Thesis for the Degree of Master of Science

A Study on the Environment of Snow and Ice Accretion in the Heavy Snow Fall Region

by

Ji-Han Sim

Department of Environmental Atmospheric Sciences

The Graduate School

Pukyong National University

August 24, 2018

A Study on the Environment of Snow and Ice Accretion in the Heavy Snow Fall Region
(다설 지역에서의 착설 및 착빙 발생 환경에 관한 연구)

Advisor: Prof. Won-Sik Choi

by

Ji-Han Sim

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Ji-Han Sim

Approved by:

(Chairman) Jai-Ho Oh

(Member) Gi-Sig Byun

(Member) Won-Sik Choi

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심 지 한

부 경 대 학 교 대 학 원 환경대기과학과

요 약

본 논문은 고해상도 관측복원자료를 활용하여 상습다설지역에 대해 기상 상황 및 착빙설 발생 환경을 분석하고자 하였다. 고해상도 관측복원자료는 강수량, 기온, 풍향, 풍속 자료가 사용되었고 이는 과거 관측 자료를 초기자료로 지형효과를 고려하는 정량적 강우 모형, 정량적 기온 모형, 정량적 바람 모형으로부터 산출되었다.

대표적 상습다설지역인 강원도를 대상으로 송전선로 경과지의 빙설해 사고 발생 시 기상상황과 착빙설 발생 환경을 분석하였다. 빙설해가 발생한 송전선로에 대해 사고 발생 당시의 강수량, 기온, 풍향, 풍속에 대해 분석하였고 기온과 풍속 기준에 따른 착설, 착빙 구분표에 따라 착설, 착빙 발생 환경에 대해 분석하여 사고 원인을 추정하였다.

송전선로 설계에 있어 통계적인 기상 분석은 필수적이므로 겨울철 상습다설지역에 대해 재현기간별 확률강수량을 산정하였다. 확률강수량 추정을 위해 기상관측자료를 이용하여 겨울철 강원지역의 적절한 확률분포형을 선정하였고 선정된 확률분포형을 이용하여 매개변수를 추정하고 확률 강수량을 산정하였다. 1km 해상도의 관측복원자료를 이용하여 선정된 확률 분포형을 통해 격자별 매개변수를 추정하고 착빙설 종류별 확률강수량 산정하여 분포도를 작성하여 착빙설 종류별 상습다설지역을 분석하였다.

I Introduction

Recently the transmission line is being constructed to bypass the residential area or to build the mountain area with low land utilization to prevent complaints caused by the falling land prices and the harmfulness of electromagnetic waves (Lee et al., 2006). As construction sites are limited, transmission lines are being built on mountainous areas where local abnormal weather occurs (Song et al., 2005). In winter, the transmission line in the mountainous region was broken down due to icing on the wire. From 2001 to 2016, a total of 508 malfunctions occurred with an average annual number of 32 failures (Fig. 1). Galloping phenomenon, wire elongation, and sleet jumping were the main causes of failure, and the galloping phenomenon caused 353 failures (KEPCO, 2017). The galloping phenomenon is defined as amplification of the power line movement caused by icing on the line as well as the high wind across the line. Elongation refers to the phenomenon in which wires are stretched due to the weight of the ice sheets deposited on the wires. Sleet jumping is the jump of the conductor, resulting from ice dropping off one span of an ice-covered line. In the case of galloping and sleet jumping, in which the wires vibrate up and down, the upper and the lower wires of the transmission line collide with each other, resulting in a disconnection accident. The potential for damage to transmission facilities as a result of icing events is considerable. It is believed that large amplitude oscillations of ice-covered cables is responsible for about one third of power line maintenance and operating costs (Fu et al., 2006). Despite theses problems, there have been few studies.

Meteorological conditions have a significant impact on the operability of power transmission lines, the integrity of the transmission infrastructure, and the characteristics of transmission networks (Zarnani et al, 2012). Therefore, it is important to understand the icing environment in order to prevent damage. However, since most of the ice and snow failure areas are located in mountainous areas without weather station, meteorological data in mountainous areas are required.

Lee et al. (2015) used the meteorological data of the nearest automatic meteorological instrument to identify the correlation between the average wind speed and the standard deviation of the wind direction and the galloping phenomenon. Lee et al. (2016) predicted the probability of accidents due to galloping through logistic regression analysis using statistical interpolation data of meteorological data. However, when the data of the nearest automatic meteorological instrument are used, it includes the errors due to the difference in the distance between the weather station and the transmission line and the difference due to the altitude difference. There is a limitation that it can not show the terrain effect when the interpolation method is used.

In order to overcome the interpolation method of the observed data, Degaetano et al. (2008) estimated the ice thickness using the WRF model and evaluated the prediction accuracy of the icing model compared with the actual observation thickness. Yannan et al. (2017) used weather data collected from transmission lines in China, MICAPS meteorological data, and NCEP reanalysis data to analyze the synoptic conditions and average monthly freezing duration to assess snow and ice failure. Cigre report (2006) suggested the need for meteorological modeling and statistical analysis because icing is a complex phenomenon that is affected by large changes in time and space and affected by terrain.

Therefore, in this study, synthetic precipitation, temperature, wind direction and wind speed data were produced using quantitative precipitation, temperature and wind model considering detailed topographic effects. The cause of the accident was estimated by analyzing the weather conditions and the ice and snow conditions in the transmission line where the snow failure occurred. Also, we investigated the spatial distribution of probable precipitation along with ice types to separate a heavy snow fall region.

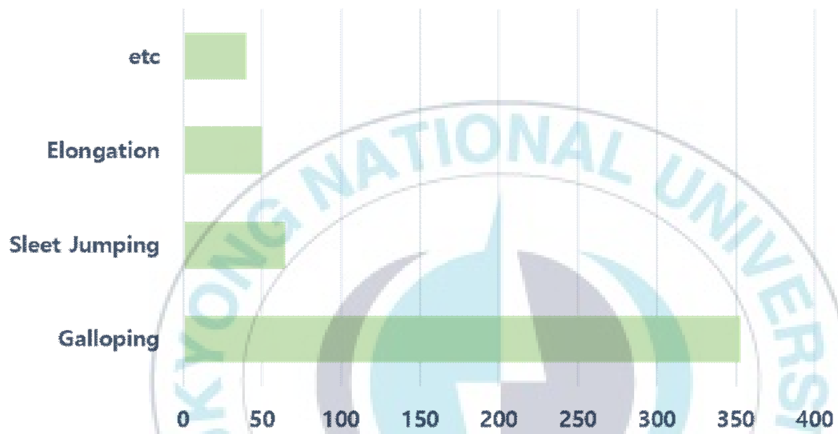

Fig. 1. Number of ice and snow failures by cause.

II Models, Data and Method

1. Models description

To analyze the environment of weather and icing at transmission, we need a high resolution data. This study used the quantitative precipitation model (QPM), the quantitative temperature model (QTM) and the quantitative wind model (QWM) to produce synthetic precipitation, temperature and wind component data at 90-m resolution.

The basic concept of the QPM is to disaggregate an “additional” amount of rainfall induced by orographic effects, as proposed by Kim (2018) and Bae (2017). The QTM which is a diagnostic model calculates a regional temperature according to the detailed topographic effect using temperature lapse rate (Kang et al., 2017). The QWM calculate a regional wind data using polynomial fitting between wind at 10m of observation and 3-dimension wind data of reanalysis data.

2. Data

2.1. Data for failure case analysis

Data for analysis of failure case was produced by the QPM, QTM and QWM. Synthetic precipitation, temperature, wind direction and wind speed data were generated at 90-m spatial resolution and hourly intervals over the target transmission line. At this time, because the transmission line locates to a height of over about 70-m, the synthetic data were produced at 70-m height.

2.2. Data for analysis of probability precipitation

To analyze a statistical estimation of probable precipitation, long-term observation precipitation data and the synthetic data were used. The former were used to select optimum probability distribution over the target region and was obtained from the automatic synoptic observing system (ASOS) of Taebaek. The period of the data is for a 30-year period (1986-2015). The latter were used to investigate the spatial distributions with the determination of probable precipitation and were produced at 1-km resolution using the QPM, QTM and QWM. Synthetic precipitation, temperature and wind data were calculated for a 10-year period (2006-2015). Both data were obtained during the winter season (Nov-Apr) occurred an icing phenomenon. The target region of spatial distributions with the determination of probable precipitation is shown in Fig. 2.

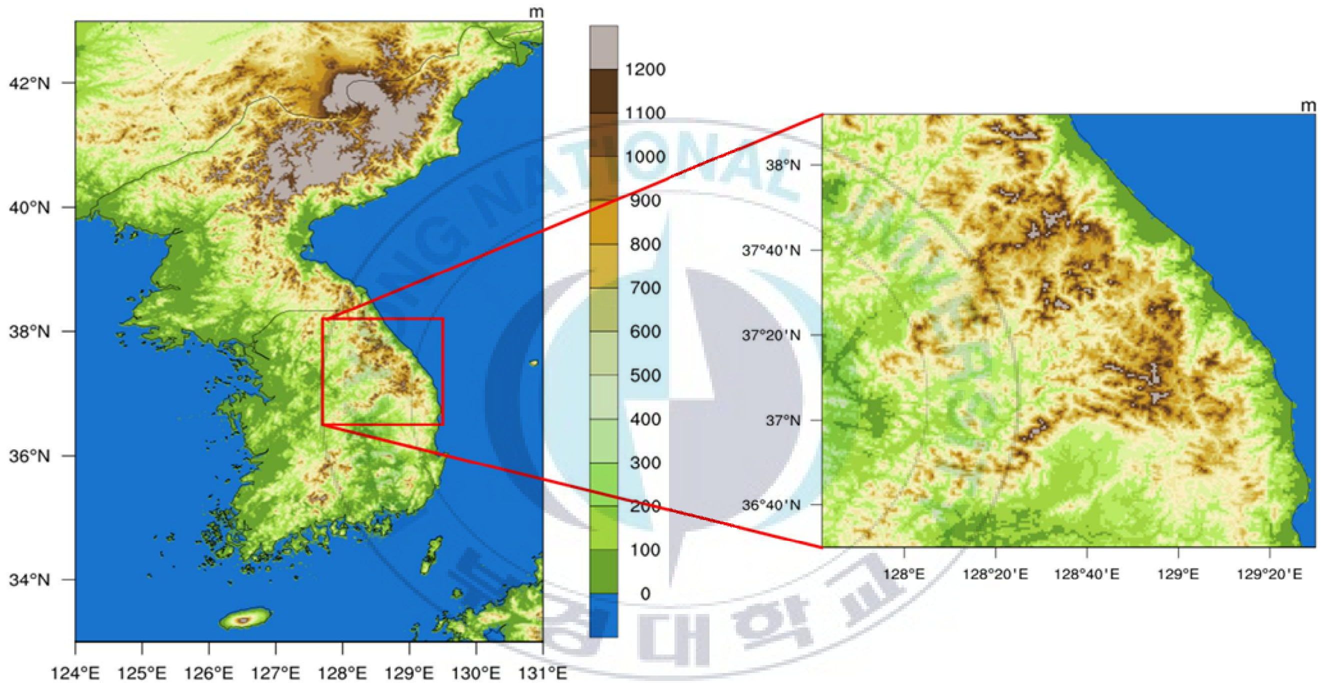

Fig. 2. Probability precipitation analysis target region and terrain elevation.

3. Method

3.1. Analysis of snow and ice accretion

Table 1 shows the classification of ice types according to temperature and wind speed (Gigre, 2006). We investigated the environment of accretion using the classification.

In this study, ice types are divided with snow accretion and ice accretion. Ice accretion occurs by supercooled water drop and also is divided with soft rime, hard rime and glaze according to place and density. The character of snow accretion is that it occurs to a height of under condensation level (about 800m) and can be easily removed by the wind. Glaze occurs under relatively high temperature and a strong wind. Soft rime occurs under a moderate wind than hard rime, and has weakly adhesion and can be easily removed by hand. On the other hand, hard rime occurs by relatively big supercooled water drop under a strong wind. Because hard rime has strong adhesion and more or less difficult to knock off, it can do a lot of damage on the transmission line. Therefore, when three cases of snow failure happened, we classified snow and ice accretion according to the classification of ice types and analyzed the environment of accretion.

Table 1. Classification of ice types according to temperature and wind speed standards.

<table>
<tr><th colspan="2">Criterion</th><th>Temperature</th><th>Wind speed</th></tr>
<tr><td colspan="2">Snow accretion</td><td>0 ~ 1.5 ℃</td><td>below 5 m s-1</td></tr>
<tr><td rowspan="3">Ice accretion</td><td>Soft rime</td><td>-10.0 ~ -2.0 ℃</td><td>below 5 m s-1</td></tr>
<tr><td>Hard rime</td><td>-8.0 ~ -2.0 ℃</td><td>5 ~ 20 m s-1</td></tr>
<tr><td>Glaze</td><td>-2.0 ~ +1.0 ℃</td><td>15 ~ 25 m s-1</td></tr>
</table>

3.2. Analysis of probability precipitation

To investigate the spatial distributions with the determination of probable precipitation, we need to select an optimum probability distribution over the target region. Heo and Kim (1995) selected gumbel (GUM) distribution as optimum probability distribution over Korea and Lim (2012) chose Generalized logistic (GLO) distribution as optimum probability distribution over Busan. Thus, optimum probability distribution is different depending on a period and a region.

Maximum annual rainfall for 6-, 12-, 18- ,and 24-hour is constructed using hourly precipitation data from ASOS of Taebaek for 30 years to select a optimum probability distribution over the target region. Using constructed data, a statistical estimation of probable precipitation is based on the method of probability weighted moments for parameter estimation, the goodness-of-fit test of chi-square ($\chi 2$) and the probability plot correlation coefficient (PPCC) suggested by Lim (2012). and then probability density function (PDF) and cumulative distribution function along with four distributions also were compared to an empirical value to choose finally optimum distribution.

Maximum annual rainfall by each cumulative time is constructed to every grid according to the classification of ice types using synthetic data with 1-km resolution to invest spatial distributions of probable distribution along with ice types. We estimate a parameter to every grid using selected probability distribution and determine the probable precipitation for investing spatial distributions.

Table 2. Probability density function of four distributions.

Probability Distributions	PDF
Normal (NOR)	$f(x)=\dfrac{1}{\sigma\sqrt{2\pi}}\exp\left(-\dfrac{(x-\mu)^2}{2\sigma^2}\right)$
Generalized extreme value (GEV)	$f(x)=\dfrac{1}{\alpha}\left\{1-\beta\left[-\dfrac{x-x_0}{\alpha}\right]\right\}^{\frac{1}{\beta}-1}\exp\left\{-\left[1-\beta\left(\dfrac{x-x_0}{\alpha}\right)^{\frac{1}{\beta}}\right]\right\}$
Generalized logistic (GLO)	$f(x)=\dfrac{1}{\alpha}\left\{1-\beta\left[\dfrac{x-x_0}{\alpha}\right]^{\left(\frac{1}{\beta}-1\right)}\right\}\left\{1+\left[1-\beta\left(\dfrac{x-x_0}{\alpha}\right)^{\frac{1}{\beta}}\right]\right\}^{-2}$
Gumbel (GUM)	$f(x)=\dfrac{1}{\alpha}\left\{-\dfrac{x-x_0}{\alpha}-\exp\left[-\dfrac{x-x_0}{\alpha}\right]\right\}$

III Results

1. Analysis of failure case

We investigated three case of snow failure to understand the environment of weather and icing during the transmission line outage (Table 3). Target transmission lines are located in a mountains higher than 500 meters and are shown in Fig. 3. The period of analysis is 7 days due to the character of icing which lasts for several days.

To analyze weather condition, synthetic precipitation, temperature at 70m, wind direction at 70m, and wind speed at 70m were used. Also, to analyze snow and ice accretion, we classified the types of ice according to the classification of ice types using synthetic data (Table 1).

Table 3. Ice and snow Failure case at the transmission line.

	CASE 1	CASE 2	CASE 3
Transmission Line	154kV Taebaek-Gohan	154kV Hoenggye	345kV Donghae-Sinjechun
Station number	86-100	30-40	38-50
Time of accident	21 January 2012, 1027 KST	12 January 2009, 0921 KST	13 February 2011, 1110 KST
Period	16 January 2012, 0000 KST - 22 January 2012, 2300 KST	07 January 2009, 0000 KST - 13 January 2009, 2300 KST	08 February 2011, 0000 KST - 14 February 2011, 2300 KST

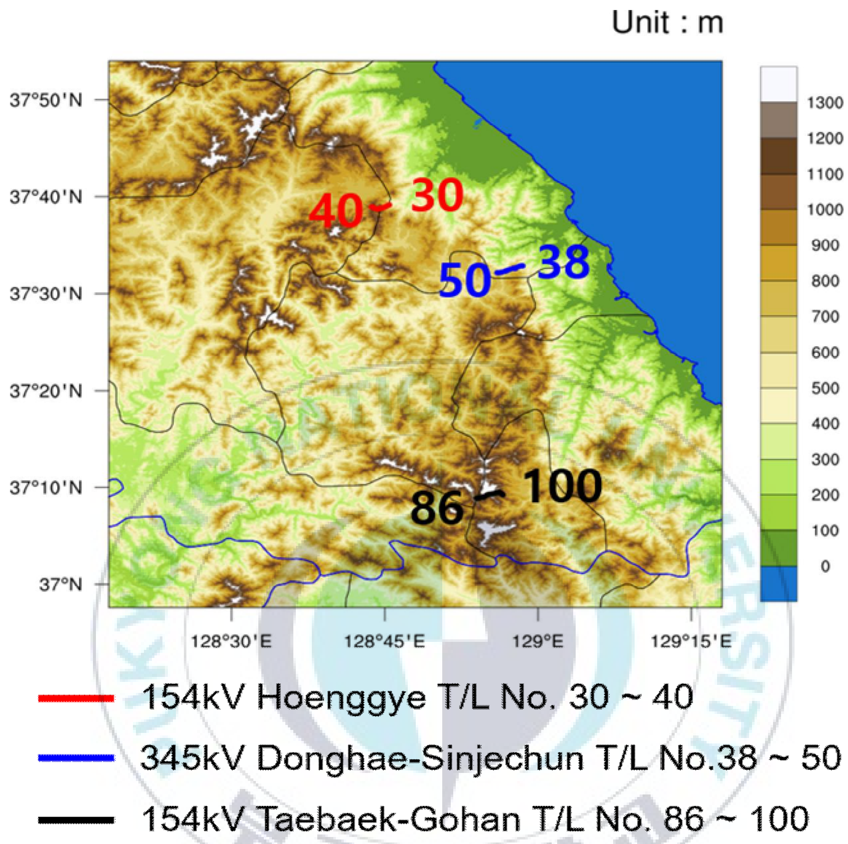

Fig. 3. Location of transmission lines.

1.1. CASE 1: 154kV Taebaek-Gohan T/L

The snow failure of 154kV Taebaek-Gohan transmission line station no. 86-100 which is located within a 1137 to 1377 meter happened 1027 KST on January 21, 2012. Especially section of station no.95 to 98 had the strong elongation phenomenon and two electric confusion (KEPCO, 2017).

1.1.1. Analysis of weather condition

It was three synthetic precipitation during the period. The first is from 1500 KST to 2100 KST on January 17, 2012, the second is from 0200 KST on January 19 to 0000 KST on January 21, 2012, and the third is from 1600 KST to 2300 KST on January 21, 2012 (Fig. 4). The third exclude from the analysis because it was after the snow failure. During the first and second period, the average, maximum, and minimum of variables over the all sections were shown as Table 4.

During the period of first precipitation (total seven hours), average accumulated synthetic precipitation was 2.56 mm at all sections, maximum was 6.57 mm at no.93, and it was no synthetic precipitation from no.91-2 to 91-3. The average synthetic temperature at 70m was −4.35 ℃ at all sections, maximum was −3.57 ℃ at no.100, and the minimum was −4.96 ℃ at no.94 (Fig. 5). The lowest synthetic temperature during all period was −5.76 ℃ at 2000 KST on January 17 at station no.94 which had the minimum value of all sections. Average synthetic wind speed, maximum value, and minimum value were 6.95 ms^{-1} at all sections, 7.35 ms^{-1} at no.94, and 6.41 ms^{-1} at no.100 (Fig. 6). The highest synthetic wind speed was 7.75 ms^{-1} during all period at 1800 KST on January 17 at station no.94 recorded maximum value.

During the period of second precipitation (total 47 hours), average accumulated precipitation at all sections was 35.3 mm and maximum precipitation was 83.3 mm at station no.98. It was higher than precipitation of the first period. Also, wind speed was higher than the wind speed of the first period. Average of all sections was 9.55 ms^{-1}, and maximum was 14.24 ms^{-1} at 1200 KST on January 19 nearby station no.86. However, it is presumed that it was not effected on the transmission line of station no.86 due to little precipitation. The rainfall intensity was over 4 mmh^{-1} nearby the transmission line of station no.98, which recorded maximum precipitation. At that time, hourly wind speed was over 10 ms^{-1}.

During the analysis period, the prevailing wind was east-northeast, and all direction of the wind was except north and south (Fig. 7). The prevailing wind was east-northeast, before the snow failure from 0200 KST on January 19 to 0000 KST on January 21, and most wind speed was from 12 to 16 ms^{-1}.

Table 4. Summary of the average, maximum, and minimum of variables over the all sections

Period	Synthetic variables	Average	Maximum	Minimum
1500 KST on January 17, 2012 -2100 KST on January17, 2012 (Total seven hours)	Precipitation	2.56 mm	6.57 mm (no.93)	0 mm (no.91-2~91-3)
	Temperature at 70m	-4.35 ℃	-3.57 ℃ (no.100)	-4.96 ℃ (no.94)
	Wind speed at 70m	6.95 ms^{-1}	7.35 ms^{-1} (no.94)	6.41 ms^{-1} (no.100)
0200 KST on January 19, 2012 -0000 KST on January21, 2012 (Total 47 hours)	Precipitation	35.3 mm	83.3 mm (no.98)	1.9 mm (no.91-2~91-3)
	Temperature at 70m	-4.22 ℃	-3.53 ℃ (no.100)	-4.87 ℃ (no.94)
	Wind speed at 70m	9.55 ms^{-1}	9.82 ms^{-1} (no.100)	9.26 ms^{-1} (no.94)

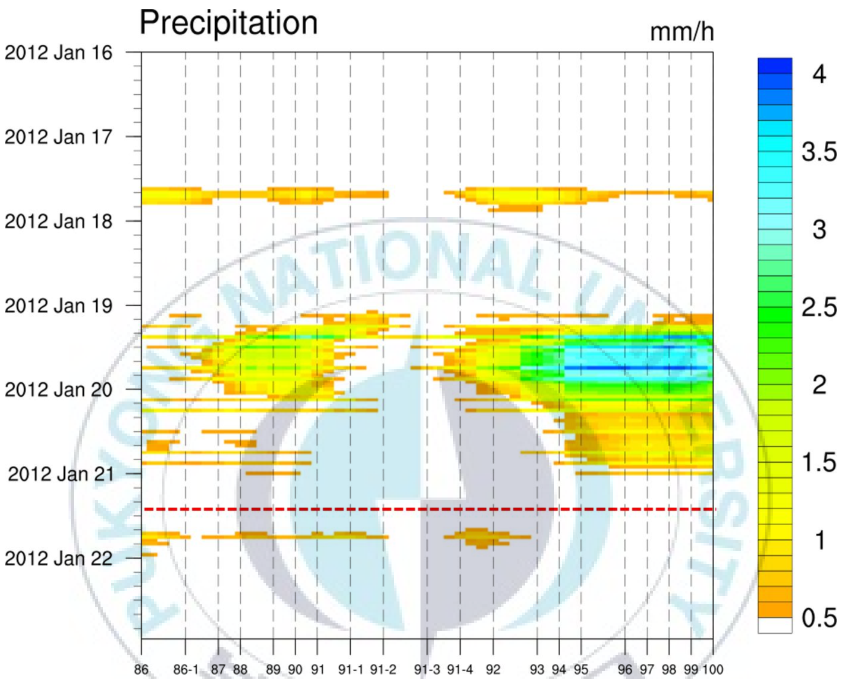

Fig. 4. Distribution of precipitation at the Taebaek-Gohan transmission line before and after the accident (Red dot line: Time of the accident).

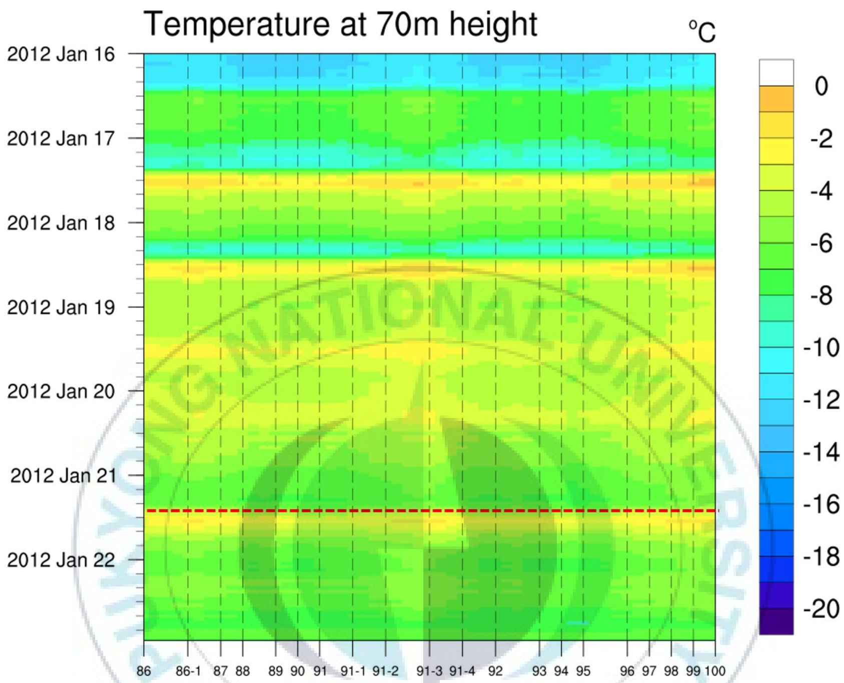

Fig. 5. Same as Figure 4, but variable is temperature at 70m.

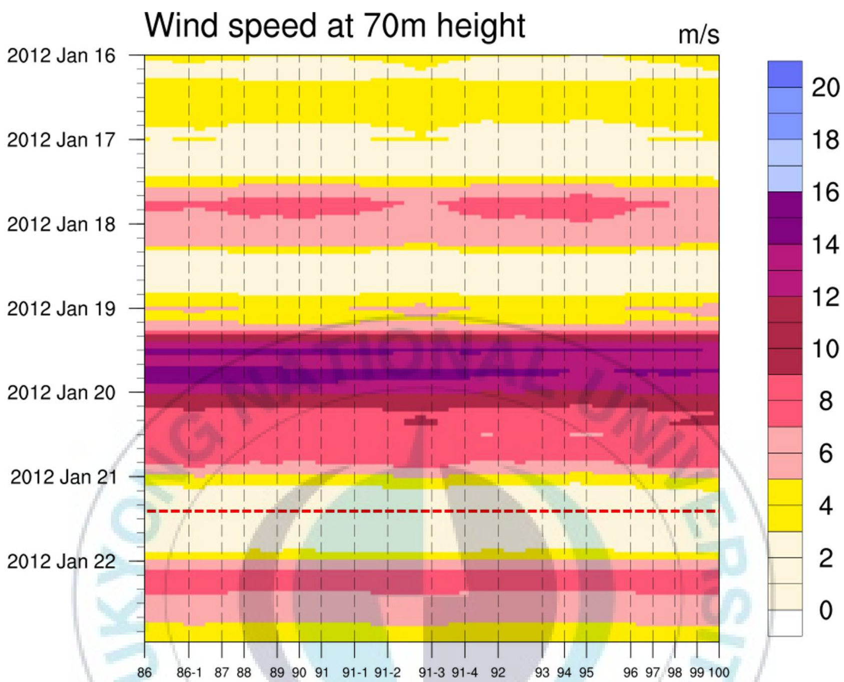

Fig. 6. Same as Figure 4, but variable is wind speed at 70m.

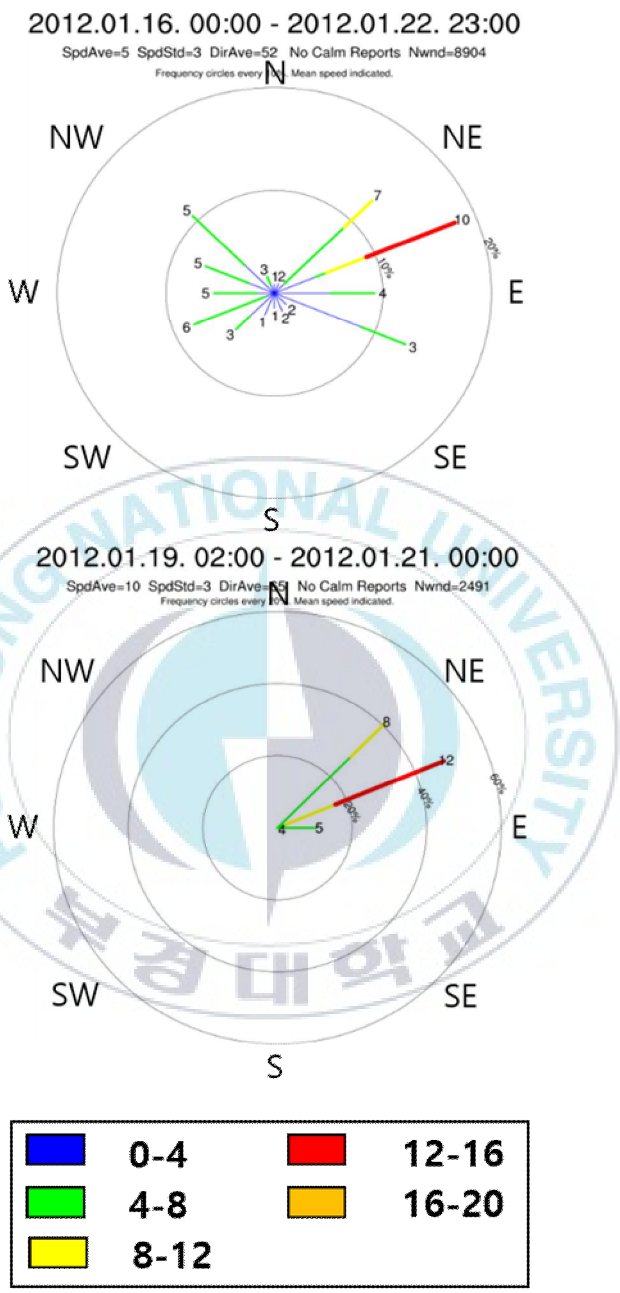

Fig. 7. Wind rose during the target period.

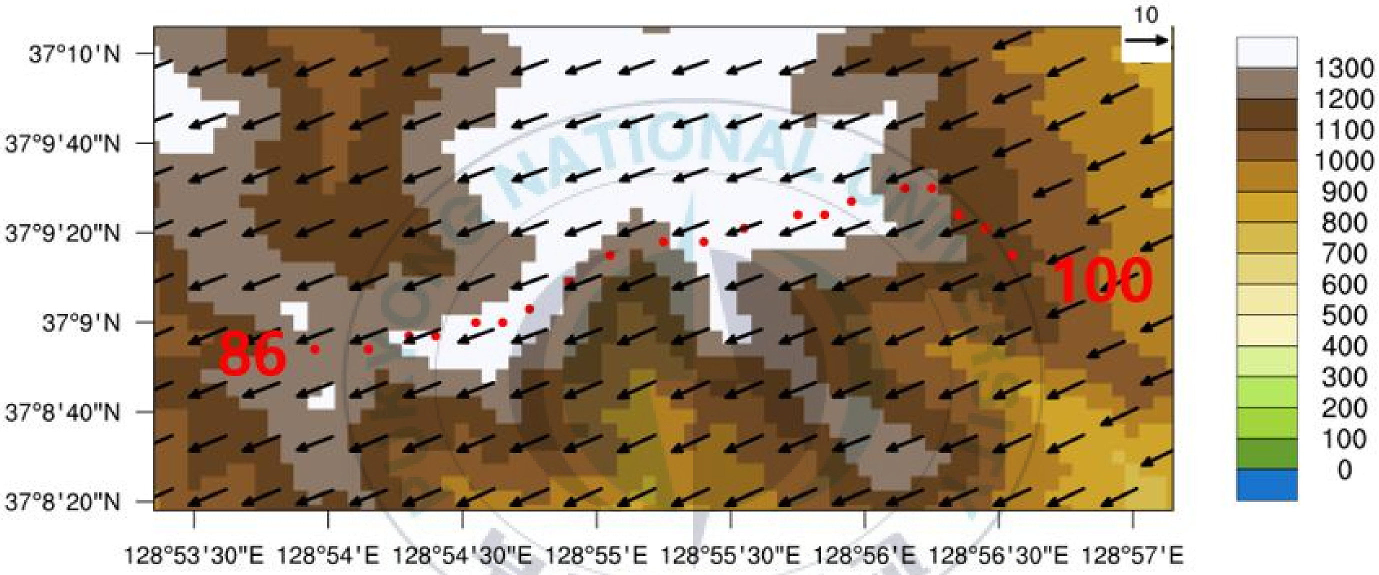

Fig. 8. Location of targer transmission line and wind direction at 70m.

1.1.2. Analysis of snow and ice accretion

We analyzed the distribution of precipitation and the accumulative time when the environment of icing was created according to the classification of icing types by temperature and wind speed (Fig. 9, 10). Snow accretion was excluded from analysis because the target transmission is distributed over the condensation level (about 800 m).

The environment of glaze was not created (not shown), the environment of soft rime and hard rime were created during the analysis period. The environment of soft rime was created for three hours during the first precipitation, and for one hour during the second period.

During the first period, average accumulated precipitation of all sections was 0.41, and maximum was 1.44 at station no.91-1 under the environment of soft rime. During the second period, the environment of soft rime was created for one hour at 0000 KST on January 21, average accumulated precipitation was 0.15 mm, and maximum was 0.77 mm at station no.97. The environment of soft rime was created for one hour and two hours, except station no.87~88 and 91-3~91-4 where the environment was not created.

When the distribution of hard rime was compared to the distribution of precipitation, most precipitation was under the environment of hard rime. Specially, the rainfall intensity was over 2 mmh^{-1} at from 0900 to 23000 KST on January 19, and maximum was 3.94 mmh^{-1}. The environment of hard rime was created for a maximum of 47 hours at station no.100, and for a minimum of two hours at station no.91-2~91-3 (the average of all sections was 26.3 hours). Also, station no.98, where accumulated precipitation was 82.72 mm, was recorded the most accumulated precipitation. The distribution of snow accretion, soft rime, hard rime and glaze in different temperatures and wind speeds was shown Fig. 11 at all sections during the all analysis period. Black dot is the distribution when precipitation exists, and gray dot is when precipitation does not exist. The environment of soft rime had 44.7 percent of all and hard rime was 46.8 percent.

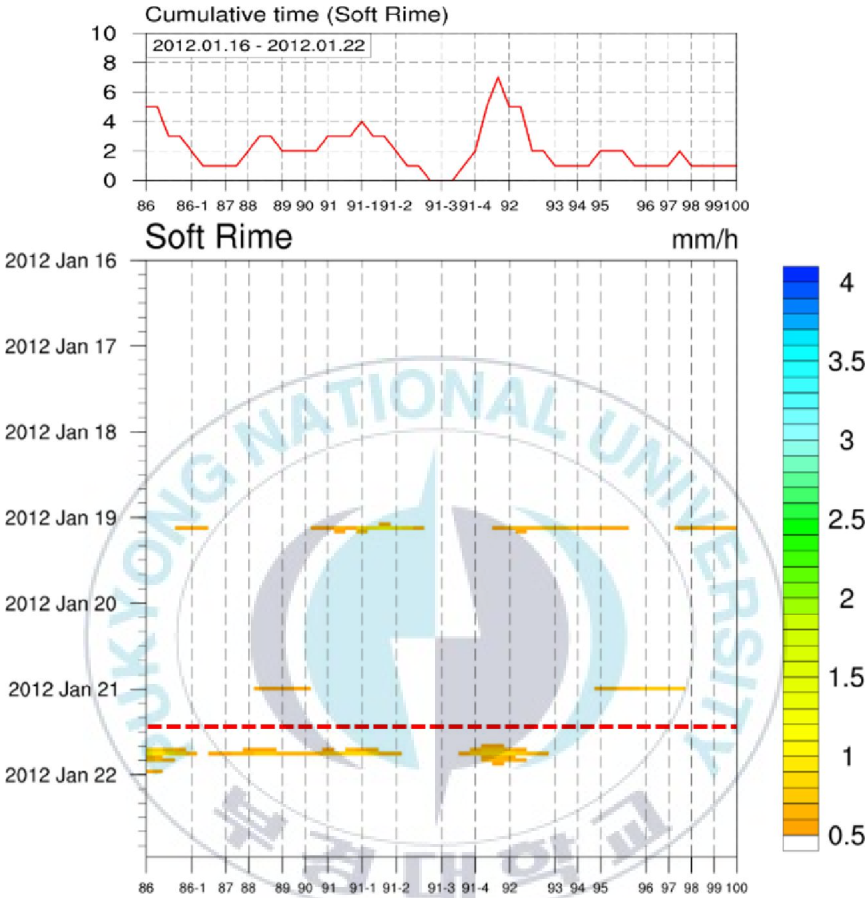

Fig. 9. Distribution of precipitation under the environment of soft rime and cumulative time at the Taebaek-Gohan transmission line (Red dot line : Time of the accident).

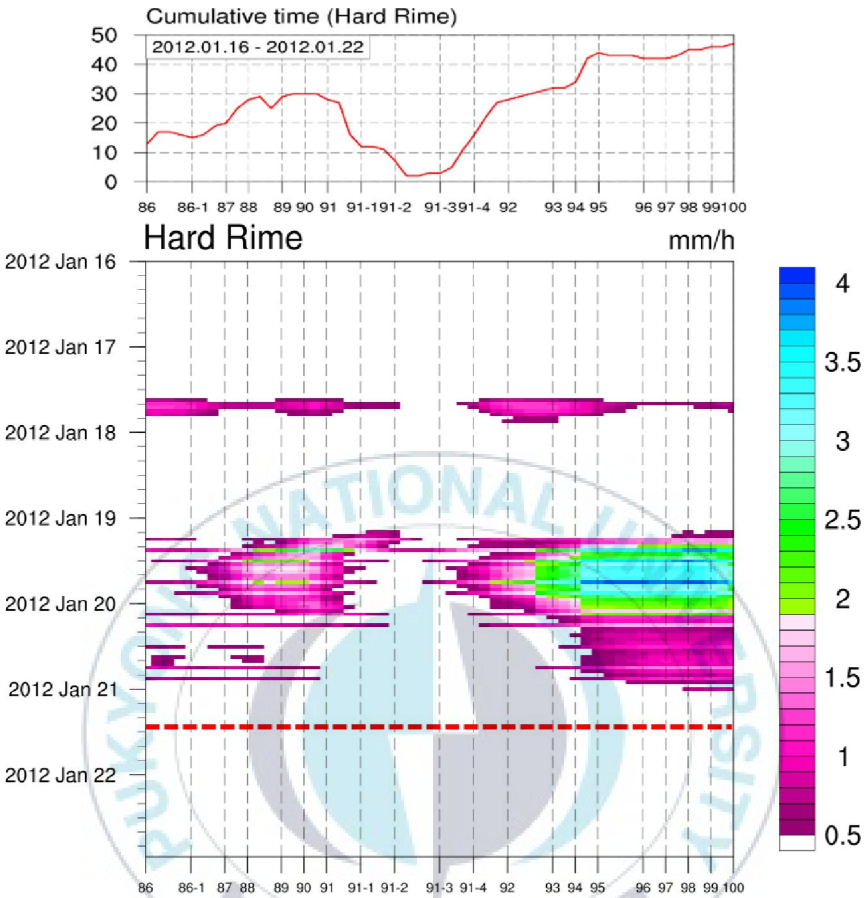

Fig. 10. Same as Figure 9, but variable is precipitation under the environment of hard rime.

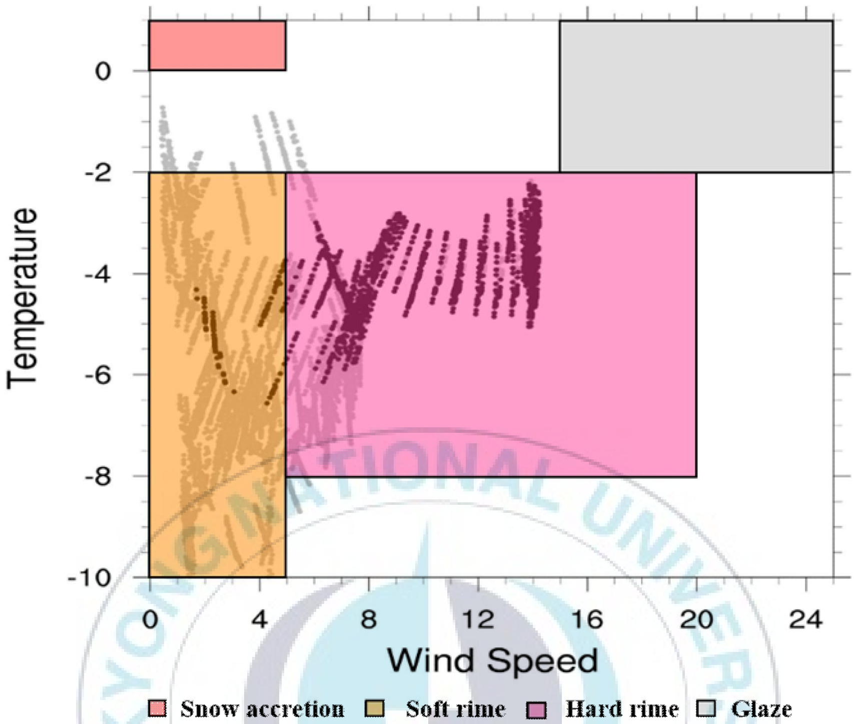

Fig. 11. Distribution of snow accretion, soft rime, hard rime and glaze in different temperatures and wind speeds at the Taebaek-Gohan transmission line.

1.1.3. Analysis of failure cause

Before the snow failure, although the environment of soft rime was created for 1-2 hours, it is presumed that soft rime do not effect on the transmission line at that time, because cumulative time was not long, and soft rime has weakly adhesion. In case of hard rime, the precipitation under the environment of hard rime was a maximum of 3.94 mmh^{-1}, and the environment of hard rime was created for 47 hours. Specially, most of precipitation was at station no.98, which seems to caused by the winds blowing in the east-northeast. This is consistent with the KEPCO (2017) report that the upper power line underwent a severe elongation phenomenon at station 95-98. Also, the temperature increased before the snow failure.

Therefore, the cause of snow failure, which occurred at 154kV Taebaek-Gohan transmission line, seems that the icing created for 47 hours covered the line, and the sleet jumping occurred because the icing on the wires fall off by high temperature or any reason.

1.2. CASE 2: 154kV Hoenggye T/L

The second case of 154kV Hoenggye transmission line station no.30-40 which is located within a 592 to 1211 meter happened 0921 KST on January 12, 2009. The cause of snow failure is the contact fault of differential transmission line by the icing at station no.30-40 (KEPCO, 2017).

1.2.1. Analysis of weather condition

Like the case 1, the distribution of synthetic precipitation, temperature at 70m, wind speed at 70m, and wind direction at 70m were analyzed using synthetic data at 54kV Hoenggye transmission line.

Synthetic precipitation was for 6 hours from 1000 to 1500 KST on January 9, and maximum accumulative precipitation was 4.46 mm at station no.34-1~35(Fig. 12). Also, before the snow failure, the temperature at 70m was very lower than other period for 12 hours from 16 KST on January 11 to 04 KST on January 12, and the average temperature of all sections was −13.17 ℃, Maximum was −10.93 ℃ at station no.30, Minimum was −14.07 ℃ at station no.35 (Fig. 13). Likewise, the wind speed at 70m was also very high before the accident. During the period from 00 KST on January 11 to 09 KST on January 12, the average wind speed of all sections was 15.9 ms^{-1}, Maximum was 17 ms^{-1} at station no.35, Minimum was 12.5 ms^{-1} at station no.30 (Fig. 14). At that time, the prevailing wind was west-northwest which occupied 60 percent of all wind direction, and west wind and north-west wind were 20 percent respectively.

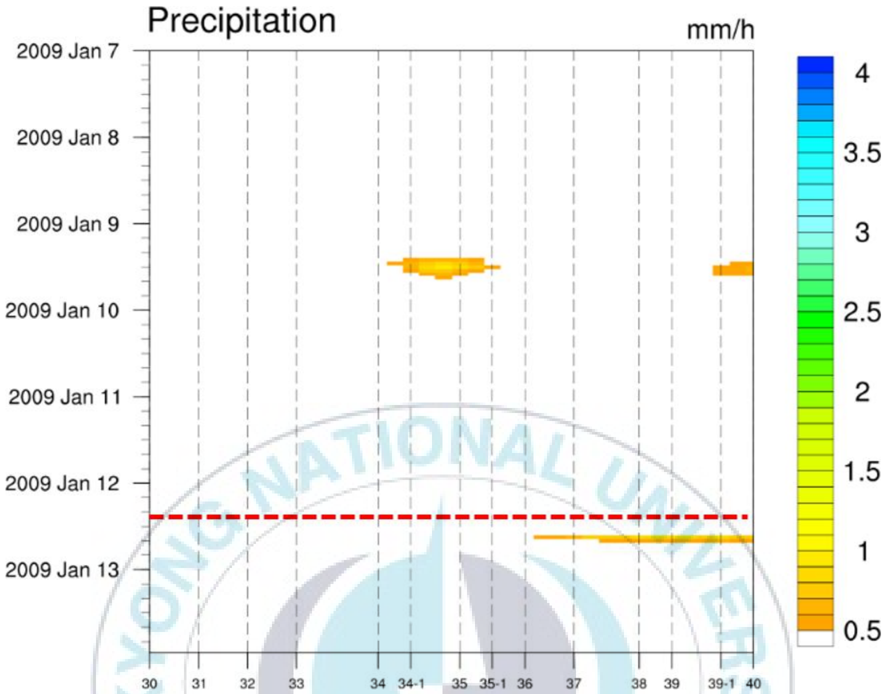

Fig. 12. Distribution of precipitation at the Hoenggye transmission line (Red dot line:Time of the accident).

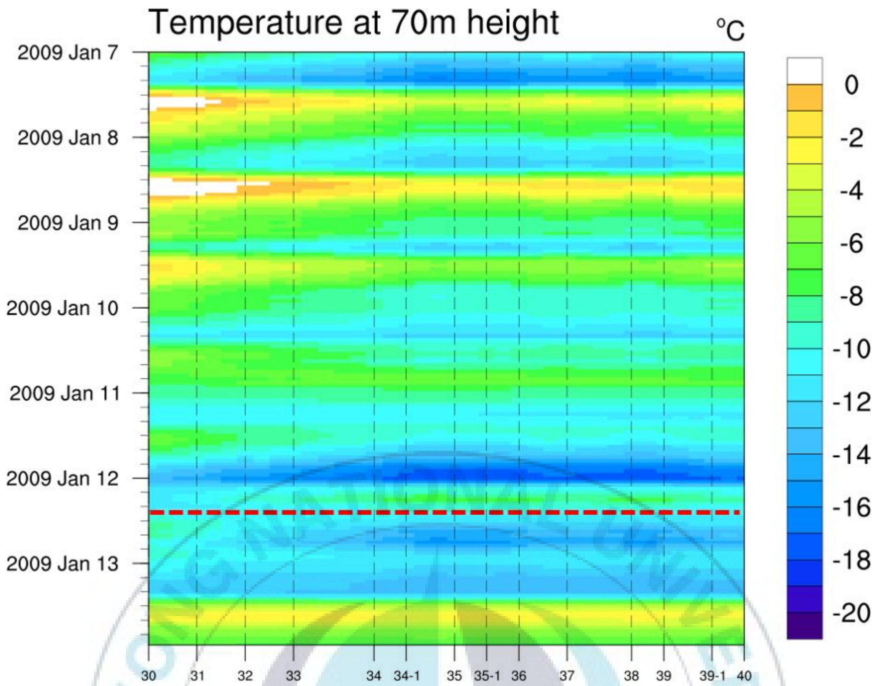

Fig. 13. Same as Figure 12, but variable is temperature at 70m.

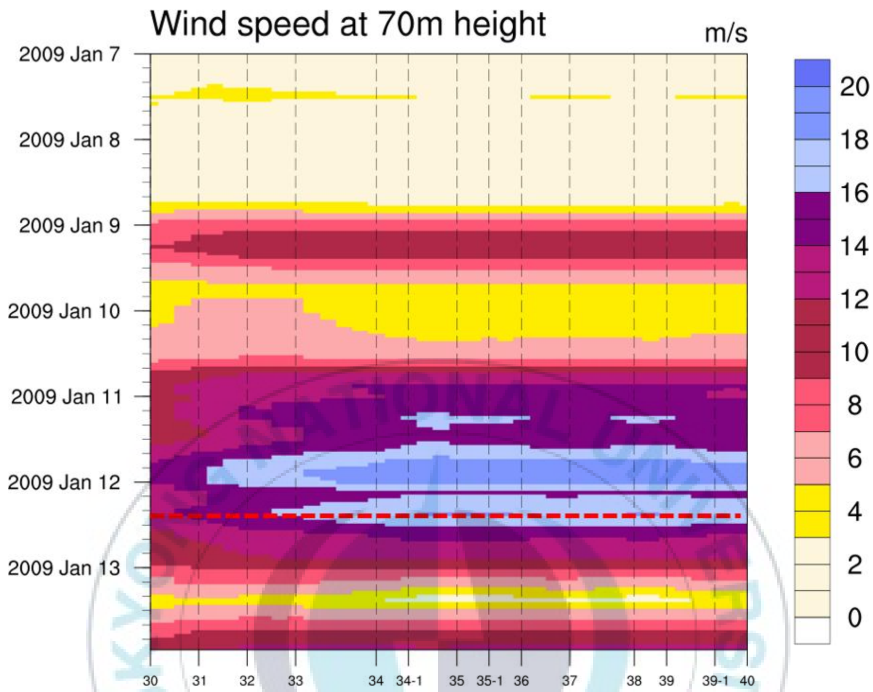

Fig. 14. Same as Figure 12, but variable is wind speed at 70m.

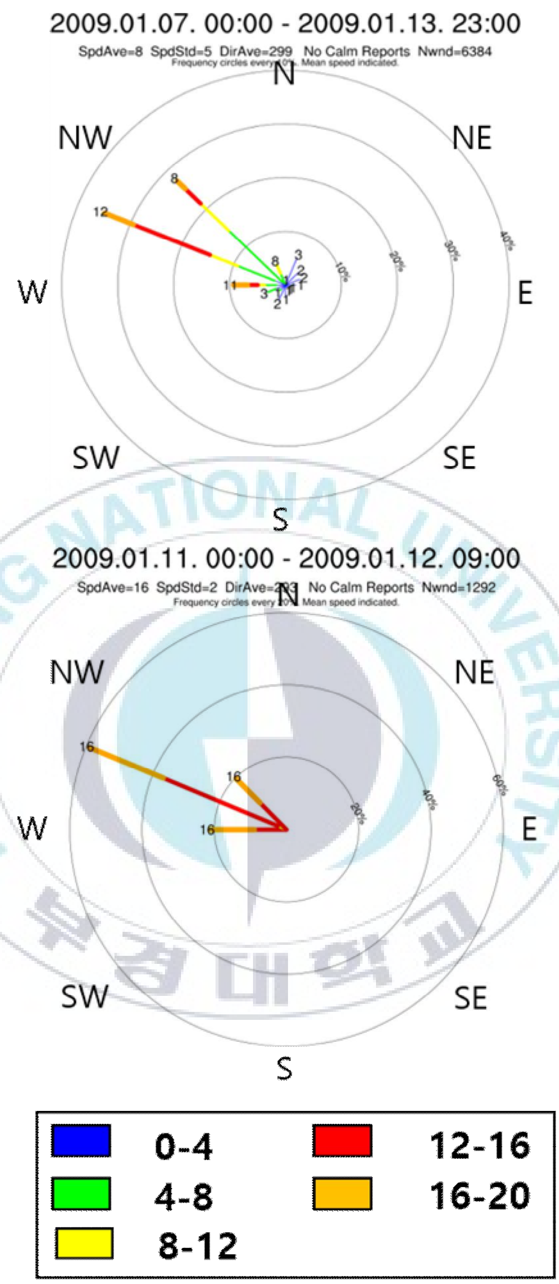

Fig. 15. Same as Figure 7.

1.2.2. Analysis of snow and ice accretion

During the analysis period, all precipitation was under the environment of hard rime which was created for six hours at station no.34~45 and for four hours at station no.39-1~40 (Fig. 14). We need to analyze the distribution of icing types in different temperature and wind speed during the period when precipitation was not existed because the accident happened by very low precipitation in comparison to case 1. The environment of snow accretion had 0.7 percent of all and soft rime and hard rime were 21.4 percent and 21.8 percent respectively.

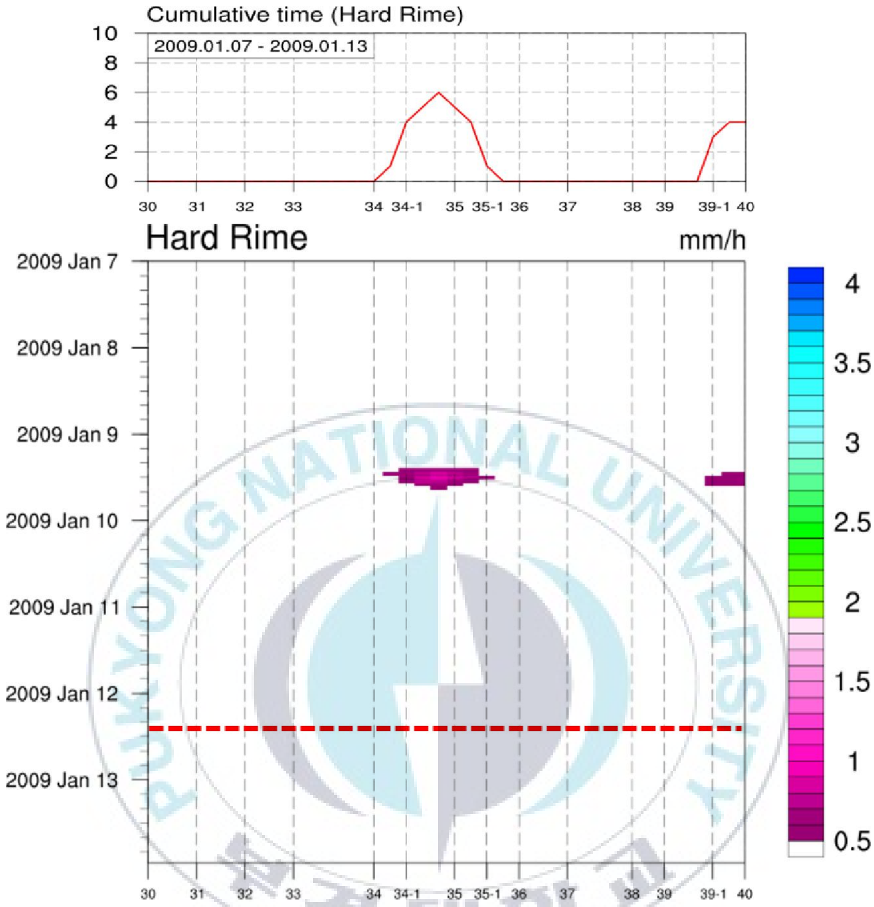

Fig. 16. Distribution of precipitation under the environment of hard rime and cumulative time at the Hoenggye transmission line (Red dot line : Time of the accident).

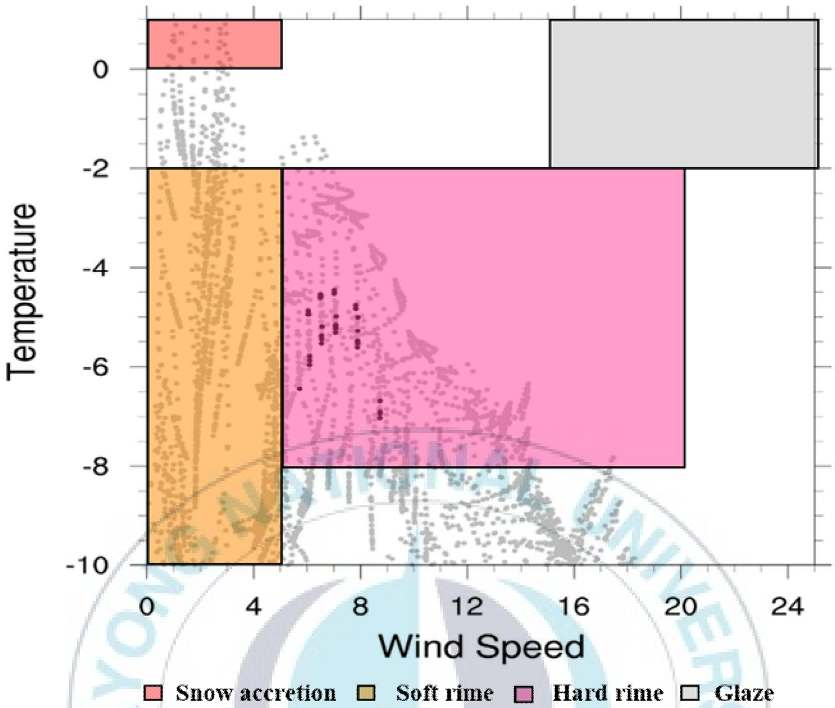

Fig. 17. Same as Figure 11, but target transmission is Hoenggye.

1.2.3. Analysis of failure cause

Although precipitation was very lower than other case, snow failure happened by contacting each line. The cause of icing under the low precipitation seems that the supercooled water drop in the fog and cloud crashed the transmission line, because the environment of soft rime and hard rime occupied total 40 percent of all. Also, before the accident for 1 day, the strong wind was blowing at the average speed of 15.9 ms^{-1}. Therefore, it is presumed that the failure of the 154kV Hoenggye transmission occurred by galloping phenomenon.

1.3. CASE 3: 345kV Donghae-Sinjechun T/L

The snow failure of 345kV Donghae-Sinjechun transmission line station no. 38-50 which is located within a 576 to 836 meter happened 1110 KST on February 13, 2011. Especially section of station no.40-41 underwent sleet-jumping phenomenon and electric confusion (KEPCO, 2017).

1.3.1. Analysis of weather condition

It was two synthetic precipitation during the period. The first is from 2100 KST on February 8 to 0700 KST on February 9, 2011, and the second is from 2100 KST on February 10 to 2100 KST on February 12, 2011 (Fig. 18). During the first and second period, the average, maximum, and minimum of variables over the all sections were shown as Table 5.

During the first period, average accumulated precipitation of all sections was 7.2 mm, and maximum was 18.2 mm at station no.44~45. At that time, the average temperature at 70m was −2.8 ℃, and maximum and minimum were −1.6℃ at station no.38 and −3.3 ℃ at station no.44~45 respectively (Fig. 19). the average wind speed at 70m was 7.1 ms^{-1}, and maximum and minimum were 7.4 ms^{-1} at station no.45 and 6.4 ms^{-1} at station no.38 respectively (Fig. 20).

During the second period, average accumulated precipitation was 83 mm, and maximum and minimum were 95.9 mm at station no.45 and 74.6 mm at station no.43 respectively. The average temperature (−7 ℃) was lower than the temperature of the first period. Maximum temperature was −5.5 ℃ at station no.38, and minimum temperature was −7.9 ℃ at station no.45. Likewise, average wind speed (5.8 ms^{-1}) was lower than the wind speed of the first period, and Maximum and Minimum were 5.9 ms^{-1} at station no.41 and 5.2 ms^{-1} at station no.38.

Before the accident, temperature was very low, with an average of −15.7 ℃ from 2000 KST on February 12 to 1110 KST on February 13, 2011. In case of wind speed, strong wind of 9 ms^{-1} or more was distributed from 0000 to 1200 KST on February 12, and relatively weak wind from 2 - 5 ms^{-1} was distributed until the accident occurred. The wind direction varied widely from west-northwest to east wind for the entire period. When the wind speed became stronger, north or north-northeaster wind blew from 8 to 12 ms^{-1}. Before the accident, relatively weak wind from 4 − 8 ms^{-1} blew from west-northwest (Fig. 21).

Table 5. Same as table 4.

Period	Synthetic variables	Average	Maximum	Minimum
2100 KST on February 8, 2011 -0700 KST on February 9, 2011 (Total 11 hours)	Precipitation	7.2 mm	18.2 mm (no.44~45)	0 mm (no.38~41, 49~50)
	Temperature at 70m	-2.8 ℃	-1.6 ℃ (no.38)	-4.96 ℃ (no.44~45)
	Wind speed at 70m	7.1 ms^{-1}	7.4 ms^{-1} (no.45)	6.4 ms^{-1} (no.38)
2100 KST on February 10, 2011 -2100 KST on February 12, 2011 (Total 49 hours)	Precipitation	83 mm	95.9 mm (no.45)	74.6 mm (no.43)
	Temperature at 70m	-7 ℃	-5.5 ℃ (no.38)	-7.9 ℃ (no.45)
	Wind speed at 70m	5.8 ms^{-1}	5.9 ms^{-1} (no.41)	5.2 ms^{-1} (no.38)

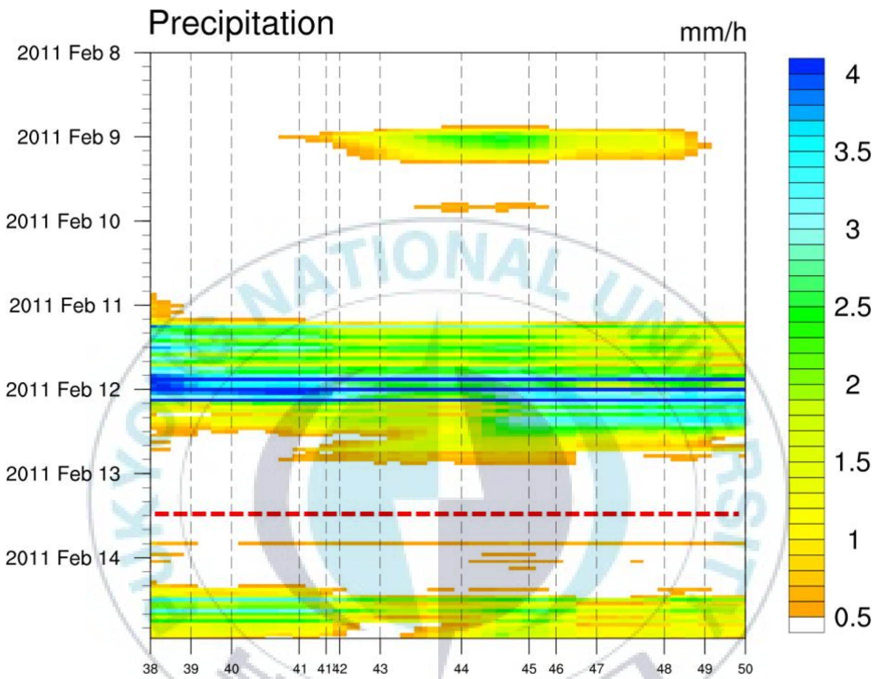

Fig. 18. Distribution of precipitation at the Donghae-Sinjechun transmission line (Red dot line: Time of the accident).

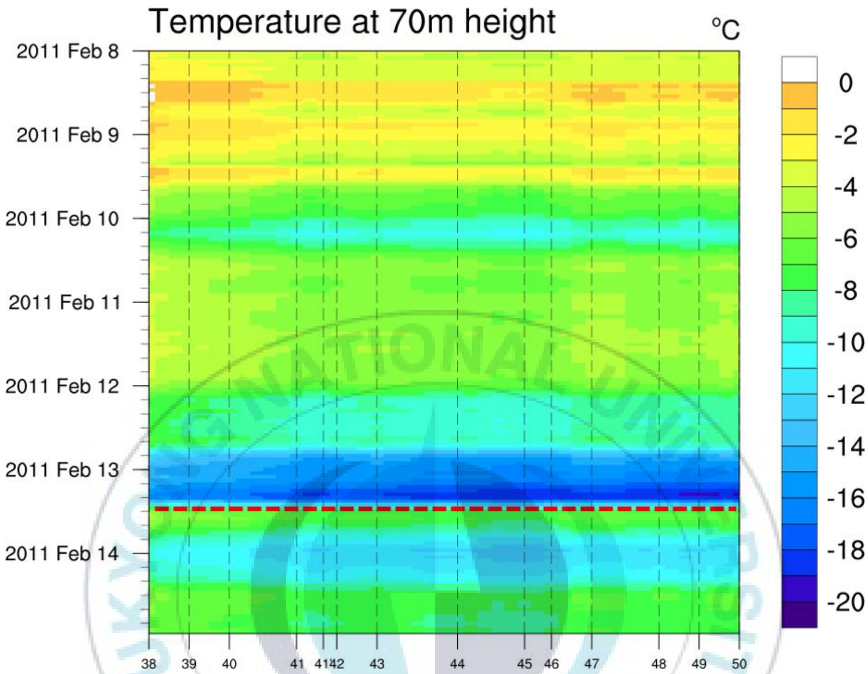

Fig. 19. Same as Figure 18, but variable is temperature at 70m.

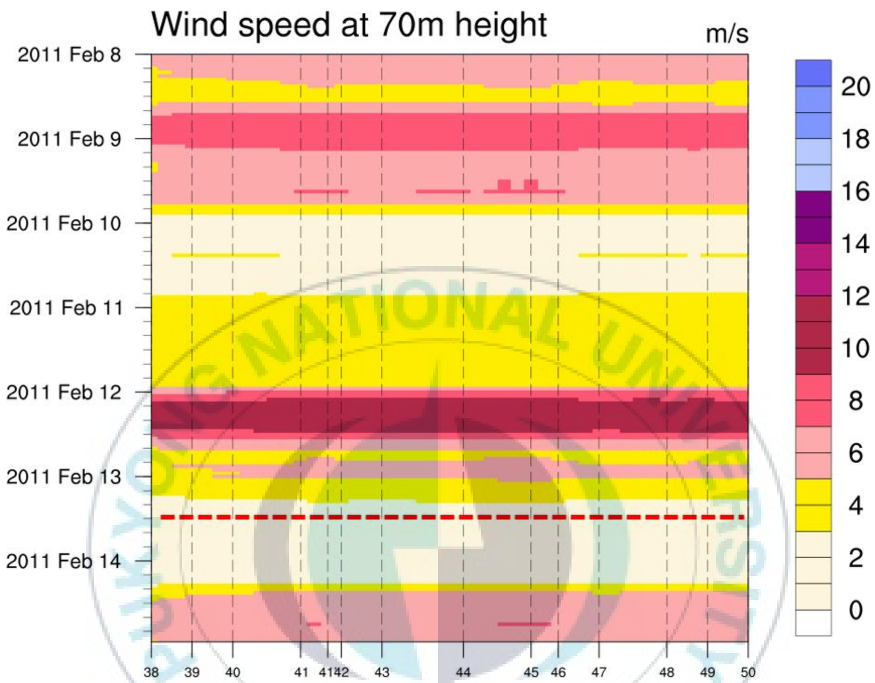

Fig. 20. Same as Figure 18, but variable is wind speed at 70m.

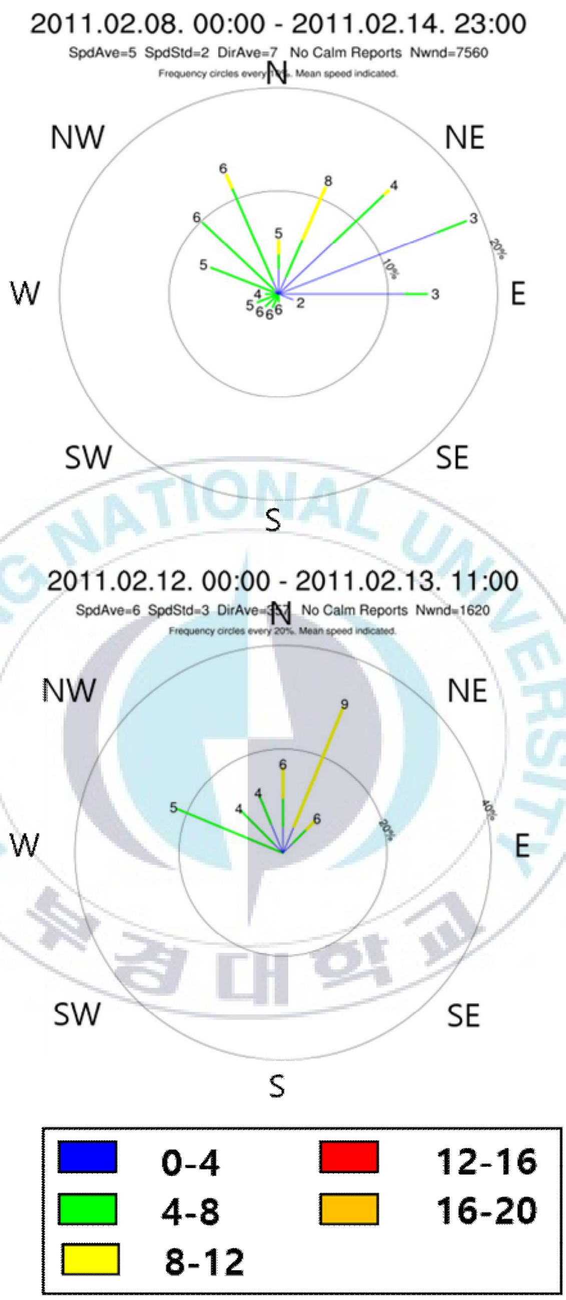

Fig. 21. Same as Figure 7.

1.3.2. Analysis of ice and snow accretion

The environment of snow accretion, soft rime, and hard rime was created during the analysis period. However, the environment of snow accretion lasted very short and excluded from analysis.

Precipitation under the environment of soft rime was distributed from 21 KST on February 10 to 22 KST on February 11. The average accumulated precipitation was 40.5 mm, the maximum was 61.7mm at station no.38, and the minimum was 29.9mm at station no.49. The accumulation time of soft rime environment was from 18 to 27 hours (station no.38) in the whole section (Fig. 22).

Precipitation under the environment of hard rime occurred twice in total from 2100 KST on February 8 to 0700 KST on February 9, 2011 (11 hours) and from 2300 KST on February 11 to 1500 KST on February 12, 2011 (12 hours) (Fig. 23). During the first environment of hard rime, the average accumulated precipitation was 6.8 mm, the maximum was 18.2mm at station no.44-45. During the second period, the average accumulated precipitation was 16.3 mm, the maximum was 32.8 mm at station no.38, and the minimum was 10 mm at station no.44. The accumulation time of hard rime environment was from 4 to 15 hours (station no.38) in the whole section. The environment of soft rime had 38.1 percent of all and hard rime were 29.2 percent (Fig. 24).

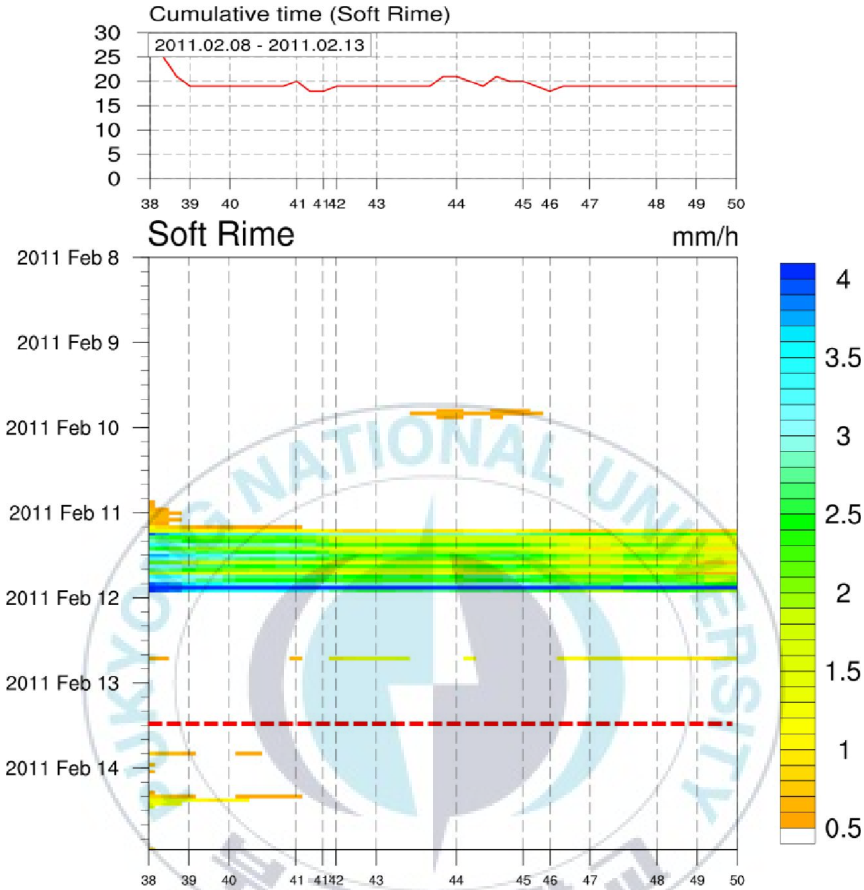

Fig. 22. Distribution of precipitation under the environment of soft rime and cumulative time at the Donghae-Sinjechun transmission line (Red dot line : Time of the accident).

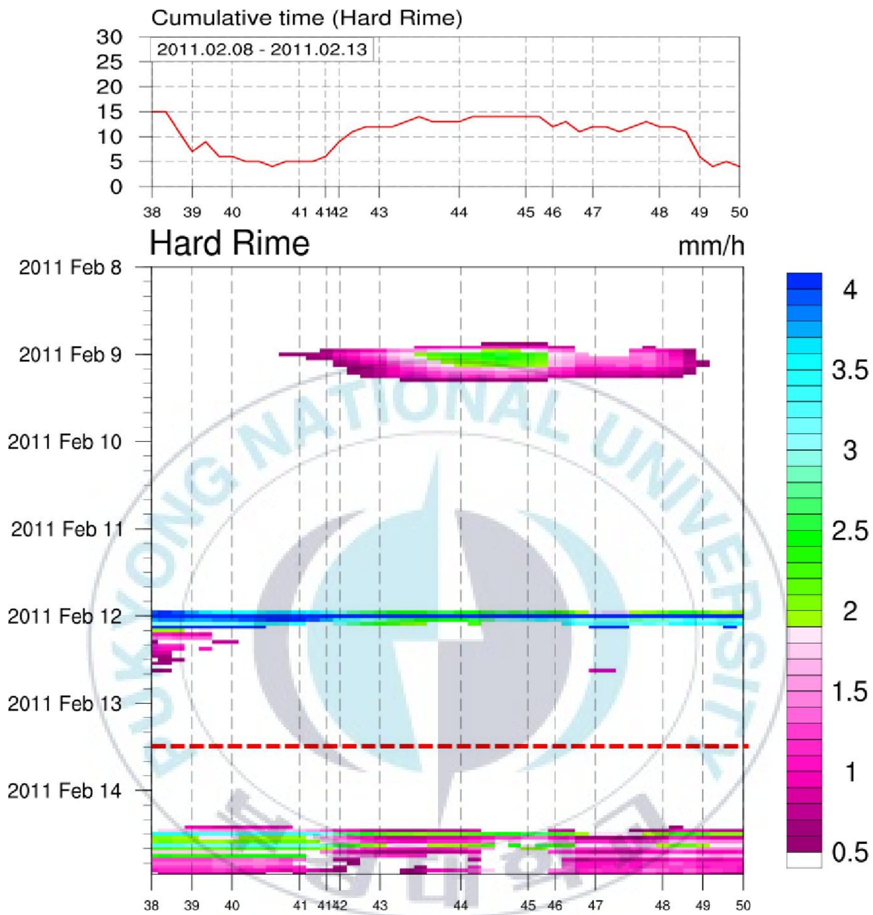

Fig. 23. Same as Figure 22, but variable is precipitation under the environment of hard rime.

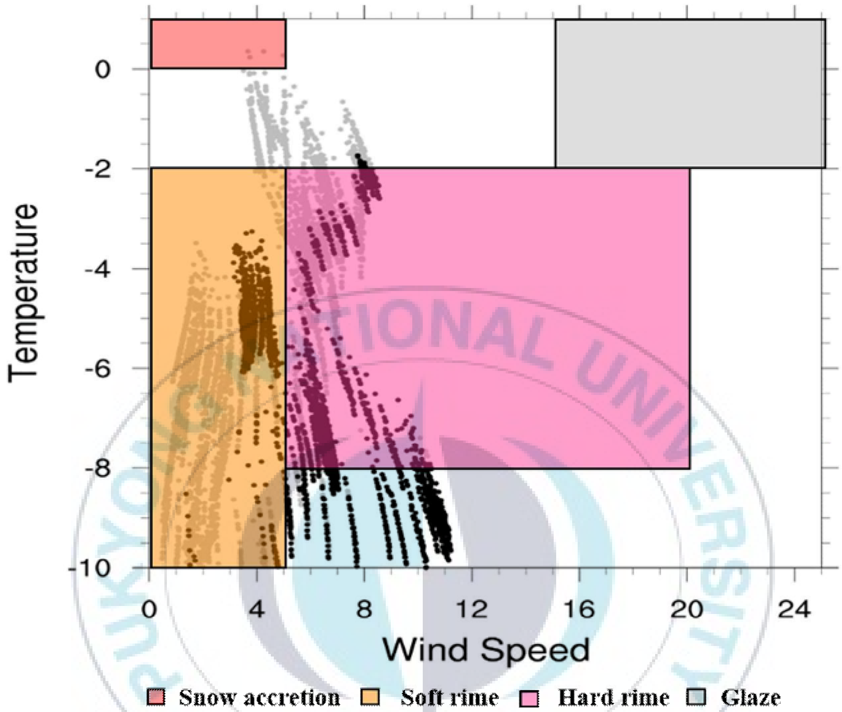

Fig. 24. Same as Figure 11, but target transmission is Donghae-Sinjechun.

1.3.3. Analysis of failure cause

As a result of analyzing the snow failure, the environment of soft rime and hard rime occupied 38.1 and 29.2 percent respectively, and the average temperature was −15.7 before the accident. Therefore, it was analyzed that icing on the wire caused by the environment of soft rime and hard rime fell off by any reason and then the conductor jumping up and contacted each other.

2. Analysis of probable precipitation

In this study, we studied about the effect of icing types through analysis of snow failure cases. Also, it is important to analyze probable precipitation by icing types. Therefore, in this study, we selected the optimum probability distribution over the target area in winter using long-term observation precipitation data. And then, investigated the spatial distributions with the determination of probable precipitation at 1-km resolution by icing types using synthetic data.

2.1. Determination of optimum probability distribution

Parameter estimation was calculated using the annual maximum precipitation data from ASOS of Taebaek by the accumulative time (Table 5). The result of the goodness-of-fit test of chi-square and the PPCC (Table 6) was that in the case of the NOR distribution, all of the durations was accepted by the chi-square but except 12 hours, all of the durations wasn't accepted by the PPCC. In case of the GEV and GLO distribution, all durations were accepted by the PPCC, but some of the durations wasn't accepted by the chi-square. And finally, in case of GUM distribution, all durations were adopted by the PPCC and chi-square.

The CDF and PDF of four distributions were compared to an empirical value to select the optimum probability distribution (Fig. 25). The CDF of all distributions were little different, but the peak of the PDF of the GUM distribution was similar to EMP.

Therefore, in this study, the gumbel distribution was selected as the optimum probability distribution in the winter over the target region, because all durations were accepted by the goodness-of-fit test of chi-square and the PPCC, and the CDF of the GUM distribution was similar to empirical distribution.

Table 6. Annual maximum precipitation during 1986 through 2015 in winter at Taebaek ASOS.

year	6h	12h	18h	24h
1986	20.2	21.4	21.4	21.7
1987	23.3	30.3	32.9	38.5
1988	13.1	19.8	24.5	26.8
1989	25.5	48.9	63.1	65.6
1990	21.8	34.6	43.8	49.5
1991	20.7	23.8	25.9	26.9
1992	24.5	28	28.5	28.5
1993	24.5	33	35.5	37.5
1994	12.5	16	17	18
1995	24.5	28	29.5	29.5
1996	26.5	31.5	31.5	31.5
1997	16	21.5	22	22
1998	28.5	42	53	60.5
1999	15	20.5	26	26
2000	9	11.5	15.7	19.2
2001	12	22.5	29.5	31.5
2002	14.5	19	19	19
2003	12.5	20.5	27.5	31.5
2004	18	25.5	27	28.5
2005	17	25.2	29.1	29.1
2006	13	13.5	13.8	13.8
2007	47	53.5	56.5	59.5
2008	13	20.5	26.5	31.5
2009	13.5	18.5	18.8	18.8
2010	22.5	28.5	28.5	28.9
2011	20.7	37.7	46.2	48.7
2012	20	37.5	45.5	49.5
2013	19.1	25.1	25.5	25.6
2014	27.5	33.5	36	37
2015	13.5	19	19.7	19.9

Table 7. Summary of parameter estimations of normal (NOR), generalized extreme value (GEV), generalized logistic (GLO) and gumbel (GUM) distributions for several rainfall durations.

Rainfall duration		6 h	12 h	18 h	24 h
NOR	x0	19.647	27.027	30.647	32.483
	Xmin	9	11.5	13.8	13.8
	Xmax	47	53.5	63.1	65.6
	α	6.967	9.705	11.77	12.981
	β	0	0	0	0
	VALIDITY CHECK	O	O	O	O
GEV	x0	16.207	22.194	24.569	25.748
	Xmin	9	11.5	13.8	13.8
	Xmax	47	53.5	63.1	65.6
	α	5.528	7.598	8.619	9.374
	β	-0.044	-0.056	-0.115	-0.126
	VALIDITY CHECK	O	O	O	O
GLO	x0	18.418	25.237	28.035	29.52
	Xmin	9	11.5	13.8	13.8
	Xmax	47	53.5	63.1	65.6
	α	3.693	5.113	5.997	6.572
	β	-0.194	-0.203	-0.246	-0.254
	VALIDITY CHECK	O	O	O	O
GUM	x0	16.373	22.467	25.117	26.385
	Xmin	9	11.5	13.8	13.8
	Xmax	47	53.5	63.1	65.6
	α	5.671	7.899	9.58	10.566
	β	0	0	0	0
	VALIDITY CHECK	O	O	O	O

Table 8. Goodness-of-fit test of precipitation data.

Cumulative time		6	12	18	24
NOR	χ2	3	3.67	4.33	4.33
	check	O	O	O	O
	PPCC	0.92	0.97	0.95	0.94
	check	X	O	X	X
GEV	χ2	7.33	3	6.33	6.33
	check	X	O	X	X
	PPCC	0.96	1	0.99	0.98
	check	O	O	O	O
GLO	χ2	5.33	1	4	3.33
	check	X	O	X	O
	PPCC	0.97	0.99	0.98	0.97
	check	O	O	O	O
GUM	χ2	5.33	3	4.33	3
	check	O	O	O	O
	PPCC	0.96	1	0.99	0.98
	check	O	O	O	O

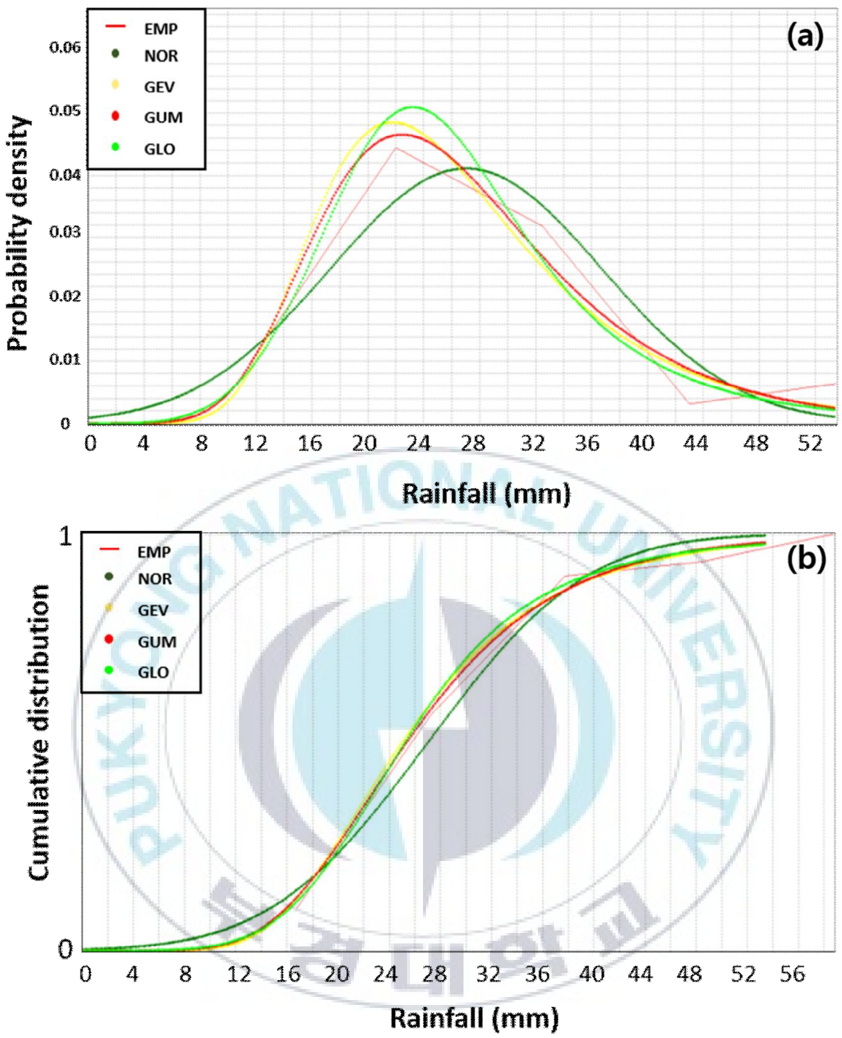

Fig. 25. (a) Probability density and (b) cumulative distribution for 12-hour rainfall duration. EMP means a empirical value calculated with the observed precipitation data.

2.2. Analysis of probability precipitation

The parameter estimated by the GUM distribution put in the inverse CDF of GUM distribution, and then calculated the probable precipitation by the return period. Equation (1) is the CDF of the gumbel distribution and equation (2) is the inverse CDF of the gumbel distribution. x_0 is the location parameter, α is the scale parameter, T is the return period, and x_T is the probable precipitation by the return period.

$$F_x = \exp\left[-\exp\left(-\frac{(x-x_0)}{\alpha}\right)\right] \tag{1}$$

$$x_T = x_0 - \alpha^* \ln\left[-\ln\left(1-\frac{1}{T}\right)\right] \tag{2}$$

The calculation formula of parameter estimation using the method of probability weighted moments is equation (3)-(7). l_1 and l_2 are 1th and 2th L-moment respectively, $M_{1,0,0}$ and $M_{1,1,0}$ are probability weighted moments of a sample, X_i is ith data in ascending sort order, and ϵ is 0.5772157 as Euler's number (Moon et al, 2016).

$$l_1 = M_{1,0,0} = \bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{3}$$

$$M_{1,1,0} = \frac{1}{n}\sum_{i=1}^{n}\frac{i-1}{n-1}X_i \tag{4}$$

$$l_2 = 2M_{1,1,0} - M_{1,0,0} \tag{5}$$

$$\alpha = \frac{l_2}{\ln 2} \tag{6}$$

$$x_0 = l_1 - \epsilon * \alpha \tag{7}$$

The result of probable precipitation at Taebaek ASOS is table 7. It means that precipitation of 12 accumulative time will be 58.8 mm every 100 years in the winter at Taebaek ASOS.

In the same way, the annual maximum synthetic precipitation data was constructed with synthetic data by icing type, calculate probable precipitation every grid, and investigated the spatial distribution of probable precipitation over the target area.

Spatial distributions of probable precipitation of a 100-year return period are shown as Fig. 26 and 27. In case of snow accretion (Fig. 26(a)), the longer accumulative time, the greater probable precipitation at the shore of Sokcho and Yeongyang. In case of soft rime (Fig. 26(b)), as the accumulative time increases, the probable precipitation is high at Samcheok and Uljin. The probable precipitation of hard rime is high along the Taebaek mountain which is high topography and the highest value is 120.3 mm among the icing types. The probable precipitation of glaze, like the hard rime, is high at the high topography, but it is very low value.

Table 9. The estimated probable precipitation for several cumulative time and return period.

Return period (year)	Cumulative Time			
	6 h	12 h	18 h	24 h
2	18.5	25.4	28.6	30.3
3	21.5	29.6	33.8	35.9
5	24.9	34.3	39.5	42.2
10	29.1	40.2	46.7	50.2
20	33.2	45.9	53.6	57.8
30	35.6	49.2	57.5	62.1
50	38.5	53.3	62.5	67.6
70	40.4	56	65.7	71.2
80	41.2	57	67	72.6
100	42.5	58.8	69.2	75
150	44.8	62	73.1	79.3
200	46.4	64.3	75.9	82.3
300	48.7	67.5	79.7	86.6
500	51.6	71.6	84.6	92

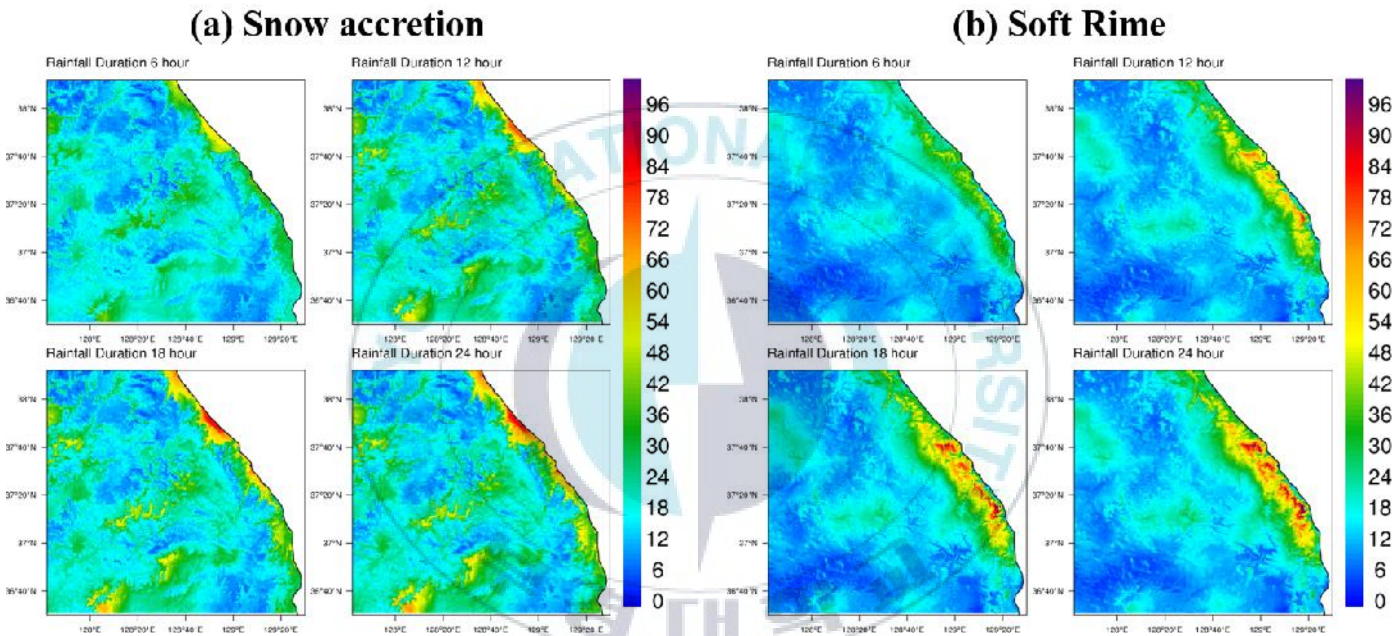

Fig. 26. Spatial distributions of probable precipitation of a 100-year return period.

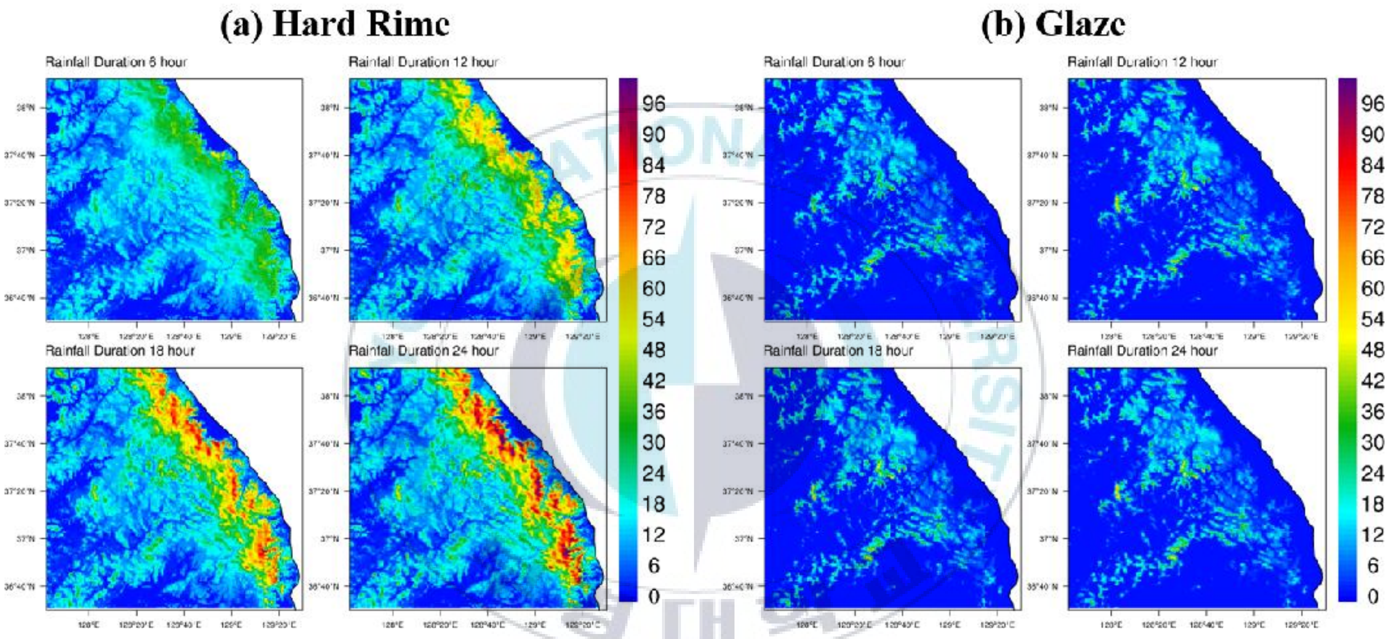

Fig. 27. Spatial distributions of probable precipitation of a 100-year return period.

IV Summary and conclusion

In this study, high resolution synthetic precipitation, temperature, and wind data were produced using QPM, QTM, and QWM considering detailed topography effect, and we analyzed the environment of weather and icing at the transmission line where the snow failure occurred.

In the case of the Taebaek-Gohan transmission line failure, it was presumed that the icing caused by the environment of hard rime lasting for up to 47 hours fell off due to the increased temperature before the accident and the upper and lower lines contacted by the sleet jumping phenomenon. In the case of the Hoenggye transmission line failure, unlike the previous case, the precipitation was not distributed much, but the snow failure happened. As a result of the analysis, it was analyzed that the galloping phenomenon happened due to the icing caused by the supercooled water droplets in a fog or cloud as well as the strong wind of the average wind speed of 15.9 ms^{-1}. In the case of the Donghae-Sinjechun transmission line failure, it was analyzed that icing on the wire caused by the environment of soft rime and hard rime fell off by any reason and then the conductor jumping up and contacted each other (sleet jumping).

By analyzing the cases of snow failure at the transmission line, the importance of understanding the weather conditions and the icing environment was understood. In this study, the distribution of probable precipitation was investigated to identify the heavy snow fall region by icing types.

To estimate probable precipitation, the optimum probability distribution was selected using Taebaek ASOS data. From the results of chi-square test and PPCC test and comparison of the PDF and the empirical probability density function, gumbel distribution was selected as an optimum probability distribution over the target areas.

The annual maximum synthetic precipitation data was constructed with synthetic data by icing type, calculate probable precipitation every grid, and investigated the spatial distribution of probable precipitation over the target area. In case of snow accretion, the longer accumulative time, the greater probable precipitation at the shore of Sokcho and Yeongyang. In case of soft rime, as the accumulative time increases, the probable precipitation is high at Samcheok and Uljin. The probable precipitation of hard rime is high along the Taebaek mountain which is high topography and the highest value is 120.3 mm among the icing types. The probable precipitation of glaze, like the hard rime, is high at the high topography, but it is very low value.

This study investigated the environment of weather and icing at the mountainous area using synthetic data. This is the only study that analyzed the meteorological environment of the transmission line using high resolution synthetic data. If we analyze the weather conditions of various snow failure cases, it is possible to predict the occurrence environment of snow and icing conditions. Also, it is expected that the distribution of probable precipitation by type of icing will be a good basic data when it is used to determine the wire thickness and the equipment for preventing snow failure in the transmission line construction.

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