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연 구 논 문
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Three Cases with the Multiple Occurrences of Freezing Rain in One Day in Korea (12 January 2006; 11 January 2008; and 22 February 2009)

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Abstract From the hourly data of 75 Korean weather stations over a 12-year period (2001~2012), this study has chosen three cases (January 12, 2006; January 11, 2008; and February 22, 2009) of multiple freezing rains and investigated the atmospheric circulations that seemed to cause the events. As a result, the receding high pressure type (2006), prevailing high pressure type (2008), and warm front type (2009) are confirmed as synoptic patterns. In all three cases, freezing rain was found in regions with a strong ascending current near the end point of a low-level jet that carried the warm humid air from low latitudes. The strong ascending current resulted from lower-level convergence and upper-level divergence. In 2006 and 2009, the melting process was confirmed. In 2008, the supercooled warm rain process (SWRP) was confirmed. In contrast to existing SWRP theory, it was found that the cool air produced at the middle atmosphere and near the earth's surface led to the formation of freezing rain. The sources of this cool air were supposed to be the evaporative latent heat and the cold advection coming from the northeast. On the other hand, a special case was detected, in which the freezing rain occurred when both the soil surface temperature and surface air temperature were above 0^{o}C. The thickness distributions related to freezing rain in Korea were found to be similar to those in North America. A P-type nomogram was considered for freezing rain forecasting; however, it was not relevant enough to Korea, and few modifications were needed.

Key words: Freezing rain, melting process, supercooled warm rain process, synoptic pattern

1. Introduction

Freezing rain is that rain droplets turn to ice as they encounter the earth's surface or any other object. This causes damage, such as traffic accidents, high-tension wire disconnection, and forest damage. For instance, more than $16.3 billion in damage occurred because of freezing rainstorms in the United States between 1949 and 2000 (Changnon, 2003). In addition, ice formation because of freezing rain in the wings, propellers, and rotors of aircraft is known to be the leading cause of air accidents (Sand et al., 1984; Pike, 1995; Ashenden and Marwitz, 1997). For this reason, many studies have been conducted on freezing rain.

Among those, the studies on the development process of freezing rain can be largely divided into two types. First is the melting process (MP), also known as the common development process, where the warm humid layer exists above the cold surface layer in a vertical distribution (Brooks, 1920; Meisinger, 1920). The ice crystals form in the clouds below −10^{o}C; as the crystals fall, they pass through the warm layer above 0^{o}C at the lower level, melt, and fall as rain droplets. The layer close to the earth's surface is also below 0^{o}C, so the rain droplets adhere to objects on the earth's surface, form into ice, and become freezing rain. The process is accompanied by the melting and freezing of precipitation particles and the granting of access to the latent heat, which in turn changes warm air to cold and vice versa (Wexler et al., 1954; Stewart, 1985). Hence, an inversion layer gradually collapses

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in the bottom of the middle level, leading to the dissolution of the freezing rain.

However, some freezing rain cases do not correspond with this theory, as they appear when all vertical temperature distribution of the atmosphere is below 0°C (Young, 1978; Bocchieri, 1980). Thus, in order to explain the development process in those cases, the supercooled warm rain process (SWRP) (Huffman and Norman, 1988) was proposed. When the temperature of clouds is in the range of −10~0°C and the clouds are without ice nuclei or sufficiently large water droplets, only supercooled water drops exist (Huffman and Norman, 1988). In this case, the supercooled water drops in the clouds grow into precipitation through the warm rain process (forming rain by the collision and consolidation of the liquid particles). In the SWRP, this atmospheric condition continues to the earth's surface, and freezing rain is formed. Depending on the region, the SWRP is a more powerful cause for the formation of freezing rain than the MP (Rauber et al., 2000).

Besides the studies on the development process of freezing rain, there have been studies on atmospheric circulation and climatological characteristics related to the formation of freezing rain. To summarize the result of the studies by Steenburgh et al. (1997), Weber (1998), Rauber et al. (2001), and Mireles et al. (2003), the synoptic patterns for freezing rain can be largely divided into the receding high pressure (RH) type, prevailing high pressure (PH) type, warm front (WF) type, and cold air damming (CAD) type. Freezing rain frequently occurs in North America, so many studies can be found that are related to this region (Mckay and Thompson, 1969; Gay and Davis, 1993; Stuart and Isaac, 1999; Cortinas, 2000). Those studies have focused on the freezing rain phenomenon and on a wide range of freezing precipitation, such as sleet, ice pellets, and so on. Freezing rain is not a rare phenomenon in Europe and is quite frequently observed in the central European countries with continental climate, such as in Germany, Hungary, and Croatia (Carrière et al., 2000). For the Asian region, a study on abnormally frequent freezing rain in a province in southern China in January 2008 found the cause to be a blocking high over Siberia (Zhou et al., 2009; Sun and Zhao, 2010). Some recent studies have focused on the climatological changes of freezing rain due to global warming (Cheng et al., 2011; Lambert and Hansen, 2011).

Even though many studies have been conducted in the global community, the Korean studies are lacking and the only research on this topic seems to be one conference presentation (Kim et al., 2009). Therefore in the case of Korea, the development processes and the weather conditions related to freezing rain have never been carefully studied. However, freezing rain occurs frequently in Korea, and a great deal of damage has been caused by it (Kong et al., 2012). In these situations, because of the lack of related studies, the proper preparation was not made. Therefore, in order to serve as the first full-fledged domestic study on freezing rain, this study investigated the weather condition in three cases, in which freezing rain was observed in more than two locations and more than three times in one day.

2. Data and occurrence status

2.1 Data

1) The soil surface temperature (ST), surface air temperature (AT), daily precipitation, and SYNOP message from 75 weather stations belonging to the Korea Meteorological Administration (KMA) were used for analysis. The ST and AT were observed at the soil surface and 1.5 m above the earth's surface, respectively (KMA, 2002). The SYNOP message includes the air temperature, wind speed, wind direction, current weather, and other information from the specific weather station in compliance with the standards of the Global Telecommunication Systems (GTS). As of 8 May 2001, those weather factors have been recorded hourly, and this study used 12 years of these data up till 31 December 2012. Within the analysis period, the AT was recorded hourly, but the ST was recorded every six hours (not averaged but instantaneous) until 31 January 2008. Therefore, hourly records of the ST are only available in most stations after 1 February 2008.

2) In Korea, the observation of the upper atmosphere is done only in Osan (47122), Gwangju (47158), Baengnyeongdo (47102), Heuksando (47169), Jeju (47185), Pohang (47138), and Sokcho (47090). Therefore, not every freezing rain occurrence spot includes upper-atmosphere observation data. Thus, the upper-atmosphere data at the closest observation location to the freezing rain occurrence spot was selected from the past upper-atmosphere observation data stored by Wyoming

Table 1. The observation time (LST) of the freezing rain recorded in the ww code and the Remarks respectively.

Case 1			Case 2			Case 3		
12 Jan 2006			11 Jan 2008			22 Feb 2009		
Station	Time		Station	Time		Station	Time	
	Code	Remarks		Code	Remarks		Code	Remarks
47102 (Baengyeongdo)	15:00, 16:00, 17:00, 20:00, 21:00, 22:00	14:53~15:07, 17:40~23:40	47129 (Seosan)	09:00	08:05~09:30	47284 (Geochang)	09:00	08:40~09:50
47112 (Incheon)	16:00, 17:00	15:45~17:30	47130 (Uljin)	11:00, 12:00	11:30~12:10	47279 (Gumi)	09:00, 10:00	08:50~10:10
47108 (Seoul)	17:00, 18:00, 19:00	16:45~19:30	47137 (Sangju)	-	05:04~05:25, 08:06~08:20			
47119 (Suwon)	17:00, 18:00	16:50~18:50						
47201 (Ganghwa)	17:00, 18:00	-						
47133 (Daejeon)	-	17:21~17:43						
47101 (Chuncheon)	-	23:50~24:00						

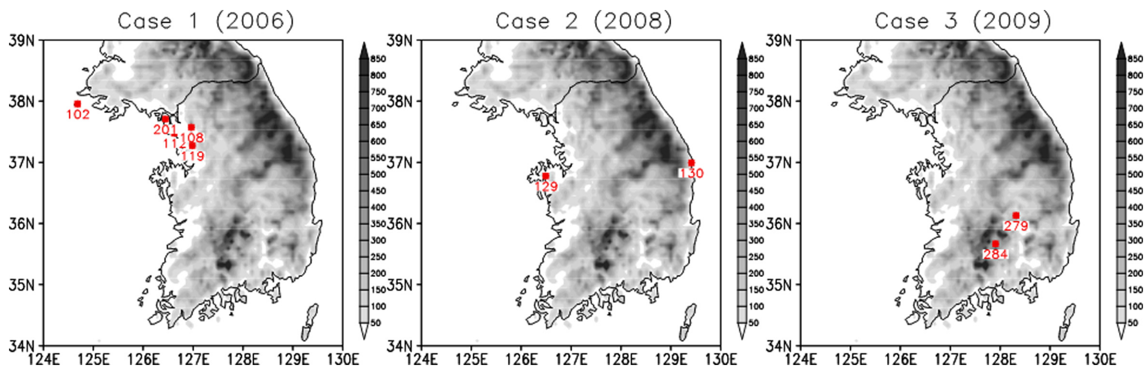

Fig. 1. The distributions of the weather stations which observed freezing rain (mark, 47---) for each case. Shaded regions are topography (m).

University (http://weather.uwyo.edu/upperair/sounding.html). This data provides the vertical distribution of the air temperature, dew-point temperature, humidity, and the like in 6~12 hr intervals.

3) In order to analyze synoptic atmosphere circulation, NOAA's Twentieth Century Reanalysis (20CR) grid data was used. The interval between longitude and latitude of 20CR was $2.0^o \times 2.0^o$, composed of 24 layers at six-hr intervals, and the used variables were air temperature, geopotential height, omega, zonal wind, and meridional wind.

4) In order to get a detailed thickness value in Korea, geopotential height data from NASA's Modern-Era Retrospective Analysis for Research and Applications (MERRA) were used. The interval between longitude and latitude was $0.5^o \times 0.5^o$ at six-hr intervals, and

Table 2. Detailed weather changes recorded in the ww code and the Remarks (═: mist, ●: rain, ▲: ice pellet, ⁂: sleet, ✱: snow) before and after the freezing rain. The bold with italic font in time column denotes the observation time of the freezing rain.

Case	Date	Station	Form	Time (code: ww, remarks: symbol)
Case 1	12 Jan 2006	47102 (Baengyeongdo)	Code	***15:00~17:00*** (66), 18:00 (60), 19:00 (61), ***20:00~22:00*** (66), 23:00~24:00 (61)
			Remarks	***14:53~15:07*** (▲), 15:07~17:40 (●), ***17:40~23: 40*** (▲), 23:40~24:00 (●)
		47108 (Seoul)	Code	00:00 (10), ***17:00~19:00*** (66), 20:00~24:00 (61)
			Remarks	00:00~02:20 (═), ***16:45~19:30*** (▲), 19:30~24:00 (●)
		47112 (Incheon)	Code	08:00~15:00 (10), ***16:00~17:00*** (66), 18:00~24:00 (61)
			Remarks	07:30~24:00 (═), ***15:45~17:30*** (▲), 17:30~24:00 (●)
		47119 (Suwon)	Code	00:00 (10), 03:00~07:00 (10), ***17:00~18:00*** (66), 19:00~24:00 (61)
			Remarks	03:00~07:20 (═), 18:30~24:00 (═), ***16:50~18:50*** (▲), 18:50~24:00 (●)
		47201 (Ganghwa)	Code	***17:00~18:00*** (66), 19:00~24:00 (61)
			Remarks	-
		47133 (Daejeon)	Code	04:00~14:00 (10)
			Remarks	***17:21~17:43*** (▲), 17:43~21:48 (●), 22:44~24:00 (●)
		47101 (Chuncheon)	Code	03:00~10:00 (10), 12:00 (10)
			Remarks	20:20~24:00 (═), 20:30~23:40 (✱), 23:40~23:50 (⁂), ***23:50~24:00*** (▲)
Case 2	11 Jan 2008	47129 (Seosan)	Code	06:00~07:00 (60), 08:00 (68), ***09:00*** (66), 10:00~11:00 (21), 13:00~14:00 (61), 15:00~18:00 (60), 19:00 (21), 20:00 (68)
			Remarks	09:30~24:00 (═), 05:42~07:10 (●), 07:10~08:05 (⁂), ***08:05~09:30*** (▲), 09:30~09:45 (●), 10:15~10:35 (●), 12:25~18:40 (●), 19:20~21:40 (⁂)
		47130 (Uljin)	Code	05:00~07:00 (60), 08:00~10:00 (61), ***11:00~12:00*** (66), 13:00 (61), 14:00~16:00 (71), 17:00 (68), 18:00 (60), 19:00 (21), 20:00 (60)
			Remarks	04:45~11:30 (●), ***11:30~12:10*** (▲), 12:10~13:30 (⁂), 13:30~15:40 (✱), 15:40~18:20 (⁂), 19:40~23:10 (●), 23:10~23:40 (⁂), 23:40~24:00 (●)
		47137 (Sangju)	Code	04:00 (21), 06:00 (24), 07:00 (60), 08:00 (61), 09:00~10:00 (60), 11:00~17:00 (61), 18:00 (60), 19:00~24:00 (61)
			Remarks	03:05~03:15 (●), ***05:04~05:25*** (▲), 06:10~08:06 (●), ***08:06~08:20*** (▲), 08:20~24:00 (●)
Case 3	22 Feb 2009	47279 (Gumi)	Code	***09:00~10:00*** (66), 11:00 (21), 12:00~13:00 (68), 14:00~16:00 (61)
			Remarks	19:10~24:00 (═), ***08:50~10:10*** (▲), 10:10~10:30 (⁂), 10:30~11:40 (✱), 11:40~13:10 (⁂), 13:10~19:20 (●)
		47284 (Geochang)	Code	***09:00*** (66), 10:00~16:00 (61)
			Remarks	13:40~24:00 (═), 08:05~08:40 (●), ***08:40~09:50*** (▲), 09:50~20:20 (●)

data on four layers (1000, 850, 700, and 500 hPa) were used.

All data used in this study are at intervals of 6~12 hrs except the ST, AT, and precipitation data, so it is difficult to get accurate information at the time of the freezing rain occurrence. Thus, the closest time to the freezing rain occurrence was selected for the analysis. Because the upper atmosphere and grid data followed the Coordinated Universal Time (UTC), it was aligned with Local Standard Time of Korea (LST, LST = UTC + 9 hr) which is the standard observation time of KMA.

2.2 Case selection

The current weather (ww) codes for freezing rain (including freezing drizzle) in the SYNOP message are 56, 57, 66, and 67 (WMO, 1995). During the analysis period (2001~2012), these codes were recorded 45 times in the record observation. Among these, three cases had freezing rain at more than two locations and more than three times in one day: 12 January 2006 (15 times); 11 January 2008 (three times); and 22 February 2009 (three times) (Table 1). From here on, the freezing rain cases of 2006, 2008, and 2009 are referred to as C1 (Case 1), C2 (Case 2), and C3 (Case 3), respectively. Figure 1 shows the spatial distributions of weather stations that observed freezing rain. Cases with freezing rain occurring at multiple locations were chosen because they were expected to exhibit strong manifestations of the causes for freezing rain.

2.3 Observation and recording of freezing rain

Besides the current weather code of SYNOP message, the weather phenomenon is also recorded in the ground weather record table (GWRT) by an observer's hand every day. Remarks in the GWRT also account for the beginning and finishing time of specific weather phenomena like as SYNOP message. The manuals for ground weather observation of KMA (KMA, 2002) do not distinguish between freezing rain and ice pellets (ww: 79); they record only ice pellet in the Remarks. This means that the ww codes of 56, 57, 66, 67, or 79 are only recorded to the weather symbol ▲ for ice pellets (Table 2). This is because it is very difficult to strictly distinguish between freezing rain, ice pellets, sleet, and so on, as they occur within a short time frame. However, this is why the manuals for ground weather observation need to be improved, since this record can't accurately reflect whether the actual precipitation of the ww code was 56, 57, 66, 67, or 79.

Hence, it is not uncommon to find record differences between the ww code and the Remarks (Table 1). For example, in C1, the weather in 47201 (Ganghwa) was recorded as freezing rain in the ww code but not in the Remarks. Moreover, 47102 (Baengnyeongdo) of C1 at 16:00 and 17:00 and 47130 (Uljin) of C2 at 11:00 have a record observation, but in the Remarks, there is no record of the continuation of the observations. On the other hand, 47133 (Daejeon) and 47101 (Chuncheon) of C1 and 47137 (Sangju) of C2 have records in the Remarks, but not in the ww code.

Therefore, although the ww code has recorded 45 incidents of freezing rain since 2001, we cannot determine that freezing rain occurred only 45 times. Because we can see many ▲ in the Remarks, we suppose that freezing rain happened more than 45 times. However, since there would be no end if we were to start considering uncertainties, this study only used the SYNOP message with an accurate record of the ww code of 56, 57, 66, or 67 for analysis.

Table 2 traces the weather throughout the days on which freezing rain occurred. As mentioned previously in Table 1, some errors were found in the records of 47201 (Ganghwa), 47133 (Daejeon), 47101 (Chuncheon), and 47137 (Sangju). In C1 and C3, as soon as the precipitation began, freezing rain started and turned to rain. However, in C2, the precipitation started as rain, turned into freezing rain, and then turned back into rain. In all three cases, freezing rain turned into rain or sleet. In addition, during the period of observation of the three cases, the record did not show the ice pellet in the ww code.

3. Synoptic scale circulation

3.1 Distribution of the pressure field

Figure 2 is the geopotential height field at 1000 hPa at the time closest to the freezing rain occurrence. Korea in C1 was located in the western edge of the strong high pressure area with the center near the Primorsky Krai. The trough, which developed in the middle of the east coast region of China, affected the west coast regions of Korea. In C2, the trough with the center in the east coast region of China stretched through to the East Sea. C3 was very similar to C2,

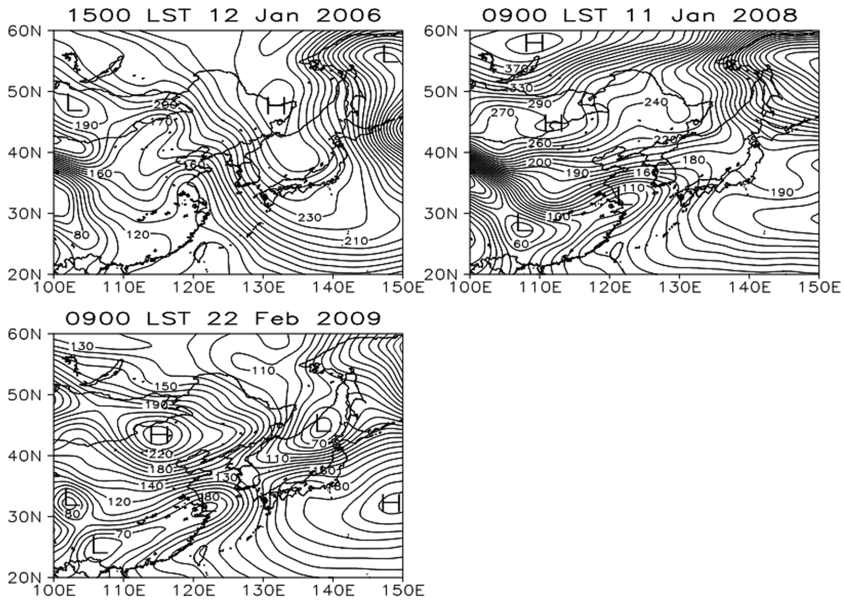

Fig. 2. The spatial distributions of the geopotential height fields (m) at 1000 hPa for each case.

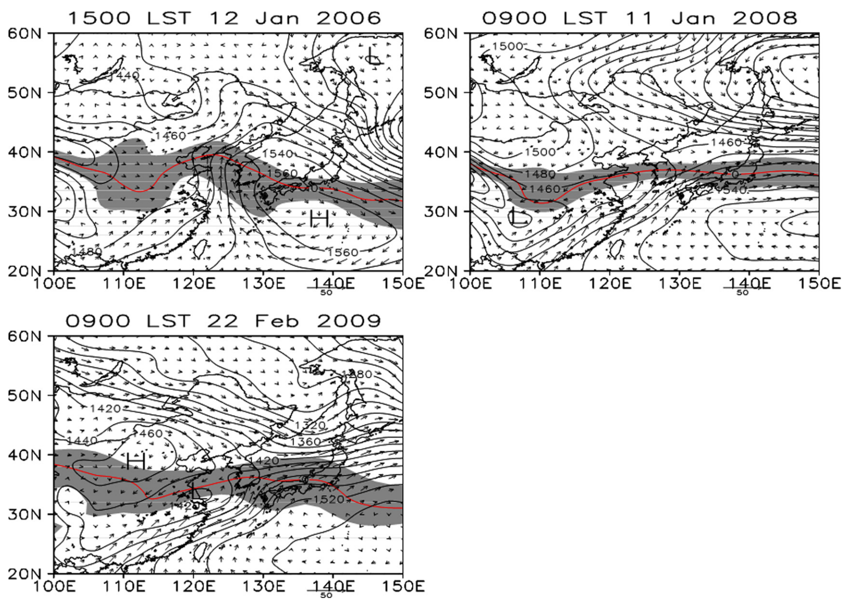

Fig. 3. Same as Fig. 2, but for 850 hPa. The shaded region is the air temperature between −5°C and 5°C, and the solid thick line in shaded region is isotherm of 0°C. The vectors are wind field at 850 hPa (m s^{-1}).

except the center of the deformation field was located in central Korea in C3, as opposed to the East Sea in C2. In C2 and C3, the warm front from the low pressure was expected. In other words, the freezing rain occurring from the warm front was in accordance with the patterns confirmed in previous studies (Meisinger, 1920; Rauber et al., 2001; Cheng et al., 2004) on freezing precipitation and the fronts. Hence, if we were to distinguish by pressure distribution patterns, C1 is an RH type because the high pressure over Primorsky Krai moved in a southeasterly direction, and C2 and C3 look like a WF type. C2 is more like

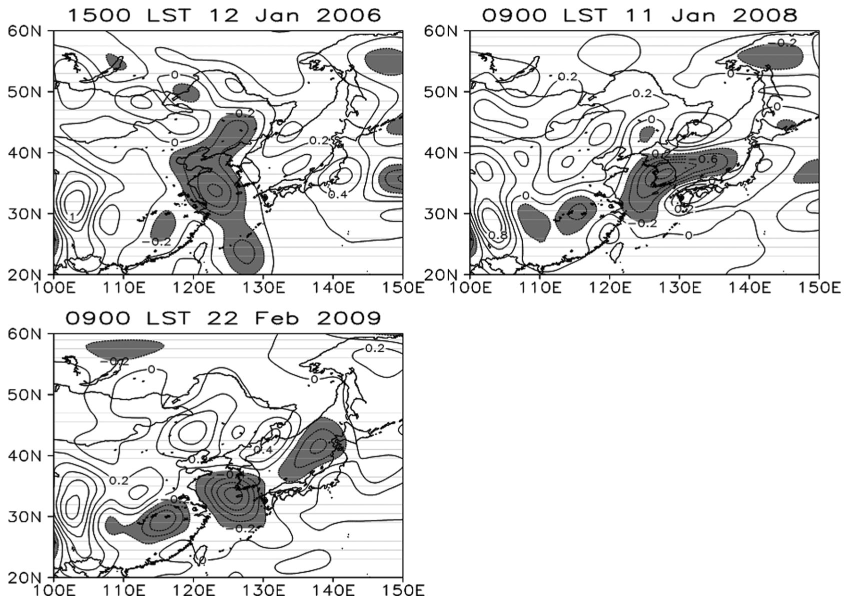

Fig. 4. Same as Fig. 2, but for the vertical velocity (Pa s^{-1}) at 700 hPa. The shaded regions are the vertical velocity less than −0.2 with interval of 0.2.

a PH type than a WF type because the cold advection existed near the earth's surface (confirmed in Chapter 4.4). C2 could also induce an easterly wind current toward Korea; the possibility of CAD from an easterly wind current has existed, but this study does not discuss the analysis of CAD type in detail. In this case, the low-level cold air coming from the northeast could intensify the frontal activity.

The southern wind seems to play a dominant role in the pressure field at 850 hPa, and it is evident that the air current joined from the low latitudes is approaching Korea (Fig. 3). In C1, a wide range of air currents near 20^{o}N joined together, passed the West Sea, and flowed into the north of Korea. Freezing rain occurred at the right edge of this current. In C2 and C3, the axis of outflow of the deformation field is located in Korea, where the warm air of the south and the cold air of the north meet. It is known that the front and the precipitation develop around the deformation field (Patoux et al., 2005). Freezing rain generally develops in the region at 850 hPa with an air temperature around −5~5^{o}C (Weber, 1998); all cases in Korea are located in this range. Furthermore, all of the freezing rain occurrence spots are located near the isotherm of 0^{o}C. In the case of C1, the ridge of the 0^{o}C isotherm shows a northward movement of the warm current.

3.2 Effect of ascending current and low level jet

From examining the vertical velocity at 700 hPa (Fig. 4) right before the occurrence of freezing rain, Korea was found to be located in the center of a strong vertical velocity in all three cases. The region with strong vertical velocity for C1 is located mainly in the West Sea, but considering that the freezing rain in other regions occurred two hours later than in 47102 (Baengnyeongdo), it seems to have moved eastward and affected the west coast region of Korea. The strong vertical velocity greater than −1 Pa s^{-1} of C2 crosses Korea from the east to the west. For C3, it is located in the southwest of Korea and affects the southwestern regions.

In the wind speed and moisture flux at 850 hPa (Fig. 5), the presence of a low level jet of wind velocity greater than 14 m s^{-1} from the low latitudes to Korea showed that all cases had the inflow of warm humid air from the south. In C1, the low level jet accompanied by moisture was directed toward the West Sea, but considering the time difference mentioned before, the low-level jet was expected to end in the west coast region of Korea where freezing rain occurred. The low-level jets of C2 and C3 also extend

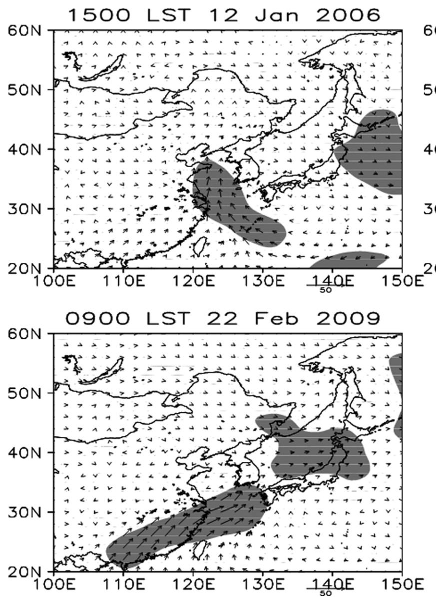

Fig. 5. Same as Fig. 2, but for the moisture flux (10^{-5} m s^{-1}, vector) at 850 hPa. The shaded regions are wind speed greater than 14 m s^{-1}.

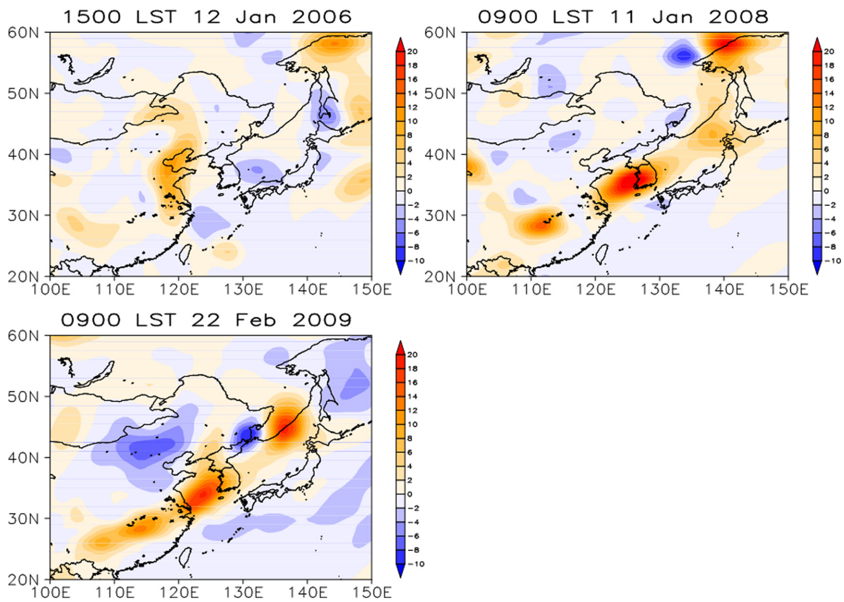

Fig. 6. Same as Fig. 2, but for the frontogenesis (10^{-9} K s^{-1} m^{-1}) at 925 hPa.

to central Korea and the south coast region of the same location, respectively, and the end of downwind side of the low-level jet almost coincided with the freezing rain occurrence spot. Combining these results, the freezing rain tended to form around the end of the downwind side of the low-level jet and the area of strong vertical velocity.

3.3 Frontogenesis and temperature distribution

In order to determine whether the front developed

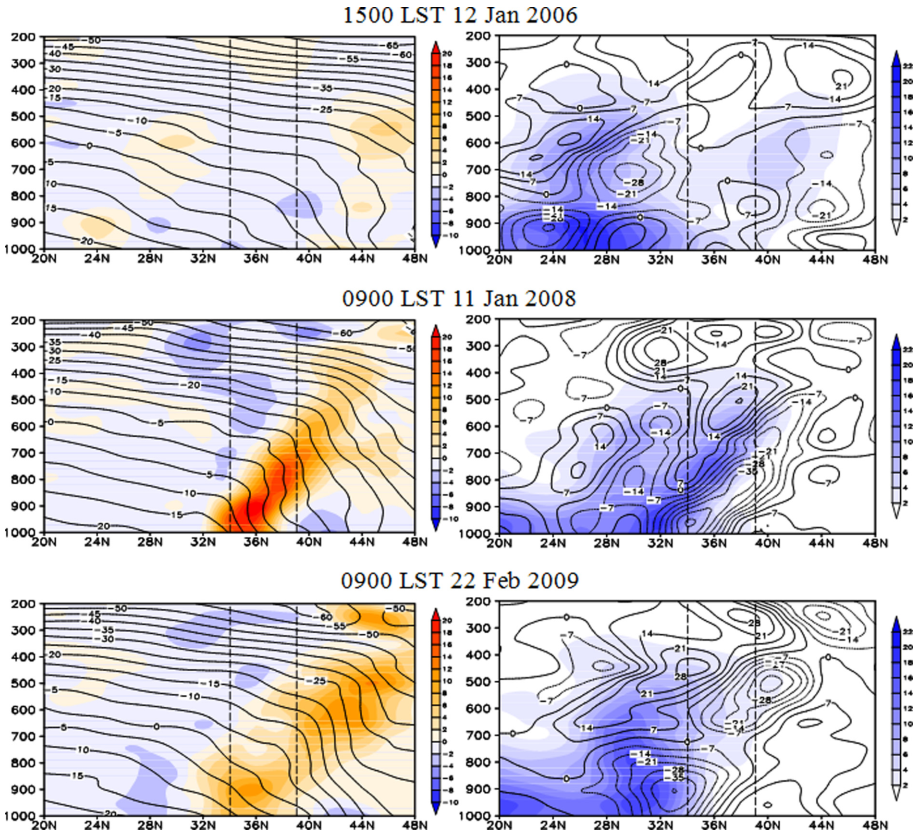

Fig. 7. Latitude-pressure (hPa) cross section of the frontogenesis (10^{-9} K s^{-1} m^{-1}, left shaded), air temperature (°C, left contour), moisture flux (10^{-5} m s^{-1}, right shaded), and divergence (10^{-5} s^{-1}, right contour) along 126°E~129.5°E. The dashed area denotes Korea (34°N~39°N).

near Korea as a result of the atmosphere conditions described in Chapter 3.1 and 3.2, frontogenesis was calculated (information about the frontogenesis equation is in the Appendix). Figure 6 shows the frontogenesis at 925 hPa. A strong frontogenesis is found near Korea in C2 and C3, and they are confirmed to be the warm fronts from low pressure in the east coast region of China shown in Fig. 2. On the other hand, the center of frontogenesis in C1 is found on the east coast region of China. Even though considering the time difference between the time of freezing rain occurrence and the spatial distribution recorded time of the frontogenesis, it was thought that C1 was somewhat influenced by frontogenesis due to the distance to Korea.

Figure 7 shows the latitude-pressure cross section of the frontogenesis, air temperature, divergence, and moisture flux along longitude of Korea (126°E~129.5°E). As shown in Fig. 6, C1 has weak correlation to the frontogenesis, as opposed to C2 and C3 where the frontogenesis has a tilted distribution along the height and clearly shows the existence of front. This front shape can be also found in the pseudo-equivalent potential temperature distributions, and it appears to be dense near Korea (no figure).

In all three cases, lower-level convergence and upper-level divergence were located near Korea, leading to the development of a strong ascending current (Fig. 4). This is evident in C2 and C3, where the center of convergence originally located in Korea, followed the front line up to the high latitude as it went to the upper level. As the moisture flux follows this convergence zone up to the divergence zone, located in the upper level of the convergence zone, the conditions of precipitation formation are satisfied. However, in the case of C3, the moisture flux is more concentrated in

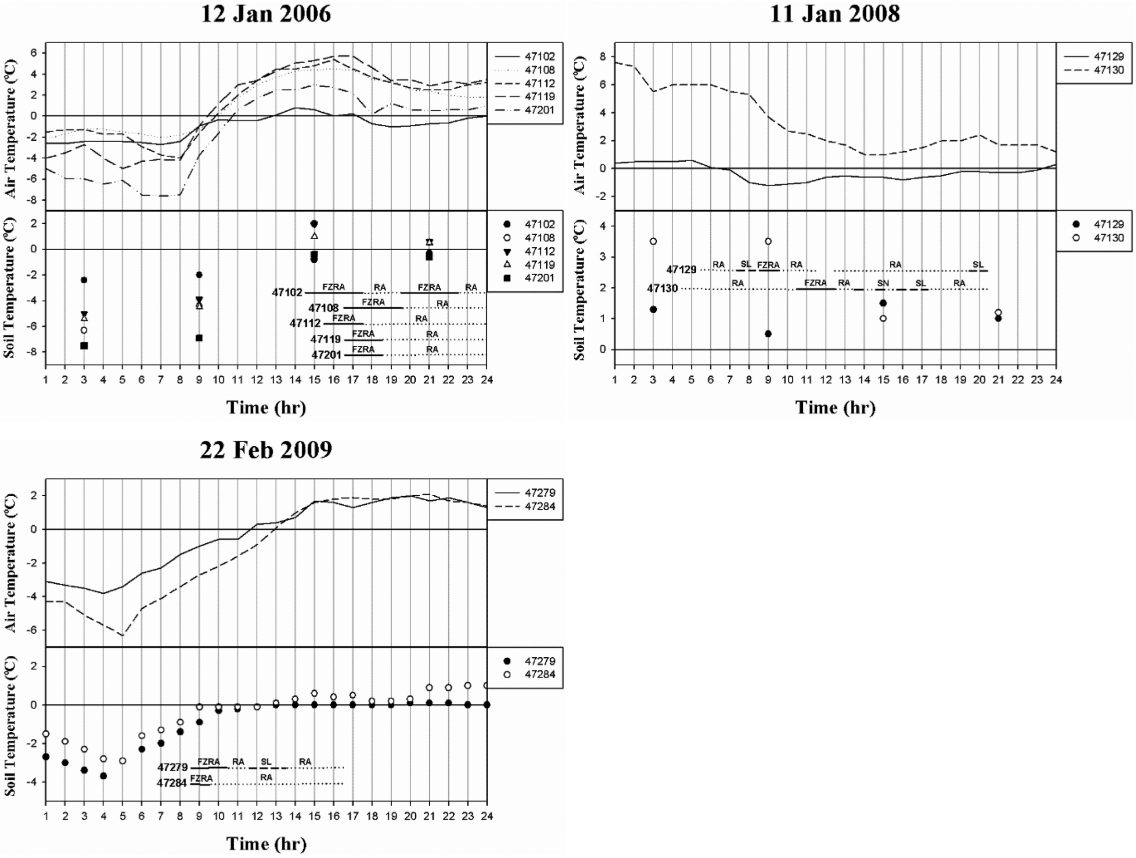

Fig. 8. The daily variation of the surface air temperature (up, lines) and the soil surface temperature (down, symbols). FZRA (freezing rain, thick solid line), RA (rain, dot), SL (sleet, dash line), and SN (snow, dot with solid line) show the shape of the precipitation in the ww code.

the southern sea region of Korea. In C1, lower-level convergence, upper-level divergence, and moisture flux were all weakly manifested near Korea.

The inflow of warm air from the south (Fig. 3) created the ridge of air temperature over Korea; this developed along the front line in C2 and C3. Particularly, in the case of C2, a quite thick isothermal layer with the temperature around 0^oC is observed, and this required more attention than just considering the ridge of the air temperature. The reason why roughly 0^oC is a common temperature in the thick atmosphere layer is because latent heat is exchanged when the phase of water changes. In this layer, the active front line activity and sufficient moisture flux could have facilitated the condensation. In addition, the divergence zone in C2 was considerably lower than in other cases, so that the air rising from the lower-level convergence immediately went through the precipitation process, fell, evaporated, and cooled the surrounding temperature. This explanation checked again in Chapter 4.3.

4. Characteristics of the occurrence spot

4.1 Distribution of soil surface temperature and surface air temperature before and after the occurrence time

Figure 8 shows the daily changes of the ST, AT, and the shape of the precipitation in the ww code. Three very important points discerned from Fig. 8 are as follows. First, in many cases, freezing rain formed when either one or both the ST and AT were above 0°C. In all locations of C1 and 47130 of C2, freezing rain occurred when AT was above 0^oC. ST was above or close to 0^oC except in 47102 and 47201. However,

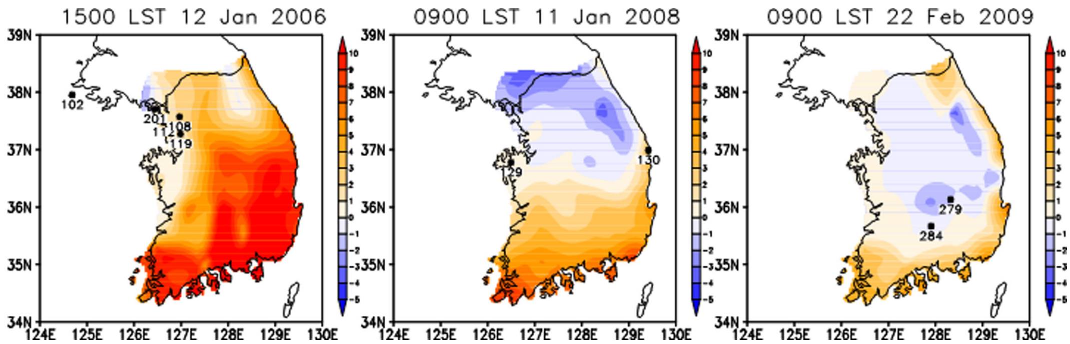

Fig. 9. The distributions of the soil surface temperature (^oC) for each case. The marks are the weather stations which observed freezing rain (47---).

freezing rain occurred when only the AT was below 0^oC in 47129 of C2 and when both the ST and AT were below 0^oC in C3. Therefore, it is a common theory that an ST and AT below 0^oC is a good environment for the formation of freezing rain, but Korea shows little difference. However, these results are not to be perfectly trusted because the AT and ST could show different observation results than the real environment since they were influenced by characteristics of observation spot (e.g., the weather instrument shelter could be affected by a lack of maintenance). These suspicious results are expected to be verified by intensive observation for freezing rain in Korea in the future.

Secondly, freezing rain occurred in the presence of rising AT. Though it was difficult to have a temperature increase due to solar heating from precipitation, in 47201 of C1, the AT changed from -8^oC at 08:00 to 3.5^oC at 15:00, showing the rising rate of 1.6^oC per hour. The AT at another location showed a similar tendency and exhibited the highest temperature at around 16:00. This is assumed that the strong warm advection of the day influenced the formation of freezing rain. This warm advection was expected to be the southern wind current from the low latitude (Fig. 3). Similarly, in C3, the AT also continued to rise even though the effect of precipitation, and this seems to be due to the presence of warm advection of the warm front (Fig. 6).

Thirdly, the cause of freezing rain for C2 was that one or both the ST and AT were falling. In 47130, the ST and AT were both above 0^oC all day, but the AT decreased and hit its lowest point at 14:00. Immediately before that, freezing rain occurred. The ST also suddenly decreased during this time and hit its lowest point. This situation could be easily explained with cold advection created by the cold eastern wind current from East Sea to the mountains. In other words, the falling water droplets in the 47130 became supercooled water droplets when passing through the cold air coming from the East Sea (Fig. 2).

In 47129, a different type of falling temperature occurs. Judging from the fact that the ST and AT cooled down before they did in 47130, the eastern wind does not account for the advent of cold advection. It rained from early in the morning and then turned to sleet. Then the precipitation type changed back and forth from freezing rain between 08:05 and 09:30 to sleet between 19:20 and 21:40 (Table 2). The cause of these changes will be discussed later in Chapter 4.3.

4.2 Soil surface temperature distribution and relationship with precipitation distribution

Figure 9 depicts the spatial distribution of the ST at the time closest to the freezing rain occurrence. The temperature was below 0^oC in a very small region of C1 near the mid-west coast region, where the occurrences of freezing rain were concentrated. The freezing rain occurrence spots of C2 are located near the border between the southern region above 0^oC temperature and the central region below 0^oC. In particular, 47130 is located in the northern-most part of the protruding warm sector. 47284 and 47279 of C3 are both located in the region of below 0^oC. These results show that the favorable soil surface temperature for freezing rain was not only in the region with temperature below 0^oC but also in the transitional region where the ST changed from higher than 0^oC to lower

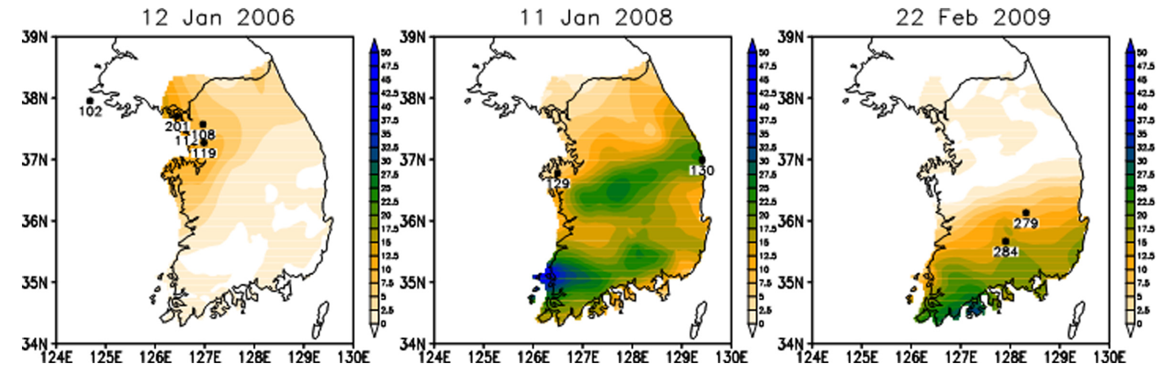

Fig. 10. Same as Fig. 9, but for the daily accumulation precipitation (mm).

than 0°C.

Figure 10 shows the daily accumulation of precipitation with freezing rain occurrence spots for each case. In all cases, freezing rain was found close by, but not where the precipitation was most concentrated. It is thought that a concentrated precipitation zone of C1 was located in the middle of the west coast region. In other words, the freezing rain occurred in the five locations close to this concentrated precipitation zone. For C2, freezing rain occurred at the two locations in the east end and in the west end of Korea, which are at the edge of the concentrated precipitation zone. Because freezing rain occurred at 47129 two hours prior, the northeastward movement of the precipitation zone is thought to have formed freezing rain first in the 47129 area. Freezing rain in C3 occurred at two locations in the interior regions, which are at the edge of the concentrated precipitation zone. In general, freezing rain occurred near the major precipitation zone, which shows the relationship between freezing rain occurrence and synoptic atmosphere circulation.

4.3 Vertical structure of atmospheric layer at occurrence time

Theoretically, snow completely melts as it falls when the atmospheric layer temperature is above 0°C and thickness is greater than about 300 m. In addition, when the layer temperature is below 0°C and thickness is greater than about 400 m, the falling water droplets freeze at this layer (Djuric, 1994). Figure 11 shows the upper-atmosphere observation data of the closest location and time to the freezing rain occurrences for each case. C1 (Baengnyeongdo in Fig. 11) exhibits above 0°C at 975~800 hPa. This layer also shows relative humidity greater than 80%, which is expected to have influenced the formation of precipitation. Therefore, the solid precipitation formed in the upper atmosphere melted away when passing through about 1600 m long atmospheric layer above 0°C, and then it developed into supercooled water droplets as they went through a roughly 350 m long layer below 0°C above the surface of earth. Thus, even when the ST is about 0.5°C, freezing rain could have formed.

From the lowest level to 850 hPa, the vertical distribution of C3 (Gwangju in Fig. 11) also shows a roughly 1500 m atmospheric layer with air temperature above 0°C. This case also has relative humidity greater than 80% up to 300 hPa, suggesting that the solid precipitation may have developed in the upper atmosphere. Hence, the falling precipitation particles, as they went through the layer lower than 850 hPa with temperature above 0°C, melted away and arrived at the surface of the earth in liquid form. However, they became freezing rain because both the ST and AT were below 0°C (Fig. 8). This process is similar to that of C1. Therefore, the freezing rain occurrences of C1 and C3 followed the MP explained in the introduction.

In contrast, C2 shows a different temperature distribution than the previous two cases. The vertical structure of C2 is from the observations of Osan (47122) and Sokcho (47090), where are close to Seosan (47129) and Uljin (47130) respectively. Considering that the freezing rain occurrence spots are far away from each other (one in the east and the other in the west) and the influence of the Taebaek Mountains, it makes more sense to explain the phenomenon with the temperature curve of the closet weather observation stations.

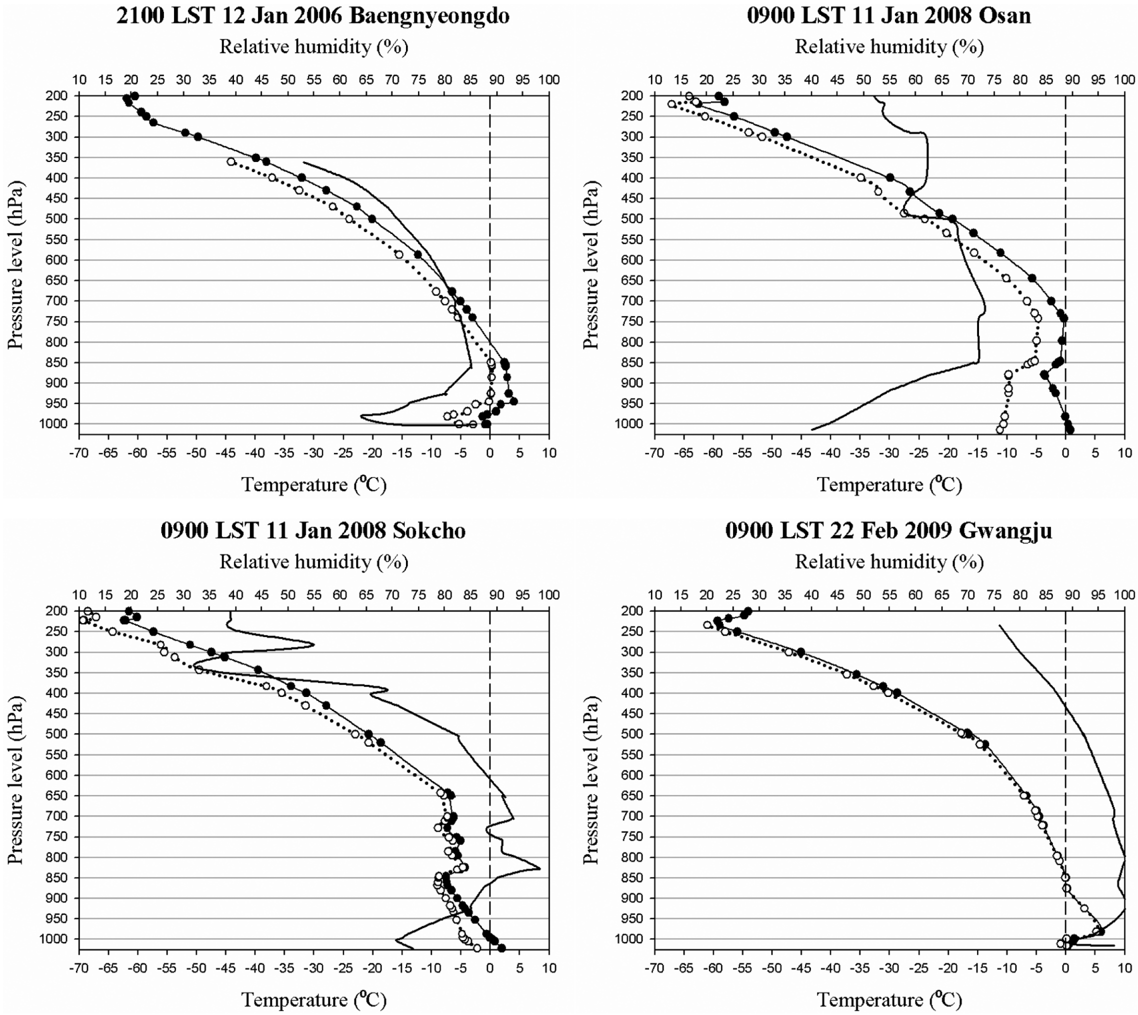

Fig. 11. The vertical distributions of the air temperature (solid line with a closed circle), dew-point temperature (dotted with an open circle), and relative humidity (thick solid line) for each case.

In the case of the former (Osan-Seosan), the air temperature was close to or below 0°C from 980 hPa to 725 hPa, and it went down to −4°C at around 875 hPa. The relative humidity was greater than 70% from 850 hPa to 650 hPa. Thus, precipitation developed with an air temperature profile higher than −10°C. This profile is similar to the SWRP explained in the introduction, in which supercooled water droplets do not freeze into ice crystals, but develop via a warm rain process. However, it is difficult to assume that they were not frozen when passing through the 2300 m layer with temperatures close to and below 0°C, which even go down to −4°C at around 875 hPa. At this point, we would have to suppose that the freezing rain was formed when ice particles completely melted by passing through about 300 m of layer above 0°C near the earth's surface, which is highly unlikely. Assuming that not all droplets froze when falling, and the 2300 m layer with the temperature close to and below 0°C was only temporary as the temperature fluctuated above and below 0°C. The results are in accordance with those shown in Table 2. Furthermore, since the atmospheric layer below 850 hPa is relatively dry, the falling water droplets could have evaporated and cooled the surrounding temperature (Fig. 8). Consequently, this could be explained as a supplementary process to the SWRP theory that has an evaporation effect. The latter case (Sokcho-Uljin) is similar, except

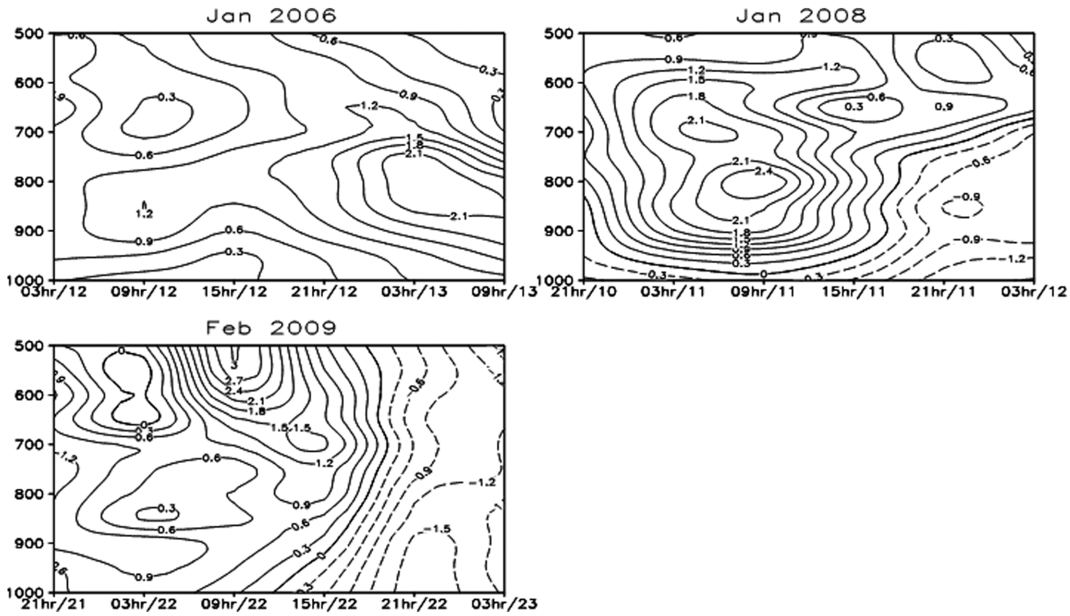

Fig. 12. Time-pressure cross section of the vertical mean temperature advection (10^{-4} ^{o}C s^{-1}) along Korea (34^{o}N~39^{o}N, 126^{o}E~129.5^{o}E) for each case.

it shows a pronounced cold distribution above 925 hPa at around −5^{o}C. This is assumed to be the cold air coming from the East Sea (Fig. 2).

4.4 Changes in vertical temperature advection over time

Figure 12 shows the time-pressure cross section of the vertical mean temperature advection in Korea (34^{o}N~39^{o}N, 126^{o}E~129.5^{o}E). The dominant warm advection was found in C1. Around 900~750 hPa, in particular, strong warm advection flowed in from the early morning of 12th, which then strengthened sharply at 18:00. Freezing rain started right before this warm advection strengthened (15:00). As shown in Fig. 11, the solid precipitation formed in the upper level fell in a thawed state due to the warm advection of the middle level, and it cooled near the earth's surface, where the warm advection was less strong than it had been at the middle level. As soon as the warm advection was strengthened, they all turned into rain droplets (Table 2). The warm advection at 850 hPa, 03:00 on the 22nd in C3 was the smallest value in the vicinity. After this point, the warm advection quickly strengthened, had a sharp increase at around 09:00, and turned to cold advection from a once predominant warm advection in the upper level. The freezing rain that occurred right before the warm advection sharply increased and when a relatively weak warm advection was flowing in near the earth's surface mirrors what happened in C1.

C2 shows a somewhat different trend. Summarizing with Fig. 12 only, the solid precipitation falling from the upper atmosphere melted while passing through the strongest warm advection at 800 hPa; it became liquid and then formed into freezing rain influenced by the cold advection of the bottom level. However, Fig. 11 does not show any layer with temperature above 0^{o}C in the middle level. Furthermore, the freezing rain development processes of 47129 and 47130 are also quite different, so it is not sufficient to draw conclusions only from the effects of temperature advection. In these locations, the regional cold air played a key role as previously mentioned. Only the cold advection of the earth's surface shown in Fig. 2 and Fig. 8 is partially confirmed here.

5. Application of thickness for freezing rain forecast

5.1 Thickness field

Thickness is a one of the important factor that determines the type of precipitation falling on the earth's

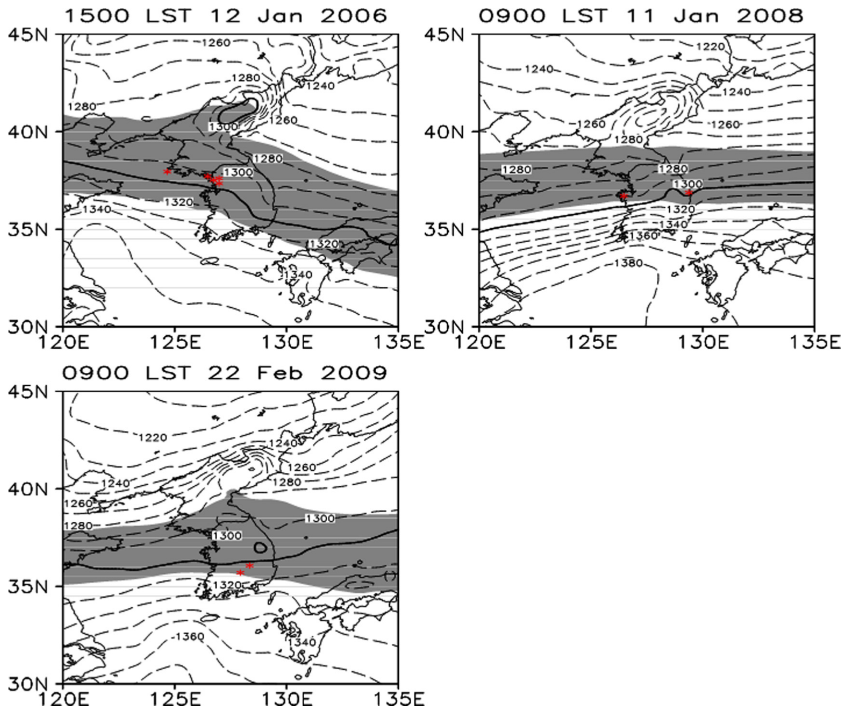

Fig. 13. The distributions of the thickness field (m) for each case. The regions between 5340 m and 5460 m in the 1000~500 hPa thickness are shaded. The dash lines denote the 1000~850 hPa thickness with the thick solid line of 1310 m. The star marks are the weather stations which observed freezing rain.

surface. However, using the thickness for deciding the type of precipitation is now almost an obsolete method. Nevertheless, it should be checked in this study because there are no prior domestic studies concerning the thickness on the freezing rain phenomenon in Korea. Between two heights, thickness is calculated with the hypsometric equation:

$$Z_2 - Z_1 = \frac{R_d \overline{T}_v}{g_0} \ln\left(\frac{P_1}{P_2}\right).$$

In this equation, Z_1 and Z_2 represent the geopotential height, R_d represents the dry gas constant, $\overline{T}_v$ represents the mean virtual temperature of the layer, g_0 represents the globally averaged acceleration due to gravity at the earth's surface, and P_1 and P_2 represent pressure. In North America, where freezing rain frequently occurs, the thickness at 1000~850 hPa is greater than 1290 m when freezing rain, sleet, or ice pellets occurred (Pettegrew et al., 2008). As Gordon (1998) proposed, freezing rain is likely to occur when the thickness at 1000~500 hPa is between 5340 m and 5460 m or less than 1310 m at 1000~850 hPa. Actually, freezing rain occurs mainly in the range of these thickness values (Gay and Davis, 1993; Rauber et al., 2001). However, this is not an absolute condition, as some freezing rains have been observed outside of this thickness range.

Thickness distributions at 1000~500 hPa and 1000~850 hPa were examined for freezing rain in Korea (Fig. 13). In all cases, freezing rain that occurred in Korea was located in the range of 5340~5460 m at 1000~500 hPa. In addition, except for C3, freezing rain occurrence spots are located where the thickness is in the 1300~1310 m range at 1000~850 hPa. The occurrence spots of C3 are around 1310~1320 m, showing a slight difference, but it can be concluded that the locations are in the vicinity of 1310 m. Therefore, the thickness distribution suitable for the occurrence of freezing rain in Korea is similar to that of North America.

5.2 Classifying freezing rain using the P-type nomogram

In the southeast region of the United States, where freezing rain occurs frequently, the P-type nomogram

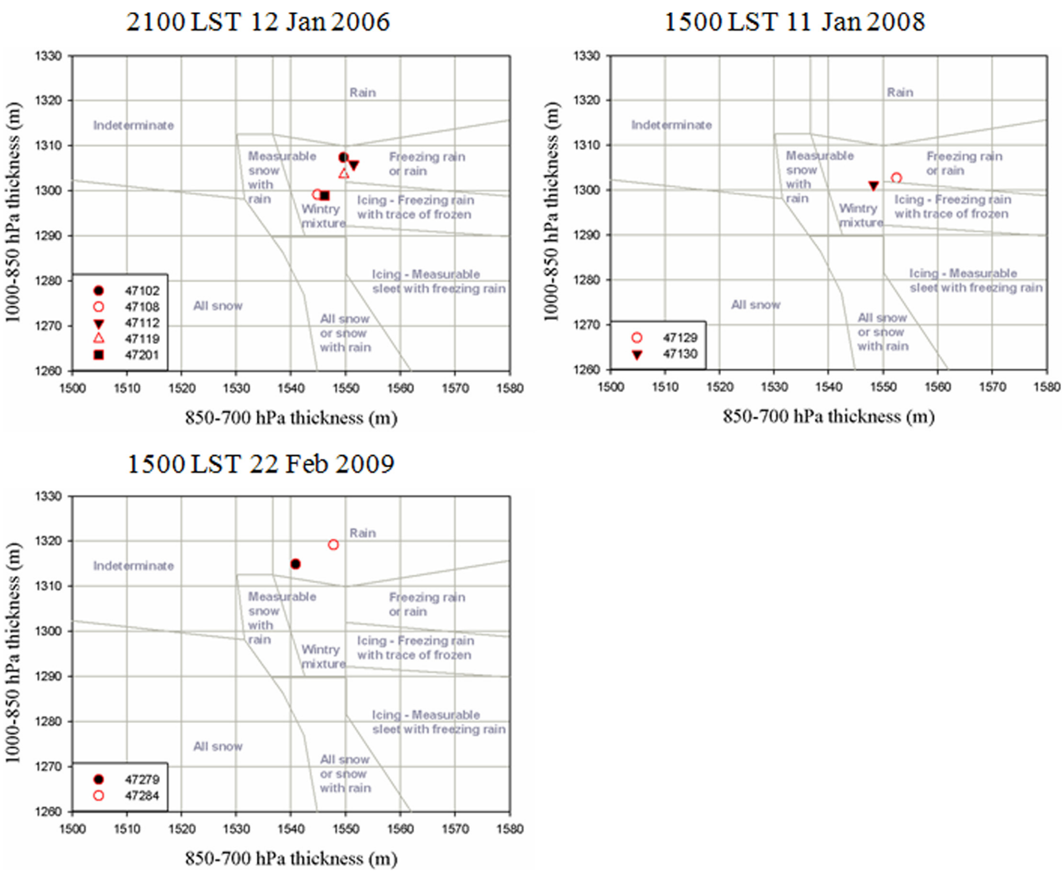

Fig. 14. The P-type nomogram for each case. Symbols represent the thickness value of weather stations which observed freezing rain. Gray texts show the separated area for the type of precipitation.

is used to forecast (refer to http://www.meas.ncsu.edu/nws/www/trend for details). The P-type nomogram is a diagram that uses the thickness of 1000~850 hPa and 850~700 hPa to classify the dominant precipitation form during a six-hour period prior to a certain point. This diagram is made by using the past precipitation data in the southeast region of the United States.

In Chapter 5.1, the thickness distributions suitable for the occurrence of freezing rain in North America and Korea are similar. Accordingly, the P-type nomogram was also applied to Korea (Fig. 14). As a result, only the freezing rain observed in 47112 (Incheon) of C1 and 47129 (Seosan) of C2 are classified as “freezing rain or rain”. The precipitation from the other locations demonstrated much deviation, and they are classified as ice pellets, sleet, combination precipitation, or rain. Therefore, in order to use the P-type nomogram, some modifications were needed to reflect the actual circumstances in Korea.

6. Summary and discussion

In this study, three freezing rain cases that occurred in Korea were selected, and the causes and development processes of those cases were investigated. The freezing rain was occurred in only restricted regions of Korea over a short period, so it was hard to gather the precise data for analysis. Moreover, errors were detected in observing and recording of freezing rain. Considering these points, the observation data of the closest weather station to the freezing rain occurrence spot and at the time closest to the actual occurrence in SYNOP message were used for analysis.

To summarize, the results of the analysis were similar to those found in previous studies: the three cases also showed RH type (2006), PH type (2008), and WF type (2009). In the development process of freezing rain, MP and SWRP are also found. However, in the latter, in contrast to the existing SWRP theory, the evaporative latent heat effect and cold advection near the earth's surface had a combined effect on the formation of freezing rain. The existing theory that freezing rain would form when the ST and AT were both below 0°C was found to be not relevant to this study. Rather, the opposite was more frequently observed. Therefore, more compact and precise observations and studies for surface conditions and their relation to freezing rain in Korea are needed.

We also found that freezing rain occurred in restricted areas at the end point of the downwind side of the low-level jet, which carries warm humid air from low latitudes and in the regions where a strong ascending current develops. Along the distribution of pressure field, the low-level jet is related to the wide range of confluence near Korea (the confluence of the air current from the north and the south), and the strong ascending current was the result of lower-level convergence and upper-level divergence.

Warm advection existed in the middle atmosphere and influenced the melting of solid precipitation falling from the upper level. In some cases, freezing rain occurred as the warm advection started to strengthen; in other cases, freezing rain occurred when the warm advection was the strongest. This means that the freezing rain is formed not only by temperature advection, but by meeting certain favorable layer conditions for it. Thus, this result reconfirmed that the freezing rain can occur when an adequate amount of warm advection is present for the melting of solid precipitation.

Finally, the thickness distributions at 1000~500 hPa and 1000~850 hPa in Korea were examined and were found to be in accordance with findings from North America. Using this as reference, the application of the P-type nomogram used in the United States for forecasting freezing rain was considered for Korea. However, the method used in the United States was not directly relevant to Korean circumstances, and modifications were needed.

Acknowledgments

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Appendix

As the horizontal potential temperature gradient on an isobaric surface was stronger, the frontogenesis strengthened. This can be expressed with the following equation:

F (frontogenesis)

$$= \frac{d}{dt}\nabla_h\theta \quad \text{(frontogenesis function; Petterssen, 1936)}$$

Keyser et al. (1988) simplified this equation by resolving **F** into natural coordinates [(s, n); s is locally tangent to the isentrope and n is rotated 90° counterclockwise of s], gives:

$$(1)\quad \boldsymbol{F} = F_n\boldsymbol{n} + F_s\boldsymbol{s};\ \boldsymbol{s} = \boldsymbol{n}\times\boldsymbol{k},\ \boldsymbol{n} = -\left|\nabla_h\theta\right|^{-1}\nabla_h\theta$$

$$(2)\quad F_n = -\frac{d}{dt}\left|\nabla_h\theta\right| = -\left|\nabla_h\theta\right|^{-1}\left[\frac{\partial\theta}{\partial x}\left(-\frac{\partial u}{\partial x}\frac{\partial\theta}{\partial x} - \frac{\partial v}{\partial x}\frac{\partial\theta}{\partial y}\right) + \frac{\partial\theta}{\partial y}\left(-\frac{\partial u}{\partial y}\frac{\partial\theta}{\partial x} - \frac{\partial v}{\partial y}\frac{\partial\theta}{\partial y}\right)\right]$$

$$(3)\quad F_s = \boldsymbol{n}\cdot\left(\boldsymbol{k}\times\frac{d}{dt}\nabla_h\theta\right) = -\left|\nabla_h\theta\right|^{-1}\left[\frac{\partial\theta}{\partial y}\left(-\frac{\partial u}{\partial x}\frac{\partial\theta}{\partial x} - \frac{\partial v}{\partial x}\frac{\partial\theta}{\partial y}\right) - \frac{\partial\theta}{\partial x}\left(-\frac{\partial u}{\partial y}\frac{\partial\theta}{\partial x} - \frac{\partial v}{\partial y}\frac{\partial\theta}{\partial y}\right)\right].$$

Where θ is potential temperature and ∇_h is horizontal gradient operator $[(\partial/\partial x)\boldsymbol{i} + (\partial/\partial y)\boldsymbol{j}]$ ($\boldsymbol{i}$, $\boldsymbol{j}$ are each unit vector in x and y direction). F_n is the change of magnitude of thermal gradient (the minus sign is necessary because $\boldsymbol{n}$ and $\nabla_h\theta$ are oppositely directed) and F_s is the change of direction of thermal gradient (counterclockwise rotation is positive) (Keyser et al., 1988). Therefore, $\boldsymbol{F} > 0$ implies frontogenesis, whereas $\boldsymbol{F} < 0$ implies frontolysis.

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