Synoptic Climatology of Cyclogenesis over East Asia, 1958–1987

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(Manuscript received 16 August 1990, in final form 1 December 1990)

ABSTRACT

A climatological analysis of cyclogenesis over east Asia and the adjacent northwest Pacific for the period 1958–87 based on the Beijing Meteorological Center's historical surface maps is presented. The most active cyclogenetic areas were: 1) the lee sides of the Altai–Sayan, Stanovoi, and Great Xinganling mountains, and 2) the East China Sea and the Sea of Japan. The former was related to lee cyclogenesis and the latter to coastal cyclogenesis.

After zonal average, the primary zone of cyclogenesis emerged between 45° and 50°N, constituted mainly by the Altai–Sayan lee cyclogenesis. The Altai–Sayan lee cyclogenesis occurred in all seasons, with peak frequencies from April to May and from August to September. The secondary zone of cyclogenesis, located at 30°–35°N with half the frequency of the primary zone, was a result of East China Sea cyclogenesis. The coastal cyclogenesis occurred only in the cold season and disappeared in summer and early autumn. The total cyclogenetic events over east Asia reached a minimum in January. By contrast, cyclogenesis is still quite active over North America in January.

The trend of east Asia cyclogenesis showed a decline from 1958–77, which was coincident with the finding of Whittaker and Horn in North America. After 1977, no such decline was found.

1. Introduction

The spatial distribution and temporal variations of cyclogenesis are important to both weather and climate in the extratropics. Petterssen (1956) was the first to study cyclone and anticyclone frequency over the Northern Hemisphere for the period 1899–1939. Klein (1957, 1958) extended Petterssen's analysis by conducting a census of cyclone and anticyclone tracks for the same time period. He compared the mean zonal wind at 700 mb with the mean distribution of cyclones and anticyclones. Aside from these two studies that dealt with the entire Northern Hemisphere, regional cyclone activities also have been investigated. Colucci (1976) studied winter cyclone frequency over the eastern United States for the period 1905–54. Reitan (1974, 1979) examined the frequency of North American cyclogenesis for the midseason months from 1951 to 1970; Zishka and Smith (1980) compiled a study of North American cyclone and anticyclone activity for January and July, 1950–77. The frequency of cyclogenesis in approximately the same area during the period 1958–77 was analyzed by Whittaker and Horn (1981). These studies provided a comprehensive and detailed description of the synoptic climatology for the cyclone and anticyclone activity in the North American sector.

For the east Asian sector, Wu and Liu (1958) did a census of cyclogenesis for the midseason months, 1951–55. Chung et al. (1976) studied the frequency of cyclogenesis for the year 1958, using a 2.5° latitude–longitude grid, and examined the role of a major mountain barrier in cyclogenesis. A climatological analysis of cyclogenesis for the period 1951–60 was presented by Zhu et al. (1981). These studies improved our knowledge of the temporal and spatial distribution of cyclogenesis over east Asia, where Petterssen's statistics suffered from data scarcity. Since the 1950s, the synoptic reports over east Asia have increased dramatically. There is a need to refine and update the climatology of cyclogenesis using data of much longer duration.

In this paper, the geographical distribution, and the seasonal and interannual variation, of cyclogenesis over the east Asian sector are analyzed using a 30-yr dataset, from 1958 to 1987. Based on these analyses, a more

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detailed synoptic climatology of cyclogenesis over east Asia and the adjacent northwest Pacific area is presented.

2. Data and analysis procedures

The data used in this study were derived from sea-level pressure maps twice a day (0000 and 1200 UTC), analyzed and published by the Beijing Meteorological Center, China, for the period 1958–87. The region studied is shown in Fig. 1. Since only a few synoptic surface reports in India, Pakistan, and Afghanistan were received by the Beijing Meteorological Center, the analyses over these regions are not reliable. Also, an accurate sea-level pressure analysis over the Tibetan Plateau (which has an altitude of more than 5000 m) is nearly impossible. For these reasons, we excluded from our study the cyclogenesis events over these areas (regions west of 100°E and south of 35°N, which is shaded in Fig. 1).

Cyclogenesis is defined as the initial point of the cyclone with at least one closed isobar on a 5-mb increment analysis. The lifetime of a cyclone has to be at least 24 h. Since we are interested mainly in baroclinic systems, cyclones without surface fronts, heat lows, monsoon depressions, tropical cyclones, or those transformed from tropical cyclones are omitted. In cyclogenesis frequency counts, a 2.5° latitude–longitude grid was used. The latitude–longitude quadrangles in the study area were numbered sequentially. Each cyclone case was identified by the number of the quadrangle, the date and time, every 12 h. The frequency of cyclogenesis is expressed as the number of cyclogenesis occurrences counted in each quadrangle per month. It should be noted that, owing to the larger interval of the isobaric analysis, some nondeveloping, smaller-scale cyclones would not be counted.

Over most areas in the region studied, the averaged height is below 1 km so that the sea surface pressure analysis is reasonably accurate. For the Mongolian

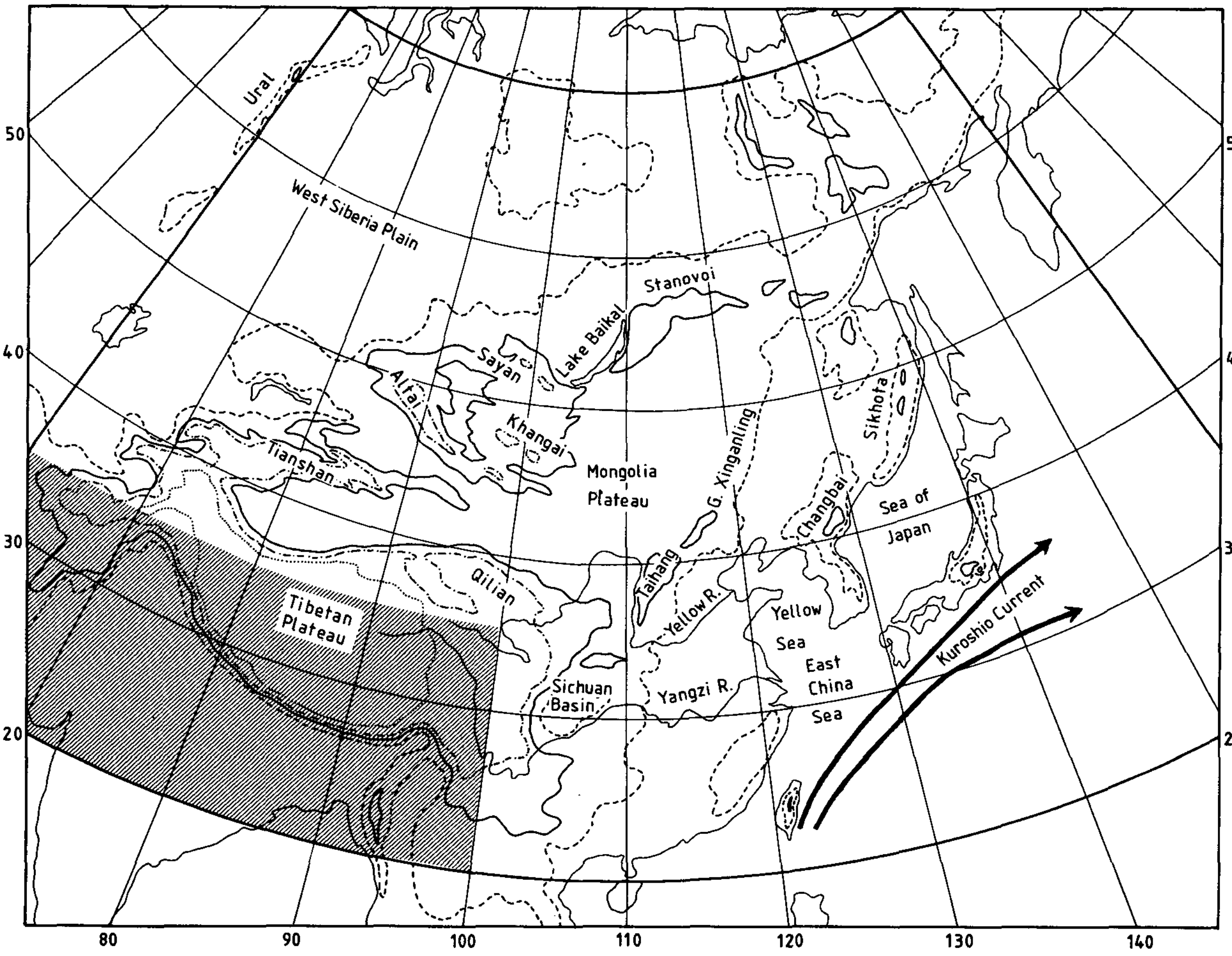


FIG. 1. East Asia sector, the mountain complex, and the locations of places referred to in the text. Heavy solid line encloses the study areas. The terrain height contours are indicated as follows: dashed lines, 0.5 km; thin solid lines, 1.5 km; dash–dotted lines, 3 km; and dotted lines, 5 km. Thick arrows show the Kuroshio current schematically. The shaded area denotes the region where the cyclogenesis event was not counted in the study.

Plateau and northwestern China, where the mean height ranges 1–1.5 km, the surface temperature is higher (lower) than that in the free atmosphere during warm (cold) season. According to Zhu et al. (1981), the calculated sea-level pressure can have a lower (higher) bias of 2–4 mb. Since our study utilized sea-level pressure analysis with a contour interval of 5 mb, it should have only a minimal impact on our statistical results.

3. Areal distributions

Figure 2 depicts the areal distribution of the annual frequency of cyclogenesis for 1958–87. Two areas of concentrated cyclogenesis can be found: one from 40° to 55°N and 95° to 125°E and the other from 27.5° to 40°N and 115° to 145°E. The axis of the maximum frequencies of cyclogenesis was oriented from northeast to southwest. The former, from east of Lake Baikal to east of Qilian Mountain, was related to lee cyclogenesis; the latter, from the Sea of Japan to the East China Sea, was a result of coastal cyclogenesis.

Three high-frequency centers existed in the area east of Lake Baikal to Qilian Mountain. These three centers were also noted in previous studies (Wu and Liu 1958; Chung et al. 1976; Zhu et al. 1981). The total events within this area reached 1720 over the 30-yr period. This implies that on the average about 4.8 cyclones were initiated per month. The highest frequency of cyclogenesis was located over the Mongolian Plateau, on the lee side of Altai–Sayan Mountains. This kind of cyclone can be called an "Altai–Sayan cyclone." Altai–Sayan (including Khangai and Tianshan) consists of a series of mountains with an average height of 2 km. Starting from the south of Lake Baikal, it extends southwestward for nearly 1200 km. To the west of Altai–Sayan lies the west Siberia plain; to its east the Mongolian Plateau with an average elevation of 1 km. The frequencies of Altai–Sayan cyclogenesis are comparable with those of the Alpine lee cyclogenesis in Europe (Petterssen 1956) and the Colorado and Alberta cyclogenesis in North America (Whittaker and Horn 1981). The lee of Altai–Sayan is one of the major cyclogenesis regions in the Northern Hemisphere.

The Altai–Sayan cyclone usually formed as a sec-

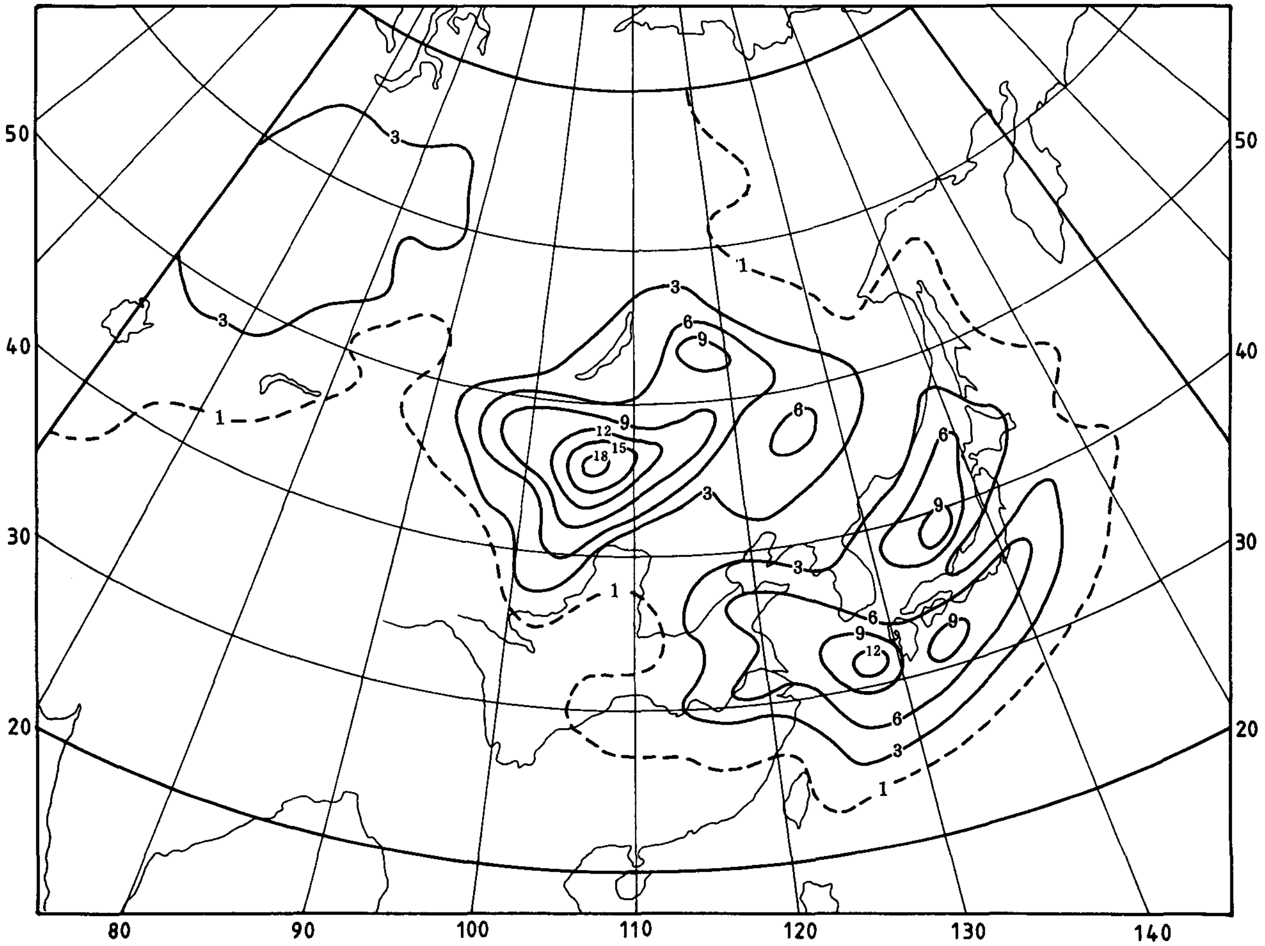


FIG. 2. Annual number of cyclogenetic events (10^{-2}) per 2.5° quadrangle per month for the period 1958–87.

ondary low when a primary (parent) cyclone swept by the north of the mountains, in a way very similar to that of Alpine cyclones (Chen and Lazic 1990). A case of cyclogenesis on 1200 UTC 3 March–1200 UTC 4 March 1986 is shown in Fig. 3. The primary cyclone was located in the western Siberia plain with a surface front extending from the cyclone center southwestward to Tianshan Mountain. In the midtroposphere, a pronounced trough was located to the west of the surface cyclone. During the next 24 h, the primary cyclone passed north of Lake Baikal and weakened. The surface front was deformed by the orography and a new cyclone was initiated with a central pressure of 1010 mb. Although the central pressure was higher than that of the primary cyclone 24 h earlier, the geostrophic vorticity field as implied by the pressure gradient indicated that the lee cyclone was stronger than that of the primary cyclone. At 500 mb, a new trough was formed to the west of the lee cyclone. A statistical study of a 500-mb mobile trough by Sanders (1988) showed that the largest frequency of trough genesis was centered near 45°N,100°E, 700 km upstream of the Altai–Sayan lee cyclogenesis maxima.

The other two high-frequency centers encompassing smaller areas were located east of Lake Baikal (south of Stanovoi Mountain) and east of the Great Xinganling Mountains (northeast of China), respectively. The former is called the "Baikal cyclone" and the latter the "northeast low" in Chinese literature. The horizontal scales of Stanovoi and the Great Xinganling mountains are also on the order of 1000 km, and the averaged elevation ranges from 1.5 to 2 km. We also note that the maximum cyclogenesis axis extended southward to the east of Qilian Mountain.

The cyclogenetic area from the east coast of China to the East China Sea and the south of Japan shown in Fig. 2 is in general agreement with the results of Hanson and Long (1985). However, the primary center of cyclogenesis frequency over the East China Sea in Fig. 2 was located about 5° farther north. A secondary center was located south of Japan, which was also found by Miller and Mantis (1947) for the winters of 1932–36 but was absent in Hanson and Long's study. The area of primary maximum cyclogenesis was closely related to the warm Kuroshio current (shown in Fig. 1) to the south of Japan, where the sea surface temperature gradient was large (Hanson and Long 1985). Cyclones initiated in this area usually moved northeastward into the northern Pacific and sometimes developed rapidly. A typical case during AMTEX 75 has been studied in detail by Chen et al. (1983; 1985) and Chang et al. (1987). Their results showed that the sensible heat flux from the Kuroshio current, which destabilized the lower layer of the polar air mass, and the release of latent heat both contributed to the development. The high frequency of cyclogenesis over the Sea of Japan can also be identified in Petterssen's study (1956).

Aside from these major centers, there were two secondary cyclogenesis regions along the lower Yangzi River and Yellow River, respectively. The former occurred in spring, and the latter in summer. Cyclones generated in those areas often produced a significant amount of rain, which is crucial for the agriculture in China. Finally, it should be noted that the lee side of the Ural Mountains was also a region of frequent cyclogenesis.

The areal distribution of cyclogenesis frequency in the four seasons is depicted in Fig. 4. During the winter, only a few cyclones were initiated over the mainland. However, a high-frequency center over the Mongolian Plateau indicates that the orographically forced cyclogenesis still existed (Fig. 4a), but the frequencies were considerably lower than the annual averages (Fig. 2). This is quite different from that in North America and Europe where lee cyclones are most active in the winter. Cyclogenesis was active in the East China Sea, south of Japan, and over the Sea of Japan (Fig. 4a) with winter frequencies higher than those of the annual averages.

Spring was the most active cyclogenetic season in east Asia. The frequencies of cyclogenesis in the lee of Altai–Sayan and Stanovoi were 1.5 times larger than the annual values. The frequencies over the East China Sea and the Sea of Japan doubled the annual averages (Fig. 4b). Another cyclogenetic region appeared along the Yangzi River with a maximum frequency at the lower valley. Cyclogenesis usually occurred in this area when a midtropospheric trough propagated from the eastern Tibetan Plateau and became superimposed upon a low-level baroclinic zone (Tao 1979).

The cyclogenetic area moved northward to the Yellow Sea in summer (Fig. 4c). The cyclogenesis over East China Sea and south of Japan was almost absent. A relatively high-frequency center was located at the lower Yellow River valley, on the lee side of Taihang Mountain. We also notice that a relatively high-frequency center appeared in the lee of Great Xinganling. The Altai–Sayan lee cyclogenesis was still the primary cyclogenesis during the summer.

In the autumn, the general pattern of cyclogenesis frequencies was similar to that in the summer (Fig. 4d). This is because the large-scale circulation pattern did not change until the middle of October (Yeh et al. 1959).

It should be noted that the general patterns of cyclogenesis on the lee side of Altai–Sayan and Stanovoi mountains did not appear to be altered between cold and warm seasons, although the frequency in winter was rather small. The coastal cyclogenesis also existed in all seasons, except that the locations moved northward from the East China Sea in the winter and spring to the Yellow Sea in the summer and autumn.

In order to reveal the tracks of the cyclones generated over the areas aforementioned, the total cyclone events in each quadrangle was also counted. From the cyclone frequency maps, the cyclone tracks can be found. Fig-

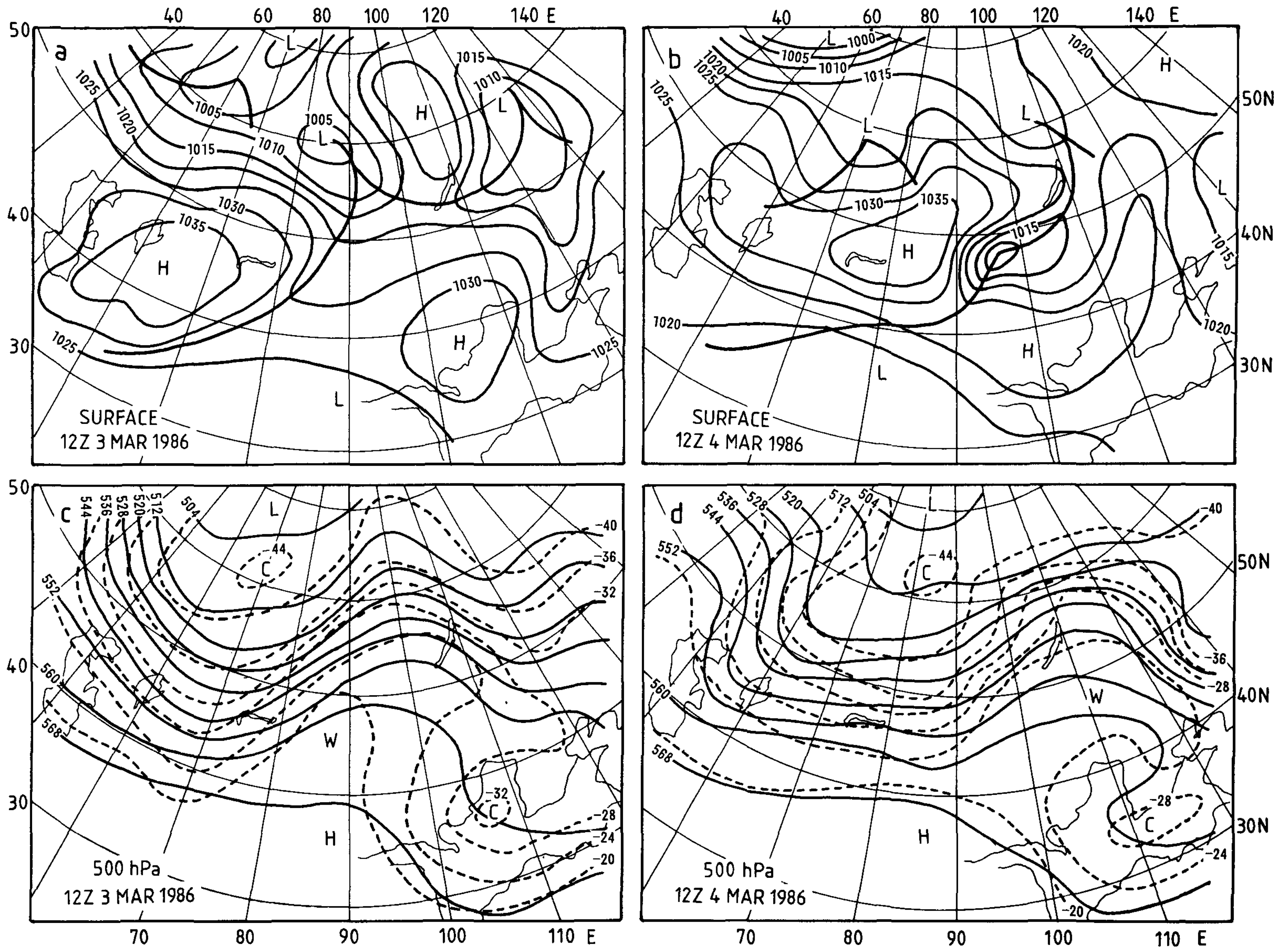


FIG. 3. A case of Altai–Sayan lee cyclogenesis. The surface analysis for (a) 1200 UTC 3 March 1986 and (b) 1200 UTC 4 March 1986. Heavy solid lines indicate the surface fronts, isobars (thin lines) in every 5 mb. The 500-mb height contours (solid lines, in every 40 gpm) and isotherms (dashed lines, in every 4°C) for (c) 1200 UTC 3 March 1986 and (d) 1200 UTC 4 March 1986.

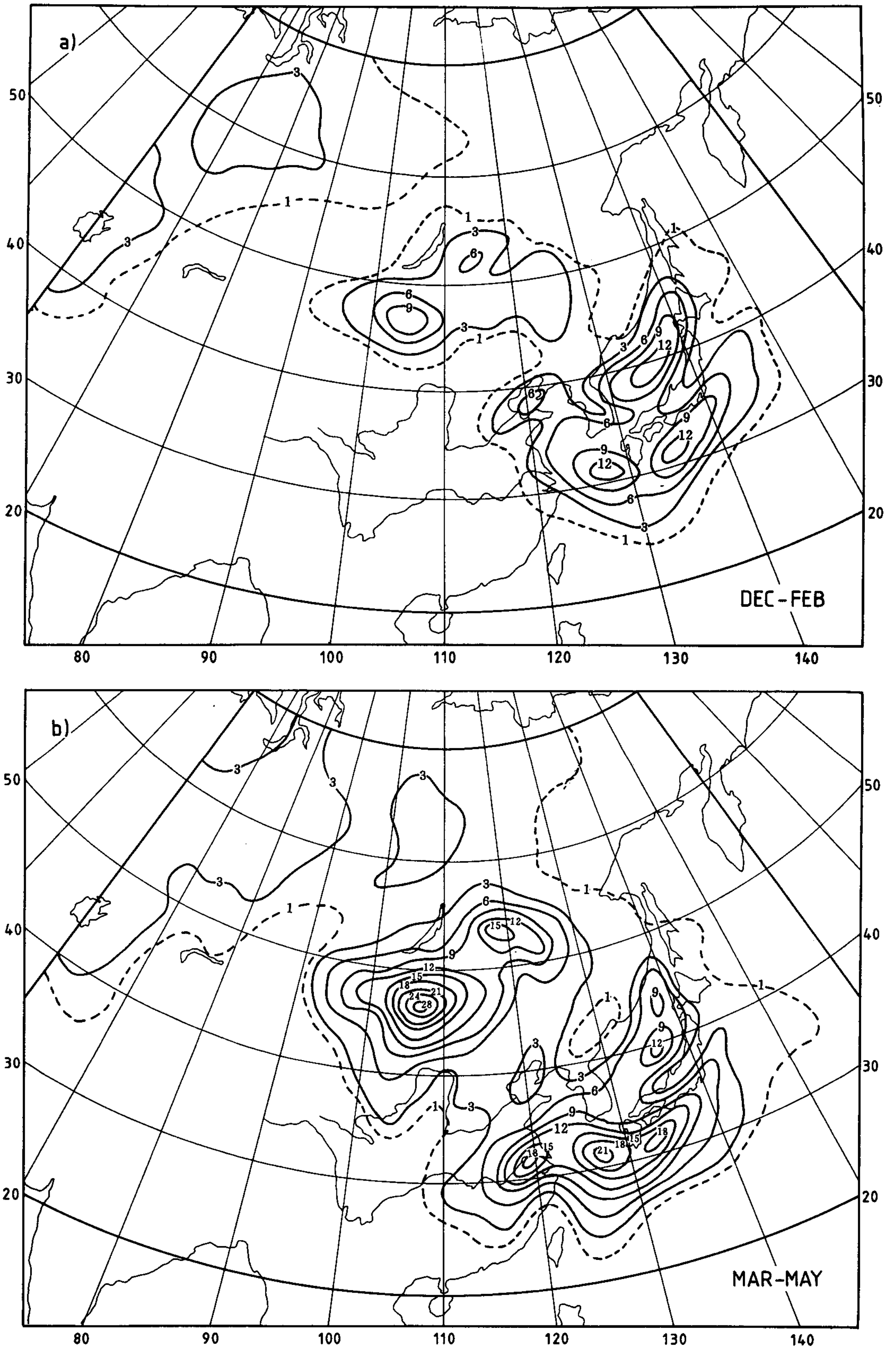
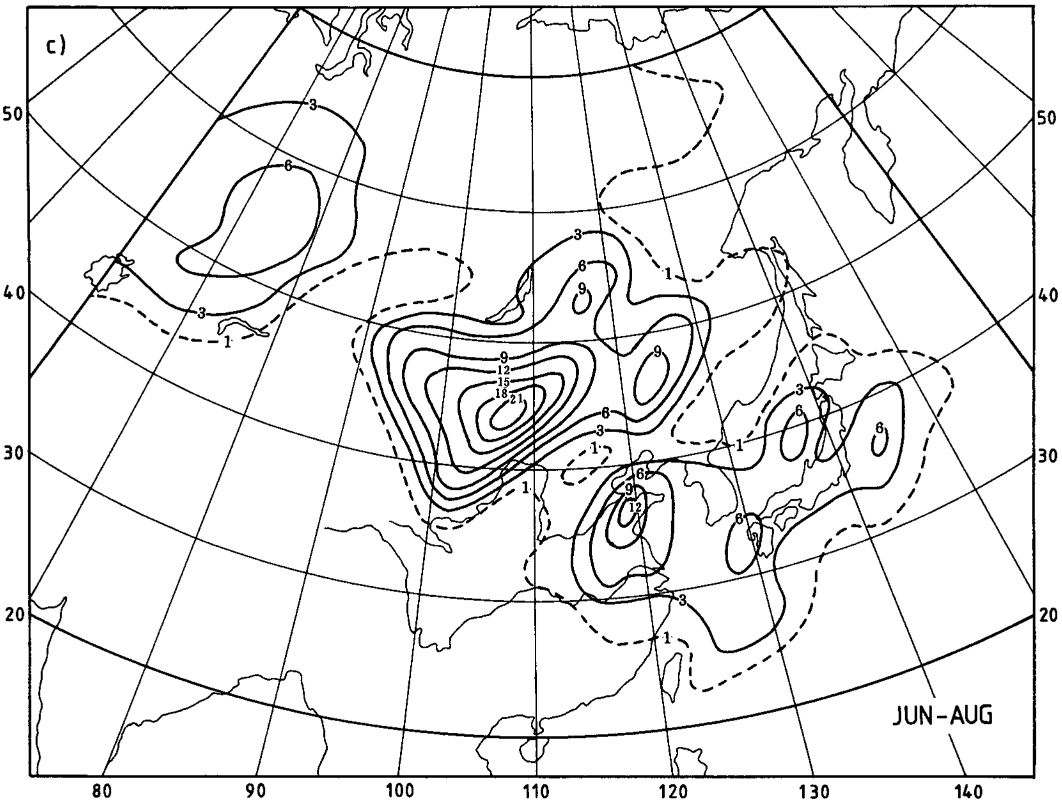


FIG. 4. Number of cyclogenetic events (10^{-2}) per 2.5° quadrangle per month for (a) winter, (b) spring, (c) summer, and (d) autumn for the period 1958–87.



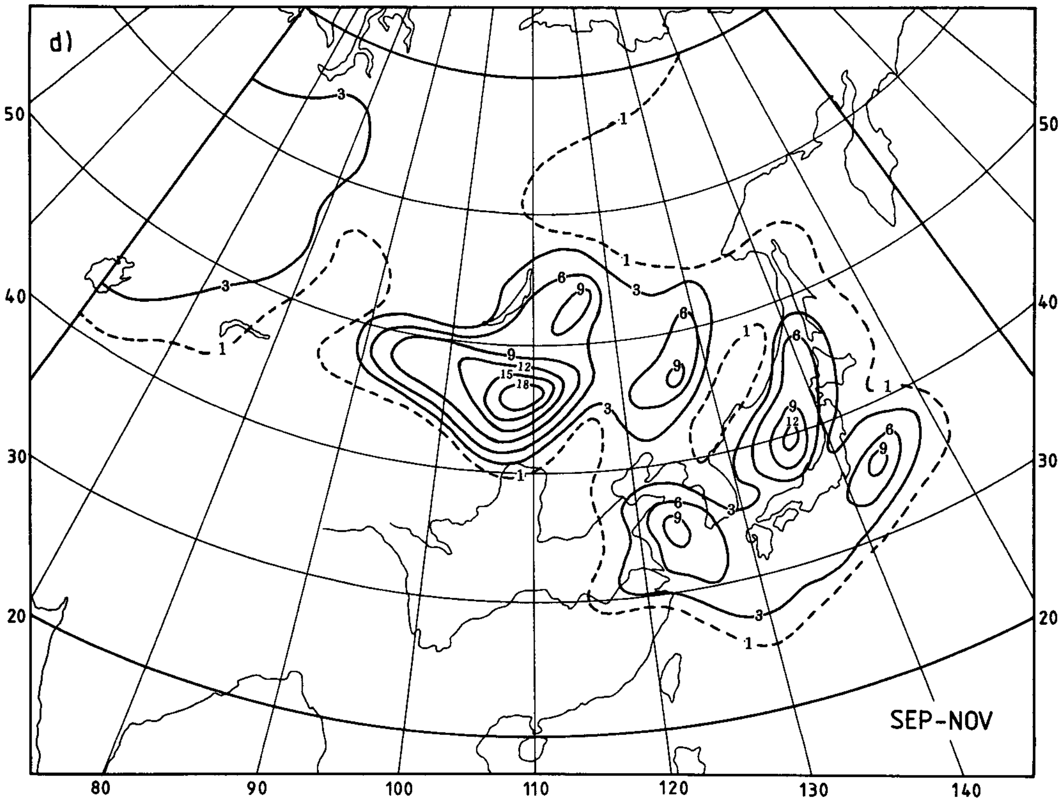


FIG. 4. (*Continued*)

ure 5 shows the cyclone frequency for the four seasons. In the winter (Fig. 5a), four preferred cyclone tracks can be identified. Two tracks began in the East China Sea and the Yellow Sea which were coincident with the cyclogenesis areas (Fig. 4a) off the east Asia coast. These two tracks continued northeastward to the north Pacific and were parallel to each other. Another track began in the lee of Altai–Sayan Mountains, it continued southeastward and merged with the track from the Yellow Sea. The fourth track entered the northwestern boundary of our study area along 57°N, originating from Ural Mountains. It extended eastward and terminated in north Siberia. Most cyclones moving along this track acted as the parent cyclones of Altai–Sayan lee cyclones as aforementioned.

Cyclones were most active over the Mongolian Plateau, Sea of Japan, south of Japan and western Siberia plain in spring (Fig. 5b). The tracks were quite similar to those in winter except that over the Mongolian Plateau. Two cyclone tracks originating to the east of Lake Baikal and the lee of Altai–Sayan Mountains, respectively, merged near 50°N, 125°E and then extended eastward into the Pacific.

Three tracks appeared on the summer frequency map (Fig. 5c). The two tracks that dominated over the east Asia coast in winter and spring disappeared. Instead, a strip of maximum frequency extended eastward from the Yellow Sea to the Pacific. This coincided with the variation of the cyclogenesis frequency from spring to summer (Figs. 4b,c). Little change can be found for the two tracks originated in Mongolian Plateau and west Siberia. In autumn (Fig. 5d), the two tracks off the east Asia coast reappeared; however, the frequency was lower than that in spring.

4. Latitudinal and seasonal distribution

We define the latitudinal frequency of cyclogenesis as the frequency in each quadrangle summed along latitude belts in the study area shown in Fig. 1. Figure 6 depicts the latitudinal frequency for the period 1958–87. A major peak was located between 42.5° and 52.5°N with a maximum value of 1.94 per 2.5° latitude per month in the 45°–47.5°N zone. This peak is associated with Altai–Sayan cyclogenesis. Two other minor peaks with half the frequency of the major peak were found at 30°–32.5°N and 37.5°–40°N, coincident with the east China Sea and the Sea of Japan cyclogenesis. Compared with the North American sector, where only one major peak at 35°–40°N was observed (Whittaker and Horn 1981), the most frequent cyclogenetic zone in east Asia was located farther north. Also, the cyclogenetic zone near 30°N was absent in the North America sector.

Figure 7 shows the latitudinal and monthly distribution of cyclogenesis over east Asia. Heavy solid lines are drawn through the zone of maximum activity. The major cyclogenetic zone at 45°–47.5°N persisted in all seasons, with maximum frequency from April to May and from August to September. Its location was very steady. This zone was mainly provided by the Altai–Sayan cyclogenesis. The southern zone at 30°–32.5°N, associated with coastal cyclogenesis, existed in the cold seasons and disappeared between July and October.

The monthly variation of cyclogenetic events over east Asia is depicted in Fig. 8. The winter months showed the lowest frequencies, with a minimum in January, while spring and early summer months had the greatest frequencies, with a maximum in May. The increase in frequency from January to May reached 204% (i.e., the cyclogenetic events were doubled in spring compared with winter). In the North American sector, the minimum frequency occurred in September and the maximum in March. The frequency increased only by 23% from September to March (Whittaker and Horn 1981). This shows the considerably larger seasonal variation in cyclogenesis frequency over east Asia as compared with that over North America. The monthly variations of frequency in the areas north and south of 40°N indicate that the seasonal variation over east Asia was largely controlled by cyclogenesis north of 40°N (associated with the Altai–Sayan cyclogenesis).

5. Interannual variations

Reitan (1979) has noted a downward trend in the frequency of North American cyclonic events during the period 1949–76. The decrease of the total number of cyclones–anticyclones in January and July and the decline of cyclogenesis frequency over North America from 1950 to 1970 has also been documented by Zishka and Smith (1980) and Whittaker and Horn (1981), respectively.

Figure 9 shows the annual number of cyclogenetic events in east Asia for the period 1958–87. The 30-yr mean for these cyclogenetic events is 190.2 per year, and the standard deviation is 21.4 per year. The decline of the number of cyclogenetic events from 1958–77 is evident. After 1977, no decline can be found. A least-squares regression line in the form of $y = b + mx$ is fitted to the data of 1958–77 (y is the number of cases of cyclogenesis, x = year − 1957, m is the rate). The regression equation together with the correlation coefficient (r) are given in the figure. The decline was significant at the 0.5% level. We found $m = -1.75$ and $r = -0.45$ for the east Asia cyclogenesis trend, while the values for North America during the same period are $m = -8.6$ and $r = -0.73$, respectively (Whittaker and Horn 1981). The correlation coefficient for the linear representation of the cyclogenesis trend in east Asia was smaller than that in North America. The decline rate in east Asia was only one-fifth of that in North America, indicating that the decline in cyclogenesis in east Asia was not as pronounced as that in North America.

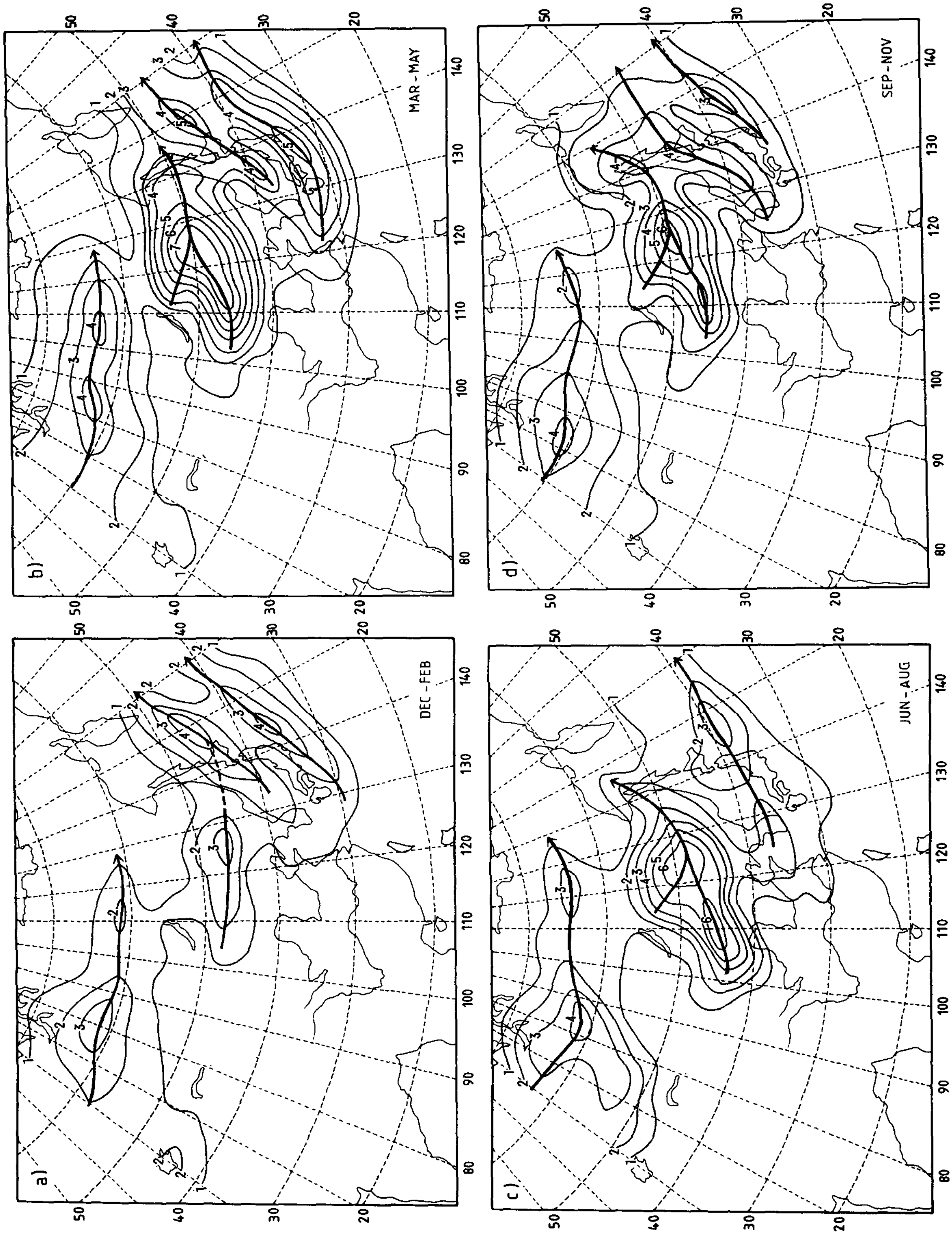


FIG. 5. The distribution of cyclone events (10^{-1}) per 2.5° quadrangle per month for (a) winter, (b) spring, (c) summer, (d) autumn for the period 1958–87.

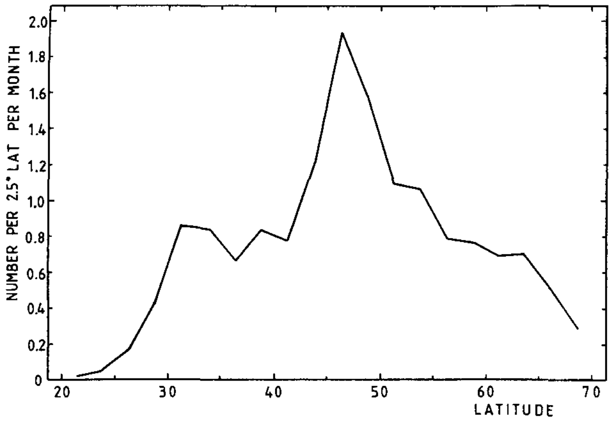


FIG. 6. Latitudinal distribution of cyclogenetic events per 2.5° latitude per month in east Asia during the period of 1958–87.

There are no satisfactory explanations for the declines either in North America or in east Asia. Such decreases must be related to changes in the general circulation. Recently, Yi and Wang (personal communication, 1990) found a cooling trend in the midtropospheric temperature over east Asia from late 1950 to late 1970, which may be related to the decline of cyclogenesis. However, a considerable amount of work is needed before this hypothesis can be verified.

6. Summary and discussion

The key features in the synoptic climatology of cyclogenesis over east Asia can be summarized as follows:

1) Cyclogenetic events were concentrated in two areas: on the lee side of major mountain ranges (i.e., Altai-Sayan, Stanovoi, and Great Xinganling), and off the east Asia coast. The former was related to lee cyclogenesis and the latter to coastal cyclogenesis. Among these areas, the Altai-Sayan lee side was the most active cyclogenetic area in east Asia. The Sichuan Basin, located on the lee side of the Tibetan Plateau, was not a favorable region for baroclinic cyclogenesis, even though it was a favored location for summertime lower-tropospheric mesoscale vortices. The cyclogenesis of the east Asia coast can be separated into two groups: one over the East China Sea (include south of Japan) and the other over the Sea of Japan. The former was associated with the warm Kuroshio current.

2) After zonal average, a belt of very pronounced cyclogenesis in all seasons was located at 45°–50°N, which was related to the Altai-Sayan lee cyclogenesis. Another active zone at 30°–35°N, related to the coastal cyclogenesis, was presented in the cold seasons and absent from July to October. Averaged over the east Asia sector, cyclogenesis frequency reached a maximum in May and a minimum in January. The seasonal variation of cyclogenesis frequency was considerably

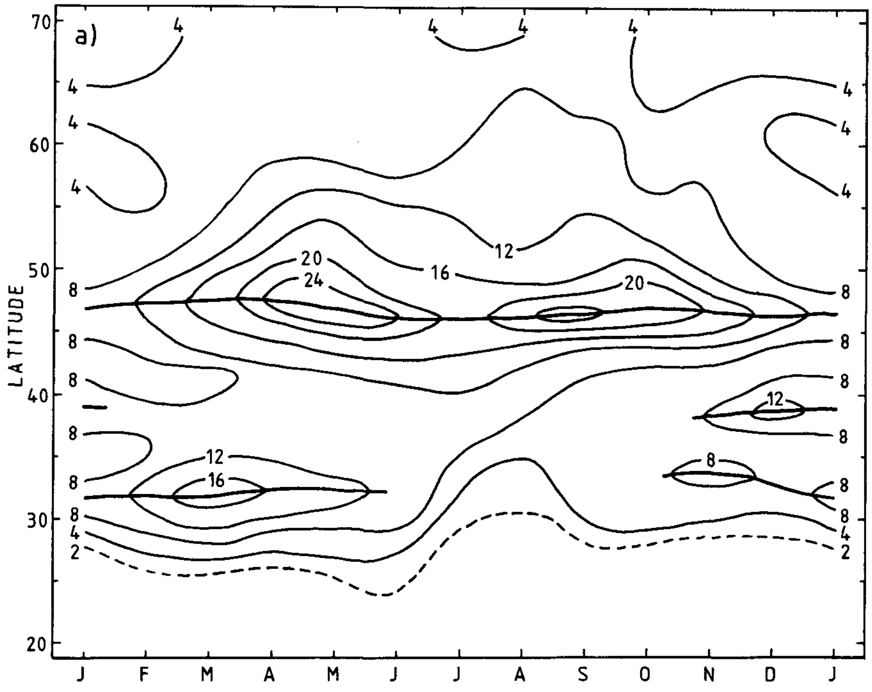


FIG. 7. Latitudinal and monthly distribution of cyclogenetic events (10^{-1}) per 2.5° latitude per month for 1958–87.

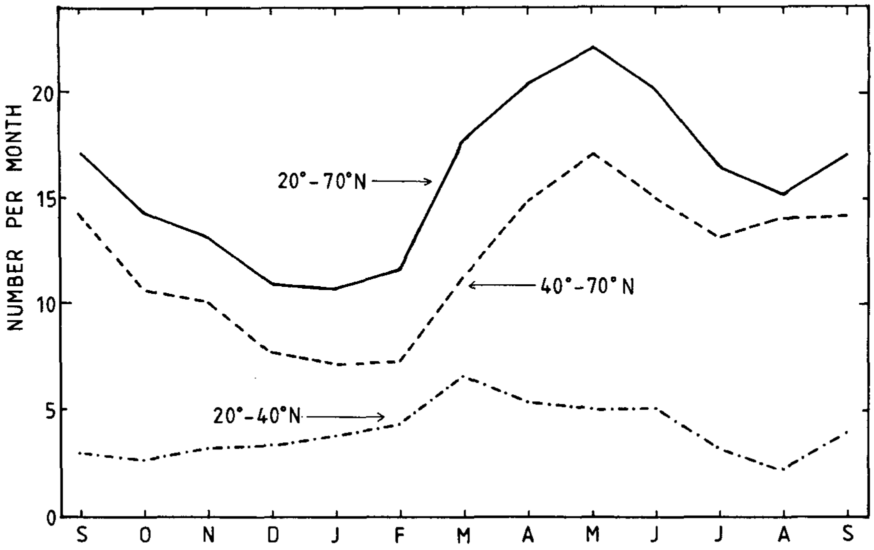


FIG. 8. Monthly variations in cyclogenetic events in east Asia for the period 1958–87. Solid line presents total events; dashed line, events north of 40°N; and dash-dotted line, events south of 40°N.

larger over east Asia than over North America. The increase in cyclogenesis frequency from January to May reached 204% over east Asia, while that over North America was only 23% from September (minimum) to March (maximum).

3) There was a decline in cyclogenetic events over east Asia from 1958 to 1977, which was coincident with the decrease of cyclogenetic events in North America during the same time period. After 1977, no such decline was found.

A somewhat surprising result from our study is the lack of cyclogenesis in the lee of the Tibetan Plateau. Chung et al. (1976) found a local maximum in cyclogenesis frequency over the Sichuan Basin (east of the Tibetan Plateau) which was absent in our results. We noted that this local maximum was not supported by the statistical studies of either Wu and Liu (1958) or Zhu et al. (1981). During the warm season, weak cyclonic circulations (not associated with low-pressure centers) usually occur over the Sichuan Basin in the lower troposphere. Most of the time, they do not develop into baroclinic cyclones. Occasionally, when a short-wave trough over the Tibetan Plateau (near 500 mb) moves out of the plateau, a vortex at 850 and 700 mb can be seen over the basin, producing heavy precipitation (Tao 1979). This type of vortex is called the southwest (SW) vortex in China. A detailed case study for a SW vortex was provided by Kuo et al. (1986; 1988). The SW vortex is a lower tropospheric circulation often attaining its maximum intensity at 700 mb. Normally, no closed isobars are found at the surface. Also the vortex does not possess frontal structures that are associated with baroclinic cyclones. The SW vortex formed as a special kind of lee cyclogenesis, distinctly different from the Altai–Sayan lee cyclogenesis and Alpine lee cyclogenesis. Only when the vortex moves eastward to the middle or lower Yangzi River valley and interacts with an existing baroclinic zone will a surface frontal cyclone be generated. During the cold season, the Tibetan Plateau, a large land mass with an elevation of 5 km, splits the upper-level westerlies into two branches. The transient baroclinic waves do not traverse this high land but rather by-pass to the north and south of the Plateau. The Sichuan Basin is located within a calm wind wake zone with stable

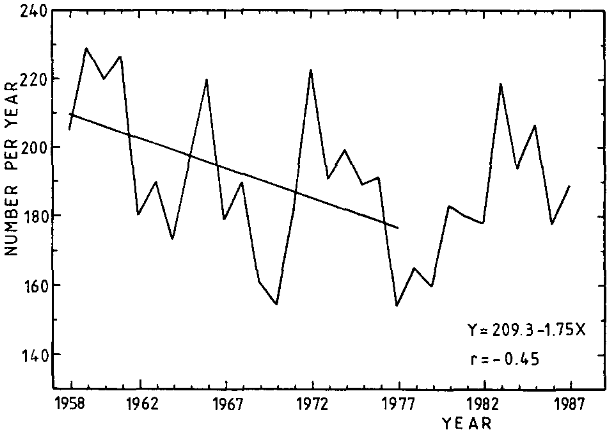


FIG. 9. Yearly variation and corresponding linear regression line for the number of cyclogenetic events in east Asia for the period 1958–87.

stratification (Yeh and Gao 1979). This might explain the lack of cyclogenesis in the lee of the Tibetan Plateau.

Another interesting finding in this paper is the infrequency of cyclogenesis over east Asia in winter. The exact reason for the lack of cyclogenesis is unknown. We speculate that there are two main reasons. First, during the winter, the midlatitude stationary trough was located at the east coast of Asia (Wallace 1983). On the other hand, the lower-latitude subtropical jet formed a stationary ridge along 140°E. The large-scale stationary waves in the middle and lower latitude were opposite in phase (Krishnamurti 1961; Wallace 1983). The confluence of quasi-stationary upper-level polar and subtropical jet streams resulted in a large-scale midtropospheric sinking motion, unfavorable for cyclone formation and development (Boyle and Chen 1987). Second, during the winter the continent is quite cold due to radiation cooling. This results in high static stratification and sets up for a semipermanent monsoonal, cold anticyclone. The high static stability is also unfavorable for cyclone formation and development.

Obviously, for an individual cyclogenesis event, the cyclone is driven mainly by a transient baroclinic wave and its interaction with a low-level baroclinic zone (Petterssen 1956). Although the frequency is lower, the Altai–Sayan lee cyclogenesis still occurs during the winter. This indicates that transient baroclinic waves in the polar jet did produce lee cyclogenesis when they interacted with low-level orographically deformed fronts (Chen and Lazic 1990). However, possibly due to both the high static stability and the lack of moisture, those cyclones hardly achieved a great intensity (Boyle and Chen 1987).

Despite the lack of continental cyclogenesis during the winter, the coastal cyclogenesis was abundant over east Asia. Apparently, the transient baroclinic disturbances on the subtropical jet were quite active in the cold season. The interaction between these transient baroclinic waves and surface baroclinicity associated with sea surface temperature gradient across the east China Sea resulted in frequent cyclogenesis over this area (Hanson and Long 1985).

In summary, our statistical results appear to support Danielson's (1973) view that "the baroclinic instability determines when, and the mountains (or the land and sea contrast) determine where, the cyclone will form."

Acknowledgments. The authors are indebted to Professor Frederick Sanders, Mr. Stanley Trier, and two anonymous reviewers for their constructive comments that led to a significant improvement in this paper.

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