積雨雲之研究(二)

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On The Life Cycle of Cumulus Rain Clouds

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Case 2 has $\gamma_e = 0.0065C\ m^{-1}$ (standard atmosphere), a little more conditionally unstable than case 1, but the picture of the resulted model clouds, is quite different from that of case 1, as can be seen dy comparing fig 2 and fig 1. After the formation of the cloud 2-1, its top rises at a moderate rate up to a height of 3.2 km where it keeps steady for about 20 minutes. Inside the cloud, the field of the LWC, however, is not steady. After t=34 min, it seems that the cloud is about to lose its LWC at a slow rate. This is indicated by the vertically narrowing of the 2 g kg^{-1} contour in fig 2. The falling of the upper part of this contour might be due to precipitations, while the rising of the lower part might be due to the evaporation of the droplets resulted from the entrainment which, in this case, perhaps does not introduce appreciable cooling effect, as we can see there is no much change in temperature field at this time. The reduction of the LWC is equavalent to the reduction of downward drag. The air in the core region thus enjoys less resistence and accelerates upward at a greater rate. The cloud top then rises again to about 4 km. During this second rising, a maximum accumulation of LWC occurs as indicated by the small

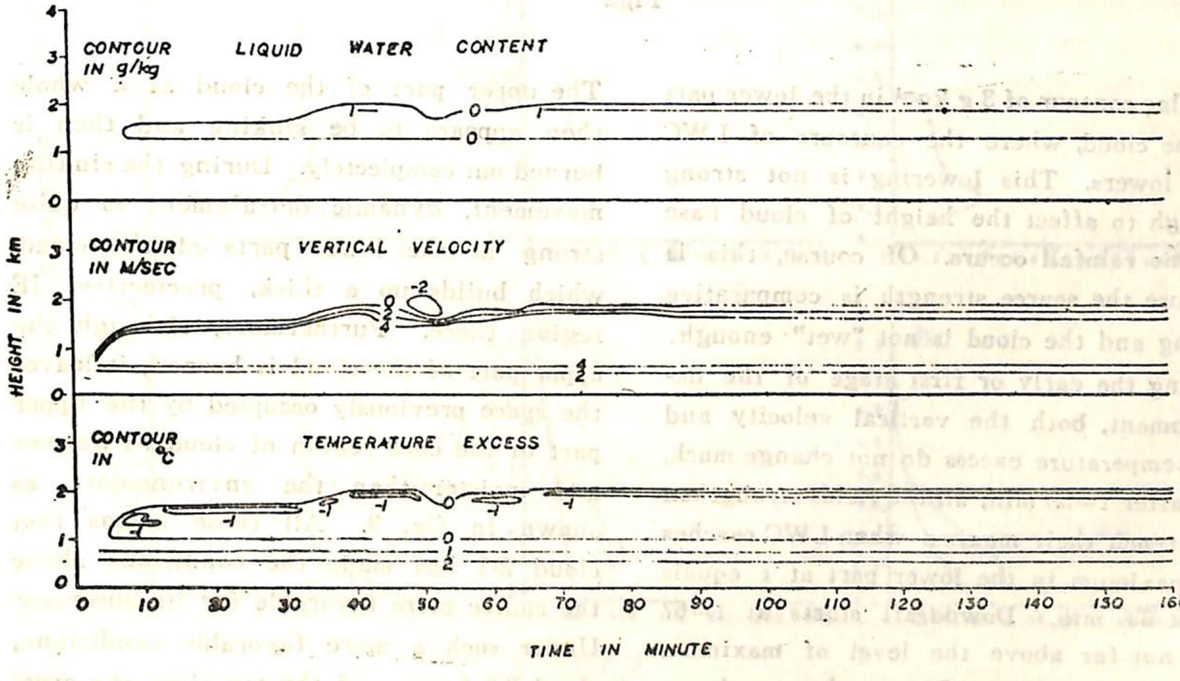

Fig 1

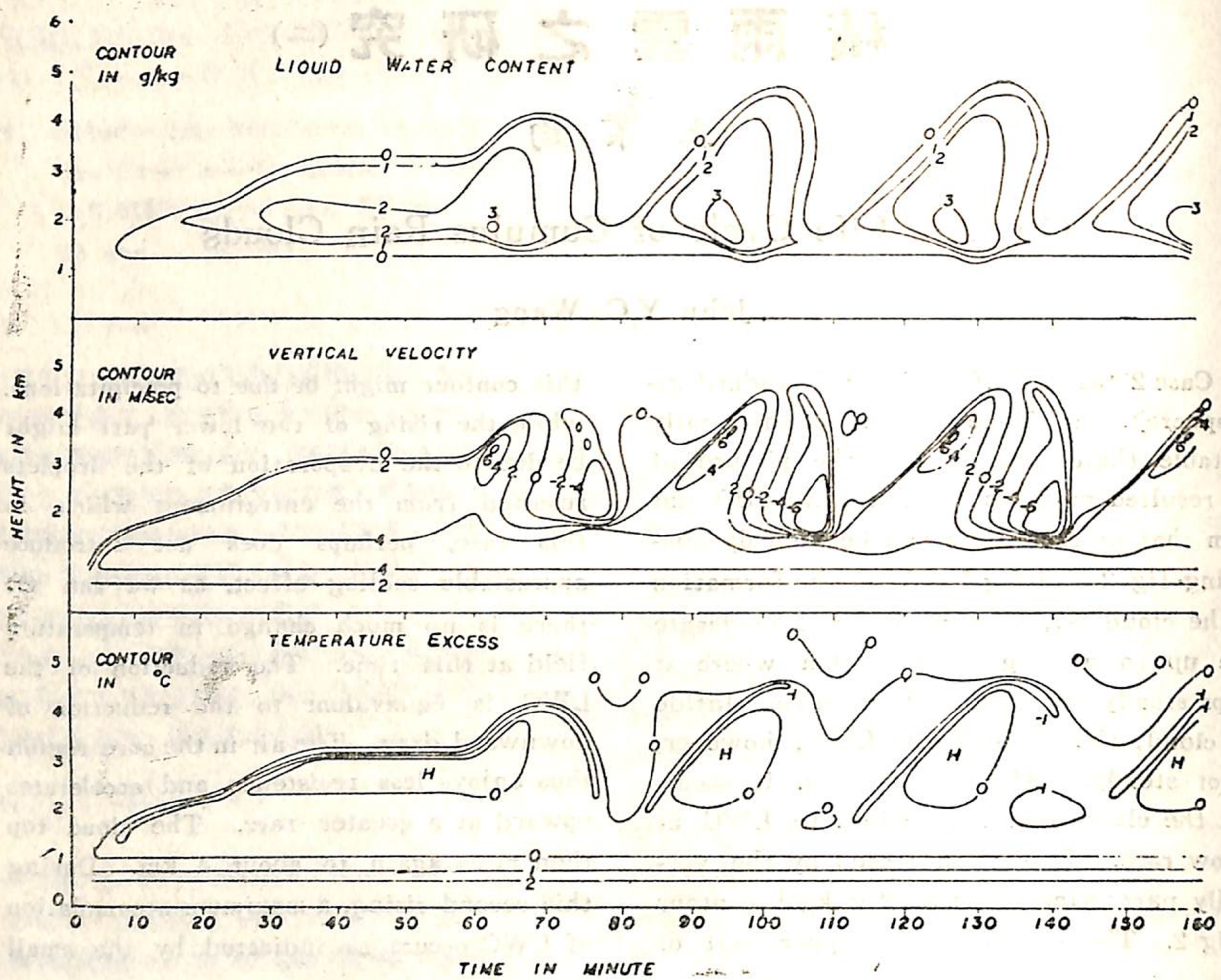

Fig2

circular contour of 3 g kg⁻¹ in the lower part of the cloud, where the contours of LWC also lowers. This lowering is not strong enough to affect the height of cloud base and no rainfall occurs. Of course, this is because the source strength is comparative strong and the cloud is not "wet" enough. During the early or first stage of the development, both the vertical velocity and the temperature excess do not change much, but after t=55 min, all the fields strengthen and reach their maxima when LWC reaches its maximum in the lower part at t equals about 63 min. Downdraft starts at t=67 min not far above the level of maximum LWC concentration. It stengthens and extends upward rapidly up to the cloud top. The upper part of the cloud as a whole then appears to be sinking and then is burned out complectely. During the sinking movement, dynamic detrainment is quite strong at the lower parts of the cloud, which builds up a thick, protective, IE region there. Furthermore, although the upper part of the cloud is burned, it leaves the space previously occupied by the upper part of the core region of cloud 2-1 warmer and moister than the environments, as shown in fig. 3. All these means that cloud 2-1 has made the conditions above the source more favorable for its successor. Under such a more favorable conditions, cloud 2-2 forms and the top rises at a greater rate and to a greater height than that

of cloud 2-1. This cloud is moister than the first one, as indicated by the -3 g kg⁻¹ closed contour. The precipitations fall through the cloud base, but are evaporated compltely in the subcloud region. Hence, this process only lowers the cloud base and produces no rain at the source. Exactly the same process as we have described before, the rapidly upward extending downdraft soon burns out the nost upper part of the cloud 2-2, as indicated fig 2. Cloud 2-3 is produced right after the dissipation of cloud 2-2, which looks almost the same and has same fate as cloud 2-2. The cloud activity becomes periodic with a life span of about 30 min for each cloud except cloud 2-1, and is superimposed with a thin cold plume cloud of about 600 m thick on the bottom of the periodic clouds. Here we should mention that below about 2 km, the clouds are everywhere cooler than the environment. Above this height, it is warmer, with small maximum temperature excesses arround 0.6C, as listed in table 3, which, together with the small depth of the warm region, might be the reasons why the peeiodic plume clouds can not turn to be self-sustained cumulus clouds. The

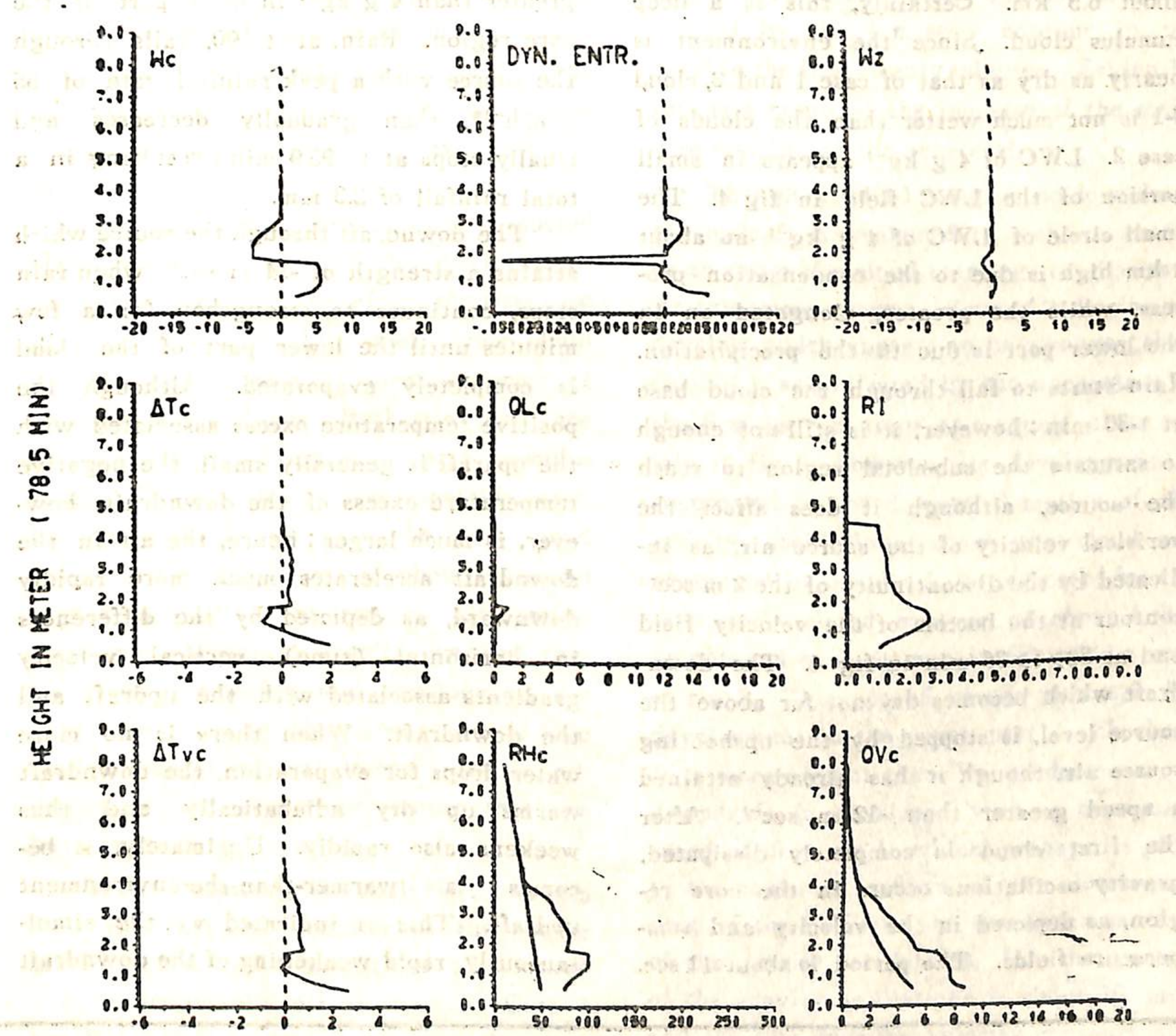

Fig 3

variations in the field of vertical velocity are strong, however, the downdrafts of greater than 6 m sec^{-1} are stopped by the upcoming air from the source. This, of course, is because the clouds do not have enough rain drops for evaporation in the downdrafts which then warm up dry adiabatically, therefore, it may also be said that the dawndrafts are burned out by themselves.

Case 3 has γ_e=0.008C m^{-1}, conditionally more unstable than the first two cases, therefore, after its formation, the top of cloud 3-1 rises repidly to a great height of about 6.5 km. Certainly, this is a deep cumulus cloud. Since the environment is nearly as dry as that of case 1 and 2, cloud 3-1 is not much wetter than the clouds of case 2. LWC of 4 g kg^{-1} appears in small portion of the LWC field in fig 4. The small circle of LWC of 4 g kg^{-1} at about 4 km high is due to the condensation process, while the greater, elongated on in the lower part is due to the precipitation. Rain starts to fall through the cloud base at t-30 min ; however, it is still not enough to saturate the sub-cloud region to reach the source, although it does affect the veritical velocity of the source air, as indicated by the discontinuity of the 2 m sec^{-1} contour at the bottom of the velocity field and at 38>t>36 min in fig 4. The downdraft which becomes dry not far above the source level, is stopped by the upshooting source air, though it has already attained a speed greater than -12 m sec^{-1}. After the first cloud is completely dissipated, gravity oscillations occurs in the core region, as depicted in the velocity and temperature fields. The period is about 11 sec. Such oscillations suppresses the rising source air when its motion is downward and enhances when upward. The rising source air, on the other hand, pushes the oscillations upward. When the motion pertaining to gravity oscillations becomes upward at the third time at t=70 min, the combined effect causes the fast formation of cloud 3-2, a deep cumulus cloud formed in an environment which has been made favorable by cloud 3-1. The top of cloud 3-2 rises rapidly to an even greater height of 7 km and, of course, with a stronger vertical velocity of 10 m sec^{-1} and a greater LWC greater than 4 g kg^{-1} in most part of the core region. Rain, at t=90, falls through the source with a peak rainfall rate of 55 mm/h^{-1}*, then gradually decreases and finally stops at t=95.9 min ; resulting in a total rainfall of 2.3 mm.

The downdraft through the source which attains a strength of -14 m sec^{-1} when rain stops, continues to strengthen for a few minutes until the lower part of the cloud is completely evaporated. Although the positive temperature excess associated with the uparaft is generally small, the negative temperature excess of the downdraft, however, is much larger ; hence, the air in the downdraft accelerates much more rapidly downward, as depicted by the differences in horizontal (time), vertical velocity gradients associated with the updraft and the downdraft. When there is no more water drops for evaporation, the downdraft warms up dry adiabatically and thus weekens also rapidly. Untimately, it becomes a warmer-than-the-environment updraft. This is indicated vy the simultaneously, rapid weakening of the downdraft and rapid warming of the air at the source level when t is about 100 min. After this time, when the lower part of the cloud is washed out, what left behind are the damping gravity oscillations in the lower part of the core region and an altocumulus cloud floating in the middle atmosphere. As the end of the discussion of there two clouds, we should mention the result that the rain of the first cloud does not reach the source and the appearance of the strong vertical gradient of the vertical velocity between the source level and 1 km height, might be taken as an indication that our anticipative boundary conditons at the source might have some defect. But, more probably, this may also indicate that any rain drops, no matter how large, can not penetrate an unsaturated layer is a bad assumption.

For the first three cases discussed above, the source air and the environment are relatively dry. Therefore, the first case produces a steady, thin, cold plume cloud and the second case produces a series of periodic plume clouds. Both two cases are non-precititive. They have only cumulus stage. In the third more unstable case, having cloud 3-1 to pave the way, cloud 3-2 could reach a height of about 7 km and give a rainfall at the source. Comparing these very different results, we see that the cloud formation and development are very sensitive to the lapse rate of the environmental virtual temperature in addition to the source parameter that we have studied in Papar A.

In the following, we shall first increase only the relative humidity of the source air in case 4, and then both of the source and environmental air in case 5. Case 4 has RH_s=80% (only 5% increase than before). The various fields of the produced clouds are shown in fig 5. After the souce started emitting for a few minutes, cloud 4-1 is formed. Because of the precipitation, the cloud development is shecked by the drag due to the accumulated water in the lower part of the cloud. Rainfall occure at the cloud base but is not able to penetrate the sub-cloud region to reach the source; resulting in a little lowering of the cloud base. Comparing the vertical velocity field of this cloud to that of case 2, we see that cloud 4-1 produces no downdraft. This is due to the fact that the updraft of cloud 4-1 is strong, as indicated by the much greater height reached and much greater height reached and much greater area occuppied by the 4 m sec^{-1} contour in the cloud in the first twenty minutes. Evidently, this is a result of the increase of the moisture content of the source air.

Though cloud 4-1 produces no downdraft, the updraft is weakened to such an extent as to cause the cloud starting to dissipate. At this time, hower, cloud 4-2 begins to develop, which appears to be stronger than cloud 4-1, as indicated by the appearance of the 6 m sec^{-1} contour at t equals about 40 min in fig 5, however, its development is suppressed by the downward motion of the gravity oscillations above the cloud top generated by cloud 4-1, as indicated by the -2 m sec^{-1} closed contour at about 4 km height and at t=40 min in the middle row of fig 5. This second cloud, although its development in the upper part is checked, it is more violent than its predecessor. A downdraft is developed with a maximum speed of -5 m sec^{-1}, which perhaps is due to the combined effects of the downward drag of the LWC and the downward motion of the gravity oscillations, for the period of the gravity oscillations is about 10 min and the two negative velocity contours are separated about 20 min, and furthermore, there is no reason for the gravity oscilla-

* This is calculated from the Marshall and palmer relation (1948), $M=74R^{0.88}$, where M is the LWC in g m^{-3} and R, the rainfall rate in mm/hr^{-1}.

tions to amplify, from -2 m sec^{-1} to greater than -4 m sec^{-1}. If this is the case, the next upward motion of the gravity oscillation and the updraft from the source are co-operative. Cloud 4-3 is then developed and the top rises at a rate greater than cloud 4-1, The irregularity in the rate of rise of the top of cloud 4-3 at t=69 min is again, due to the residual gravity oscillations which are later wiped out completely by the developing cloud. Cloud 4-3 develops to a height of about 6 km, about 4 minutes after the rain has reached and fallen through the source. It this cloud, the time of the initiation of downdraft above the cloud base and that of the arrival of rain at the source is about the same, t=80 min. The peak rainfall rate and the total rainfall at the source are 80 mm hr^{-1} and 5.7 mm, respectively. The duration of rain is less than 10 min. Both the rainfall rate and the total rainfall are greates than that of cloud 3-2. This is because of the increase of 5% of relative humidity of the source air. The downdraft attains its maximum strength of -10.9 m sec^{-1} at the source at a time a little later than the rain stops. After that, the lower part of the cloud is washed out and the downdraft warms up dry adiabatically; hence gravity oscillations are generated afterward, with progressively smaller amplitudes. Note also, oscillations also exist in the height of the upper cloud after the altocumulus is dissipated.

Case 5 has RH_s increased to 90%, and RH_e increased to 80% at 0 m and decreases to zero at 9400 m. The temperature excess at the source is reduced to 1C, while the environment is the standard atmosphere. A single deep cumulus cloud with rain is produced. Because of the high RH_s the cloud base is quite lower than the previous cases. The cloud top rises smoothly to 4.5 km when rain arrives at the source, afterward, the top continues to rise to 6.2 km. This later development, of course, like the previous cases, is due to the removal of downward drag in the middle level of the cloud. All the features of this cloud is very much like that of cloud 3-2, except that the latter is about 1 km higher than the former. This is because the environment of the latter is more unstable than the former. Furthermore, the decrease of the temperature excess at the source has offsetted to some extent the effects of the increases of the moisture content in both the source air and the environmental air. It is therefore improper to scrutinize this cloud in comparison with the others. Nevertheless, from the facts that the duration of rain is longer and total rainfall is greater than the previous cases, it seems to us that water vapor content in both the source air and the environmental air is more important than the excess at the source. in so far as rainfall is concerned. for, after all, a cloud is made of water while the temperature excess, especially that at the source is more or less a trigger. Evenmore, in an environment like that of case 3, more unstable and less wet, a rain cloud needs a predcessor to pave the way first, while in case 5, does not need any.

Case 6 is a special one (fig 7). It has its environmental and source conditions exactly the same as that of case 4. We first delete the precipitation mechanism from our model. and allow the cloud to reach a steady state for a while. Then, we introduce the precipitation mechanism. The produced cloud, after its formation, has its top rises at the same rate and also to the same height as cloud 4-1, where the cloud top keeps steady for a brief time, and than rises a little and keeps steady again. The LWC has horizontal contours and increases with height. These indicate that the liquid water field also has attained a steady state. The vertical velocity and the temperature fields, though appearing steady in the first glance, have a tendency of strengthening. Ignoring these, we introduce the precipitation mecnanism at t=70 min, which immediately Introduce a turmoil in all fields. The liquid water starts to precipitate. The updraft starts weakening and the downdraft starts a little above the cloud base. The LWC attains a maximum of 7.15 g kg^{-1}, much larger than its counterpart in cloud 4-1. The rain arrives at the source at t=80 min. The downdraft through the source attains its maximum of -12 m sec^{-1} when rain ceases. In comparison with cloud 4-3 or case 4, this cloud is much wetter. Its peak rainfall rate is more than 100 mm hr^{-1}, and the total rainfall is 8.1 mm, as compared to 80 mm hr^{-1} and 5.7 mm of cloud 4-3. That is because at the early time of the develop ment, the model is non-precipitation, so that more liquid water is brought up to much higher level than that in case 4. When the precipitation mechanism is introduced, of course, there is more water available for precipitation. The reason for us to run this case is to try to find out the difference if precipitation mechanism other than (2.1) and (2.2) were used. In order to do so, the simplest way is what we have done, because it implies that the condensation nuclei are all fine enough so that all the condensed liquid water droplets could be brought up to a much higher level; resulted in greater storage of liquid water in the cloud and a heavier rainfall. Therefore, this case may be taken as a proof that the precipitation mechanism adopted in a model plays quite a decisive role for the behavior of a rain clouds.

In the above, we have discussed our experimental clouds individually. If we look at all the figures, we shall see that within a cloud, the temperature field is the least variable one while the velocity field is the most. In the temperature field, the temperature field, excess within a claud is in most case small and hardly exceeds 1C (and never 2C at least in our model clouds). This may lead us to think that, in the cloud, the released latent heat is converted to the kinetic energy as soon as it is available. The vertical velocity thus increased immediately induces stronger entrainment, or lateral mixing, which dilutes and cools the air in the core; resulting in small positive temperature excess. Therefore, it seems to us that the attempt of using the temperature excess obtained from pseudo-adiabatic cooling as a measure of the thermal force which drives the circulation on a radial-vertical plane of a hurricane is quite improper, The largest temperature variations are associated with the downdraft and stronger than -3C appears ih more than one cloud. Just above and at the cloud top, the temperature excess is also alway negative, and in most cases, larger than -1C. In the former case, since the downdraft is generally stronger and shortlived than the updraft, it seems there is no much time for the entrainment to warm up the downdraft as it does to cool the updraft. In the latter case, it is partially due to the dry adiabatic cooling of the air just above the cloud top being pushed upward by the rising tower, and partially due to the so-called mixing-on-top which brings forth strong evaporational cooling.

In the velocity field, there are great variations, as depicted by the figures. Generally, we see that and updraft takes a longer time to reach its maximum, while a downdraft takes a much shorter time. This might be due to the fact that in the updraft, the drag force of the liquid water droplets is opposite to the direction of motion, but in a downdraft, it is not, and in addition, it is also co-directional to the negative buoyancy. Furthermore, we also see that dry downdraft warms up at a dry adiabatic lapse rate and loses its strength quickly. This is indicated in the figures that if we draw a vertical line through the time of the cessation of rain, strong horizontal (time) gradients of both the vertical velocity and the temperature exess at the source level exist almost immediately on the right side of this line. Here, we should mention another point that in cloud 3-1, there appears a very strong vertical gradient just above the source at t equals about 37 min. As we have pointed out before, this leads us to doubt whether there is any defect in our variable boundary conditions or not, but most probably, it m'ght be due to the assumption that no rain drops can penetrate an unsaturated layer. Another feature worthy of mentioning is that whenever a downdraft develops, the dynamics of the upper and the lower part of a cloud will be de-coupled. Under suitable conditions, the dynamics in the upper part may cause a "burst" of the cloud top.

Since we have already discussed a lot about LWC field, here, we need only to mention another interesting feature produced in our experiments. That is, when the lower part of a deep rain cloud is washed out by downdraft, what left behind is a long-lasting, inactive altocumulus cloud floating in middle atmosphere. This is very often observed, as we usually see patches of small, disorganized clouds floating in the sky after a shower in over.

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有關層流與旋流動力學參考文獻

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