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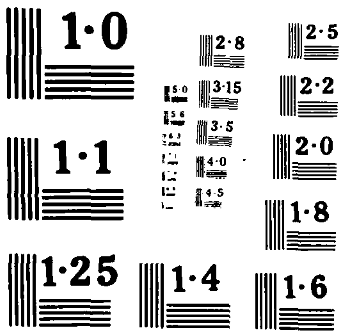
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A SENSITIVITY STUDY OF A ONE-DIMENSIONAL TIME-DEPENDENT WARM CUMULUS CLOUD MODEL

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In this sensitivity study a one-dimensional time-dependent computer cloud model was initiated with a composite of two soundings from day 226 of the GATE project. The soundings were recorded on August 14, 1974 at 1200 Z, off the west coast of Africa from two ships, the DALLAS (USA) and VISE (USSR). The model simulates the life cycle of a cylindrical shaped warm cumulus cloud which is in hydrostatic equilibrium. Although it is formulated in one-dimension, it includes effects from the surrounding environment by turbulent and dynamic entrainment. A series of model runs were executed in which several parameters were varied in order to observe their effects on the evolution of the model cloud. These parameters were: cloud radius, heat pulse duration, cloud condensation nuclei, and model time step duration.

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11. A Sensitivity Study of a One-Dimensional Time-Dependent Warm Cumulus Cloud Model

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1. INTRODUCTION

As part of a project to study the usefulness of atmospheric models, work with a cumulus cloud model was done on the Cyber computer at the Air Force Geophysics Laboratory, at Hanscom Air Force Base. This work was accomplished under the auspices of the Cloud Physics Branch, Atmospheric Science Division.

In this study a cloud model initialized with a composite of two soundings from the GARP (Global Atmospheric Research Program) Atlantic Tropical Experiment (GATE) was used. Cloud simulations were made with this one dimensional, cylindrical, time-dependent model of the life cycle of an isolated warm cumulus cloud (Silverman, and Glass, 1973). The sensitivity of the model with respect to several variable parameters was tested through a series of model runs. These runs tested the effect on the model cloud due to varying the cloud radius size, the duration of the heat pulse, the nucleus spectrum and the time step.

2. MESOSCALE ENVIRONMENT AND SOUNDING DATA

On August 14, 1974, day 226 of the GATE program, a sounding was taken off the west coast of Africa from each of two ships, the Vise and the Dallas. The Vise, from the U.S.S.R., was positioned 08° 30' north and 23° 37' west. The Dallas, from the U.S.A., was positioned 07° 15' north and 24° 48' west. The soundings were taken at 1200 Z, late morning local time. These soundings consisted of the usual thermodynamic variables (pressure, temperature and humidity). A composite of the two soundings was used in the model, (Figure 1). The mesoscale environment during this day was obtained from four aircraft missions flown through a small line of towering cumulus clouds above the ships. These clouds began at approximately the same latitude and longitude as the Vise, and ran northwest to southeast. The conditions north of the line were clear with light winds (4-5 m/s) with cooler, moister air than that behind. As seen by an aircraft observer:

> "In penetrating the line from the northern side, the wind speed on the surface increased substantially as soon as the leading edge of the cloud mass had been crossed. This was evidenced by the sudden appearance of white caps on the surface. It appeared to this observer that near the leading edge, the surface wind speed was greater than the wind speed higher in the sub-cloud layer. In fact, the surface wind speed seemed even greater than the wind speed as low as 30 meters. On the back side of the line, the wind speed was higher than ahead of the line. The trailing edge of the line was very ragged and indefinite. Cloud bases were indefinite and it was hazy. From our vantage point in the subcloud layer, there were no visible towering cumulus; the only evidence of a well defined line of convection was on the radar." (Pennell, 1974)

3 MODEL DESCRIPTION

The cumulus cloud model used in this study combines a vertical equation of motion, an equation of mass continuity, a thermodynamics equation, and equations of continuity of water vapor and liquid hydrometeers.

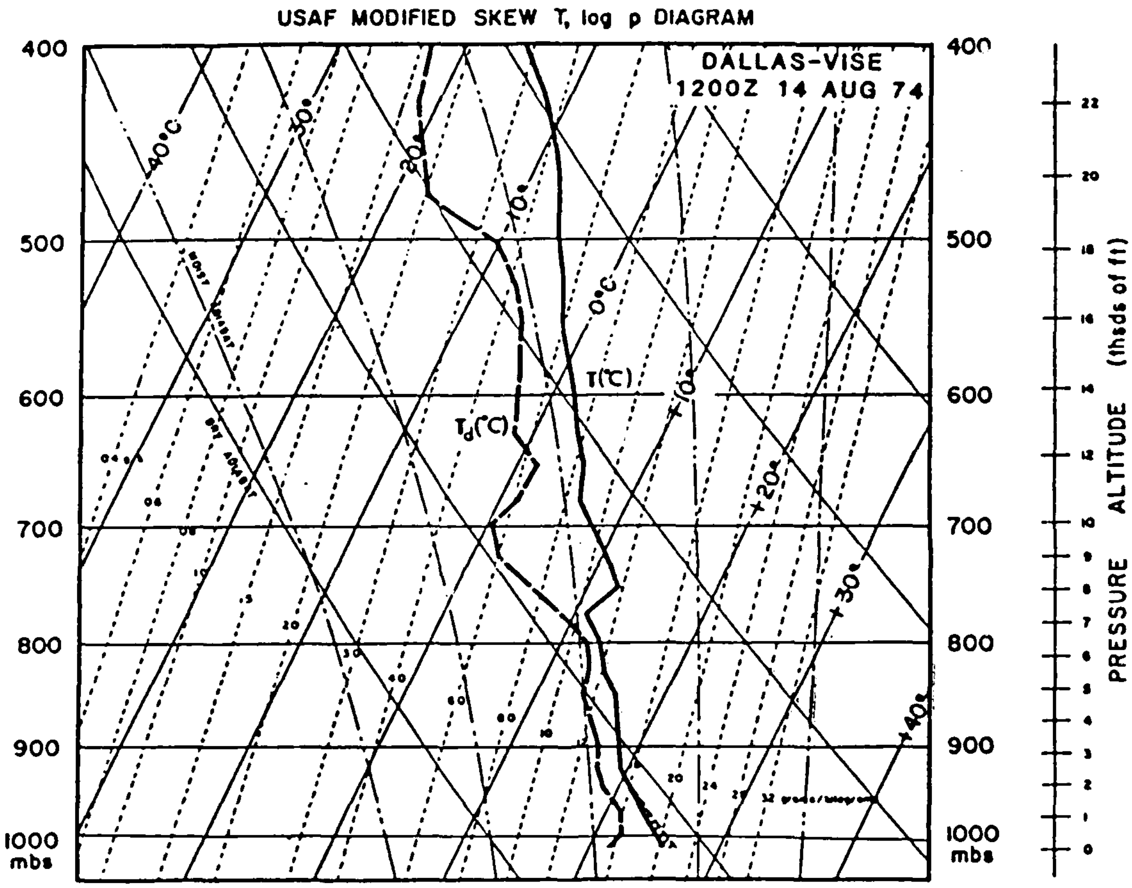

Figure 1. Composite GATE soundings taken at 1200 Z on August 14, 1974 off the west coast of Africa.

During the model's execution a droplet spectrum evolves from an inserted nucleus spectrum by condensation, stochastic coalescence, and droplet break-up. This droplet spectrum is defined with the use of 67 logarithmically spaced Eulerian size classes. The radii of these particles range from 2 to 4040 μm. One limitation in the model is that there exists no mechanism to activate more nuclei above the base of the cloud. Although it is represented in one dimension, the model does allow the dynamic interactions between the cloud cylinder and the outside environment. These interactions are modeled by two terms, turbulent and dynamic entrainment. The first term produces lateral mixing of environmental air into the cloud, and the second simulates the horizontal inflow and outflow of air required to satisfy mass continuity. An outline of the model's basic logic is presented in Figure 2.

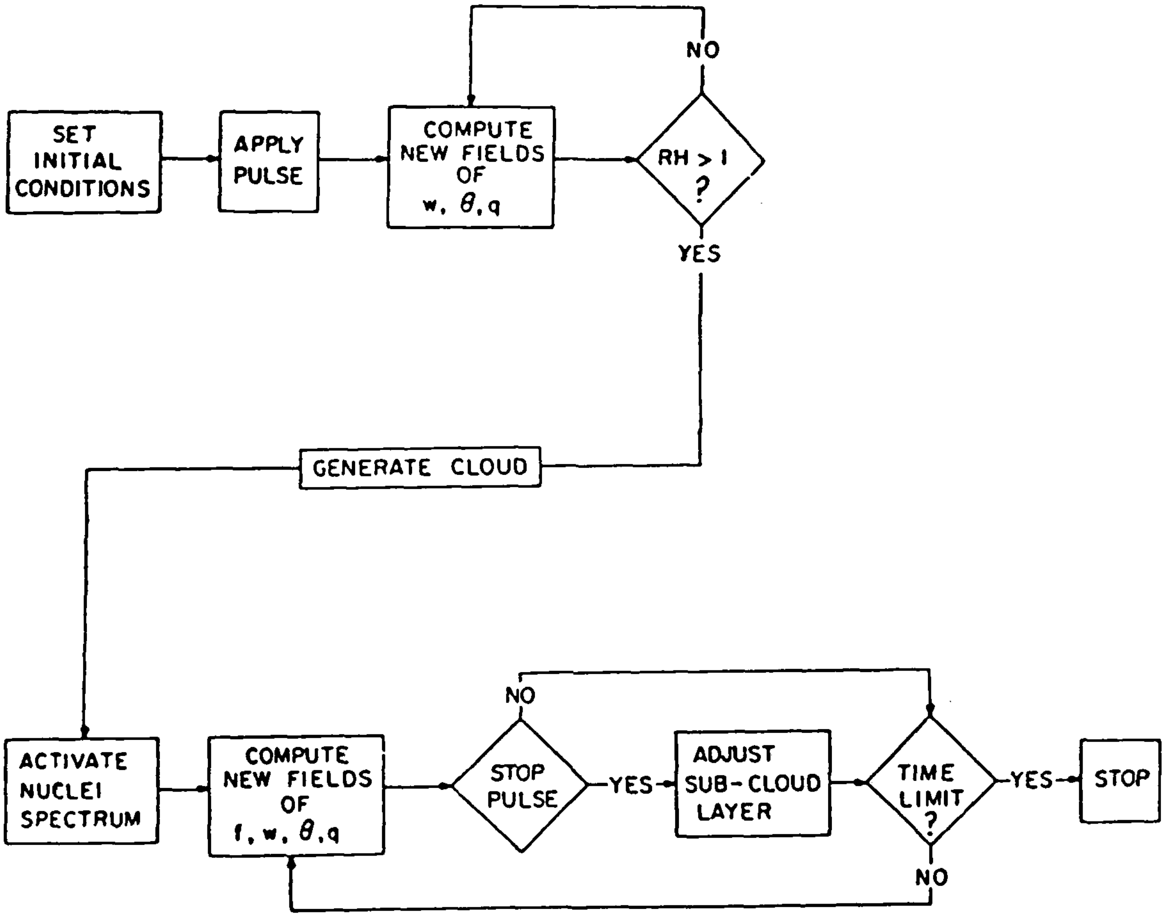

Figure 2. Flow chart of model logic

The data needed to run the model are: a sounding data file, a nucleus spectrum, and several variable parameters which include the cloud's radius dimension, the grid interval, the heating pulse and the heating pulse duration. When the model begins execution a composite sounding, is read in and the pressure, temperature and humidity are calculated for each grid level. The grid levels were set at 100 meter elevation increments for this study. This sets the initial conditions. In the next step an excess temperature pulse (see buoyant pulse in Figure 1) is inserted into the lower grid levels to initiate positive vertical motion. This pulse generates the advection of moisture and temperature up into the cloud cylinder. The cloud base is then determined. It is defined as the lowest level at which the relative humidity is at or exceeds 100 per cent. After the cloud base height is determined the nucleus spectrum is inserted and condensation begins. The droplet spectrum evolves from the nuclei present. This spectrum continues to evolve at each of the grid levels until the positive velocity in the cloud cylinder ceases. Eventually, when the terminal velocity of the drops exceeds the updraft velocity, precipitation occurs.

4. SENSITIVITY ANALYSIS

The sensitivity of the model with respect to four variable parameters was tested through a series of model runs. These runs and their corresponding parameters are summarized in Table 1. The parameters tested were the cloud radius, the duration of the cloud initiating heat pulse, the cloud condensation nuclei, and the cloud time steps.

RUN	A	B	D	E	F	H
BASE(M)	1000	2000	2000	2000	2000	2000
HEAT PULSE(SEC)	CON	CON	600	1200	1200	1200
NUCLEUS SPECTRUM	MARI	MARI	MARI	MARI	CONT	MARI
TIME STEP	VARIES	VARIES	VARIES	VARIES	VARIES	CONST

"CON" = CONTINUOUS
"MARI" = MARITIME
"CONT" = CONTINENTAL
"CONST"= CONSTANT

Table 1. Summary of initial model conditions for indicated runs.

4.1 Model sensitivity to the cloud radius

The effect of the cloud radius on the model cloud's vertical development was tested by comparing the results from running the model with a 1 km radius (Run A) and with a 2 km radius (Run B). The magnitude of mixing of environmental air into the cloud depends on this parameter. This relationship can be seen from the model's vertical velocity, w, equation (1).

$$\frac{\partial w}{\partial t} = -w\frac{\partial w}{\partial z} + K\frac{\partial^2 w}{\partial z^2} + g\left[\frac{\theta - \theta_e}{\theta_e} - Q\right] - \frac{8Kw}{R^2} + Aw \qquad (1)$$

where $A = 0, U_R \geq 0$ or $\frac{2U_R}{R}, U_R < 0$

In this equation R is the cloud's radius, θ is the potential temperature, Q is the liquid water content, and K is the eddy viscosity coefficient. The last two terms in this equation are the turbulent and the dynamic entrainment, respectively. U_R represents the inflow and the outflow of air required to maintain continuity. This is set equal to zero for outflow since the environment is assumed to be unchanging.

The cloud base was calculated to be at 600 meters elevation for both Runs A and Run B. The model calculations in Run A produced a small cloud in which a negligible amount of precipitation size drops formed. The cloud that formed in Run B was longer lived and much deeper than the cloud that formed in Run A. A significant amount of precipitation occurred during Run B. The maximum amount of water in this cloud was obtained 26 minutes after the cloud base was formed. Some comparisons of the cloud characteristics for the two runs are shown in Table 2.

RUN	CLOUD RADIUS (KM)	MAX. HEIGHT (M)	TOTAL LWC IN IN CLOUD AT 26 MIN (G/M^3)	CUMULATIVE WATER CONDENSED AFTER 30 MIN. (G/M^3)
A	1.0	1250	2.9	20.0
B	2.0	2650	25.7	92.0

Table 2. Model cloud characteristics using indicated radius.

4.2 Model sensitivity to the heat pulse duration

The motion initiating heat pulse used for all of the model runs had a maximum value of 0.9° C at ground level, and decreased to 0.2° C at 400 meters elevation. Although the sounding used indicates a relatively stable environment, the line of cumulus clouds and the wind field which were observed when the soundings were recorded suggest that these clouds developed in a region of convergence. For this reason a continuous updraft was assumed; therefore, the buoyant pulse was kept on continuously during Run B. In order to test the importance of the buoyant pulse that maintained cloud development in this environment, Run B was compared with Run E in which the heating pulse was continued for 20 minutes, and also with Run D in which the heat pulse was continued for only 10 minutes. Figure 3 shows the time history of the liquid water in the cloud and as rain for Run B. Figure 4 is a similar history for Run E.

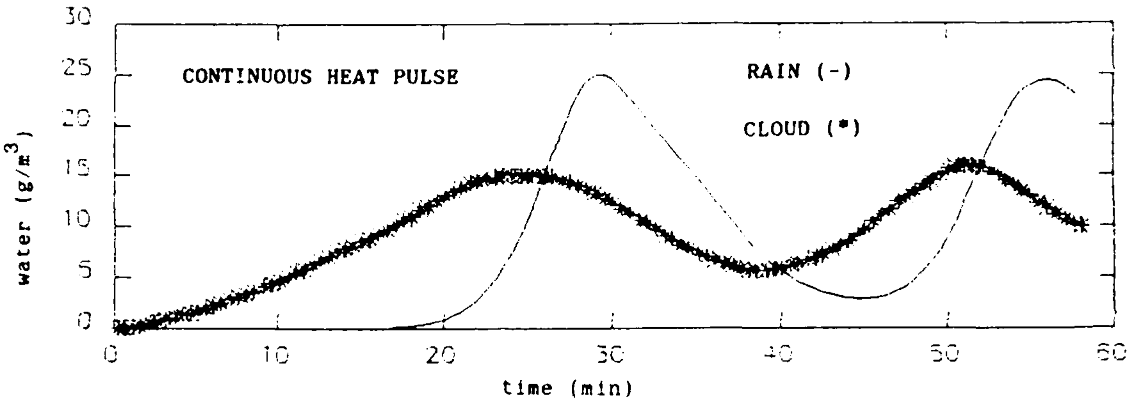

Figure 3. The comparison of cloud and rain water in Run B

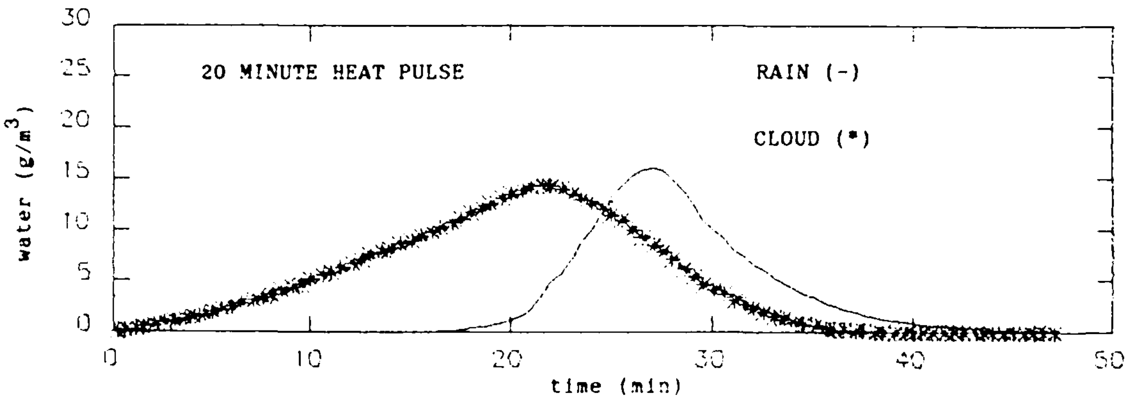

Figure 4. The comparison of cloud and rain water in Run E

As can be seen by comparing Figures 3 and 4, the continuous pulse caused new cloud growth and precipitation after the initial cloud development. The importance of the pulse duration in this environment is also shown in Run D, where the pulse was shut off after 10 minutes of cloud life, well before precipitation size drops had formed. This cloud did not grow very deep and very little precipitation formed. Some comparisons are summarized in Table 3.

RUN	PULSE DURATION (MIN)	MAX. HEIGHT (M)	TOTAL LWC IN CLOUD (G/M^3)	
B	CONT.	2650	25.7	(t = 26 min.)
E	20	2550	22.2	(t = 26 min.)
D	10	1650	6.5	(t = 6 min.)

Table 3. Pulse duration comparisons.

4.3 Model sensitivity to the nucleus spectrum

The nucleus spectrum, inserted at the cloud base, also effects the life of the model cloud. Since the soundings used in the model were made over the ocean, a nuclei spectrum typical of this maritime environment was used in the model runs. In this section the influence of the nucleus spectrum on cloud growth and precipitation amount was tested by comparing results of model calculations in Run E with Run F in which a continental spectrum was inserted to replace the maritime spectrum. A study of cloud condensation nuclei (CCN) over various parts of the world by Twomey and Wojciechowski (1969), presented in *Microphysics of Clouds and Precipitation* (Pruppacher and Klett) showed that continental air masses generally contain more CCN than maritime air masses. These differences are reflected in the maritime and continental spectra used in this sensitivity study, (Figure 5).

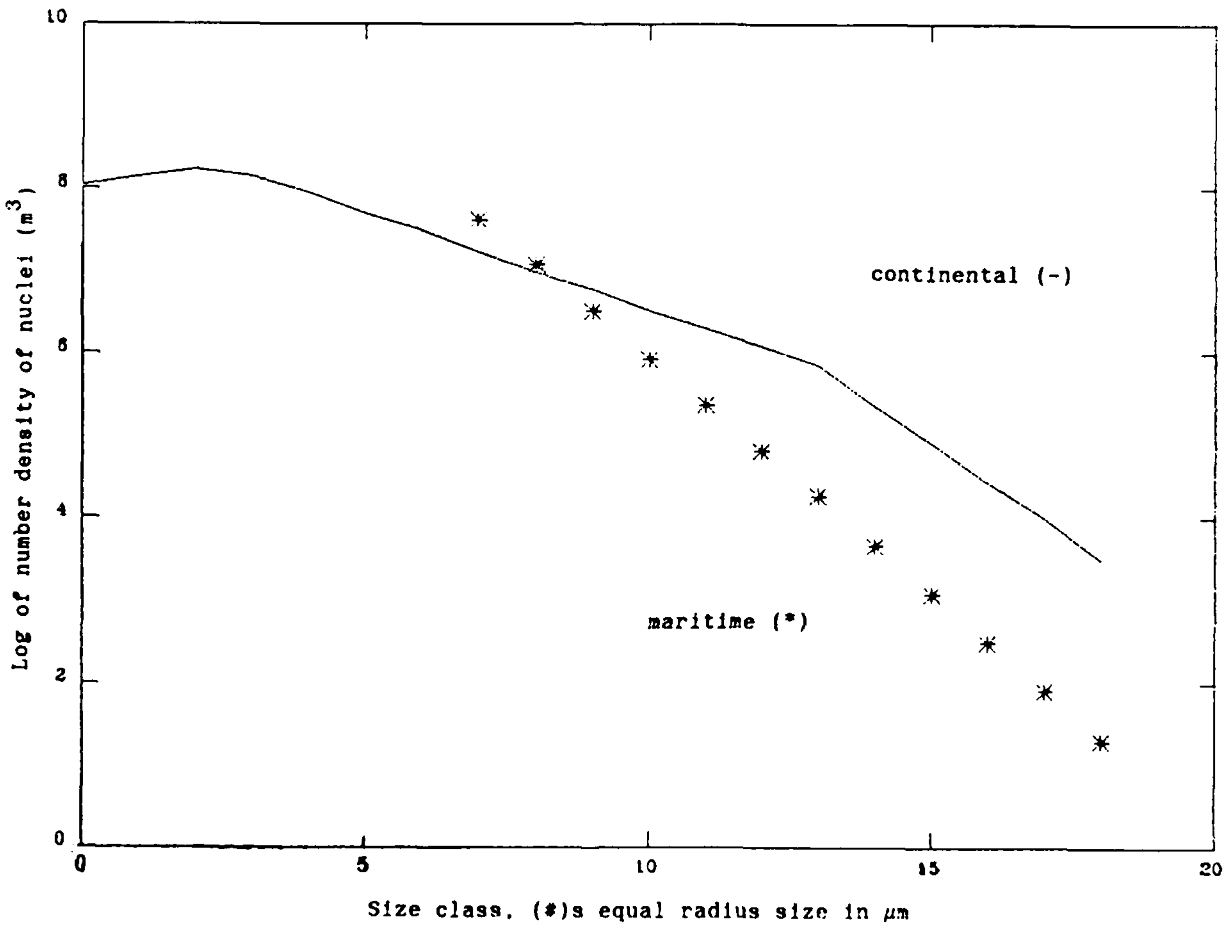

Figure 5. The number density of condensation nuclei versus size class

As can be seen in the figure the continental spectrum has a large number of very small condensation nuclei. The total number density of the continental and maritime spectra are, respectively, 730 cm^{-3} and 60 cm^{-3}. Figures 6 and 7 show the distribution of the total amount of liquid water in the cloud system with time for Runs E and F.

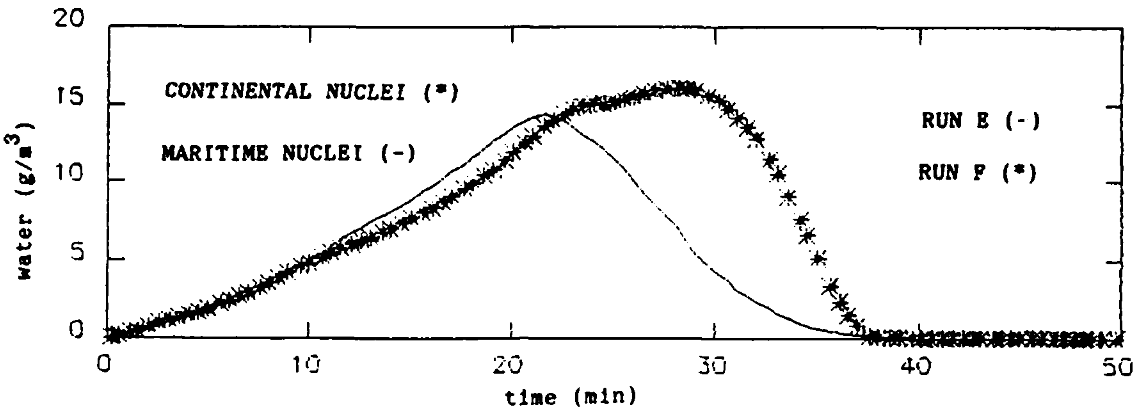

Figure 6. Cloud water comparison of Runs E and F

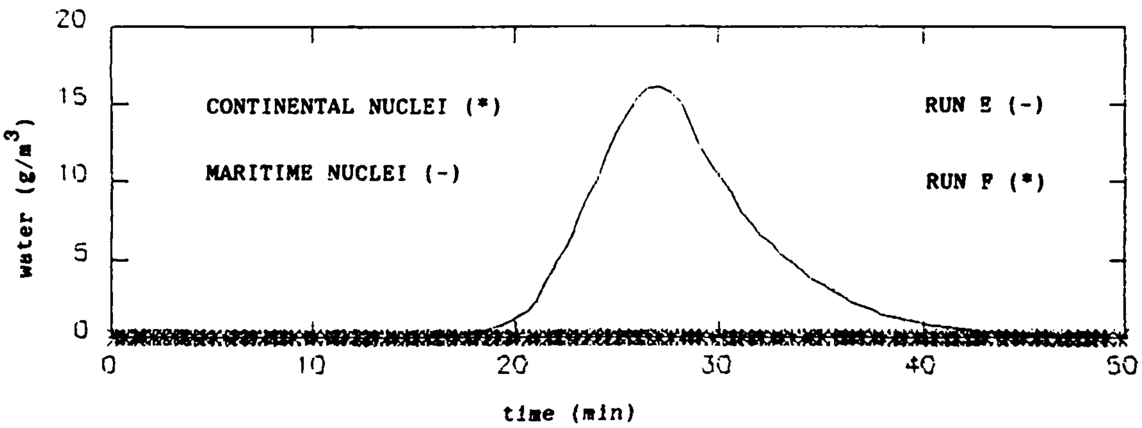

Figure 7. Rain water comparison of Runs E and F

Figure 6 compares the amount of water in the two runs due to cloud size droplets (radius less than or equal to 100 μm) and Figure 7 shows liquid water due to precipitation size drops (radius greater than 100 μm). Comparison of Figures 6 and 7 show the rapid conversion of cloud liquid water to precipitation liquid water after 15 minutes of cloud life in Run E, while in Run F, the conversion was slow and did not occur until after 30 minutes of cloud life. Most of the condensed water remained as small drops and less total precipitation was produces in the model in Run F than in Run E, (Figure 7). This was because there were large numbers of CCN competing for condensing water when the continental nuclei were present and fewer cloud droplets were able to grow to rain drop size.

4.4 Model sensitivity to the time step

The final phase in our model sensitivity study was to compare the results obtained when a variable time step was used to the results obtained when this time step was kept constant. This time step, DELT, is a function of the maximum vertical velocity, the grid interval, and the turbulent diffusion. A constant time step of 5 seconds was chosen. This step was always less than required by the model processes. Comparison of Run H with Run E showed no significant differences.

5. CONCLUSIONS

A sensitivity study was done with a time-dependent model of the evolution of an isolated warm cumulus cloud. This model was initiated with a composite sounding from a GATE project to observe the effects on the growth of the cloud due to the cloud radius size, the duration of the cloud initiating heat pulse, the cloud condensation nuclei, and the time steps. An optimum cloud radius size was determined which would create a rain producing cumulus cloud. This radius was 2 km. A smaller radius would increase the effect of turbulent and the dynamic entrainment and inhibit the evolution of the model cloud. The duration of the vertical heat pulse was changed during model runs to control the time length of the simulated updraft and observe the effect on cloud growth. We concluded that a constant heat pulse would best simulate the assumed environment in this study and would produce the maximum amount of precipitation. It was established that the best nucleus spectrum to use to initiate rain producing, also, is a maritime nucleus spectrum. In this spectrum there are fewer nuclei on which water can condense. Therefore, more particles will evolve into rain drops than with a continental nucleus spectrum because fewer CCN are competing for the water vapor. Our final test showed that a time step based on numerical stability gives results which were similar to results when the time step was held constant. Therefore, comparison with calculations from other models, where time step is held constant, is valid.

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