NOTES AND CORRESPONDENCE

Climatology of Explosive Cyclones off the East Asian Coast

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ABSTRACT

The climatology of explosive cyclogenesis off the east Asian coast was studied, based on 30 years (1958–87) of surface analyses. There were two favorable areas for explosive deepening, one over the eastern Sea of Japan, and the other over the northwestern Pacific, east and southeast of Japan. The latter was located close to the warm Kuroshio Current. The frequency of explosive cyclogenesis reached a local minimum over Japan. The geographic distribution of explosive-cyclone frequency suggests that the explosive cyclogenesis is influenced by the Japanese islands. In addition, a positive correlation is found between explosive-cyclogenesis frequency and the El Niño episodes during 1958–87. The physical relationship between these two phenomena, however, is not well understood.

1. Introduction

The climatology of explosively developing cyclones in the Pacific has been studied by many authors (Sanders and Gyakum 1980; Roebber 1984; Gyakum et al. 1989). Their results provided a large-scale statistical distribution of coastal and maritime explosive cyclones. The purpose of this note is to examine the activity of explosive cyclogenesis off the east Asian coast over a 30-yr period (1958–87), from which detailed spatial and temporal variations of explosive cyclogenesis can be analyzed.

2. Procedure

The surface maps from 1958 to 1987 compiled twice daily (0000 and 1200 UTC) and published by the Beijing Meteorological Center (BMC) are used. The region studied extends from 20° to 60°N and from 100° to 160°E. Figure 1 shows a typical distribution of synoptic surface data reporting stations used at BMC for surface analyses in the 1980s. The resolution of ship observations over the ocean east of Japan was sufficiently high enough to allow proper detection of explosive cyclogenesis but was inadequate for determining the exact intensity of these storms, especially extreme events.

Sanders and Gyakum (1980) defined 1 bergeron as a 24-h pressure fall of 24 mb at 60°N. All the pressure falls in our study were latitudinally adjusted and expressed in bergerons. The criterion for an explosively deepening event is a 24-h pressure fall greater than 1 bergeron. Cyclones that were transformed from a tropical storm into a baroclinic disturbance with rapid deepening were excluded. The position of maximum deepening was taken to be the location of the cyclone center at the midpoint of the 24-h period of most rapid intensification. The formation position was taken as the initial location of a cyclone with at least one closed isobar on a 5-mb increment analysis. The explosive-cyclogenesis events were counted in a 2.5° latitude × 2.5° longitude box. A two-dimensional, five-point spatial smoothing (one-eighth of the total of four times the given frequency, plus the sum of the surrounding unsmoothed frequencies) was carried out on the raw frequencies. A contour analysis was then performed on these frequencies, which are assumed to be centered on the given quadrilateral.

3. Areal distributions

A total number of 363 explosive cyclones were found off the east coast of Asia from 1958 to 1987. During

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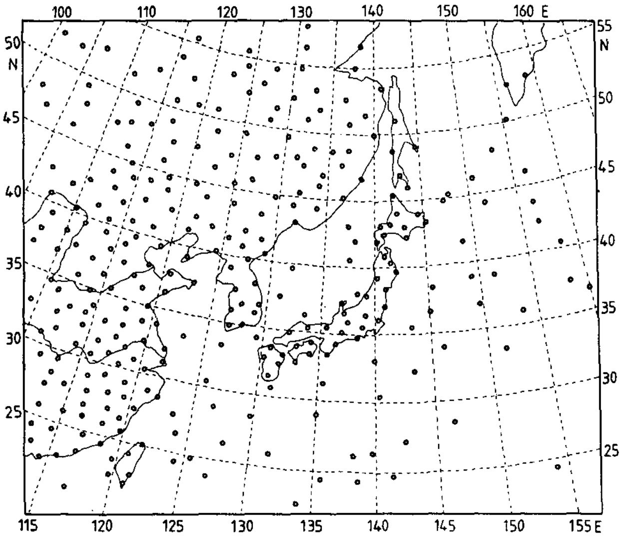

FIG. 1. Coverage of the synoptic surface data received at BMC at 0000 UTC 24 April 1983. The data distribution is typical for the 1980s.

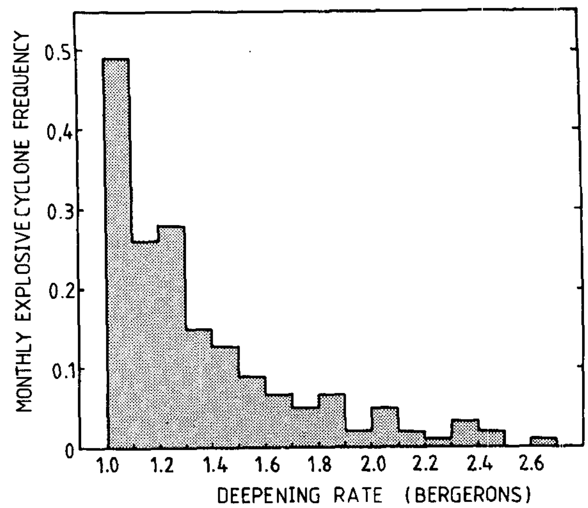

FIG. 3. Monthly explosive-cyclone frequency as a function of deepening rate (bergerons) for the cold seasons 1958–87.

this period, only 13 explosive cyclones (3.6%) were detected in the warm season between May and September. Therefore, our analysis is focused on the cold season (October–April). Explosive cyclogenesis occurred most frequently in December, January, and March (Fig. 2). This is different from that off the North American coast where only one maximum was found in January and where the explosive-cyclogenesis frequency in March was only one-half of the value in January (Sanders and Gyakum 1980). The abundant explosive cyclones off the east Asian coast in March was coincident with the a high frequency of cyclogenesis over this area (Chen et al. 1991). About 92% of explosive cyclones off the east Asian coast had a deepening rate less than 1.8 bergerons (Fig. 3), that is, the weak and moderate explosive cyclones according to Sanders' (1986) criterion.

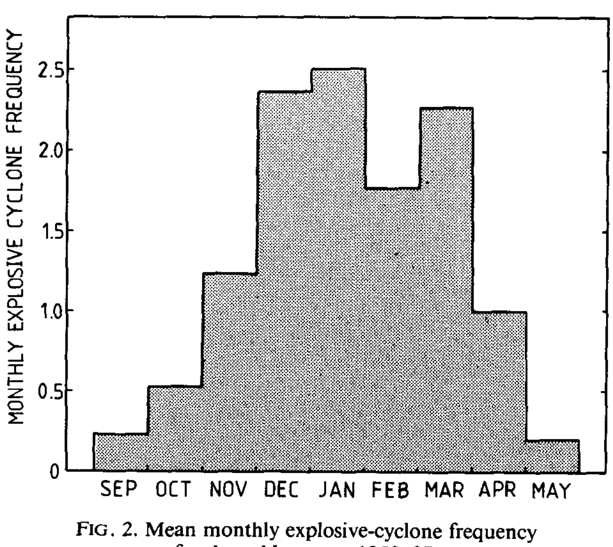

FIG. 2. Mean monthly explosive-cyclone frequency for the cold seasons 1958–87.

Table 1 compares the explosive-cyclogenesis events off the east Asian coast with those off the North American coast (Sanders 1986) for the period January 1981–November 1984. There were no radical differences in the total explosive-cyclone frequencies between these two regions during this period, except that the number of strong explosive cyclones off the east Asian coast was only one-third of that off the North American coast. Similar results were obtained by Sanders and Gyakum (1980). The fewer ship observations east of Japan may lead to an underestimate of strong explosive-cyclone events. In contrast, the frequency of moderate explosive cyclones off the east Asian coast was higher than that off the North American coast. As a result, the total frequency of strong and moderate explosive cyclones was nearly the same in these two regions.

Figure 4 shows the geographical distribution of explosive-cyclone frequency off the east Asian coast. Ex-

TABLE 1. The number of explosive cyclone events (October–April) off the East Asian coast and North American coast from January 1981 to November 1984. Strong: >1.8 bergerons; moderate: 1.3–1.8 bergerons; weak: 1.0–1.2 bergerons. The frequency is defined as the number of explosive-cyclone events per month.

	East Asian coast		North American coast	
	Events	Frequency	Events	Frequency
Strong	4	0.15	12	0.44
Moderate	34	1.26	19	0.70
Weak	22	0.81	23	0.85
Total	60	2.22	54	2.00

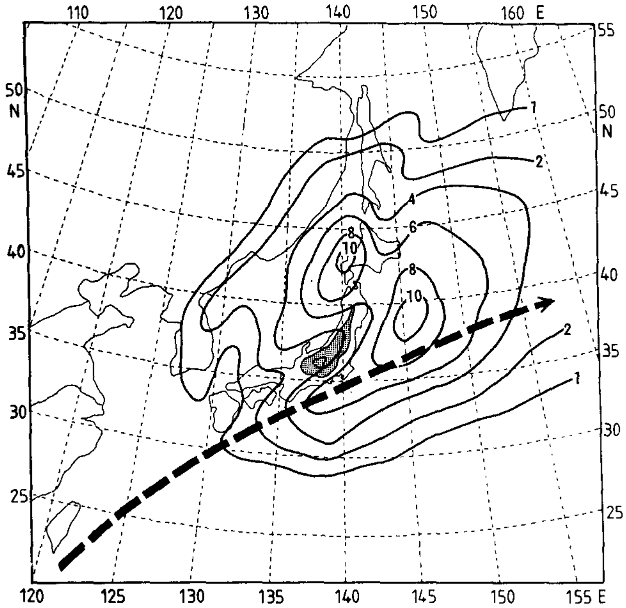

FIG. 4. Geographic distribution of explosive cyclone events in each 2.5 quadrilateral (smoothed) during the cold seasons 1958–87. Heavy dashed arrow represents the mean position of the Kuroshio Current. The Japan alps with height over 500 m is shaded.

cept for a few over the Korean peninsula and along the northeastern China coast, there were no explosive cyclones over the east Asian continent. This was different than the results of North America, where a number of explosive cyclones occurred over the continent (Sanders and Gyakum 1980).

Two areas of distinctly higher frequency can be observed. One was located along the east coast of Japan and the other over the eastern Sea of Japan. These two areas were coincident with the high-risk voyage areas defined by Couper (1983). The first high-frequency band started from the East China Sea and extended northeastward to the east of Honshu. The maximum frequency center was located at 38.75°N, 146.25°E, coincident with the findings of Sanders and Gyakum (1980), Roebber (1984), and Gyakum et al. (1989). The distribution of cyclogenesis frequency over this region was collocated with the mean position of the Kuroshio Current. Davis and Emanuel (1988) provided observational evidence of the effects of surface energy fluxes on the development of explosive cyclones in this area. A typical explosive cyclone, which developed in this area during the Air-Mass Transformation Experiment (AMTEX 75), was studied by Chen et al. (1983, 1985). Their results showed that sensible and latent heat fluxes from the Kuroshio Current can destabilize the lower atmosphere and contribute to rapid deepening. Nuss and Kamikawa (1990) diagnosed cases of an explosive and a nonexplosive cyclone. Large positive surface heat and moisture fluxes in the updraft region were found in the explosive case. In contrast, only weak surface energy fluxes were found in the nonexplosive case. Since upper-air observations are sparse to the east of Japan, no detailed observational studies of air–sea interaction exist. Our results, at least, support the positive impact of the warm ocean current on explosive cyclogenesis over this area, as suggested by Gyakum et al. (1989).

The second area of frequent explosive cyclogenesis stretched along the eastern part of the Sea of Japan with the maximum positioned to the west of Hokkaido (43.75°N, 141.25°E). It was located about 1000 km north of the Kuroshio Current. The sea surface temperature (SST) gradient over this region was weaker than that in the vicinity of the Kuroshio Current (Japan Meteorological Agency 1958–87). This band was not found in the previous studies (Sanders and Gyakum 1980; Roebber 1984; Gyakum et al. 1989). The analysis area of these earlier studies was limited to the east of 130°E, while most of the explosive cyclones developed in this region started their rapid deepening to the west of 130°E. A case of such an explosive cyclone was presented by Chen and Dell'Osso (1987). They found that the sensible heat flux contributed only 18% to the development. Although the generalization of these results awaits further studies, it seems that the air–sea interaction plays a less important role for the explosive cyclones that developed in this area compared with those to the east of Japan.

A region of low frequency was evident between these two local maxima. This relatively low-frequency band was located over the islands of Japan, and its value was about one-half of that in the high-frequency areas. Such a pattern of cyclone frequency distribution has not been observed off the North American coast (Sanders and Gyakum 1980; Roebber 1984). The distribution of explosive cyclones off the east Asian coast is apparently influenced by the presence of the Japanese islands. As pointed out by Anthes (1983), the sea level pressure forecasts in a numerical model depend strongly on surface friction. Graystone (1962), Bushby (1968), Danard (1969), and Anthes and Keyser (1979) found that the central pressures of cyclones in 24-h forecasts were 5–25 mb lower without friction. The increased surface friction over land may be one of the reasons for the decreased explosive-cyclone frequency. Moreover, the islands of Japan disrupt the distribution of SST, as well as air–sea interaction off the east Asian coast, which may also affect the locations of rapid deepening.

The geographic distribution of the frequency of weak, moderate, and strong explosive cyclones is shown in Figs. 5a–c, respectively. The frequency distribution of the weak explosive cyclones displayed a pattern similar to that of total explosive cyclones. The frequency of moderate cyclones decreased over the eastern Sea of Japan but remained as a local maximum. The bands of maximum frequencies of moderate and strong explosive cyclones lay along a northeast–southwest-oriented line in the vicinity of 36°N to the east of 135°E, which is closer to the northern boundary of the Ku-

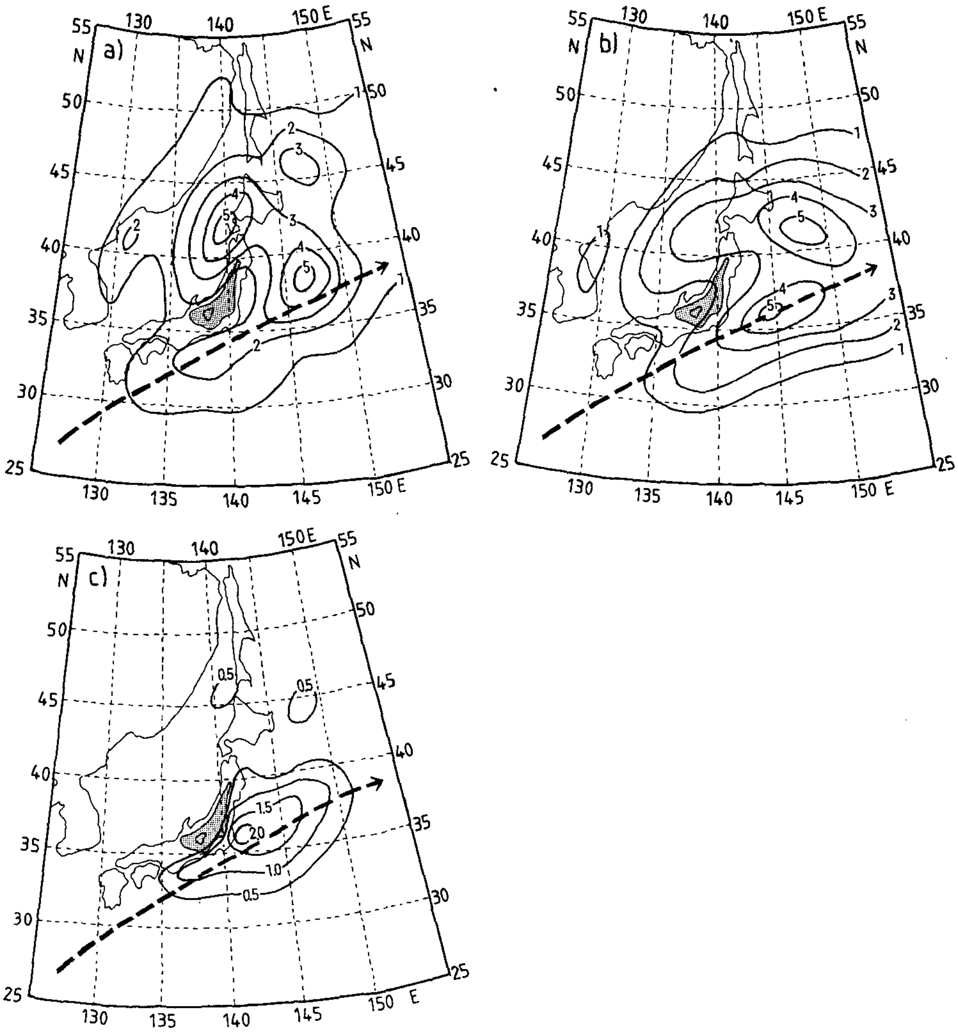

FIG. 5. Geographic distribution of explosive cyclone events in each 2.5 quadrilateral (smoothed) during the cold seasons 1958–87 for (a) weak, (b) moderate, and (c) strong cyclones. Heavy dashed arrow represents the mean position of the Kuroshio Current. The Japan alps with height over 500 m is shaded.

roshio Current. This suggests that air–sea interaction may be more important for strong and moderate events than for weaker ones. On the other hand, it should be noted that the Japan alps, which include the Mount Fuji range, are located from 35° to 38°N, with a mean elevation of 1000 m, immediately to the west of the maximum frequency band. It is speculated that for moderate and strong explosive cyclones developed to the east of Japan, orographic forcing may play a role in their rapid intensification. However, detailed case studies are needed to verify this hypothesis.

Two prominent formation areas, one to the south of Japan over the East China Sea and the other over the western Sea of Japan, can be seen in Fig. 6. These two locations were displaced slightly southwestward from the primary explosive deepening areas. By examining cases of cyclogenesis in those areas, about 65% of the cases of rapid deepening were found to occur approximately 12 h after the cyclone was formed. In addition, another two regions of cyclone formation (with lower frequency) were located over the lower Yangzi and Yellow river valleys, respectively. A number of explosive cyclones originated over the continent that were obviously not related to air–sea interactions in their incipient stage.

4. Interannual variations

The year-to-year variation of explosive cyclogenesis in the cold seasons is depicted in Fig. 7a. The mean number of explosive cyclone events per year was 11.7, with a standard deviation of 5.3, indicating that the interannual variability is substantial.

There were six El Niño events between 1958 and 1987 (also shown in Fig. 7a). An El Niño event can last about 1 year. The onsets of El Niño episodes oc-

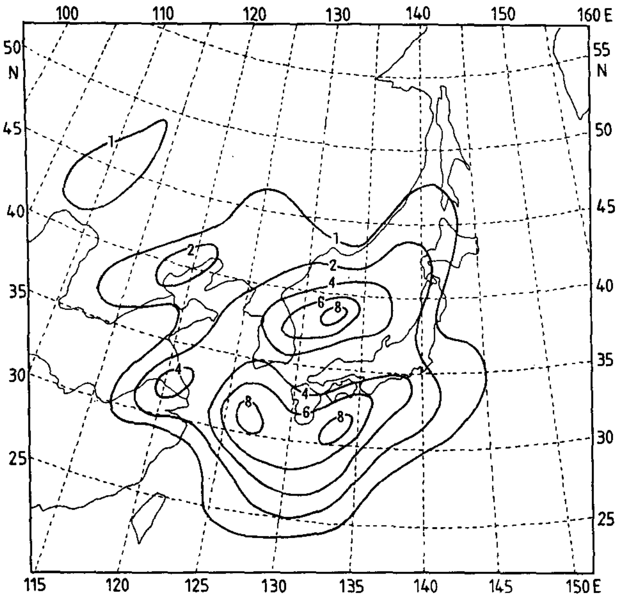

FIG. 6. The formation position of the explosive cyclone in each 2.5 quadrilateral (smoothed) during the cold seasons 1958–87.

curred in January 1965, 1969, 1972, and 1976 (Quinn et al. 1978), and spring 1982 (Quiroz 1983), and September 1986 (Bergman 1987). Signals of the El Niño events along the South American coast were observed about 3–6 months after their onset, and the region of anomalously warm sea surface temperature reached the central Pacific by the following fall or winter (Horel and Wallace 1981). Here the cold season is defined as from October to the following April, similar to our definition. Therefore, the relationship between the El Niño years and the explosive cyclone events can be examined. A relative maximum number of explosive-cyclone frequency at (or after) every El Niño episode is quite apparent in Fig. 7a, especially for the strong and moderate El Niño events. For the moderate 1976 El Niño, a minor peak in explosive cyclogenesis frequency was still observed, although it did not appear to be an important anomaly. The mean explosive-cyclone events in the El Niño years reached 16.6, with a standard deviation of 3.8, while the mean and standard deviation were 10.2 and 4.3, respectively, in the La Niña years. The explosive-cyclone events in the El Niño years was 1.6 times greater than that in the La Niña

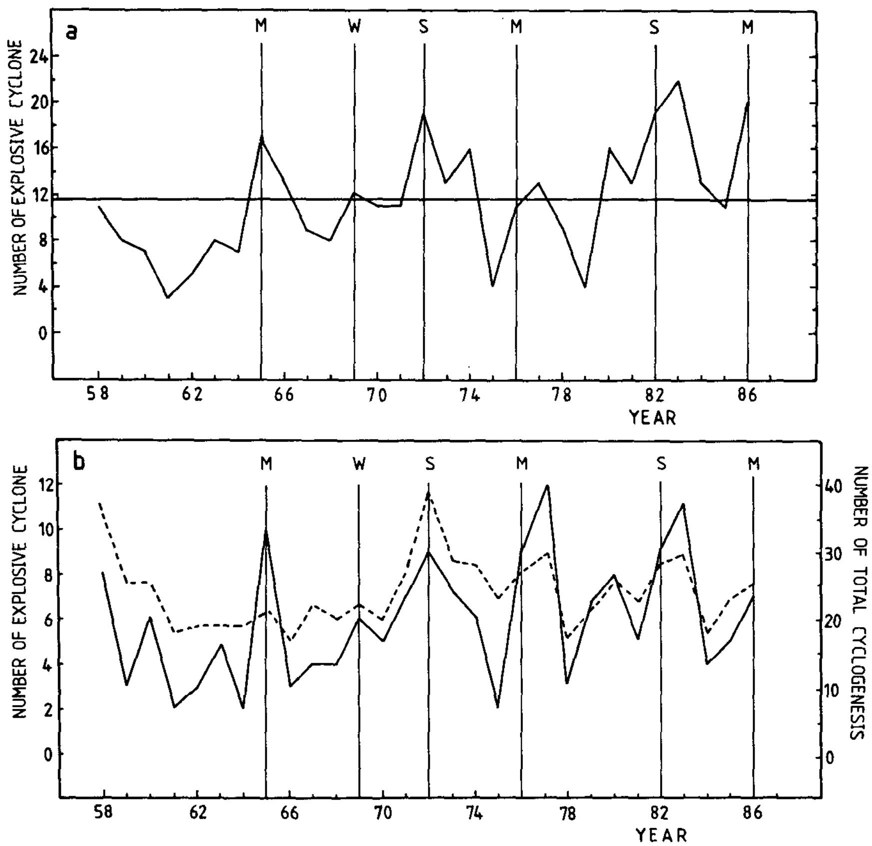

FIG. 7. (a) Yearly variation of explosive cyclone events in the cold seasons for the period 1958–87. (b) Yearly variation of explosive cyclone events (solid line) and total cyclogenesis (dashed line) in the East China Sea in the period 1958–87. The letters W, M, S refer, respectively, to years when a weak, moderate, or strong El Niño event took place (according to Quinn et al. 1978; Quiroz 1983; and Bergman 1987).

year. Hanson and Long (1985) found a tendency of more frequent cyclone formation over the East China Sea (20°–24°N, 120°–150°E) during El Niño years. The yearly frequencies of total cyclogenesis and those of explosive cyclones in the East China Sea are shown in Fig. 7b. The interannual variation of these two frequencies are quite similar, with a correlation coefficient of .63. More cyclogenesis and explosive-cyclone events occur in the El Niño years.

Figure 8 shows the monthly variation of the explosive-cyclone frequency for the 6 El Niño years and the other La Niña years. In an El Niño year, higher cyclogenesis frequency was observed during autumn and spring, but no significant difference was found between these two weather regimes in December and January.

There is no satisfactory explanation for this relationship at this time. Several authors have used atmospheric general circulation models to simulate the atmospheric response to the SST anomaly. Mechoso et al. (1987) found that the midlatitude westerlies were enhanced over the Pacific in a simulation with a positive SST anomaly, which led to an increase of synoptic-scale transient baroclinic waves. Their results are consistent with the observed interannual variation of transient waves for five winters (1972–77), which showed a similar increase during the El Niño winters of 1972/73 and 1976/77 (Fraedrich and Böttger 1978). It is reasonable to speculate that the increased synoptic-scale transient waves may be associated with an increase of explosive cyclogenesis events. A modeling study of the seasonal circulations in response to the observed El Niños in 1962–76 was carried out by Lau (1985). The composite charts of model anomalies in typical El Niño episodes (1965, 1969, and 1972) showed a cyclonic circulation at 950 mb and a negative height at 1000 mb to the east of Japan during spring and autumn (Figs. 9c,d and 11c,d of Lau 1985). Those anomalies

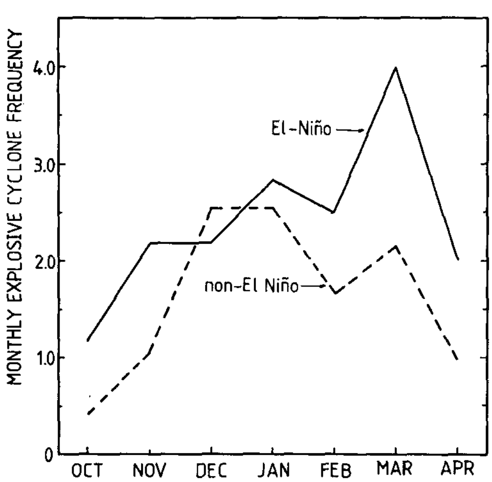

FIG. 8. Averaged monthly explosive-cyclone frequency during El Niño years (solid line) and La Niña years (dashed line).

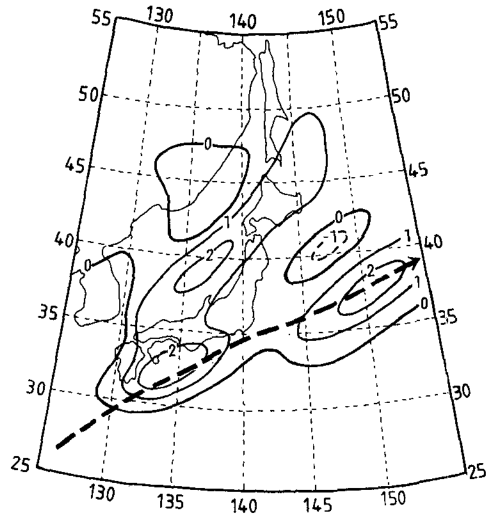

FIG. 9. The difference of the geographic distribution of explosive-cyclone frequency between El Niño and La Niño year. Units are 10^{-1} events per 2.5 quadrilateral. Heavy dashed arrow represents the mean position of the Kuroshio Current.

indicate that more explosive cyclones (at least, stronger cyclones) occur in this area during El Niño episodes.

Figure 9 depicts the differences in the geographical distribution of explosive-cyclone frequency between El Niño and La Niña years. A band of positive deviation of frequency was located along the Kuroshio Current. This suggests that the increase of explosive cyclone events over the East China Sea and south of Japan in El Niño episodes may be partly related to the change of SST associated with the Kuroshio Current. An example is the strong El Niño year of 1982–83. In addition to the anomalously warm SST in the equatorial east Pacific, there was a positive SST anomaly (>1°C) along the Kuroshio Current and a negative outgoing longwave radiation (OLR) anomaly (< -20 W m^{-2}) over the same area in the spring of 1983 (Figs. 3 and 9 of Chen 1983). The increased SST and convective activity over this area may be associated with the development of explosive cyclones. Ten explosive cyclones were observed off the east coast of Asia in March and April 1983, in sharp contrast to the climatological mean of 3.3 events in these 2 months. Chen (1983) also noted that a tremendous westerly jet dominated the northern Pacific and several Pacific storms struck the west coast of the United States. Similar patterns of anomalies of SST and OLR in the vicinity of the Kuroshio Current were also observed in the spring of 1987, which was a moderate El Niño event (Wagner 1987). These diagnostic results suggest that a relationship may exist between El Niño and the SST associated with the Kuroshio Current, although further analysis is needed to confirm this speculation. On the other hand, note that the positive deviation in the Sea of Japan remains somewhat obscure, which cannot be explained by the temperature variation of the Kuroshio Current.

5. Summary

The main results in this paper can be summarized as follows.

1) There were two areas of high explosive-cyclone frequency off the east Asian coast; one in the eastern part of the Sea of Japan, and the other over the northwest Pacific, east of Japan. The latter was located close to the warm Kuroshio Current.

2) The frequency of explosive cyclones displayed a local minimum over the Japanese islands. This suggests that the presence of the islands of Japan may have an impact on the climatological distribution of explosive cyclones off the east Asian coast.

3) An increase of explosive cyclone events off the east Asian coast in every El Niño year was evident during the period of 1958–87, although the physical relationship is not well understood.

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