A STUDY OF TWO-BRANCH ONE-DIMENSIONAL NUMERICAL MODEL: EFFECTS OF CLOUD–PRECIPITATION DEVELOPMENT ON THE FORMATION OF VERTICAL CIRCULATION IN A SUPERCELL STORM

Xu Huanbin (许焕斌) and *Wang Siwei* (王思微)

Academy of Meteorological Science, State Meteorological Administration, Beijing

Received October 25, 1986

ABSTRACT

A one-dimensional time-dependent numerical model has been designed to simulate the vertical circulation in a supercell storm. The model includes two branches: one describes the developing process of cloud-precipitation and supplies the liquid hydrometeors; the other simulates the development of downdraft. The calculation indicates that the dry-cold ambient airflow breaking into the rearpart of cloud plays a critical role in the genesis of the downdraft in meso-scale circulations, while the transport of liquid hydrometeors satisfies the requirement for the persistance of moist adiabatic process, otherwise the downdraft will be damped. In addition, the simulation shows that the intensity of the downdarft varies with the strength of the ambient air injection, with the amount of liquid hydrometeor transport, and with the microstructure of hydrometeors.

I. INTRODUCTION

The genesis and development of many weather phenomena associated with convection usually depend on the existence of a vertical circulation. Bergeron (1960) presented a vertical cross-section (see Fig. 1) illustrating the formation and interaction of convectional weather

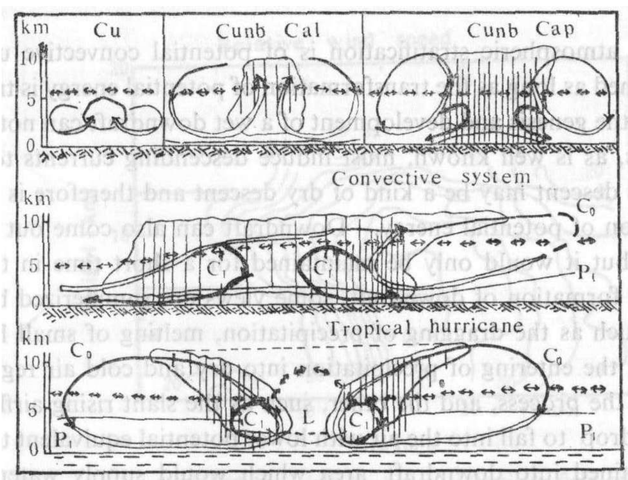

Fig. 1. Schematic vertical cross sections for main precipitation mechanisms (after Bergeron, 1960). Dashed line shows the ice-nucleus level; P_1, the isobar; and hollow and bold arrows, the air-currents at heat source and sink, respectively.

systems. Therefore it is reasonable to study the development of the strong convectional system from the point of view of the formation and maintenance of the vertical circulation, and it would be more beneficial if the different effects of macro and micro processes are further studied.

II. THE FORMATION PROCESS OF STRONG CONVECTIONAL MESO-SCALE CIRCULATION

The strong convectional meso-scale circulation is normally formed as follows. It begins with the appearance of some cells and jets around a large area with potential unstability. A few hours later these cells and jets gradually extend towards that unstable area, and finally develop into a strong convectional circulation under the intensification of some trigger forces. Some characteristics in the above process have been revealed by many observations, such as Nelson (1977), Zhang (1981) and Shou (1982), etc.

In general, supercell hailstorm is of meso-scale and can be characterized by a meso-scale convective circulation (see Fig. 2). The hailstorm makes up the core of strong convective system. From Fig. 2 we can see the following features:

(1) There exists a strong updraft consisting of the warm moist air flowing in a slant way to the left at low levels and a downdraft consisting of the cold dry air flowing to the right from the back of the cloud body at middle levels, thus a auto-trigger and auto-maintenance system has been formed.

(2) A large amount of condensation water provided by the updraft, not only enables hail embryos to grow up, but also supplies the downdraft area with adequate water via advection and turbulence.

(3) The down-impulse of downdraft is capable of promoting the full release of unstable energy, as a result, both ascent and descent flows may be nearly wet adiabatic. In this way the convection would be intensified to a high degree. The most important factor in the formation of the convective circulation is the genesis of a strong wet downdraft near the main updraft area.

III. THE FORMATION OF THE WET DOWNDRAFT

1. When the atmospheric stratification is of potential convective unstable type, a wet updraft can be formed as long as the transformation of potential energy is triggered. However, the conditions for the genesis and development of a wet downdraft can not be met all the time. Ascending currents, as is well known, must induce descending currents to compensate there. Unfortunately, this descent may be a kind of dry descent and therefore is unfavourable to the quick transformation of potential energy. Downdraft can also come out of the dispersion of cloud body itself, but it would only be maintained for a short time in this case.

2. As for the formation of downdraft, some views are summerized by Browning (1977), on the one hand, such as the dragging of precipitation, melting of small hail, and cooling by evaporation during the entering of precipitation into dry and cold air region, the function of which is to initiate the process, and the other, such as the slant rising airflow which would be helpful for the raindrop to fall into the air with lower potential equivalent temperature, and the hydrometeors entrained into downdraft area which would supply water droplets beneficial for the evaporation, the function of which is to develop and maintain the process. However, the whole process of formation of the strong wet downdraft has hardly been described either

by physical model or by numerical model. Takeda (1971) conducted a numerical experiment with a 2-D time-dependent convectional cloud model, resulting in a slant updraft and a rear downdraft. The downdraft did not flow out from the middle and upper level of the atmosphere, it, in fact, was a small circulation consisting of low air. This simulation case differs greatly from the structure shown in Fig. 1. The cause for this is that the used model, only taking account of the drag, evaporation of precipitation, and turbulent exchange is too simple to simulate the true process. In fact, we believe that a strong wet downdraft can be devoloped only if the following conditions are met: (1) the dry and cold flows break advectively into cloud at middle and upper levels, and (2) adequate water can be acquired from the flows during the evaporation.

3. Observations show that in the meso-scale strong convection system its low layer is wet and warm, but high level is dry and cold with strong wind shear. Meanwhile there exists a strong wind region at the middle level shown in Fig. 3. The strong wind seems not to be always able to enter a cloud, three possibilities can be considered:

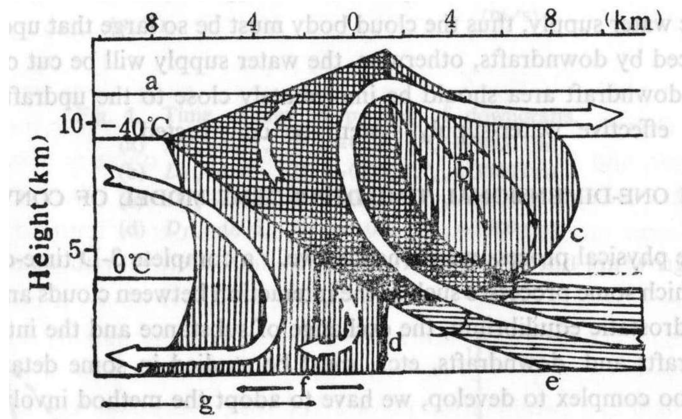

Fig. 2. Model of airflow within severe storms. Vertical section through centre of storm along direction of motion. Horizontal shading shows updraft and vertical shading the bulk of the radar echo (After Browning and Ludlam, 1962).
a—tropopause; b—freely falling hail size diminishing with distance ahead; c—forward overhang; d—wall; e—gust front; f—hail; g—rain.

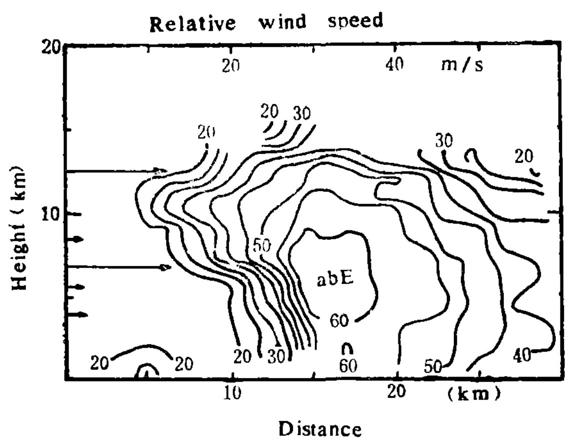

Fig. 3. Vertical radar section at 1224 CST showing erosion of reflectivity field by rear downdraft. Contours are in dBz. Vectors show relative environmental winds (0600 sounding) in this plane. Major tic marks indicate 10 km in distance and 20 m/s in wind speed (after Nelson, 1977).

(1) the flows run around a cloud, and then a pressure stationary area is formed between both flows and cloud body;

(2) the flows penetrate into a cloud and get rising with updrafts; and

(3) the flows penetrate a cloud and make the rising air damped or even a descending air developed.

In the third case, if water vapour can be fully supplied, the continuous addition of rear cold air will promote the development of a strong downdraft at the back of the cloud.

4. Under the condition of the entrance of dry cold air, whether a strong wet downdraft can be developed depends on the water supply of clouds. If the water supply is not enough, the descending air will become a dry adiabtic process prior to its full development. For example, an air-mass, while descending wet-adiabatically from 500 hPa to the ground, has its saturation specific humidity about 8 g/kg increased. If one part of the above air-mass mixing with N parts of dry and cold air masses does the same, then $8N$ g/kg of water would be needed. Obviously it is difficult for a static cloud to provide so much of water. The rich water source must be a dynamic water supply, thus the cloud body must be so large that updrafts can not be dispersed or replaced by downdrafts, otherwise, the water supply will be cut off. Another essential is that the downdraft area should be immediately close to the updraft one. Only in this way, can an effective water-supply system be constructed.

IV. TWO-BRANCH ONE-DIMENSIONAL TIME-DEPENDENT MODEL OF CONVECTIVE CLOUD

To express the physical process mentioned above. a complete 3-D time-dependent model is considered, in which some processes such as the interaction between clouds and environmental winds, the non-hydrostatic equilibrium, the exchange of substance and the interruption of airflow between updrafts and downdrafts, etc. must be studied in some detail. Because this kind of model is too complex to develop, we have to adopt the method involving the physical discretion and the combination of simple models instead. In doing so the sudden entrance of the dry cold flow at the middle level is recognized by a physical discretion in the simulation; water supply is prepared by a cloud in which updrafts prevail; this is the first branch including the vertical motion equation, thermodynamic equation, continuity equations of air, cloud water, rain and hail, as well as the condensation of water vapour, autoconversion of cloud and rain, freezing, melting and evaporation of cloud and rain drops. The second branch describes the mixing process of dry cold air at middle level with cloud after its getting into cloud, and the development process of wet downdrafts under the condition of water supply. The equations involved in this branch is the same as in the first one. All the equations and expressions can be found in Wisner (1972) and Xu et al (1985).

V. COMPUTATION RESULTS

The development of downdrafts is depicted in Fig. 4. A comparison of cases a, b and c in Fig. 4 shows the effects of water supply on the development of downdrafts, the amount of the water supply is the largest in case c, the smallest in case b, and the medium in case a, while the strength of downdrafts reaches the maximum in case c, the next in case b. But in case a, downdrafts hardly develop downward, even lead to the onset of updrafts, due to the positive buoyancy caused by gravity subsidence. A comparison of cases b and d shows the influence of subsidence area, the maximum value of downdrafts decreases with decreasing radius of the area because of the strengthening of entrainment mixture.

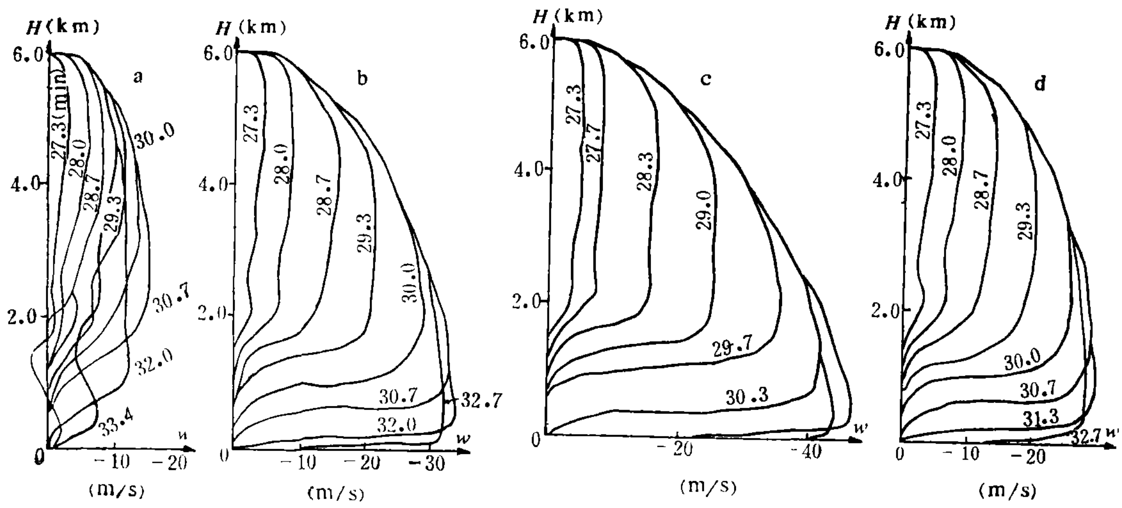

Fig. 4. Time change in profiles of downdrafts.
(a) $D_{fa}=0.01$, $D_{fb}=0.01$, $R_{cx}=3000$ (m);
(b) $D_{fa}=0.05$, $D_{fb}=0.05$, $R_{cx}=3000$ (m);
(c) $D_{fa}=0.1$, $D_{fb}=0.1$, $R_{cx}=3000$ (m);
(d) $D_{fa}=0.05$, $D_{fb}=0.05$, $R_{cx}=1500$ (m).

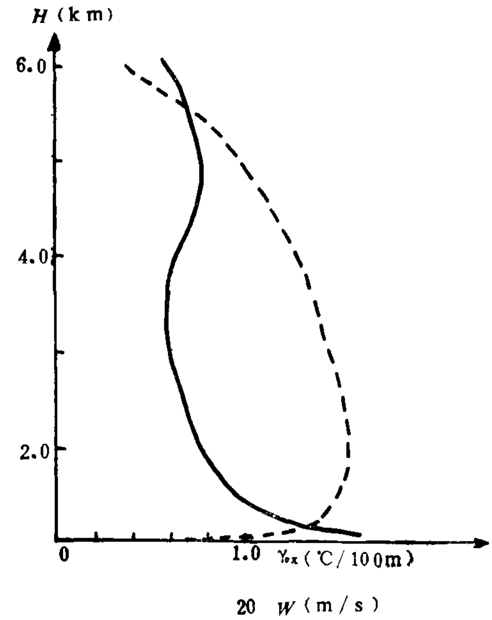

Fig. 5. The profiles of downdrafts and vertical lapse-rate of temperature in a column of descending airflow.

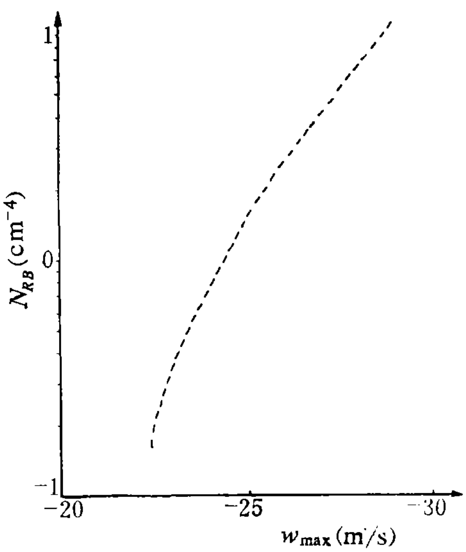

Fig. 6. The maximum downdraft speed versus the interception values of raindrop size distribution.

Fig. 5 gives the vertical lapse-rate of temperature in the downdrafts of case b. It can be found that even though the velocity of downdrafts reaches a great value, the lapse-rate only at middle level is close to the wet adiabatic, while at the low level it is less than, but close to, the dry adiabatic. That is also reflected in the profile of velocity of downdrafts, i.e. the accleration of subsidence exists at the middle level. Nevertheless, the buoyance is still negative and the descent motion still can be maintained because the temperature in the descending branch is lower than that of surroundings, of course, even lower than that inside clouds. However, in the layers of super-adiabatic lapse-rate the velocity of downdrafts decreases.

Analysis of computation results indicates that the fullness of cloud water-supply is the most important. If supply is full, the downdraft is of wet adiabatic; otherwise, maybe deviates far from it. Raindrops also evaporate in the process, but the descending air with raindrops is often of between dry and wet adiabatic. Therefore it seems important to the development of downdrafts that the water source comes mainly from cloud or rain, besides, the size distribution of raindrops also needs considering. In other words, the microstructure of hydrometeor in cloud gives great influence on the development of downdrafts (see Fig. 6). If dry and cold flows get into a cloud rich in water, a strong downdraft with short life time may break out, which is probably associated with the genesis of downburst.

VI. DISCUSSIONS

The vertical circulation in Fig. 2 not only possesses the mechanisms for auto-starting and auto-maintenance (Burtsev, 1980), but also is very powerful. The reason for the latter is that both the wet updrafts and downdrafts make the stratification as stable as possible in the course of changing potential energy into kinetic energy, thus the circulation has such a strong turning-over ability that some unstable potential energy which can not be initiated by weak system, is forced to release. This is why the weak convection cannot be developed in some cases, but the strong one does. It also shows that once the circulation is set up, it may extend towards the warm area without the help of fronts, and that it can hold the stability regardless of the influence of local inhomogeneity. On the other hand, in the formation of the circulation, the development of cloud and precipitation plays a key role. Although the maintenance of the circulation needs consuming much water and leads to reducing the precipitation efficiency, the local precipitation is still great in virtue of the strenthening of convection and the increasing of total condensation. Furthermore, in the formation of the circulation, the interaction among the vertical distribution of wind, the moving state of cloud, and the physical process of cloud and precipitation is of great importance, therefore a caraful study should be done regarding environment, cloud body and the microphysical process within the cloud as a whole, which is helpful for seeking the relation between convectional weather and macro-weather pattern. In addition, it is to be explored that what causes the strong convective weather such as hail, heavy rain and squall line. Along with the different weather patterns, the different physical processes of cloud and precipitation will be an essential factor to investigate.

REFERENCES

Atkinson, B.W. (1981), *Meso-Scale Atmospheric Circulation*, Academic Press, London, pp. 346.

Bergeron, T. (1960), Problems and methods of rainfall investigation, *Geophy. Monograph*, No. 5, 4—30.

Browning, K.A. (1977), The structure and mechanism of hailstorms, *Meteor. Monogr.*, No. 38, 20—21.

Burtsev, I.I. (1980), Hail suppression activities in the Soviet Union, Papers presented at the Third WMO Scientific Conference on Weather Modification, Vol. **2**. 552.

Zhang Peiyuan (1981), The characters of vertical circulation of squall hailstorm in different developing stages, *Report of Meteor. Science and Technology of Academy of Meteorological Science*, 7 (in Chinese).

Xu Huanbin and Wang Siwei (1985), A numerical model of a hail-bearing convective cloud (2): including biparameter size-distribution evolution caused by melting, *Acta Meteorologica Sinica*, **43**: 162—171 (in

Chinese).

Nelson, S.P. (1977), Rear flank downdraft: A hailstorm intensification mechanism, in *Proceedings of 10th Conference on Severe Local Storms*, Omaha, 521—525.

Shou Shaowen (1982), The formation and structure of hailstorm, *Journal of Nanjing Institute of Meteorology*, No. 2, 223—228 (in chinese).

Takeda, T. (1971), Numerical simulation of a precipitation convective cloud: The formation of a "long-lasting" cloud. *J. Atmos. Sci.*, **28**: 350—376.

Wisner, C., Orville, H. D. and Myers, C., A numerical model of a hail-bearing cloud. *J. Atmos. Sci.*, **29**: 1160 –1181.