Quasi-equilibria of the Rotunno-Emanuel Tropical Cyclone Model

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Abstract

Long-term integrations using the Rotunno-Emanuel (RE) model demonstrate that given sufficient elapsed time the weak initial vortex specified by RE can also lead to tropical cyclogenesis, albeit at a slower growth rate. Thus the RE notion of the finite-amplitude nature of tropical cyclogenesis is valid only if the period of examination is limited to the first eight days. These results also show that, if initial vortex as specified by RE is used, prior to cyclogenesis the model state does not resemble the observed pre-genesis disturbances in the sense that there is no precipitation in the center of the disturbance. Another experiment using the same model but with the initial vortex replaced by a disturbance with a different structure shows that a state resembling the observed pre-genesis disturbances can be simulated and this state can lead to spontaneous cyclogenesis, a rapid transition between two quasi-equilibria. This spontaneous cyclogenesis is associated with the generation of a new convective region at large radius and its subsequent contraction, which reminds one of the observed eye-wall replacement, but the distinction from the latter is obvious.

1. Introduction

Rotunno and Emanual (1987; hereafter RE) constructed an axisymmetric model of tropical cyclone (TC). Non-hydrostatic and with cloud physics, this model resolves cloud-scale convection. This model was used to study tropical cyclogenesis (hereafter abbreviated as cyclogenesis) using special initial conditions. The initial conditions used by RE consist of background vertical temperature and humidity profiles which are neutral to convection and a vortex of solid rotation in the inner most radius, surrounded by a Rankine vortex, which is tapered off to zero at large distance. The initial sea-level pressure and temperature perturbations are in gradient wind and thermal wind balance with the initial tangential winds. Similar type of initial vortex is used in most axisymmetric tropical cyclone models (e.g., Ooyama 1969). RE found that, with the initial condition parameter V_m (maximum surface tangential wind, defined in Eq. 37 of RE; it determines the strength of the initial vortex.) =12 m/s, cyclogenesis occurs within 2 to 3 days but with V_m = 2 m/s cyclogenesis fails to occur within 8 days. RE did not show the results after 8 days. Based on these results RE concluded that an initial vortex of sufficient amplitude is important to cyclogenesis. RE mentioned that the experiment with V_m = 2 m./s could lead to cyclogenesis if the integration period was extended, but for practical purposes (presumably they meant that what happened after 8 days should not be meaningful.) cyclogenesis did not occur. The desire to understand the above results, which RE called the finite amplitude nature of cyclogenesis, motivated the present study (see also Emanuel 1989). We are particularly interested in whether the RE model has two separate and unconnected quasi-equilibrium states: one corresponds to the tropical

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cyclone and the other to the undeveloped disturbance and whether the evolution leading to the two states depends on the initial condition. Our experiments and results are described in the next section and some discussions on the results are provided in the last section.

2. Experiments

Emanuel kindly provided the RE model with some minor updates. We used it to repeat and extend the RE experiments. Since we were not provided with the initial temperature and humidity vertical convectively neutral profiles corresponding to SST=26.5°C, as described in RE, but with neutral profiles corresponding to SST=23.5°C, we generated, from these profiles, the initial neutral profiles correspond to SST=26.5°C. We first computed the relative humidity of these given profiles and kept it and added 3°C to the temperature profile at all levels and then proceeded with the procedure that RE used to remove convective instability.

Our results from repeating the RE experiments reveal that given enough elapsed time even the smallest V_m can lead to cyclogenesis. Figs. 1a and 1b show the minimal sea-level pressure (hPa) and maximum tangential wind (m/s) in four experiments, E1 through E4, with initial V_m equal to 1, 3, 6, 12 m/s respectively. The settings of E4 are the same as those of the RE control experiment. The experiment with initial V_m equal to 1 m/s clearly shows no development prior to day 16 and between day 16 and day 18 a TC develops. The minimal sea level pressure drops rapidly in four days, reaches a minimum

of 965 hPa around day 28 and then gradually equilibrates to around 990 hPa. Though this cyclogenesis takes longer to reach its peak than what is normally observed in nature, this experiment clearly shows that cyclogenesis occurs suddenly and before and after the transition the model state is in two complete different quasi-equilibria. The onset is earlier when the initial vortex is stronger.

Fig. 2 shows precipitation as a function of time and radius for the four experiments, E1 through E4. One prominent feature of these figures is that prior to the onset process there is very little precipitation. This is the result of using convectively neutral initial condition. Thus the model cyclogenesis is associated with the start of convection. This is distinct from the observed transition. The observed cyclogenesis evolves from a preexisting disturbance, which has precipitation for quite some time prior to the cyclogenesis.

Thus, there is the question of whether the RE model can simulate something resembling the observed pre-genesis disturbances. An additional experiment, E5, shows that this is the case. E5 is a repeat of E1 except that in the initial condition the factors of 1 and −1 are multiplied to the tangential wind field at each vertical grid column alternatively in the radial direction. The initial temperature and pressure fields are then computed using these tangential winds in the same way as described in RE. Thus, there are little temperature and pressure perturbations in the initial condition.

Figs. 3a and 3b shows the minimum sea-level pressure and maximum tangential wind as functions of time in E5. Between days 20 and 23 there is a growth of the disturbance. After an apparent overshooting, the disturbance soon settles to an intensity that is comparable to that of the observed pre-genesis disturbances. Fig. 4a shows the

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tangential wind at hr 0 of day 52. It shows a TC-like structure with sub-TC intensity. Further integration of this experiment reveals a spontaneous cyclogenesis process starting around day 70. It takes only three days for the TC to reach its peak. Fig. 4b shows the tangential wind at hr 0 of day 73. It shows a TC structure with maximum winds at 20km radius. Thereafter, the TC gradually dies down and returns to a pre-genesis state. Fig. 5 shows the precipitation field as a function of time and radius. It shows that in the dying down process the eye-wall radius reduces and eventually the precipitation is concentrated at the center of the pre-genesis disturbance. This is then followed by another cyclogenesis , which is associated with the contraction of a convective ring. Apparently, the model state alters between a tropical cyclone state and a pre-genesis state. The transition into the tropical cyclone state, the cyclogenesis, is rapid. However the transition back to the pre-genesis state is rather slow.

Figs. 6a and 6b show the same precipitation field as Fig. 5 of the first two 40-day segments but covering a wider radius. They reveal that in the pre-genesis stage convection develops outside of 250 km radius and then moves toward the center at a very slow speed (~0.2 m/s) as the center disturbance weakens. The spontaneous cyclogenesis is associated with the final stage of the contraction of this convection region, whose speed remains slow (~0.35 m/s). This contraction reminds one of the eye-wall replacement found in observations (Willoughby et al. 1982) and in an MM5 simulation of Hurricane Floyd (1999) (Tenerelli and Chen 2002). However, the scale and the duration of this contraction are much larger and longer and it is associated with a rapid sea-level pressure drop and a maximum tangential wind increase of magnitudes that are found only

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in cyclogenesis. The eye-wall replacement in the mature tropical cyclones involves relatively little changes in these two quantities.

3. Discussion and summary

We have found that the initial vortex specified by RE leads to cyclogenesis even with weak amplitude. It only takes longer to start. Therefore for the RE finite amplitude nature interpretation to hold, it is necessary to use the specific initial vortex they prescribed and to require that cyclogenesis to occur within eight days. Our results from the RE model show that the model does support a quasi-equilibrium state that resembles the observed pre-genesis disturbances. A different initial condition is required to reach this state first. And after initial adjustment the model state transits between this pre-genesis state and the full-fledged TC state. Apparently, the initial vortex as specified by RE is quite different from these two states.

To have a realistic simulation it is necessary that the model's quasi-equilibrium states matches closely those of the nature and the initial condition of the model is located on a trajectory of in the model quasi-equilibrium evolution space. Granted that models are never perfect, they can only be used for a limited period and therefore the realistic initial condition become important, if one's purpose is to do a short-term realistic simulation. On the other hand, if one's purpose is to understand the physical mechanism, the requirement on the model is not that stringent (as long as it does not miss the major quasi-equilibria or the oscillation modes that one intend to study.) Also an idealized initial condition can be used in order to demonstrate a particular point. The vortex plus

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neutral profiles type of initial condition that RE used is for the purpose of demonstrating that convective instability in the initial profile is not necessary for cyclogenesis. Also the saturated core initial condition used by Bister and Emanual (1997) is another example.

The answer to our question raised in the introduction is that the RE model does not have two unconnected quasi-equilibrium states. The model state transits between two regions in the phase space, one resembling the tropical cyclone state and the other the pre-genesis disturbance. Which of the two regions the model state enters into first depends on the initial conditions. The type of initial conditions that RE used leads to the tropical cyclone region first (so does the one that Bister and Emanuel (1997) used.) And a different type of initial conditions is needed for the model state to enter the pre-genesis state first. The spontaneous cyclogenesis found in E5 exhibits some characteristics which remind one of the observed eye-wall replacement. But it is clearly distinct from the eye-wall replacement.

Although the physical mechanism of the spontaneous cyclogenesis in the RE model remains to be explored, some arguments can be put forth to support the experimental results we obtained. The model shows that there are two quasi-equilibrium states in the model one corresponding to a TC and the other to a pre-genesis disturbance. This is much more reasonable than the case that only one of the two states exists. If only the pre-genesis disturbance existed as the quasi-equilibrium state, than the model would not be able to simulate cyclogenesis. If only the TC state existed as the quasi-equilibrium state, then spontaneous cyclogenesis would not be simulated. The fact that spontaneous cyclogenesis occurs means these two quasi-equilibrium state are not completely separate. This is also quite reasonable. This means that the TC in the model eventually has to die

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down (in its transition into the pre-genesis state). In that process convection in the core diminishes and convection in far field develops and strengthens so that the total rainfall does not change rapidly. So the remaining questions are why the transition into the TC state is much more rapid than the reverse transition and the fact that the outer convection region contracts. These questions will be our future research foci.

Is the spontaneous cyclogenesis in the RE model realistic? Observations do show that sometimes pre-genesis disturbances turn into TC without obvious triggers. But, the observed cyclogenesis is not associated with the contraction of an outer convective ring. However this should not be used to invalidate the model results, since the observed cyclogenesis is not an axisymmetric event and the axisymmetry of the model should be taken into account.

In summary the contribution of this work lies in its exploration of the quasi-equilibria of the RE model solutions. Our experiments reveal that the RE model has two quasi-equilibria: one corresponding to the pre-genesis disturbance and the other to the TC. The transition from the former to the latter is fast and spontaneous, while the reverse transition is slow. Which quasi-equilibrium the model falls into first depends on the initial condition. The type of initial vortex used by RE can lead to cyclogenesis even with very weak amplitude. A different type of initial condition is needed for the model to fall into the pre-genesis disturbance first. Finally there is an obvious need of repeating our experiments with other tropical cyclone models, both 2-D and 3-D.

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Figures

Fig. 1. Minimal sea-level pressure in hPa (a) and maximum tangential wind in m/s (b) of E1 through E4, as functions of time (days).

Fig. 2. Precipitation (mm/day) as a function of time (days) and radius for E1 through E4.

Fig. 3. Minimum sea-level pressure in hPa (a) and maximum tangential wind in m/s (b) of E5 as functions of time (days).

Fig. 4. Tangential wind (m/s) at hr 0 of day 52 (a) and day (73) of E5 as a function of height (km) and radius (km).

Fig. 5. Precipitation (mm/day) as a function of time (days) and radius (km) for E5.

Fig. 6. Same as Fig. 5, but showing wider radius for days 0-40 (a) and 40-80 (b).
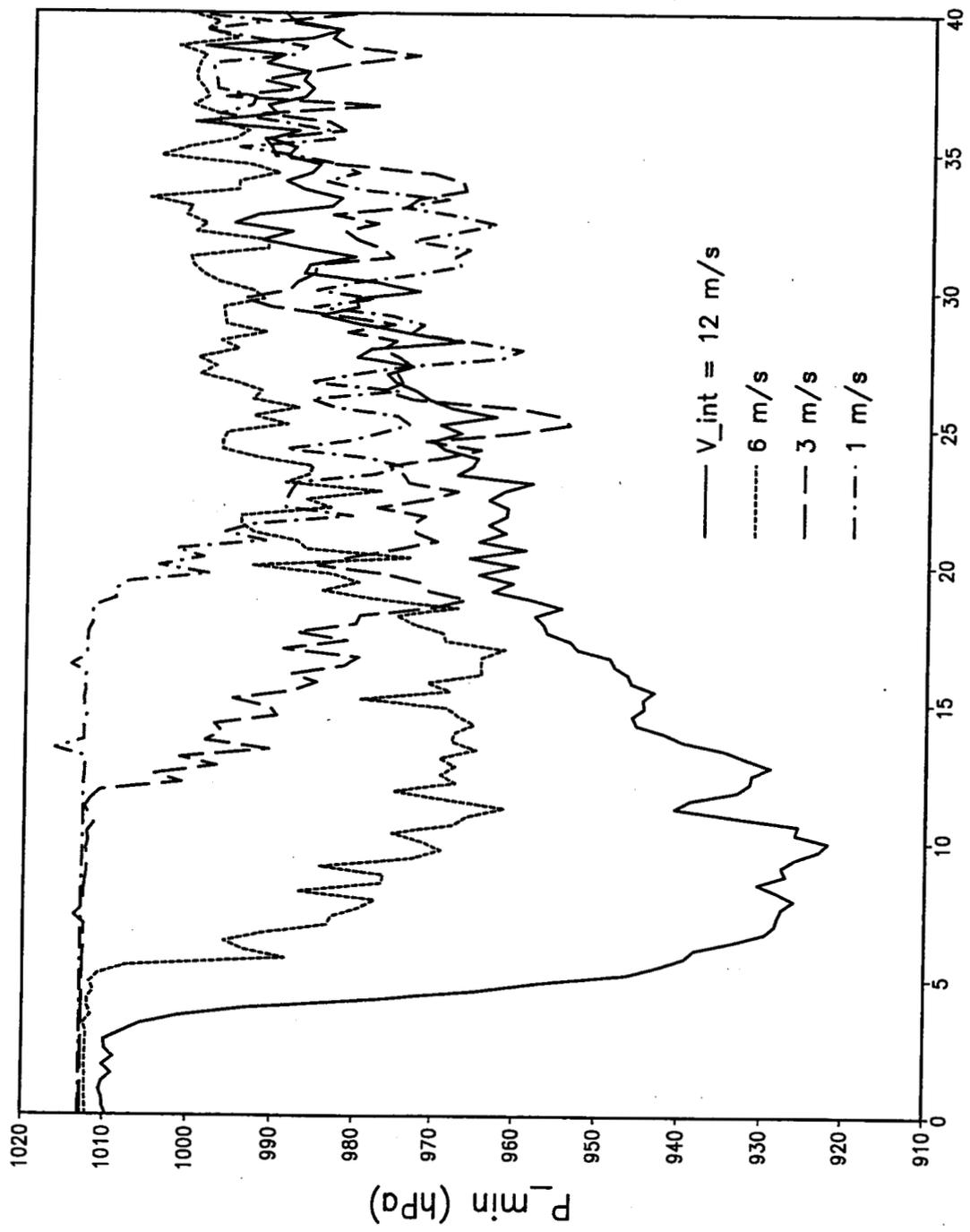
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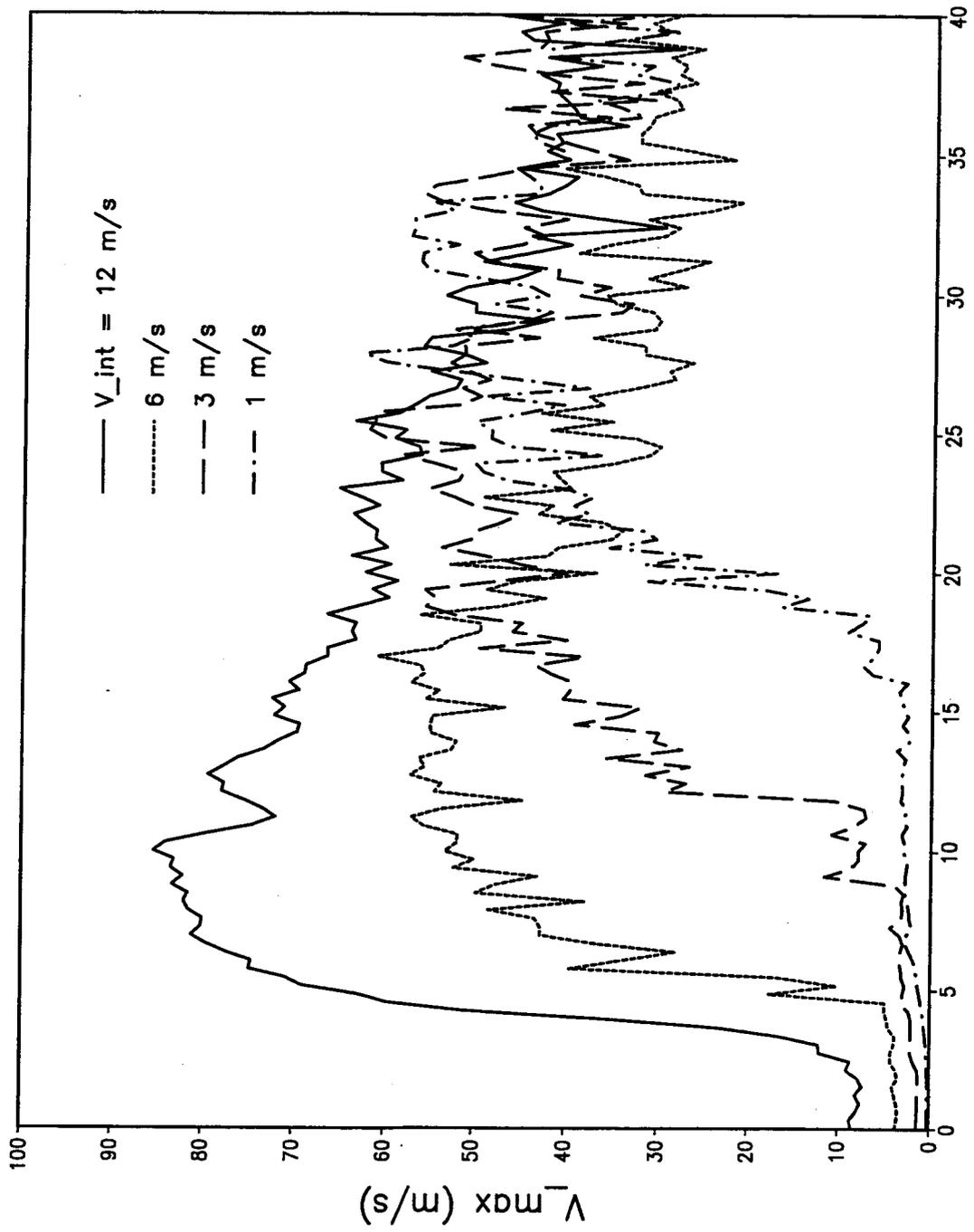
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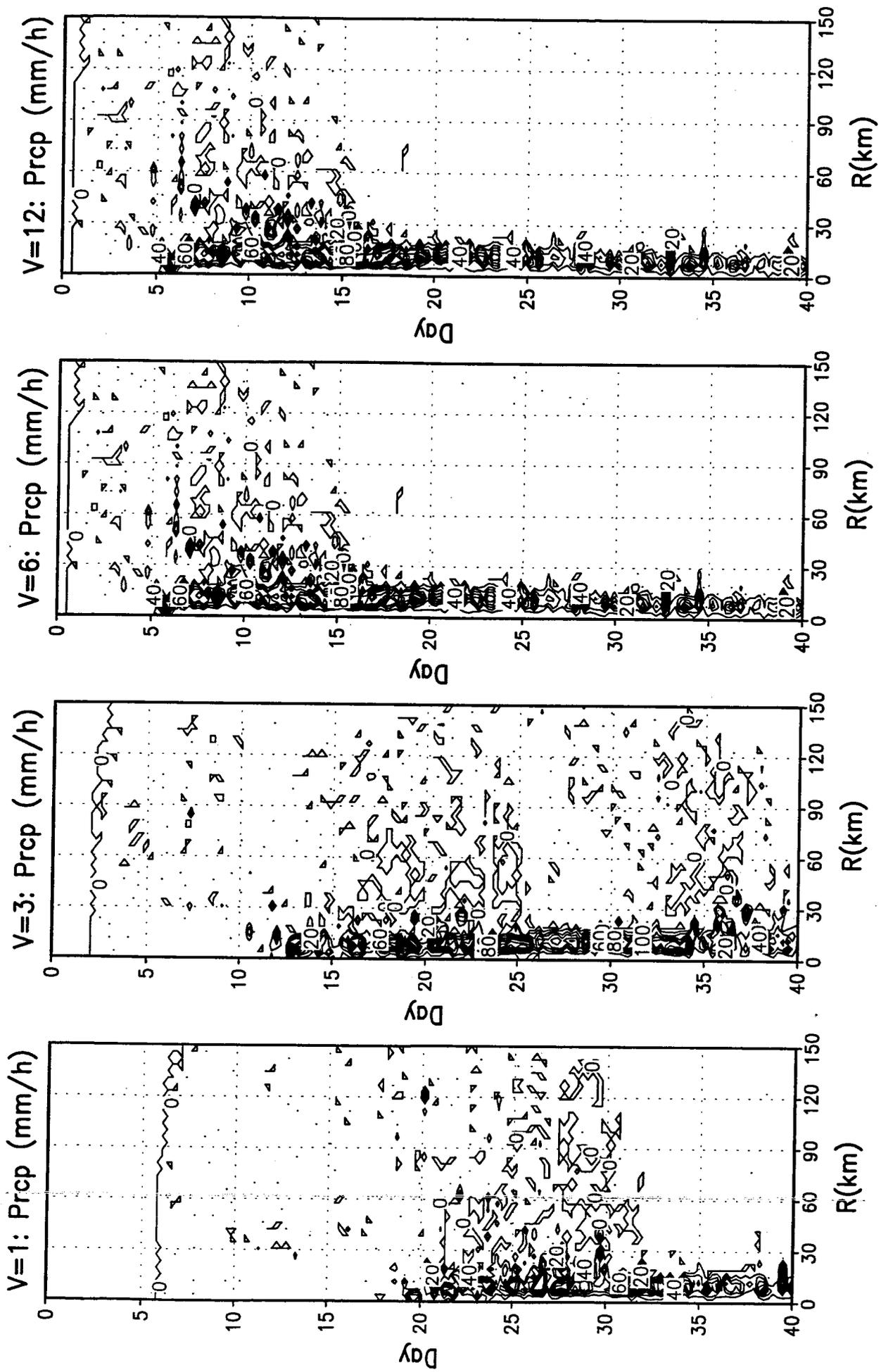
Fig. 2
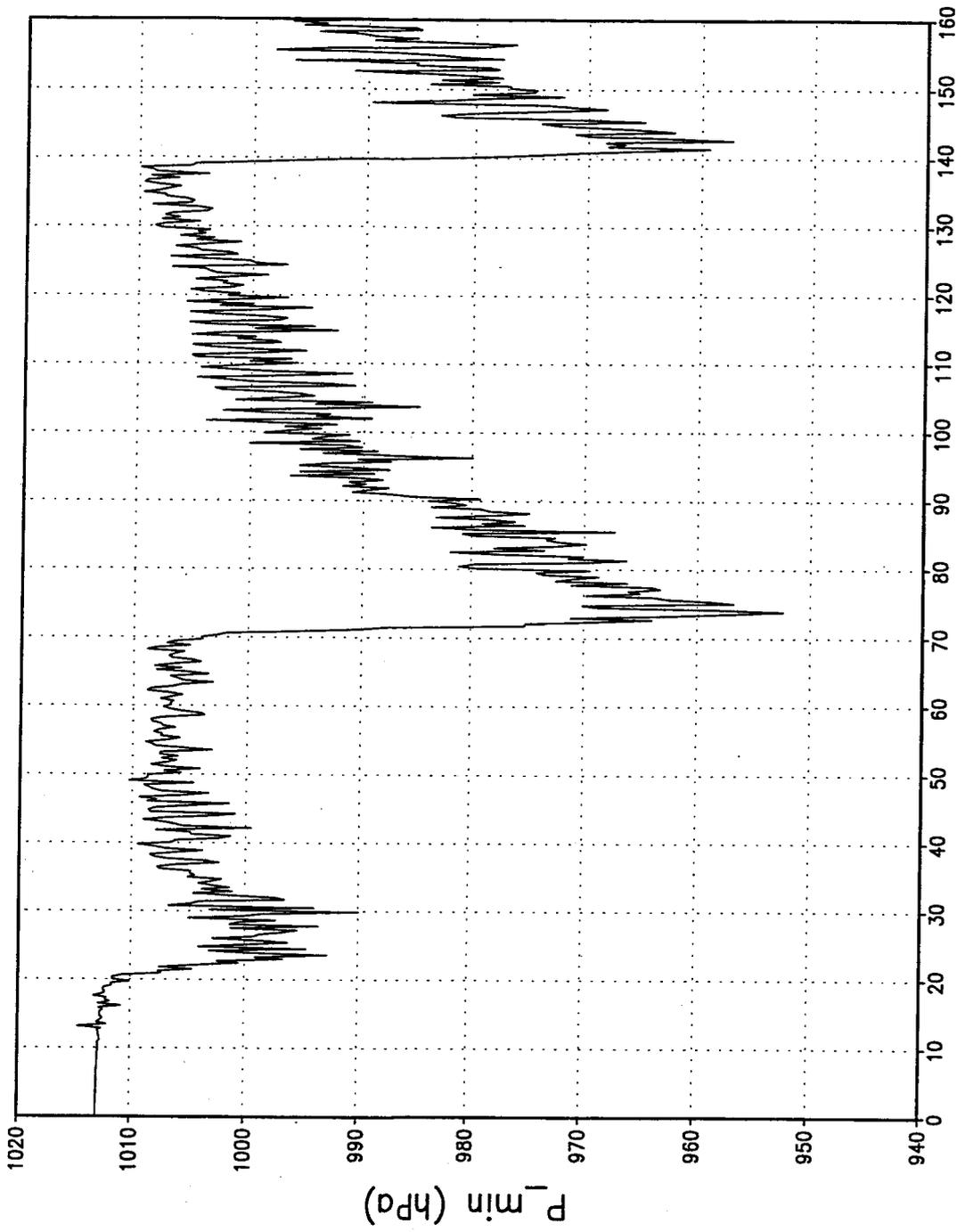
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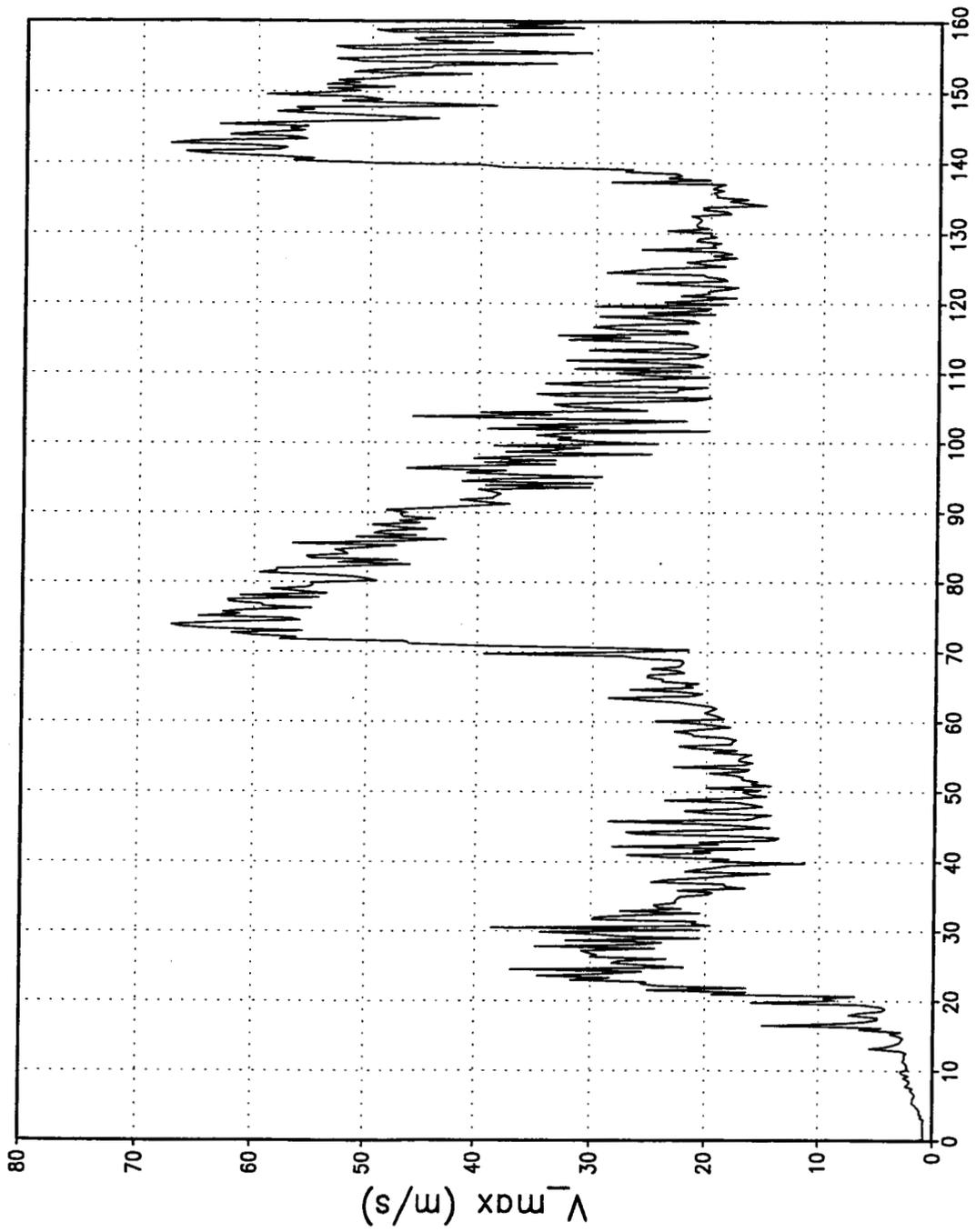
Fig. 3.b

V_init = 1 m/s + Full RAD: V DAY 52

R (km)

Z (km)
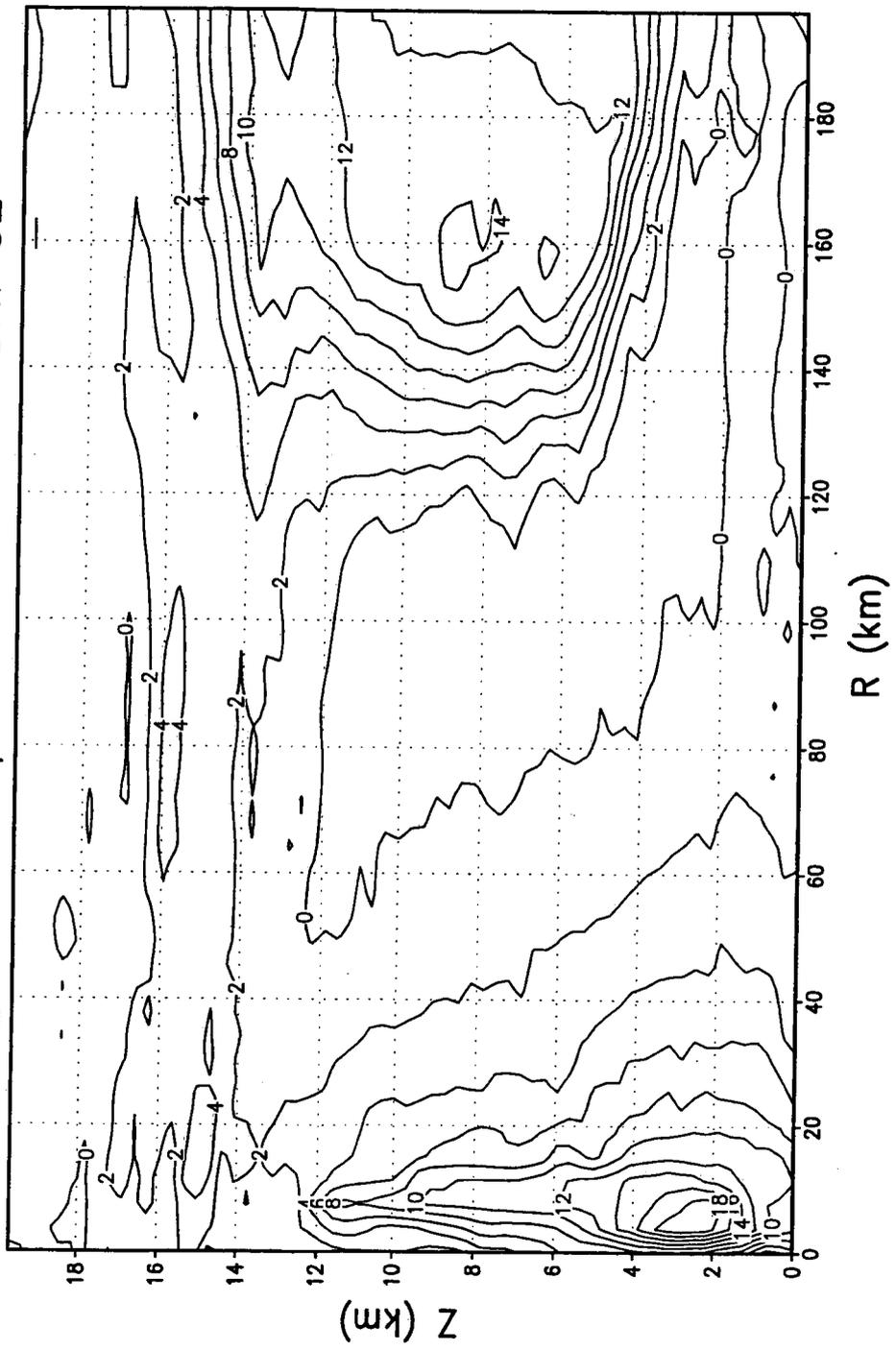
4.a

V_init = 1 m/s + Full RAD: V DAY 73

4.b

V=1 Exp 5: Prcp (mm/h)

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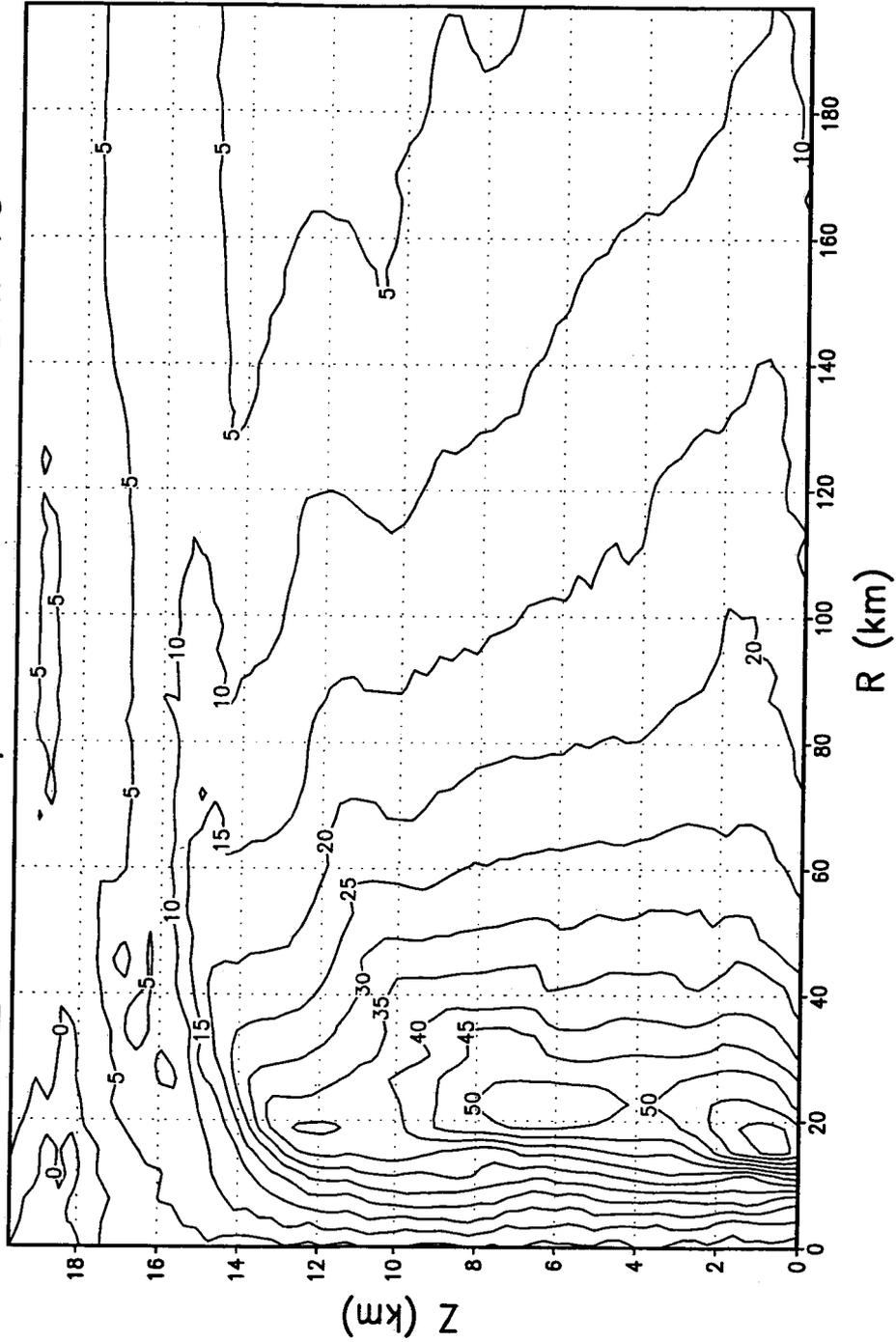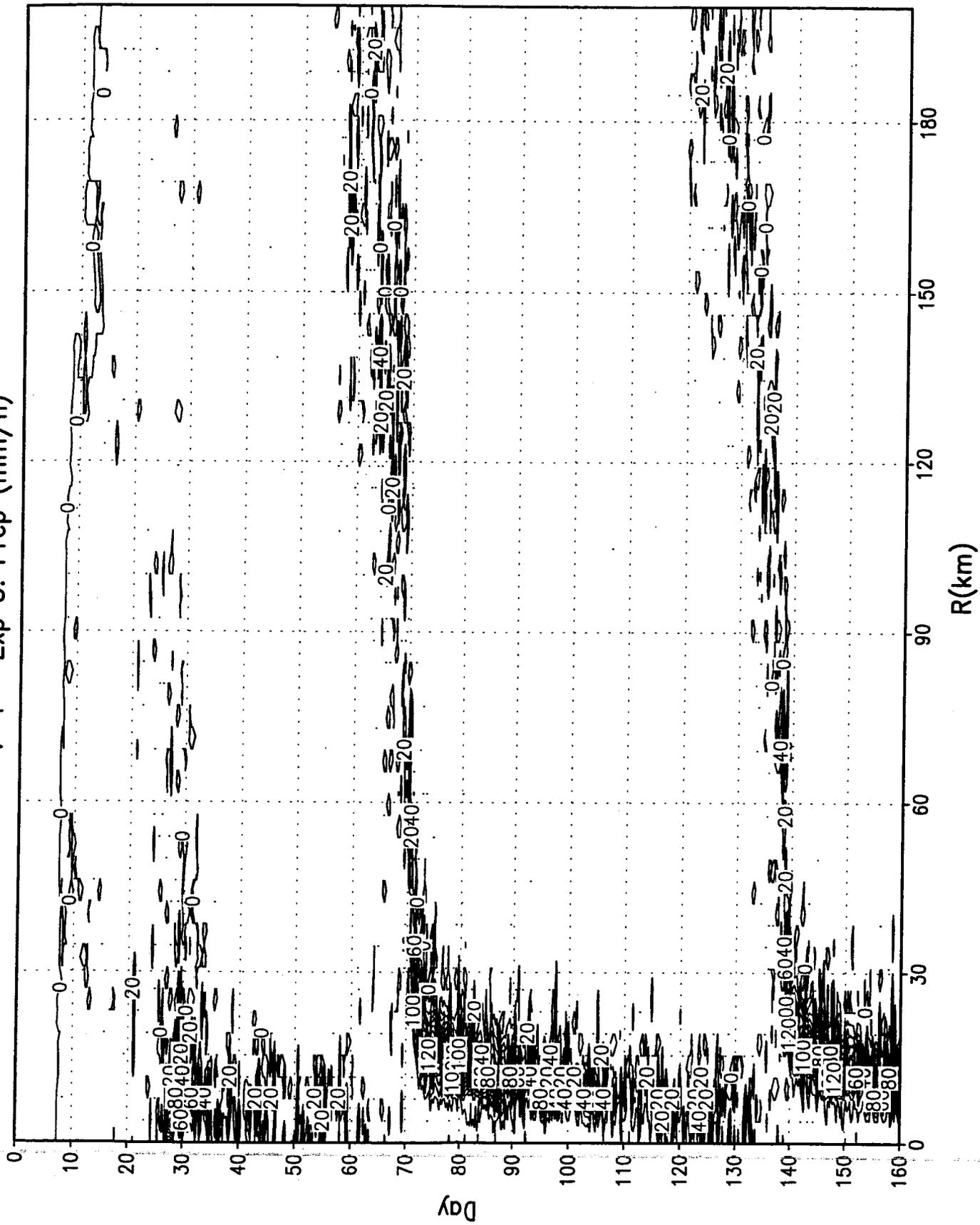
V=1 EXP 5: Prcp (mm/h)

V=1 EXP 5: Prcp (mm/h)

6.b