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On the Climatological Aspects of Explosive Cyclones Over the Western North Pacific and East Asia Coastal Areas

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ABSTRACT

Twice daily synoptic charts at surface, 850, 700 and 500 hPa and mean sea surface temperature maps for the winter season as well as each month were used to study the climatological aspects of explosive cyclones over the western North Pacific and East Asia coastal areas in the September-April periods of 1974-1984. Geographical distribution of frequency, interannual and seasonal variations of frequency and frequency distribution of different intensities of explosive cyclones were analyzed. The relationships of cyclones to a 500 hPa trough, lower-tropospheric baroclinity and sea surface temperature gradients were studied at the formation and explosive stages.

It was found that explosive cyclones tended to form and to deepen rapidly along the shoreward edge of the warm Kuroshio current over the area of the maximum SST gradient. They also frequently formed and deepened rapidly about 700-800 km ahead of the 500 hPa trough. Results suggest that the flux of sensible heat and latent heat from the warm ocean surface and latent heating over the cyclone area in addition to the baroclinic process may have had positive effects on the formation and rapid deepening of explosive cyclones over the western North Pacific.

(Key words: Explosive cyclone, Sea surface temperature gradient, Sensible heat flux, Latent heat flux, Baroclinity, Baroclinic process)

1. INTRODUCTION

Rapidly intensifying extratropical cyclones (*i. e.* explosive cyclones) have become one of the major interests of researchers in recent years especially since 1980 when Sanders and Gyakum published a well-known paper on the synoptic-dynamic climatology of "bombs", the term they used to describe such events. These storms often produce large amounts of precipitation and generate strong winds, high waves and low visibilities (Sanders and Gyakum 1980; Bosart 1981; Gyakum 1983 a). They are considered among the most severe weather events affecting heavily populated coastal areas and open oceans, thus constituting a forecast problem of primary importance. The forecast capability of these meteorological events is limited

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by the scarcity of observations over oceanic areas and an incomplete understanding of the physics of these storms.

To shed greater light on the different aspects of explosive cyclones, research efforts by numerous investigators have focused on diagnostic studies of both individual cases or composite ones (*e. g.* Bosart 1981; Gyakum 1983a, b; Bosart and Lin 1984; Uccellini *et al.* 1984, 1985; Rogers and Bosart 1986; Wash *et al.* 1988; Gyakum 1991; Lin and Wang 1994), numerical simulation studies (*e. g.* Anthes *et al.* 1983; Chen and Dell'Osso 1987; Kuo and Reed 1988; Kuo and Low-Nam 1990; Reed and Simmons 1991), numerical weather prediction (NWP) model evaluation studies (*e. g.* Sanders 1987b; Reed *et al.* 1988) as well as climatological and statistical studies (*e. g.* Sanders and Gyakum 1980; Roebber 1984; 1989; Sanders 1986; 1987a; Gyakum *et al.* 1989). Explosive cyclones are predominantly a maritime phenomenon and occur most frequently in winter over the North Atlantic and the North Pacific. While the North Atlantic storms have been explored extensively and intensively, only relatively few studies on the North Pacific storms can be found in the open literature. This is especially true with regard to storms over the East Asian coastal area and the western North Pacific. A few examples nevertheless exist, and these include diagnostic studies of a composite case by Lin and Wang (1994) and an individual case by Nuss and Kamikawa (1990), numerical studies by Chang *et al.* (1987) and Chen and Dell'Osso (1987). Although quite a few papers dealing with the climatological aspects of cyclones over this region have been published (*e. g.* Chung *et al.* 1976; Chen and Yeh 1982; Hanson and Long 1985; Chen *et al.* 1991), it is believed none dealing with explosive cyclones in the open literature are available. Thus, to study the climatological aspects of these storms is one of the major motivations for this paper.

Agreement has generally been found among different studies on real cases that explosive cyclones invariably occur within the mainly baroclinic westerlies (*e. g.* Sanders and Gyakum 1980; Rogers and Bosart 1986; Sanders and Davis 1988). Strong baroclinity, as manifested by a large temperature contrast in the lower-troposphere, is obviously an essential component of any explosive cyclone. The climatological study of baroclinity of the storm environment in the lower-troposphere is, therefore, essential in grasping a better understanding of explosive cyclones. Various studies, such as synoptic-dynamic, numerical, climatological and statistical ones, support the fact that in addition to the ordinary baroclinic instability, most cases of explosive cyclones are results of certain other physical mechanisms (*e. g.* Sanders and Gyakum 1980; Bosart 1981; Anthes *et al.* 1983; Roebber 1984; Chang *et al.* 1987; Liou and Elsberry 1987). One of these is the latent heat release in precipitating frontal clouds (*e. g.* Bosart 1981; Anthes at al. 1983; Chang *et al.* 1987; Kuo and Reed 1988; Reed *et al.* 1988). Another process that is often suggested as a likely cause of rapid intensification is the flux of sensible and latent heat from the ocean surface (Bosart 1981; Davis and Emanuel 1988; Nuss and Kamikawa 1990). However, model experiments reveal a wide range of impact of the fluxes with small negative or even no influence in some cases (*e. g.* Kuo and Reed 1988; Kuo and Low-Nam 1990; Reed and Simmons 1991; Kuo, Reed and Low-Nam 1991), yet large positive effects are noted in others (*e. g.* Chen and Dell'Osso 1987; Uccellini *et al.* 1987; Mailhot and Chouinard 1989). The remarkably varying impact of fluxes on marine explosive cyclogenesis have been attributed to differences in geographical location, stage of development, degree of atmospheric preconditioning and the shortcoming of flux formulation (Bosart 1981; Kuo and Reed 1988;

Nuss and Kamikawa 1990; Kuo, Reed and Low-Nam 1991; Reed and Simmons 1991). The flux of sensible and latent heat from the ocean surface is closely related to the sea surface temperature (SST) and its gradient in addition to the surface air temperature and wind speed. Therefore, the climatological study of SST and its gradient (∇SST) under a storm center is also important to further understand explosive cyclones.

The main purpose of this study has been to reveal the climatological characteristics of explosive cyclones over the western North Pacific. The geographical distribution of cyclones at formation and the rapid deepening stages are analyzed. The frequency distribution and the relationship between storms and 500 hPa though are also discussed. Additionally, the baroclinity in the lower-troposphere and the SST gradient is studied.

2. DATA AND ANALYSES

Synoptic charts at 0000 and 1200 UTC at surface, 850, 700, and 500 hPa published by the Japan Meteorological Agency (JMA) were used to identify the explosive cyclone events in the September-April periods of 1974-1984. These charts were also employed to obtain the 500 hPa trough positions and lower-tropospheric temperature gradients in relation to the storms. The seasonal and monthly mean sea surface temperature (SST) maps published by the Japan Hydrographic Association (1978) were used to obtain the SST gradient under the storm center. The area of interest covered the East Asia coastal area and the western North Pacific over 20°-60°N, 120°-160°E. It should be noted that the frequency distribution of cold-season explosive cyclones in the area of 25°-90°N, 130°E-10°E obtained by Sanders and Gyakum (1980) indicated a maximum center of storm formation near 42.5 °N. However, the maximum frequency of winter cyclone formation over East Asia and the western North Pacific was found to be in the area of 25°-30°N, 120°-125°E by Chen and Yeh (1982), over 25°-30°N, 125°-130°E by Hanson and Long (1985), and over 30°-35°N, 125°-135°E by Chen *et al.* (1991). It is interesting to determine whether the area of maximum frequency of cyclone formation is also the area of maximum frequency of explosive cyclone formation over the western North Pacific. This is one of the reasons for the choice of this area for this study.

The deepening rate in terms of bergeron, as defined by Sanders and Gyakum (1980), is 24 hPa pressure fall within a 24-hour period at 60°N (latitude of Bergen). A geostrophically equivalent rate was then obtained for arbitrary latitude f by multiplying this rate by (sin ϕ/sin 60°). Since the area of interest covered 20°-60°N, one bergeron in this study was defined as a 24-hour pressure fall equivalent to 24 hPa at 45 °N which is the latitude of the maximum frequency of explosive cyclone formation obtained by Sanders and Gyakum. This can be compared to that at 60°N by Sanders and Gyakum (1980) and that at 42.5°N by Roebber (1984). Thus, one bergeron was taken to range from 11.4 hPa $(24\ h)^{-1}$ at 20N (the southern limit) to 29.8 hPa $(24\ h)^{-1}$ at 60°N (the northern limit) in this study. An explosive cyclone event was then determined when all the following criteria were satisfied:

1) The cyclone had a deepening rate of at least one bergeron during its life period within the area.
2) The cyclone formed within the area and existed at least 24 hours.
3) The cyclone was neither transformed from a tropical cyclone nor formed by the merging of cyclones.

The formation stage was determined by the time the cyclone formed, while the maximum deepening rate stage (*i. e.* explosive stage) was set at the time the deepening rate reached its maximum during its life period. The geographical distribution of frequency was then analyzed with a 5° × 5° latitude-longitude quadrangle grid.

3. RESULTS AND DISCUSSION

3.1 Geographical Distribution

The total frequency of explosive cyclones at the formation stage in the cold season (September-April) and the winter mean SST are presented in Figure 1. The maximum center occurred over the ocean between Taiwan and Kyushu in the area of 25°-30°N, 125°-130°E, in

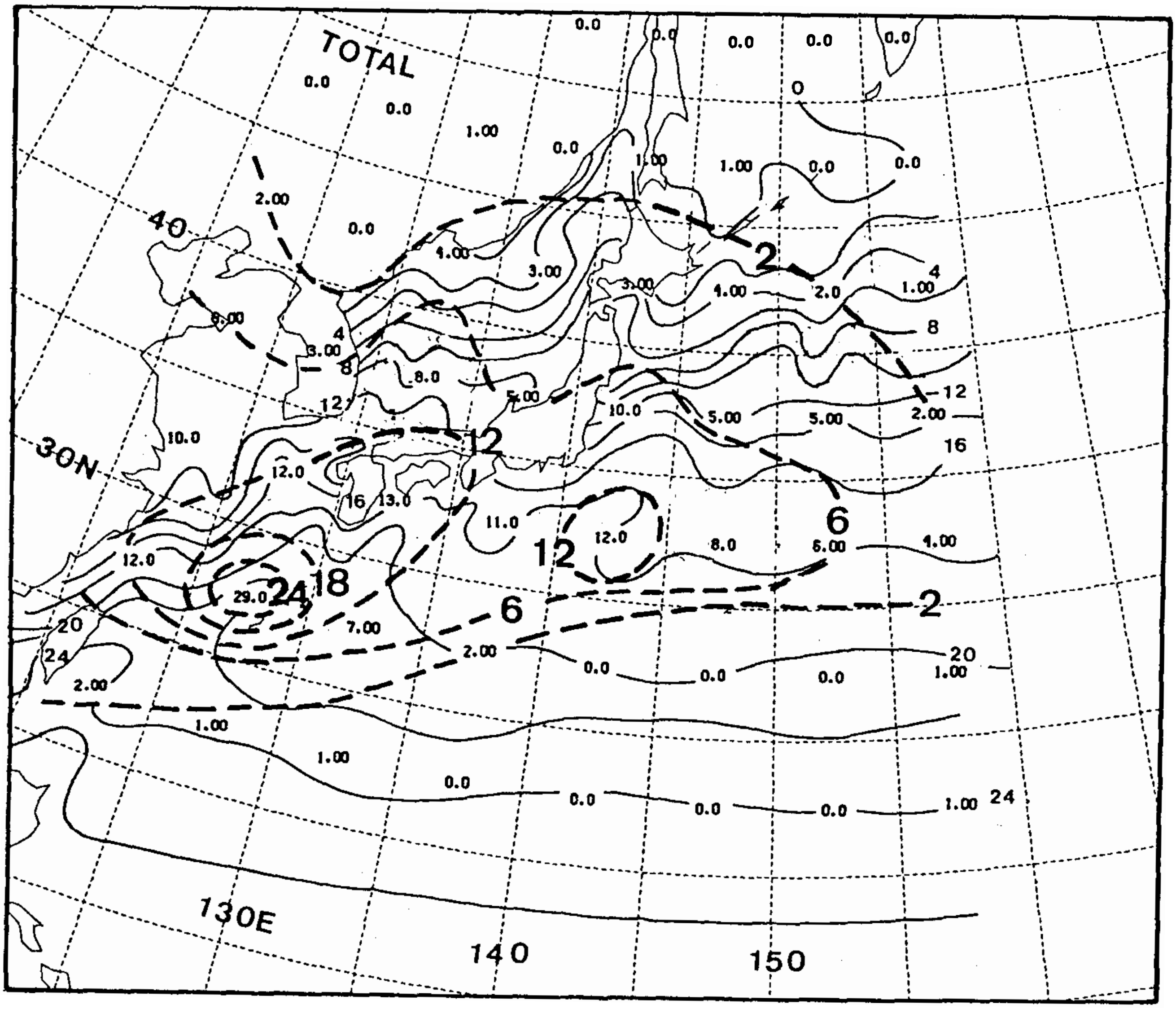
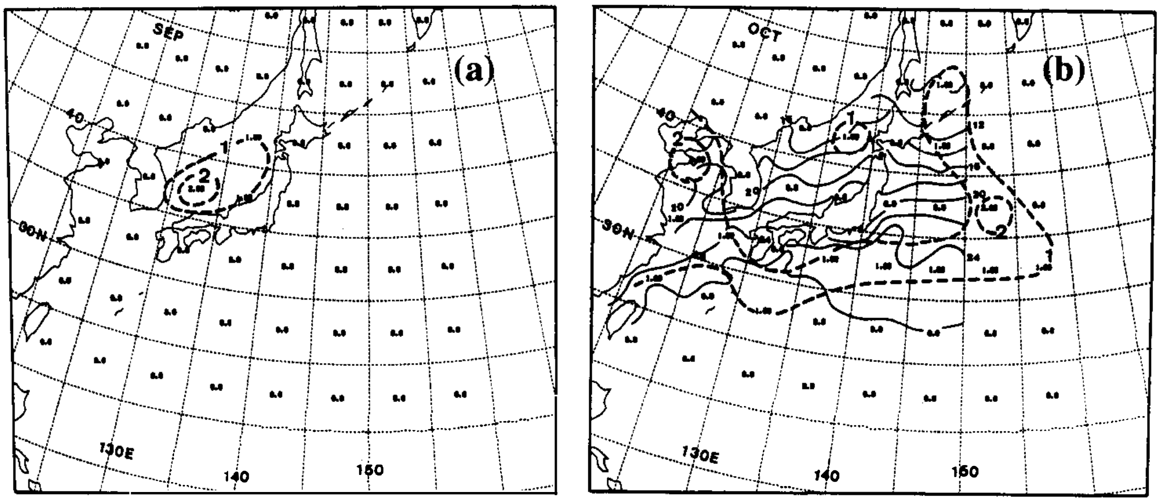


Fig. 1. Geographic distribution of all explosive cyclones at the formation stage in the cold seasons (September-April) of 1974-1984. Frequencies are plotted in the 5-degree latitude/longitude grid square and analyzed at 6-event intervals (dashed). The sea surface temperature (SST) in winter were analyzed at 2°C intervals (solid).

agreement with that observed by Hanson and Long (1985) for winter cyclones. While the explosive cyclones tended to form over a wide range of SST from 0 to 24°C, the axis of maximum frequency appeared to be located along the warm Kuroshio current over the warm side of the maximum SST gradient. It is expected that the cold air passed over the warm SST from the north or northwest. The fluxes of sensible and latent heat from the ocean surface were enhanced in the area of the maximum SST gradient. The positive effects of these fluxes to cyclogenesis are anticipated during the incipient stage of the cyclone (Bosart 1981; Bosart and Lin 1984; Nuss and Kamikawa 1990). Therefore, that the maximum frequency axis was along the Kuroshio suggests that the fluxes of sensible and latent heat from the ocean surface was a positive factor at the formation stage of the explosive cyclone. Figure 2 illustrates the frequency distribution at the formation stage in each month and the corresponding mean SST. The maximum center was located to the southeast of Japan Islands in November-December and gradually shifted southwestward to the area between Taiwan and Kyushu. The SST gradient along the shoreward edge of the Kuroshio current began to increase and to be better organized in January. This was the time that the frequency of cyclone formation showed a substantial increase over that in December. Apparently, the cyclone had a tendency to form along the warm ocean current over the warm side of the maximum SST gradient each month. This was particularly evident from November-April, again indicating that the flux of sensible and latent heat from the ocean surface over the area of the maximum SST gradient may have had a positive impact on the explosive cyclone at its incipient stage.

After the formation stage, the cyclone tended to move northeastward and pass across the isotherms of SST (not shown). Figure 3 presents total cyclone frequency at the explosive stage and the mean SST in the cold season. The maximum center was found to the southeast of Japan Islands. It was located about 2000-2500 km to the northeast of the maximum center at the formation stage shown in Figure 1, reflecting the general northeastward direction of the storm movement. The storm centers at explosive stage covered a wide range of SST from 0° to 22°C, in agreement with that observed by Sanders and Gyakum (1980). The axis of maximum frequency tended to be located along the warm Kuroshio current to the warm side of the maximum SST gradient. This again implies that the flux of sensible and latent heat from the ocean surface over the area of maximum SST gradient was a positive factor in the rapid deep-



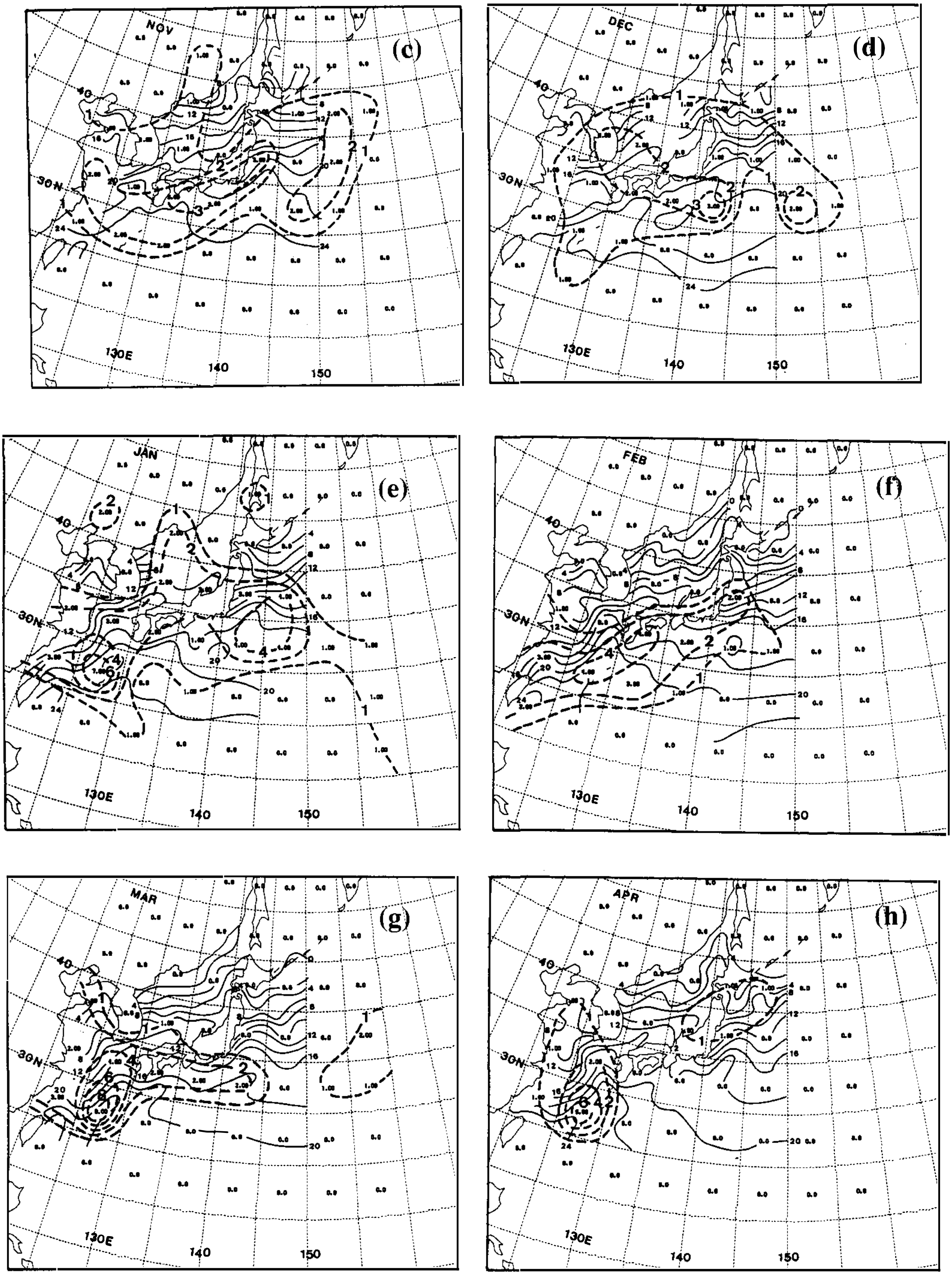


Fig. 2. Geographic distribution of explosive cyclones at the formation stage in each month of September-April, 1974-1984. Frequencies were analyzed at 2-event intervals (dashed) and the SST in each individual month at 2°C intervals (solid).

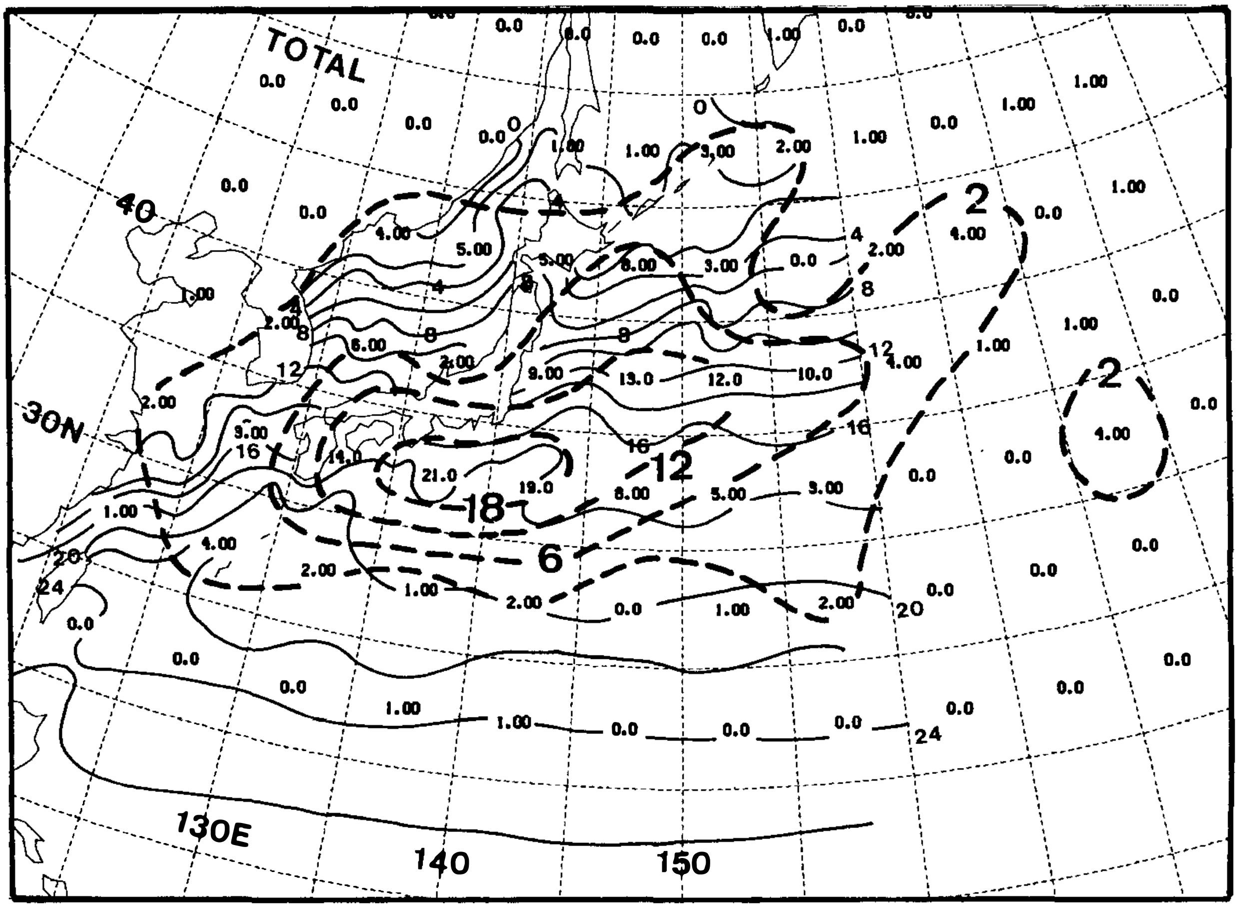


Fig. 3. Geographic distribution of all explosive cyclones at the maximum deepening stage in the cold seasons (September-April) of 1974-1984. Plots and analyses are the same as in Figure 1.

ening of the explosive cyclone. The winter storm was usually accompanied by convection to the southeast of Japan from the synoptic experience. A case study of the winter storm by Chen *et al.* (1983) and Chang *et al.* (1987) indicated that the latent heating may have played an essential role in cyclone intensification over the same area. Thus, it is suggested that latent heating was a possible factor in the rapid deepening of the explosive cyclone over the western Pacific.

3.2 Frequency Distribution

The monthly frequency of explosive cyclones obtained in this study along with the cyclone frequency in the area of 20 °-40 °N, 120 °-150 °E obtained by Hanson and Long (1985) and Whittaker and Horn (1982) are presented in Figure 4. In the period of September-April, there was a tendency for cyclone frequency to increase and reach its maximum in February for Whittaker and Horn's curve and in April for Hanson and Long's curve. The frequency of the winter cyclones over the Kuroshio current region obtained by Chen and Yeh (1982) showed a maximum in February. In this study, although the curve also exhibited an increasing trend in explosive cyclone frequency in the earlier months analyzed, the maximum frequency occurred in January, a finding which is in agreement with Sanders and Gyakum's (1980) results. The

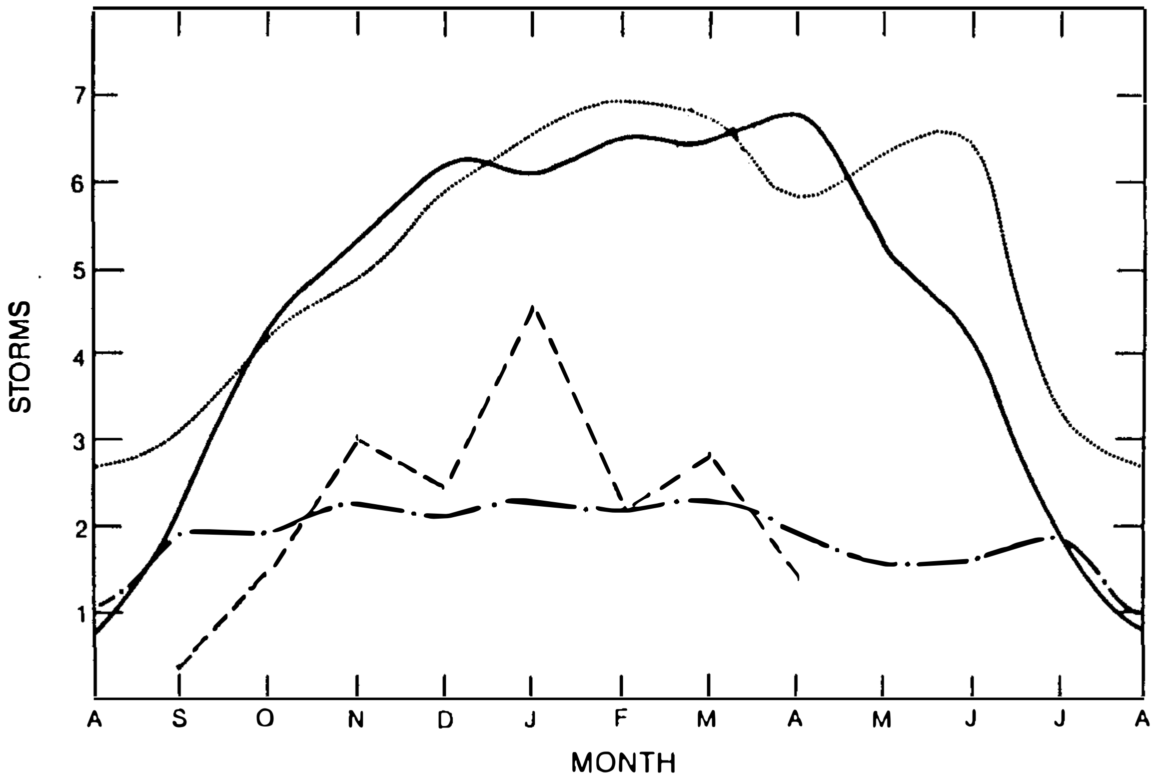


Fig. 4. Explosive cyclones in each month studied and averaged from 1974-1984 (dashed). The solid curve (average) and dash-dotted curve (standard deviation) are the results from Hanson and Long (1985) in storms per month in the area of 20-40°N, 120-150°E, and the dotted curve shows the results from Whittaker and Horn (1982) in the same area.

maximum frequency of explosive cyclones occurred in January, when the SST gradient along the shoreward edge of the Kuroshio current began to increase and to be better organized as discussed in section 3.1. January was also the month with the most frequent cold air outbreaks and the coldest air temperature within any year. This again suggests that the flux of sensible and latent heat from the ocean surface over the area of the maximum SST gradient may have been an important positive factor in the development of explosive cyclones.

The annual frequency distribution is plotted in Figure 5. It exhibits a great interannual variation with a minimum frequency of 10 events in 1974 and 1976 and a maximum frequency of 27 events in 1984. How this interannual variation relates to the ENSO events is a topic of great interest and is worthy of further study. The results of Hanson and Long (1985) supported the possibility of a link between interannual variability of storm formation over the East China Sea and quasi-biennial oscillation. This link seemed to be absent for the explosive cyclones over a similar area because the quasi-biennial variation of frequency could not be observed.

The frequency distribution of explosive cyclones with different intensities is presented in Figure 6. It should be pointed out that the intensity of an explosive cyclone in this study in terms of bergeron units cannot be compared with those rates obtained in other studies (*e. g.* Sanders and Gyakum 1980; Gyakum 1983a) using different definitions. However, the relative importance of the occurrence frequency at different intensities could be assessed. Statistical analyses of 12- and 24-hour deepening rates distribution for all surface lows over the area

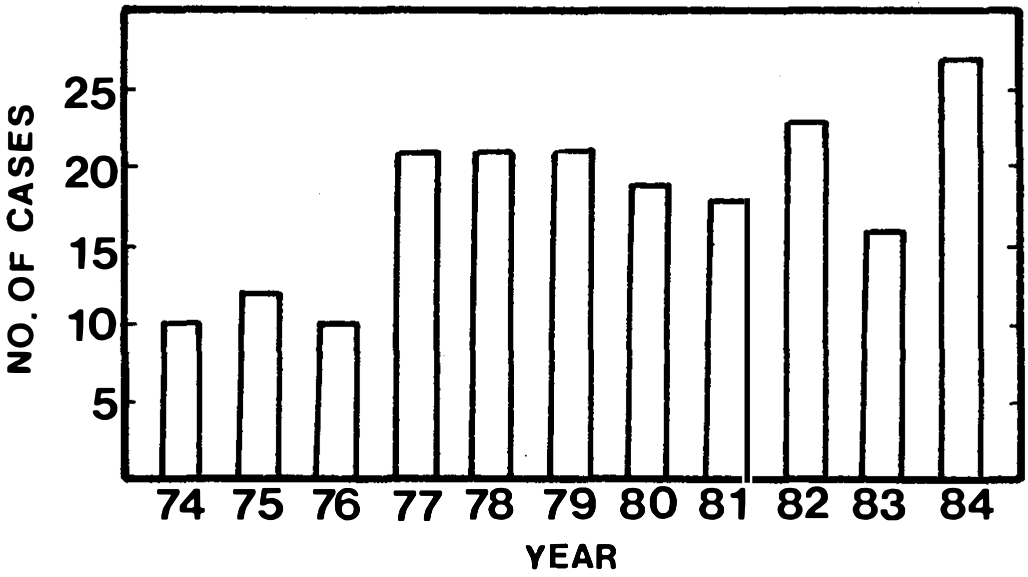


Fig. 5. Annual distribution of explosive cyclones occurring from September-April for each year from 1974-1984.

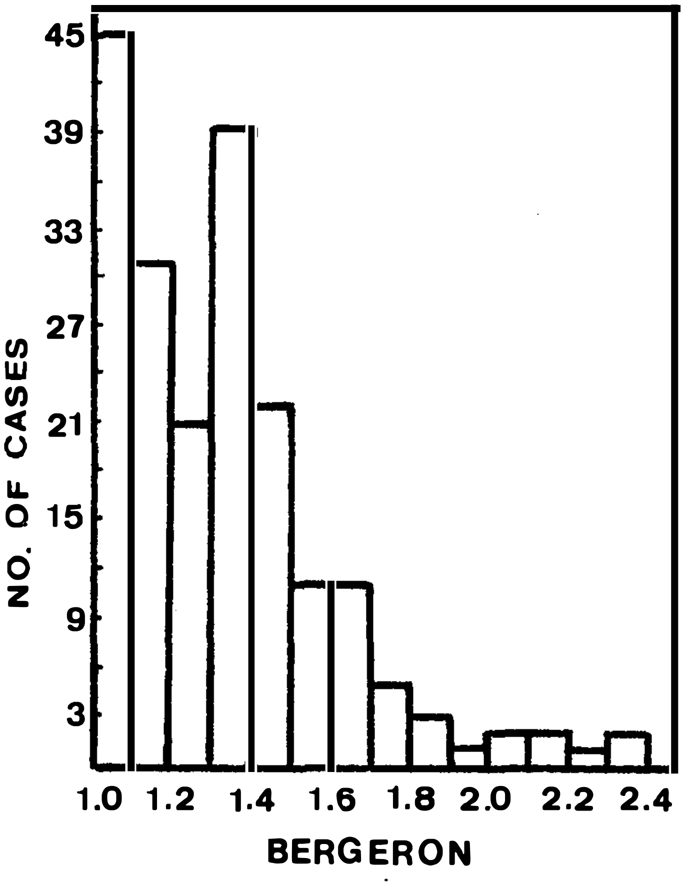


Fig. 6. Frequency distribution of explosive cyclones with different intensities in Bergeron (24-hour pressure fall is equivalent to 24 hPa at 45°N) in September-April for 1974-1984.

from 130°E to 10°E by Roebber (1984) showed statistical significant departures from normality, with the largest deviations occurring along the tail of the distribution associated with the most rapid deepening. The frequency distribution of explosive cyclones in Figure 6 exhibits a similar pattern to that presented in Figure 3 of Roebber's paper over the tail region with the most rapid deepening. Thus, the conclusion suggested by Roebber is also valid for the explosive cyclones over the western North Pacific and East Asian coastal area in this study. In other words, most cases of explosive cyclogenesis in this study may have formed as the result of some additional physical mechanisms distinct from ordinary baroclinic instability. Three-year data sample sets studied by Sanders and Gyakum (1980) revealed a more frequent occurrence of bombs (≥ 1.0 bergeron) in the North Pacific (158 events) than in the North Atlantic (109 events). However, the Atlantic had a greater frequency of occurrence (15 events) than the Pacific (6 events) of intense bombs (≥ 2.0 bergeron). For the 48 cases of bombs in the North Atlantic studied by Sanders (1986), there were 20 events with weak intensity (< 1.3 bergeron), 16 with moderate intensity (1.3-1.8 bergeron) and 12 with strong intensity (> 1.8 bergeron). Among the 198 cases of explosive cyclones analyzed in this study, 97 were considered weak events, 90 moderate and 11 strong events. Thus, a relatively low percentage of the explosive cyclones had strong intensity over the western Pacific and the overall area of the North Pacific as compared with that over the North Atlantic.

3.3 Relationship to the 500 hPa Trough

The synoptic-climatology of 500 hPa circulation changes during explosive cyclogenesis studied by Konrad and Colucci (1988) revealed that most bombs are not associated with locally identifiable 500 hPa circulation changes. On the other hand, however, Sanders and Gyakum (1980) observed that bombs usually formed about 400 n mi downstream from a mobile 500 hPa trough. A synoptic-climatological study of 48 events of bombs over the West Central North Atlantic by Sanders (1986) further illustrated that a high correlation existed between the 500 hPa positive vorticity advection (PVA) over the surface cyclone and the simultaneous surface deepening rate. Thus, an explosive cyclone appears to fundamentally be a baroclinic disturbance in which the low-level response to a given upper-level forcing is remarkably large. With the aim of further understanding this vertical coupling for the explosive cyclone over the western North Pacific, the relationship between the 500 hPa trough and the cyclone center at the formation and explosive stages were analyzed.

The analyses of cyclone center positions with respect to the long-term mean (30 years) geopotential height pattern at 500 hPa in each month (figures not shown) revealed that cyclones almost always formed and deepened explosively within or ahead of the planetary-scale troughs, which agrees well with Sanders and Gyakumís findings (1980). As the area of maximum positive vorticity usually coincides with trough at 500 hPa, the positive vorticity advection may well be expected over the area downstream of a trough. Hence, the relationship between the cyclone center and the simultaneous 500 hPa trough position was analyzed and is presented in Figure 7. It is clear that explosive cyclones most frequently formed and deepened explosively at about 700-800 km ahead of a trough, another finding which agrees well with that observed by Sanders and Gyakum (1980). It is also apparent that the overall distance between the cyclone center and the 500 hPa trough tended to be shortened at the explosive stage. This is consistent with what might be expected for the baroclinic development of an extratropical cyclone. 70% of the cyclones were ahead of a 500 hPa trough within 1000 km at the formation stage and 82% at the explosive stage. Among the 198 cases of explosive cyclones analyzed, 40% had a distance shortening, 24% distance increasing and 24% had no change in distance at the explosive stage. A 12% share was without a 500 hPa trough at the

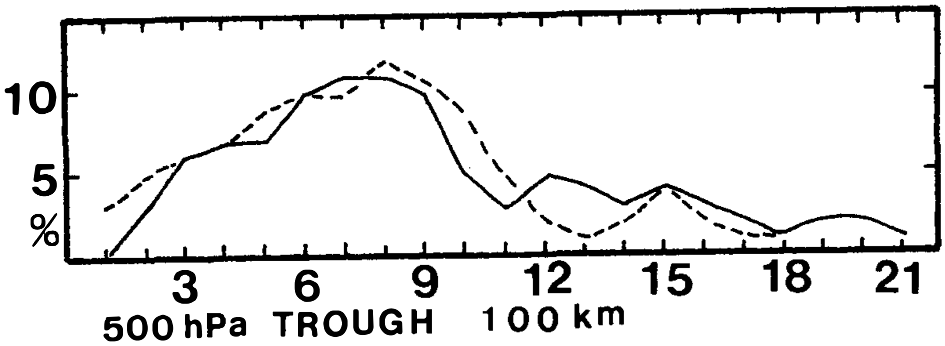


Fig. 7. Cyclone center position at the formation stage (solid) and at the maximum deepening rate stage (dashed) with respect to a 500 hPa trough. The X axis is the distance (×100 km) between the cyclone center and the 500 hPa trough normalized by sin 30°/sin ϕ, while the Y axis is the percentage occurrence of explosive cyclones.

formation stage, indicating that some explosive cyclones had Petterssen's type A development, as first suggested by Wash *et al.* (1988).

3.4 Relationship to Lower-tropospheric Baroclinity

As it is generally agreed that baroclinic instability is the major mechanism for explosive cyclogenesis, the large low-level temperature contrast is obviously then an essential element in the rapid deepening of a cyclone. In this regard, the temperature gradients at 850 and 700 hPa for the storm environment were analyzed at the formation and explosive stages and are presented in Figures 8 and 9.

At 850 hPa, cyclones formed most frequently in the baroclinic environment with a temperature gradient of 3°C $(250\ \text{km})^{-1}$ and explosively deepened most frequently in a 3°C $(200\ \text{km})^{-1}$ environment. The overall temperature gradient tended to increase during the explosive stage. This agrees with what might be expected from the baroclinic instability in that the front tends to form during cyclogenesis. 62% of all cyclones formed with strong baroclinity of ≥ 3 °C $(300\ \text{km})^{-1}$, and this figure increased to 73% at the explosive stage. At this explosive stage, 45% of the cyclones experienced a baroclinity increase, 31% a decrease, and 24% were without change. This likely means that the explosive mechanism is a combination of the baroclinic process and some other mechanism or mechanisms, such as latent heating and/or flux of sensible and latent heat.

At 700 hPa, cyclones formed and explosively deepened most frequently with baroclinity of 3°C $(200\ \text{km})^{-1}$. Again, similar to that at 850 hPa, the overall temperature gradient increased in the explosive stage. 63% of the cyclones were formed with strong baroclinity of ≥ 3°C $(300\ \text{km})^{-1}$, and this percentage increased to 72% at the explosive stage. At the explosive stage, 39% of the cyclones underwent a baroclinity increase, 39% a decrease, and 22% had no change. The lower percentage of 39% baroclinity increase at the explosive stage at 700 hPa as compared with 45% at 850 hPa suggested the shallowness of some surface fronts during explosive cyclogenesis.

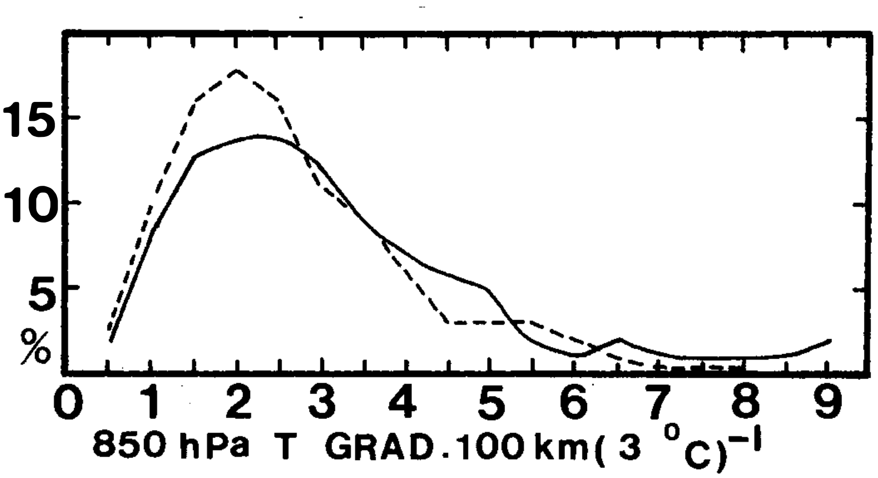


Fig. 8. Inverse temperature gradient at 850 hPa over the cyclone center position at the formation stage (solid) and at the maximum deepening rate stage (dashed). The X axis is the inverse temperature gradient normalized by sin 30°/sin ϕ in 100 km (3°C)$^{-1}$, while the Y axis is the percentage occurrence of explosive cyclones.

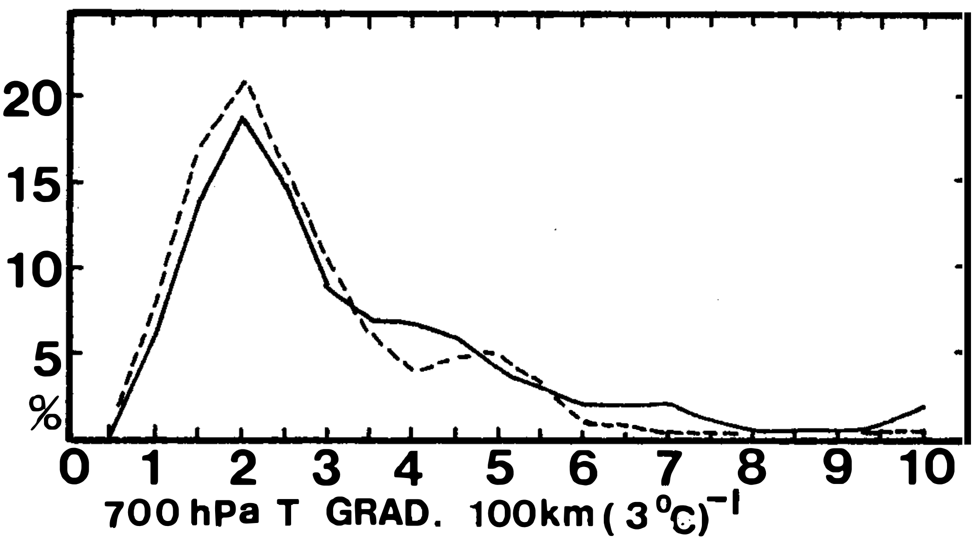


Fig. 9. Same as in Fig. 8, except at 700 hPa.

3.5 Relationship to See Surface Temperature Gradient

Explosive cyclones over the western Pacific, as discussed in section 3.1, tended to form and deepen explosively over the warm Kuroshio current and over the warm side of the maximum ∇SST along the shoreward edge of the Kuroshio current. This conforms with the results of climatological studies by Sanders and Gyakum (1980) and Hanson and Long (1985). The frequency distribution of the cyclones with respect to different underlying ∇SST at the formation and explosive stages is presented in Figure 10. Clearly, the frequency is positively correlated to the intensity of ∇ SST, which fits well with the results of Hanson and Long (1985). 67% of the cyclones were over the strong $\nabla SST \geq 1°C$ (180 km)$^{-1}$ at the formation stage, and this increased to 72% at the explosive stage. The corresponding frequency over $\nabla SST \geq 1°C$(360 km)$^{-1}$ was 89% at the formation stage and 92% at the explosive stage. In other words, explosive cyclones tended to form mainly over the strong ∇ SST and the overall frequency tended to increase over the strong ∇ SST at the explosive stage. This together suggests that the flux of sensible and latent heat from the ocean surface may have had a positive impact on the formation and rapid deepening of explosive cyclones.

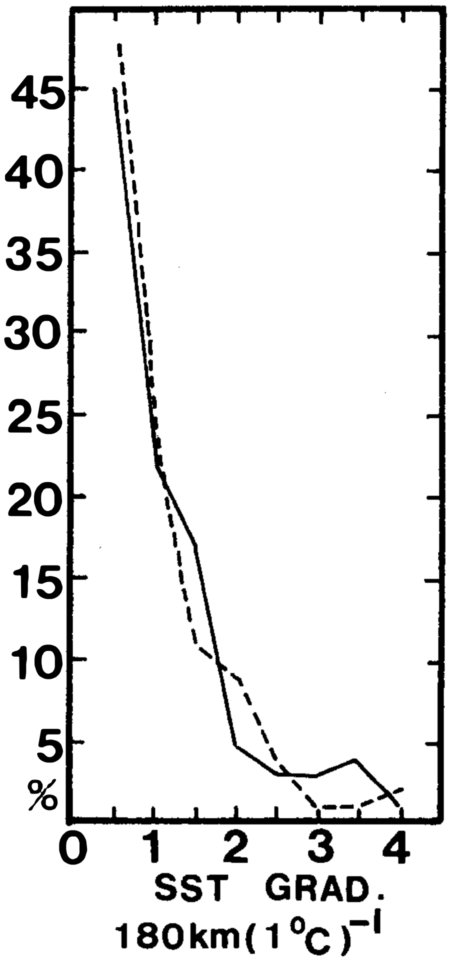


Fig. 10. Inverse sea surface temperature gradient under the cyclone center position at the formation stage (solid) and at the maximum deepening rate stage (dashed). The X axis is the inverse sea surface temperature gradient normalized by sin 30°/ sin ϕ in 180 km $(1°C)^{-1}$, while the Y axis is the percentage occurrence of explosive cyclones.

4. SUMMARY

Explosive cyclones are included among the most interesting meteorological events and have been under intensive and extensive study in recent years because of both the accompanying severe weather and the incomplete understanding of the physics of such cyclones. Different approaches have been used to investigate these cyclones including case studies, numerical simulations, model evaluations, and climatological and statistical studies. Numerous papers have been published on the cyclones over the western North Atlantic. However, only a few studies have been conducted on their counterparts over the North Pacific. The main purpose of this paper has been to present some results on the climatological aspects of these cyclones over the western North Pacific and the East Asia coastal areas.

Historical weather maps published by the Japan Meteorological Agency and the historical mean sea surface temperature charts published by the Japan Hydrographic Association were used to obtain the parameters of interest. The spatial and temporal distribution of cyclone frequency was analyzed. The relationships of explosive cyclones to a 500 hPa trough, lower-tropospheric baroclinity and the sea surface temperature gradient were explored. The following summarizes the results:

1) The maximum frequency of explosive cyclones was found to be located along the shoreward edge of the warm Kuroshio current over the maximum SST gradient at the formation and the explosive stages. This tends to suggest that the flux of sensible and latent heat from the ocean surface over the area of the maximum SST gradient may have had a positive impact on the formation and rapid deepening of cyclones.
2) It is suggested that latent heating was to be a possible factor in the fast deepening of the explosive cyclones as they frequently and rapidly deepened over the area where the cyclone was generally accompanied by active convection.
3) The frequency of explosive cyclones exhibited a remarkable interannual variability but showed no signs of a discernible periodic cycle. A clear seasonal variation with the peak frequency in January was also noted.
4) The frequency distribution of explosive cyclones with different intensities implies that most cases of explosive cyclogenesis over the western North Pacific may have formed as the result of some additional physical mechanism or mechanisms distinct from ordinary baroclinic instability. Also, only a relatively low percentage of explosive cyclones had strong intensity over the western North Pacific as compared with the percentage over the North Atlantic.
5) Explosive cyclones most frequently formed and deepened explosively at about 700-800 km ahead of the 500 hPa trough. The overall distance between the cyclone center and the 500 hPa trough tended to be shortened at the explosive stage, in agreement with that might be expected for the baroclinic development of an extratropical cyclone.
6) The overall temperature gradient in the lower troposphere over the cyclone center showed an increase at the explosive stage, consistent with that may be expected from baroclinic instability in that the front tended to form during cyclogenesis.
7) The frequency of explosive cyclones was positively correlated to the intensity of the SST gradient and the majority of cyclones formed and rapidly deepened over the area of a strong SST gradient, supporting the fact that the flux of sensible and latent heat from the ocean surface may have had a positive impact on the formation and rapid deepening of explosive cyclones.

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