A Simplified Concept of Hygroscopic Seeding

H. D. Orville, Chengshu Wang, and F. J. Kopp

Institute of Atmospheric Sciences
South Dakota School of Mines and Technology
Rapid City, SD

ABSTRACT

A bulk-water microphysical convective cloud model is used to investigate the maximum effect of hygroscopic seeding. Using the fact that the desired cloud seeding effect is to transform the cloud from a continental one to a maritime one makes hygroscopic seeding a particularly easy process to simulate in bulk-water microphysics cloud models. In those types of cloud models one only has to change the autoconversion threshold (i.e., the onset of coalescence) and the number concentration and dispersion characteristics of the cloud water to switch from a continental-type cloud to a maritime-type cloud. The continental cloud has no autoconversion, the maritime cloud an extremely efficient autoconversion process. Admittedly, this tests two extreme situations and makes the assumption that the effects of hygroscopic seeding will be somewhere between the two extremes, the maximum effect being represented by the maritime-type cloud. Very preliminary results indicate that the hygroscopic seeding would be quite efficient on small to moderate size clouds but its effect is much less definite on larger clouds. The dynamics of the clouds are crucial to the results.

1. Introduction

Hygroscopic seeding has received renewed interest in the past few years due to studies conducted in South Africa. Mather *et al.* (1996), Cooper *et al.* (1997), Mather *et al.* (1997), Bigg (1997), have studied the effects of seeding convective clouds in South Africa with hygroscopic flares and found strong indications of rainfall increases, as much as 30% to 60% increases from individual cloud complexes. Several kilograms of salt are released into the clouds as small micron (or fraction of a micron) size particles. The numerical calculations of Cooper *et al.* (1997) considered both condensation and coalescence using initial cloud condensation nuclei (CCN) characteristic of continental and maritime clouds. Cloud seeding simulations considered the sizes, chemical composition, and number concentrations of the salt material. Results indicated a rapid transfer of the cloud water into rain water in seeded cloud parcels in many of the seeding experiments. Presumably, continental-type clouds would be transformed to maritime-type clouds by the seeding, making them more efficient precipitators.

We have been numerically simulating cloud seeding techniques for a number of years using more complicated dynamic models but with much less complex or complete microphysics than Cooper *et al.* Some of our efforts have been devoted to salt seeding (Kopp *et al.*, 1996), in which we simulated the transport of the seeding agent and its interactions with the cloud and rain water. Both wing-mounted flares and cabin-hopper release of the seeding material were simulated. In our simulations the flares are assumed to produce micron size particles affecting the size distribution of the cloud droplets and activating a coalescence process within the cloud. The hoppers are assumed to release large (tens of microns) size salt particles capable of immediately becoming raindrop embryos within the cloud domain. These effects are parameterized in the modeling work (see Kopp *et al.*, 1996). The model results were mixed, some clouds producing more rain and some less. The cloud dynamics and their interactions with the microphysics were crucial to the results.

1.1 Outline of the current study

Perhaps hygroscopic seeding could be even less complicated to simulate than the above study would indicate. Using the fact that the desired effect is to transform the cloud from a continental one to a maritime one makes hygroscopic seeding a particularly easy process to simulate in bulk water microphysics cloud models. In those types of cloud models one only has to change the autoconversion[1] threshold and the number concentration and dispersion characteristics of the cloud water to switch from a continental-type cloud to a maritime-type cloud. The continental cloud has no autoconversion, the maritime cloud an extremely efficient autoconversion process. *So to test the effects of hygroscopic seeding one has only to run a cloud model with the same atmospheric sounding, but with model conditions appropriate for either a continental cloud or a maritime cloud.* The basic assumption is that the maritime case represents the maximum effect of hygroscopic seeding on a continental convective cloud. The seeding material would have to be dispersed completely throughout the cloud and cause coalescence to occur immediately. Admittedly, this tests two extreme situations; the actual effect of the seeding would be somewhere between the two extremes.

The purpose of this paper is to show two examples of cloud development – one moderate, the other a strong cloud case – and to demonstrate the effects of continental or maritime microphysics in two different runs for each case, thereby revealing the maximum effect of hygroscopic seeding (the maritime run as compared to the continental run). We can then speculate on the effects of such seeding on the South African clouds or any continental convective clouds. In addition, the results reveal the effects of hygroscopic seeding on the total development of the clouds, including the microphysical ice processes.

2. Brief description of model

The model used in this study is a two-dimensional, slab-symmetric, time-dependent, deep-convection cloud model (2DTD), with bulk water microphysics included. It has been developed from the works of Orville (1965), Liu and Orville (1969), Wisner *et al.* (1972), Orville and Kopp (1977), and Lin *et al.* (1983). The typical domain of the model is 20 km in both the *x* and *z* directions with a 200 m grid interval. The main dependent variables are: atmospheric wind, potential temperature, water vapor, cloud liquid, cloud ice, rain, snow, and graupel/hail (in the form of ice pellets, frozen rain, graupel, and small hail).

The model contains five classes of hydrometeors: cloud water, cloud ice, rain, snow, and high-density precipitating ice (graupel/hail). The production of these hydrometeors is simulated by using bulk water techniques. Rain, snow, and graupel have appreciable terminal velocities, while cloud water and cloud ice are considered to have zero terminal velocities and therefore follow the trajectories of the airflow. Helsdon and Farley (1987a) provides a summary of the primary cloud microphysical processes and interactions simulated in the model.

The basic equations are nonlinear partial differential equations which include the first and third equation of motion, a potential temperature equation, and the equation of state for a mixture of air and water vapor. The vorticity equation is derived from the equations of motion and continuity. The input to the model is in the form of an atmospheric sounding giving the temperature and dewpoint structure and the vertical profile of the horizontal wind.

3. Results

A sounding taken from North Dakota is used as initial conditions in the simulations. The continental runs have the autoconversion process turned off. The maritime runs have autoconversion turned on as soon as any cloud water appears. In addition, the cloud water is assumed to have a number concentration and dispersion characteristic of maritime clouds.

3.1 North Dakota Moderate Cloud Case

A sounding from Bismarck, North Dakota, 28 June 1989 (Fig. 1) was used to illustrate the effects of different microphysical characteristics (either maritime or continental) on a moderate size convective cloud. The simulated clouds represent early,

[1] Autoconversion is numerical modeling jargon used to describe the transformation of cloud water (composed of small droplets) to rain water (composed of large drops). Coalescence of the cloud droplets is the presumed physical process to effect the transformation.

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smaller cloud development on this day because the morning sounding was used. Later in the day, after extensive surface heating and the movement through the area of an upper level trough, a larger, convective complex moved through the area. Our second case resembles these clouds more closely.

Figure 1 shows the temperature and dew-point curves. Considerable instability is evident. Surface heating of 200 w/m^2 and lower-level convergence of $5x10^{-5}$ s^{-1} were simulated. A sine function with maximum amplitude of 1.5°C applied at time zero was used to initiate a temperature perturbation in this case. No water vapor perturbation was applied.

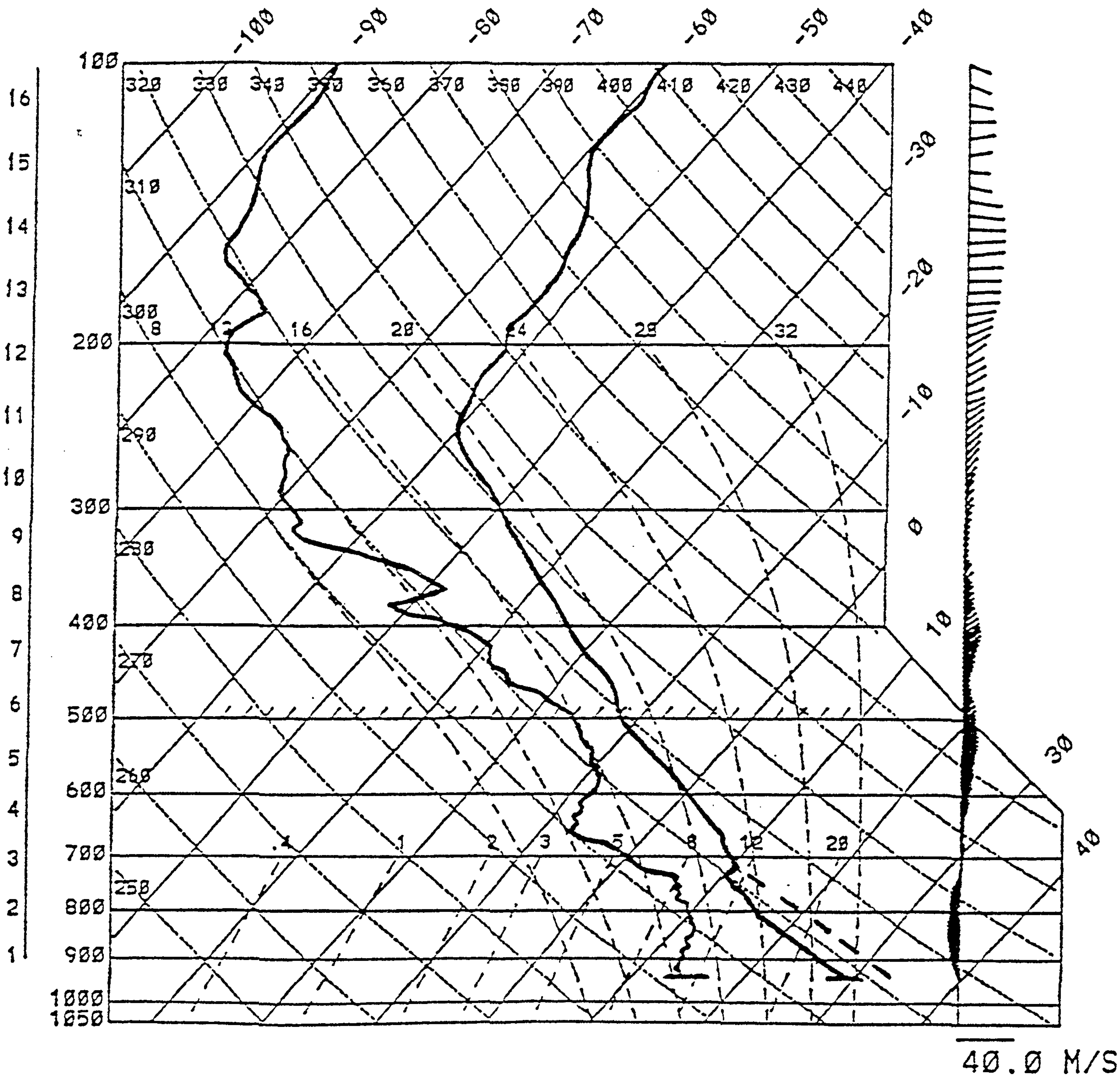


Figure 1: An atmospheric sounding from Bismarck, ND for the afternoon of 28 June 1989. The temperature curve is on the right, dewpoint temperature on the left. The wind barbs on the right indicate wind direction and speed; upper winds are blowing towards the east.

Figures 2 and 3 show the general history of the types of clouds that form using this sounding and this initiating perturbation. Figure 2 is for the continental conditions, Fig. 3 the maritime microphysical conditions. The only difference between the two runs is in the autoconversion threshold (0 for the maritime cloud and 20 g/kg for the continental cloud case) and the number concentration and dispersion coefficient (100 cm^{-3} and 0.45 for the maritime case, 972 cm^{-3} and 0.15 for the continental case [the number concentration taken from observations]). The large threshold for the continental cloud case means that no autoconversion occurs in the continental cases.

The history figures show two cells in each case developing in a bubble-like fashion. The precipitation shows up much earlier in the maritime run than in the continental run, and is rain in Fig. 3 at 18 min and snow in Fig. 2 at 24 min. Almost no graupel/hail appears for the continental run. The snow processes appear in both runs at similar times. More snow is evident in the continental run in the three later time panels of Figs. 2 and 3. The snow process eventually leads to graupel/hail in the continental run and melts into small amounts of rain (Fig. 2, 36 min). The graupel/hail process is much more evident in the maritime run, although little hail reaches the ground.

The dynamics of the clouds are very similar, as indicated in the graph of the vertical velocity maximum, Wmax, Fig. 4. Maximum vertical velocities of about 26 m/s occur in both runs. The greater velocity in the maritime run at about 42 mins due to the more vigorous development of a third cell to the right of the domain.

Shown in Fig. 5 is the accumulated rainfall and hailfall at 90 min in the two runs. More rain has accumulated in the maritime cloud run as well as a redistribution of rain. Figure 6 shows the time history of the rain fallout. Rain appears earlier in the maritime cloud, as would be expected, at 24 min in the maritime cloud and 38 min in the continental cloud. Twice as much rain occurs in the maritime case (34 vs. 17 kton/km). Negligible amounts of hail occur in both runs.

These results show clearly the effects of early coalescence in a cloud. The production of rain leads to the formation of graupel/hail in the updraft of the maritime cloud and a more precipitation-efficient cloud. Presumably, extremely efficient hygroscopic seeding would cause a similar effect on a continental cloud having these general dynamic characteristics.

3.2 North Dakota Strong Cloud Case

The same sounding was used as in the previous case. However, a random temperature perturbation method was used to initiate cloud after 30 min of surface heating. In addition, the model domain was extended to 30 km in the horizontal. These changes lead to a more vigorous cloud system being developed. As in the previous case and using the same numbers, the autoconversion threshold and the number concentration and dispersion are changed to produce the continental and maritime clouds.

Figures 7a, b and 8a, b show the evolution of the clouds in this case, Fig. 7 for the continental clouds and Fig. 8 for the maritime clouds. Figure 9 shows the graphs of Wmax for the two situations. The clouds grow rapidly, topping out at about 13 km, one km higher than in the previous case. Vertical velocities greater than 40 m/s occur in the continental run, slightly less in the maritime run because of the earlier loading of the updraft. The maximum in the continental run coincides with the rounded cloud dome in Fig. 7a, 87 min panel). After about 90 min the vertical velocity maxima are greater in the continental run; the greater dynamics of the continental clouds lead to the greater precipitation production and fallout. The clouds in both runs form a large anvil cover, much as occurred on this day in nature (Boe and Johnson, 1990).

The precipitation development is quite different in the early stages in the continental run compared with the maritime run. The continental clouds produce precipitation through the ice processes, the maritime clouds through the warm rain and ice processes. Rain reaches the ground about 10 min earlier in the maritime run, 80 min vs. 90 min, Fig. 10. Hail falls about 5 min earlier in the maritime run and is less than in the continental run (Fig. 11). The maritime run produces 20% less rain and 58% less hail than the continental run, due to the weaker dynamics of the maritime run.

4. Discussion

These two cloud situations produce very different results, depending on whether the clouds are maritime or continental in character. The smaller, less vigorous clouds produce more rain (and no hail) if they initiate a rain process as soon as cloud water is produced (the maritime clouds). The

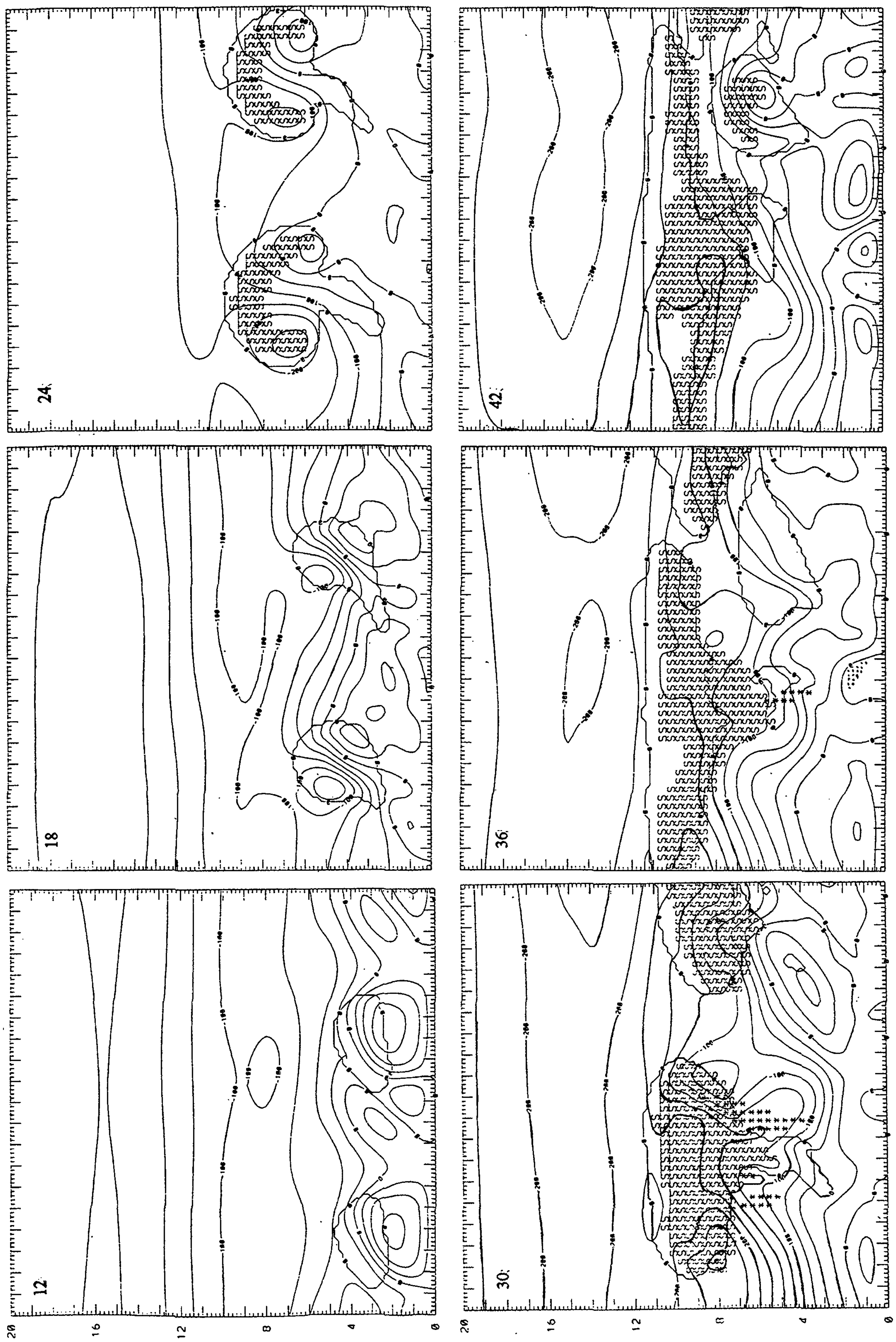


Figure 2: The panels show the evolution of the clouds for the continental run, moderate size cloud. Simulated real times are shown in the upper left corner of each panel. Cloud areas are outlined by a solid line, and streamlines are also solid. The symbol S indicates snow mixing ratios > 0.5 g/kg, asterisks and dots, graupel/hail and rain mixing ratios > 1.0 g/kg, respectively, and horizontal dashes indicate cloud ice mixing ratios > 0.5 g/kg. The contour intervals for the streamlines are either 25 or 50 kg/m/s in the various panels. The distance along the X and Z axes are in km (each major tick mark is 1 km).

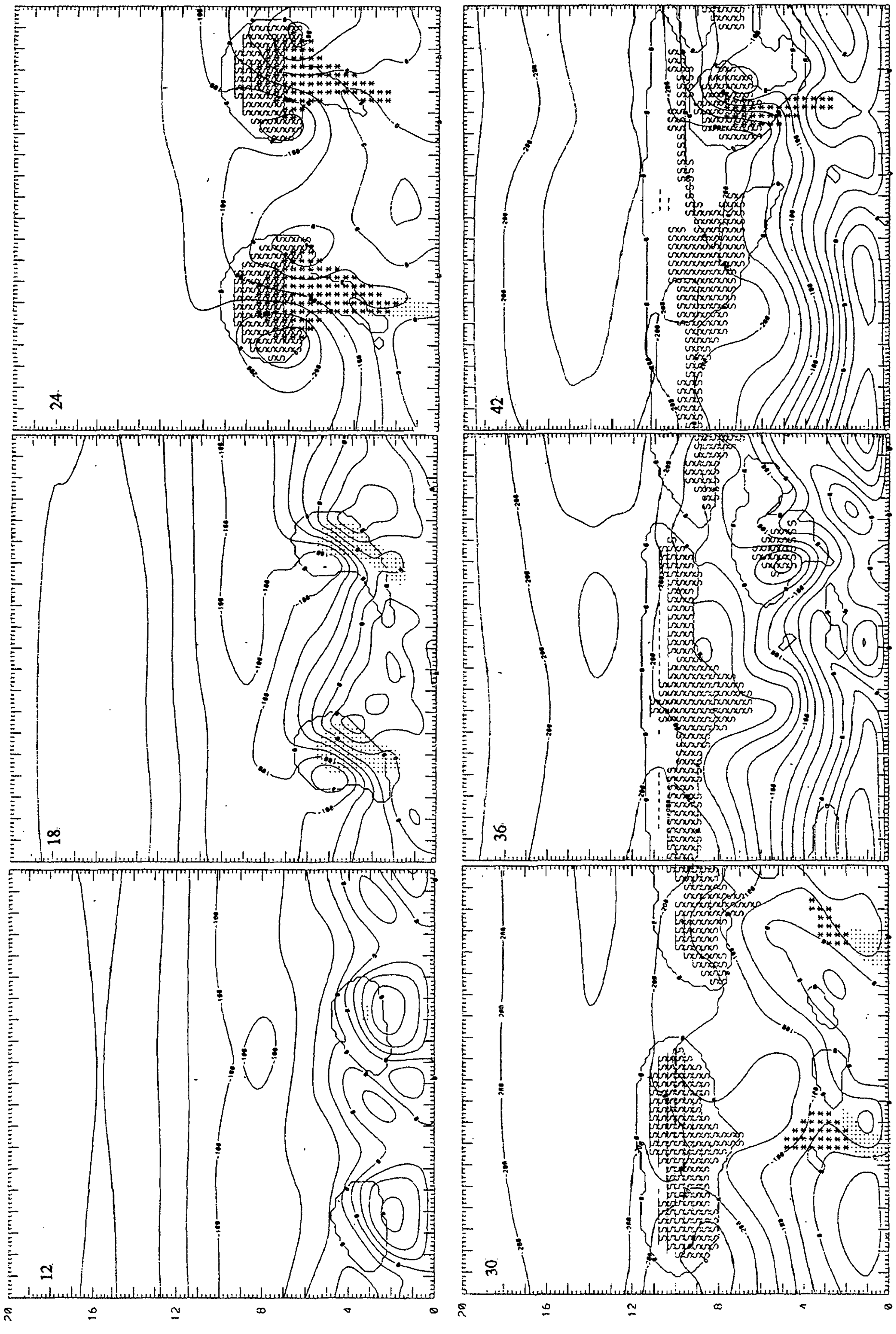
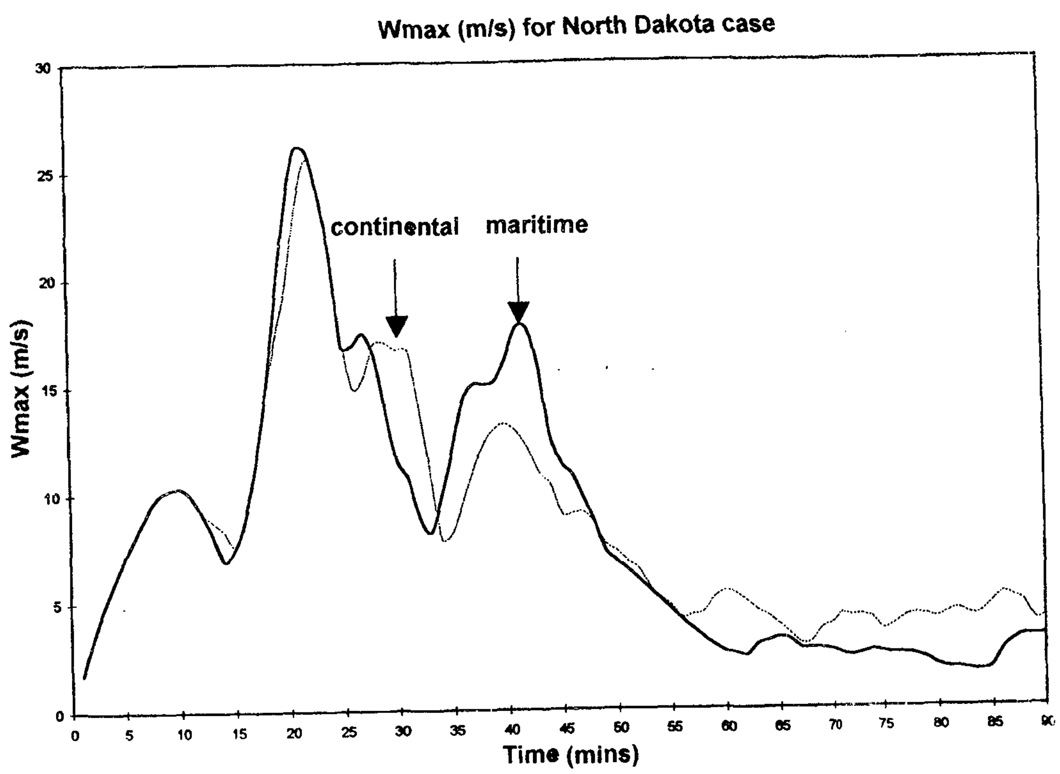
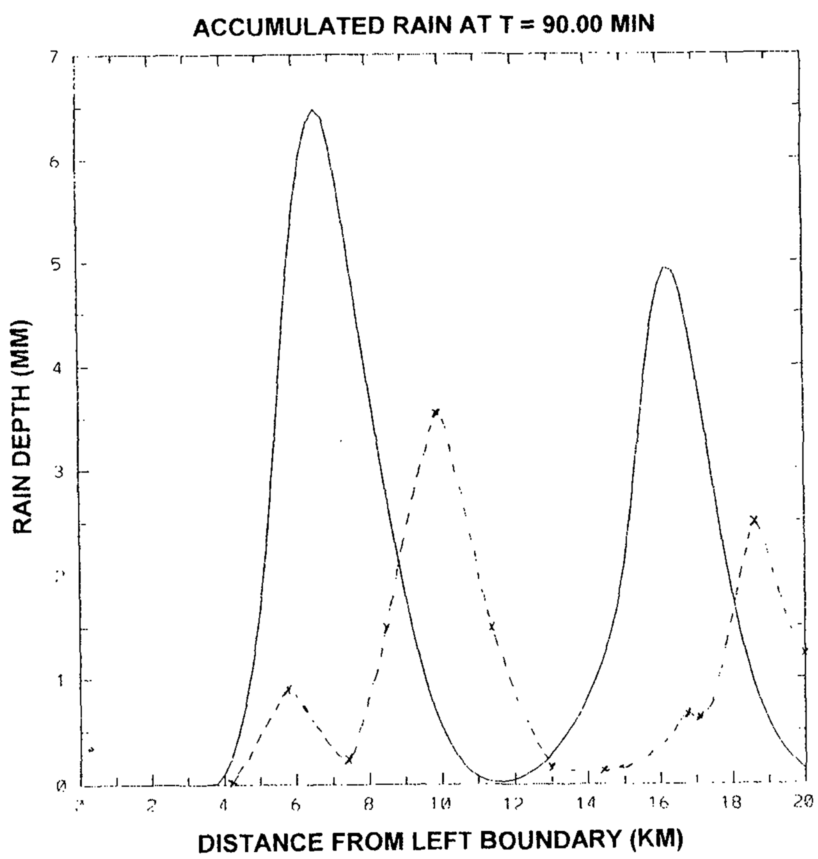


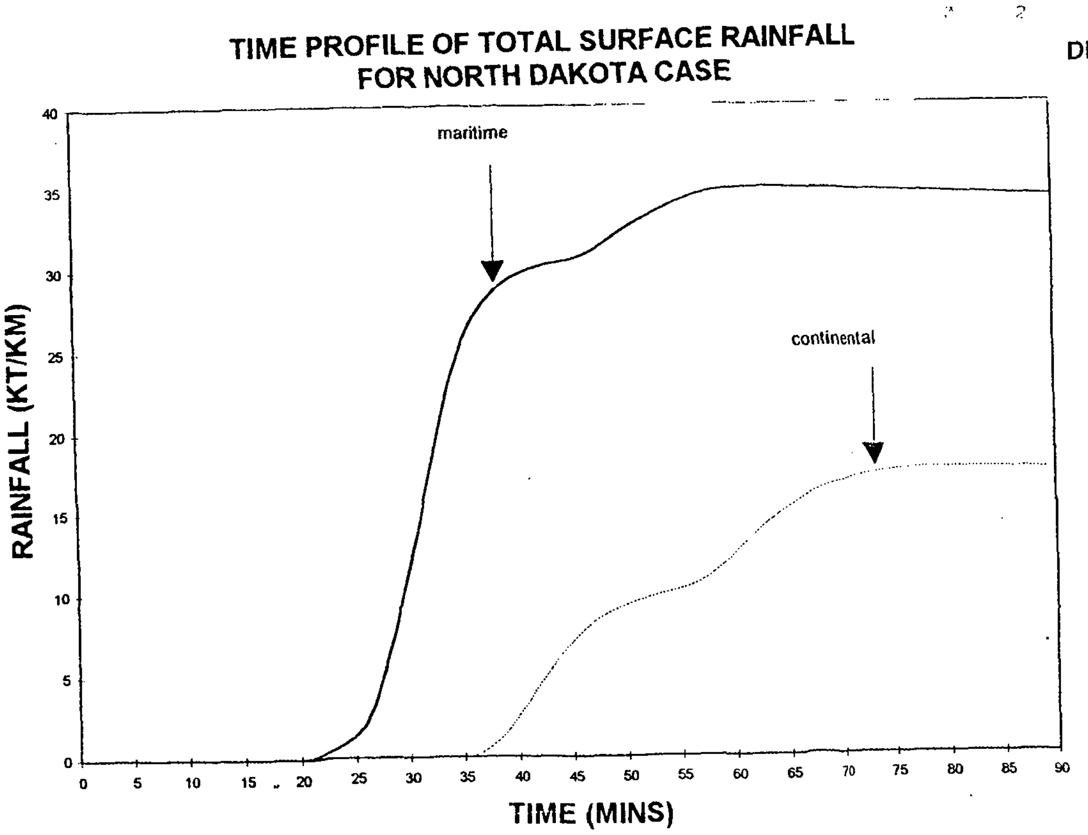
Figure 3: As in Fig. 2, except for the maritime run, moderate size cloud case.



← *Figure 4: The evolution of the maximum vertical velocity for the continental and maritime clouds.*



→ *Figure 5: The accumulated rain at the ground after 90 min of simulate real time for the continental (dashed line) and maritime clouds (solid line), moderate size cloud case. Rain depth is in mm.*



← *Figure 6: The accumulation of rain vs. time. Total rainfall is in kton/km.*

7a

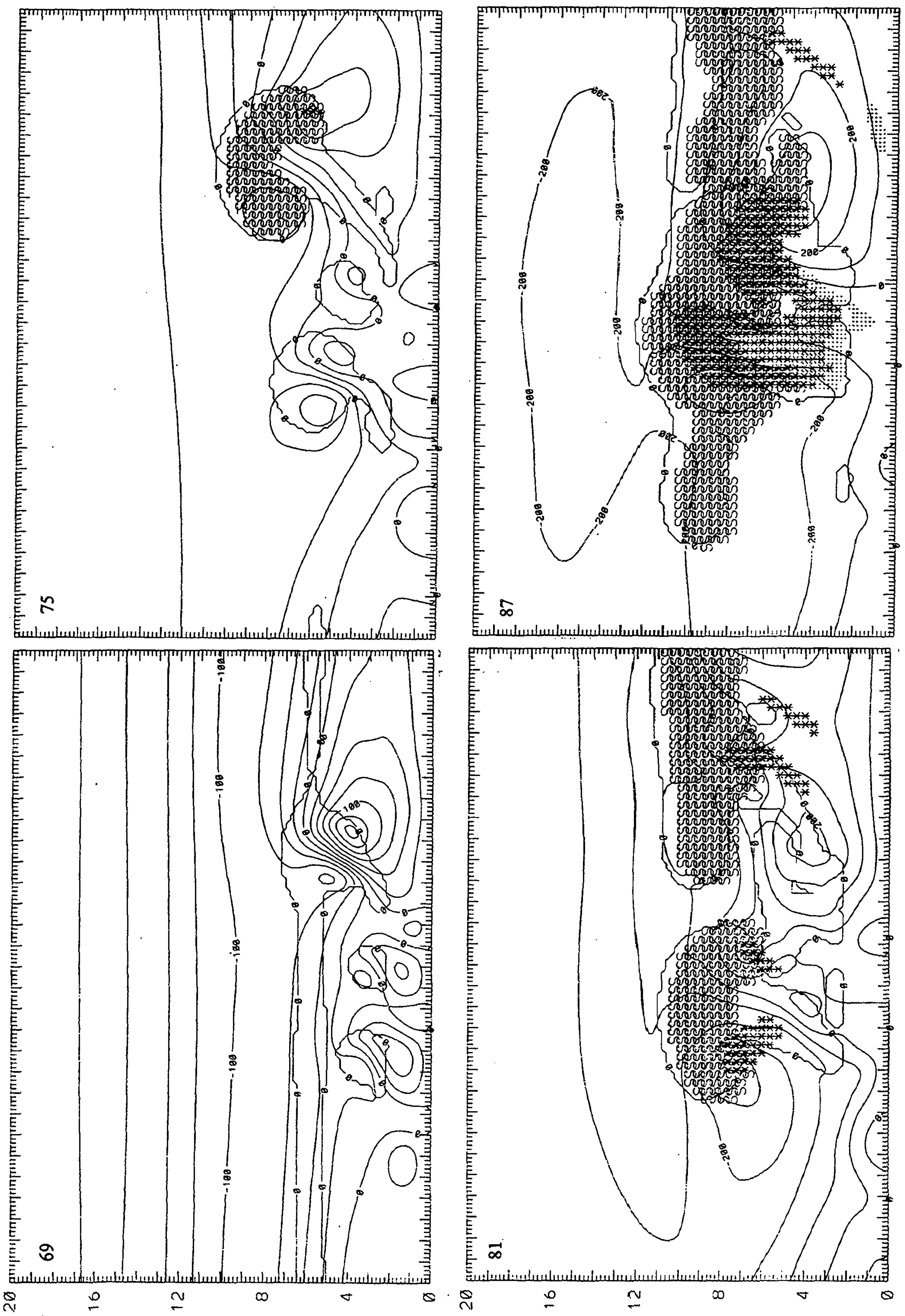
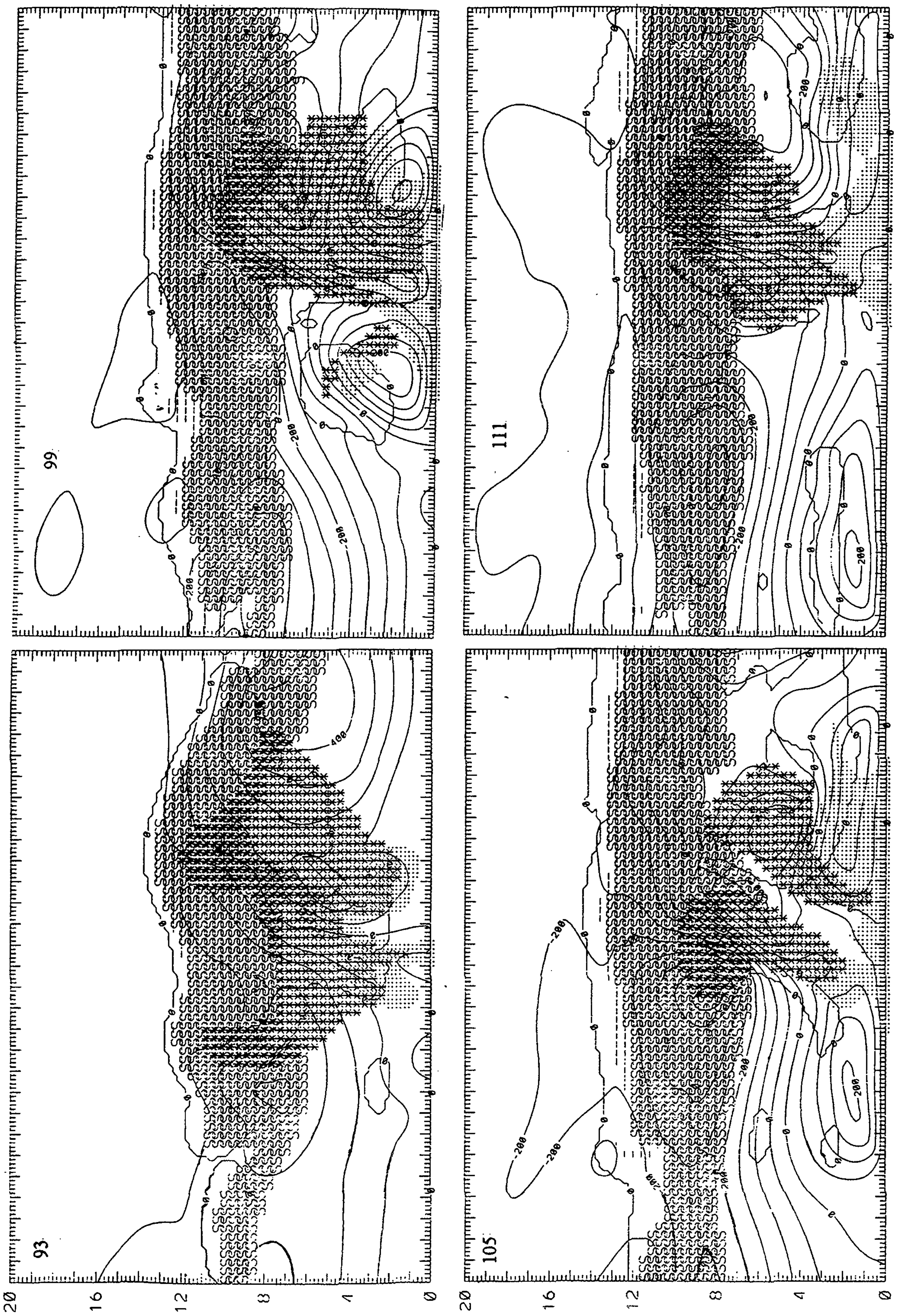


Figure 7a,b: As in Fig. 2, except for the continental clouds, strong cloud case. Figure 7a and 7b are for the early and later stages of the cloud evolution, respectively.

7b



8a

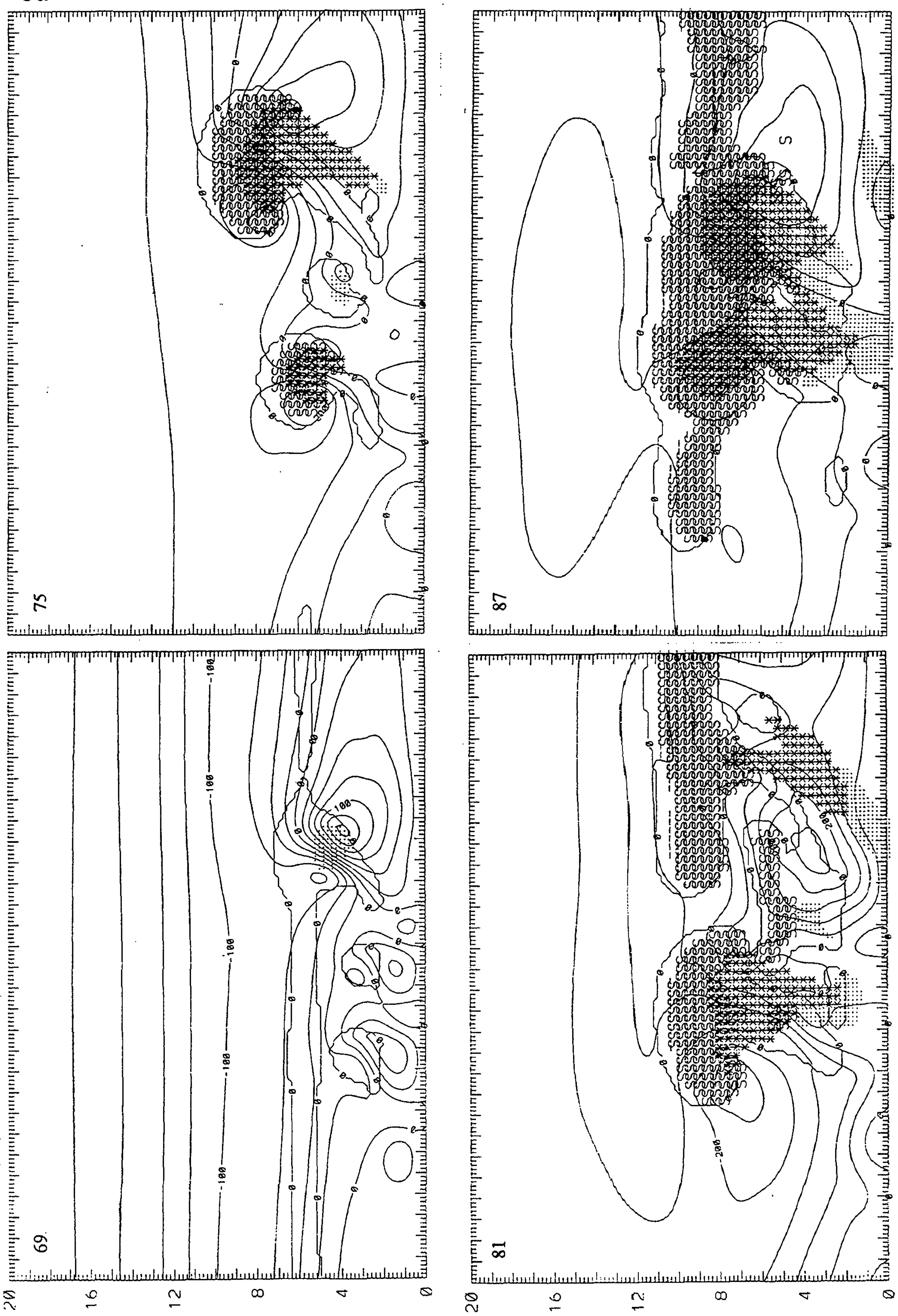
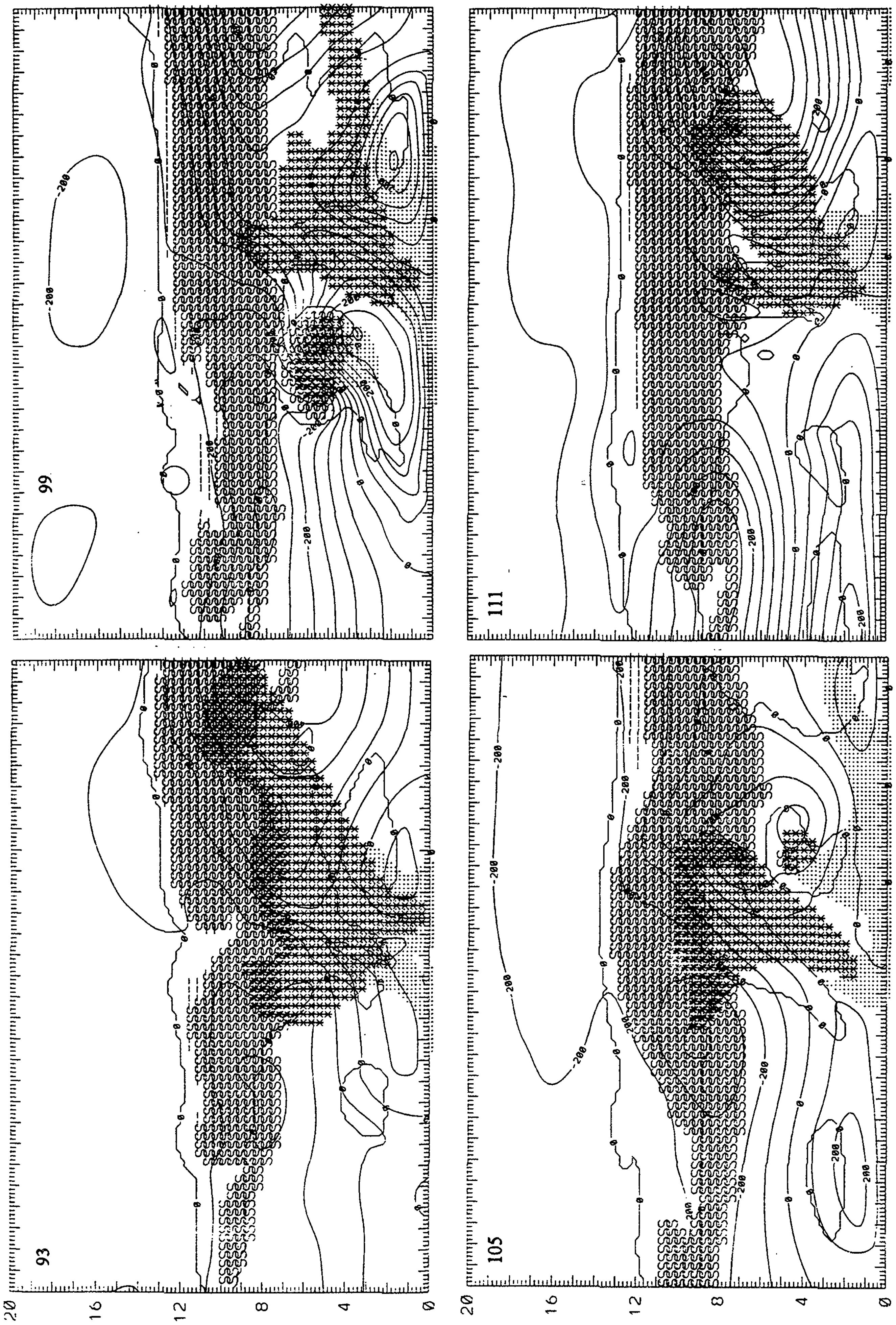


Figure 8a,b: As in Fig. 2, except for the maritime clouds, strong cloud case. Figure 8a and 8b are for the early and later stages of the cloud evolution, respectively.

8b



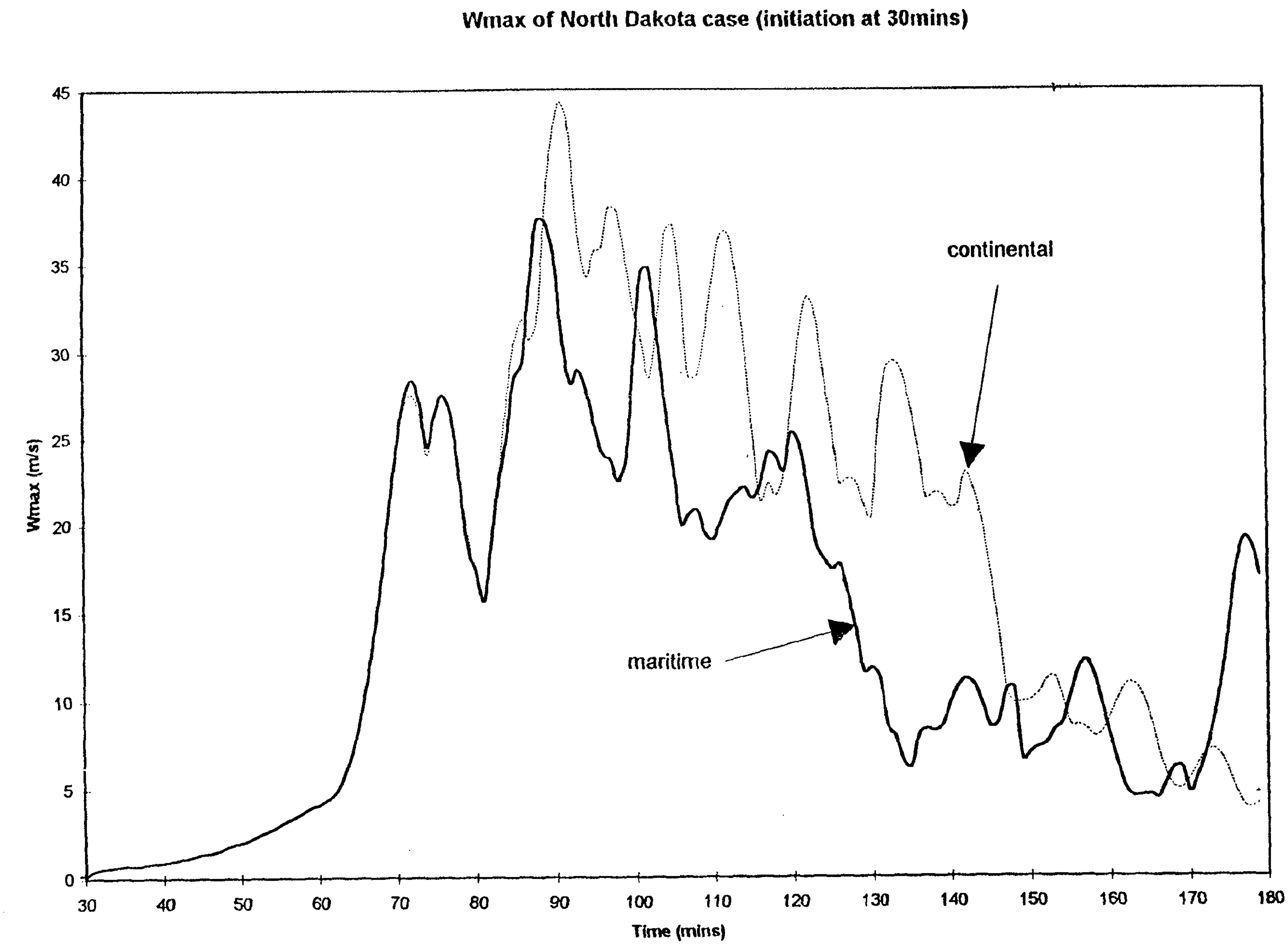


Figure 9: As in Fig. 4, except for the stronger cloud case.

delay in the rain process and the initiation of precipitation through the ice process (continental clouds) reduce the amount of rain formed and the amount of rain on the ground. Hygroscopic seeding of these continental-type clouds should lead to an increase in rainfall, perhaps doubling the rain amount in a perfectly-executed experiment. The hygroscopic seeding affects the timing of the precipitation formation and the initiation of the ice processes, particularly the formation of graupel/hail (via the processes of the freezing of rain and the interaction of rain and cloud ice to form snow and graupel/hail).

The stronger cloud system situation gave opposite results, in some sense. The maritime clouds still rained and hailed at an earlier stage of their life cycle, but their net precipitation turned out to be less than from the continental-type clouds. The continental clouds developed stronger updrafts and more rain and hail in this more unstable situation. Hygroscopic seeding of this type of continental clouds should result in a decrease in rain and hail.

Other cases have been run, some using the more-complete seeding treatment mentioned above (Kopp, *et al.* 1996). The seeding-agent runs always give results intermediate to the two extremes, continental or maritime.

These preliminary numerical results once again indicate the complexity of cloud seeding and the crucial importance of the interaction of the microphysics and the dynamics of the clouds. Admittedly, the concepts are idealized, but the results seem quite plausible.

Some very recent results from Takahashi and Kawano (1998) add a bit more plausibility to the results above. They studied maritime and continental rainbands using a two-dimensional cloud model,

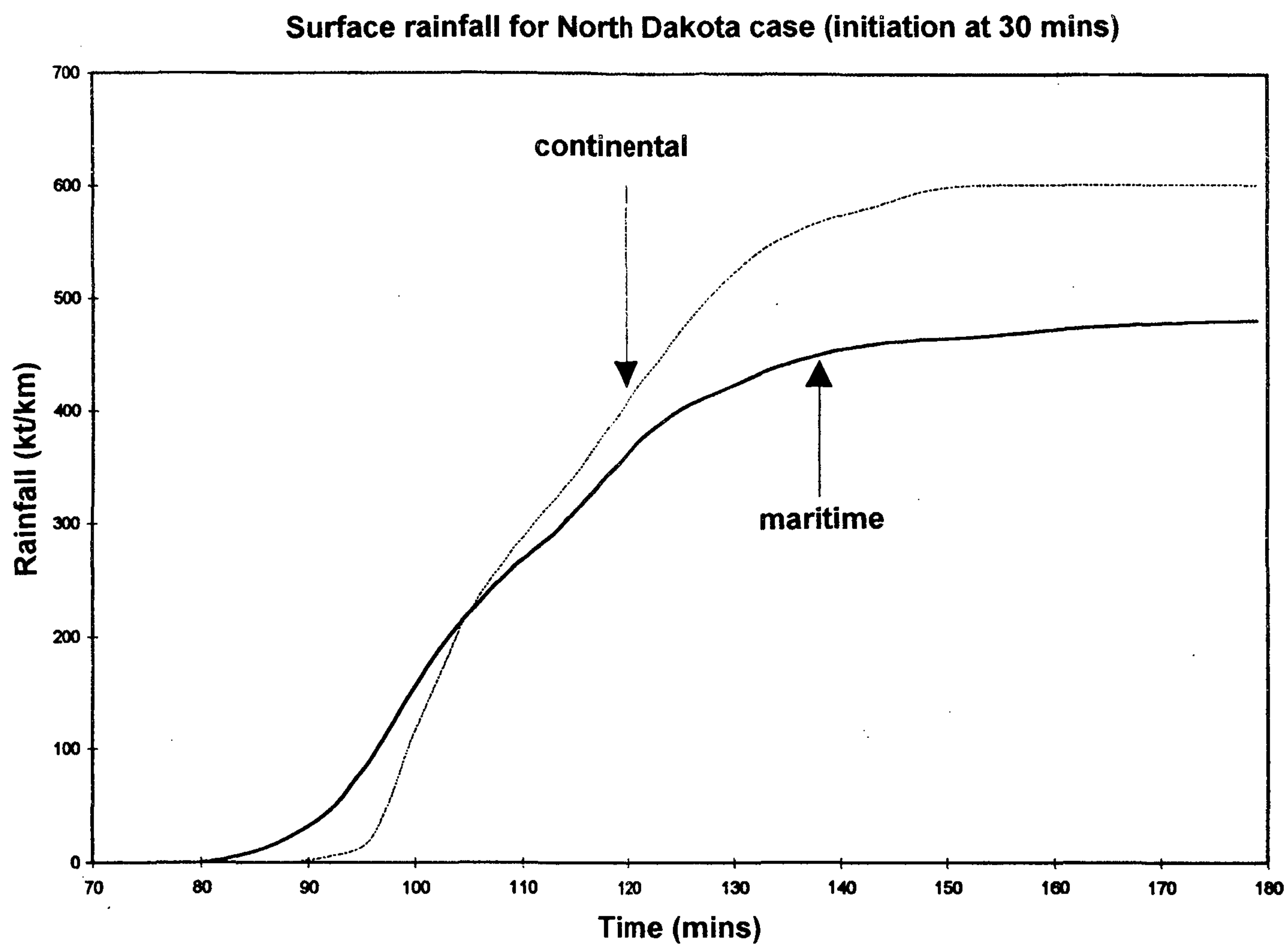


Figure 10: The surface rainfall vs. time for the continental and maritime clouds, strong cloud case.

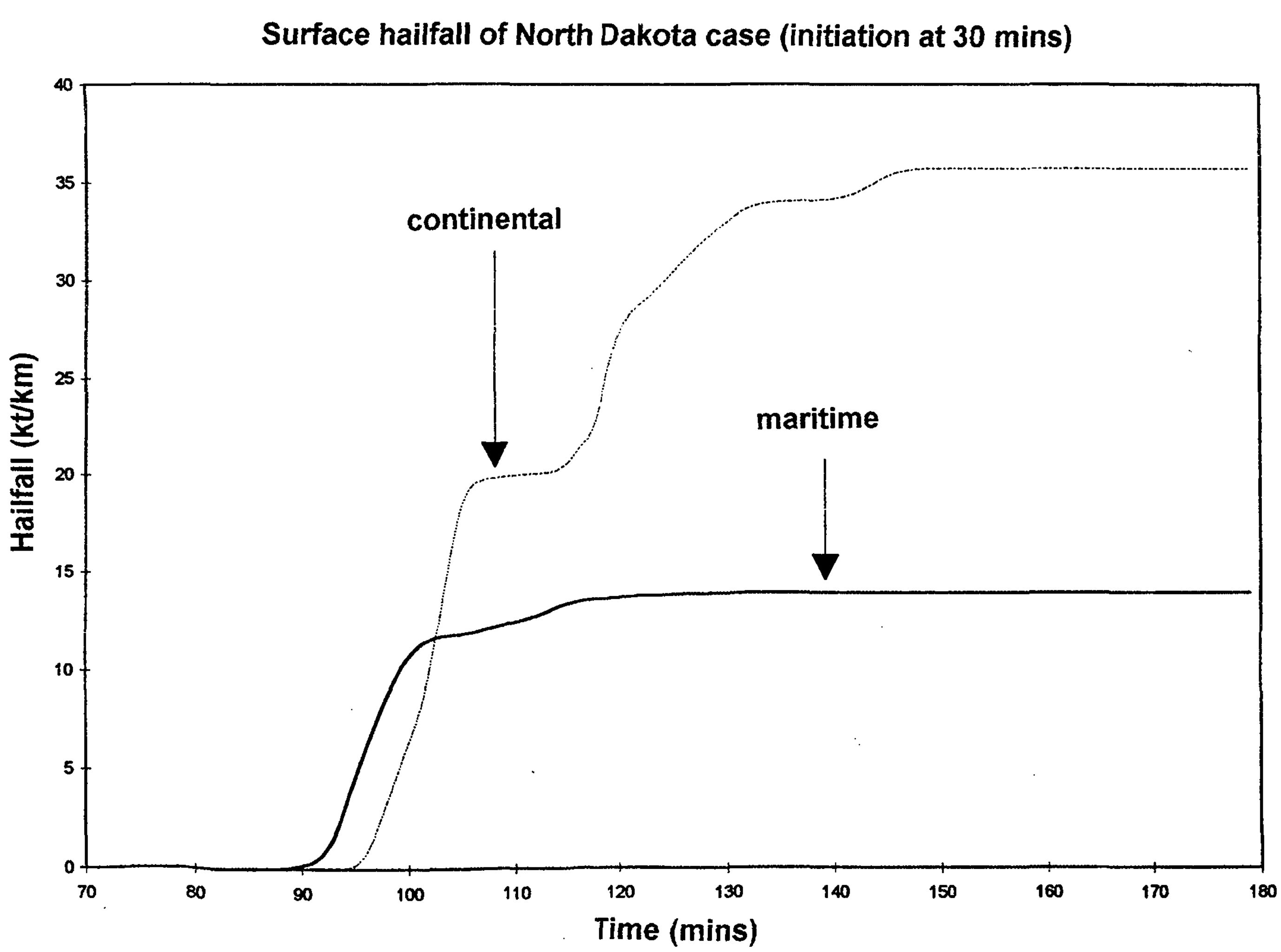


Figure 11: The surface hailfall vs. time for the continental and maritime clouds, strong cloud case.

but with detailed microphysics. The tropical sounding they used produced weaker clouds than those illustrated above (updraft maxima of magnitude 7 to 13 m/s). They showed results out to two hours of simulated real time in the weaker cloud situation and one hour in a stronger cloud situation. In neither case was the precipitation fallout completed. The pertinent maritime cloud situations produced more rain than the continental cloud situations, the differences becoming smaller the more vigorous the clouds. In the weaker cloud case, the maritime cloud produced more than double the amount of precipitation from the continental cloud. In the stronger cloud case, the maritime cloud produced about 15% more rain than the continental cloud (Wmax of 10 to 15 m/s), but note that the precipitation was not completed in any of the cases.

The analysis of the South African data and discussion by Bigg (1997) indicate a complex dynamic situation to explain the South African seeding results. The reasoning depends on the early development of rain and the generation of downdrafts close to the updrafts. Our 2D model results of just two different cloud cases suggest a more microphysical explanation, but do not yet fit the broad selection of clouds seeded in South Africa. In addition, the 2D dynamics of the cloud model do not test the outflow hypothesis of Bigg very well.

These preliminary results lead to further speculations about the effects of hygroscopic seeding. In weak to moderate continental convective cloud situations the effects of hygroscopic seeding should be to increase the precipitation amounts. In stronger cloud situations, the seeding effects may go either way depending on the dynamics of the clouds. In very strong continental convective clouds, with much of the cloud mass being transported out of the anvil, hygroscopic seeding may allow precipitation to form and fall out of the updraft before being transported into the anvil.

5. Conclusions

In our opinion, the simulation of two extreme cloud microphysical situations may set limits on the effects to be expected from hygroscopic seeding. Comparison of maritime and continental-type clouds provides the answers, the maritime runs representing the maximum effect of hygroscopic seeding of continental convective clouds. The results can be quite different, depending on the strength and vigor of the cloud development. Relatively weak to moderate continental-type clouds should react positively to hygroscopic seeding, producing more rain on the ground (hail is not expected). More vigorous, continental-type clouds may produce less rain and less hail in response to hygroscopic seeding of such clouds. However, these are very preliminary results; the method should be tried on clouds produced from many different atmospheric soundings. We also suggest that other modelers could try this technique of running their models in both maritime and continental mode and seeing what difference in precipitation would occur to help establish a range of results to be expected from hygroscopic seeding.

More complete simulations with fully three-dimensional cloud models and more complete microphysics would be desirable. The computer time and analysis effort will be considerable.

6. Acknowledgments

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