THE EFFECT OF VERTICAL TRANSPORTS OF HEAT AND MOISTURE BY CUMULUS CONVECTION IN TYPHOON

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ABSTRACT

By utilizing the denser upper-air observations from the Okinawa region and Japanese islands during August 17—23, 1975, the vertical transports of heat and moisture by cumulus convection in the typhoon No. 7507 have been calculated. It is found that there exist a large apparent heat source (Q_1) and a moisture sink (Q_2) in the southern part of the typhoon at the disturbance, growing and mature stages. The magnitudes of the apparent heat source and moisture sink are rather small, or turn into the apparent heat sink in the northern sector of the typhoon. In the southern part of the typhoon, the total cloud mass flux (M_C) is positive, whereas in the northern part of the typhoon M_C is negative. The above-mentioned distributions of Q_1, Q_2 and M_C agree well with the major cloud patterns.

In the southern part of the typhoon, Q_2 is positive because the drying effect is always larger than the evaporative cooling, whereas in the northern part of the typhoon, the opposite case is true because both the drying and evaporating effects of liquid water make a negative contribution to Q_2.

I. INTRODUCTION

Numerous investigators, such as Yanai (1973), Ogura and Cho (1973), Ogura and Cho (1974), Nitta and Esbensen (1974), Arakawa and Schubert (1974), Nitta (1975, 1976, 1977), have estimated the budgets of mass, heat and moisture in the tropical disturbances or trade winds over the West-Pacific and the North-Atlantic Oceans and have found the significant variations of the large-scale budgets from case to case. In fact, their results have reflected the differences in cloud properties and their vertical transports, but all the previous estimates have been carried out for weaker tropical disturbances or an undisturbed trade regime. Little have been done for estimating the vertical transport of heat and moisture in the tropical cyclone, especially over the West-Pacific Ocean. This paper is aimed at calculating the vertical transports of heat and moisture by cumulus at the different developmental stages of the typhoon No. 7507, based on the large scale budget calculation and simple cloud model in order to understand the relationship between the convective activity and the development of the typhoon circulation.

II. DATA AND COMPUTATIONAL ASPECTS

The computational domain covers a region of 118.5—141.0°E, 16.0—42.5°N. The data of radiosondes, surface observation and ship report have been gathered as many as possible from different sources in this region. Then a subjective analysis was applied to

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15 levels (surface, 900, 850, 800, 700, 600, 500, 400, 300, 250, 200, 150, 100, 70 and 50 hPa). A specially careful check of the spatial and temporal continuity was given for the adjustment of the analyzed meteorological fields and synoptic systems whenever necessary. Finally, the values of winds (u, v), temperature (T), dew-point temperature (T_d) and geopotential height (H) were read every 1.5° latitude/longitude. The time period under study spanned from 00Z GMT, August 17 to 00Z GMT, August 23, 1975, namely, from the initial disturbance stage detected in the East China Sea to landing on the coast of Japan and eventual weakening. Four stages have been divided for the entire life cycle of this typhoon: (i) the disturbance stage (from 00Z August 17 to 12Z August 18): the mean central surface pressure was 996 hPa with the maximum sustained winds less than 18 m/s; (ii) the developing stage (from 00Z August 19 to 00Z August 21): the mean central pressure was 985 hPa with the maximum sustained winds of 22 m/s; (iii) the mature stage (from 12Z August 21 to 12Z August 22): the mean central surface pressure was 970 hPa with the maximum sustained winds of 34 m/s; and (iv) the weakening stage (00Z August 23): the mean central surface pressure was 985 hPa with the maximum sustained winds being 23 m/s. We shall only present the results for the first three stages.

The thermodynamic equation and moisture conservation equation are given below respectively:

$$\frac{\partial S}{\partial t}+\nabla\cdot(S\vec{V})+\frac{\partial S\omega}{\partial P}=Q_R+L(C-e), \tag{1}$$

$$\frac{\partial q}{\partial t}+\nabla\cdot(q\vec{V})+\frac{\partial q\omega}{\partial P}=-C+e, \tag{2}$$

where $S=C_pT+gz$ is dry static energy, C_pT the enthalpy, gz the potential energy, q the specific humidity, L the condensation latent heat, Q_R the radiative heating (cooling), C the condensation rate, e the reevaporation rate, and $\vec{V}$ and ω indicate the horizontal wind vector and the vertical velocity in p-coordinates respectively.

Averaging Eqs. (1) and (2) over an area, one can obtain:

$$Q_1=\frac{\partial \bar{S}}{\partial t}+\nabla\cdot(\bar{S}\bar{\vec{V}})+\frac{\partial \bar{S}\bar{\omega}}{\partial P}=\bar{Q}_R+L(\bar{C}-\bar{e})-\frac{\partial \overline{S'\omega'}}{\partial P}, \tag{3}$$

$$Q_2=-L\left(\frac{\partial \bar{q}}{\partial t}+\nabla\cdot(\bar{q}\bar{\vec{V}})+\frac{\partial \bar{q}\bar{\omega}}{\partial P}\right)=L(\bar{C}-\bar{e})+L\frac{\partial \overline{q'\omega'}}{\partial P}, \tag{4}$$

where the overbars denote the areal averaging and the variables with the primes indicate the departures from the areal average, which may be considered as the effects of the Cu convection. The left-hand sides of Eqs. (3) and (4), only including the large-scale averaging variables, are the apparent heat source (Q_1) and the apparent moisture sink (Q_2) respectively, which may be estimated alone by using of the large-scale variables. In deriving Eqs. (3) and (4), the horizontal eddy transport terms are omitted, i. e., $\nabla\cdot(\overline{\vec{V}'s'})=0$ and $\nabla\cdot(\overline{\vec{V}'q'})=0$.

Taking the life cycle of the cumulus ensemble into account, Cho has obtained the following heat and moisture equations:

$$Q_1-Q_R=-M_c\frac{\partial \bar{S}}{\partial P}, \tag{5}$$

$$Q_2 = -L(\bar{q}^* - \bar{q}) \int_{P_T}^{P} \frac{\sigma^*(P')}{\tau_{P'}} dP' + LM_C \frac{\partial \bar{q}}{\partial P}, \qquad (6)$$

where M_c represents the total mass flux of cumulus clouds, $\bar{q}^*$ the environmental saturation specific humidity, P_t the pressure level of cloud top, $\tau_{P'}$ the life span of the cumulus cloud when the Cu cloud reaches its maximum height, and $\sigma^*(P')$ is the effective fractional density function of the cloud area. The first term in the right-hand side of Eq. (6) represents the evaporation of liquid water (Q_l). Eq. (5) indicates that the apparent heat source Q_1 is generated by the adiabatic warming of the compensating downward motion in the environment induced by the convection activity. The variations of Q_2 consist of two parts: the evaporation of the liquid water (Q_l) which can moisten the atmosphere, and the drying effect of the compensating downward motion in the environment, i. e. $LM_C(\partial \bar{q}/\partial p)$.

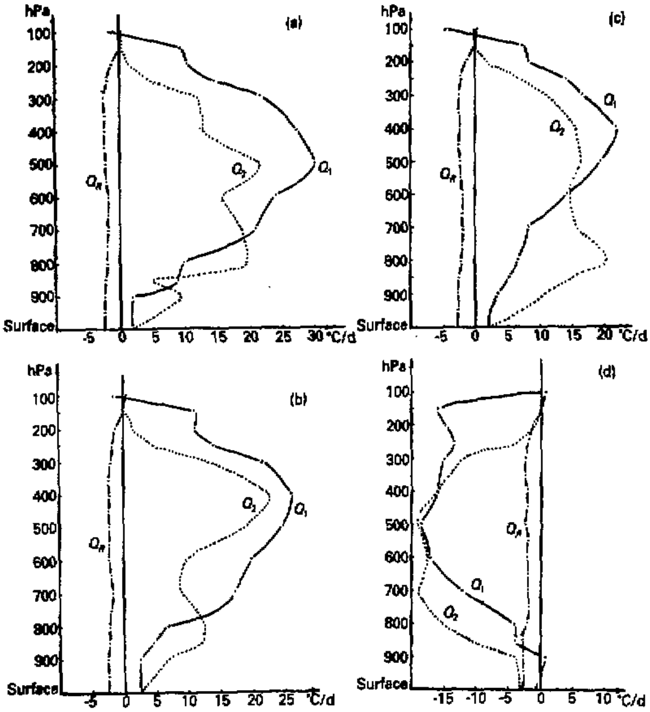

Fig. 1. The average vertical profiles of Q_1 dan Q_2 for the typhoon No. 7507 at the different developmental stages. (a) the disturbance stage and averaged over the region with the radius of 450 km in the southern half sector of the typhoon; (b) the developing stage and the averaged area is the same as (a); (c) the mature stage and the averaged area is also the same as (a); (d) the mature stage, but averaged over the region with the radius of 350 km in the northern half sector of the typhoon. Unit: °C/day.

III. THE DISTRIBUTIONS OF Q_1 AND Q_2

Figure 1 is the average vertical profiles of Q_1 and Q_2 at different developmental stages, showing the peak of Q_1 found at 500 hPa in the southern half sector of the typhoon at the disturbance stage. There are two peaks of Q_2: one at 500 hPa and the other at 800 hPa. This fact shows the importance of both Cu convection and the continuous precipitation for the heating and moisture fields at the disturbance stage. Q_R is taken from the climatological data (Dopplick, 1972). In the northern half sector of the typhoon, Q_1 is weak, only accounting for one-fifth of Q_1 in the southern half sector (not shown). The heights of the peaks of Q_1 and Q_2 are found at 700 hPa and 800 hPa, respectively, showing that the major heating area in the typhoon is situated in the southern part of the typhoon. This result is in good agreement with the direct estimate of the heating field (Ding et al., 1985).

At the developing stage of the typhoon (Fig. 1b), the profiles of Q_1 and Q_2 are basically similar to those at the disturbance stage, only with a major difference in that the heights of the peak of Q_1 and Q_2 extend up to 400 hPa. This upward extension may be related to the enhancement of convective vertical transports. Q_1 and Q_2 in the northern half sector of the typhoon are still small. At the mature stage (Fig. 1c), Q_1 is still located at 400 hPa, but the two peaks of Q_2 are found at 500 hPa and 800 hPa respectively. This remarked vertical separation of the peaks of Q_1 and Q_2 reflects the major importance of the convective process in creating the heating field at the mature stage. Fig. 1d shows the profiles of Q_1 and Q_2 in the northern half sector of the typhoon at the mature stage. The negative Q_1 at all layers, i.e. the apparent moisture source, is rather different from the condition in the southern half sector of the typhoon. This fact shows the existence of a strong evaporative process of the liquid water, for instance, the dissipation of clouds, with the result of moistening of environmental atmosphehre. The observed evidence of reduced cloudiness is consistent with this physical process (Ding et al., 1985). The maximum of the apparent heat sink in this region is found at 500 hPa, which was created due mainly to the evaporative cooling of cloud droplets. This situation is much similar to that for the trade wind cumulus (Nitta and Esbensen, 1974).

Fig. 2 is the N-S cross-sections of Q_1 and Q_2 through the typhoon center at the beginning of the mature period, showing the maxima of Q_1 and Q_2 to the south of the typhoon center found at 500 hPa and 700 hPa respectively, at a distance of about 150 km away from the typhoon center. Owing to the different vertical height of Q_1 and Q_2, it may be inferred that the effect of the cumulus vertical transport should be significant. To the north of the typhoon center, both Q_1 and Q_2 are negative (the apparent heat sink and apparent moisture source), which is in good agreement with the result shown in Fig. 1d. It can be seen that the maximum evaporative cooling occurred at 600 hPa.

IV. THE VERTICAL DISTRIBUTIONS OF THE TOTAL CLOUD MASS FLUX (M_C)

The total cloud mass flux (M_C) representing the activity of Cu convection is the most important quantity characterizing the cloud properties. Based on Eq. (5), M_C may be directly estimated from Q_1, Q_2 and the environmental static stability $\partial \bar{S}/\partial P$. After the derivation of M_C, the following expression may further be used to estimate the compensating mass flux between clouds ($\tilde{M}$) induced by their activity:

$$\tilde{M} = \bar{M} - M_C, \qquad (7)$$

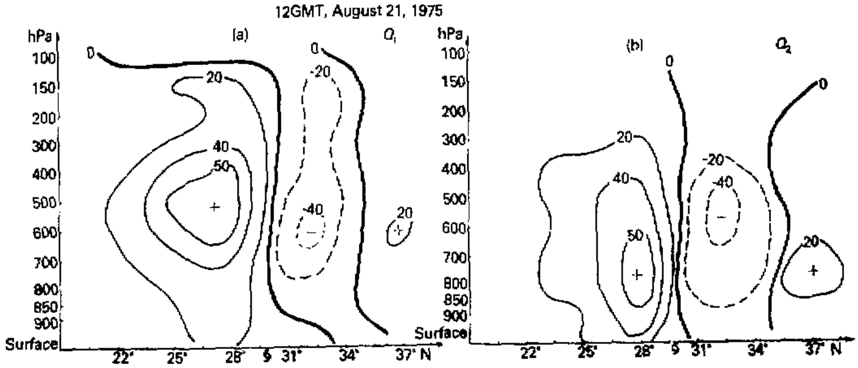

Fig. 2. The N-S vertical cross-section of Q_1 and Q_2. The solid lines represent the apparent heat source and apparent moisrure sink; the dashed lines denote the apparent heat sink and apparent moisture source. Unit: °C/day.

where $\bar{M} = -\bar{\omega}$ and $\bar{\omega}$ is the vertical velocity in p-coordinates obtained with the large-scale variables.

Figure 3 shows the vertical profiles of M_C, $\bar{M}$ and $\tilde{M}$ at the different stages. At the disturbance stage, there exists the positive maximum of M_C at 500 hPa and the negative (downward) $\tilde{M}$ in the southern half of the typhoon (Fig. 3a), thus making the average of M_C and $\tilde{M}$, i. e. $\bar{M}$, less than M_C. The M_C in the northern half of the typhoon is much smaller than that in the northern half (100 hPa/day). At the developing stage, the maximum of M_C extended upward to 400 hPa. This implies that the vertical upward extension of the height of $\bar{M}$ (or $\bar{\omega}$) mainly reflects the enhancement of deep Cu convection. $\tilde{M}$ is very weak in the middle and upper troposphere, with the negative $\tilde{M}$ being in all layers below 600 hPa. In the northern half sector of the typhoon, the height of the maximum M_C is found at 800 hPa with the magnitude of 120 hPa/day (not shown). At the mature stage, the maximum of the positive M_C further reached up to 300 hPa, so did $\bar{M}$. It shows the existence of a large amount of deep Cu convection in this region. $\tilde{M}$ is very weak. In the northern half of the typhoon, M_C is negative, showing the predominance of descending motion of clouds (Fig. 3d). Cho's cloud model includes the downward motion caused by the evaporative cooling of liquid water. Thus, the negative mass flux may be produced. As previously pointed out, the evaporative cooling of cloud droplets causes the large apparent moisture source, apparent heat sink and negative cloud mass flux. In his parameterization scheme of the total cloud mass flux, Nitta (1975) did not take the effect of the evaporative cooling caused by the descending motion into account, so that he obtained the positive M_C everywhere. Latter, having included the effect of the downward motion, he obtained the similar results to those described above. Thus, the estimates of Q_1, Q_2 and M_C presented here may be considered to be reasonable.

Figure 4 is the horizontal distribution of M_C at 500 hPa at the mature stage, showing the ascending motion mainly in the southern and south-eastern sectors and the strong descending motion in the northern sector of the typhoon. This pattern of M_C is consistent with the cloud patterns of the typhoon. The magnitude of M_C estimated here is somewhat

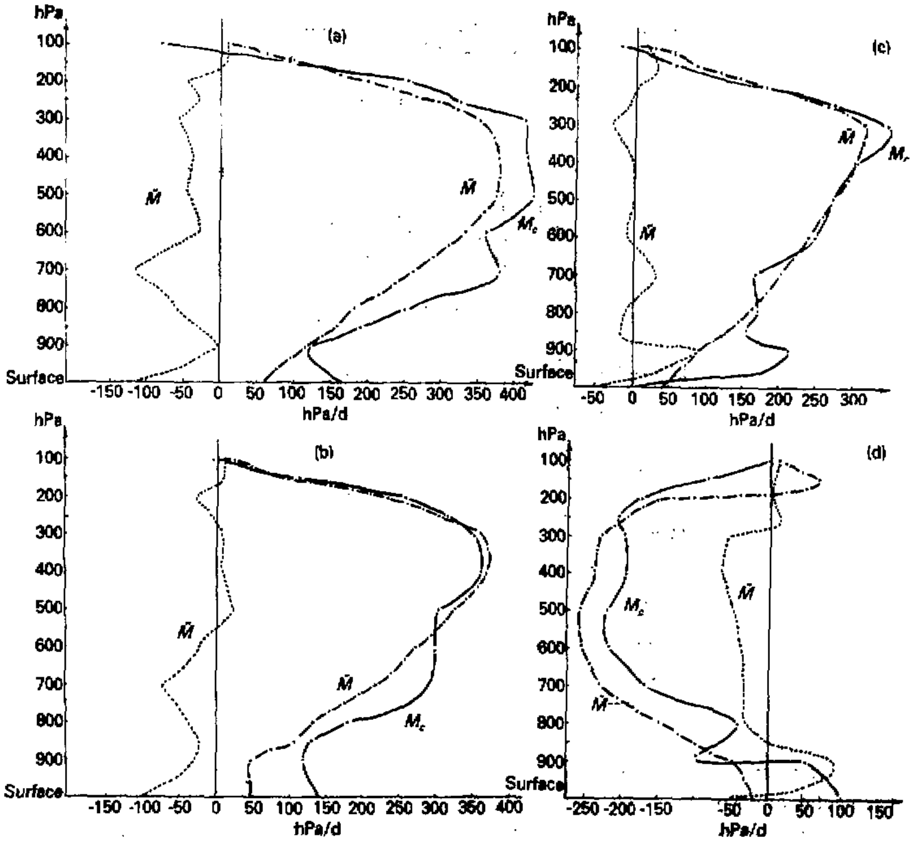

Fig. 3. The average vertical profiles of M_c, $\bar{M}$ and $\tilde{M}$ for the typhoon No. 7507 at the different developmental stages. (a) the disturbance stage (the southern half sector); (b) the developing stage (the southern half sector); (c) the mature stage (the southern half sector); (d) the mature stage (the northern half sector). The averaged area is the same as Fig. 1. Unit: hPa/day.

greater than that calculated by others due mainly to the fact that our M_c has been estimated by using denser radiosonde observations while the results obtained by other investigators are the averages for rather large areas or estimated based on the basis of data sets of the coarser horizontal resolution (Yang and Krishnamurti, 1981).

V. THE EFFECT OF CUMULUS CONVECTION ON THE BUDGET OF MOISTURE IN THE TYPHOON

Figure 5 shows the budget of moisture estimated from Eq. (6). Q_2 consists of $LM_c\ \partial\bar{q}/\partial P$ (drying effect) and Q_l (evaporative cooling). At the disturbance stage, $LM_c\ \partial\bar{q}/\partial P$ is much greater than Q_l in the southern half sector of the typhoon, thus

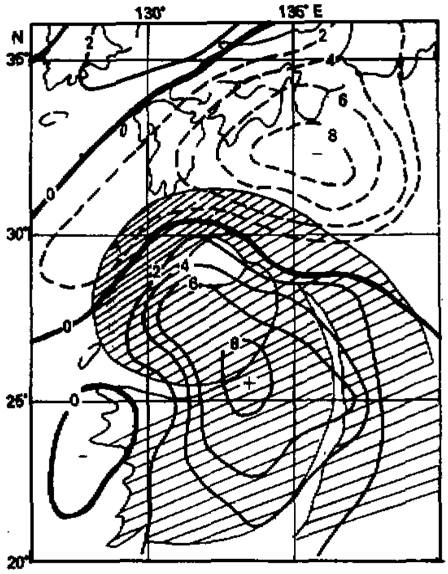

Fig. 4. The horizontal pattern of the total cloud mass flux (M_C) at 500 hPa at 12 GMT, August 21, 1975. The solid lines represent the positive values and the dashed lines denote the negative values. The shaded area is the major cloud areas depicted from the satellite cloud picture at the nearly same time. Unit: 10 hPa/d.

creating very large positive Q_2 (the apparent moisture sink) with a result of drying the environmental atmospehre. The maximum drying effect occurred at 700 hPa where a peak of Q_2 might be seen. At the developing stage (Fig. 5b), the profiles seem to be similar to those at the disturbance stage, but the peak of $LM_C\, \partial\bar{q}/\partial P$ extended upward to 500 hPa, which was related to the occurrence of the peak of Q_1 at the upper level. The large Q_l is found in the middle troposphere (700—500 hPa). For the first two stages, the drying effect in the northern half sector of the typhoon is very small, with the large Q_l, thus creating very small positive Q_2 (weak apparent moisture sink) (not shown). At the mature stage, Q_l in all the layers of the troposphere is very small with the contribution to the peak of Q_2 basically stemming from $LM_C\, \partial\bar{q}/\partial P$. In this period, both Q_l and $LM_C\, \partial\bar{q}/\partial P$ in the northern half of the typhoon are negative, due to the moistening effect generated by the evaporative cooling and the downward cloud mass flux. The maximum Q_2 is found in the layer of 700—500 hPa.

VI. SUMMARY

Based on the estimates of the vertical transport of heat and moisture by cumulus convection during the evolution of the typhoon No. 7507, the following results have been obtained:

1) In the southern half sector of the typhoon, the apparent heat source and moisture sink are very large at the disturbance, developing and mature stages. As the typhoon de-

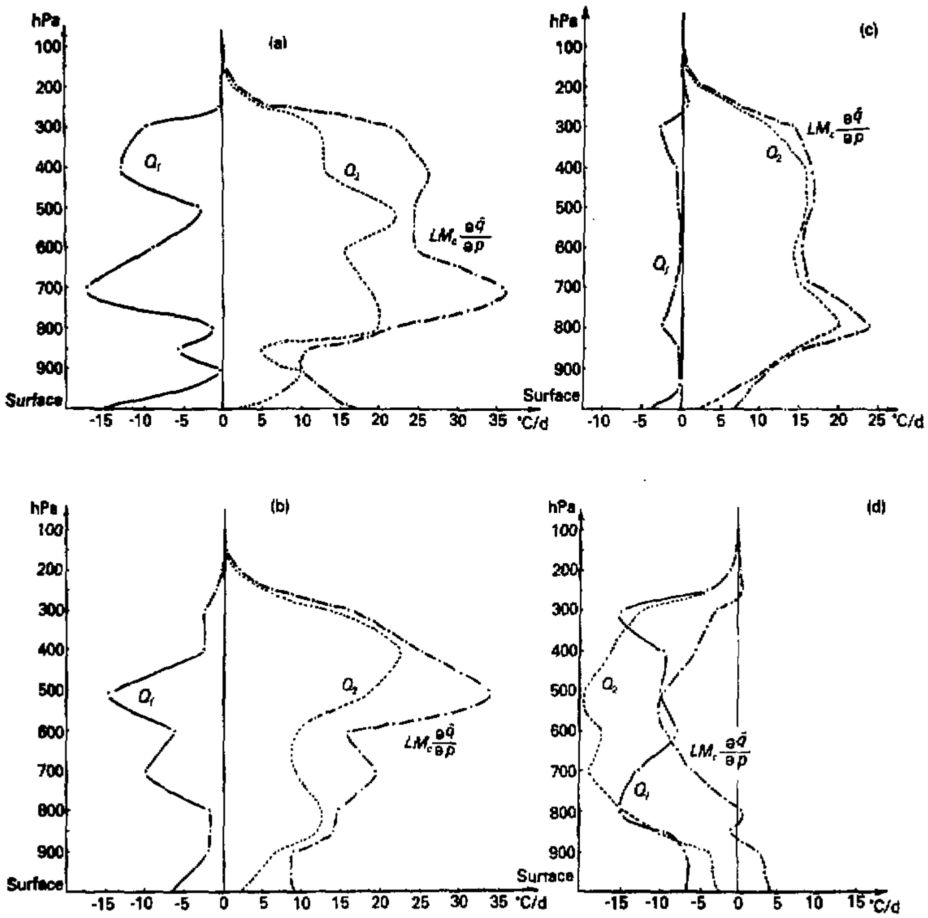

Fig. 5. The average vertical profiles of $LM_C\ \partial\bar{q}/\partial P$, Q_1 and Q_2 at the different developmental stages of the typhoon No. 7507. (a) the disturbance stage (the southern half sector); (b) the developing stage (the southern half sector); (c) the mature stage (the southern half sector); (d) the mature stage (the northern half sector.) The averaged area is the same as Fig. 1. Unit: °C/day.

veloped, the peak of Q_1 extended from 500 hPa to 400 hPa. The two peaks of Q_2 are found at 500 hPa and 700 hPa respectively. These vertical profiles of Q_1 and Q_2 suggest that the Cu convection may play a very important role in the vertical transport of the cloud properties. This result is consistent with active development of Cu convection in the southern half sector of the typhoon. In the northern half of the typhoon, Q_1 and Q_2 are generally negative, showing the significant importance of the evaporative cooling of cloud droplets. This situation may be associated with the dissipative process of Cu clouds.

2) At the three stages of the typhoon, there is a large positive Cu mass flux in the southern half sector of the typhoon, with the peak of M_c at 500 hPa at the disturbance stage, extending upward to 300 hPa at the mature stage. Correspondingly, a similar change occurred in the average field of the vertical velocity. The compensating vertical motion caused by Cu convection is downward. In the northern half sector of the typhoon, M_c is negative or small positive values, due to the evaporative cooling effect there.

3) In the southern half sector of the typhoon where the Cu convection is very active, $LM_c\ \partial\bar{q}/\partial P$ has large positive values (drying effect) at all the stages while Q_l is negative, thus creating the large positive Q_2 (the apparent moisture sink). Therefore, the latent heat release of Cu convection is the primary physical process in the southern half sector of the typhoon. In the northern half sector of the typhoon, both $LM_c\ \partial\bar{q}/\partial P$ and Q_l are negative, thus causing the large negative Q_2 (the apparent moisture sink).

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