Shorter Contribution

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A Comment on the Creation of Warm Core in Incipient Tropical Cyclone

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A detailed case study of typhoon formation made by the present author (9) has revealed the process of creation of a warm core at the center of a pre-existing disturbance, and its importance for further development of the disturbance into a typhoon. In a succeeding semi-theoretical paper (10), the author has given an explanation of typhoon formation in which the inertial instability along vertically inclined isentropes associated with the warm-cored structure was considered to be the most important factor determining the growth of typhoon-scale convection. Kasahara (3) has also presented an analysis of scale of atmospheric convections and got the same conclusion.

Though it is certain that the creation of the warm core is the result of liberation of latent heat of condensation, there remain many problems in the warming process which require further studies. In order to visualize the problems, some additional materials obtained at the analysis of typhoon Doris 1958 will be shown.

Figs. 1-4 are twelve hourly presentation of isotherms and streamlines at 200, 300, 400 and 500 mb-surface. In this period of 36 hours, an easterly wave under a high-level anticyclone developed into an incipient vortex. As seen in the figures, the system of disturbance was originally cold-cored, but it changed into a typical warm-cored one. An interesting fact is that *the warm core formed first at the layer between 300 and 400 mb and then it expanded further downward*. A remarkable change of the correlation between the thermal structure of the system and the vertical circulation will be seen in Fig. 5. These vertical cross-sections show tempera-

ture anomaly (from the mean sounding at Eniwetok island for July 1958) and the large-scale vertical motion estimated from the continuity equation. The maximum positive anomaly in temperature was created at about 400 mb. A similar observation made by research aircraft in hurricane Daisy 1958 has been presented by Colón *et al.* (1).

In the previous paper, the author tried a budget calculation of heat and moisture during the 36 hours. The heat source Q_1 and the amount of condensed water in unit of heat liberation Q_2 were estimated simply by the first law of thermodynamics and the continuity relation of water vapor as

$$Q_1 \equiv \frac{c_p}{(p_0/p)^{(\gamma-1)/\gamma}} \left\{ \frac{\partial \theta}{\partial t} + \nabla(\theta \mathbf{V}) + \frac{\partial}{\partial p}(\theta \omega) \right\}$$

and

$$Q_2 \equiv -L \left\{ \frac{\partial q}{\partial t} + \nabla(q \mathbf{V}) + \frac{\partial}{\partial p}(q \omega) \right\}$$

respectively, where c_p , γ , L are as usual, θ the potential temperature, q the mixing ratio, $\mathbf{V}$ the horizontal wind vector, and ω is the large-scale vertical p -velocity obtained from the continuity equation of the air. Utilized finite increment in horizontal plane was 4 degree in both latitude and longitude, and the vertical increment was 200 mb.

The result of estimation of Q_1 and Q_2 showed a fairly good coincidence. Therefore the source of heat could be identified with the released heat of condensation. The heat liberation was observed even in the earliest 12 hours in which cooling of the upper air proceeded. However, the amount of released heat was not sufficient to raise up temperature

(a)

(a)

(b)

(b)

(c)

(c)

(d)

Fig. 1

(d)

Fig. 2

(a)

(b)

(c)

(d)

Fig. 3

(a)

(b)

(c)

(d)

Fig. 4

Figs. 1~4. Changing thermal field in a formative tropical cyclone during through 00GCT, July 20 to 12GCT, July 21, 1958. Thin arrowed lines are streamlines.

Fig. 5. Vertical cross section of temperature anomaly (solid) in the formative tropical cyclone with vertical p -velocity (dashed).

- (a) top: at the wave stage with cold core.
 (b) bottom: at the creation of warm core in the upper troposphere.

of the upper air against the cooling effect by existing heat flux convergence $-\{V(\theta V) + \partial(\theta\omega)/\partial p\}$. In later 24 hours, the amount of heat liberation exceeded the cooling effect and resulted in the warming of the upper air.

It should be remarked that any special assumption on thermodynamic process was not involved in the calculation. Namely, the calculation was entirely based on observed values of θ , q , V and ω which are essentially of a large-scale sense. Therefore the calculation did not follow either of dry or moist adiabatic process. If we consider a fully saturated upward motion as usually assumed in theoretical or numerical studies, the observed warming from above will be very difficult to explain. Because the stratification of the tropical atmosphere is locally unstable for moist-adiabatic process in the lower troposphere and locally stable in the upper troposphere, a warming from below in a fully saturated air must result when a vertical

motion is imposed.*

The result of the budget calculation shows that the air should not be considered in state of complete saturation, or in other words, the air does not follow the moist adiabatic process so far as a large-scale motion is concerned. Actually the saturation was never found in utilized radiosonde observation, whereas a significant individual change in both potential temperature and mixing ratio was occurring. A sound interpretation of the former calculation may be that the treated air was a compound of saturated (not directly detectable by conventional observation) and unsaturated airs.

It is rather natural to imagine a model of atmosphere in which most part of air is not saturated and stable with respect to vertical motion and only a small portion of air is occupied by clouds. Tropical cumulus or cumulonimbus is built by buoyancy force of saturated and warmer air than the surrounding clear spaces. When a synoptic-scale vertical motion is imposed on the whole atmosphere, the cloud towers may be formed here and there. When the numbers of such clouds are relatively small, the imposed vertical motion would yield a cooling of the total air as observed in the first 12 hours. However, the increase of clouds and heat liberation and transport may result in the warming of the total air finally. The accumulation of heat released and transported by cloud towers may explain the warming at about 400 mb.

It is also remarked that the tropical atmosphere, if assumed in complete saturation, is too unstable to form a large-scale convection such as tropical cyclone (2, 4, 8, 10). Only when we assume an atmosphere with stable stratification as a whole, we get a reasonable scale of tropical cyclones (10). To include a process of heating in such an atmosphere, we must recognize that the role of small cumulus convections, even though they are limited in a certain small portion in space, may be essential for heat liberation and its upward transport.

Recently, a detailed cloud observation in

* This was shown by Kasahara's (2) numerical experiment.

hurricane (5) has revealed that the area of active convection is only several per cent of the total space even in the core of hurricane. Riehl and Malkus (6, 7) has proposed the significant role of these *hot towers* in heat transport. To get a further quantitative linkage between the cumulus convections and the synoptic-scale atmospheric motions, we must study not only the behavior of individual cumulus convections, but also their ability in transport of heat and moisture. Further, at least, some of their statistical characters such as density, average height, and horizontal spacing must be understood as functions of observable parameters such as static stability and large-scale vertical motion.

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発生期の熱帯低気圧における warm core の形成について

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