumulated in a region and released over a broad depth results in slightly more rain from a severe storm.

SUMMARY

Numerical simulation of the release of effluents from power parks has focused on the excess heat and vapor interactions with severe storms. A two-dimensional, time-dependent cloud model was applied to the problem and used with three atmospheric soundings giving realistic looking model severe storms. Two of the soundings came from the High Plains (Fleming, CO, and Huron, SD), the other from Miami.

Eleven cases were run. In one case excess vapor was added instantaneously (a "one shot" addition) in a volume, to simulate the storage of vapor in the boundary layer and then sudden ingestion into a severe storm. Seven of the other ten cases allowed the vapor to be added continuously at a level consistent with tall, natural draft cooling towers. Various power park configurations and effluent rates were tested. Three control cases, in which no excess vapor and heat were added in the lower boundary, were used to compare with the "seeded" cases.

We tested the following situations: 1) a "standard" power park location in the right of the domain where there was direct inflow to the simulated storms; 2) a power park location to the left of the domain directly under the developing storms; 3) a "double strength" power park on the right; and 4) a 100% sensible heat case [normally 80% of the heat effluent was latent heat (vapor) and 20% sensible heat].

Storm development was different and was affected to varying degrees by the effluents of the power park in the Fleming case. The power park created its own dynamics which interacted with the flow of the developing storm to produce storms of different intensity. All except one of the power park cases produced less rain and hail, with the 100% sensible heat case showing approximately a 75% decrease in both rain and hail maxima. This can be directly attributed to the rapid cloud development in front of the storm, which saps the energy of the storm leading to early dissipation of the storm system. The wet cooling tower cases showed a small decrease in precipitation with a shift in the location of rainfall. The standard power park case showed less differences than any of the other cases in its rain and hail distribution. Doubling the vapor and heat flux actually decreased the precipitation slightly. One point brought out in the left park case is the earlier cloud formation if the power park is under the area where initial cloud development would normally take place.

The case of the instantaneous, "one shot" addition of water vapor to a 1 km deep lower boundary region produced slightly more total precipitation and a slight increase in updraft strength.

In the two Miami runs, the power park effluents interact significantly with a cloud developing overhead. The clouds develop more rapidly in the power park case, but never become as organized a system as in the natural case. The flow that develops does not augment the flow in the natural case. This results in a 50% decrease in the rain maximum, and a 66% decrease in accumulated rain at 174 min in the power park case. Hail develops in the storms, but hail accumulation on the ground is insignificant.

The two-dimensional model results for the Huron sounding showed that the dynamics and microphysics of one storm in the northern High Plains was affected to varying degrees by the addition of power plant effluents. With the power plant located directly underneath the area of cloud development, the cloud formed slightly earlier and ended earlier than the natural case did. The interaction of the power park effluents with the storm's dynamics produced a storm with less total precipitation. With the power park moved to a location not beneath the storm, it had less effect.

So the effects of the power park effluents on a severe storm depend on how and when they are incorporated into the storm. It must be emphasized again that the two-dimensional power park model results discussed here are from only three summertime convective situations. Further research should include a case in which the vapor and heat from a power park is trapped by an inversion and builds up before being released into a storm. Consideration should also be given to a possible winter situation in which a stable lower atmosphere could trap the effluents and later release them into a snowstorm. Also, the Huron and Miami results may not be completely representative due to the presence of a mountain in the model.

The ultimate effects of power park effluents on severe storms are not readily determined by simple additive calculations. Complex interactions occur which can only be tested through realistic numerical simulations. Careful observations of the long term climatological changes near large power plants should be maintained for long periods of time to determine the actual effects of the plants on the weather.

TABLE OF CONTENTS

1426 114

LIST OF FIGURES

1. INTRODUCTION

The primary objective of our research was through numerical simulation studies to determine the effects of excess heat and vapor from large power parks on heavy rain and hailstorms.

A two-dimensional, time-dependent cloud model has been modified to simulate the addition of heat and vapor from a hypothetical power park. The cloud model has been under development for many years and successfully applied to several convective situations. The most recent application was a simulation of a hailstorm reported by Orville and Kopp (1977).

For this study, the model was run using three types of severe storm atmospheric soundings. The first type can be classified as Type I using the classification system established by Fawbush and Miller (1954). This type of sounding generally produces a family of tornadoes. The atmospheric sounding from the well documented Fleming Storm (Browning and Foote, 1976) was used as a Type I sounding. This was a dangerous hailstorm which eventually produced a tornado in its 12 plus hours of existence.

The second sounding used can be classified as a Type II atmospheric sounding (Fawbush and Miller, 1954). The sounding used was taken three hours prior to a tornado touching down in downtown Miami, Florida (Hiser, 1967). This storm is typical of a Type II which produces a single tornadic event.

A Type IV sounding was taken near Huron, South Dakota, on a day in which severe storms occurred.

For each sounding, the total effluent from the cooling towers in the power park was calculated and inserted into the model in a cross sectional area of the park's heating and moistening volume, and is described below.

The model was run until all the precipitation had fallen or until the simulation had progressed where valid comparisons could be made. Then the model was run again using the same initial sounding except that the effluent (vapor and heat) from the power park was excluded. Several other effluent variations were also simulated. For the Fleming storm cases, three other runs were made. One involved doubling the power park concentration of effluent which, in effect, halved the area of the power park. Another involved using an effluent that was made up of 100% sensible heat, which is designated to simulate a park made up of dry natural draft cooling towers (Lee, 1978). The last case in this series involved placing the power park on the other side of the ridge. This was done to see the effects location had on storm development.

The Miami and Huron storm cases were done in a similar manner with fewer park variations. In the end, there were 10 cases that could be analyzed, in addition to a case in which an instantaneous, one-time impulse in water vapor was added over a 1 km deep region.

Results show that in most of the cases the effects of the excess heat and vapor on the severe storms were minimal, with less rain and hail occurring. The circulations of the severe storms were modified, particularly by the 100% sensible heat case, so that less severe convection resulted.

2. STORM MODEL DESCRIPTION AND MODIFICATIONS FOR THE POWER PARK

2.1 Hydrodynamic and Cloud Physics Formulation

A two-dimensional, time-dependent cloud model with 200 m grid spacing covering an area of 20 x 20 km^2 in the X-Z plane is used for this study. The model has been developed from the work of Orville (1965), Wisner et al. (1972), and Orville and Kopp (1977). Conservation equations form the basis for the model with several other equations defining certain hydrodynamic, thermodynamic, and precipitation processes.

2.1.1 Hydrodynamic equations

The hydrodynamic equations are those for deep convection and are similar to those of Takeda (1971), Schlesinger (1973), and Hane (1973). The basic equations are the first and third equations of motion, the equation of state for moist air, the definition of potential temperature and a density weighted stream function equation, and a vorticity equation. Nonlinear eddy coefficients from Drake et al. (1974) are used. A direct Poisson solver is used to solve for the stream function (Rognlie and Kopp, 1976).

2.1.2 Water conservation

The cloud physics processes are governed by the equations in Wisner et al. (1972) and the parameterization techniques of Liu and Orville (1969), Kessler (1969), and Srivastava (1967). Five classifications of water substances are considered: water vapor, cloud water, cloud ice, rain, and precipitating ice. The rain and precipitating ice consist of liquid drops and ice particles that fall with appreciable terminal velocities, while the cloud water and cloud ice particles are assumed to be small enough so that their terminal velocities can be neglected.

The interaction of the above water substances is shown in Fig. 1. Note the interaction of water substances through evaporation, condensation, melting, Bigg freezing, autoconversion, accretion, shedding, and the Bergeron process. Marshall and Palmer (1948) type distributions are used for rain, with different coefficients used for graupel (or hail).

Water vapor from the power park is added as a source term to the continuity equation for water vapor, i.e.,

$$\frac{\partial q}{\partial t} = -\vec{V} \cdot \nabla q + \nabla \cdot (K_h \nabla q) - P_R - P_I + \frac{\partial q_T}{\partial t}$$

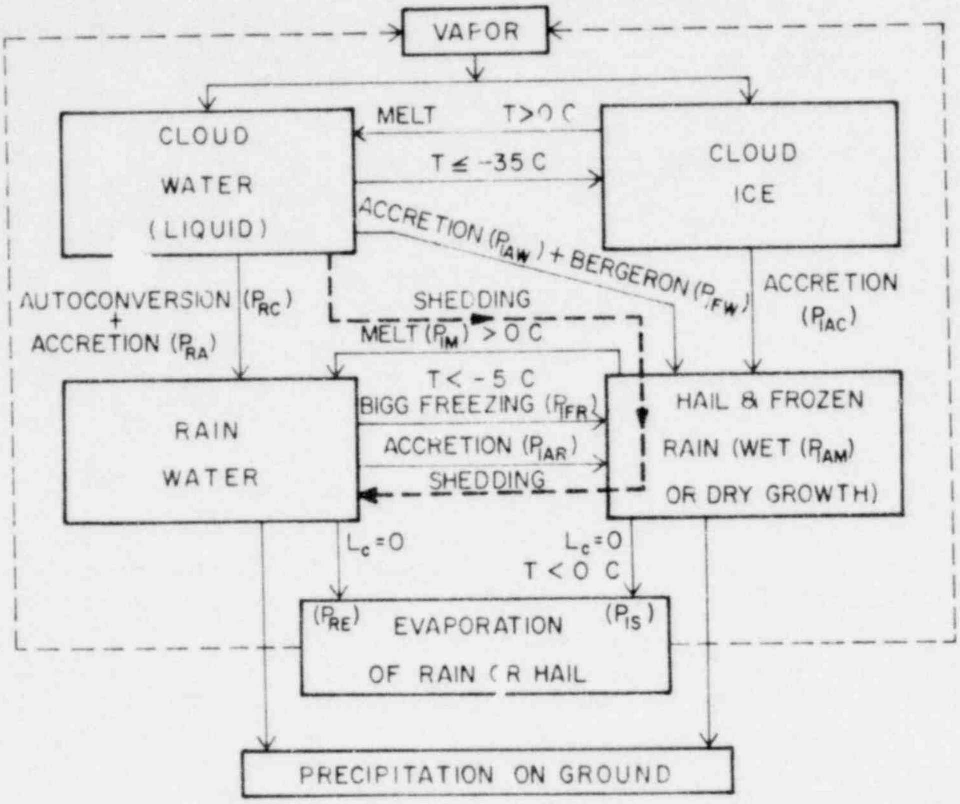


Fig. 1: Cloud physics processes simulated in the model.

where $\partial q_T/\partial t$ is the source term in g g^{-1} s^{-1} and has an order of magnitude of 10^{-6} g g^{-1} s^{-1}, q_T is the mixing ratio of the tower water vapor in g g^{-1}, q is the mixing ratio of cloud liquid and vapor in g g^{-1}, t is time in sec, $\overline{V}$ is velocity, ∇ is the Del operator, K_h is the heat eddy coefficient in cm^2 s^{-1}, P_R is the production rate of rain in g g^{-1} s^{-1}, and P_I is the production rate of hail in g g^{-1} s^{-1}. Further explanation of the equations can be found in Orville and Kopp (1977). Explanation of the source term will follow in Section 2.2.

2.1.3 The thermodynamic equation

Heat from the power park also has to be added to the model atmosphere. This is done through the thermodynamic energy equation (for an entropy related variable) [Orville and Kopp, 1977)]

$$\frac{\partial \phi'}{\partial t} = -\vec{V} \cdot \nabla\phi' + \nabla \cdot (K_h \nabla\phi') + \frac{L \partial q_T}{C_p T_{oo} \partial t} + \frac{\partial \theta_T}{\Theta \partial t} + \ldots.$$

where L is the latent heat of vaporization in ergs g^{-1}, C_p is the specific heat of air in ergs g^{-1} $°K^{-1}$, T_{oo} is a reference temperature in °K, ϕ' is the entropy variable (dimensionless), θ_T is the potential temperature of the tower air in °K, θ is the reference potential temperature in °K, and all other terms are as previously defined.

The second to last term above represents the latent heat contribution to entropy. The water vapor in this term comes directly from the power park effluent. The last term represents the energy added through the sensible heating of the air caused by the power park effluent. Further explanation of the thermodynamic energy equation, other related thermodynamic equations, and symbols can be found in Orville and Kopp (1977).

2.2 Additional Modifications to Include Power Park Effluents

The power park is an industrial park arrangement of power plants. The actual number of plants, cooling towers, park areas, and generating capacity can vary depending upon socioeconomic considerations.

The total electrical generating capacity of the power park in this study is 48,000 MWe with an overall efficiency of 33-1/3% for wet and 30% for dry natural draft cooling towers. This means that the capacity of waste energy generated is 96,000 MW and 112,000 MW, respectively. With 200 m grid spacing in an X-Z model, it is impossible to model in detail the plumes from each tower since the towers are generally 60 meters in diameter at the top. Also we are dealing with widely spaced power plants and towers which are not in a position where we could draw a single plane through each tower. We therefore assumed that the effluents from the towers are evenly distributed over the area of the power park for a depth of 200 m. For our standard park, this is a volume of 38.4 km^3 that will be receiving the heat and moisture on a per unit of time basis. A cross sectional slice is then taken of the above volume through the center of the park, perpendicular to the longitudinal axis (Fig. 2). Hopefully this minimized the edge effects associated with the mixing of the air at two ends of the park, which is the best we can do with a two-dimensional model.

Since the natural draft cooling towers receive the excess heat from the power plants and the towers separate the excess heat into forms of latent and sensible heat, a way was found to determine their respective proportions to the total heat. Dickey and Cates (1973) describe the steps necessary to determine the dry airflow through a tower and its exit wet bulb temperature, which is assumed to be saturated. This means that the exit wet bulb temperature is also the dew point and dry bulb temperature. The airflow and the exit temperature are functions of the tower dimensions, tower capacity, ambient dry bulb temperature, and relative humidity

For all the case runs, the Potomac Electric Power Company Chalk Point Unit #3 assumed to be operating at 100% capacity was used in calculating the proportions of latent and sensible heats to the total

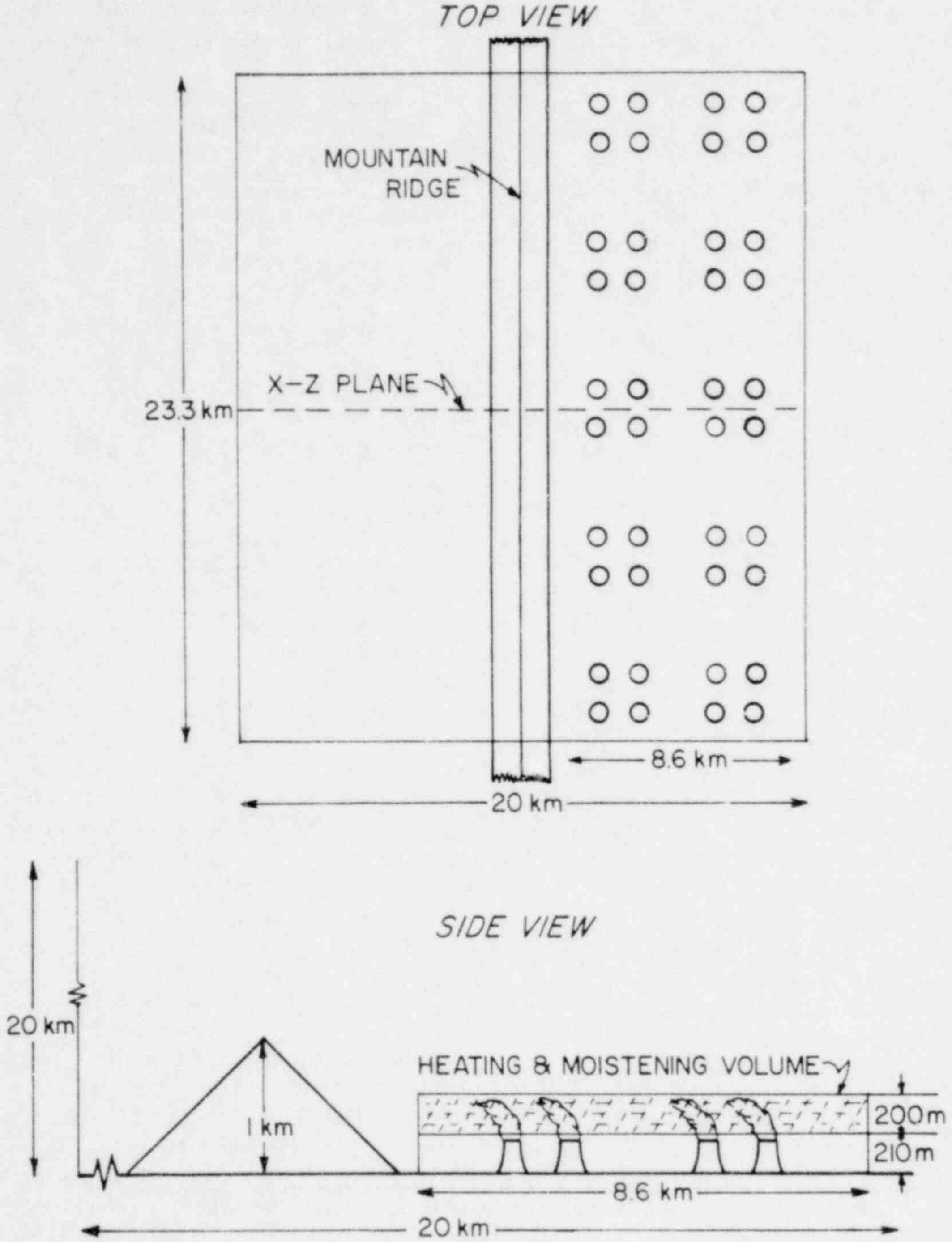


Fig. 2: The top view shows the standard park configuration to the right of the ridge. The side view shows the volume into which the moisture and heat is added.

waste energy. From the surface conditions in each run, we know the dry bulb temperature and relative humidity. The steps for calculating the dry airflow and exit wet bulb temperature are straightforward; an example is given by Dickey and Cates (1973). The steps include calculating the ambient wet bulb temperature and using several graphs to calculate the density of the ambient air and the mixing ratios of the ambient air and the exiting tower air. Below are the formulae for calculating the latent heat (LHT) and sensible heat (SHT) for a single tower per unit of time.

Units

$$\mathrm{LHT} = (r_T - r) \cdot \mathrm{DAF} \cdot L \qquad [\mathrm{ergs\ s^{-1}}]$$

$$\mathrm{SHT} = (r_T \cdot C'_p + C_p) \cdot \mathrm{DAF} \cdot (T_e - T_a) \qquad [\mathrm{ergs\ s^{-1}}]$$

where

r_T	- saturation mixing ratio of the tower air	$[\mathrm{g\ g^{-1}}]$
r	- mixing ratio of the ambient air	$[\mathrm{g\ g^{-1}}]$
DAF	- dry airflow through the tower	$[\mathrm{g\ s^{-1}}]$
T_e	- exit wet bulb temperature	[°C]
T_a	- ambient air temperature	[°C]
C'_p	- specific heat for water vapor	$[\mathrm{ergs\ g^{-1}\ K^{-1}}]$
C_p	- specific heat for dry air	$[\mathrm{ergs\ g^{-1}\ K^{-1}}]$
L	- latent heat	$[\mathrm{ergs\ g^{-1}}]$

The latent heat and sensible heat calculations done above very rarely, when totaled, equaled the total waste heat pumped into the tower. The figures were usually within 7% of the total. Some of the error is due to interpreting the graphs (Dickey and Cates, 1973); they state, "The accuracy of the curve system has a scatter of ±7%." The proportions of latent and sensible heats to the total waste energy was determined by dividing the latent and sensible heat numbers by the sum of the latent and sensible heat numbers. Now that the proportion of latent and sensible heats per unit of time are known, we can take these respective proportions times the total waste heat and derive the total latent and sensible heat outflow per unit of time.

We make the assumption that the Chalk Point Unit #3 operating at 110% capacity could represent a tower of a different size with the same atmospheric conditions.

We mentioned earlier that the heat outflow is distributed over the area of the park to a depth of 200 m. We need to convert the outflow figures so that we can use them in the model as source terms in the appropriate equations at selected grid points, identified below.

Units

$$\frac{\partial q_T}{\partial t} = \frac{LHT \cdot TE}{L \cdot A \cdot \Delta z \cdot \rho_T \cdot (LHT + SHT)} \qquad [g\ g^{-1}\ s^{-1}]$$

$$\frac{\partial \Theta_T}{\partial t} = \frac{SHT \cdot TE}{C_p \cdot A \cdot \Delta z \cdot \rho_T \cdot (LHT + SHT)} \qquad [°C\ s^{-1}]$$

where

ρ_T	- density of the ambient air	$[g\ m^{-3}]$
TE	- total waste energy	$[ergs\ s^{-1}]$
L	- latent heat of vaporization	$[ergs\ g^{-1}]$
A	- area of the park	$[m^2]$
Δz	- 200 m, the height over which the effluent is spread initially	[m]

The latent and sensible heat outflows from the towers are now in a form compatible with the model equations. The units are $g\ g^{-1}$ and $°C\ s^{-1}$, and are of an order of magnitude of 10^{-6} and 10^{-4}, respectively.

2.3 Boundary Conditions

The model has a rigid top boundary with all variables held constant, side boundaries where the horizontal gradients are set equal to zero, and the lower boundary where the vorticity and stream function are held constant and are set equal to zero. Evaporation and heating rates at the surface are set arbitrarily (in line with observations). Heat and vapor are diffused into the lowest grid points located 10 m above the surface (Orville, 1965). In addition, the lowest grid points of the model can have heat and moisture added and thus simulate the heat and moisture from a power park made up of mechanical draft cooling towers, although this is not tested in this study. These changes at the lower boundary are advected and diffused into the surrounding grid points. Cloud shadow effects are simulated via Liu and Orville (1969). Cloud substance is not permitted to form at the lower boundary but precipitation can fall through the lower boundary, and that which does is accumulated to give a predicted depth of rain and hail on the ground.

As we mentioned earlier, the standard area of the park is 192 km^2. In our model, we have only enough room to represent a park with a maximum width in the x-direction of 8.6 km. In the model, we have kept the width constant but have varied the length which, in turn, varies the concentration of latent and sensible heat concentrations added to the model. The variation of length is done in the y-direction. As the length of the park decreases, the concentration of park effluents increases (simulating the reduced spacing of cooling towers). By taking a cross section through the middle of the power park for the effluent input, and by keeping the ends of the power park at a minimum length at greater than 11 km from each other, we should have minimized the edge effects. Only a three-dimensional model would be able to handle these edge effects.

The park is generally upwind so that the effluent will hopefully stay within the region of integration for the longest time. For natural draft cooling towers, the park effluent is added to the model at one grid level above the lower boundary. This places the area being enriched by the park with heat and moisture an average of 210 m above the ground.

2.4 Initial Conditions and Sounding Discussion

The model uses the data from a radiosonde sounding as initial conditions. The data input to the model includes temperature, dew point, and pressure from various heights of the sounding. The horizontal wind component in the direction of the storm's movement was reduced for all the runs by 80% and then incorporated into the model as an additional initial condition. The wind velocity was reduced because a two-dimensional model is unable to handle the flow of horizontal winds around the sides of convective clouds. Left untouched, a horizontal wind shear would greatly diminish cloud development by inhibiting the formation of surface eddies and cloud growth. The reduction of winds also has the advantage of allowing the simulated storm to stay longer within the area of integration.

The first sounding used is the "Fleming storm" sounding taken at Sterling, Colorado, on 21 June 1972. This sounding best represents the atmospheric conditions at the time of the storm. The surface temperature was adjusted to account for the amount of solar insolation that occurred between the time of the sounding and the occurrence of the storm. Figure 3 shows the plot of the Fleming storm sounding. This sounding is representative of a class of severe storm soundings for the northern Great Plains in that it exhibits a high level inversion between 700 and 400 mb, a conditionally stable atmosphere above and below the inversion, a relatively moist area below the inversion, and a very dry area above the inversion. Following the criteria of Fawbush and Miller (1954), the Fleming storm sounding could be classified as representing a Type I air mass. The sounding has an inversion with a wind shear component of greater than 30 kts perpendicular between the wind in the dry air above the inversion and the flow in the moist air below. The Lifted Stability Index is around -8°C, which is more unstable than the average Type I air mass. However, the only exception to the inclusion of the Fleming storm sounding as a Type I air mass is that the dew point at the surface should be over 13°C and have a relative humidity of greater than 65%. The Fleming surface dew point is 11.2°C with a relative humidity less than 65%. The storm resulting from this sounding has been well documented by Browning and Foote (1976) and is a National Hail Research Experiment (NHRE) case.

The second sounding used was taken at Miami, Florida, on 18 June 1959 at 00Z. Three hours later, a thunderstorm produced a tornado over downtown Miami (Hiser, 1967). Figure 4 shows the sounding associated with this storm. This sounding is typical of a Type II air mass sounding in which there is no inversion and the relative humidity is greater than 65% up to at least 6 km. Surface temperature is over 27°C, and the upper level winds over Miami were in fair agreement with the Fawbush-Miller (1954) criteria for Type II sounding.

The third sounding chosen for initial input was the Huron sounding taken at 0000 GMT on 14 July 1972 (Fig. 5). Huron radar observations show that there was widespread thundershower activity during the afternoon and severe thunderstorms in the evening on this date. The surface temperature was adjusted to account for cooling due to cold outflow from earlier thundershowers. The horizontal wind was normalized to 337°, and the component in this direction was reduced by 75%.

The sounding is closest to fulfilling the criteria of the Fawbush and Miller (1954) Type IV air mass in which continental tropical air is overrun by maritime polar air at 5000 to 8000 ft above the ground, giving the sounding an inverted "V" shape. These soundings generally produce violent straight-line windstorms and hail in the High Plains. The Listed Index is -6.8, which is more unstable than the usual Type IV, but the Total Totals Index is 50, which is slightly less than the required 53.

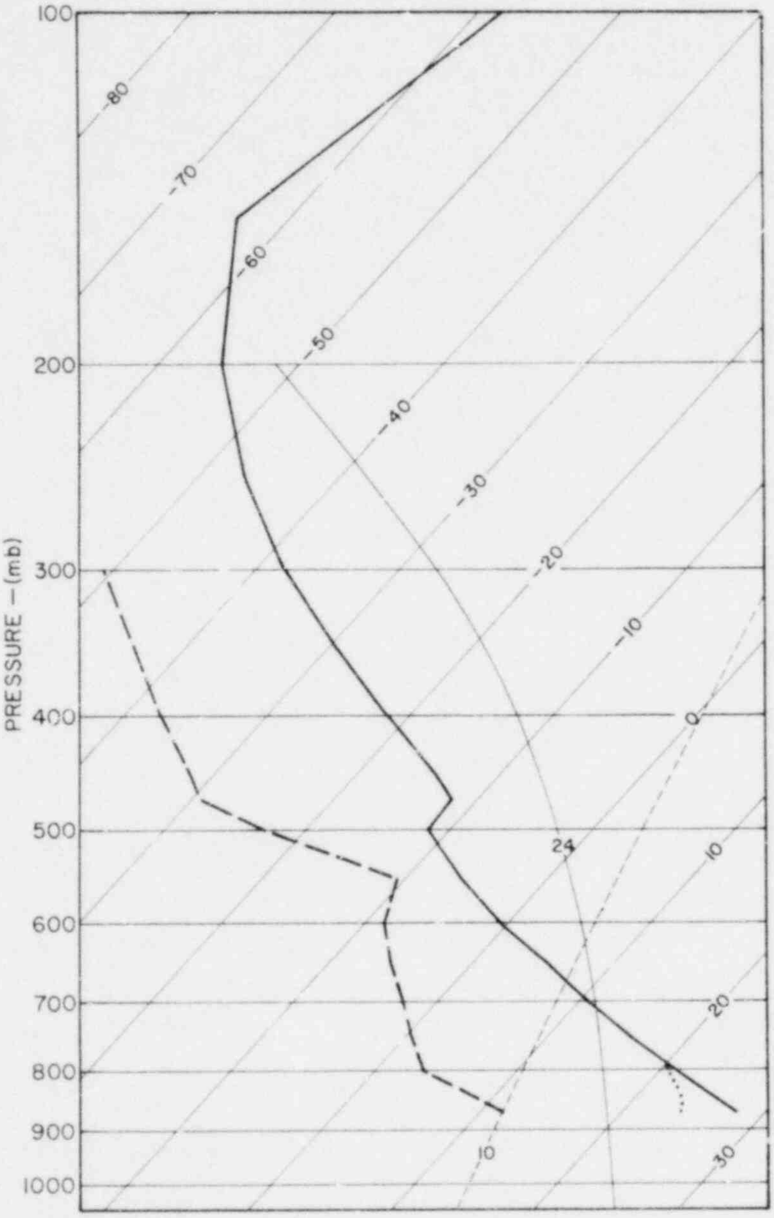


Fig. 3: An atmospheric sounding from Sterling, CO, 21 June 1972. Dashed line is dew point; solid line, the temperature on a Skew T-log P chart; and the dotted line is the observed value for temperature.

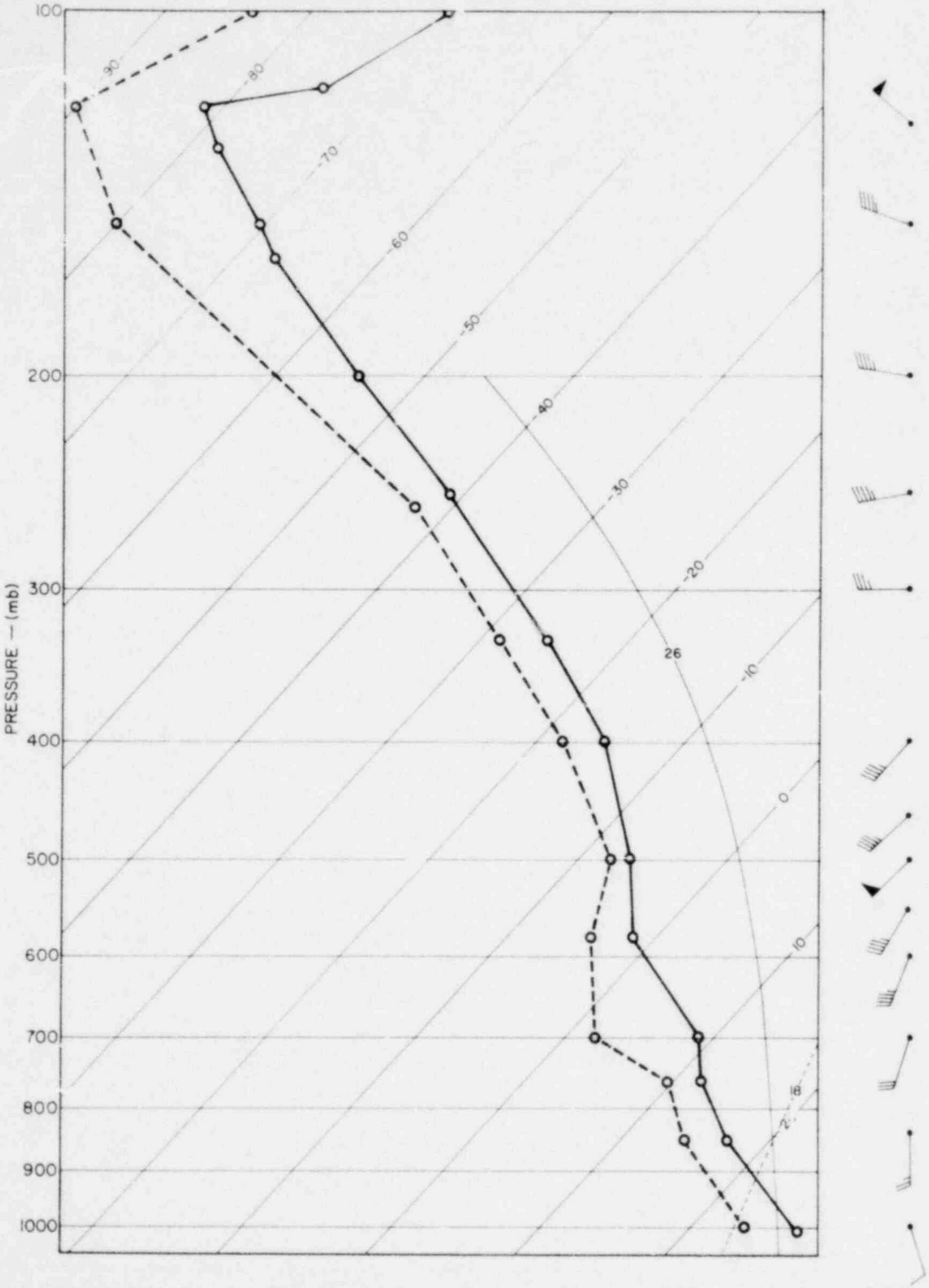


Fig. 4: This is the Miami rawinsonde sounding at 00Z on 18 June 1959 on a Skew T-log P chart. The solid line is temperature and the dashed line is dew point.

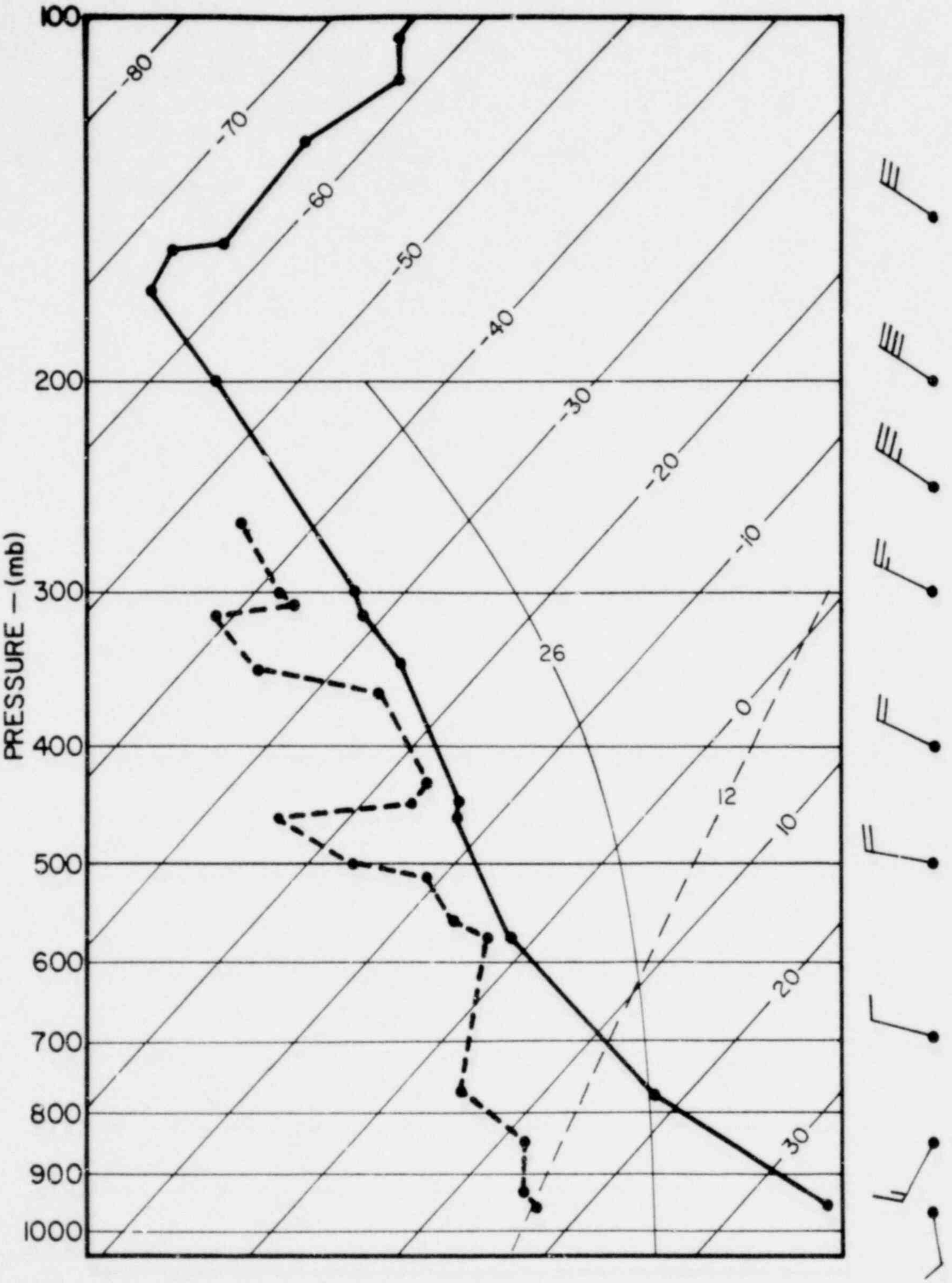


Fig. 5: Huron 0000 GMT rawinsonde sounding for 14 July 1972. Solid line is temperature; dashed line is dew point temperature.

1426 128

The Type I and Type II air mass soundings cover a good percentage of severe storm cases that occur here in the United States. A Type III air mass sounding is similar to a Type II sounding except it is a great deal cooler with surface temperatures ranging from 20°C down to 10°C. This type of sounding is generally responsible for Great Lakes, West Coast, and northeastern United States waterspouts. A Type IV air mass sounding has moisture in the higher portions of the lower layer with the lowest part of the layer being extremely dry. This air mass produces violet straight-line windstorms from the southwestern desert areas eastward into the High Plains (Miller, 1967).

3. RESULTS - BRIEF DESCRIPTION

More complete descriptions of the model results can be found in the individual papers and theses listed in Section 8.

3.1 Early Experiment - "One Shot" Addition

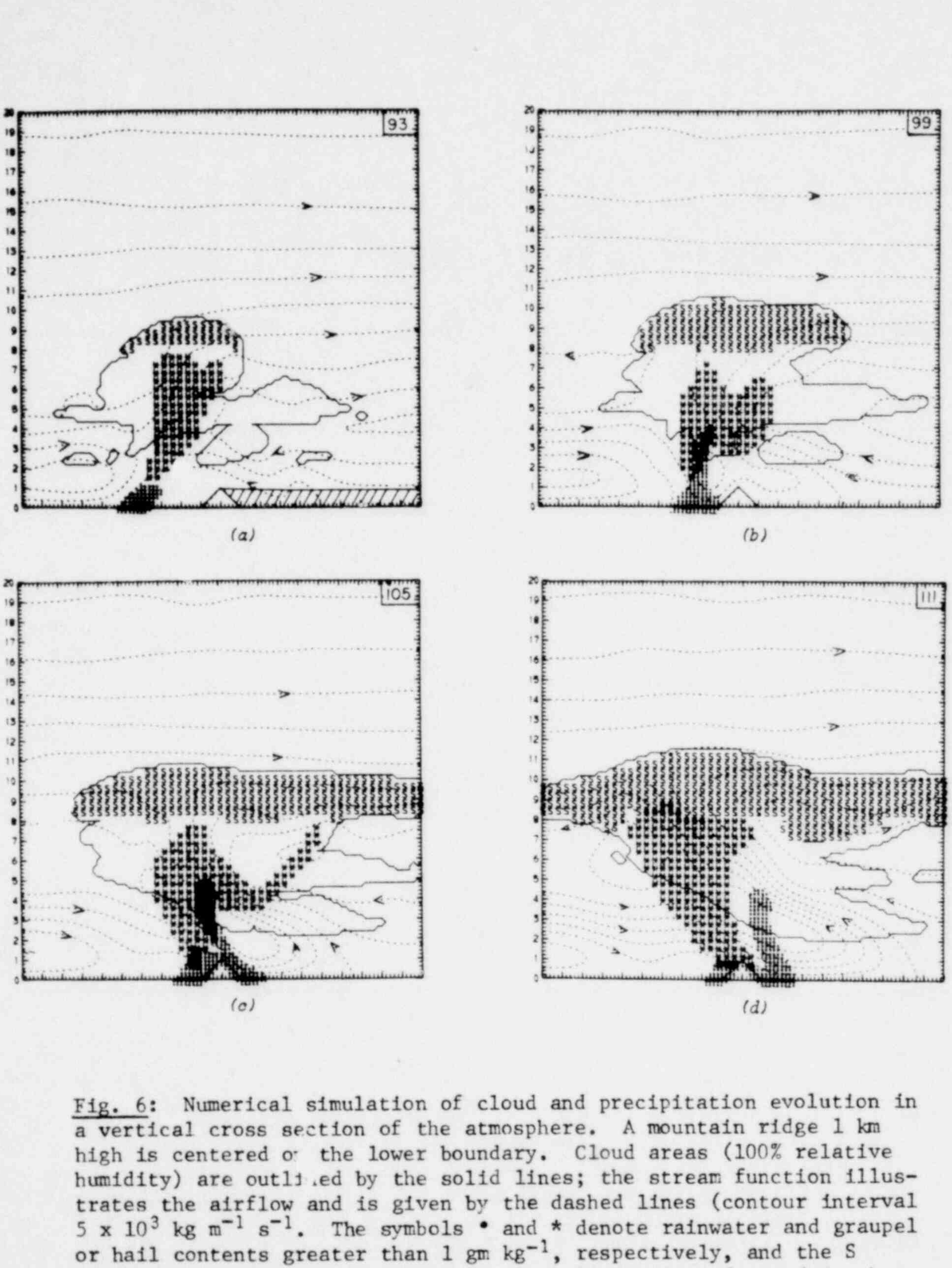
At the beginning of the contract period, a simpler method was used to give a first look at the effects of vapor additions on a simulated severe storm. An instantaneous source of vapor (0.5 g kg^{-1}) was applied to a region 1 km deep and 10 km wide (at approximately 250 grid points in the model). This amount of vapor is equivalent to a vapor source of 2.5×10^7 g s^{-1} spread over a region 10 km x 20 km, and the vapor accumulated over a one-hour period in a 1 km deep boundary layer. This instantaneous, one shot addition of vapor is applied at 93 minutes of simulated real time in the severe storm model (Fleming sounding). This time is just prior to the model storm reaching severe storm proportion.

Figures 6a-d show the general results of the severe storm portion of the simulation, and also indicate the region in which the additional water vapor was introduced. The subsequent integrations show diffusion and advection of the total water vapor field throughout the domain. Careful analysis of the various printouts of the vapor, cloud, rain, and hail fields shows differences in the "modified" versus the "unmodified" cases. These differences, evident in the two major cloud cells which make up the model storm, are approximately 0.5 g kg^{-1} increases in vapor (as to be expected), several tenths g kg^{-1} increases in cloud liquid, rain, and hail, and 2 to 3 m s^{-1} increases in maximum updraft speed.

Results indicate a slight redistribution of the precipitation to the right of the grid and a rain increase, hail decrease, and very slight total precipitation increase. The integrated values at 141 min are an increase of 5 kT km^{-1} in rain (172 to 177 kT km^{-1}, and a decrease of 4 kT km^{-1} in hail (48 to 44 kT km^{-1}), leaving a small net increase in precipitation for the power park case.

3.2 Fleming Storm

All later cases used the source terms in the vapor and temperature equations at the 210 m level grid points. The cross sections for 66 min and 102 min show the general development of the storm in the five Fleming storm cases. The first four cases (Figs. 7a-d) show the main cloud being fed by air from both the right and left. The strength of the main updraft in Figs. 7a-e draws in air from the lower left-hand corner into the main cloud.



(a) (b)

(c) (d)

Fig. 6: Numerical simulation of cloud and precipitation evolution in a vertical cross section of the atmosphere. A mountain ridge 1 km high is centered on the lower boundary. Cloud areas (100% relative humidity) are outlined by the solid lines; the stream function illustrates the airflow and is given by the dashed lines (contour interval 5×10^3 kg m^{-1} s^{-1}. The symbols • and * denote rainwater and graupel or hail contents greater than 1 gm kg^{-1}, respectively, and the S denotes cloud ice regions. Simulated real time is indicated in the upper right-hand corner. Major tick marks are 1 km apart. In Fig. 6a, the hashed region indicates the area of the instantaneous moisture addition.

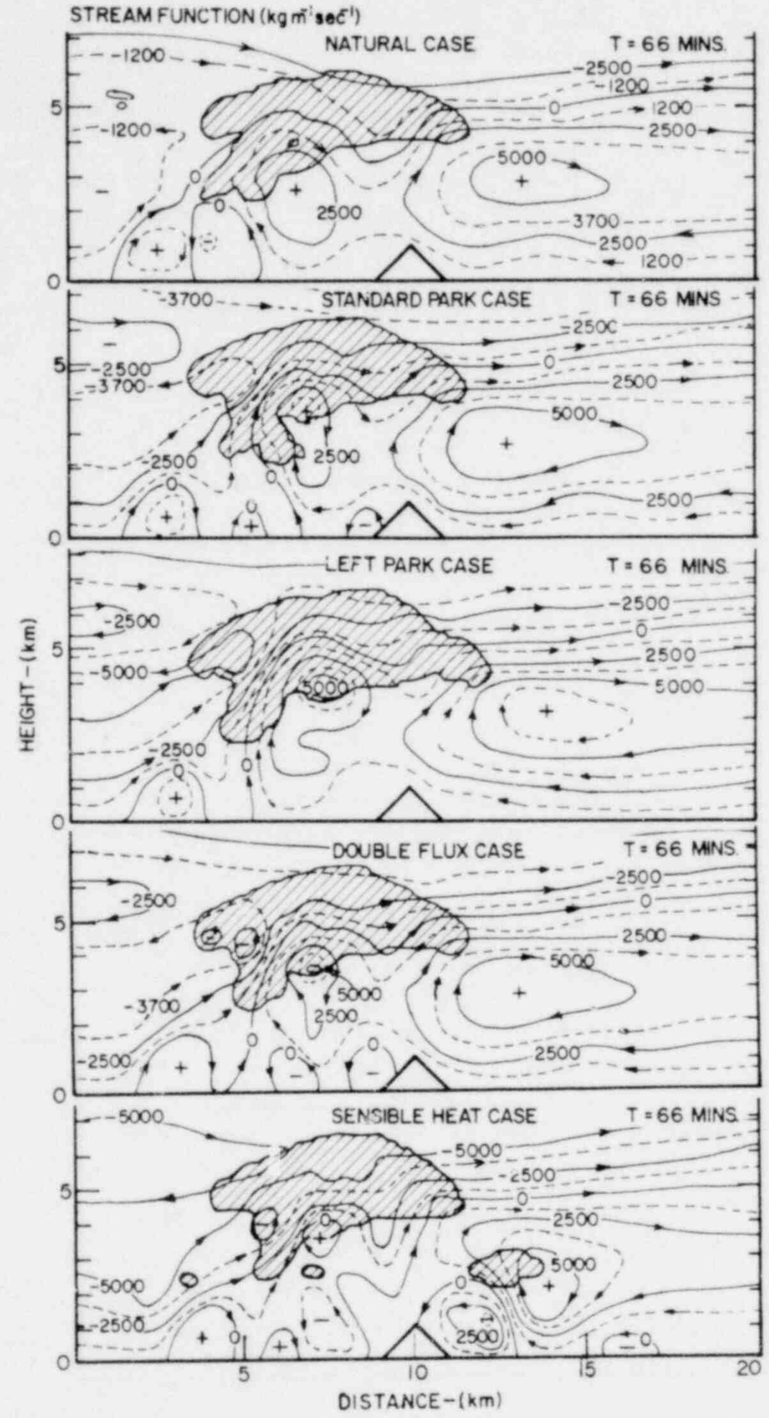


Fig. 7: The stream function field of the Fleming storm cases at 66 min. The clouds are the shaded areas.

In the first four cases of Fig. 7, the closed circulation pattern just to the right of the main updraft (at 6 km in from the left boundary) is a main feature. Each pattern is shaped differently, and the contours indicate that the flow of air in the main updraft is weakest in the natural case (Fig. 7a), followed by the 100% sensible heat case (Fig. 7e). The standard park and double flux cases (Figs. 7b and d) are strong but of about equal strength. The main updraft is the strongest in the left park case (Fig. 7c). The 100% sensible heat case has formed a strong secondary circulation over the right side of the grid, causing a second cloud to form.

The sequences at 102 min (Fig. 8) show significant differences in most of the cases. The standard park case is most like the natural case. The storm in the left park case has moved further to the right in the domain and is weakening. The double flux case shows slightly less rain and hail, with most of the precipitation distributed below 5 km. The 100% sensible heat case exhibits the greatest differences. The major convection has ceased and precipitation has nearly all fallen to the ground.

The dynamics of each storm is different from that of the natural case. This difference in dynamics is evident in the accumulated rain and hailfall and the time at which the storms end. Figure 9 compares the natural case rainfall with that of the standard park, the left park cases, the 100% sensible heat, and the double flux cases. The rainwater distribution in the natural case and the standard park and double flux cases are similar. However, the latter two cases exhibit a small distribution shift to the right. The left park case does not show the two-peak distribution of these three cases, which is caused by the location of the mountain ridge. The high ground of the ridge is a depository for hail, saving it from melting if it were to fall another km to the plain. Consequently the cases with rain and hail fallout on the ridge line show a peak in hail there and a dip in rain. Table 1 gives the rain, hail, and total accumulated precipitation in the various cases. The 100% sensible heat shows greatly reduced rainfall.

3.3 Miami Storm

The Miami storm results are shown in Figs. 9b and 10a-b. The natural case at 141 min (Fig. 10a) shows a vigorous, active convective storm, with convergent inflow (flow from both left and right in the lower levels). The power park case storm is nearly as big (Fig. 10c), but not as broad as the natural case. In addition, the power park case is being fed by low level flow primarily from the right side. Figure 10b shows the natural case storm still active, with copious amounts of rain and precipitating ice. However, 10d shows that the power park case storm has nearly dissipated, mostly anvil cloud remaining. Figure 9b and Table 1 show the accumulated

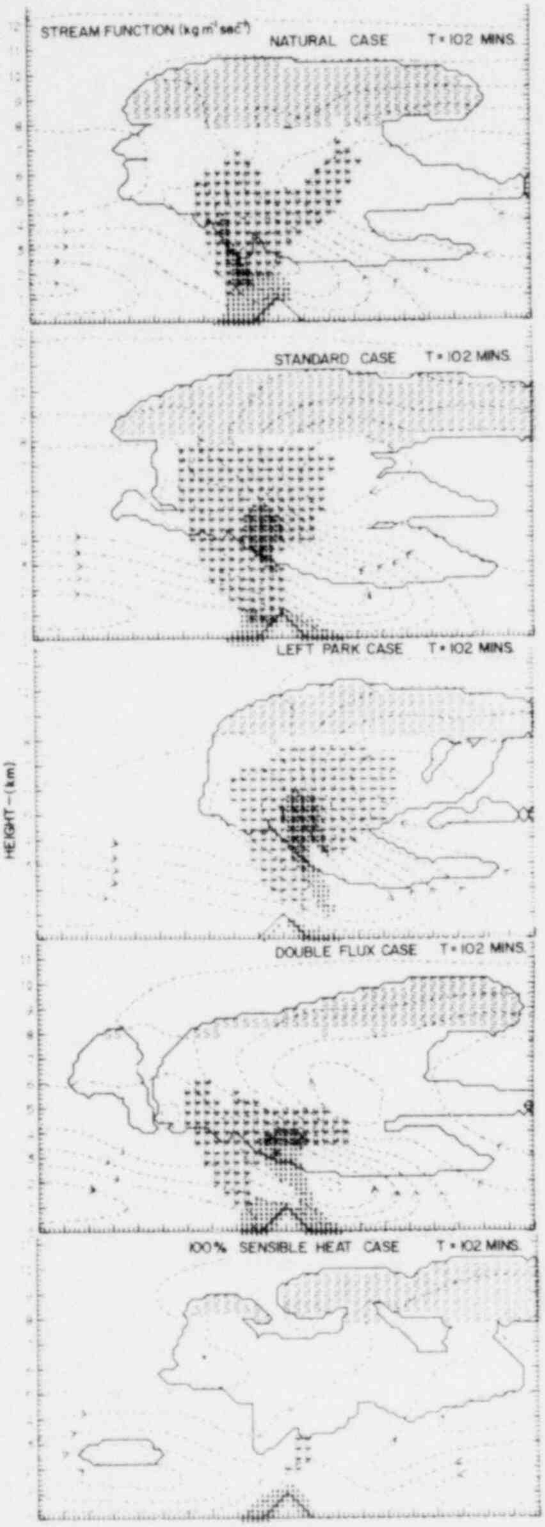


Fig. 8: Same as Fig. 7 but for a contour interval of 5000 kg m^{-1} s^{-1}. Rain and hail over 1 g kg^{-2} are depicted as dots and asterisks, respectively.

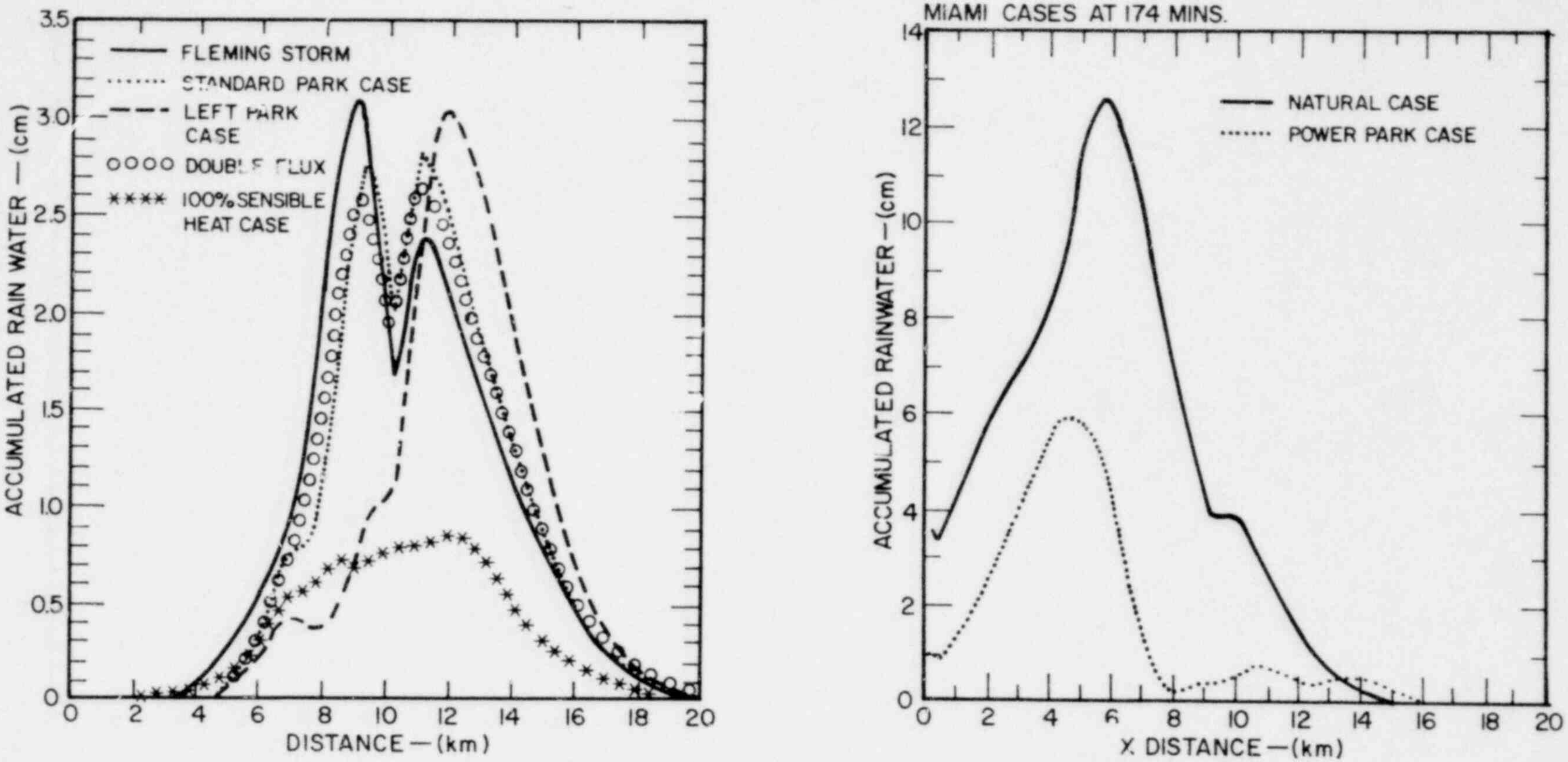


Fig. 9: (a) A comparison of the natural case rainfall with that of the standard park, the left park cases, the 100% sensible heat, and the double flux cases. (b) This compares the rainfall of the two Miami storm cases at 174 min.

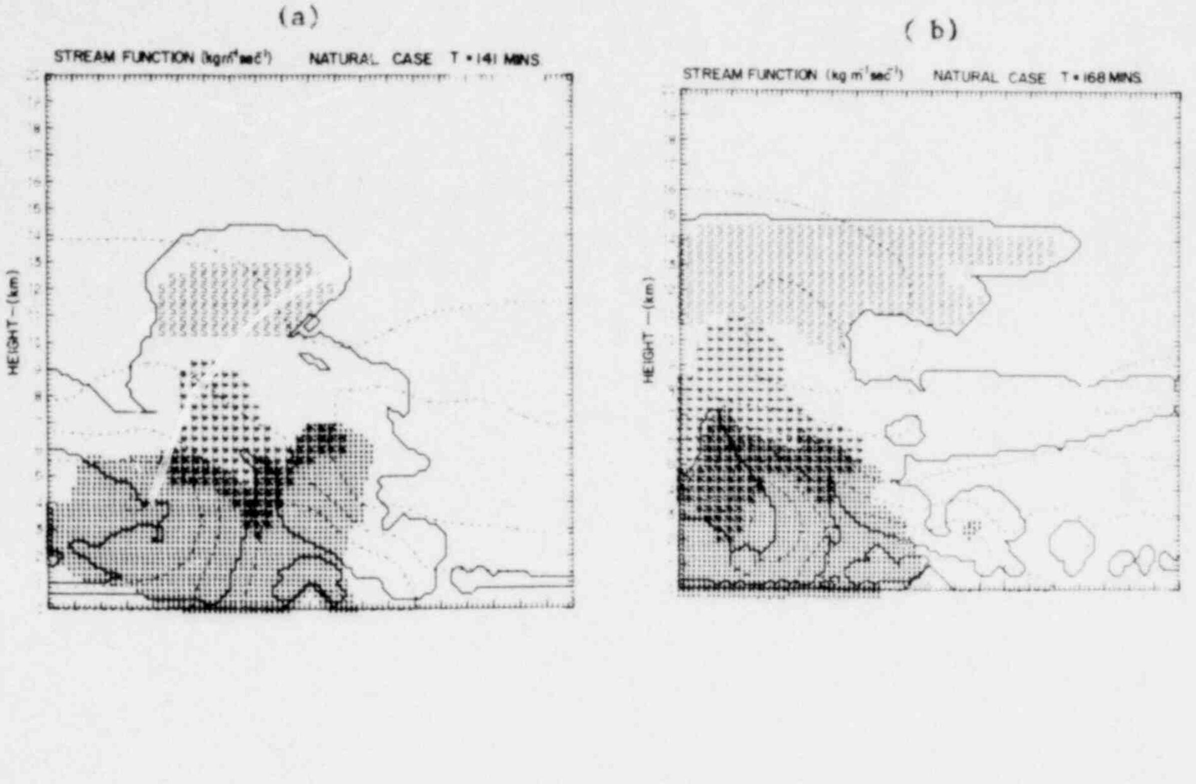


Fig. 10: The stream function for the natural (a & b) and power park (c & d) cases of the Miami storm at 141 and 168 min. Contouring is 10000 kg m^{-1} s^{-1} for a, b & d and 5000 kg m^{-1} s^{-1} for c.

TABLE 1

Precipitation Results (kT km^{-1})

	Rain	Hail	Total	% Change from Natural Case
Fleming				
Natural	178.2	47.4	225.6	
Standard (Right Park)	175	41.3	216.3	(- 4%)
Left Park	152	31.5	183.5	(-19%)
Double Flux	175	31.3	206.3	(- 9%)
100% Sensible	65.1	3.8	68.9	(-69%)
Miami				
Natural	803	Negligible	803.0	
Standard	290	Negligible	290.0	(-64%)
Huron				
Natural	251	3.0	254.0	
Standard	244	2.9	246.9	(- 3%)
Left	233	2.0	235.0	(- 7%)

rainfall; much more has fallen in the natural case. There were reports of over 6 inches of rain in some south Florida areas on this day.

3.4 Huron Storm

A natural case, a "standard park" case, and a "left park" case were simulated. The natural case was used as a control, while the standard park case used the same sounding but added the effluents from a 48,000 MWe power park to the right of the mountain ridge. The left park case added the effluents to the left of the ridge. The results were analyzed for differences in cloud dynamics and precipitation due to the additional heat and water vapor from the power park.

Clouds were initiated at about 30 min of real time simulation. By 54 min (Fig. 11), the updraft in the left cloud is stronger than that in the right cloud. The strength of this updraft has by now completely reversed the airflow in the lower left corner. The flow up the right mountain slope is still feeding into the right cloud, but the updraft within the right cloud actually slopes to the right with height. The air leaving the right side of the left cloud descends and joins the right cloud's updraft.

Rain and hail contents of greater than 1 g kg^{-1} are depicted by dots and asterisks, respectively, in Fig. 11. It can be seen that both rain and hail have formed in the right cloud. In the left cloud, the standard park case has no rain, and rain has just begun to form in the natural case; but the left park case has extensive rain, an indication of the added vapor from the power park.

Figure 12 shows the storm at 63 min. There is hail throughout the left cloud, which has loaded the updraft so much that a downdraft starts to form throughout the cloud. The updraft portion which remains on the right is beginning to merge with that of the right cloud, giving it new strength. The right slope of the mountain is now experiencing flow to the right. The streamline which does join the updraft from the right originates at the right edge of the domain, so the standard park effluents are still cut off from the storm.

Figure 13 (72 min) shows that the storm is now almost totally front feeding. A feeder cloud has developed to the right of the storm and there is widespread rain and hail throughout the updraft region. This heavy loading causes rapid collapse of the updraft. A gust front has formed and is about 4 km in from the right boundary.

In Fig. 14, the gust front has moved off the field of integration to the right. At this point, the cloud is cut off from all surface moisture and it begins to die. By 115 min, all the precipitation from the natural and standard park cases has reached the ground and the storms have decayed into stratified layers. The left park case ended earlier at 110 min.

The dynamics of the three cases is only slightly different. The general flow, cloud location, and precipitation fields, even out to 84 min, are almost the same with the left park case showing the greatest difference. The clearest indication of any change due to the presence of the power park is in the total amounts of rain and hail accumulated at the surface.

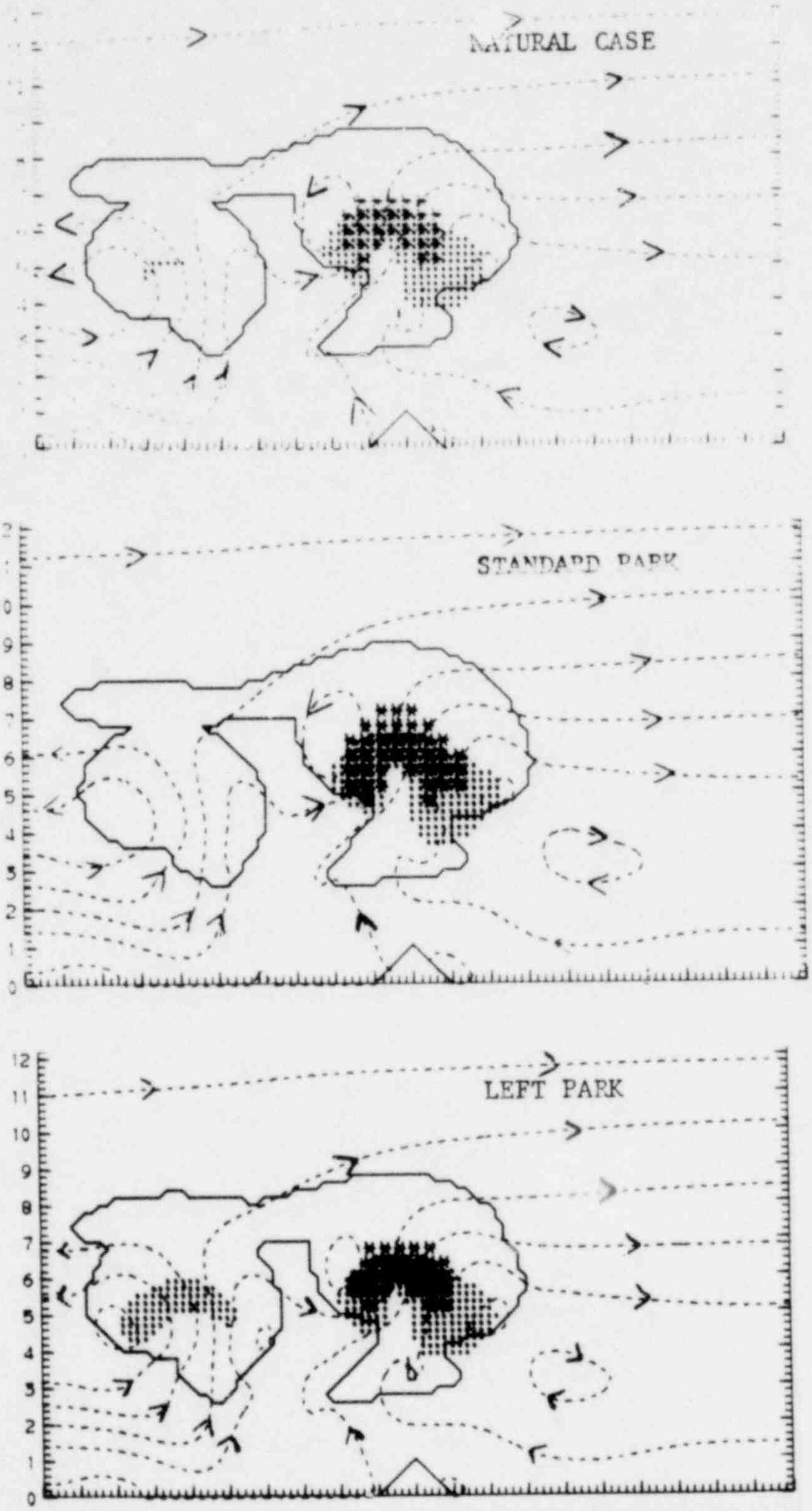


Fig. 11: Stream function field at 54 min. Rain and hail contents of greater than 1 g kg^{-1} are depicted by dots and asterisks.

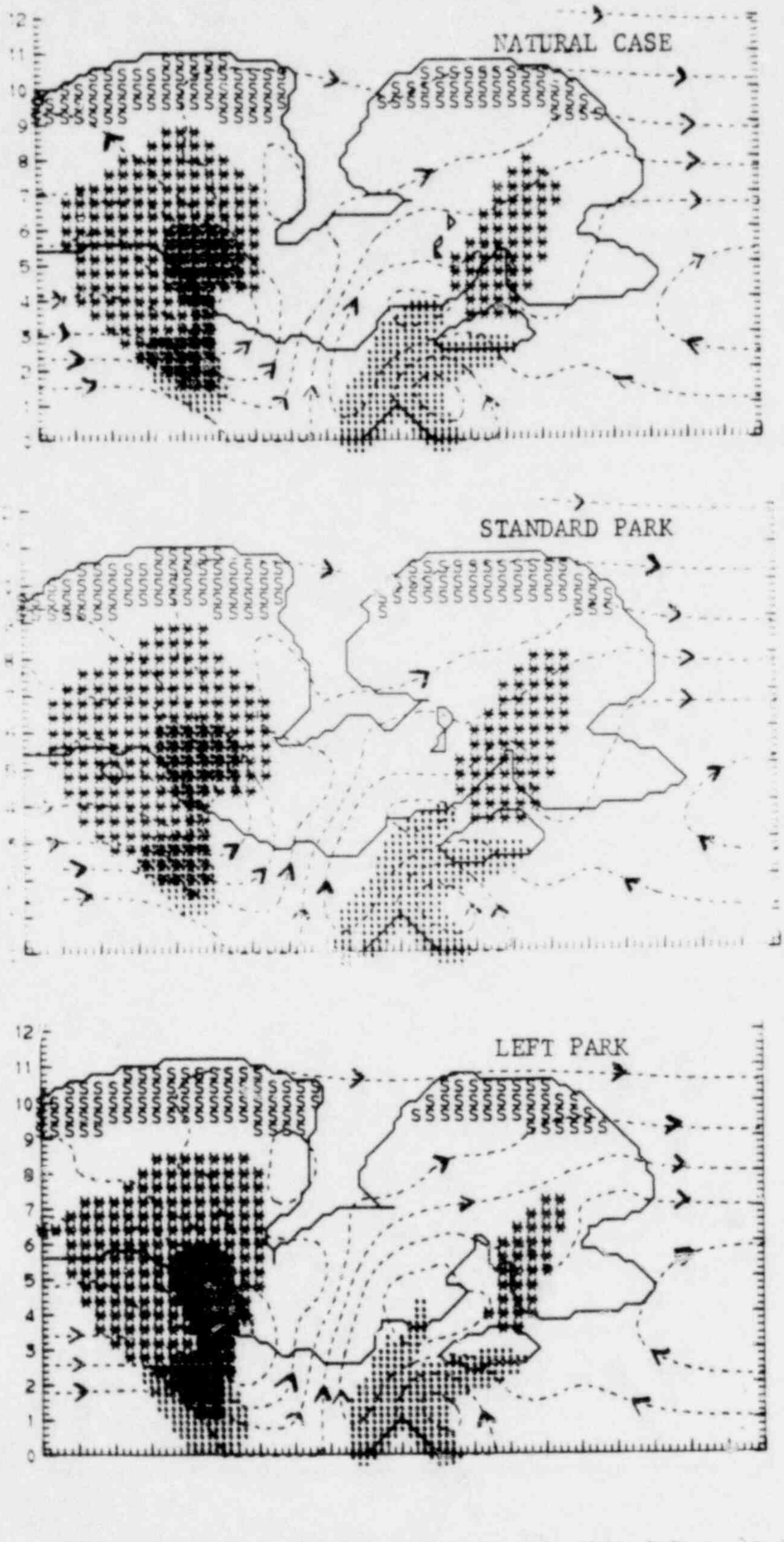


__Fig. 12:__ Same as Fig. 11, but at 63 min.

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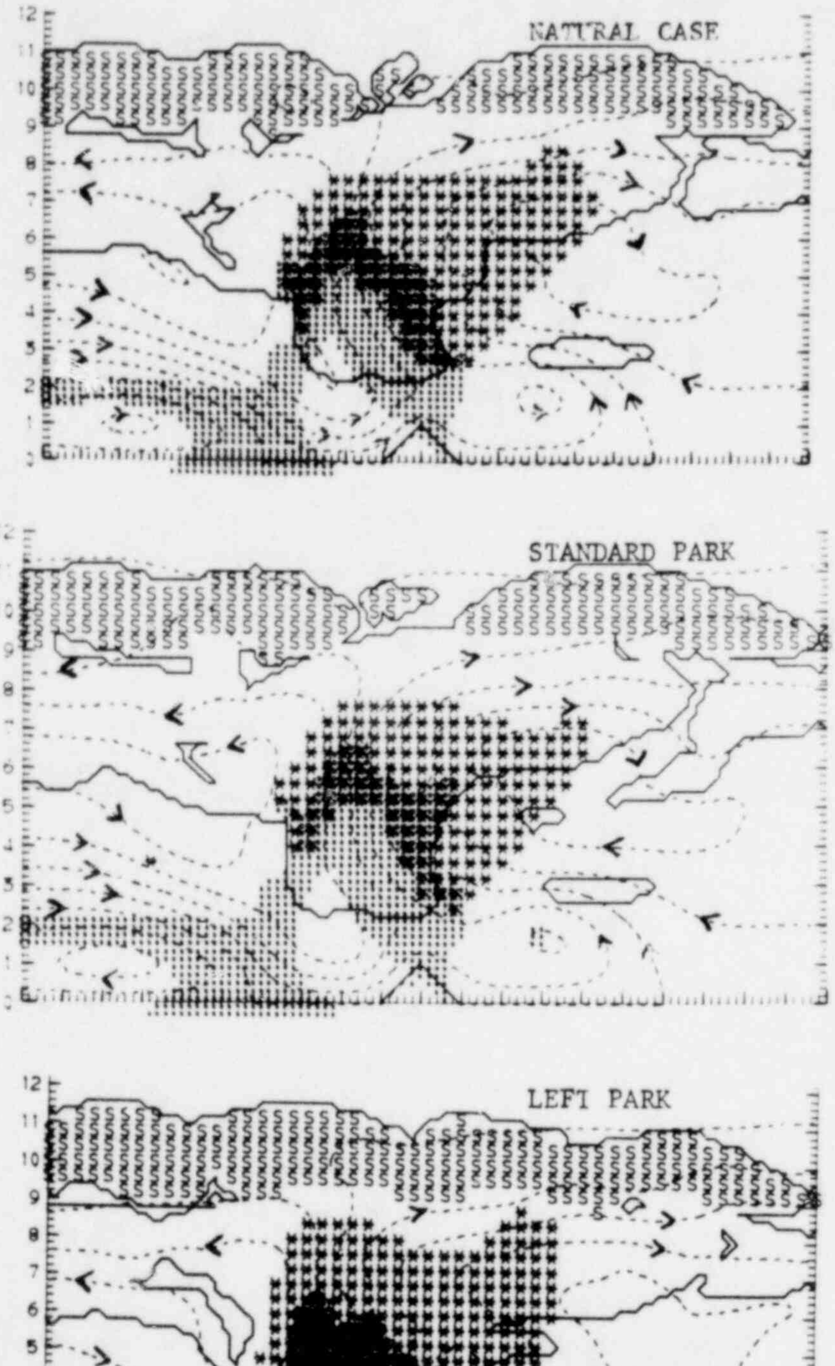

NATURAL CASE

STANDARD PARK

LEFT PARK

Fig. 13: Same as Fig. 11, but at 72 min.

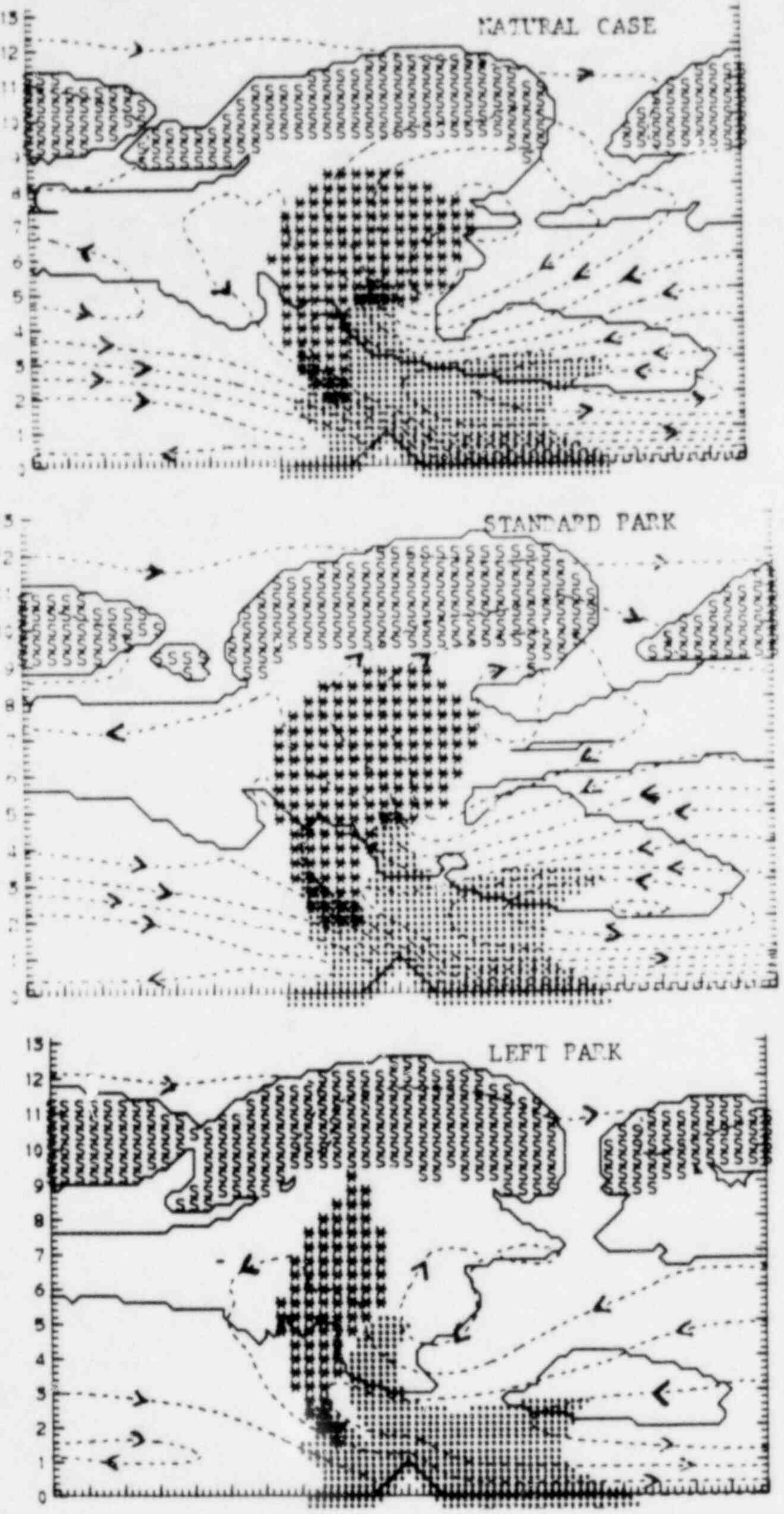

Fig. 14: Same as Fig. 11, but at 84 min.

Figure 15 and Table 1 compare the rainfall amounts. The rainwater distributions are almost the same, but the left park case had less rain. The standard park case distribution is shifted slightly to the left of the natural case distribution, and the left park case distribution is even farther to the left and smaller. At the left maximum, the standard park is greatest; and between the maxima, the left park case is greatest. The total accumulated rain on the ground for the natural case was 251.2 kT km^{-1}. The standard park total was 244.4 kT km^{-1}, a 2.7% decrease compared to the natural case. The left park total was 233.3 kT km^{-1}, a 7.1% decrease.

Figure 16 compares the hailfall amounts. Both the natural and the standard park cases had maxima at 5.2 and 10 km. The maximum at 10 km is due to the mountain peak, where hail has less air to fall through and melt. The standard park case had more hail at 5.2 km and less hail at 10 km. The left park case is almost the same as the natural case at 5.2 km, but had much less hail near 10 km. The total accumulated hail on the ground for the natural case was 3.0 kT km^{-1}. The standard park case total was 2.9 kT km^{-1}, a 3.2% decrease, and the left park case total was 2.0 kT km^{-1}, a 31.3% decrease.

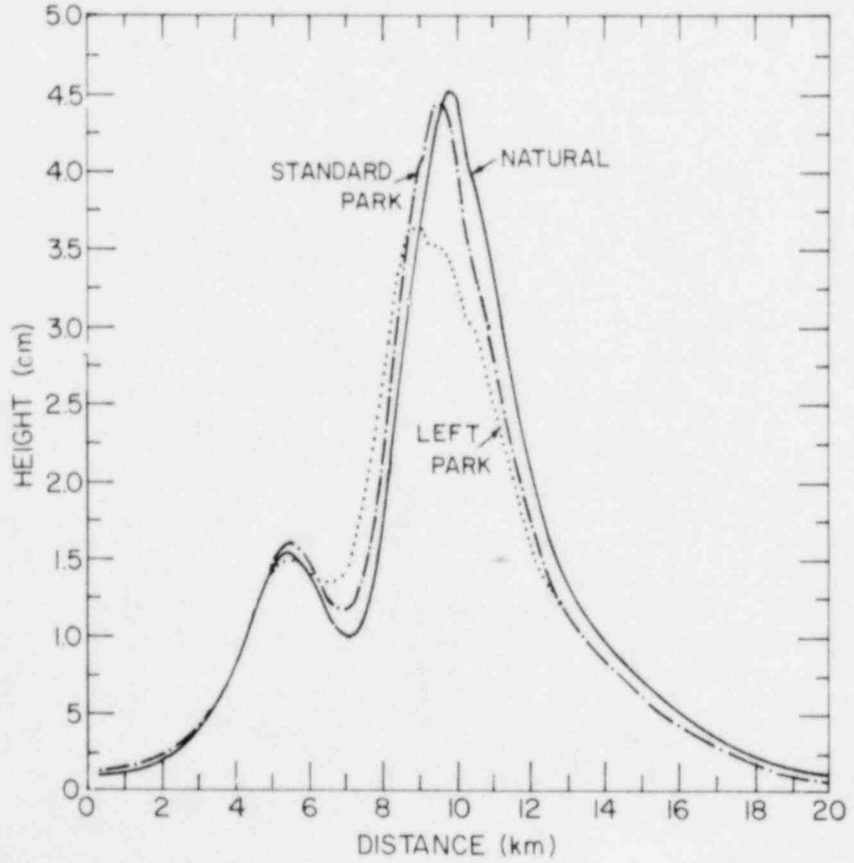

Fig. 15: Accumulated rainwater for the Huron case.

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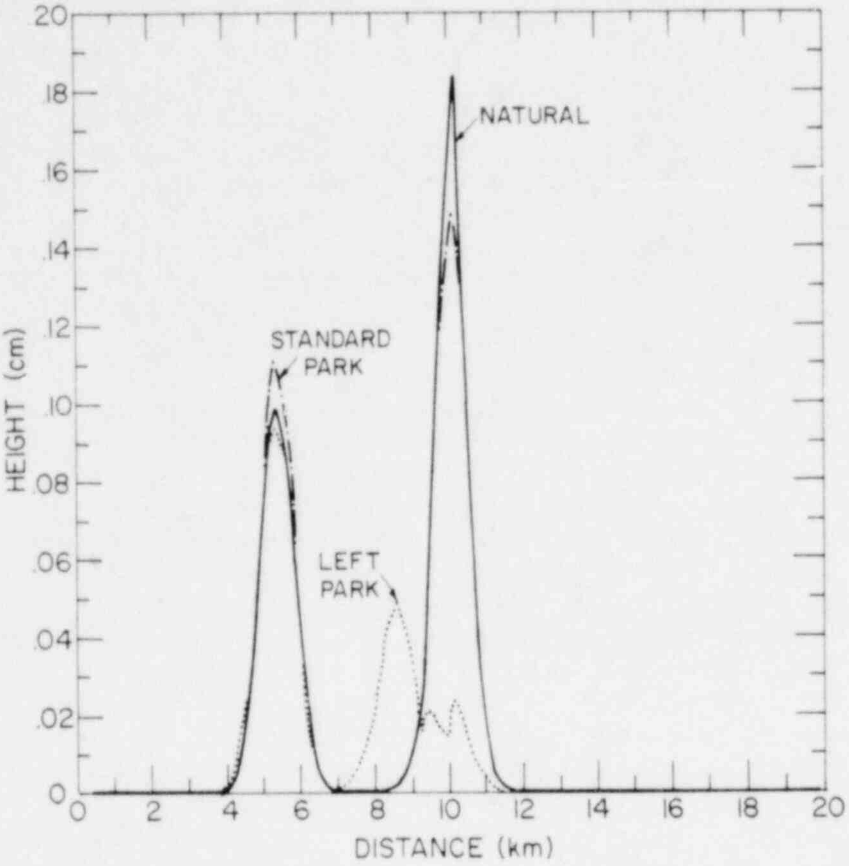

Fig. 16: Accumulated hail in the Huron case.

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4. DISCUSSIONS AND CONCLUSIONS

The 11 cases (three soundings) have shown some of the influence of power parks on severe storm development. Storm development was different and was affected to varying degrees by the effluents of the power park. The power parks create their own dynamics which interact with the flow of the developing storm to produce storms of less, to greatly less, precipitation output.

One of the really significant changes comes about after 66 min of real time simulation in the Fleming storm case. This is a time when the heat and/or moisture from the various parks had enough time to develop and interact with the natural dynamics to produce readily noticeable changes. The addition of heat and moisture from the wet cooling towers have supplied enough moisture to sustain the growth of the original cloud. In the dry cooling tower or 100% sensible heat case, there was enough heat affecting the dynamics to create a more vigorous cloud growth to the right of the original cloud development. The vigorous cloud developed a downdraft that interacted with the downdraft from the cloud system to the left. The result was a cessation of low level moisture into both cloud systems and the premature death of both systems.

The cloud in the natural case was very weak at 66 min, and the new development to the rear saved the original cloud from dying slowly. The new development took over with good growth characteristics and rejuvenated the natural case. However, the clouds of the wet cooling tower cases grew faster, and by 102 min their gust fronts were better developed. This can be attributed to the effects of the power parks.

One of the more noticeable changes is the quantity and distribution of the rain and hail. All except one of the power park cases produced less rain and hail, with the 100% sensible heat case showing approximately a 75% decrease in both rain and hail maxima. The wet cooling tower cases show a small decrease in precipitation with a shift in the location of rainfall. The standard power park case shows less differences than any of the other cases in its rain and hail distribution for the Fleming storm series of cases. The double park case showed slightly more of a change with a little less rain and hail than in the standard park case. However, the distributions of rain and hail were very similar to the standard case. The left park case showed a total rainfall slightly less than the natural case in the Fleming storm series, but the distribution shows a large single peak instead of the double peaks as in the other wet tower cases. The 100% sensible heat has rain and hail peak amounts that are 30% and 13% of the natural case. This can be directly attributed to the rapid cloud development in front of the storm, which saps the energy of the storm leading to early dissipation of the storm system. One point brought out in the left park case is the earlier cloud formation if the power park is under the area where initial cloud development would normally take place.

The case of the instantaneous, one-shot addition of water vapor to a 1 km deep region produced slightly more total precipitation and a slight increase in updraft strength.

In the two Miami runs, the power park effluents interact significantly with a cloud developing overhead. The clouds develop more rapidly in the power park case, but never become as organized a system as in the natural case. The flow that develops is not "complementary" to the flow in the natural case. This results in a 50% decrease in the rain maximum, and a 66% decrease in accumulated rain at 174 min in the power park case. Hail develops in the storms, but hail accumulation on the ground is insignificant.

The two-dimensional model results for the Huron sounding showed that the dynamics and microphysics of one storm in the northern High Plains was affected to varying degrees by the addition of power plant effluents. With the power plant located directly underneath the area of cloud development, the cloud formed slightly earlier and ended earlier than the natural case did. The interaction of the power park effluents with the storm's dynamics produced a storm with less total precipitation. With the power park moved to a location not beneath the storm, it had less effect.

Compared to the studies made for other climates, the effect on total accumulated rain and hail is slightly less than that of the Fleming study, and much less than the effect seen in the Miami study.

Apparently the atmosphere in a tropical region like Miami reacts more strongly to additional heat and vapor, even though the climate is already warm and moist. But in a cooler, drier region like that of Huron, the atmosphere requires much more heat and moisture to form clouds in the summer, and will therefore not be affected as much by effluents of a power park.

The "one shot" addition case is quite different from the Huron, Fleming, and Miami cases in which the water vapor was added continuously over a longer period of time. However, it should be noted that the evaporation rates from the power park would add about 1 cm of precipitable water to a column in the atmosphere in 12 hours, and the power park simulations extended over only two hours duration.

So the effects of the power park effluents on a severe storm depend on how and when they are incorporated into the storm. It must be emphasized again that the two-dimensional power park model results discussed here are from only three summertime convective situations. Further research should include a case in which the vapor and heat from a power park is trapped by an inversion and builds up before being released into a storm. Consideration should also be given to a possible winter situation in which a stable lower atmosphere could trap the effluents and later release them into a snowstorm. Also, the Huron and Miami results may not be completely representative due to the presence of a mountain in the model.

The ultimate effects of power park effluents on severe storms are not readily determined by simple additive calculations. Complex interactions occur which can only be tested through realistic numerical simulations. Careful observations of the long term climatological changes near large power plants should be maintained for long periods of time to determine the actual effects of the plants on the weather.

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16. ABSTRACT *(200 words or less)*

A two-dimensional, time-dependent model has been developed which gives realistic simulations of many severe storm processes, such as heavy rains, hail, and strong winds. The model is a set of partial differential equations describing time changes of momentum, energy, and mass (air and water substances such as water vapor, cloud liquid, cloud ice, rainwater, and hail). In addition, appropriate boundary and initial conditions taken from weather sounding data are imposed on a domain approximately 20 km high by 20 km wide with 200 m grid intervals to complete the model. Modifications have been made to the model which allow additional water vapor and heat to be added at several lower grid points, simulating effluents from a power park.

The results indicate that a power park emitting 80% latent heat and 20% sensible heat has little effect on the simulated storm. A case with 100% sensible heat emission leads to a much different solution with the simulated storm reduced in severity and the rain and hail redistributed. A case in which water vapor is accumulated in a region and released over a broad depth results in slightly more rain from a severe storm.

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