Budget analysis of absolute vorticity, simulated by a nonhydrostatic model, for the maintenance mechanisms of the intensity of Typhoon SONGDA (T0418) under traveling over the Sea of Japan

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In 2004, ten typhoons landed on the Japan Islands. Among them, Typhoon SONGA (T0418) maintained its strong winds until approaching Hokkaido Island through the Sea of Japan, and caused serious disasters there. Warm sea surface temperature (*SST*) is necessary for the maintenance of the intensity of typhoons. However, when typhoons travel over the northern Sea of Japan with the cool *SST* (< 24 ^{o}C), the supply of water vapor from the sea rapidly decreases and consequently typhoons cannot maintain their intensity. On the other hands, some typhoons receive such an influence of westerly waves as the baroclinic instability and the inflow of upper-level high potential vorticity (*PV)*, and redevelop as an extratropical cyclone. In this study, the maintenance mechanisms of the intensity of T0418 under traveling over the Sea of Japan are examined from the budget analysis of absolute vorticity ζ_a, by using the Japan-Meteorological-Agency (JMA) nonhydrostatic model with a horizontal grid of 5km (5km-NHM) and focusing on the inflow of upper-level high PV.

The 345K-isentropic*PV* field (Fig. 1) shows that the high *PV* lager then 8 PVU is found around the center of T0418 that traveled over the Sea of Japan. Another anomaly of high *PV* (2-4 PVU) flowed from the southwest toward the center of T0418. This area corresponded to the dark region with high brightness temperature in the infrared image observed by meteorological satellite, and it also corresponded to the down-motion region because the height shown in Fig. 1 deceases toward T0418. The inflow of high *PV* was found remarkably at the height of 7-9 km. Therefore, this high PV inflow could exert an influence on the maintenance of the intensity of T0418.

The initial conditions of 5km-NHM are produced from the JMA regional and mesoscale analyses (ranal and manal) at 21 JST (= UTC + 9 h) on 07 September, and its boundaries are given from the forecast of the JMA regional spectral model. Bulk-type microphysics with the ice phase are used in conjunction with the Kain-Fritsch convective parameterization scheme. The increase of the central pressure of T0418, analyzed by the JMA, is not found in the simulation results (Fig. 2a). The simulations indicate that T0418 approached Hokkaido Island maintaining its intensity. Hereafter, the results from the ranal are used, because the simulated Typhoon Track is closer to the JMA analysis (Fig. 2b).

A sensitive experiment without precipitation

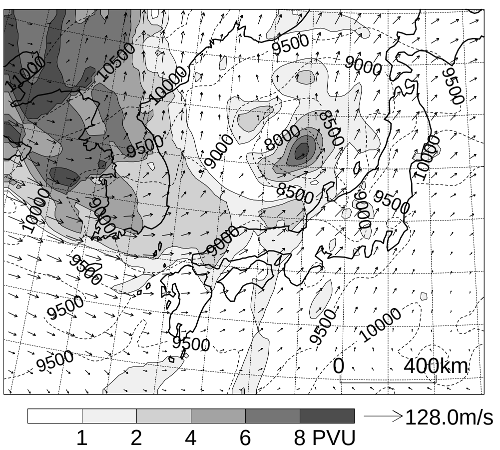

Fig. 1 345K-isentropic potential vorticity and wind vector field depicted by the JMA regional analysis at 21JST 07 September 2004. Broken lines show the heights.

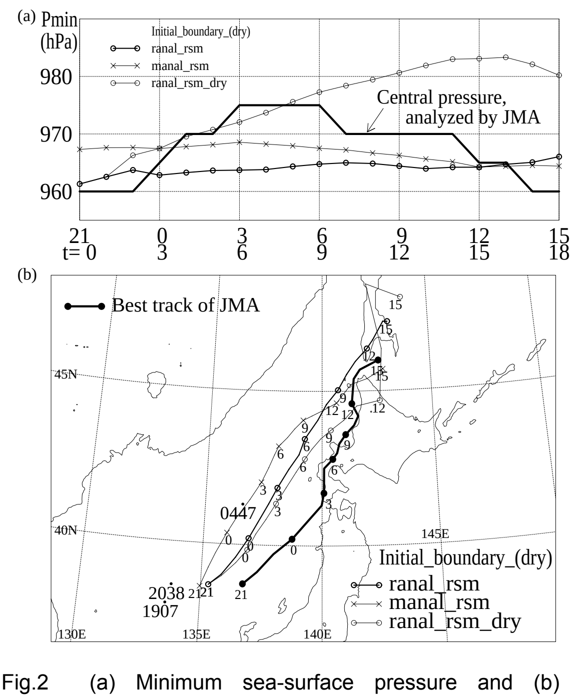

Fig.2 (a) Minimum sea-surface pressure and (b) analyzed and simulated central position of T0418. The dots with 4 numbers (time) show the potions of the center of T0418 estimated by satellite data.

process (*DRY*) is conducted to examine the effect of moist convection on the maintenance of the intensity of T0418. The results (Fig. 2a) show that the intensity of T0418 continuously decays, and its central pressure increases by about 20 hPa in comparison with that of *CNTL*. This indicates that convective activities are necessary for the maintenance of the intensity of T0418 even under the effect of westerly waves.

ζ_a is defined as

$$\zeta_a = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} + f \quad , \qquad (1)$$

where f is Coriolis parameter. The time difference of ζ_a is obtained from (1) as

$$\frac{\partial \zeta_a}{\partial t} = -\mathbf{v}_h \nabla_h \zeta_a - w\frac{\partial \zeta_a}{\partial z} - \zeta_a\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) - \left(\frac{\partial w}{\partial x}\frac{\partial v}{\partial z} - \frac{\partial w}{\partial y}\frac{\partial u}{\partial z}\right) \quad . \qquad (2)$$

Here, the 1st , 2nd, 3rd and 4th terms of the right hand side (*RHS*) of (2) mean the horizontal and vertical advections, divergence and tilting, respectively. The divergence and tilting terms present the extension / pressure of vertical vorticity in a vertical direction, and the change from horizontal vorticity to vertical one, respectively. The budget of (2) calculated from the results of 5km-NHM are analyzed. Noted that they are averaged in the horizontal scale of 400 km to exclude the influence of vorticity with the convective scale.

The vertical profile of the time change of ζ_a around the center of T0418 (Fig. 3a) shows that the maximum of ζ_a, located at a height of 2 km in the initial condition, slightly decreases until t = 2 h, and then it increases with the 1-km drop of its height. This indicates that, since the vertical structure of T0418 considerably changes within t = 4 h, T0418 decays as a typhoon but develops as an extratropical cyclone. In the *DRY* experiment (Fig. 3b), the maximum of ζ_a monotonously decreases until t = 15 h. This corresponds to the decay of the intensity of T0418 in the case without precipitation process.

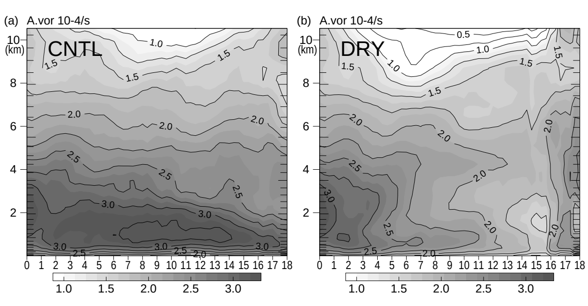

Fig. 3 Time-height cross section of absolute vorticity around the center of T0418, averaged in the horizontal scale of 400km, simulated by 5km-NHM in (a) *CNTL* and (b) *DRY* experiments.

The budget analyses of ζ_a, averaged for 3 hours around the period when the structure of T0418 changes, are shown in Fig. 4. Before the structure of T0418 changes (Fig. 4a), the amplitudes of all terms in the *RHS* of (2) are very small above a height of 6 km. Below that height, the divergence and vertical advection terms cancel each other out, and the intensity of ζ_a is maintained almost by these two terms. The divergence term is rewritten in the use of continuity equation as

$$-\zeta_a\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) = \zeta_a \frac{\partial w}{\partial z} \quad . \qquad (3)$$

Therefore, both the divergence and vertical advection terms can be estimated by one-dimensional (vertical) profile of ζ_a and w. This means that the vertical structure of T0418 is determined mainly by convective activities, which produce vertical motions in typhoons, before it changes.

After the structure of T0418 changes (Fig. 4b), the profile of each term of the *RHS* of (2) becomes complicated, and its amplitude increases above a height of 6 km, but for the horizontal advection term. This shows that upper-level atmosphere exert a significant influence on the maintenance of the intensity of T0418, in addition to convective activities.

Vorticity in a high *PV* air that flows into T0418 is extended vertically, and consequently ζ_a is enhanced around the height of 5 - 9 km. This enhancement cancels out the decrease of ζ_a that is caused by weaken convective activities due to cool *SST*, and it maintains the intensity of T0418.

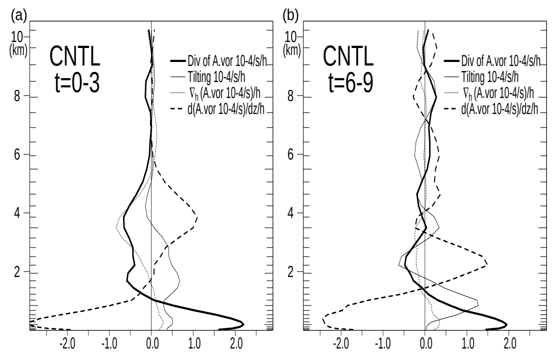

Fig. 4 Budget analyses of absolute vorticity averaged during (a) t = 0 - 3 h and (c) t = 6 - 9 h, simulated by 5km-NHM. Bold, thin, dotted and broken lines denote the horizontal and vertical advection, divergence and tilting terms, respectively