Climatology of Surface Cyclogenesis and Cyclone Track in East Asia

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Abstract

In this study, frequencies of surface cyclogenesis and cyclone track in East Asia were investigated using high-resolution and long-term reanalysis data of ERA40 in the reduced Gaussian grid system. The use of the high-resolution data enables to detect a smaller scale cyclone and to identify the detailed distribution of cyclogenesis. A cyclone center was defined in the surface pressure anomaly using a modified method after Serreze (1995), suitable for high elevation area.

Surface cyclogenesis frequently occurs in several specific areas in all seasons. The frequent areas are mostly narrower than those shown in previous studies, although the analyzed cyclone in this study includes a meso-α scale cyclone. The areas of high-frequency cyclogenesis are distributed in the lee of mountains, basins, the Pacific Ocean to the east of Japan, the Sea of Japan, the Kuroshio Current region to the south of Japan, and the East China Sea. In particular, the followings were revealed as the new findings from previous reports; the inactive cyclogenesis in the lee of Tahsinganling in summer; the frequent cyclogenesis in the Hebei Plain except for summer; and the cyclogenesis maxima around the mouth of the Yangtze River and in the East China Sea to the northeast of Taiwan in winter.

The seasonal variation of cyclogenesis differs among each cyclogenesis maximum. The activity of cyclogenesis peaks during spring and autumn in the Mongolian Plateau and the Sichuan Basin, while that is during spring in the Hebei Plain and the mouth of the Yangtze River, and during winter in the East China Sea to the northeast of Taiwan.

The cyclones generated in East Asia are classified into two major types depending on their lifetime and synoptic situation at the time of cyclogenesis. One is the cyclone originated in the northern region; the Mongolian Plateau and the Hebei Plain. The cyclone arises when a synoptic trough approaches the windward mountain, namely, it has a property of lee cyclone. The lifetime of the cyclone depends on the intensity of synoptic trough. Deeper trough with large positive vorticity enables the cyclone to have longer
lifetime. While the other is the cyclone originated in the southern region; the mouth of
the Yangtze River, and the East China Sea to the east of China and to the northeast
of Taiwan. That is meso-α cyclone caused by cumulus convection, with a relatively
long lifetime compared to the cyclone in the northern region. It is suggested that this
characteristic of lifetime is related to the fact that the southern cyclone can persist for
several days by the mechanisms of development and maintenance of a meso-α cyclone,
which differs from those of baroclinic instability.

The present study shows climatology of surface cyclones including meso-α scale cy-
clones in East Asia by the statistical analysis using the high-resolution data and the
optimal detection method. The knowledge gained from this study is expected not only to
update the past understanding, but also to improve the cyclone prediction and to assist
the understanding of phenomena linked to the cyclone.

**keywords:** surface cyclone, cyclogenesis, cyclone track, objective analysis,

East Asia, climatology
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Chapter I

INTRODUCTION

1.1 General background

East Asia is located at the eastern edge of the Eurasian continent, and its east side opens to the Pacific coast (Fig. 1.1). The area extends from 20°N to 55°N, under the migration pathway of midlatitude cyclones. Past studies reported that the East Asia is not only a passing area of cyclone, but also its formation area (Petterssen 1950; Whittaker and Horn 1984).

In spring and autumn, weather is affected by migration of low and high pressure systems in this region. Precipitation near the front associated with a cyclone provides water resource, important for organisms. However, the amount of rainfall varies greatly throughout the passing area of cyclones. Particularly in winter and early spring, the cyclone has few clouds as well as little rain in interior terrain because of the dry atmospheric condition. The dry cyclone is one of the characteristics of the cyclone in East Asia. On the other hand, a relatively large amount of rain falls over the coastal and ocean regions through the year.

The landuse of East Asia contains many categories in response to complex topography. There are arid regions in the north side of the Tibetan Plateau and the wet region in the east side (Fig. 1.2). Although the amount of rainfall and its seasonal variation differ among the local areas, summer precipitation accounts for 60 % of annual precipitation in the arid region such as the Gobi and Taklamakan Deserts (Fig. 1.3). Previous studies reported that the summer rain, which is valuable as water for the arid region, is related to the midlatitude troughs (Yatagai and Yasunari 1995; Itano 1998).
In the Gobi and the Taklamakan Deserts, dust storm sometimes occurs in spring, instead of rain events. If strong wind blows in a cold sector associated with synoptic disturbance, a lot of dust particles are efficiently raised into the air, because the amount of dust generation generally depends on wind velocity. Airborne dust is then transported to downwind regions following migration of the cyclone and affects on local communities of surrounding regions by damaging crops, blocking traffic, and respiratory distress.

In addition, low and high pressure systems are well known as an effective transport process of dust and air pollution emitted from metropolitan area in the coastal region to the remote area such as Hawaii and North America (Duce et al. 1980; Parrington et al. 1983; Husar et al. 2001; Uno et al. 2001). This fact attracts an attention from the point of not only atmospheric transport, but also climate effect to earth radiation balance (IPCC 2007).

The cyclogenesis over the ocean intensifies its activity in winter, although it is inactive over the land. The cyclone generated in the East China Sea and passing through the southern coast of Japan often brings large amount of snowfall to Japan and sometimes causes a traffic trouble in the large cities along the coastal region.

As mentioned above, the midlatitude cyclone in East Asia has a large impact to the passing areas. Therefore, understanding of the genesis and track of them is one of major issues closely connected with human lives. The knowledge is also expected to contribute the improvement of forecast accuracy of cyclone, because the model accuracy in the formation of new cyclones often determines the reliability of the numerical prediction, particularly in the leeward region of the cyclogenesis. However, the investigation of cyclone for East Asia is few compared to North America and Europe, especially the generation mechanism from climatological point of view. It is best time to survey these matters, because we can easily obtain the long-term reanalysis data, usable to the climatological study.
1.2 Previous study on the cyclogenesis and the cyclone track in East Asia

Cyclone activity in East Asia was examined by Chung et al. (1976) (hereafter Chung76) from statistical viewpoint. They analyzed the frequency of cyclogenesis in Northeast Asia with surface weather maps obtained between 1958 and 1959. They indicated that areas of high-frequency cyclogenesis are distributed in the lee of the major mountains, while the most active area is located in the Mongolian Plateau (Fig. 1.4). Chen et al. (1991) (hereafter Chen91) investigated the seasonal changes of cyclogenesis and cyclone tracks observed in Northeast Asia and the surrounding ocean from 1958 to 1987. They reported that the lee cyclogenesis is active during spring and autumn, while the activity of the oceanic cyclone is at its maximum in winter (Fig. 1.5). This result corresponds to that described by Whittaker and Horn (1984).

The distribution of cyclogenesis over land shown by Chen91 roughly agrees with that obtained by Chung76 but sprawls more widely (Figs. 1.4 and 1.6). Although the reason for the discrepancy is not clear, it is inferred to relate to the different length of the analyzed period or the difference in the definitions of the surface cyclone between Chung76 and Chen91. The cyclones analyzed in Chen91 include larger cyclone than those of Chung76.

Several previous studies examined oceanic cyclones in East Asia. Yu (1980) focused on Taiwan low, which formed over the sea to the east and northeast of Taiwan in winter season. The study suggested that the warm Kuroshio current is important for the development of the Taiwan low, because the maximum axis of its tracks coincides with the Kuroshio current. Hanson and Long (1985) and Chen and Lu (1997) also pointed out the relationships between the gradient of sea surface temperature (SST) and the formation of cyclone in the East China Sea, although the climatological distribution of cyclogenesis in this region differs among previous studies.

Recently, many studies have reported the cyclone activity from automatic analysis method using objectively analyzed data (e.g., Murray and Simmonds 1991; Sinclair 1997;
Gulev et al. 2001), although above reports were based on subjective analyses. Ueno (1991a) objectively defined an extratropical cyclone center by a concave grid on the 1000 hPa geopotential height produced by U. S. National Meteorological Center (NMC) to investigate the cyclone activity in the Northern Hemisphere. Pinto et al. (2005) defined a cyclone as a pressure minimum in the vicinity of the local maxima of quasi-geostrophic relative vorticity, calculated from the laplacian of sea level pressure. There are many ways used for the automatic detection of surface cyclone in previous studies. However, most of them have only shown two major maxima of cyclogenesis in East Asia. One is located at the Mongolian Plateau, and the other is located at the east of Japan. These results have not demonstrated any high frequency area corresponding to the small-scale mountains that are shown in Chung76. The major factor of the difference could be attributed to the inadequacy of the cyclone detection method.

Most methods for detecting surface cyclones have been based upon Sea Level Pressure (SLP) of the objectively analyzed data in past studies. However, SLP is likely to contain a considerably large bias caused by the extrapolation of pressure to the sea level, particularly in the mountainous area. Ueno (1991b) also pointed out this bias as a cause of the discrepancy between the cyclones objectively analyzed using gridded data and those subjectively analyzed in weather maps. In addition to SLP, pressure level data is also unsuitable for the cyclone analysis in the region with rough terrain. Therefore, Sickmoller et al. (2000) and Wang et al. (2006) have excluded the elevated areas higher than 1000 m from their results. Since the plateau and mountains are broadly distributed in East Asia, surface cyclones should be analyzed by a method that is not strongly affected by difference in altitude.

1.3 Purpose of this study

As mentioned above, the study of the surface cyclone activity in East Asia has been reported. However, most of them were based on the subjective analysis with weather
maps, while the study by objective analysis includes some problems in this region. In addition, most studies for a formation mechanism of cyclone were exclusively case studies, not for the climatological study.

The purposes of this study are: (1) to objectively redefine the detailed distribution of cyclogenesis and cyclone track in East Asia using high-resolution data and an optimal method, (2) to reveal the generation mechanism of cyclone from climatological point of view, and (3) to classify the surface cyclone in East Asia according to its climatological features.
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Chapter II

DATA AND METHODOLOGY

2.1 Data

2.1.1 ERA40

This study used the 6-hourly surface pressure of the European Centre for Medium-range Weather Forecasts (ECMWF) 40-year reanalysis data (ERA40) in a reduced gaussian grid system from October 1966 to August 2002 to analyze a surface cyclone. ERA40 is one of the reanalysis data suitable for a climatological investigation during long periods in East Asia (Inoue and Matsumoto 2004). The reduced gaussian grid points are drawn in Fig. 2.1, of which number of horizontal grid per circle of latitude decreases as one approaches the poles. The data has a high spatial resolution of approximately 125 km, that allows to identify a location of cyclogenesis.

ERA40 with regular interval of $2.5^\circ \times 2.5^\circ$ was used to obtain the synoptic meteorological feature at the time when surface cyclogenesis was analyzed. The used elements are geopotential height, temperature, zonal wind, meridional wind, and vorticity of pressure levels at 850, 700, and 500 hPa.

2.1.2 NCEP/NCAR reanalysis

The NCEP/NCAR reanalysis data (hereafter, NCEPI) is produced in a joint project between the National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) and calculated with a fixed version of a data assimilation and operational forecast model during the project.

Six-hourly data of NCEPI was used for the initial and boundary data of a regional
atmospheric modeling system (RAMS). Because the RAMS, used in this study, has been adjusted with NCEPI as input data. The horizontal resolution of NCEPI is a regular interval of $2.5^\circ \times 2.5^\circ$. Geopotential height, zonal wind, meridional wind, temperature, and relative humidity at the pressure level are used in Chap. IV.

### 2.1.3 NCEP/DOE reanalysis II

In addition to ERA40 at the reduced gaussian grid points, this study used the 6-hourly NCEP/DOE reanalysis II data (hereafter, NCEPII) in order to analyze a surface cyclone and to discuss the difference of results driven from difference of analyzed data source. NCEPII is based on the NCEPI and aims to improve the NCEPI by fixing the errors and by updating the parameterizations of the physical processes of the model. The horizontal resolution of NCEPII is $2.5^\circ \times 2.5^\circ$. We used the 6-hourly surface pressure from 1979 to 2006 to define a surface cyclone.

### 2.1.4 Best track data

This study used the analysis information of tropical cyclone in best track data to determine whether an analyzed cyclone by the detection method is a tropical cyclone. The best track data is provided by the Regional Specialized Meteorological Center (RSMC) Tokyo-Typhoon center, which is operated by Japan Meteorological Agency (JMA) and includes the analysis and the forecasts of tropical cyclone information from 1951 to present. The contents of the data involve the center position of a tropical cyclone, accuracy of determination of cyclone center, direction and speed of movement, central pressure, maximum sustained wind speed, maximum wind gust speed, and radii of over 50 and 30 knots wind areas, while this study used the analysis of center position of tropical cyclone.

### 2.2 Detection method of a cyclone system

This study uses the surface pressure to define a surface cyclone, since SLP contains large bias by the reduction of pressure to sea level in high elevation area, as described in
Chap. I. However, it is difficult to detect a cyclone in raw surface pressure data because the data strongly depends on the topography. In order to remove the pressure difference caused by the surface elevation, the pressure anomaly is estimated by subtracting the 6-hourly climatology of the surface pressure, which is obtained from 36 years data after taking a 31-day running average of the original 6-hourly data. A surface cyclone is then searched in the anomaly data of surface pressure. These procedures are newly adopted for the analysis in East Asia and the original point in this method.

The anomaly data at the model grid points are projected to the Cartesian grid system with a uniform interval of 125 km by use of the linear interpolation assuming an approximation of the polar stereo projection method. This interpolation was applied to ERA40. The detection method for the surface cyclone is divided into two steps. The first step is to identify the cyclone center in the anomaly data, while the second step is to connect the positions of the same cyclones through the analyzed periods. The detection method is modified from the algorithm developed by Serreze (1995).

In the first step, the pressure differences are calculated between the target grid point and one of the outermost grid points (8, 16, and 24 grid points) of the three lattices (3×3, 5×5, and 7×7 grid points, respectively) centered at the target grid point. If the surface pressure anomaly at the target grid is at least 0.8 hPa for ERA40 (1.5 hPa for NCEPII) lower than that of all outermost grid points for at least one of three lattices, the target grid point is identified as a candidate of the cyclone center. When the candidates of cyclone center separately exist after all grid points are inspected, the candidate is defined as the cyclone center. When several cyclone candidates are located on the adjacent grid points, the cyclone center is defined to be at the mean coordinate of these grid points.

In order to estimate the bias by use of anomaly data instead of raw surface pressure, the candidates of cyclone center obtained both from the raw surface pressure and the anomaly data were compared over the ocean (Fig. 2.2). Although the number of candidates detected in the anomaly data is about 10% larger than that in the surface pressure, the
distribution of candidates shows similar characteristics between the two data.

In the second step, a link of the surface cyclone centers is determined by the nearest-neighbor method using 6-hourly sequential data of the cyclone center obtained by the former procedure. The nearest-neighbor method searches cyclone centers in a rectangle whose eastern boundary is 800 km and whose three other boundaries are 600 km (800 km for NCEPII) away from a cyclone center in the previous stage (before 6 hours). Then, the nearest cyclone from the cyclone center in the previous stage is identified as the same cyclone. The cyclones that did not meet these conditions were determined to be those that decayed (cycloysis) in the previous stage or newly developed (cyclogenesis) in the current stage.

During the entire analysis period, all cyclone centers were traced from cyclogenesis to cycloysis using the process described above. Cyclones with the lifetime shorter than 24 hours were excluded from further analysis. Typhoons and extratropical cyclones that had been transformed from tropical cyclones were also eliminated by reference to the Best track data of the Regional Specialized Meteorological Center.

2.3 Verification of the method

2.3.1 Comparison with weather maps

In this section, the objectively analyzed cyclones with the method mentioned above are compared with those on the weather map in a case at 18 UTC 20 March 2002. Five cyclones are illustrated on the weather map of JMA around Japan on the day; (1) at the north part of China, (2) at the east to the Korean Peninsula, (3) at the Pacific Ocean to the east of Japan, (4) at the east to Sakhalin, and (5) at the east to Kamchatka Peninsula (Fig. 2.3a). The three cyclones of them, located in the areas of (1), (3), and (5), are drawn by the closed contours, and thus they are a developed cyclone which has the large gradient of surface pressure near the cyclone center. While the cyclones located in the areas of (2) and (4) are denoted as the low-pressure area, and thus a weak cyclone without
any closed contour lines.

The analyzed cyclones in NCEPII using the new method are indicated in Fig. 2.3b. The cyclone centers (red stars) are located only in the areas of (1), (3), and (5). While the cyclones analyzed in ERA40 are picked up also in the areas of (2) and (4) as well as (1), (3), and (5) (Fig. 2.3c). This result shows that the new detection method enables to detect not only the developed cyclone, but also the weak cyclone if the high spatial resolution data like ERA40 is used. The method tends to detect the relatively strong cyclone in the analysis using the lower resolution data such as NCEPII.

2.3.2 Comparison with previous studies

This section conducts the validation for the detection method of surface cyclone used in this paper. First, the distribution of detected cyclone in NCEPII is compared with that shown in Sinclair (1997) for the North Pacific, where the orographic effect is negligible and we can estimate the difference of the results caused by the difference of the method. The applicability of the method is evaluated for East Asia with rough terrain by the comparison of the result from ERA40 with that of previous studies.

Pacific Ocean

Figure 2.4 indicates the distributions of cyclone track and cyclone event during winter, analyzed in Sinclair (1997). The track density is defined as the number of surface cyclone tracks passing through a grid point during a specific period. Thus, a surface cyclone is counted only once for a certain grid point. While the cyclone event is the number of all cyclone centers, including the points of cyclogenesis and cyclolysis, analyzed within a grid point during a specific period. That is, a cyclone is counted repeatedly for the grid point throughout the staying of the cyclone. The contour lines in Fig. 2.4 show the frequency of those per 5° grid per month averaged for October – March from 1980 to 1986.

The cyclone track density (Fig. 2.4a) is enlarged from 30°N to 60°N, while the center of the track density is distributed from 35°N in the western Pacific to northeastward, around
45°N – 55°N in the eastern Pacific. The cyclone event is also enlarged between 30°N and 60°N same as the track density (Fig. 2.4b). However, it has some localized maxima in the Gulf of Alaska and near Kamchatka Peninsula. Sinclair (1997) commented that the slower-moving systems in the Gulf of Alaska give extra weight there and allow a surface cyclone to be counted more times. This can be applied to the reason for the high frequency near the Kamchatka Peninsula. These characteristics of the cyclone track and the cyclone event reported by Sinclair (1997) indicated the typical feature of the cyclone activity in the North Pacific during winter, because these characteristics are demonstrated in other previous studies (Whittaker and Horn 1984; Gyakum et al. 1989).

Figure 2.5 shows the distribution of frequency of cyclone track and cyclone event analyzed in NCEPII in this study. The contour value in Fig. 2.5 is normalized with an average per 5° grid per month for October – March as same as that of Fig. 2.4, except for the averaged year from 1980 to 2005. The frequency areas of cyclone track density are distributed around 35° N – 40° N in the east of Japan, and then shifts toward the north in east side of the North Pacific and reaches at the latitude of 50° N in the west of the North America. Particularly, the maximum density area is located in the east of Japan around 35° – 40° N, 145° – 170° E.

The distribution of cyclone event is active over the area of 30° – 60° N with several maxima. The high frequency areas are also located in the Sea of Japan, the east of Japan, the east of the Sakhalin, the south of the Aleutian Islands, in addition to the east of the Kamchatka Peninsula and the gulf of Alaska shown by Sinclair (1997). The results of this paper and Sinclair (1997) have some differences in the location of the maxima and the frequency of cyclone event. The values of cyclone track density and cyclone event in this paper are one quarter of those of Sinclair (1997). The difference seems to be derived from the difference of the definitions of surface cyclone between Sinclair (1997) and this study. However, the new detection method of this paper is concluded to enable to detect well the surface cyclone over the ocean, since the distributions of cyclone event and track
demonstrates similar characteristics with that of previous study except for several points mentioned above.

**East Asia**

To validate the detection method for East Asia with the mountain regions, the frequency of cyclogenesis was compared with those given by Chung76 (Fig. 1.4) and Chen91 (Fig. 1.6). Figure 2.6 shows the mean cyclogenesis frequency analyzed by ERA40 during the entire period of 36 years. The frequency of cyclogenesis is estimated as a number of cyclogenesis in a grid point during the entire period. The contours indicate the frequency of cyclogenesis per grid point per 30 days.

The distribution of cyclogenesis obtained in the present study tends to concentrate in several specific areas. These areas are narrower than those obtained in previous studies. The high-frequency regions of cyclogenesis are located in the lee of the Tahsiganling and the Altai-Hangayn-Sayan Mountains in addition to the Hexi Corridor, the Hebei Plain, the mouth of the Yangtze River, and the Sea of Japan. These features are common with the distribution shown by the previous studies, although the present analysis indicates multiple maxima of cyclogenesis in the Altai-Hangayn-Sayan Mountains and associated with some small-scale mountains, instead of the single large maximum shown by Chung76 and Chen91. On the other hand, the high frequency in the Sichuan Basin is indicated in this study and Chung76. In addition to that, the cyclogenesis maxima in the Dzungaria Basin and the Pacific Ocean to the east of Japan are identified only in the present study. The lee cyclone of the Wuyi Mountain shown by Chung76 and the coastal cyclogenesis in the west of Kyusyu and the south of Shikoku shown by Chen91 are not detected in the present analysis. Since the distribution of cyclogenesis almost agrees with those of the previous studies except for several maxima, the present detection method seems to successfully identify most cyclones illustrated in surface weather maps.
Fig. 2.1. Reduced N80 gaussian grid of ERA40 on (a) Northern Hemisphere and (b) Southern Hemisphere.
Fig. 2.2. Distributions of the centers of cyclone candidates analyzed by the detection method of this study in (a) raw surface pressure of ERA40 and (b) anomaly data of the surface pressure. The colors denote the number of candidates per grid point throughout the analyzed period.
Fig. 2.3. Distributions of the cyclone centers at 18 UTC 20 Mar 2002 in (a) JMA observational weather map, (b) NCEPII, and (c) ERA40 in the gaussian grid system. Surface pressure anomaly from climatology indicated by shading. Black stars and red stars denote the position of cyclone candidates and cyclone centers, respectively.
Fig. 2.4. Cyclone statistics of (a) Track density and (b) Cyclone event in the North Pacific for October – March during 1980 – 1986, shown in Sinclair (1997). The contour lines show the frequency of those per $5^\circ$ square per month.
Fig. 2.5. Frequency distribution of (a) cyclone tracks and (b) cyclone events over the North Pacific, analyzed in NCEPII. The contour lines show the frequency of those per 5° square per month averaged for October – March from 1980 to 2005.
Fig. 2.6. Distribution of annual frequency of cyclogenesis in East Asia from 1966 to 2002. The contour lines show the frequency per grid point per 30 days.
Chapter III

STATISTICAL ANALYSIS OF CYCLONE ACTIVITY IN EAST ASIA

3.1 Frequency of cyclogenesis and cyclone track

3.1.1 Seasonal variation of frequency of cyclogenesis

Seasonal variation of the frequency of cyclogenesis on ERA40 is illustrated in Fig. 3.1. Most cyclones are generated in several specific areas throughout the year, while the frequency of cyclogenesis in each maximum area clearly shows a seasonal variation. As reported in Chen91, cyclogenesis over the land is active in spring and inactive in winter. On the other hand, over the sea, the activity is the maximum in winter and the minimum in summer.

The cyclogenesis is inactive during winter around the Mongolian Plateau in the lee of the Hangayn Mountain and the Hexi Corridor. Cyclogenesis around the mouth of the Yangtze River is often detected throughout the year, while the frequency there is higher in spring. Although the center of the maximum frequency of cyclogenesis is usually located at the Yangtze River, the center shifts approximately 3 degrees northward in summer. These characteristics are roughly similar to that reported in Chen91 (Fig. 1.5), except for the location of the maxima around the mouth of the Yangtze River. On the other hand, cyclones formed relatively infrequently in the lee of Tahsinganling in summer, whereas Chen91 showed the cyclogenesis in the area is most active in summer. In addition, it should be noted that the Hebei Plain is an active area in cyclogenesis except for summer. The maximum area is fixed in the plain through the year. Over the Dzungaria Basin and the Sichuan Basin, surface cyclones often generate in all seasons. These features differ...
from those of Chen91.

High-frequency area of cyclogenesis is located in the Sea of Japan and the Pacific Ocean to the east of Japan throughout the year, while it is evident in winter. The frequency is also high in the coastal sea to the east of China in winter and spring, and in the Kuroshio Current region to the south of Japan in spring. The distribution of maritime cyclogenesis in this study has similar feature to that in Chen91 in summer and autumn, while the location of the maxima substantially differs particularly in winter.

The present analysis shows some prominent active areas of winter cyclogenesis around the East China Sea, namely, in the sea to the northeast of Taiwan and near the mouth of the Yangtze River. On the other hand, Chen91 showed that the active areas locate in the west of Kyushu and the Kuroshio Current region to the south of Japan. These cyclones originated around the East China Sea are well known as a cyclone passing along the south coast of Japan. The cyclone often brings a heavy snow in coast region and causes some social damages.

3.1.2 Seasonal variation of cyclone track

The density of the cyclone track is illustrated in Fig. 3.2. The contour lines indicate the density per grid point per 30 days.

The cyclone tracks around Japan in winter are classified into three major routes: (1) those generating in the East China Sea to the northeast of Taiwan or around the mouth of the Yangtze River and moving east along the southern coast of Japan; (2) those generating around the mouth of the Yangtze River or the Hebei Plain and moving east through the north of Japan; and (3) those generating in the Mongolian Plateau and moving east or to the Sea of Japan. In spring, the tracks are also classified into three: (4) those generating around the mouth of Yangtze River and going east through the southern coast of Japan via the East China Sea, (5) those generating around the mouth of Yangtze River or the Hebei Plain and going east through the Sea of Japan, and (3). In summer and autumn, the major cyclone tracks are: (6) those generating in the south of Shikoku and going east,
(7) those generating in the Hebei Plain and going to the Sea of Japan, and (8) those generating in the Mongolian Plateau and moving eastward. Those cyclone tracks show roughly the same characteristic as those of Chen91.

3.2 Characteristics of the cyclone generated in each cyclogenesis maximum area

There are several cyclogenesis maxima in East Asia as mentioned in Sec. 3.1. The characteristics of cyclone and cyclogenesis in each maximum area are investigated in this section. The following six areas are defined as the area with high frequency of cyclogenesis; ALTAI, YS, SCHI, YANG, ECHI, and TAIW. The geographical locations of the areas are denoted in Fig. 3.3 and Table 3.1.

3.2.1 Monthly variation of cyclogenesis

The monthly variations of cyclogenesis frequency in each maximum area are shown in Fig. 3.4. The bar charts indicate the occurrence frequency of cyclogenesis per month.

The cyclogenesis activities of the ALTAI and SCHI regions have two peaks in spring and autumn. The cyclogenesis in the ALTAI region is most active in April, followed by September, May, and June. The cyclogenesis in the SICH region occurs frequently during March – May and infrequently in summer. While the YS, YANG, and ECHI regions demonstrate one peak of cyclogenesis in spring. The cyclogenesis in the YS area is active from February to May. The number of cyclogenesis in the active months reaches twice or three times more than those in inactive months from July to October. The YANG region has high frequency cyclogenesis during February – June, in particularly it is enhanced in March. The cyclogenesis in the ECHI region increases its activity in March, April, May, and June, while it has less frequency in summer. The TAIW region denotes different characteristics from above areas, that is, the cyclogenesis activity elevates in winter, while spring is also active season next to winter. The cyclones are scarcely generated in summer.
3.2.2 Lifetime of cyclone

The lifetime of cyclone is investigated in each cyclogenesis maximum area in this section. Figure 3.5 shows the occurrence frequency of lifetime of the cyclones, generated in each maximum area, with an interval of 6 hours. The numbers in parentheses at the upper right corner of the figures indicate the number of cyclones generated in each area during the analyzed periods.

The cyclone with shorter lifetime occurs more frequently than that with longer lifetime. The occurrence frequency of cyclone decreases as the lifetime gets longer. This characteristic is common in all maximum areas. While the six areas can be classified into two groups, if we notice the cyclone with a lifetime longer than 4 days. Table 3.2 indicates the proportion of the cyclone with longer lifetime and one with shorter lifetime compared to 4 days. One group involves the SCHI, ALTAI, and YS regions, in which the probability of cyclogenesis with shorter lifetime is relatively high. More than 85% of the cyclones originated in the areas disappear within 4 days from their genesis. While the cyclones, generated in the ECHI, YANG, and TAIW regions, have relatively longer lifetime and subsist more than 4 days at a rate of thirty to forty percent. In particularly, the cyclone in the TAIW area tends to have longer lifetime than those in other regions.

Section 3.1 indicated that the high-frequency area of cyclogenesis concentrates in several narrow areas. This result suggests that the cyclogenesis occurs under the influence of some local effects. Considering the point, the cyclone with short lifetime is inferred to be induced as a result of local effects, while the drive by the local effect is temporary and can not make the cyclone to maintain the structure for several days and to develop further. On the other hand, the longer lifetime of cyclone suggests the existence of the different driving force that enables the cyclone to progress. The lifetime of cyclone seems to relate to cyclogenesis mechanism as well as a characteristic of synoptic scale condition at the time of cyclogenesis. The synoptic meteorological feature at the cyclogenesis is investigated in next section.
3.3 Synoptic situation of cyclogenesis

This section focuses on the four areas of six high-frequency areas; ALTAI, YS, YANG, and TAIW, and carries out the composite analysis in order to understand the meteorological feature when the cyclogenesis occurs. Figure 3.6 shows the composite (left side) and composite anomaly fields (right side) of geopotential height and potential temperature at 500 hPa and 700 hPa when the cyclones were produced in the ALTAI region. The composite anomaly fields were calculated by subtracting the climatology for each season; DJF, MAM, JJA, SON, from the composite data. The composite of 500 hPa geopotential height indicates that the contour lines meander over the Mongolian Plateau and a weak trough is present around 103° E. The composite anomaly field shows that the ALTAI area is located at the front of negative anomalies of geopotential height and potential temperature. While the positive (warm) anomaly of potential temperature is present in the forward to the ALTAI area. At the level of 700 hPa, the composite of geopotential height clearly demonstrates the synoptic trough over the eastern part of Mongolia, around 105° – 110° E (Fig. 3.6c). The trough at 700 hPa is located more eastward than that of 500 hPa and its amplitude is larger. The negative anomaly of 700 hPa geopotential height is centered in the southeast to that of 500 hPa and close to the ALTAI area. The warm anomaly of potential temperature exists in the forward of the negative anomaly of height, while the cold anomaly, in the backward. The vertical tilt of center positions of negative height anomaly between 500 hPa and 700 hPa reminds the structure of baroclinic disturbance. This result suggests the presence of synoptic trough when the cyclogenesis occurs in the ALTAI region.

When the cyclones are generated in the ALTAI area, the strong westerly passes through the ALTAI region or south of the region at both levels (Fig. 3.7). The positive anomaly of wind speed is predominant from west to south of the ALTAI region as well as the enhancement of vorticity close to the region.

For the cyclogenesis in the YS area, the synoptic trough in the composite field of
500 hPa is less remarkable than that for the ALTAI cyclone (Fig. 3.8). However the composite anomaly shows that the negative height anomaly is located over Inner Mongolia to Hebei province. The anomaly trough in the 700 hPa lies around 110° – 115° E over the Hebei Plain (YS region) at the southeast of that in 500 hPa, although the trough on the composite map is obscurity at the 700 hPa level. The YS region is located in the southeast to the anomaly troughs of 500 hPa and 700 hPa. The relationship of positions between both anomaly troughs suggests that the synoptic disturbance triggers the cyclogenesis in the YS area as well as the ALTAI area.

The axis of strong wind is passing through the north of the YS region at both levels, although the positive anomaly of wind velocity is distributed from west to north and northeast of the area (Fig. 3.9). The positive vorticity in the composite anomaly is located at the north side of the YS region at the 500 hPa level, while it intrudes into the region at the 700 hPa level (Figs. 3.9b and 3.9d).

When the cyclone forms in the YANG region, the 500 hPa geopotential height shows an obvious ridge around the 130° E and weak meandering like a trough in the east of the Tibetan Plateau (Fig. 3.10). The composite anomaly of geopotential height also has a notable feature of the ridge centered in the east of the Korean Peninsula. At the levels of 700 and 850 hPa, the ridge is clearly shown at the roughly same location as that of 500 hPa. In addition, the low altitude (low pressure) area extends in the north of the Yangtze River, while it becomes more clearly in the lower level.

The strong wind dominates around the southern coastal region of China from the southeastern edge of the Tibetan Plateau to the mouth of the Yangtze River in the three levels (Fig. 3.11). The large positive vorticity prevails just north of the strong wind area, where the two wind flows from different directions, southeast and north, encounter and produce a sharp wind shear line. The centers of positive vorticity anomaly are located in the same place between three levels, namely, the area with cyclonic vorticity areas are upstanding from 850 hPa to 500 hPa.
In the case of the TAIW cyclone, the contour lines of compositied geopotential height extend in the west-east direction, with less meandering (Fig. 3.12). The composite anomaly from the climatology of height and potential temperature are widely negative, that is, the geopotential height shifts southward compared to that of climatology. The sharp thermal contrast is present along the coastal line in the southern part of China. The strong westerly prevails in the south of the Tibetan Plateau. In addition, the positive vorticity is located in the southern part of China from the southeastern edge of the Tibetan Plateau to the Yangtze River in the levels of 700 and 500 hPa, while it is distributed along the southern coast of China and in the northeast of Taiwan at 850 hPa. The cyclonic vorticity at the northeast of Taiwan is enhanced exclusively in the lower level.

When the cyclogenesis occurs in the ALTAI and YS regions in the north part of East Asia, the composite analyses of height and potential temperature indicate the baroclinic structure with a synoptic scale. That is, the cyclones generated in these regions are lee cyclones, produced as a result of the stretching effect of vorticity associated with the trough in the lee side of mountains. On the other hand, the cyclones originated in the YANG and TAIW regions are meso-scale cyclone, notable exclusively in the lower level. Ogura (2005) suggested that the YANG cyclone is exposed near the coastal region where the cloud convection is active and the positive vorticity along the horizontal wind shear from the southeastern edge of the Tibetan Plateau to the mouth of the Yangtze River is stretched. However, this characteristic is absent in the TAIW region. The further analysis is needed to clarify the reason of the concentrated cyclogenesis in the TAIW region.
Table 3.1. List of the geographical locations of six areas defined as the cyclogenesis maxima.

<table>
<thead>
<tr>
<th>Region name</th>
<th>Latitude, Longitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALTAI</td>
<td>44° – 50°N, 102° – 116°E</td>
</tr>
<tr>
<td>YS</td>
<td>37° – 40°N, 115° – 119°E</td>
</tr>
<tr>
<td>YANG</td>
<td>30° – 33°N, 117° – 122°E</td>
</tr>
<tr>
<td>ECHI</td>
<td>27° – 30°N, 122° – 126°E</td>
</tr>
<tr>
<td>TAIW</td>
<td>23° – 27°N, 122° – 126°E</td>
</tr>
<tr>
<td>SICH</td>
<td>27° – 32°N, 104° – 108°E</td>
</tr>
</tbody>
</table>

Table 3.2. Occurrence probability of cyclones with longer and shorter lifetime in each cyclogenesis maximum area.

<table>
<thead>
<tr>
<th>Lifetime</th>
<th>Occurrence probability (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ALTAI</td>
</tr>
<tr>
<td>&lt; 4 days</td>
<td>88.74</td>
</tr>
<tr>
<td>≥ 4 days</td>
<td>11.26</td>
</tr>
</tbody>
</table>
Fig. 3.1. Distribution of the frequency of cyclogenesis for (a) DJF, (b) MAM, (c) JJA, and (d) SON from 1966 to 2002, analyzed in ERA40. The contour lines show the frequency per grid point per 30 days. The topography is indicated by shading.
Fig. 3.2. Distribution of the cyclone track density for (a) DJF, (b) MAM, (c) JJA, and (d) SON during 1966 – 2002, analyzed in ERA40. The contour lines show the frequency per grid point per 30 days. The topography is indicated by shading.
(Continued.)
Fig. 3.3. Geographical locations of six areas with high frequency of cyclogenesis.
Fig. 3.4. Monthly variations of cyclogenesis averaged during 1966–2002 in the areas of ALTAI, YS, YANG, ECHI, TAIW, and SICH. The bar charts indicate the occurrence frequency of cyclogenesis per month per each area.
Fig. 3.5. Histogram of lifetime of cyclones generated in (a) ALTAI, (b) YS, (c) YANG, (d) ECHI, (e) TAIW, and (f) SICH from 1966 to 2002 with an interval of 6 hours. The upper right chart in each figure is the enlarged drawing of the histogram more than 4 days of lifetime. The number in parentheses at the upper right corner of each figure indicates the number of all cyclones generated in each area during the analyzed periods.
(Continued.)
Fig. 3.6. Composite of (a) geopotential height (contour) and potential temperature (shaded) in 500 hPa level at the cyclogenesis in the ALTAI region, (b) its anomalies from climatology, and (c)-(d) in 700 hPa level for the corresponding components, respectively. The contours of composited height are drawn with an interval of (a) 50 m and (c) 30 m, while those of composite anomaly in (b) and (d), 10 m in the range with the absolute value over 10m. The gray square shows the ALTAI region. The topography of 3000 m is indicated by the green line.
Fig. 3.7. Composite of (a) wind vector, wind velocity (shaded), and vorticity (contour) at the cyclogenesis in the ALTAI region, (b) its anomalies from climatology, and (c)-(d) in 700 hPa level for the corresponding components, respectively. The contours of vorticity are drawn in the positive range larger than $1 \times 10^{-6} \text{m/s}^2$ for the composite figures of (a) and (c), while that is in the range with the absolute value over $0.5 \times 10^{-6} \text{m/s}^2$ for the composite anomaly figures of (b) and (d), with an interval of $0.5 \times 10^{-6} \text{m/s}^2$. The gray square shows the ALTAI region. The topography of 3000 m is indicated by the green line.
Fig. 3.8. Same as in Fig. 3.6, except for those at the cyclogenesis in the YS region (gray square).
Fig. 3.9. Same as in Fig. 3.7, except for those at the cyclogenesis in the YS region (gray square).
Fig. 3.10. Composite of (a) geopotential height (contour) and potential temperature (shaded) in 500 hPa level at the cyclogenesis in the YANG region, (b) its anomalies from climatology, (c)-(d) in 700 hPa level, and (e)-(f) in 850 hPa level for the corresponding components, respectively. The contours of composited height are drawn with an interval of (a) 50 m, (c) 30 m, and (e) 25 m, while those of composite anomaly in (b), (d), and (f), 10 m in the range with the absolute value over 10m. The gray square shows the YANG region. The topography of 3000 m is indicated by the green line.
Fig. 3.11. Composite of (a) wind vector, wind velocity (shaded), and vorticity (contour) at the cyclogenesis in the YANG region, (b) its anomalies from climatology, (c)-(d) in 700 hPa level, and (e)-(f) in 850 hPa level for the corresponding components, respectively. The contours of vorticity are drawn in the positive range larger than $1 \times 10^{-6} \text{m/s}^2$ for the composite figures of (a), (c), and (e), while that is in the range with the absolute value over $0.5 \times 10^{-6} \text{m/s}^2$ for the composite anomaly figures of (b), (d), and (f), with an interval of $0.5 \times 10^{-6} \text{m/s}^2$. The gray square shows the YANG region. The topography of 3000 m is indicated by the green line.
Fig. 3.12. Same as in Fig. 3.10, except for those at the cyclogenesis in the TAIW region (gray square) and the contour lines in (f) drawn with an interval of 5 m in the range with the absolute value over 5 m.
Fig. 3.13. Same as in Fig. 3.11, except for those at the cyclogenesis in the TAIW region (gray square).
Chapter IV

CASE STUDY OF CYCLONE IN THE ALTAI AND TAIW REGIONS

In Chap. III, the characteristics of surface cyclone in East Asia are indicated from the statistical point of view. The composite analysis in Sec. 3.3 suggested that the synoptic meteorological feature at the time of cyclone formation differs between the northern region and the southern region. The cyclogenesis in the northern region, ALTAI and YS, is related to the synoptic trough, while in the southern region, YANG and TAIW, seems not to have direct connection with troughs. Although composite analysis is useful for getting a general characteristic of cyclone, its result does not contain how the cyclone was actually generated and developed, and what the relationship between the cyclone and synoptic disturbance might be. Therefore, the following sections focus on the ALTAI cyclone and the TAIW cyclone and performs case studies of each cyclone in order to understand the characteristics of these cyclones furthermore.

4.1 Northern area – Case of ALTAI cyclone –

The Mongolian Plateau (ALTAI region) is located in the lee of the Altai-Hangayn-Sayan Mountains and one of the active areas of cyclogenesis in northeast Asia. In addition, the region has relatively arid climate and the Gobi Desert is distributed in the south of the region. In the Gobi Desert, sever dust storms often occur in spring and cause great damages in the surrounding regions. Several previous studies reported that most dust events in the Gobi Desert are caused by strong wind associated with synoptic disturbances, which is generated in the Mongolian Plateau (e.g., Mitsuta et al. 1995; Takemi and Seino
This section focuses on the dust event in the Gobi Desert and the cyclone, which produced the dust storm.

### 4.1.1 Model descriptions and experimental design

#### Regional atmospheric model

The Terrestrial Environmental Research Center-Regional Atmospheric Modeling System (TERC-RAMS), which is a compressive nonhydrostatic model, was used for the detailed analysis of an ALTAI cyclone (Okamura and Kimura 2003). The original RAMS was developed at Colorado State University (Pielke et al. 1992). Differences from the original RAMS are briefly described in Yoshikane et al. (2001) and Sato and Kimura (2003). The vegetation type in the calculating domain was assumed to be the semi-desert type, in which the initial condition of soil water has a uniform value of 0.2 (the ratio of soil water to saturated soil water). The sea surface temperature (SST) was obtained from the monthly NOAA Optimum Interpolation SST V2 data in April 2000 (Reynolds and Smith 1994). The change of the atmospheric condition associated with cumulus convection was calculated using the Arakawa-Schubert cumulus parameterization (Arakawa and Schubert 1974).

For the representation of ALTAI cyclone, two numerical experiments, RUN1 and RUN2, were conducted. The purpose of RUN1 is to simulate ambient meteorological conditions around the dust storm and to provide wind data for the tracer particle model. RUN2 is a nested simulation to obtain the detailed meteorological field for the case of 19 April 2000. The domain of RUN1 covers East Asia and has 120 × 90 horizontal grid points with an interval of 50 km (Fig. 4.1). The polar-stereo-coordinate system centered at 39° N and 108° E is used in this model. The model atmosphere has 30 layers with a 110 m depth in the lowest level stretching up to 900 m in the upper level, while ten layers are below 3000 m from the ground surface. RUN1 was integrated 96 hours from 00 UTC 17 April to 00 UTC 21 April. The initial and boundary conditions were determined by
NCEPI every six hours. A weak nudging toward the NCEPI was prescribed using a time constant of 86400 seconds (24 hours) for every grid point in the model domain to achieve higher reproducibility of the synoptic disturbances.

RUN2 was calculated for 24 hours from 12 UTC 18 April to 12 UTC 19 April within the nested grid area indicated by the inner dashed square shown in Fig. 4.1. The boundary conditions of RUN2 are provided from the outside domain, which is the same as RUN1. The nested region has $182 \times 182$ grid points with an interval of 10 km, while the vertical grid system and the center position of the domain are the same as those of RUN1. The experimental design in this study is summarized in Table 4.1.

**Tracer model**

The tracer experiment was performed from 12 UTC 18 April to 00 UTC 21 April to simulate the relative positions of dust to the cold front and the cyclone. We used a Lagrangian-type particle model (Kimura and Yoshikawa 1988; Tsunematsu et al. 2005), which is a random-walk diffusion model simulating three processes, i.e., dust emission, transport, and deposition.

The source area of the tracer particles is assumed to be the area classified as “bare desert,” “semi-desert,” or “semi-desert and shrubs,” according to the classification by the Global Ecosystem Legend of the U.S. Geological Survey (USGS) (Loveland et al. 2000), and is shown in Fig. 4.1 by shading. The Taklamakan Desert and the Tibetan Plateau are eliminated from the source area in order to focus on the dust observed over the Gobi Desert. The tracer particles are emitted to the atmosphere when wind velocity exceeds the threshold velocity $10 \text{ m s}^{-1}$ at the lowest level, which is roughly 55 m above ground. The particle emission is activated only between 12 UTC 18 April and 12 UTC 19 April, when the cold front passed through the source area. The emitted tracer particle is transported by the three-dimensional wind. While the particles are removed only when they outflow from the lateral boundary of the calculating domain, because the sedimentation, dry deposition, and wet deposition of tracer particles are ignored in this model. The tracer
particles, which flowed out of the calculating domain once, do not return to the domain. Additional explanations for the tracer model are given in the Appendix.

4.1.2 Data analysis and results of numerical experiments

All cyclone tracks originated in the Mongolian Plateau (ALTAI region) for spring throughout the analyzed period are shown in Fig. 4.2. Most of cyclones move eastward or northeastward, while the rest move southeastward and pass through the Sea of Japan. The cyclone shown by the thick lines was generated in the Mongolian Plateau on 18 April 2000 and then produced the dust storm in the Gobi Desert on 19 – 20 April.

Figure 4.3 shows true color images of the Moderate Resolution Imaging Spectroradiometer (MODIS) on the satellite “Terra.” The MODIS is a radiometer with 36 spectral bands, we used the Level 1b data of channels 1, 3, and 4 with a spatial resolution of 1 km to create true color images. The images are composites of several scans during several hours.

On 19 April, the developing cyclone is located in the Mongolian Plateau. The location of the cyclone center is identified by the letter “L” in Fig. 4.3a. A dust outbreak was observed in the Gobi Desert by MODIS during 0340 to 0350 UTC (1040–1050 local time: LT). The cloud area (“CA” in Fig. 4.3a) extends from 42° N, 110° E toward southwest with a width of about 200 – 400 km. The numerous small white patches scattered to the west of 100° E are snow-covered areas on the mountains in the Tibetan Plateau and the Altai-Sayan Mountains. A dense dust area (DDA), which is enclosed by an ellipse, is located just southeast of the CA. The sparse streaks of dust are shown around 40° N, 102° E to the northwest of the CA.

On 20 April, the cyclone moves eastward around 45° N (Fig. 4.3b). The dust in Fig. 4.3b was observed from 0245 to 0255 UTC (1045–1055 LT). The distributions of clouds and dust extend along a line from 40° N, 120° E to 30° N, 105° E, which seems to be parallel to the front. Dust is identified near the center of the cyclone as well as in the cold sector. The horizontal distribution of clouds and dust as shown in Fig. 4.3b is often
observed in a typical dust event caused by strong winds following a cyclone system (Liu et al. 2003; Uno et al. 2001; Wang and Fang 2006).

The synoptic features are indicated in Fig. 4.4 from 06 UTC 18 April to 06 UTC 20 April at one day intervals. The geopotential height (solid lines), air temperature (shaded), and wind vector (arrows) at 500 hPa or 700 hPa of NCEPI are shown in each figure. The 700 hPa maps demonstrate the meteorological condition in the lower level near the ground, especially around the Gobi Desert, because the elevation in the area reaches more than 1000 m.

At 06 UTC 18 April, the trough is located over the Altai-Sayan Mountains (Figs. 4.4a and 4.4d). The cold air advection is shown on the west side of the trough at 700 hPa. On the next day, the trough deepens and the warm/cold air advection is intensified at both levels. Strong winds blow on the south side of the trough of 700 hPa (Fig. 4.4e). The trough develops further by 06 UTC 20 April, while the thermal advection weakens. At this time, the cyclone reaches in the stage between deepening and maturation, as shown by the fact that the center axis of the cyclone is close to upstanding.

Figure 4.5 indicates meteorological variables of RUN2 and the tracer distribution at 04 UTC 19 April 2000. The illustrated area is Region A, shown by the square in Fig. 4.3a. The geographical location of Region A is shown in Fig. 4.1.

The shaded area in Fig. 4.5b depicts a strong wind area with wind velocity greater than 10 m s\(^{-1}\) at the lowest level. The wind direction of the strong wind is between west and northwest, while the weak southeasterly wind prevails in the east of the strong wind area. The blue dashed line shows the position of a surface cold front defined by the maximum wind shear. The cold air mass is located in the west of the cold front, and the warm one in the east (Fig. 4.5a).

Figure 4.5c shows the vertically integrated cloud water, which is the total amount of cloud water in the column atmosphere. The simulated cloud agrees well with that observed from satellite, shown in Fig. 4.3a, except for the overestimation of the simulated
cloud line along the cold front. The distribution of tracer particles in Fig. 4.5d is limited only in the cold sector and corresponds to the strong wind area shown in Fig. 4.5b. The head of a dense particle area, which is the southeastern boundary of the dense particle area, is located more leeward than the cloud area (Figs. 4.5c and 4.5d) and close to the cold front.

The relationship of the positions between simulated dust and cloud area is quite similar to those observed in the MODIS image (Fig. 4.3a). This fact suggests that the model well simulates the production mechanism of the dust storm. Therefore, we can conclude that dust was actually lofted by the strong westerly or northwesterly wind exclusively in the cold sector of the cold frontal system as suggested by the model. This result is consistent with that of previous studies (e.g., Uno et al. 2001; Shao and Wang 2003).

At this time, most tracer particles are restricted to an altitude of 1500 m or less from the ground surface, i.e., the mixed layer, where the potential temperature and the water vapor mixing ratio are vertically constant (not shown). The tracer particles disperse in the entire mixed layer as a result of turbulent mixing. However, it is difficult to transport further above the mixed layer, since the diffusion coefficient is almost zero. The dust layer is controlled by the mixed layer, but almost independent of the thickness of the cold air mass of the frontal system.

Figure 4.6 shows the cloud area of RUN1 and tracer distribution at 04 UTC 20 April in Region B, shown by the square in Fig. 4.3b. Figure 4.6a shows the total amount of cloud water in the column atmosphere. The cloud area is distributed along the cold front (long blue dashed line), which is defined by the maximum thermal contrast at the lowest level. Secondary front (short blue dashed line) is also located at the downwind of the cold front. The front seems to be a mesoscale frontal system caused by cold pools induced by convection. The simulated cloud reproduces well that observed from MODIS (Fig. 4.3b). Most of the tracer particles are still located in the cold sector (Fig. 4.6b), as well as those on the previous day. However, the particles near the well-developed convective cloud
are distributed between two fronts, because the cold frontal structure is deformed by the condensation heating and obscured. There are few clouds and many tracer particles in the cyclone center located at around 44° N, 119° E. The distribution agrees well with that observed in the MODIS image.

In order to gain a further understanding of the transport route of dust particles, a trajectory analysis was carried out through the entire period from the emission time to the end of the tracer experiment. Thus, the starting time and the terminating time of the trajectories depend on the particles. The solid lines in Fig. 4.7 show the trajectories of some selected particles. The trajectories were projected on the ground surface and illustrated from the starting point to the terminating point of each particle. The instantaneous positions of the particles at the same times of Figs. 4.3a and 4.3b are illustrated on the trajectory by the circles and stars, respectively. The dotted lines show the position of the cold front, which has been shown in Figs. 4.5 and 4.6. The figure also indicates all emission points of the particles with gray dots.

The trajectory of the particles is similar to that of the airflow from the cold sector around the cyclone (e.g., Figs. 10 and 15 of Reed et al. 1994; Carlson 1980; Mass and Schultz 1993). Tracer particles are transported southeastward in the early stage by a strong northwesterly wind (cf. Fig. 4.5). Near the cold front, those particles diverge into two main flows both in parallel with the front. One flow goes to north or northeast, that is the direction to the center of the cyclone, and the other goes to south or southwest, that is the opposite direction of the center. The tracers are then distributed along the western side of the cold front (cf. Fig. 4.6). The result suggests that dust around the cyclone center has been produced in the cold sector and transported southeastward and then northward along the cold front.

4.1.3 Summary

This section focused on a case of the ALTAI cyclone and investigated the dust event caused by the cyclone. The simulated meteorological features and tracer particles agreed
with those observed in the satellite images. The dust event occurred near the cloudless cold front associated with the cyclone on 19 April 2000 and distributed within the cyclone center on 20 April. The main findings of the present section are summarized below.

1. Surface cyclone produced in the Mongolian Plateau as the synoptic trough approached.
2. Strong northwesterly wind and cold air intruded into the Gobi Desert following the passage of cold front.
3. Dust was produced by a westerly or northwesterly wind in the cold sector of the cold frontal system.
4. Dust moved toward the cold front. Near the front, the dust flow separated into two main flows both in parallel with the front, one dust flow going toward the center of the cyclone and the other, toward the opposite direction of the center.

4.2 Southern area – Case of TAIW cyclone –

4.2.1 Case study of the cyclone generated on 25 January 2002

Selected cyclone was generated at 06 UTC 25 January 2002 and passing through the Kuroshio region. The cyclone track is drawn in Fig. 4.8 by the thick line. The thin lines illustrated in the figure show the tracks of all cyclones originated in the TAIW region during winter. The TAIW cyclone generally moves toward east over the sea in the south of Japan. The analyzed cyclone was generated over the East China Sea to the northeast of Taiwan, moved northeastward, and then passed along the southern coast of Japan to the Pacific Ocean. This cyclone tracked the northerly route among the TAIW cyclones.

The synoptic features on ECMWF operational 0.5° interval data for 0, 24, and 54 hours from the cyclogenesis are shown in Fig. 4.9. At 06 UTC 25, the surface cyclogenesis occurred at the northeast of Taiwan (Fig. 4.9d). At the time, the high pressure from continent covered the Yellow Sea and the west part of Japan. The warm air blew in the cyclone center particularly in the east of Taiwan associated with southerly and
southeasterly winds. At the level of 500 hPa, the synoptic trough is not present near the surface cyclone, although the developed troughs are located over the Sea of Okhotsk and the east of Mongolia in addition to the weak one over the southeast of China around 110°E.

After one day of the cyclone formation, the surface cyclone has moved northeastward and reached to the west of Kyusyu (Fig. 4.9e). It is notable that the surface cyclone is drawn as the several closed contour lines with an interval of 5 hPa, although it was shown only by one closed contour line one day before. The synoptic trough is located west of the surface cyclone over the Yellow Sea at 500 hPa. The trough axis is inclined toward west as the altitude increases. The feature means the further progression of the cyclone.

At 12 UTC 27, the surface cyclone moves to the east of Japan as it have quite developed (Fig. 4.9f). The surface pressure of the cyclone center has fallen at 974.6 hPa (not shown in figure). The stationary front is formed in the southeast side to cyclone center, that is clearly confirmed as the wind shear line. The cut-off vortex is situated in the 500 hPa level above the surface cyclone center.

In order to investigate the evolution of the cyclone, the cyclone track and pressure change of the cyclone center are shown in Fig. 4.10. The location and the surface pressure of the cyclone center are denoted by the circle with an interval of 6 hours. When the cyclone satisfies the definition of “bomb” within next 12 hours, the point is drawn by the double circle. Sanders and Gyakum (1980) introduced the criteria of “bomb” with using SLP, that is $24(\sin \phi / \sin 60^\circ)$. When the lapse of center pressure exceeds the criteria within 24 hours, the cyclone is classified as a “bomb”. The definition in this study was modified from the criteria of Sanders and Gyakum (1980) to that for 12 hours, and thus a cyclone is defined as “bomb” when the pressure of cyclone center falls more than $12(\sin \phi / \sin 60^\circ)$ within subsequent 12 hours. The double circles shown in Fig. 4.10 reveal that the cyclone was developed within next 12 hours to the extent of “bomb”.

The growth of the cyclone started along the Kuroshio current over the East China
Sea and the south of Japan within 2 days after its genesis. The surface pressure of the cyclone center fell down from 1010.5 hPa at 18 UTC 25 to 981.1 hPa at 18 UTC 26. Ogura (2000) describes the suitable condition for the growth of oceanic cyclone as followings: (1) the potential vorticity anomaly in the upper level, (2) the large flux of condensation heating, and (3) the large flux of heat and water vapor from sea surface. If the conditions apply the case of the analyzed cyclone, the Kuroshio current is a region with large sensible heat and latent heat fluxes to the atmosphere in winter, where the cyclone steeply developed. In addition, the synoptic trough with large vorticity migrated and coupled with the surface cyclone when the cyclone was passing through the Kuroshio region. And then the condensation heating in the convection is implied to be large, because the cyclone brought relatively heavy precipitation to Kyusyu on 26 January (not shown in figure). Therefore, it is concluded that the synoptic situation around the Kuroshio region was suitable for the cyclone development.

4.2.2 Cyclone passing through the southern coast of Japan in winter

The cyclone originated in the East China Sea is well known as the cyclone passing along the southern coast of Japan, which often bring a heavy snow in the coastal region and causes some social damages. This section studies the southern coastal cyclone of Japan from the statistical point of view.

The cyclone tracks in winter illustrated in Fig. 3.2a were classified into three major routes: (1) those generating in the East China Sea to the northeast of Taiwan or around the mouth of the Yangtze River and moving east along the southern coast of Japan; (2) those generating around the mouth of the Yangtze River or the Hebei Plain and moving east through the north of Japan; (3) and those generating in the Mongolian Plateau and moving east or to the Sea of Japan. It should be noted that the major route (1) consists of two cyclone tracks: one originates near the mouth of the Yangtze River, and another, in the East China Sea to the northeast of Taiwan. These two merge south of Kyusyu
and move further east along the southern coast of Japan. This fact was not shown in Chen91. These two cyclones with different origins contribute to the frequency of the winter cyclones passing along the southern coast of Japan.

Figure 4.11 shows the cyclone tracks and the genesis points of all cyclones that passed through the Kuroshio Current region (blue rectangle) in winter during the analyzed period. The size of the red circles indicates the number of cyclogenesis of the cyclone in each grid point. The origins of these cyclones are distributed primarily in three areas: the Kuroshio region to the south of Shikoku, the region around the mouth of the Yangtze River, and the East China Sea to the northeast of Taiwan. The latter two have been mentioned above as the sources of the major route (1). Nearly half of the cyclones originate in the East China Sea to the northeast of Taiwan or around the mouth of the Yangtze River, while the other half originate in the Kuroshio region. Namely, half of the cyclone passing through the Kuroshio region form in the further windward regions.

4.2.3 Summary

This section investigated the cyclone, originated in the TAIW region and moving along the southern coast of Japan. The main findings from the case study and the statistical analysis are summarized as follows. Surface cyclone was generated as the meso-α cyclone in the northeast of Taiwan. The cyclone moved toward northeast and coupled with the synoptic trough in the west of Kyusyu. Cyclone developed steeply as passing along the southern coast of Japan. On the Pacific Ocean to the east of Japan, the cyclone achieved final stage of progression in addition that the cut-off vortex was constructed at the upper level. The origins of the cyclones passing through the Kuroshio region are mainly concentrated in three areas; the Kuroshio region, the mouth of the Yangtze River, and the East China Sea to the northeast of Taiwan.
Table 4.1. Experimental design of RAMS for the case study of ALTAI cyclone.

<table>
<thead>
<tr>
<th></th>
<th>ALTAI</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RUN1</td>
<td>RUN2</td>
</tr>
<tr>
<td>Horizontal resolution</td>
<td>50 km (120×90)</td>
<td>10 km (182×182)</td>
</tr>
<tr>
<td>Initial time</td>
<td>00 UTC 17 April 2000</td>
<td>12 UTC 18 April 2000</td>
</tr>
<tr>
<td>Initial/boundary data</td>
<td>NCEPI</td>
<td>RUN1</td>
</tr>
<tr>
<td>Integrated time</td>
<td>96 hours</td>
<td>24 hours</td>
</tr>
<tr>
<td>Center position of domain</td>
<td>(39° N, 108° E)</td>
<td>(39° N, 108° E)</td>
</tr>
</tbody>
</table>
Fig. 4.1. Domain of RUN1 and the tracer experiment, and outside domain of RUN2. The inside dashed square is the nested area of RUN2. The geographical locations of Regions A and B are shown by thick closed lines. The shaded region is the potential source area of tracer particles assumed in the tracer experiment.
Fig. 4.2. All cyclone tracks originated in the ALTAI region for spring from 1966 to 2002. The thick lines show the track of the cyclone, which produced the dust event in the Gobi Desert on 19 – 20 April 2000.
Fig. 4.3. True color satellite images observed by MODIS on the satellite Terra on (a) 19 April and (b) 20 April. Ellipse in (a) denotes a Dense Dust Area (DDA), and “CA,” a cloud area. The letter “L” designates the center of the cyclone. The inside squares in (a) and (b) indicate Region A (31°–44° N, 99°–117° E) and Region B (25°–50° N, 100°–135° E), respectively.
Fig. 4.4. Geopotential height (contour), air temperature (shaded), and wind vectors at 500 hPa for (a) 06 UTC 18 April, (b) 06 UTC 19 April, and (c) 06 UTC 20 April, and (d)-(f) at 700 hPa level for the corresponding times, respectively. The contour lines are drawn with intervals of 50 m (500 hPa) and 30 m (700 hPa). The color bar of air temperature and unit length of the wind vector are shown at the bottom in (c) for 500 hPa and (f) for 700 hPa.
Fig. 4.5. Meteorological variables simulated in RUN2 and tracer distribution in Region A at 04 UTC 19 April. (a) Potential temperature (contours); (b) wind vectors and strong wind area exceeding 10 m s$^{-1}$ (shaded) at the lowest level; (c) vertically integrated cloud water; and (d) tracer distribution. The colors of particles indicate the tracer height: green dots $\leq$ 3 km ASL and red dots $>$ 3 km ASL. The blue dashed lines show the position of the cold front defined by the maximum wind shear at the lowest level. The thick solid lines in the bottom left corner indicate the topography of an altitude of 3000 m.
Fig. 4.6. Horizontal distribution of (a) vertically integrated cloud water in RUN1 and (b) tracer distribution in Region B at 04 UTC 20 April. The color of particles is same as one of Fig. 4.5d. The blue dashed lines show the position of the cold front defined by the maximum thermal contrast at the lowest level. The thick solid lines on the lower left side depict the topography of an altitude of 3000 m.
Fig. 4.7. Trajectories of tracer particles (solid lines) and all emission points of tracers (gray dots). Twenty-two trajectories are selected and illustrated here. The lines of each particle are illustrated from the emission point to the terminal point of each particle. The circle and star indicate the position of each particle at 04 UTC 19 and 04 UTC 20 April, respectively. The dotted lines show the position of the cold front, which is same as that shown in Figs. 4.5 and 4.6.
Fig. 4.8. All cyclone tracks originated in the TAIW region for winter from 1966 to 2002. The thick line shows the track of the cyclone analyzed in this section. The double circles denote the position of cyclone center at the time shown in Fig. 4.9.
Fig. 4.9. Geopotential height (contours), potential temperature (shaded), and wind vectors at 500 hPa for (a) 06 UTC 25 January 2002, (b) 06 UTC 26, and (c) 12 UTC 27, and (d)-(f) at 925 hPa level for the corresponding times, respectively. The contour lines of geopotential height are drawn with intervals of 50 m (500 hPa) and 25 m (925 hPa). The color bar of potential temperature and the unit length of wind vectors are shown at the outside of the figures.
Fig. 4.10. Relationship between (a) cyclone track and (b) pressure change of the cyclone center. The black circles denote the point with an interval of 6 hours. The double circles indicate that the cyclone satisfied the criteria of bomb within next 12 hours.
Fig. 4.11. Distribution of the genesis point (red circles) and cyclone track (solid lines) of the all cyclones that passed through the Kuroshio region in winter (DJF) from 1966 to 2002. The Kuroshio region is indicated by a blue rectangle. The size of the red circles depends on the number of cyclogenesis (CG) per grid point.
Chapter V

DISCUSSIONS

5.1 Differences from previous studies in the distribution of cyclogensis in East Asia

As mentioned in previous sections, the distribution of cyclogensis obtained in this study shows some different features from that of Chen91 as follows: (1) the cyclogensis is inactive in the lee of Tahsinganling in summer, (2) the cyclogensis is more frequent in the Hebei Plain except for summer, (3) two cyclogensis maxima appear around the mouth of the Yangtze River and the East China Sea to the northeast of Taiwan in winter, and (4) the high-frequency cyclogensis in the Sichuan Basin and the Dzungaria Basin. It is difficult to prove the reasons of these differences, because there are several differences between this study and Chen91, such as data, method, and periods. However, the reason of (2) can be speculated to be related to the horizontal resolution of the source data, while that of (3) may be affected by both horizontal resolution and detection method. The cause of (4) seems to be related to the detection method in this paper.

The cyclone detection method in this study seems to have a bias to detect the cyclones slightly more frequently in the Dzungaria Basin and the Sichuan Basin than in other areas. When a synoptic trough approaches the basin, the surface pressure in the basin often decreases more than it does in the surrounding mountains, although the evolution of the surface depression is similar to that in the surrounding area. Since a synoptic trough generally has a baroclinic structure, the pressure evolution depends on the altitude and is different between the bottom of the basin and the surrounding mountains. On the other hand, the detection method identifies the surface cyclone by the negative pressure
anomaly relative to that of the surrounding areas. As a result, the surface depression may be orographically enhanced in the bottom of the basin when the synoptic trough is passing. The effect of this bias is small in the analysis of the surface cyclone track, because the cyclone track is counted only once for a grid point for a cyclone.

Figure 5.1 indicates the annual distribution of surface cyclogenesis analyzed in NCEPII for East Asia. The horizontal resolution of NCEPII is $2.5 \times 2.5$ degrees and nearly equal to Chen91. The result of NCEPII indicated that the distribution of the cyclogenesis in the Hebei Plain was similar to that of Chen91 showing a widespread distribution. This suggests that the difference for the Hebei Plain between ERA40 and Chen91 (NCEPII) is caused by the horizontal resolution, since the cyclogenesis distributions of Chen91 and NCEPII sprawled more widely than that of ERA40. On the other hand, the analysis of NCEPII showed similar maxima with ERA40 in the coastal region to the east of China. Thus the difference in the coastal area can be partially attributed to the difference in the method.

Takano (2002) and Sec. 4.2 have reported a case of a cyclone that generated in the East China Sea and rapidly moved eastward, developing around the Kuroshio region. Providing a scale of a cyclone is defined by the outermost closed contour line with an interval of 25 m on 925 hPa chart, the size of cyclone described in Sec. 4.2 increases approximately from 250 km at the northeast of Taiwan (06 UTC 25) to 1200 km at the west of Kyusyu (06 UTC 26) during 24 hours (Fig. 4.9). The method applied in Chen91 defines the cyclone by a closed contour line with an interval of 5 hPa on surface weather maps. Given the hydrostatic equilibration, the difference of 5 hPa corresponds with the difference of 40 m. Since the definition of Chen91 is difficult to detect small scale cyclone, the cyclogenesis reported in Chen91 may contain cyclones that reached maturity there after they generated as meso-$\alpha$ scale cyclones around the mouth of the Yangtze River or in the East China Sea to the northeast of Taiwan. On the other hand, the present analysis can detect meso-$\alpha$ scale cyclones by use of high-resolution data with an interval of 125
km. Thus, it is considered that the difference of detectable scale between two methods derived the differing results.

## 5.2 Cyclogenesis mechanisms

The composite analysis of meteorological feature in Sec. 3.3 suggested that the synoptic condition at the cyclogenesis differs between the northern and the southern parts in East Asia. In the Mongolian Plateau (ALTAI region) and the Hebei Plain (YS region) located in the northern part in East Asia, the cyclogenesis seems to occur associated with the synoptic trough in the middle level (Figs. 3.6 and 3.8). While the synoptic trough was unclear in the composite analysis for the cyclones generated in the mouth of the Yangtze River (YANG region) and the northeast of Taiwan (TAIW region). The lifetime of cyclone also varies between the northern and the southern regions. The cyclones with shorter lifetime occur more frequently in the northern area than the southern area. While the cyclones originated in the southern area often have greater longevity. The difference of lifetime among the cyclogenesis maxima seems to be related to the cyclogenesis and progression mechanisms. The cyclone originated in the northern area has a relatively short lifetime, namely, it needs the different mechanism from that of cyclogenesis in order to sustain the cyclonic structure and develop further. On the other hand, in the southern area where the cyclones have a relatively long lifetime, the cyclogenesis mechanism of these cyclones is implied to contain or link with the development mechanism.

Several previous studies have been reported that the ALTAI cyclone is caused by lee cyclogenesis in the Altai-Hangayn-Sayan Mountains (e.g. Chung76; Chen and Lazic, 1990; Han et al., 1995). Han et al. (1995) conducted some sensitivity experiments with and without mountains for two cases of cyclogenesis in the lee of the Altai-Sayan Mountains. They described that the cyclones were induced as a result of orographical effect that enhances the potential vorticity moving in the upper level or modifies the surface cold front. On the other hand, the understanding of the mechanism of cyclogenesis in the
Hebei Plain (YS region) is inadequate because of the paucity of study for the cyclone in this area. However, Chung76 suggested that the YS cyclone is a lee cyclone in the Taihang Mountain. The composite analysis in this study supports the speculation of Chung76. Therefore, the cyclones originated in the northern area (ALTAI and YS regions) are classified as a lee cyclone produced by the orographical effect (Figs. 3.6 and 3.8). If the hypothesis is accepted, what decides the lifetime of the cyclone originated in these areas?

Figures 5.2 and 5.4 show the tracks of the cyclones with longer and shorter lifetime originated in the ALTAI or the YS regions during spring. The cyclone with longer (shorter) lifetime is defined as the cyclone ranking in the top (bottom) 30% of the list of cyclones generated in each region during spring in order of the lifetime. Figures 5.3 and 5.5 show the composite and its anomaly of 500 hPa geopotential height, when the cyclones with longer and shorter lifetime were generated in the ALTAI or the YS regions during spring. Spring is most active season of cyclogenesis in both regions. When the cyclone with longer lifetime occurs, the composite anomaly of height reveals that the strong trough is located over the northwest of the ALTAI region and the thermal contrast exists between west and east to the region (Fig. 5.3a). The positive vorticity anomaly is distributed in the west of the ALTAI region (Fig. 5.3c). Although these characteristics are confirmable in the composite analysis for the cyclone with shorter lifetime, the amplitude of trough is smaller than that of the longer lifetime cyclone (Figs. 5.3a and 5.3b).

The composite analysis for the YS cyclone with longer lifetime shows common characteristics with those of ALTAI cyclone. The negative height and positive vorticity anomalies are centered in the southeast part of Mongolia and broads to just west of the YS region (Figs. 5.5a and 5.5c). Although the anomaly trough exists around Mongolia for the case of the cyclone with shorter lifetime, the YS region is under the ridge at 500 hPa. The cyclonic circulation appears over the YS region in the composite anomaly both cyclones with longer and shorter lifetime in the lower level of 850 hPa (Fig. 5.6).

The findings reveal that the cyclone with longer lifetime occurs when the large positive
vorticity intrudes over the mountain region associated with the migration of synoptic trough (Figs. 5.5a and 5.5c). While the cyclone with shorter lifetime forms, when the trough is passing in the northern side of the region and the advection of positive vorticity anomaly is weak (Figs. 5.5b and 5.5d). In addition, the condensation heating associated with moist convection may be important for the development of the lee cyclone. Because Chen and Dell’osso (1987) pointed out the importance of latent heat release for the rapid cyclogenesis along the coastal region from the numerical simulation, although they did not exclusively focused on the cyclogenesis in the YS region. Their simulation demonstrated that the cyclone becomes a shallow cyclone in the lower level in the examination under the cutoff of latent heating.

The composite analysis in Sec. 3.3 suggests that the synoptic trough does not directly contribute to the cyclogenesis in the mouth of Yangtze River (YANG region) and the northeast of Taiwan (TAIW region). There are two patterns in the synoptic condition at the cyclogenesis in these areas, that is, the cyclogenesis occurs associated with synoptic trough and without trough.

The cyclones which developed over the East China Sea were analyzed from the 1970’s to the 1980’s as typified by AMTEX field project. These previous studies reported that the cyclone observed over the East China Sea has relatively small scale of \(\sim 1000 \text{ km} \), called as a medium-scale cyclone (Saito, 1977). The medium-scale cyclone is characterized by a lower level shallow cyclone, and its development is contributed by the sensible and latent heat fluxes from warm ocean (Chen et al. 1983).

As mentioned in Takano (2002) and Chen and Lin (1999), the cyclogenesis around the Yangtze River occurs over the low-level front in the east of the Tibetan Plateau, where the strong wind shear and large vorticity are produced. Ogura et al. (2005) suggested that these situations are favorable for the development of a meso-\(\alpha\) cyclone, because the vorticity on the low-level trough is intensified as a result of the stretching effect if a strong moist convection happens. In addition, the coupling between the low-level shallow cyclone

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and the middle level trough is also an important factor for the further progression to the
synoptic scale disturbance as mentioned in Sec. 4.2.

There is a little discrepancy between the results indicated by the previous studies and
one of present study. If the medium-scale cyclone can subsist longer periods as a result of
the coupling with the middle level trough, the synoptic trough structure should be revealed
more clearly in the composite maps at the cyclogenesis of the YANG and the TAIW
cyclones. However, the confirmable trough in the composite fields was exclusively in the
lower level. This characteristic is unchanged even if the composite analysis is separately
conducted for the longer lived cyclone and the shorter lived cyclone. That is, the fact that
the TAIW cyclone has a relatively long lifetime does not seems to relate directly to the
coupling with the synoptic trough in the upper level. The following represents a typical
case of the TAIW cyclone remotely related to a middle level synoptic trough.

The cyclone associated without synoptic trough was generated at 18 UTC 11 February
2001. The cyclone track is drawn in Fig. 5.7a by the black line with circles, which show
the position of cyclone center with an interval of 6 hours. The cyclone occurred in the
northeast of Taiwan and moved to eastward over the Pacific Ocean. Figure 5.8 shows the
upper (500 hPa) and lower (1000 or 925 hPa) charts at 0, 24, 54 hours after its cyclogenesis.
The surface cyclone formed as an inverted trough (the side of low pressure bulges to the
north) at 18 UTC 11 in the northeast of Taiwan (Fig. 5.8d). The high pressure from
continent covers the western part of Japan. In the 500 hPa level, the geopotential height
sweeps toward the west-east direction. After 24 hours from its genesis, the surface cyclone
center moved to eastward and developed. The cyclone is drawn by the closed contour lines,
not a weak trough (Fig. 5.8e). However, a synoptic trough can not be confirmed over the
surface cyclone at the 500 hPa level. Two troughs migrate at this time around 50° N,
120° E and 43° N, 110° E. At 00 UTC 14, the surface cyclone moved to 155° E. Although
the synoptic trough covers the whole Japan, the contours of geopotential height have not
been modified yet above the surface cyclone. Despite a lack of obvious interaction with
synoptic disturbance, the surface cyclone has been intensified exceeding the definition of bomb as shown in Fig. 5.7b.

This cyclone originated in the TAIW region is a meso-α cyclone which seems to be caused by cumulus convection. As shown in this case, the meso-α cyclone is sometimes allowed to happen and maintain their structure without the coupling with the synoptic trough. The fact makes the TAIW cyclone to have greater longevity in two ways; one is, obviously, that the cyclone can subsist during a few days as a mesoscale cyclone by the maintenance mechanism associated with cloud convection, the other is that the longer living as a mesoscale cyclone increases the chances of coupling and developing into a synoptical disturbance. Therefore, it is presumable that the TAIW cyclone tends to have a relatively long lifetime. The several issues, however, have not revealed in this paper, for example, the role of cumulus convection for the formation and maintenance of the meso-α cyclone and the reason of the high frequency of cyclogenesis in the northeast of Taiwan. On these matters, the additional studies are needed.
Fig. 5.1. Distribution of cyclogenesis frequency analyzed in NCEP II from 1980 to 2005. The contour lines show the frequency per grid point with 2.5 deg. per 30 days.
Fig. 5.2. Cyclone tracks of cyclone originated in the ALTAI region during spring with (a) longer lifetime and (b) shorter lifetime.
Fig. 5.3. Composite anomalies at the cyclogenesis of the ALTAI cyclone with longer lifetime (a, c), and shorter lifetime (b, d). The geopotential height (contours) and potential temperature (shaded) are indicated in (a) and (b), while the vorticity (contours), wind velocity (shaded), and wind vectors in (c) and (d). The gray square shows the ALTAI region.
Fig. 5.4. Same as Fig. 5.2, except for the cyclone originated in the YS region.
Fig. 5.5. Same as Fig. 5.3, except for the composite anomalies at the cyclogenesis of the YS cyclone. The gray square shows the YS region.
Fig. 5.6. Same as Fig. 5.5, except for the composite anomalies at 850 hPa.
Fig. 5.7. Relationship between (a) cyclone track and (b) center pressure of the cyclone generated at 18 UTC 11 February 2001. The black circles denote the point with an interval of 6 hours, while the double circles, that the cyclone satisfies the criteria of bomb within next 12 hours. The arrows indicate the position of the cyclone center at the time shown in Fig. 5.8.
Fig. 5.8. Geopotential height (contours), potential temperature (shaded), and wind vectors at 500 hPa level for (a) 18 UTC 11 February 2001, (b) 18 UTC 12, and (c) 00 UTC 14, and (d)-(e) at 1000 hPa and (f) 925 hPa levels for the corresponding times, respectively. The contour lines are drawn with intervals of 50 m (500 hPa) and 25 m (1000 and 925 hPa). The color bar of potential temperature and unit length of the wind vectors are shown at the outside of the figures.
Chapter VI

CONCLUSIONS

This study was successful at detecting the detailed distribution of cyclogenesis and cyclone track in East Asia with the high-resolution data. The climatological distribution of cyclogenesis analyzed in this study agreed well with that of the previous study. While cyclogenesis tends to occur frequently in several specific areas, the broadening of which is mostly narrower than those shown in previous studies.

The high-frequency regions of cyclogenesis are distributed in the lee of the mountains, the basins, the mouth of the Yangtze River, the Pacific Ocean to the east of Japan, the Sea of Japan, and the East China Sea. Especially, this study showed that the cyclogenesis frequently occurs at the Hebei Plain except for summer. In addition, the cyclogenesis maxima locate around the mouth of the Yangtze River and in the East China Sea to the northeast of Taiwan in winter. These areas are parts of origins of the cyclones passing through the southern coast of Japan and further windward than those estimated in previous studies.

The cyclogenesis frequency has a seasonal variation, the maximum of which is spring and autumn in the Mongolian Plateau and the Sichuan Basin, while it is spring in the Hebei Plain and the mouth of the Yangtze River. In the East China Sea to the northeast of Taiwan, the cyclogenesis occurs most frequently in winter.

Surface cyclones generated in East Asia are classified into two major groups according to the characteristics of their lifetime and the synoptic situation at the time of cyclogenesis. One is the cyclone originated in the northern area; the Mongolian Plateau and the Hebei Plain. These cyclones occur when the midlatitude trough approaches the wind-
ward mountain, namely, it is lee cyclone. The lifetime of them depends on the intense of migrating synoptic trough. Deeper trough with the large positive vorticity enables a cyclone to have a longer lifetime. The other is the cyclone originated in the southern area; the mouth of the Yangtze River, the East China Sea to the east of China and to the northeast of Taiwan. These are meso-α cyclones caused by cumulus convection, with a relatively long lifetime.

The knowledge obtained in this study is expected to improve the cyclone prediction and to assist the understanding of its related phenomena such as dust storm and snowfall associated with the southern coastal cyclone in Japan. Interestingly, the statistical analysis suggested that the cyclone in East Asia contains two types of cyclone driven by the different mechanisms of cyclogenesis and evolution. These mechanisms, particularly in the cyclones originated in the southern areas, need to be investigated and discussed furthermore in the future.
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References


Tracer model descriptions

The transport of a particle is calculated by advection and diffusion terms at every time step of 120 seconds in the Lagrangian particle model. The three-dimensional wind data is provided by RUN1 every hour. The hourly wind velocity is temporally and spatially interpolated in the tracer model. The horizontal diffusion coefficient $K_H$ is determined from the horizontal dispersion width given by the Pasquill-Gifford chart under conditions of stability $C$. The vertical diffusion coefficient $K_Z$ is assumed to be equal to $K_Z$ of the heat and water vapor, which is estimated in the TERC-RAMS.

The tracer particles are initially emitted by the Monte Carlo method into the atmosphere. The emission probability of new tracer particles is estimated at every grid point assuming a simple deflation scheme offered by Gillette (1978):

$$q = C(U - U_{tr}) \times U^2,$$

where $q$ is the emission rate of the tracer particles, $U$ is the surface wind velocity, and $U_{tr}$ is the threshold surface wind velocity for dust emission. These surface velocities, $U$ and $U_{tr}$, are originally defined at the level of 10 m. In the model, however, the emission rate $q$ is estimated by the wind velocity at the lowest grid point of 55 m in the model. The threshold wind velocity is converted into that defined at the lowest level assuming the logarithmic low in the near neutral surface layer:

$$U_z = \frac{u^* \ln \frac{z}{z_0}}{k},$$

where $u^*$ is friction velocity, $k$ is the Karman constant, and $U_z$ is the wind velocity at an altitude $z$.

Although the threshold wind velocity $U_{tr}$ is often assumed to be 6.5 ms$^{-1}$ at the level of 10 m above the ground level, some reports suggested a large difference of $U_{tr}$ among several emission areas (e.g., Kurosaki and Mikami 2007). Kurosaki and Mikami (2005)
studied numerous number of weather reports and suggested that the mean threshold wind velocity for a dust outbreak is higher than 6.5 $\text{ms}^{-1}$ in Northeastern Asia, except for bare desert regions, such as the Taklamakan Desert. Kurosaki and Mikami (2007) estimated that the critical wind velocity is at least 6 – 10 $\text{ms}^{-1}$ in the Gobi Desert; thus, we assumed that it is 8 $\text{ms}^{-1}$ at the level of 10 m. If we assume the roughness length $z_0$ to be $10^{-2}$ m, the critical wind velocity defined at the lowest grid point becomes about 10 $\text{ms}^{-1}$.

If the atmospheric process is completely adiabatic, the tracer particles will transport on an isentropic surface. Diabatic process allows the particles to cross the isentropic surfaces. The model includes two diabatic processes: turbulence and grid-scale diabatic heating of the atmosphere. Turbulence is almost limited in the boundary layer and is usually negligible in the free atmosphere. Grid-scale diabatic heating is caused by radiation flux divergence, grid-scale condensation, and cumulus parameterization. The sub-grid scale transport of the particles associated with the cumulus parameterization is not considered in this model.

Beside diabatic process, the dust particles are often removed from the atmosphere by sedimentation, dry deposition, and wet deposition. The dry deposition velocity is assumed to be equal to the sedimentation velocity in the model. We can ignore sedimentation and dry deposition for small particles with a diameter of less than a few micrometers, because the sedimentation velocity of these particles is estimated to be in an order of $10^{-5}$ $\text{ms}^{-1}$. The previous observational studies reported that the number of particles with a diameter in the range of 2 – 10 $\mu$m increases during dust events, while the dust plume is dominated by the particles in the range of 2 – 3 $\mu$m (Chun et al. 2001; Sugimoto et al. 2003). Since true color images, compared to the results of the numerical experiments, are sensitive mostly to these particles with a few micrometers, we assume that the diameter of Lagrangian particles is in this range and ignore sedimentation and dry deposition in the model. The wet deposition is also ignored in the model because of the difficulty of estimation. By this assumption, number of particles may be overestimated after encounter with deep convection.