A Diagnostic Study of Explosive Development of Extratropical Cyclone over East Asia and West Pacific Ocean

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ABSTRACT

In this paper, a diagnostic analysis is made for a kind of explosive cyclone over East Asia and the West Pacific Ocean in cold season, using the level III FGGE dataset. The cyclone started developing at 0000 UTC 30 March, 1979.

Q vector analysis shows that ageostrophic wind was obvious in cyclone region. The calculation of different kinds of frontogenetical functions indicates that the development of cyclone was closely related to baroclinicity, especially at lower levels.

Isentropic analysis revealed the three-dimensional structure of cyclone development, that is, ascent of southerly warmer current and descent of northerly colder current existed around the cyclonic center during the developing process of the cyclone and is very favourable to the release of available potential energy and generation of eddy kinetic energy.

Not only shear component, but also curvature component of upper level jet contributed to the explosive development of the cyclone.

The computation of convergence of moisture flux demonstrated that the moisture probably came from the tropical ocean. The distribution of water vapor supply in this case was very advantageous to the deepening of cyclones, especially, during the well-developing period.

Comparison between East Asia–Pacific case and North America–Atlantic case (Ogura and Juang, 1990) has been conducted. The common characteristics were that there existed strong baroclinicity in both cases. However, in the latter case, the latent heat release was of secondary importance and in our case, moisture also played very important role in certain stages of the cyclogenesis, especially, during well-developing stage when it moved over oceanic surface.

Key words: Explosive cyclone, Extratropical disturbance, Frontogenesis, Isentropic analysis, Q vector

I. INTRODUCTION

In recent years, more attention has been paid to explosive extratropical cyclones. The main reasons are that this kind of cyclones usually cause the serious damages and they can not be successfully predicted, so far.

Following Bergeron's definition of a rapidly deepening extratropical low, Sanders and Gyakum (1980) defined explosive deepening as surface pressure falls at a latitudinally adjusted rate of at least 1 hPa h⁻¹ for 24 h. The latitudinal adjustment for an equivalent pressure fall at 60°N is achieved by multiplying the actual pressure fall by a factor of \( \sin \varphi / \sin 60^\circ \), where \( \varphi \) is the latitude of the cyclone center. The cyclone under the discussion developed around the latitude of 45°N. Thus, its rate of deepening of 22 hPa during 24 hour is larger than that of explosive deepening. Climatological studies show that explosive cyclogenesis occurs primarily during the cold season and is predominantly a maritime event
Most explosive deepeners intensify within or just poleward of the region of maximum baroclinicity, indicating that baroclinic process plays a significant role in explosive cyclogenesis. This is particularly true when the lower troposphere is weakly stratified because of strong fluxes from the ocean surface (Anthes et al., 1983; Orlanski and Polinsky, 1984; Reed and Albright, 1986). In addition, several case studies of explosive cyclogenesis events emphasized the importance of various processes, such as strong surface fluxes over the ocean (Bosart and Lin, 1984), convection triggered by the fluxes (Bosart, 1981), and latent heat released by condensation (Gyakum, 1983 a, b; Anthes et al., 1983; Reed and Albright, 1986; Liou and Elsberry, 1987). However, the results of a diagnostic analysis and numerical simulation of rapid cyclogenesis over Canada showed that it seemed that surface heating was not an important factor, since the cyclonic development occurred over a continent and a frozen bay. Therefore, it is hypothesized that latent heat release is of secondary importance in cyclogenesis (Ogura and Juang, 1990; Juang and Ogura, 1990).

It should be pointed out that existing research work on explosive cyclogenesis concentrated mainly on that over the Atlantic Ocean and North America. However, Roebeer (1984) revealed from statistical study that there was a high frequent area of the explosive cyclogenesis in East Asia to Japan islands. Then, Li and Ding (1989) discussed the tracks of explosive cyclones over the North Pacific from 1984 to 1985 and relevant weather patterns. Ouyang, Lu and Hou (1990) studied the temporal and spatial distributions of explosive cyclones over Asia and the Northwest Pacific Ocean from 1968 to 1987. The mentioned-above results provided the important background of explosive cyclones in this area. In terms of the statistics (Yi and Ding, 1993), four kinds of initial disturbances related with explosive cyclones in the West Pacific Ocean are found. They are: (1) polar low; (2) synoptic scale or mesoscale vortex forming near Japan; (3) tropical cyclone or modified typhoon; (4) the extratropical disturbances coming from East Asia. Among them, the fourth kind of disturbances occurred most often and, therefore, it will be focused on in this paper. Because of the limitation of observational data, structures, dynamic and thermodynamic mechanisms of explosive cyclones have not been clarified, especially in East Asia and the Pacific Ocean. For better understanding of development process of explosive cyclone in this area, a case over West Pacific Ocean in March 1979 is diagnosed in more detail in this paper.

Firstly, for discussing the relation between environmental baroclinicity and explosive development, several diagnostic methods suited to the extratropical systems are adopted, such as, frontogenous function, $Q$ vector and the divergence of $Q$ vectors. This has been emphasized that $Q$ vector, especially in lower levels, can reveal the direction of ageostrophic current and, therefore, can represent the frontal transverse circulation.

Secondly, the diagnostic analysis in this cyclogenesis study is based on the concept of isentropic potential vorticity (IPV). It is known that much of the basis for the modern cyclogenesis theory was established by the theoretical and observational work of Charney (1947), Eady (1949), Sutcliffe (1947), Sutcliffe and Forsdyke (1950), and Petterssen (1956). Later, the cyclogenesis theory was formulated in the framework of the geostrophic theory to yield the development equation, in which the Laplacian of geopotential tendency is related to the horizontal absolute vorticity advection and the differential thermal advection (Holton, 1979). In recent years, this quasi-geostrophic development equation was restated and generalized in terms of IPV. It has been known that both potential temperature and IPV are conserved following an air parcel in an inviscid and adiabatic flow and, therefore, the
concept of IPV has been used to describe the evolution of large-scale flows in a compact and precise manner. Some authors showed the important role played by upper-level IPV advection in Alpine lee cyclogenesis. (Bleck and Mattocks, 1984).

The purpose of this paper is to present the results of a diagnostic analysis in order to understand the rapid cyclogenesis better. More specifically, the objectives are to identify the physical processes responsible for rapid deepening and to relate the findings to the contemporary understanding of the rapid cyclogenesis observed in maritime "bombs".

In this paper, our case and the case in North America–Atlantic Ocean in April 1979 (Ogura and Juang, 1990) are compared. In order to facilitate reference to the large number of figures in the Ogura and Juang papers, we introduce the following nomenclature: OJ(N) refers to Ogura and Juang paper and where N designates the figure number.
II. DATA SOURCES AND SYNOPTIC OVERVIEW

In this study, we use data coming from the first version of the First GARP Global Experiment (FGGE) Level IIIb dataset analyzed by the European Center for Medium Range Weather Forecasts (ECMWF). They include 15 pressure levels: i.e. 1000, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20 and 10 hPa levels for geopotential height, temperature, horizontal wind components, vertical (p) velocity and relative humidity (below 300 hPa), and sea level pressure. These data are given at 12 h interval, with the horizontal resolution of 1.875° lat. × 1.875° long. Weather maps issued by both Chinese NMC (CNMC) and Japanese Meteorological Agency (JMA) are used. Hereafter, the time and data are expressed using the following format: 0000 UTC 29 March becomes 00Z / 29.

Fig. 1 presents the abbreviated version of CNMC and JMA surface weather maps at 12 h intervals beginning at 00Z / 29. At 00Z / 29 (Fig. 1a), an inverse trough at surface extended from East Asia continent to Korean Peninsula and there was a weak low pressure system with a value of 1000 hPa centered at 112° E and 28° N in the inverse trough and, at the same time, the other weak low existed in the Yellow Sea with central value of 1002 hPa from which a cold front extended to the continent; At 12Z / 29 (Fig. 1b), the low in the Yellow Sea disappeared and the low in the middle reaches of the Yangtze River moved northeastwards to coast area and central pressure dropped down about 6 hPa; and then, the low developed rapidly and arrived at the value of 992 hPa at 00Z / 30 (Fig. 1c) and 983 hPa at 12Z / 30 (Fig. 1d)①. In fact, the central pressure of the cyclone decreased totally by 22 hPa during the 24 h period from 00Z / 30 to 00Z / 31, and finally, with the value of 970 hPa at 00Z / 31 (Fig. 1e). From this time, the cyclone developed slowly and only 4 hPa drop of the central pressure, with the minimum of 966 hPa at 12Z / 31 (Fig. 1f). The cyclone has occluded and stopped developing.

Time series of the central pressure for the explosive cyclone at sea level is shown in Fig. 2 based on CNMC and JMA surface weather maps. The rapid deepening occurred in 24 h period from 00Z / 30 to 00Z / 31. In comparison with the case in North America (OZ (2)), minimum pressure of the case in East Asia is much lower than that in North America, even though the amplitude of deepening is very close to each other. This probably demonstrated that the cyclone in East Asia moved to oceanic surface during the latter stages, and moisture convergence played a very important role in deepening the cyclone, especially, during the rapid development stage.

![Fig. 2. (a) Time series of the sea level central pressure for the explosive cyclone over East Asia and West Pacific Ocean based on CNMC and JMA surface weather maps. Surface weather map data are shown as solid lines and FGGE data as dashed lines. (b) Temporal variations of the central pressure for cyclones A and B based on the NWS surface weather maps (OZ (2)).](image)

①FGGE data were 983 hPa at 12 Z / 30, rather than 998 hPa in Fig. 1d.)
Fig. 3. Geopotential height (solid lines) with intervals of 80 m and isotherms (dashed lines) with intervals of 4°C at 500 hPa and at (a) 0000 UTC 30; (b) 1200 UTC 30 March 1979.

Aloft, at 00Z / 29 (Fig. 3a) a 500 hPa trough extended over the coast area of East Asia, aligned in the north–south direction. One of the important characteristics was that a strong baroclinic zone was in place associated with a meandering polar jet. There was also a broad baroclinic zone that crossed over North China and, then, turned to the Northeast. The out–of–phase relationship between the temperature and geopotential field implied that the environmental conditions were very favourable to cyclogenesis (Fig. 3a). By 12Z / 30 (Fig. 3b), the 500 hPa trough had undergone substantial development. The amplitude of the system had increased and the distance between the trough and the downstream ridge had decreased, indicative of increasing divergence in the southwesterly flow aloft (Boyle and Bosart, 1986; Uccellini et al., 1984). It should also be noticed in Fig. 3b that strong warm air was advected to North Japan where cyclone was developing.

An important feature of the cyclone was that it developed and propagated within a
baroclinic zone extending northeastward from the Yellow Sea to north part of Japan.

At 200 hPa (not shown), the warm (cold) core structure of the trough (ridge) was evident; the local maximum temperature in the trough was 225 K, whereas the local minimum temperature in the ridge was 210 K. As will be shown later, much of the warm air in the 200 hPa trough was stratospheric. Downstream of the 200 hPa warm pocket at 12Z / 30, there was strong warm air advection overspreading the surface low center.

III. Q VECTOR AND FRONTOTEMPORAL FORCING

For analyzing the evolution and structure of the explosive cyclone, some physical quantities, such as, relative vorticity, divergence, vertical velocity (not shown), Q-vector and frontotemporal function are computed.

1. Distribution of Relative Vorticity

As mentioned before, during the period of 24 h from 00Z / 29 to 00Z / 30, deepening of the cyclone was only 8 hPa and after it moved over the oceanic surface, the cyclone developed explosively.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Time-height Section of Maximum Relative Vorticity (in $10^{-5}$) Associated with the Cyclone</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hl (hPa)</td>
</tr>
<tr>
<td>200</td>
<td>2.82</td>
</tr>
<tr>
<td>500</td>
<td>1.46</td>
</tr>
<tr>
<td>700</td>
<td>14.4</td>
</tr>
<tr>
<td>850</td>
<td>12.4</td>
</tr>
</tbody>
</table>

The temporal and spatial distribution of maxima of the mean relative vorticity in cyclone area is given in Table 1. The differences between the case in East Asia and that in North America are that maxima of the former concentrated in the lower troposphere and the latter was at lower levels in early stages and at upper levels in later stages; in addition, the values of maxima for the former are larger than those of the latter case (OJ (7)). Probably, it is because that the cyclonic system in our case was stronger than that in North America.

2. Computation of Q Vector

In this section, Q vector is used to diagnose the extratropical disturbances. Q vector is defined as:

$$Q = (Q_1, Q_2) = \left(-\left(\frac{k}{\theta_0}\right)\frac{\partial V}{\partial x}\right) \cdot \nabla \theta, -\left(\frac{k}{\theta_0}\right)\frac{\partial V}{\partial y} \cdot \nabla \theta$$

(1)

by Hoskins et al. (1978) and Hoskins and Pedder (1980). It means that vector Q is equal to the rate of change of potential temperature gradient moving with the horizontal geostrophic velocity. It has been known that in order to maintain geostrophic and hydrostatic
equilibrium, the $Q$ vectors must point in the direction of the low level ageostrophic flow towards ascending air. $Q$ vectors will have a component across the isotherms from cold to warm air (warm to cold) in thermally direct circulation of cold (warm) frontogenesis regions.

Fig. 4a shows the distribution of $Q$ vector and temperature fields at 850 hPa at 00Z / 30. It can be found that there are strong ageostrophic flows from cyclone center to east of Japan Sea. $Q$ vector crossed from cold air in Korea and coast area in Russia to warm air in Japan and it was equivalent to lower branch of frontal transverse ageostrophic circulation. This fact indicated that the cold front was intensifying. Fig. 4b gives the situation at 12Z / 30 and maximum of $Q$ vector had moved to North Japan.
Fig. 5. Divergence of Q vectors (in $10^{-4}$m$^{-1}$s$^{-1}$) at 850 hPa. (a) 0000 UTC 30; (b) 1200 UTC 30 March 1979.

For further discussing the frontal vertical circulation, various forms of the forcing term $F$, in the quasi-geostrophic Omega equation

$$N^2 \nabla^2 w + f \frac{\partial^2 w}{\partial z^2} = F$$

(2)

were considered, where $N$ is the buoyancy frequency and $f$ the Coriolis parameter. It can be noticed that if $w$ is approximately sinusoidal in the three space dimensions, then $F$ negative is expected to give $w$ positive, i.e. upward motion. In the conventional quasi-geostrophic form of the "Omega" equation, the forcing of vertical velocity is usually expressed as the sum of two terms associated, respectively, with vorticity and temperature advection. Consideration of each term in isolation is misleading and there can be a large degree of cancellation. In this
study, the two terms on the right hand side in the conventional "Omega" equation are combined to one term as follows:

$$F_Q = 2 \nabla \cdot Q.$$  \hspace{1cm} (3)

It is indicated that in quasi-geostrophic theory, on an f-plane vertical velocity is forced solely by the divergence of $Q$ (Hoskins et al., 1978). Convergence (divergence) of $Q$ vectors implies ascent (descent). In Fig. 5a, convergence area of $Q$ vector is located in west of Japan Sea at 00Z / 30 and $Q$ vectors at 850 hPa just point to this area and in Fig. 5b, convergence zone at 12Z / 30 has moved to North Japan.

3. Frontogenetical forcing

At surface weather maps of 00Z / 30, cyclone was located between Korean Peninsula and Japan islands. A cold front from the cyclone extends southwestward to South China. The baroclinic character of the frontal system was significant. For better understanding of frontal process, the frontogenetical function that used the $Q$ vector as forcing term was firstly computed.

Following the Hoskins' definition of the quasi-geostrophic frontogenetical function (QGF), we have

$$\frac{d}{dt} \left| \nabla \theta \right| = \frac{1}{\left| \nabla \theta \right|} \{ Q \cdot \nabla \theta \},$$  \hspace{1cm} (4)

where $\theta$ is the potential temperature and $Q$ represents $Q$ vector. Fig. 6 shows the frontogenetical functions at 00Z / 30 computed by the mentioned above definition. There was a wide frontogenetical area east of Korean Peninsula and a frontotyral area east of Japan Sea, respectively. Frontogenetical areas are thicker in the troposphere from 850 hPa to 700 hPa (Fig. 6a). At 12Z / 30 (Fig. 6b), the frontogenetical area extended eastwards and aligned a band-shape which was in close agreement with the position of the cold front at surface weather maps. A frontotyral area at 700 hPa can be found near Hokkaido (not shown).

However, generally speaking, frontogenesis area maintained in the cyclone development area from 00Z / 30 to 12Z / 30 and strong baroclinicity in the vicinity of Japan. This kind of environmental conditions were very favourable to the release of the available potential energy and producing of eddy kinetic energy and, undoubtedly, were very helpful for deepening of the cyclone (Zeng, 1979).

It should be emphasized that since thermal advection by the ageostrophic wind is not accounted for in QG theory, geostrophic frontogenesis is not valid beyond the initial stages of frontogenesis and this limitation in use of QG diagnostics must be noticed. For this reason and also for further revealing the atmospheric baroclinicity, the other kind of the frontogenetical function is computed by using the observational wind (OWF),

$$\frac{d}{dt} \left| \nabla \theta \right| = \frac{\theta_x}{\left| \nabla \theta \right|} \frac{\partial Q}{\partial x} dt + \frac{\theta_y}{\left| \nabla \theta \right|} \frac{\partial Q}{\partial y} dt + \frac{\left| \nabla \theta \right|}{2} |\partial \theta| \times \cos 2\beta$$

$$- \frac{\left| \nabla \theta \right|}{2} D - \frac{\theta_x}{\left| \nabla \theta \right|} \omega _x \theta _y - \frac{\theta_y}{\left| \nabla \theta \right|} \omega _x \theta _x.$$  \hspace{1cm} (5)

This is the two-dimensional form of frontogenesis equation in pressure coordinates (Ogura and Portis, 1982). The first two right-hand side terms represent the diabatic terms. The third is deformation term, the fourth is convergence term and the fifth is tilting term. Here $Q$ is the diabatic heating, $\beta$ is the angle from the axis of dilatation to the $\theta$ lines and $D$ is
the horizontal divergence. In this study, the diabatic and tilting term were not computed. The results show that the basic characteristics of both frontogenesis are similar to each other, especially, at 00Z / 30. Slight differences between OWF and QGF are the frontogenetical area being mainly concentrated on the south part of the cold front and frontolitical area over Hokkaido became broader for OWF at 12Z / 30. This indicated that the baroclinicity near the center of cyclone was gradually weakening and, however, in fact, the deepening of cyclone during the next 12 hour still continued from 983 hPa to 970 hPa. Therefore, it can be deduced from the mentioned—above fact that the other possible mechanism except the baroclinicity contributed to the explosive development of the cyclone, especially during the later stages. This will be discussed later.

**Fig. 6.** Quasi-geostrophic frontogenetical function (in $10^{-5}$ K m$^{-1}$ s$^{-1}$) (a) 0000 UTC 30; (b) 1200 UTC 30 March 1979.
Fig. 7. Frontogenetical function (in 1K (100 km) \textsuperscript{1} (day) \textsuperscript{-1}) calculated by the observational winds. (a) 0000 UTC 30; (b) 1200 UTC 30 March 1979.

IV. ISENTROPIC ANALYSIS AND EVOLUTION OF CYCLONE STRUCTURE

1. Isentropic analysis

Bleck (1974) described the cyclogenesis process in terms of IPV and later Bleck and Mattocks (1984) stressed the important role that upper–level IPV advection plays in Alpine lee cyclogenesis. Several authors showed that an approaching upper–level high IPV anomaly interacted with a low–level cyclonic circulation (Uccellini et al., 1985; Uccellini, 1986; Reed and Albright, 1986; Boyle and Bosart, 1986).

Ogura and Juang (1990) studied the rapid cyclogenesis over Canada and pointed out that the cyclone formed in a region of strong surface frontogenesis, moved into the region of upper–level potential vorticity advection, and eventually, developed explosively. Hoakins et
al. (1985) made a review article on the use and significance of IPV maps. In recent years, Robinson (1989) revealed that there exists certain relationship between IPV structure and baroclinic instability.

Our interest lies in describing the transition period from a shallow system to a deep one. To do so, a standard isentropic analysis is made, including computations of isentropic potential vorticity, wind fields and geopotential height (θ) on isentropic surface for the period from 00Z/30 through 12Z/31. Here, isentropic potential vorticity (IPV) is defined as

$$IPV = -\frac{\partial \theta}{\partial p} \rac{f}{\partial \theta}.$$  \hspace{1cm} (6)

Following Hoskins et al. (1985), 1 potential vorticity unit, i.e 1 PVU = $10^{-6}$ m$^2$ s$^{-1}$ K kg$^{-1}$, will be used. Further, the tropopause is defined as a surface of 2 PVU. Fig. 8a shows the IPV and

![Fig. 8. Isentropic analyses for 310 K, at (a) 0000 UTC 30; (b) 1200 UTC 30 March 1979 for wind vector (in m s$^{-1}$) and potential vorticity (in 10$^{-6}$ m$^2$ s$^{-1}$ K kg$^{-1}$).](image-url)
Fig. 9. Isentropic analyses for 295 K. (a) 0000 UTC 30; (b) 1200 UTC 30 March 1979 for wind vector (in m s\(^{-1}\)) and the geopotential height with intervals of 800 m.

wind fields on \(\theta_e = 310\) K surface at 00Z / 30. In strict sense, wind vectors should move on the isentropic surface in adiabatic condition. From Fig.8a a maximum of IPV existed in the Yellow Sea and Korean Peninsula and extended to Japan. At the same time, the strong southwestern currents transported the positive IPV to Japan islands. At 12Z / 30 (Fig.8b), the several separate centers had been combined into a large positive IPV center surrounded by the closed cyclonic circulation over Japan Sea and Hokkaido on 310 K isentropic surface. Maximum over coast area of Russia increased from 6.23 PVU at 00Z / 30 to 7.32 PVU at 12Z / 30. The currents transported the IPV to Japan islands, and it is favourable to deepening of the cyclone.
In addition, geopotential height fields and wind fields (Fig.9) were given to describe the three-dimensional characteristics of the flows. It can be observed that a wider ridge existed over the coast area of East Asia and West Pacific Ocean. Strong southerly wind in front of the ridge and northerly wind behind of the ridge can be found and this kind of the structure of dynamic and thermodynamic fields was very suitable to the development of baroclinic wave. Similar situation had been observed in the case of North America (OJ (11)). At 12Z / 30, the wave significantly amplified aloft and short wave trough over Japan Sea extended southwestward quickly. The warm air in front of the trough went up along the isentropic surface and the geopotential height contour of 800 m moved from 36°N to 43°N, that is,
Fig. 11. West–east cross-section along line AB in Fig. 10. (a) Isentropic potential vorticity (solid lines, in $10^{-6} \text{ m}^2 \text{s}^{-1} \text{K kg}^{-1}$) and potential temperature (dashed lines, in K) at 0000 UTC 30; (b) as (a) but 1200 UTC 30; (c) meridional wind (in m s$^{-1}$) at 1200 UTC 30 March 1979.
displacing of 700 km during 24 hours; the warm air in front of the trough pushed on the
isentropic surface from 800 to 5000 m; the cold air behind the trough spread southeastward
from about 6000 to 800 m. The ascending branch and descending branch of the cyclone sur-
rounded the center of the system.

2. Development of the cyclone

To illustrate the possible upper level forcing for the subsequent development of the cy-
clone, the distribution of the tropopause height at 00Z / 30 and 12Z / 30 is shown in Fig. 10,
respectively, where the tropopause is defined as PVU = 2. It can be seen that the tropopause
height was at 396 hPa over the center of the cyclone, rather than 481 hPa in North America
case (OJ (15)) and probably because the cyclone in our case occurred in lower latitudes. The
important features were that the center of the high PV anomaly was travelling nearly
eastward during the period from 00Z / 30 to 12Z / 31 and approached the center of the cy-
clone.

Fig. 11 depicts the structure of the IPV anomaly in a vertical section taken along the lines
AB and CD in Fig. 10 that crossed the center of the high IPV anomaly in west–east direction
and north–south direction, respectively. In Fig. 11, a local maximum of IPV at lower levels
represented the central portion of the cyclone. The distribution of $\theta_e$ relative to the high IPV
anomaly is similar to that determined by Ogura and Juang (1990) for a combination of an iso-
lated, balanced, circular IPV anomaly at upper levels and a cold $\theta_e$ anomaly at the earth’s
surface (OJ (17a)). The characteristics are that an isentropic surface rises as it approaches a
high IPV anomaly below the sloping tropopause and a cold dome resides just beneath the
folded tropopause. Thus, the structure shown in Fig. 11b is also quite similar to those de-
picted in explosive cyclogenesis events over the Atlantic Ocean by Boyle and Bosart (1986)
and Uccellini et al. (1985). In Fig. 11c the upper–level jets encompass the tropopause in both
sides of the high IPV anomaly, again in agreement with Fig. 11b of Ogura and Juang (1990).
However, our case is different from that of Ogura and Juang, that is, the zonal component of
wind in our case was stronger. In addition, a 500 hPa trough in North American case aligned
in the north–northeast / south–southwest direction, whereas the 500 hPa trough in our case
extended from northwest to southeast. It seems that latter pattern is favourable not only to
the development of baroclinic instability but also to that of barotropic instability.

V. ROLE OF UPPER LEVEL JET

Some authors have emphasized the role of the upper level jet in the development of ex-
plusive cyclones (Shapiro and Kennedy, 1981). Generally speaking, the forcing of the upper
level jet can induce the frontal transverse circulation, which is closely related to the severe
weather. In the past, the study on upper level jet concentrated mainly on the typical pattern
associated with a straight jet streak (Zhao and Mills, 1991). However, the situation in real at-
mosphere is very complex. Even though the wind is uniform along the flow and the jet is par-
allel to the height contours, the jet was probably embedded within a stationary wave (Newton
and Omoto, 1965). That means the ageostrophic motions are associated with speed–acceler-
ating and decelerating air parcels in the entrance and exit regions of the upper–tropospheric
jet streak respectively and the ageostrophic velocities are also related with centripetal accelera-
tions at the sharply curved trough and ridge axis of a large–amplitude Rossby wave.
In this case, 200 hPa height and wind fields were analyzed. Fig. 12a shows the height and
isotach at 200 hPa at 00Z / 30, and Fig. 12b gives the divergence field at 200 hPa. It can be
seen that a maximum of divergence field over the southern Japan was related to the shear
component because it was just located on the right of the exit of the upper level jet and the north–south banding divergence maximum extended from it seemed to be associated with the curvature component because it was just over east of Korean Peninsula ahead of the wave aloft. The later component should be emphasized. At 12Z / 30 (not shown), the situation was similar to that at 00Z / 30, both maxima of the divergence still existed, the southern one was stronger, that meant shear component contributed more significantly at this time. The more detailed discussion of the two components is beyond the scope of this paper. Anyway, the mentioned-above results have qualitatively shown the role of the forcing of the upper level jet on the rapid development of the cyclone.

VI. DIAGNOSTICS OF MOISTURE FIELD

For clarifying the importance of moisture and its relationship with cyclone development, convergence of moisture flux (CMF) is computed at the various pressure surface. At 00Z / 30, a band of CMF (Fig. 13a) extended from the South China Sea to Japan, and there were two maxima in the band. One was southeast to Korean Peninsula and the other was east to Japan. The former one was thicker than the latter one which was only limited in lower levels. At 12Z / 30, the situation had changed. The maximum over east to Japan had become wider and extended vertically from lower levels to middle levels. The western maximum disappeared. If checking the height field and wind field at isentropic surface of 295 K (Fig. 9), it can be noticed that maximum of CMF over southeast to Korean Peninsula at 00Z / 30 and that over southeast to Japan were, respectively, associated with the large scale ascending currents and, at the same time, these areas were just located beneath the main divergence area induced by the upper level jet. In turn, the cyclonic circulation at the lower level was intensified by the upper level divergence forcing. Then, moisture was, further, concentrated into the cyclone area. In this stage, the release of the latent heating contributed importantly to the development of the explosive cyclone. This fact is quite different from the case of Ogura and Juang in which surface heating and latent heat release are of secondary importance in cyclogenesis. Since the cyclonic development occurred over a continent and a frozen bay, whereas in our case the cyclone moved to the Pacific Ocean in the latter period of the cyclogenesis.

Fig. 12(a). Isotachs (solid lines) with intervals of 10 m s⁻¹ and geopotential height (dashed lines) with intervals of 200 m; (b) divergence (in 10⁻⁵ s⁻¹) at 200 hPa, 0000 UTC 30 March 1979.
VII. SUMMARY AND CONCLUSION

In this work, a diagnostic analysis is conducted for a case of explosive cyclogenesis over the Northwest Pacific during the period 29–31 March 1979, using the First GARP Global Experiment (FGGE) level IIIb dataset assimilated by ECMWF. This cyclone started developing at 0000 UTC 30 March 1979. The central pressure dropped 22 hPa during 24 h period. The conclusions are the followings:

1. In the initial stage, a cyclonic circulation moving eastwards can be found in the lower troposphere. When the maximum of the potential vorticity at upper levels approached, the cyclone intensified, and, then, developed rapidly and transformed into a thicker system.

2. Analysis of $Q$ vector showed that ageostrophic wind was obvious in cyclone region during early period of the development. The calculations of two kinds of frontogenetical functions using quasi–geostrophic theory and observed wind, respectively, indicated that the development of cyclone was closely related to baroclinicity, especially, at lower levels.

3. Isentropic analysis revealed the three–dimensional structure, that is, ascent of southerly warmer current and descent of northerly colder current in the developing process of cyclone. This display of dynamic and thermodynamic field was favorable to the release of available potential energy and generation of the eddy kinetic energy.

4. Forcing of upper level jet played an important role in the development of explosive cyclone. It should be emphasized that not only the effect of the shear part of wind but also the effect of curvature part of wind contributed significantly to the intensifying of the cyclone.

5. Computational results of the moisture flux denoted that the moisture probably came from the tropical ocean. In addition, the maxima of the convergence of moist flux were located in southeast of the cyclone. This distribution of the water vapor supply was very advantageous to the deepening and developing of cyclone, especially, during the well–developing period.

In summary, during explosive development of extratropical cyclone, the baroclinicity influences significantly at earlier stages and the release of latent heat plays an important role at later stages. The results of diagnostics consist with that of numerical simulations (Anthes, Kuo and Gyakum, 1983). As having been emphasized, the process of the explosive cyclogenesis is very complex because of involving the dynamic and thermodynamic effects and the interaction between them. Therefore, it is very necessary that more cases should be
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REFERENCES


