NOTES AND CORRESPONDENCE

Supplement to "The Coupling Development":
Accelerative Development of Extratropical Cyclones
by Using Finite Amplitude Initial Disturbances

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1. Introduction

In an earlier paper (Takayabu, 1991, hereafter referred to as T91), "the coupling development" was studied numerically using a β -plane channel, dry primitive equation model. "Coupling development" occurred when a lower level vortex was initially located at the latitude of the jet axis, with an upper level vortex to the northwest of the lower vortex. The development mechanism of the control experiment was discussed in detail. However, it was not fully discussed as to how to choose the size and location of the initial disturbances in T91.

In this note, we discuss the effect of the size and the relative location of large-amplitude initial disturbances on the evolution of cyclones using a numerical model.

2. Model and initial disturbances

The model, basic flow and the initial disturbances are basically the same as those of T91, but for a somewhat coarser horizontal grid spacing of 150 km.

The model consists of the β -plane channel (width: 7500 km, length: 10500 km) dry primitive equations with a horizontal grid spacing of 150 km and 16 levels up to 25 hPa. A simple baroclinic westerly jet profile (peak value 32 m/s, half width 3150 km) is chosen for the basic flow. The initial upper disturbance represents an upper cold vortex, which is frequently observed in the midlatitudes. The temperature anomaly is as large as $\pm 9\text{K}$. The temperature anomaly of the lower-level disturbance is $+3\text{K}$ at the surface. More details about the model are found in T91.

3. Results

3.1 Effects of the horizontal scale of the upper vortex

First, we examined the effects of the horizontal scale of the initial upper vortices on the jet axis. Figure 1 shows the development of relative vorticity near the surface. The horizontal scale is defined with the half width of the amplitude of the temperature anomaly of an isolated disturbance. In these experiments, the cyclone develops most rapidly when the horizontal scale of the initial upper vortex is between 1500 km and 2400 km. The development rate of the disturbance in these experiments corresponds well to the scale dependency of the growth rate of the most unstable normal mode (Fig. 2 of T91).

3.2 Effects of the initial location of disturbances relative to the jet axis

We next investigated how the location of the initial disturbance affects the development of the cyclone. To find the non-linear effect easily, we hereafter select 900 km as the horizontal scale of initial disturbances, because the most unstable normal mode had a minimum growth rate with the scale of 900 km (see Fig. 2 of T91). We placed upper vortices at various locations relative to the jet axis. Figure 2 indicates the relationship between time change of relative vorticity at the vortex center near the surface and the location of initial vortices relative to the jet axis.

A remarkable result is that the vortex develops most rapidly when the position of the initial vortex is shifted 600–1200 km to the north of the jet axis. Since a strong jetstreak is formed to the south of the upper vortex, a strong interaction between the upper vortex and the baroclinic jet is expected. In practice, the same process as the first stage of the coupling development (Sub-section 4.3.1 of T91)

Fig. 1. Development of relative vorticity at $\sigma=0.97$ as a function of the horizontal scale of the initial upper vortex.

Fig. 2. Development of relative vorticity at $\sigma=0.97$ as a function of the position of the initial upper vortex relative to the jet axis. The horizontal scale of these vortices is 900 km.

took place. A secondary circulation associated with the upper frontogenesis (e.g. Uccellini and Johnson, 1979) occurs and the upper vortex intrudes effectively into the lower troposphere.

When we put an initial disturbance on the jet axis, such frontogenesis did not occur. In that case, the disturbance quickly expanded along the jet axis and a new vortex appearing upstream developed more rapidly near the surface than the vortex near the center of the packet (Fig. 3). These results are similar to those of Simmons and Hoskins (1979)¹.

¹There exist some differences between Fig. 3 of this supplement and Fig. 4 of Simmons and Hoskins (1979), due to the difference in the horizontal scale of the initial disturbances. In Fig. 3, the horizontal scale of the initial vortex (900 km) is smaller than that of the most unstable normal mode (1800–2000 km). Therefore, the scale of the wave crests coincides with the most unstable wave length only around the center of the wave packet (indicated with character **b** in the figure),

On the other hand, experiments adopting a lower vortex as the initial disturbance (Fig. 4) indicate that the difference between the development rate of the cyclone on the jet axis and to the north of the jet axis was small. Since the westerly wind associated with the baroclinic flow is weak near the surface, the disturbance behaves like a linear near-neutral boundary wave (like the wave indicated in Fig. 13.1 of Gill, 1982)

and the scale of the disturbances is smaller both in the upstream (a) and the downstream (c) region. Since the initial vortex is concentrated in the upper troposphere, amplitude of the disturbance downstream near the tropopause is larger than that upstream near the surface. On the other hand, in Fig. 4 of Simmons and Hoskins (1979), dispersion of the wave packet according to the horizontal scale did not occur, because the horizontal scale of the initial disturbance is about the same as that of the most unstable wavelength.

Fig. 3. Zonal-height cross section crossing the center of the channel. The initial upper vortex (horizontal scale is 900 km) was on the jet axis (results of the experiment using 100 km grid spacing model are shown here). Contours are relative vorticity (contour interval $1 \times 10^{-5} \text{ s}^{-1}$). Air flows along the cross section are indicated by vectors (the zonal mean is subtracted). Units of vectors are horizontally 10 m/s and vertically $1 \times 10^{-5} \text{ hPa/s}$ (indicated in the bottom left corner of the figure). Three characters **a**, **b** and **c** indicate the upstream region, the center and the downstream region of the wave packet, respectively.

3.3 Effects of zonal displacement

Finally, we studied the effect of the zonal displacement of the upper and the lower vortices on the cyclone development. In the previous subsection, we discussed the effects of the upper vortex on the cyclogenesis, and found that the vortex placed at 600–1200 km to the north of the jet axis intrudes into the lower troposphere. On the other hand, when we placed the upper vortex on the jet axis in the initial state, it behaved like the linear wave which appeared in Simmons and Hoskins (1979) and dispersed zonally along the jet axis. Since we were expecting a strong interaction between the upper and the lower vortices, we specified the position of the initial upper disturbance as being 1200 km to the north of the jet axis. However, the lower vortex was left on the jet axis, because the lower vortex alone indicated no such non-linear effect in the process of the development.

Increase of the relative vorticity at the vortex center near the surface (Fig. 5) shows that it was accelerated in the period from day 2 to day 4, when the zonal displacement of these two vortices was be-

tween 750–1500 km in the manner that the lower vortex was to the east of the upper vortex. T91 has studied the development mechanism in detail using a 100 km grid model, and indicated that the accelerative development is brought about by the coupling of the upper-level and the lower-level vortices.

4. Summary and remarks

Using a dry primitive equation model, we studied the effect of the upper tropospheric forcing on the development of extratropical cyclones. We superposed a large-amplitude disturbance like an upper cold vortex on a zonally homogeneous baroclinic westerly jet. The results are summarized as follows.

1) When the initial upper disturbances are located on the jet axis, the evolution can be explained by the linear theory. The relationship between the development rate and the horizontal scale is similar to that of the most unstable normal mode. An initially isolated disturbance spreads to form a wave packet. It can be interpreted as the linear superposition of the linear waves which was discussed by Simmons and Hoskins (1979).

Fig. 4. As in Fig. 2, except for experiments adopting a shallow vortex near the surface as the initial disturbance.

Fig. 5. Relative vorticity at $\sigma=0.97$ as a function of the zonal displacement between initial upper and lower vortices. The positive values indicate that the lower vortex is placed to the east of the upper vortex. The upper vortex is 1200 km to the north of the jet axis, while the lower vortex is on the jet axis. The horizontal scale of these disturbances is 900 km.

2) The development rate increases when the initial upper disturbance is placed to the north of the jet axis. The downward intrusion of the upper vortex as a result of transverse frontogenetical circulation, helps the accelerative development of the disturbance.

These results suggest that the non-linear effects are sometimes critical for cyclone development with finite amplitude initial disturbances.

When we add a near-surface vortex to the southeast of the upper vortex, the development rate of the cyclone increased further. This is "the coupling development" case, the development mechanism of which was presented in Takayabu (1991) in detail.

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「カップリング発達」の研究への補足：有限振幅の初期擾乱を用いたことによる
温帯低気圧の発達加速について

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