積雨雲之研究(一)

王業鈞

On The Lite Cycle of Cumulus Rain Clouds

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摘　　要

利用準一維，有時序變化之降雨積雲模式，多個實驗雲模經予作出。在不同環境及雲源條件下，其中某些雲模確見產生降水，並顯示其生命循環係包含三個階段；而其他雲模則無降水產生。這些實驗雲模形式，有穩定者，週期性者及不規則者。大多數之例顯示，無降水之雲模由於其使空氣中增加溫濕，而為後繼雲模「鋪路」，因而造成後繼者產生降水。

Abstract

Using a quasi-one-dimensional, time-dependent, precipitation cumulus cloud model, a number of experimental clouds have been produced and presented. Under various environmental and source conditions, some of these clouds do produce rain and show a life cycle comprising three stages of development, while some others produce no rain. These clouds have a great variety of forms: steady state, periodic and irregular. In most cases, the non-precipitation clouds do act to pave the way for the successors by moistening and warming up the space above first, in order to enable the successor to produce rain.

1. Introduction

In a previous" report (Wang, 1973, hereafter referred as Paper A), we have presented a quasi-one-dimensional, time-dependent, non-precipitation cumulus cloud model. This model has a source of finite dimension, which emits warm and moist source air at a constant rate. By varying the rate of emission, or the source strength, we have produced a number of clouds and discovered two critical values for the cloud formation and development. Namely, a lower critical value of the source strength under which no cloud form, and an upper critical value above which the cloud draw upon the latent heat stored in the atmosphere by itself; hence, it could develop spontaneously to a much greater height. Should the source strength fall in-between the two critical values, the clouds produced have to be supported solely by supported solely by the source. In Paper A, we have named the former clouds as cumulus clouds, and the latter, plume clouds. Because our model has a source, and it is also non-precipitation, we could only use our model to study the early stages of the clouds formed over areas where similar sources are most likely to exist, namely, mountainous areas (Braham

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and Driginis, 1960). With our results, we have re-evaluated and explained in detail the observations, made by Glass and Carlson (1963) in 1960, on the clouds formed over the San-Francisce Peak, Flagstaff, Ariz.

As it has been reported in the Report of the Thunderstorm Projectt a thunderstorm usually consists several cells each undergoes a life cycle of three stages, via., cumulus stage, mature and dissipation stage. According to their observations, the key which produce such a phenomenon is the downdraft initated by the downward drag force of the falling rain drops. Since the model presented in paper A did not consider precipitation, it was not possible to produce a downdraft; consequently, not possible to show the life cycle of a storm cell.

The present study is a continuation of the previous one. Our aim is to produce the life cvcle comprising also the three stages, by introducing a precipitation mechanism into the previous model. Precipitation, or rain, is than expected, and, if strong enough, to fall through the source level. Because we expect so, we must relax the restriction of the constancy made by us on the source strength in each of the experimental cases made In Paper A, and allow the parameters of the source to vary when downdraft or rain reaches and falls through the source. The main consideration of the present study, besides the introduction of the precipitation, in thus to seek the technipue which will allow the variables of the source to vary according to the dynamics of the air, or the cloud, above the source, at an appropriate time and in an appropriate manner.

2. The model

As we have stated before, the present work is a continuation of Paper A in which we have presented our model in detail; therefore, we shall not repeat the derivations of the fundamental equation system here. The reader is suggested to read Paper A first. In this paper, we shall describe only the changes that we have made on the original model, viz., the precipitation mechanism and the variable boundary conditions at the source.

Because our interest is not on the microphysics of the hydrometeors, the precipitation mechanism adopted here is thus a very simple one, namely, that used by Takeda (1966). Accordingly, we separate the liquid water content, q_L, into two catagories: the rain water, q_{LR}, and the cloud water, q_L. They are related as follows:

$$\left.\begin{array}{l} q_{LR}=q_L-1.0 \\ q_{LC}=1.0 \end{array}\right\} \text{ if } q>1.0 \quad (2.1a)$$

$$\left.\begin{array}{l} q_{LR}=0 \\ q_{LC}=q_L \end{array}\right\} \text{ if } q\leqq 1.0 \quad (1.1b)$$

The terminal volocity of the rain water is

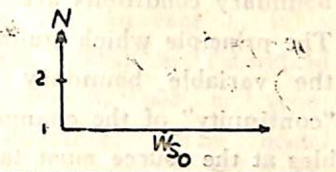
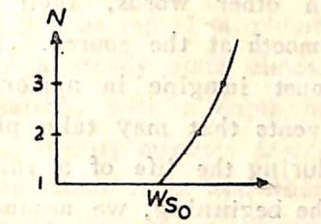
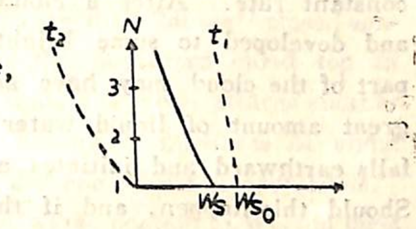
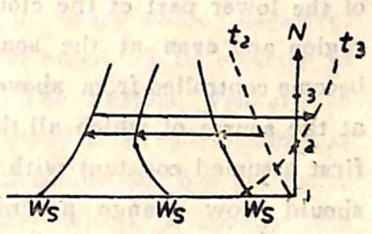
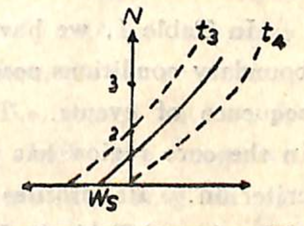
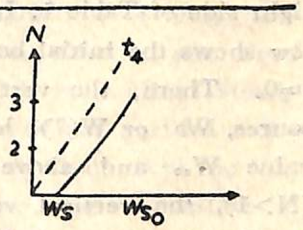
$$V=4.5q_{LR}^{1/2}, \text{ if } q_{LR}>4.0 \quad (2.2a)$$

$$V=9.0 \quad , \text{ if } q_{LR}\leq 4.0 \quad (2.2b)$$

The units for water substance is g kg^{-1} and for terminal velocity, in m sec^{-1}, positive downward. For the simplicity of the computations, we first compute q_L according to the governing equation stated in Paper A. Then we separate the resulted q_L into q_{LC} and q_{LR}, and re-compute the change of q_L according to (2.1) and (2.2). This means, we allow all the liquid water droplets to be carried upward by the updraft first, then let the larger droplets fall downward at the respective terminal velocities; resulting in a new distribution of q_L. Finally, we should remind the reader a very important assumption that we have made in the original model, namely, no liquid water droplets can fall through an unsaturated layer. This assumption is very influential on the results.

In the present study, most of the boun-

Table 1. BOUNDARY CONDITION AT THE SOURCE

INITIAL B. C. $t=0$,	$W_S=W(1)=W_{S_0}$ $W(N\geqslant 2)=0$	
CASE I. $t_1>t>0$. B. C. I	$W_S=W_{S_0}$ W(2) may increase from 0 up to greater than W_{S_0} $W_S=W_{S_0}$ $A(N\geqslant 2)$ governed by equations $A=W,\ \theta,\ q_v,\ q_L$	
CASE II. $t_2\geqslant t\geqslant t_1$, B. C. II	$W_S\geqslant 0$ $W(2)<W_S\leqslant W_{S_0}$ if W(2) decreases from greater than W_{S_0}; otherwise, stays B. C. I. $\frac{\partial A_S}{\partial t}=\frac{\partial}{\partial t}A(2)$ $\frac{\partial q_{LS}}{\partial t}=\frac{\partial}{\partial z}(\rho V_t\, q_{LR})$	
CASE III. $t_3\geqslant t>t_2$, B. C. III	$W_S<0$, $W(2)\leqslant 0$ $\frac{\partial A_S}{\partial t}=-W\frac{\partial A}{\partial z}(2)$ $\frac{\partial q_{LS}}{\partial t}=-W\frac{\partial q_L}{\partial z}+\frac{\partial}{\partial z}(\rho V_t\, q_{LR})$ $W=[W_S+W(2)]/2$	
CASE IV. $t_4\geqslant t>t_3$, B. C. II	$W_S\leqslant 0$, $W(2)>0$	
CASE V. $t_5\geqslant t>t_4$, B. C. II	$W_S>0$, $W(2)>0$ if $W_S>W_{S_0}$, set $W_S=W_{S_0}$	
CASE VI. $t>t_5$.	same as case I, sequence of events may repeat	

dary conditions are the same as in Paper A, except that at the source where the boundary conditions are quite complicated. The principle which guides us to establish the variable boundary conditions is the "continuity" of the changes of all the variables at the source must take place smoothly. In other words, their profiles must be smooth at the source. For doing so, we must imagine in apriori the sequence of events that may take place at the source during the life of a rain cloud cell. At the beginning, we assume that the source starts to emit suddenly the source air at a constant rate. After a cloud has formed and developed to some height, the lower part of the cloud may have accumulated a great amount of liquid water which then falls earthward and initiates a downdraft. Should this happen, and if the downdraft could gain sufficient strength, the dynamics of the lower part of the cloud, the subcloud region and even at the source level, shall become controlled from above. The conditions at the source of which all the variables were first assumed constant with respect to time, should now change accordingly, and the sonrce becomes a variable one.

In Table 1, we have listed the variable boundary conditions according to the possible sequence of events. The vertical velocity in the core region has been chosen as the criterion. Its profiles are shown on the right side of Table 1. In Table 1, the first row shows the initial boundary conditions at $t=0$. There, the vertical velocity at the source, Ws or W(1), had been assigned a value W_{so} and above the source level. (N>1), the vertical velocity is zero. In case 1, when $t_1>t>0$, W_s is kept constant W_{so}. W(2) and W(N>2) may all increase, for the source has started to emit source air. The boundary condition I is then: $W_s=W_{so}$, and all the other variables at N>2 are governed by the appropriate governing equations given in Paper A up to some time, say, $t=t_1$. The profile of W may then develop as shown on the right side of the second row.

In case II, when $t_2>t>t_1$, the situation may be that a downdraft may have been doveloped in the cloud and become so strong as to be able to resist the upcoming source air. That is, the source feels the downdraft. The vertical velocity at heigths not far above the source, for example, W(2), may start to decrease. When W(2) becomes smaller than W_{so}. the time is marked as $t=t_1$. As shown on the right side of the third row, the profile of W has been moved leftward and may even to the negative side. When all the air above the source becomes downward and W_s becomes zero, as shown by the dashed line on the negative side, the time is marked as t_2. This is the time that the downdraft reaehes the source. During this time interval, $t_2\geq t\geq t_1$, as is called case II, we set the local change of a variable to equal to the local change at one computational point above. For q_{Ls}, of course, the falling sain drops must also be considered in addition. This is the boundary condition II, as listed on the left side of the third row.

As the downdraft has reached and fallen through the source, the situation becomes rather simpler. We assume the changes of all the variables at the source are due to the "downward" advection. Of course, the mass convergence of q_{Ls} must also be taken into consideration, As time goes on, the downdraft may become stronger. The profile of W then moves further to the left as indicated by the horizontal, left-pointed arrows. When the downdraft becomes strongrst, its profile reaches the leftmost position. Afterward, most, probably at the time when all the rain drops have been evaporated, it shall start to move gradually to the right. When W(2) increases and becomes equal or greater the zero, the time is marked as t_3 and the boundary condition III ceases to apply, as depicted by the fourth row of Table 1. When W profile continues moving rightward, its lower end may pass the zero point. This marks t_4, as indicated by the 5th row of Table 1. Between t_3 and t_4, as called case IV, boundary condition II applies.

In case V, when $t_5\geq t>t_4$, W at all points are positive and boundary condition II also applies; however, in case of W_s becomes greater than W_{so}, we set $W_s=W_{so}$. This implies that the mechanism in the surface layer, between the source level and the ground, has not been changed stronger as time elapsed in producing an updraft through the source with its vertical velocity greater than W_{so}.

In case VI, as $t>t_5$ the situation may be expected to be the same as case I and after t_5, the same sequence of events may repeat.

3. Results and discussion

In this paper, we shall present six experimental cases. They are numbered from 1 through 6. In some cases, more than one cloud may be produced. In such cases, the clouds are numbered, for example, cloud 4-1 means the first cloud of case 4. The initial and the environmental conditions for these cases, together with some other informations, are listed in Table 2. The assignment of grid points and the comptational scheme are the same as that described in Paper A. We shall not repeat it here.

Of the first three cases, both the environmental and source air are quite dry. The relative humidity of the former, RH_e, is 50% at Z=0 m and decreases to zero at Z=9400 m, while that of the latter, RH_s, is 75%. All the other conditions are the same, except that the environmental temperature lapse rate, γ_e. In case 1, it is 0.006C m^{-1}, in case 2, 0.0065C m^{-1} (standard atmosphere) and in case 3, 0.008C m^{-1} (conditionally, quite unstable). The model cloud produced in case 1 is a thin, cold, plume cloud, formed just on top of a plume (fig 1). It attains a steady state almost right after its formation, with a depth of about 300 m. About twenty minutes later, the cloud top of this cloud rises and then falls. This is due to the strong gravity oscillations induced by the up-shooting plume air, as indicated by the -2m sec^{-1} closed contour just above the depressed cloud top in fig 1, After that, the cloud attains another steady state, having a thichness of about 750 m, up to the end of the computations.

The liquid water content (LWC) in most part is smaller than 1 g kg^{-1}. The temperature excess is every-where negative, with a minimum of about -2.1C exactly at the cloud top. The vertical velocity in most part of this cloud is greater than 4 m sec^{-1}, with a maximum of 5.2 m sec^{-1}. Such a high vertical velocity is because the source air has a high velocity, $W_s=2.0$ m sec^{-1}, and a relatively strong buoyancy force, $\triangle T=2C$, therefore, the air accelerates upward rapidly from the source until it is opposed strongly by both the negative buoyancy and ihe downward drag of the accumulated liquid water. A strong velocity gradient thus exists close to the cloud top. When the cloud is in its final steady state, the negative maximum vertical velocity in the IE region is about -3 m sec^{-1} at the cloud hight; hence, the circulation of this cloud is very much like the starting plume cloud studied by Turner (1962).

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Table 2. Experimental parameters and conditions

Case	Initial conditions	Environmental conditions	Produced clouds	Remarks
1	W_s=1 m/sec, T_s=2.0°C R_s=1000 m, RH_s=75% Q_s=8.72 g/kg	γ_e=0.006°C/m RH_e decreases from 50% at 0 m to zero at 9400 m	One steady shallow plume cloud	
2	W_s=2 m/sec, T_s=2.0°C R_s=1000 m. RH_s=75% Q_s=8.72 g/kg	Standard Atm. RH_e decreases from 50% at 0 m to zero at 9400 m	A series of shallow Cu	Same as case 1, except γ_e=0.0065° C/m.
3	W_s=2 m/sec, T_s=2.0°C R_s=1000 m, RH_s=75% Q =8.72 g/kg	γ_e=0.008° C/m RH_e decreases from 50% ät 0 m to zero at 9400 m	Two deep Cu 1st has no rain, 2nd has	Same as case 1, except γ_e=0.008°C/m.
4	W_s=2 m/sec, T_s=2°C R_s=1000 m, RH_s=80% Q_s=9.3 g/kg	Standard Atm. RH_e decreases from 50% at 0 m to zero at 9400 m	Three Cu. 1st and 2nd have no rain, third has	
5	W_s=2 m/tec, T_s=1.0°C R_s=1000 m, RH_s=90% Q_s=9.8 k kg	Standard Atm. RH_e decreases from 80% at 0 m to zero at 9400 m	One deep Cu with rain	
6	W_s=2 m sec, T_s=2°C R_s=1000 m, RH_s=80% Q_s=9.3 g kg	Standard Atm. RH_e decreases from 50% at 0 m to zero at 9400 m	One deep Cu with Rain	Same as case 4, except that the precipi tation mechanism is excluded first and the cloud is allowed to reach its steady state. Then the precipitation mechanism is introduced at t=70 min.