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ORIGINAL ARTICLE

Study on the Synoptic Meteorological Characteristics of Windstorms Occurring on the Korean Peninsula

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Abstract

Although most natural disaster related studies conducted in Korea recently have been related to typhoons or severe rainstorms, the occurrence frequency of disasters due to windstorms or rainstorms is also high. To reduce the strong wind damage caused by strong windstorms due to climate change, basic studies of strong winds are necessary. Therefore, in this study, the types and representative cases of windstorms that were observed to have been higher than 14 m/s, which is the criterion for strong-wind warnings from the Korea Meteorological Administration, were selected from among those windstorm cases that occurred on the Korean Peninsula for 10 years to conduct a statistical analysis of them and determine their synoptic meteorological characteristics. The cases of windstorms occurring on the Korean Peninsula were divided into six weather patterns according to the locations of the anticyclones/cyclones. Among these types, the SH type, which occurs when Siberian Highs expand into the Korean Peninsula, showed the highest occurrence frequency, accounting for at least the majority of the entire occurrence frequency of windstorms together with that of the EC type, which occurs when cyclones develop on the East Sea, and there was no clear yearly trend of the occurrence frequencies of windstorms. The monthly occurrence frequencies of windstorms were formed mainly by typhoons in the summer and the Siberian Highs in the winter, and the months with the highest windstorm occurrence frequencies were December and January, in which mainly the SH and EC type windstorms occurred. March showed the next highest occurrence frequency with10 times, and SH windstorms occurred the most frequently in March, followed by the CC, SC, and EC types of windstorms, in order of precedence. Therefore, attention to these types of windstorms is required. Countermeasures against storm and flood damage in Korea targeting the summer should be re-reviewed together with pre-disaster prevention plans, because cases of storm and flood damage due to windstorms occur more frequently than those due to typhoons, and they occur throughout the year.

Key words : Windstorm, Climate change, Wind damage, Weather pattern, Synoptic meteorological characteristics

1. Introduction

Recently, extreme weather due to climate change, such as typhoons, localized torrential downpours, and droughts, has been continuously increasing throughout the world and the scales of the resultant damage have been growing to the extent that the damage due to weather disasters has amounted to several trillion

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won in Korea since the beginning of the 2000s (Park et al., 2005, 2007). This is attributable to increases in sea surface temperatures due to climate change not only in the tropical oceans, but also in the seas around the Korean Peninsula, resulting in increases in the scales of typhoons or windstorms as well as in the occurrence frequency of very strong winds (Berz and Conrad, 1993; KMA, 2005).

In reviewing the studies related to strong wind damage, it was found that the amount of strong wind damage that occurred on the Korean Peninsula in April and October 2005 was approximately 9.3 billion won, accounting for approximately 0.9% of the entire amount of damage on the Korean Peninsula during the same year (Hong, 2007). In 2012, when many typhoons in particular attacked the Korean Peninsula and the entire amount of damage due to natural disasters was 1.89 trillion won, the amount of damage due to strong winds was approximately 26.71 billion won, corresponding to 2.5% of the entire amount of damage, and the number of died victims was 33(NEMA, 2013). This indicates that the human and property damage caused by strong wind is not small.

In the case of foreign countries, due to increases in windstorms following climate change, disaster prediction models are being studied to reduce wind damage due to windstorms, and the results are reflected in the insurance industry. The series of winter windstorms that hit Western Europe at the end of the 1980s and at the beginning of the 1990s caused damage exceeding several billion dollars and caused huge economic losses to the insurance industry (Berz and Conrad, 1993). This series of windstorm events greatly affected not only the Netherlands, but also British society, resulting in changes in building codes as well as attracting people’s attention to studies about preventing windstorm disasters that may occur in the future, characteristics analysis, and disaster prediction modeling (Clark, 1986; Mitchell et al., 1989; Re, 1993; Dorland et al., 1999).

However, most natural disaster related studies that have been conducted in Korea thus far are related to typhoons or severe rainstorms, and most of the strong wind damage related studies analyzed strong wind damage cases due to typhoons (Park et al., 2008; Lee et al., 2009; Jung et al., 2010).

The level of perception of the risk of typhoons or heavy rain is relatively high, because the government or local governments extensively publicize natural disasters, such as typhoon, flood, and Asian dust before the disasters occur. However, although strong wind was third in the rankings of the amounts of damage as of 2012 and strong wind damage is still occurring, concrete measures to reduce this damage have not been sufficiently prepared. This is because the level of perception of the risk of strong wind is lower compared to that of the other disasters (Hong, 2007; Song and Kim, 2013). Therefore, the awareness of the risk of strong wind should be enhanced, and measures to reduce strong wind damage should be presented through studies of the characteristics of the damage caused by strong winds and the types of strong winds that occur.

The studies of the pressure patterns that cause strong winds or windstorms include a study conducted by Ha(1998) that divided the severe weather phenomena that cause strong winds that become problems when buildings’ wind resistant designs into typhoons, winds due to cyclogenesis, frontal winds, and seasonal winds, and stated that strong winds occur as seasonal winds caused by west high east low type pressure distributions resulting from cyclone paths or accompanying fronts without presenting any statistical data or concrete cases of strong winds as grounds for that statement. A study conducted by Kim et al.(2006, 2009) that reported that the annual average number of days of strong winds increased two times compared to the 20-year average value, that strong winds were caused by typhoons the most frequently, that strong winds were mainly caused by west high east low type pressure distributions or the expansion of Siberian air mass, and that the major regions affected by strong winds showed great differences according to their geographical locations through analyses of the strong wind damage that had occurred on the Korean Peninsula and the characteristics of the occurrences. Although this study is limited by the fact that the classification of the strong winds does not cover the entire Korean Peninsula because the strong winds were analyzed using hourly wind data from Mokpo, Gunsan, Yeosu, and Wando, where strong winds mainly occur, this study presented the necessity of the construction of measures to respond to strong winds by considering the characteristics of strong winds by region, because buildings are greatly affected by strong winds. Therefore, in future studies of strong winds, windstorm cases occurring on the Korean Peninsula over a long period of time should be selected, the characteristics of the strong winds should be presented through synoptic analyses, and the strong wind types should be classified.

Therefore, in the present study, basic data will be provided that can minimize the windstorm damage that has increased along with climate change and will enable the diagnosis and prediction of windstorms in advance by determining the statistical characteristics of the occurrence of the windstorms that affect the Korean Peninsula and classify the types of weather patterns that cause the windstorms to grasp their synoptic meteorological characteristics.

2. Material and Methods

2.1. Data

The weather data used to select the windstorm cases that occurred on the Korean Peninsula were hourly data from a total of 544 surface weather observatories comprised of 467 Automatic Weather Stations (AWS) throughout the country and 77 observing points of Automated Surface Observing Systems (ASOS). This data was collected for 10 years, from 2001 through 2010. The data used to classify the types of windstorm cases were from printed weather charts issued by the Japan Meteorological Agency and weather charts provided by KMA.

2.2. Windstorm case and type analysis method

For the objective classification of the occurrence of windstorm, Dreveton et al. (1998) acknowledged the occurrence of windstorms when 100 km/h (27.8 m/s) or higher wind speeds were identified through measurement at more than 5% of the entire number of observatories. In the case of Korea, the numbers of weather stations from which the data for the study period were obtained are shown in Table 1. As can be seen in Table 1, 507 points were operated per year on average. Therefore, 10% of all of the observatories was 50.7 points, 5% (as with the previous study) was 25 points, and 2% was 10 points.

Although no criteria for the occurrence of a windstorm is currently available in Korea, criteria for strong winds and wind waves have been prepared so that windstorms may be identified on the basis of strong winds. Strong-wind warnings are issued when 14m/s or higher wind speeds or 20m/s higher instantaneous wind speeds are expected on the land and wind wave warnings are issued when 14m/s or higher wind speeds are maintained for three hours or longer on the sea(KMA, 2014).

When the occurrence of windstorms was defined as cases where 14m/s or higher winds have blown for at least two hours, the cases where strong winds appeared at 5% of all of the observatories occurred three times during the study period, on August 31, 2002, September 12, 2002, and July 10, 2006, which are too few for the study. Cases where windstorms appeared at 10 observatories (which is 2% of all of the observatories) or more occurred on 97 days,

Table 1. Annual number of weather stations at each case in Korea (2001-2010)

Year	No. of all Station	No. of 10% station	No. of 5% station	No. of 2% station
2001	443	44.3	22.15	8.86
2002	464	46.4	23.2	9.28
2003	496	49.6	24.8	9.92
2004	518	51.8	25.9	10.36
2005	519	51.9	25.95	10.38
2006	523	52.3	26.15	10.46
2007	524	52.4	26.2	10.48
2008	529	52.9	26.45	10.58
2009	529	52.9	26.45	10.58
2010	525	52.5	26.25	10.5
average	507	50.70	25.35	10.14

which is a suitable number for the classification of types, and the horizontal scales of these cases satisfied the minimum scale. Currently, AWSs installed in Korea are located at intervals of approximately 13.3km and ASOSs are located at intervals of approximately 36 km (KMA, 2014).

Therefore, in the present study, cases where 14m/s or higher strong winds have blown for two hours or longer at 10 or more points were defined as windstorm occurrence days or windstorm days, and each case where windstorms persisted for 2~3 days was regarded as one occurrence. The results of the examination of windstorm days under the foregoing definition are shown in Table 2. A total of 66 cases were found.

Since damage can be minimized by identifying pressure patterns that cause windstorms in advance and utilizing the results in forecasting, the windstorms that occurred on the Korean Peninsula during the study period were selected as windstorms and the windstorm types were presented based on the regions where the center of the cyclone or anticyclone that caused the strong winds was located, as used by Lamb (1972) (Table 2).

The windstorms were divided into six weather type according to the weather patterns on the windstorm occurrence days, the locations of the centers of the windstorms, and the moving paths of the windstorms. The criteria for classification were as follows. The first type was cases where Siberian Highs accompanied by strong winds expanded to the Korean Peninsula, and this type was named the Siberian High type (SH). The second type was cases where cyclones centered on China moved to the Korean Peninsula while causing strong winds, and this type was divided into four sub-types according to the locations of the cyclones.

The cases where windstorms occurred while cyclones developed in northern China moved to the Korean Peninsula were named the Northern China Low type (NC), the cases where windstorms occurred while cyclones developed in central China moved to the Korean Peninsula were named the Central China Low type (CC), the cases where windstorms occurred while cyclones located in the southern part of China or southern China moved to the Korean Peninsula were named the Southern China Low type (SC), and the cases where cyclones developed on the East Sea moved to the Korean Peninsula and caused strong winds were named the Eastern Coast Low type (EC).

Finally, the cases where strong winds occurred when a typhoon affected the Korean Peninsula were

Table 2. List of windstorm days and classification of windstorm type in Korea (2001-2010)

No.	Time of occurrence	Type	No.	Time of occurrence	Type
1	2001-01-07 06:00 ~ 2001-01-07 08:00	SC	35	2006-02-07 09:00 ~ 2006-02-07 18:00	SH
2	2001-03-04 20:00 ~ 2001-03-04 21:00	EC	36	2006-03-12 13:00 ~ 2006-03-12 19:00	SH
3	2002-01-07 13:00 ~ 2002-01-08 02:00	EC	37	2006-03-28 14:00 ~ 2006-03-28 19:00	EC
4	2002-07-05 11:00 ~ 2002-07-05 21:00	TY	38	2006-04-19 16:00 ~ 2006-04-20 21:00	EC
5	2002-08-31 04:00 ~ 2002-09-01 03:00	TY	39	2006-07-10 04:00 ~ 2006-07-10 15:00	TY
6	2002-12-25 09:00 ~ 2002-12-25 12:00	SH	40	2006-09-17 16:00 ~ 2006-09-17 21:00	TY
7	2003-01-03 15:00 ~ 2003-01-03 17:00	SH	41	2006-10-23 09:00 ~ 2006-10-23 15:00	CC
8	2003-01-04 14:00 ~ 2003-01-05 02:00	SH	42	2006-11-06 19:00 ~ 2006-11-07 02:00	EC
9	2003-01-27 15:00 ~ 2003-01-27 22:00	EC	43	2006-12-17 06:00 ~ 2006-12-17 15:00	SH
10	2003-01-28 17:00 ～ 2003-01-29 07:00	SH	44	2006-12-28 04:00 ~ 2006-12-28 17:00	SH
11	2003-03-03 08:00 ~ 2003-03-03 17:00	SH	45	2007-01-06 09:00 ~ 2007-01-07 05:00	EC
12	2003-04-01 06:00 ~ 2003-04-01 08:00	SC	46	2007-02-14 09:00 ~ 2007-02-14 17:00	EC
13	2003-09-12 15:00 ~ 2003-09-13 24:00	TY	47	2007-03-04 18:00 ~ 2007-03-05 24:00	CC
14	2003-11-21 13:00 ~ 2003-11-21 14:00	SH	48	2007-09-16 12:00 ~ 2007-09-16 18:00	TY
15	2004-01-12 22:00 ~ 2004-01-13 24:00	NC	49	2007-12-30 13:00 ~ 2007-12-30 19:00	EC
16	2004-02-05 01:00 ~ 2004-02-05 04:00	SH	50	2008-04-09 07:00 ～ 2008-04-09 12:00	SC
17	2004-02-22 14:00 ~ 2004-02-23 24:00	EC	51	2008-11-29 11:00 ~ 2008-11-29 16:00	EC
18	2004-04-01 24:00 ~ 2004-04-02 02:00	CC	52	2008-12-05 06:00 ~ 2008-12-05 14:00	SH
19	2004-04-27 05:00 ~ 2004-04-27 13:00	CC	53	2009-01-12 02:00 ~ 2009-01-12 04:00	SH
20	2004-07-04 06:00 ~ 2004-07-04 14:00	SC	54	2009-01-23 11:00 ~ 2009-01-23 13:00	SH
21	2004-08-19 05:00 ~ 2004-08-19 06:00	TY	55	2009-02-13 01:00 ~ 2009-02-13 12:00	CC
22	2004-09-07 05:00 ~ 2004-09-07 09:00	TY	56	2009-03-13 15:00 ~ 2009-03-13 22:00	SC
23	2004-11-26 09:00 ~ 2004-11-26 18:00	CC	57	2009-11-02 10:00 ~ 2009-11-02 11:00	SH
24	2004-12-04 22:00 ~ 2004-12-05 13:00	SC	58	2009-12-05 04:00 ~ 2009-12-05 13:00	EC
25	2005-01-31 20:00 ~ 2005-02-01 19:00	SH	59	2009-12-31 02:00 ~ 2009-12-31 07:00	SH
26	2005-02-15 17:00 ~ 2005-02-15 21:00	SC	60	2010-01-04 16:00 ~ 2010-01-04 17:00	CC
27	2005-02-19 15:00 ~ 2005-02-19 16:00	SH	61	2010-03-09 23:00 ~ 2010-03-10 04:00	SH
28	2005-03-11 15:00 ~ 2005-03-12 24:00	SC	62	2010-03-20 22:00 ~ 2010-03-21 03:00	CC
29	2005-03-24 08:00 ~ 2005-03-24 18:00	SH	63	2010-04-13 15:00 ~ 2010-04-13 18:00	CC
30	2005-09-05 21:00 ~ 2005-09-06 21:00	TY	64	2010-04-28 17:00 ~ 2010-04-28 19:00	CC
31	2005-11-28 18:00 ~ 2005-11-28 22:00	NC	65	2010-09-01 23:00 ~ 2010-09-02 07:00	TY
32	2005-12-04 15:00 ~ 2005-12-04 18:00	EC	66	2010-10-25 16:00 ~ 2010-10-26 10:00	SH
33	2005-12-17 15:00 ~ 2005-12-17 20:00	SH	67	2010-11-08 24:00 ~ 2010-11-09 03:00	EC
34	2005-12-21 13:00 ~ 2005-12-21 24:00	SH	68	2010-12-03 06:00 ~ 2010-12-03 13:00	SH

*time of occurrence by local standard time(LST)

Table 3. Occurrence frequency of windstorm days according to weather patterns (2001-2010)

Weather pattern	Type	Occurrence frequency of storm day											
		‘01	‘02	‘03	‘04	‘05	‘06	‘07	‘08	‘09	‘10	total	%
Siberian High	SH	0	1	4	1	5	4	0	1	4	4	24	35.3
Low pressure	NC	0	0	0	1	1	0	0	0	0	0	2	2.9
	CC	0	0	0	3	0	1	1	0	1	4	10	14.7
	SC	1	0	1	3	2	0	0	0	1	0	8	11.8
	EC	1	1	1	1	1	3	3	1	1	1	14	20.6
Typhoon	TY	0	2	1	2	1	2	1	0	0	1	10	14.7
Total		2	4	7	11	10	10	5	2	7	10	68	100

named the Typhoon type (TY). The SH type is similar to the Siberian High type presented by Moon (1982) and Park et al. (1991) in which strong windstorms occurred when cold Siberian Highs expanded from the northwest side of the Korean Peninsula after cyclones passed the Korean Peninsula (Lee, 2011). The NC, CC, and SC types are similar to the Low pressure patterns (III-1, III-b, III-c) presented by Park et al. (1991) respectively and the TY type is similar to the Typhoon type (type VI) presented by Park et al. (1991). However, the EC type in which cyclones develop on the East Sea is presented for the first time.

3. Results and discussion

3.1. Yearly windstorm occurrence frequencies

Table 3 shows the occurrence frequencies of windstorms occurring on the Korean Peninsula according to weather patterns and years. The weather patterns that showed the highest occurrence frequency was the SH type, which occurred 24 times during the period of the present study, accounting for 35.3% of the entire number of times of occurrence. The weather patterns that showed the second highest occurrence frequency was the EC type, in which cyclones developed after moving to the East Sea, causing strong winds that occurred 14 times, accounting for 20.6% of the entire number of times of occurrence. The CC and TY types occurred third most frequently with10 times (14.7%) each and the SC type occurred fourth most frequently with 8 times (11.8%). The weather patterns that showed the lowest frequency was the NC type, which occurred two times (2.9%) during the study period.

Therefore, among the windstorms that occurred on the Korean Peninsula during the study period, the SH type showed the highest frequency followed by the EC type. That is, at least 55.9% of the entire occurrence frequency was attributable to the SH and EC types, indicating that the majority of the windstorms that occurred in Korea was caused by the expansion of Siberian Highs and the development of cyclones in the East Sea(refer to Fig. 1). Although windstorms frequently occurred when typhoons hit the Korean Peninsula, more cases of windstorms occurred due to other weather patterns during the period of the present study. Therefore, countermeasures against storm and flood damage on the Korean Peninsula should include storm and flood damage caused by windstorms in addition to the damage caused by typhoons.

In reviewing the yearly windstorm occurrence frequencies, 2004 had the highest occurrence frequency with 11 times, followed by 2005 and 2006 with10 times each, and 2001 and 2008 had the lowest windstorm occurrence frequency with two times each. No particular yearly characteristics could be found.

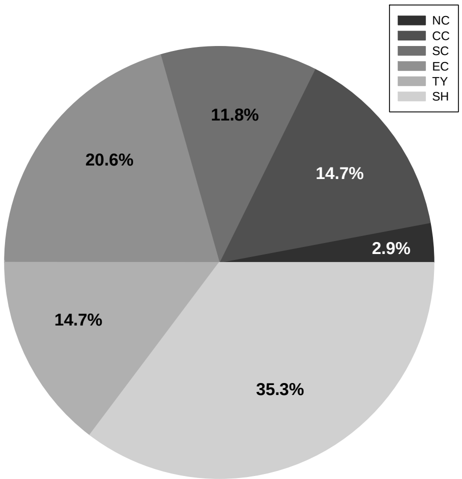


Fig. 1. Occurrence frequency and percentage of windstorm days by weather patterns (2001-2010).

In reviewing the yearly weather patterns, the SH type occurred one through five times in each of eight years during the study period (except for 2001 and 2007) and among the cyclone types, the EC type occurred at least once in all the years during the study period. Therefore, attention should be paid to the SH and EC types. The CC type and the SC type occurred 10 times and 8 times respectively for five years, and the NC type appeared the least frequently. The CC type in particular showed a tendency of occurrence frequencies increasing over time (refer to Fig. 2). The TY type occurred during most years, except for certain years in which typhoons did not affect Korea.

Therefore, the year in which windstorms occurred the most frequently during the study period was 2004 (11 times), followed by 2005 (10 times) and 2006 (10 times), and windstorms occurred the least frequently in 2001 (2 times) and 2008 (2 times). The windstorm types that occurred almost every year were cases where Siberian Highs expanded to the Korean Peninsula (SH type) and cases where cyclones developed in the East Sea (EC type).The cases of typhoons (TY type) and the CC type resulting from the movements of cyclones in central China appeared at least once per year on average. Countermeasures against storm and flood damage in Korea have mainly targeted the summer, but these should be re-reviewed together with pre-disaster prevention plans because cases of storm and flood damage due to windstorms occur more frequently than those due to typhoons.

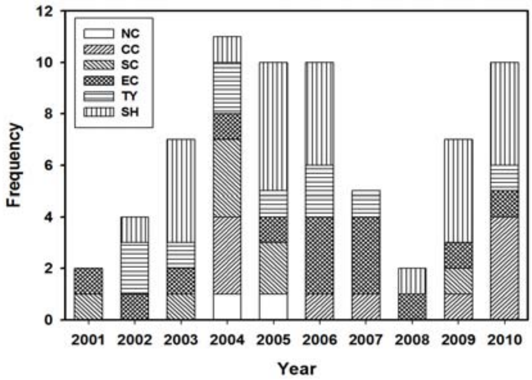


Fig. 2. Yearly occurrence frequency of windstorm by weather patterns (2001-2010).

3.2. Monthly windstorm occurrence frequencies

In reviewing the monthly occurrence frequencies of the windstorms that occurred in Korea from 2001 through 2010(refer to Fig. 3), the occurrence frequencies were generally higher in winter compared to summer, as December and January showed the highest occurrence frequency with12 times each and May and June showed the lowest occurrence frequency with no windstorms at all.

Among windstorm types, in winter, the SH type occurred the most frequently, followed by the EC type. On the other hand, in summer, all the windstorms that occurred were the TY type, except for July, during which one SC type occurred. The SH type that showed the highest occurrence frequency throughout the study period occurred from October through March, with the highest frequency in December. The EC type that showed the second highest occurrence frequency occurred mainly from

November through April of the next year with three times each in November, December, and January, indicating that it occurred mainly in winter. Although the SH type windstorms occurred the most frequently until the end of March (4 times), the occurrence frequencies of windstorms caused by the movements of cyclones such as the CC (2 times), SC (2 times), and EC (2 times) types increased in March. In April, the frequencies of the CC (4 times), SC (2 times), and EC (1 time) types increased, indicating that the occurrence frequencies of strong winds and windstorms on the Korean Peninsula increased in the spring because the cyclones that occurred in central and southern China frequently moved as the Siberian Highs became weaker.

Therefore, the monthly occurrence frequencies of windstorms were mainly attributable to typhoons in the summer and Siberian Highs in the winter, and the months in which windstorm occurrence frequencies were the highest were December and January, during which the SH and EC type windstorms mainly occurred. The month that showed the next highest occurrence frequency was March, during which10 windstorms occurred. Attention should be paid to the SH type windstorms, which came the most frequently, followed by CC, SC, and EC type windstorms, in order of precedence.

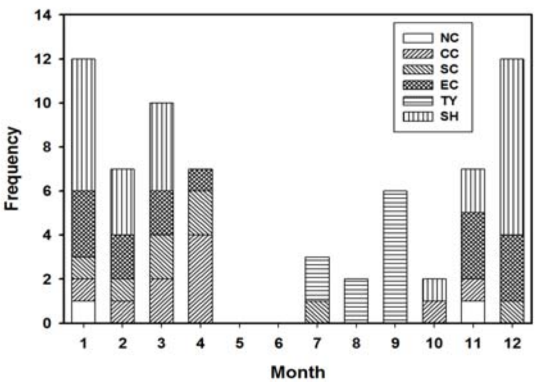


Fig. 3. Monthly occurrence frequency of windstorm by weather patterns (2001-2010).

3.3. Synoptic meteorological characteristics of windstorms by pressure pattern

As for the windstorms that occurred on the Korean Peninsula as set forth in the above section by type, the SH type occurred the most frequently with 24 times, followed by EC (14 times), CC (10 times), TY (10 times), SC (8 times), and NC (2 times) types, amounting to a total of 68 cases (refer to Table 3). To examine the synoptic meteorological characteristics of windstorms by type, the days on which strong winds were observed at the largest number of points were selected as representative cases. This is because days with more points where strong winds are higher than the level of the strong-wind warning (14 m/s or higher) are synoptically and meteorologically more representative and meaningful in interpretation.

Three representative windstorm days were selected for each type in the order of the number of points where strong winds were observed, beginning with the largest number, and the pressure patterns, periods of occurrence, durations, and the time and date at which the highest wind speed in each occurrence period appeared and the number of observation points are shown in Table 4. In the case of the NC type, three windstorm days could not be selected, because only two case days occurred during the period of the present study and between the two case days, the case day on which the number of observation points was larger was shown.

As can be seen in the Table 4, the pressure pattern during which strong winds were observed at the largest number of observatories was the TY type, followed by the SH type, and the pressure pattern during which strong winds were observed at the smallest number of observatories was the NC type. Among the NC, CC, SC, and EC types, which are related to cyclone movements, the CC type had strong winds observed at relatively many observatories, followed by the EC type rather than

Table 4. Representative windstorm days by each weather patterns in Korea (2001-2010)

Type	No.	Time of occurrence	Duration time	Peak time	No. of the Observed station
TY	5	2002-08-31 04:00 ~ 2002-09-01 03:00	24	2002-08-31 18:00	41
	13	2003-09-12 15:00 ~ 2003-09-13 24:00	10	2003-09-12 21:00	41
	39	2006-07-10 04:00 ~ 2006-07-10 15:00	12	2006-07-10 07:00	33
NC	15	2004-01-12 22:00 ~ 2004-01-13 24:00	3	2004-01-12 23:00	11
CC	55	2009-02-13 01:00 ~ 2009-02-13 12:00	12	2009-02-13 09:00	23
	47	2007-03-04 18:00 ~ 2007-03-05 24:00	27	2007-03-05 06:00	22
	23	2004-11-26 09:00 ~ 2004-11-26 18:00	9	2004-11-26 12:00	19
SC	24	2004-12-04 22:00 ~ 2004-12-05 13:00	14	2004-12-05 02:00	20
	20	2004-07-04 06:00 ~ 2004-07-04 14:00	9	2004-07-04 10:00	15
	28	2005-03-11 15:00 ~ 2005-03-12 24:00	8	2005-03-11 24:00	14
EC	45	2007-01-06 09:00 ~ 2007-01-07 05:00	20	2007-01-06-15:00	19
	38	2006-04-19 16:00 ~ 2006-04-20 21:00	26	2006-04-20-16:00	19
	9	2003-01-27 15:00 ~ 2003-01-27 22:00	8	2003-01-27 17:00	17
SH	34	2005-12-21 13:00 ~ 2005-12-21 24:00	11	2005-12-21 15:00	24
	29	2005-03-24 08:00 ~ 2005-03-24 18:00	11	2005-03-24 15:00	22
	33	2005-12-17 15:00 ~ 2005-12-17 20:00	6	2005-12-17 17:00	20

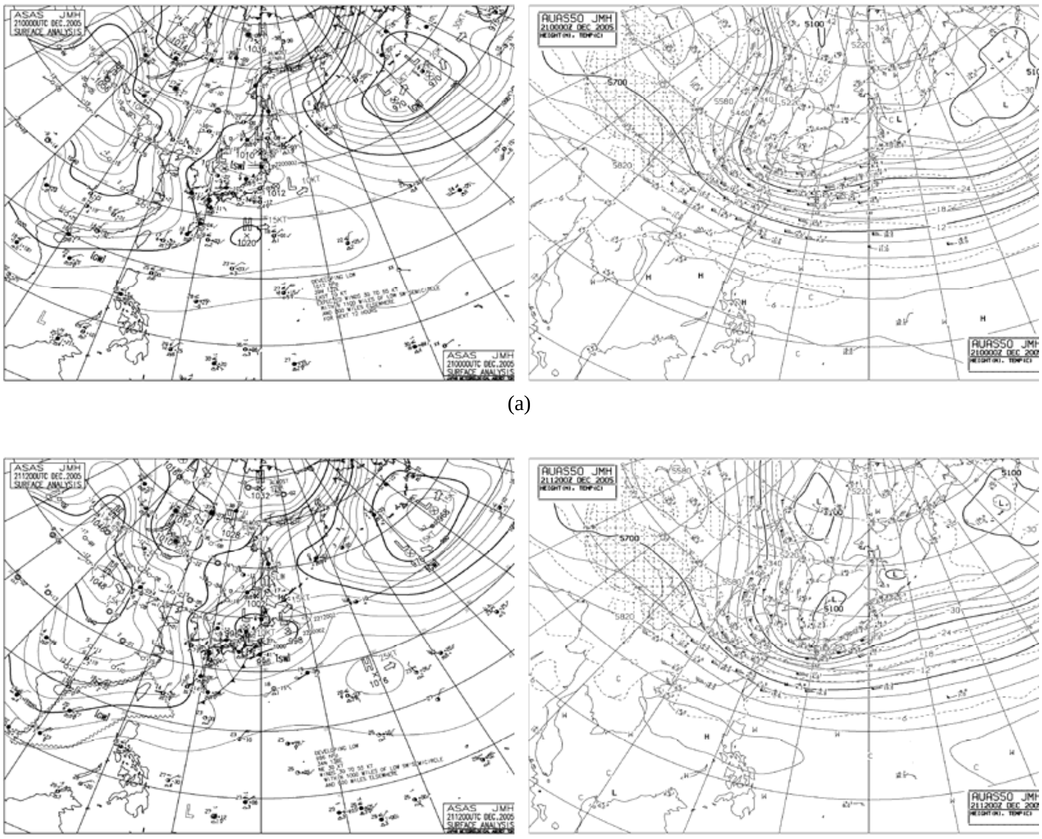
the SC type.

The case in which the duration of strong winds not slower than 14 m/s was the longest was a CC type windstorm during which strong winds were observed for 27 hours from 1800 LST on March 4, 2007 to 2400 LST on March 5, 2007, and the time at which strong winds were observed at the largest number of points was 0600 LST on March 5, during which strong winds were observed at 22 points, corresponding to 4% of the entire observing points. Although the scale was smaller compared to that of windstorms caused by typhoons, the durations and scales of the strong winds caused by extratropical cyclones were shown to be long and large. The second longest duration was an EC type windstorm that persisted for 26 hours from 1600 LST on April 19, 2006 to 2100 LST on April 20, 2006, and the scale of this case was thought to have been a little smaller compared to the above mentioned case because strong winds were observed at only 19 points at 1600 LST on April 20, 2006.

Therefore, since the frequencies of TY, SH, CC, and EC types were shown to be relatively high among the weather patterns that occurred on the Korean Peninsula according to the number of points at which strong winds were observed and their durations, and although there were some differences, the synoptic meteorological characteristics of the cases of these types will be examined.

3.3.1. Representatives of the SH type

The SH type, which is the weather pattern that showed the highest windstorm occurrence frequency on the Korean Peninsula, refers to cases where windstorms were caused when Siberian Highs expanded to the Korean Peninsula. This type of windstorm with 14 m/s or higher strong winds was observed at the largest number of points on December 21, 2005, followed by March 24, 2005 and December 17, 2005 (refer to Table 4). Among these cases, the synoptic meteorological characteristics of



(a)

(b)

Fig. 4. Weather charts at the surface (left), 500 hPa (right) of (a) 0900 LST 21, December and (b) 2100 LST 21, December, 2005 as a SH type.

December 21, 2005, in which strong winds were observed at the largest number of observing points, was examined.

On December 21, 2005, strong winds blew from 1300 LST to 2400 LST. In reviewing the surface weather chart and the 500 hPa upper layer weather chart at 0900 LST on December 21, 2005, which was before the strong winds blew, a 1008 hPa cyclone was located in the center of the East Sea of Korea, a Siberian High expanded to the southeastern region of China on the west side of Korea on the surface, northwesterly winds were blowing in Korea due to the effect of the Siberian High, and the same winds could be expected to blow thereafter as well (see Fig. 4(a)). It can also be seen that if the anticyclones became stronger, the northwesterly winds would increase further, and not only precipitation phenomena but also strong winds could be expected depending on the regions, because the air that passed the west coast contained water vapor. In the 500 hPa upper layer, the front side of a pressure trough was located on the Korean Peninsula and contour lines were distributed in the east-west direction, showing that northwesterly winds or southwesterly winds were blowing strongly, and it could be expected that the power of the anticyclones would expand greatly because of the fast movements of the pressure system.

On the surface weather chart and the 500 hPa weather chart at 2100 LST on December 21, 2005, which was12 hours later (see Fig. 4(b)), it can be seen that strong northwesterly winds were blowing on the surface because of the expansion of the Siberian High and because the cyclone on the East Sea had moved eastward a little. However, the central pressure had decreased to 992 hPa, thereby preventing the further expansion of the anticyclones, and therefore the winds were expected to become gradually weaker. On the 500 hPa upper layer weather chart, the rear side of the pressure trough was located on the Korean Peninsula, so the effect of the Siberian High was expected to become gradually weaker.

Therefore, it can be seen that the windstorm that occurred on December 21, 2005 on the Korean Peninsula is attributable to the expansion of a Siberian High, and that the rear side of the pressure trough became located over the Korean Peninsula as the pressure trough in the upper layer passed the Korean Peninsula, and the strong winds became gradually weaker as the cyclone on the East Sea became stronger and restrained the expansion of the anticyclones.

3.3.2. Representatives of the EC type

The weather pattern that caused the second largest number of windstorms on the Korean Peninsula was the EC type, which refers to cases where windstorms occurred on the Korean Peninsula when cyclones located in the East Sea were developing. Selected cases of this type occurred on January 6, 2007, April 20, 2006, and January 27, 2003, in order of precedence from the case with the largest number of points where 14m/s or higher strong winds were observed. Among these cases, the case on January 6, 2007, in which strong winds were observed at many points, was selected for the analysis of the synoptic meteorological characteristics.

Although strong winds blew from 0900 LST on January 6, 2007 to 0500 LST on January 7, 2007 in this case, winds at the level of the strong-wind warning persisted for approximately 20 hours, as the wind speed was shown to be below 14m/s at 0400 LST on January 7. A 1018 hPa cyclone located in the vicinity of Manchuria on the north side of the Korean Peninsula at 2100 LST on January 5, which was before strong winds blew, moved southeastward, was supplied with water vapor, and developed into a 1008 hPa cyclone accompanying a front on the East Sea on the north side of Wonsan by 0900 LST on January 6(refer to Fig. 5(a)~(b)). Consequently, strong winds began to blow on the Korean Peninsula and persisted throughout the day. At 2100 LST on January 6, the center of the cyclone located in the East Sea moved eastward a little, but strong winds were still blowing on the Korean Peninsula while the central pressure increased to 994 hPa(refer to Figure 5(c)). At 0900 LST on the next day, January 7, the Siberian High expanded and the cyclone in the East Sea moved to the Japanese Archipelago, so that the effects of the developed cyclone on Korea stopped (refer to Fig. 5(d)).

These phenomena could be identified in the 500 hPa upper layer weather chart too, as if they were supporting the surface pressure patterns as such (refer to Fig. 5(e)). The cyclone on the surface moved southeastward to the East Sea because of the effect of the strong cyclone cell located in the Manchuria region on the north side of the Korean Peninsula and the fast air movements in the east-west direction. A pressure ridge existing on the Japanese Archipelago restrained the eastward movement of the cyclone on the sea on the east side of the Korean Peninsula, which increased the water vapor supply, so that the cyclone developed and led to the development of windstorms accompanied by strong winds. These phenomena persisted throughout the day, and as can

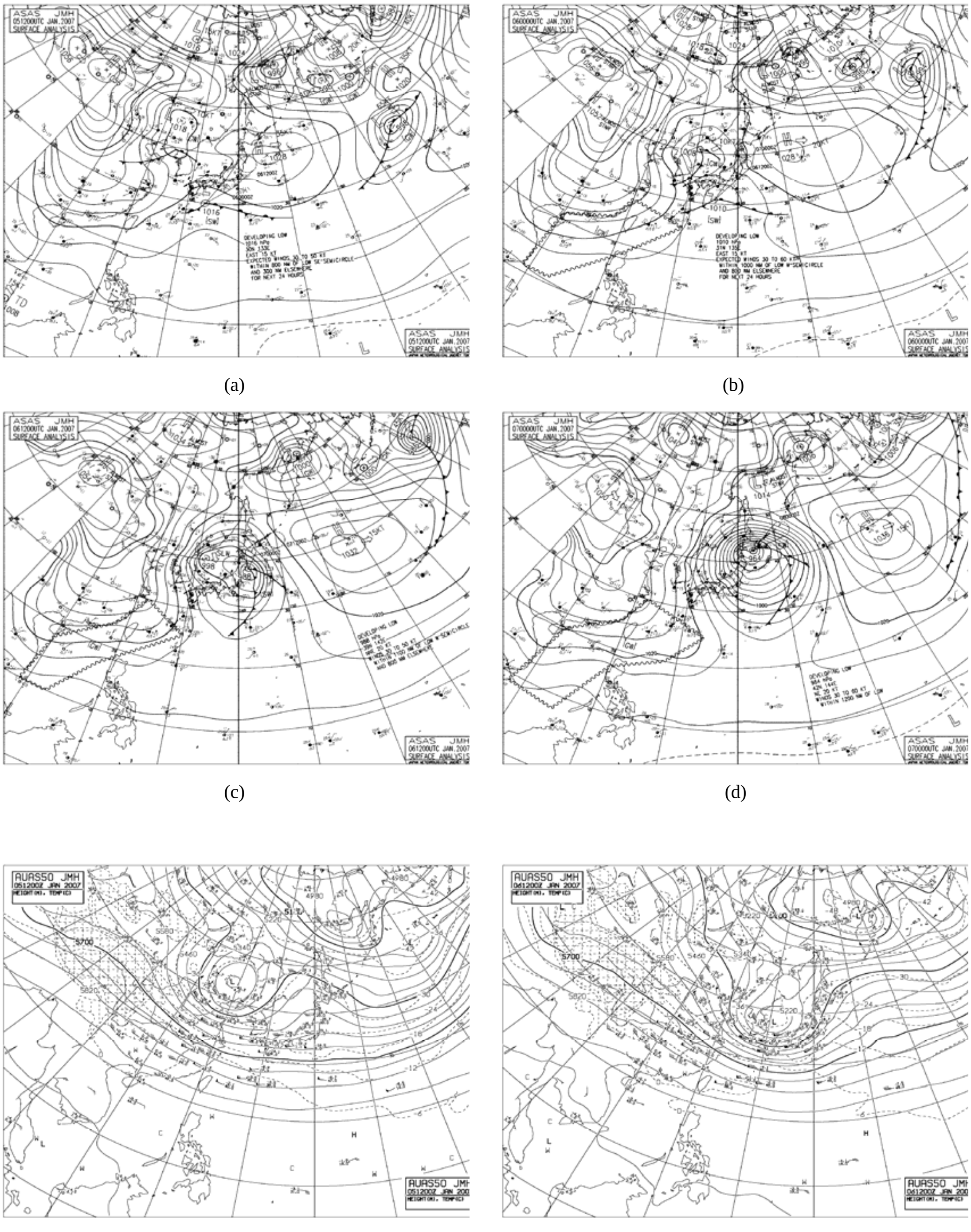


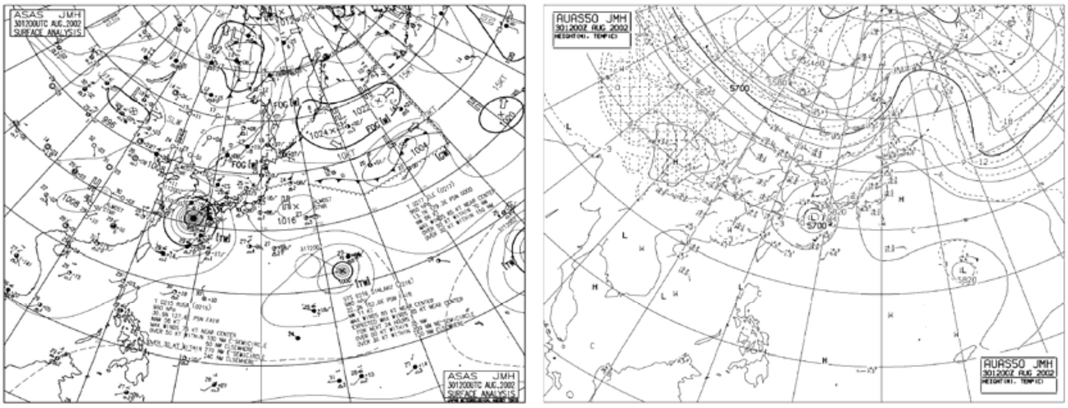
Fig. 5. Weather charts at the surface of (a) 2100 LST 5, January, (b) 0900 LST 6, January, (c) 2100 LST 6, January, (d) 0900 LST 7, January and at 500 hPa of (e) 2100 LST 5, January, (f) 2100 LST 6, January, 2007 as a EC type.

be seen in the upper layer weather chart at 2100 LST on January 6, the cyclone cell moved southeastward to the Korean Peninsula and located at the rear of the pressure trough, so that the cyclone in the East Sea could keep developing and westerly winds, including northwesterly or west-southwesterly winds, appeared. Thereafter, the effects of the cyclone developed in the East Sea stopped following the expansion of the Siberian High (refer to Fig. 5(f)).

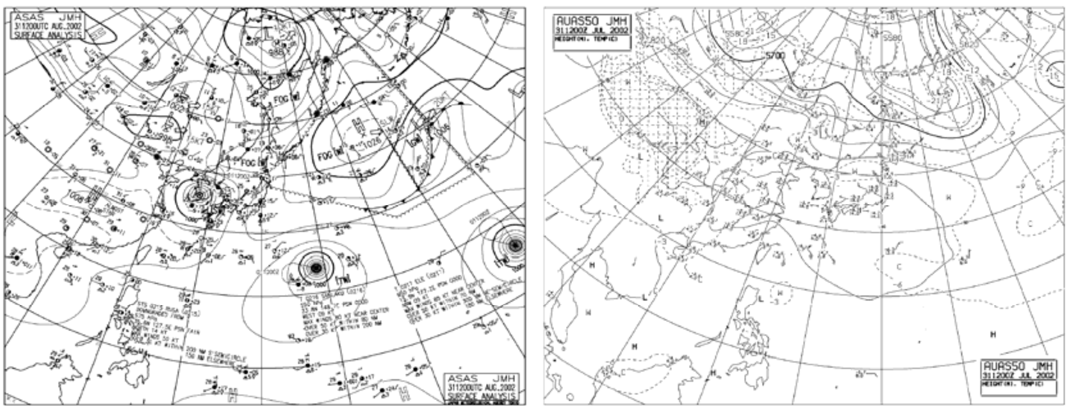
Therefore, it can be seen that the EC type, in which windstorms are caused on the Korean Peninsula by cyclones developing in the East Sea, is a pressure pattern that occurs every year, and that the cyclones in the East Sea are supplied with more water vapor when the pressure ridge on the Japanese Archipelago restrains the eastward movement of the cyclones and led to the occurrence of windstorms accompanied by strong winds on the Korean Peninsula.

3.3.3. Representatives of the TY type

The TY type of weather pattern caused the third largest number of windstorms on the Korean Peninsula during the study period, and three cases of this type appeared on August 31, 2002, September 12, 2003, and July 10, 2006 (refer to Table 4). All



(a)



(b)

Fig. 6. Weather charts at the surface (left), 500 hPa (right) of (a) 2100 LST 30, August, and (b) 0900 LST 31, August, 2002 as a TY type.

these cases were observed at points with relatively more strong winds compared to other points. Among these cases, the synoptic meteorological characteristics of the case that appeared on August 31, 2002 were examined.

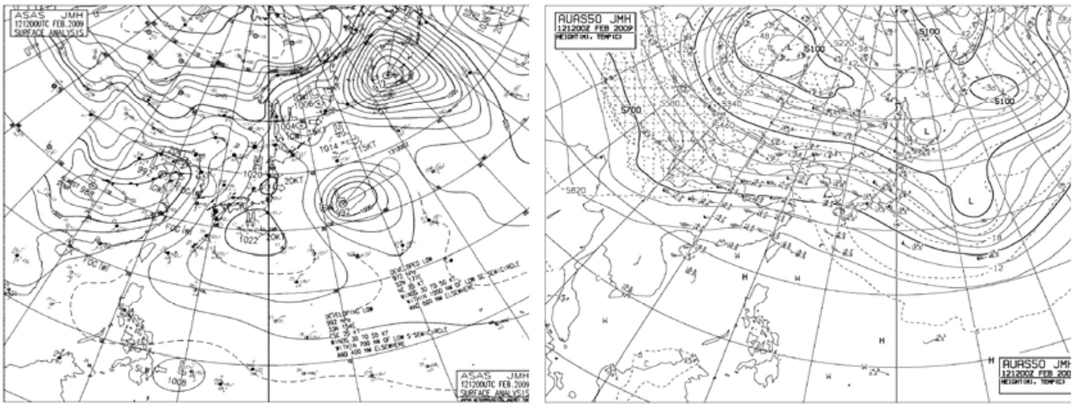
The windstorm persisted from 0400 LST on August 31, 2002 to 0300 LST on September 1, 2002 and strong winds persisted for 24 hours. In reviewing the surface weather chart and upper layer weather chart at 2100 LST on August 30, which was before strong winds blew (refer to Fig. 6(a)), it can be seen that the center of typhoon Rusa (0215) was located in the sea on the south side of the Korean Peninsula and that some regions, including Jeju-do, were not yet affected by the typhoon. In the 500 hPa upper layer weather chart, the typhoon area of concentric circles was located in the sea on the south side of the Korean Peninsula, indicating that Korea might be affected by strong winds caused by the typhoon. Very strong winds caused by the typhoon began to appear thereafter, and at 0900 LST on the next day, August 31, the surface weather chart and upper layer weather chart (refer to Fig. 6(b)) showed that the typhoon area of concentric circles landed on the Korean Peninsula, indicating that strong winds and precipitation phenomena could be expected throughout the Korean Peninsula.

Therefore, in the case of the windstorm caused by the typhoon that landed on the Korean Peninsula on August 31, 2002, it can be seen that strong winds and precipitation phenomena could be expected throughout the Korean Peninsula from immediately before the landing of the typhoon on the Korean Peninsula to the moment at which the typhoon completely passed the Korean Peninsula according to the typhoon area of concentric circles, and that the strong winds and precipitation phenomena stopped as soon as the effects of the typhoon disappeared.

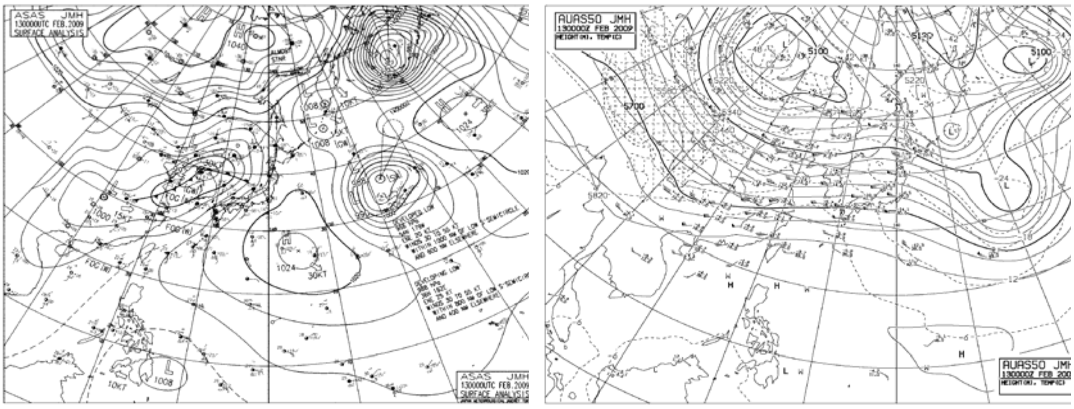
3.3.4. Representatives of the CC type

In addition to the TY type, another weather pattern that caused the third largest number of windstorms on the Korean Peninsula during the study period was the CC type, which results from the effects of cyclones centered in central China moving to the Korean Peninsula. This type showed many points where strong winds were observed on February 13, 2009, March 5, 2007, and November 26, 2004, in order of precedence (as shown in Table 4). From among these cases, the first case in which strong winds were observed at the largest number of points was selected as a representative case. On February 13, 2009, strong winds began to blow at 0100 LST and persisted for approximately 12 hours until 1200 LST.

A pressure trough that was in central China developed into a cyclone with a central pressure value of 992 hPa in the vicinity of the Shantung Peninsula in China by 2100 LST on February 12, 2009, accompanied by a front that became a pressure pattern that affected the Korean Peninsula(refer to Fig. 7(a)). In reviewing the 500 hPa upper layer weather chart at the same time point, it can be seen that the front side of the pressure trough was located on the Korean Peninsula so that surface cyclones could develop and that a weak pressure ridge existed in the East Sea on the east side of the Korean Peninsula, which was expected to move eastward while reinforcing surface anticyclones. In reviewing the surface weather chart and the 500 hPa upper layer weather chart at 0900 LST on the next day when strong winds persisted (refer to Fig. 7(b)), it can be seen that cyclones accompanied by fronts were located from the southern to the northern regions of the Korean Peninsula and that strong winds and precipitation could be expected throughout the regions ahead of the fronts. In the upper layer, a pressure trough approached the Korean Peninsula closely so that strong winds would appear, while the



(a)



(b)

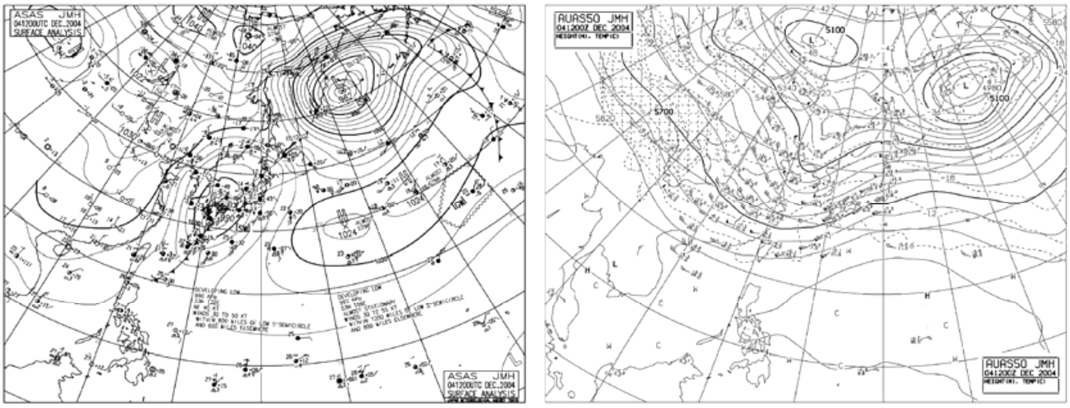
Fig. 7. Weather charts at the surface (left), 500 hPa (right) of (a) 2100 LST 12, February, and (b) 0900 LST 13, February, 2009 as a CC type.

pressure trough that had affected the East Sea would appear in the Japanese Archipelago so that the cyclones would move eastward faster and the strong wind would gradually stop.

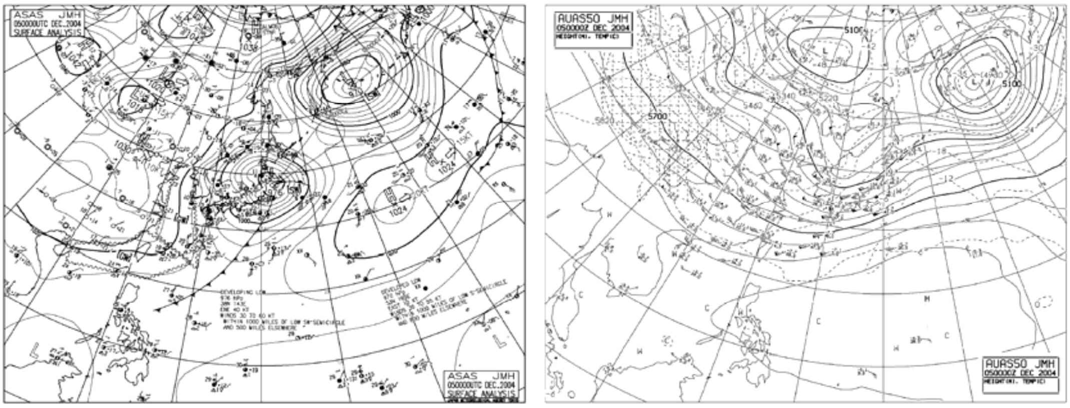
Therefore, it can be seen that in cases where cyclones developed in central China move to the Korean Peninsula accompanying windstorms, strong winds appear in front of the fronts because fronts accompany the cyclones and induce precipitation phenomena, which would not persist very long.

3.3.5. Representatives of the SC type

The pressure pattern that caused the fifth largest number of windstorms on the Korean Peninsula during the study period was the SC type, referring to cases where cyclones that developed in the southern region of China caused windstorms while they were moving to the Korean Peninsula. Three cases of this type were selected as shown in Table 4: December 5, 2004, July 4, 2004, and March 11, 2005, in order of precedence from the case in which strong winds were observed at the largest number of points. From among these cases, the case on December 5, 2004, in which strong winds were observed at the largest number of points, was selected as a representative



(a)



(b)

Fig. 8. Weather charts at the surface (left), 500 hPa (right) of (a) 2100 LST 4, December and (b) 0900 LST 5, December, 2004 as a SC type.

case for the analysis of the synoptic meteorological characteristics. In this case, strong winds blew for 14 hours from 2200 LST on December 4, 2004 to 1300 LST on December 5, 2004.

In reviewing the surface weather chart and upper layer weather chart at 2100 LST on December 4, 2004, which was one hour before the strong winds began (refer to Fig. 8(a)), it could be seen that a cyclone with a front that existed across the southern China region and the South China Sea 12 hours earlier passed the South Sea of Korea and developed into a cyclone centered on Kyushu, Japan, while causing a windstorm accompanied by strong winds on the Korean Peninsula. In reviewing the 500 hPa upper layer weather chart, it can be seen that a pressure trough gradually approached the Korean Peninsula and southwesterly winds blew strongly, explaining the development and movements of the cyclones on the surface.

At 0900 LST on December 5, 2004, which was12 hours later (refer to Fig. 8(b)),the cyclone that had been located in the vicinity of Kyushu, Japan moved northeastward and located in the Japanese Archipelago, thereby showing a pressure pattern in which the strong winds gradually stopped. In the upper layer too, the pressure trough was located in the southern region of the Korean Peninsula and the rear of the pressure trough was located in the northern region of the Korean Peninsula so that the Korean Peninsula would be affected by the anticyclone developing and expanding in Siberia together with temporary strong winds in the late afternoon.

Therefore, it can be seen that in the case of the SC type, in which windstorms occurred when cyclones that developed in the southern region of China or southern China moved to the Korean Peninsula, the cyclones that developed in the warm sea in the south developed into cyclones accompanied by fronts while passing the South Sea of the Korean Peninsula and became weaker while they were passing the Japanese Archipelago, so that the windstorms that had been affecting the Korean Peninsula became weaker.

4. Conclusions

Weather patterns and representative cases of windstorms by type were selected from among those windstorm cases that occurred in Korea for 10 years from 2001 through 2010 based on the numbers of observatories at which 14 m/s or higher strong winds, which is the criterion for the strong-wind warning of KMA, were observed, and the synoptic meteorological characteristics of the cases were determined.

The cases of windstorms occurring on the Korean Peninsula were divided into six weather types (SH, EC, TY, CC, SC, and NC) according to the locations of anticyclones/cyclones. Among these types, the SH type, which occurs when Siberian Highs (SH) expand into the Korean Peninsula, showed the highest occurrence frequency, accounting for at least the majority of the entire occurrence frequency of all the windstorms together with that of the EC type, which occurs when cyclones develop in the East Sea, and there was no clear yearly trend of the occurrence frequencies of windstorms. The monthly occurrence frequencies of the windstorms were formed mainly by typhoons in the summer and Siberian Highs in the winter, and the months with the highest windstorm occurrence frequencies were December and January, in which mainly the SH and EC types of windstorms occurred. March showed the next highest occurrence frequency with10 times, and SH windstorms occurred the most frequently in March, followed by CC, SC, and EC type windstorms in order of precedence.

According to the results of the analysis of the synoptic meteorological characteristics of windstorm types with relatively high occurrence frequencies, the weather pattern during which strong winds were observed at the largest number of observatories was the TY type, followed by the SH type, and the weather patterns during which strong winds were observed at the smallest number of observatories was the NC type. Among the NC, CC, SC, and EC types, which are related to cyclone movements, the CC type had strong winds observed at relatively more observatories, followed by the EC type rather than the SC type. As for the synoptic meteorological characteristics of the SH type, it can be seen that the windstorms that occurred on the Korean Peninsula were attributable to the expansion of a Siberian High, that the rear side of the pressure trough became located over the Korean Peninsula, that strong winds persisted as the pressure trough in the upper layer passed the Korean Peninsula following the fast movements of the pressure system, and that the strong winds became gradually weaker as the cyclone in the East Sea became stronger and restrained the expansion of the anticyclones. Next, it can be seen that the EC type, in which windstorms are caused on the Korean Peninsula by cyclones developing in the East Sea, is a pressure pattern that occurs every year, and that the cyclones in the East Sea are supplied with more water vapor when the pressure ridge in the

Japanese Archipelago restrains the eastward movement of the cyclones leading to the occurrence of windstorms accompanied by strong winds on the Korean Peninsula. On the other hand, in the case of the TY type caused by typhoons landing on the Korean Peninsula, it can be seen that strong winds and precipitation phenomena were induced by the typhoon area of concentric circles throughout the Korean Peninsula from immediately before the landing of the typhoon on the Korean Peninsula to the moment at which the typhoon completely passed the Korean Peninsula and that strong winds and precipitation phenomena stopped as soon as the effects of the typhoon disappeared.

In the case of the CC type, in which cyclones that developed in central China move to the Korean Peninsula accompanying windstorms, strong winds appear in front of fronts because fronts accompany the cyclones and induce precipitation phenomena that does not persist very long. On the other hand, it can be seen that in the case of the SC type, in which windstorms occurred when the cyclones that developed in the southern region of China or southern China moved to the Korean Peninsula, the cyclones that developed on the warm sea in the south developed into cyclones accompanied by fronts while passing the South Sea of the Korean Peninsula and became weaker while they were passing the Japanese Archipelago, so that the windstorms that had been affecting the Korean Peninsula became weaker.

Therefore, countermeasures against storm and flood damage in Korea targeting the summer should be re-reviewed together with pre-disaster prevention plans, because cases of storm and flood damage due to windstorms occur more frequently than those due to typhoons, and they occur throughout the year. However, the synoptic meteorological characteristics of all types could not be defined in the present study because the study period was short and the frequencies of the windstorms were low, and accordingly, related damage situations could not be presented. Therefore, the present study has the limitation that the occurrence of the windstorms could not be linked to damage.

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