Master's Thesis

Impact of Local Sea Surface Temperature on Heavy Snowfall in Yeongdong Region

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(Disaster Management Engineering)

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Approved by

Advisor
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Abstract

This research investigates the impact of local sea surface temperature (SST) on the intensity of snowfall in Yeongdong region which is strongly affected by a synoptic scale factor (East Asian Winter Monsoon, EAWM). Characteristics of snowfall in Yeongdong region, in particular the relationship with EAWM and SST were examined based on observational analysis, and sensitivity experiments with a regional climate model (RCM) were conducted. In sensitivity experiments, local SST was replaced with the climatological SST in winter season for 33 years (1982~2014). Analyses of the composite maps for each strong and weak EAWM year demonstrate that favorable synoptic condition (eastward surge of Siberian High over the northeastern part of the Korean Peninsula, enhanced easterly wind anomaly, and anomalous warm SST over the East Sea) makes a large amount of snowfall during the weak monsoon year. The observational analysis shows both atmospheric and oceanic conditions are important to occur abnormal heavy snowfall in Yeongdong region and analyses of SST experiment suggest that the intensity of snowfall can be significantly affected by local SST when the synoptic condition is favorable. Local SST acts as a source of energy for the formation of heavy snowfall, and it regulates heat and moisture fluxes. When positive SST anomaly exists, latent heat fluxes over the East Sea and moisture convergence on Yeongdong region are enhanced. On the contrary, negative SST anomaly leads to reduced latent heat fluxes and decreased moisture convergence. However, these results are necessarily accompanied with a favorable synoptic condition for heavy snowfall in Yeongdong region. Without the surge of Siberian High and the inflow of easterly wind, SST has no significant impact on the amount of snowfall in Yeongdong region. In addition, both atmospheric and oceanic conditions should be completely favorable to occur a large amount of snowfall.

Key words: Sea surface temperature (SST), heavy snowfall, Yeongdong region, East Asian Winter Monsoon (EAWM) and regional climate model (RCM)

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Chapter Ⅰ

Introduction

Yeongdong region, eastern coastal area in Korea, frequently suffers from severe snowfall events due to the combined effect of steep slopes of Taebaek mountain range and proximity to the East Sea (Chung et al., 2004; Kim et al., 2005; Kim and Chung, 2006; Lee et al., 2006; Han and Lee, 2007; Lee and Kim, 2008). There have been several studies to investigate the characteristics and occurring mechanisms of snowfalls in Yeongdong region based on observations (Jhun et al., 1994; Lee and Kim, 2008, 2009; Jung et al., 2012; Jung et al., 2014). There are three main occurring processes of snowfall over Yeongdong region. First, the eastward expansion of Siberian High to the northeastern area of the Korean Peninsula generates the northeasterly winds over the East Sea and Yeongdong region. Subsequently, the cold air advection over the East Sea surface, which is relatively warmer than the atmosphere, induces a thermal inversion that develops convective clouds in response to the sensible heat, latent heat, and moisture fluxes over the ocean surface. Finally, the northeasterly wind transports the generated convective clouds over the ocean into the coastal region. Not only the eastward surge of Siberian High but also the appearance of low-pressure systems over the southern part of the Korean Peninsula has an important effect on snowfall in South Korea because the low-pressure systems also induce the easterly winds into Yeongdong region and cause the uneven heavy snow in the corresponding area. Thus, the formation of the easterly winds is the most necessary condition to occur snowfall over Yeongdong area, and it determines the duration snowfall. Also, the snow disappears simultaneously over the region when the easterly winds dissipate. The reason is that the easterly wind induced into Yeongdong region could transport the convective clouds over the ocean into the coastal region. Consequently, snowfall in Yeongdong region is entirely influenced by the synoptic factor. Meanwhile, Choi and Kim (2010) suggested that the surge of the Siberian High to the northeastern part of the Korean Peninsula is a much more dominant synoptic pattern for heavy snowfall in Yeongdong region than the appearance of low-pressure systems passing over South Korea. They showed the cases of heavy snow event accompanied by the surge of Siberian High occupied more than twice than those by the low-pressure system.

The intensity of snowfall in Yeongdong region is significantly affected by a synoptic scale factor, and the interannual variability of the synoptic factor is associated with the winter monsoon over East Asia. There have been many efforts to understand the variation of winter monsoon circulation because East Asia Winter Monsoon (EAWM) directly effects the climate variations over East Asia (Wu and Wang, 2002). Jhun and Lee (2004) defined an East Asian Winter Monsoon Index (EAWMI), which reflects the 300hPa meridional wind shear related to the jet stream and it was defined to describe the variability of the winter monsoon in midlatitude East Asia. Siberian High plays a significant role in determining the intensity of EAWM. EAWM is significantly controlled by the interannual variation of Siberian High, and there is a strong correlation between EAWM and the development of Siberian High. Therefore, EAWMI may represent very well the seasonal mean winter precipitation over Yeongdong region where the surge of Siberian High is a dominant synoptic factor for snowfall.

Although the synoptic scale factor has a considerable impact on the occurrence of snowfall over Yeongdong region, there are also local effects on the intensity of snowfall in that area. Several previous studies indicated that the orographic lifting due to the Taebaek Mountain and the abundant moisture and heat from the East Sea were the causes of the more frequent and heavier snowfall compared to other regions. In case of Yeongdong area, the topography is considered as one of the important regional factor in intensifying snowfall (Lee and Lee, 1994; Jhun et al., 1994; Lee and Kim, 2008, 2009; Lee et al., 2010; Cho and Kwon, 2012; Jung et al., 2012; Cho et al., 2015). Lee and Kim (2008) suggested topographic effect as the key factor in the formation of heavy snowfall in Yeongdong region through a numerical experiment that removed the topography over the Taebaek Mountains. Lee and Lee (1994) also showed that the height of the topography significantly affects the amount of snowfall. On the other hand, there are lots of studies considering the effect of the East Sea on heavy snowfall in Yeongdong region (Cha et al., 2011; Cho and Kwon, 2012; Jung et al., 2012). Cha et al. (2011) described the importance of sea surface temperature (SST) as a source of moisture and heat for severe snowfall, and they showed higher SST could modify the vertical fluxes of heat and moisture in the atmospheric boundary and produce convection, and it increases the intensity of snowfall. Jung et al. (2012) also showed that increased SST tends to enhance the precipitation amount because higher SST can provide more sensible heat and latent heat fluxes. Nevertheless, there was little correlation between SST over the East Sea and the interannual variability of snowfall amount in Yeongdong region. SST as a regional factor of heavy snowfall in Yeongdong area is often examined through various sensitivity experiments using a numerical model, but few studies have conducted the role of SST to the long-term variability of snowfall. In recent times, there is increasing trend of SST over the East Sea (Fig. 1.1), and the uneven and irregular heavy snowfall in Yeongdong region has frequently occurred. Therefore, to understand the characteristics of recent extraordinary heavy snow events, the study how local SST influences on the intensity of snowfall are needed to be done.

In this research, we investigate the relationship between EAWM and the amount of snowfall in Yeongdong region for 33 years (from 1982 to 2014) and examine the local impact of SST on heavy snowfall. Sensitivity experiments to local SST over the East Sea region are conducted using regional climate model (RCM). Results of this study may suggest not only the impact of synoptic and local factors on snowfall but also the specific role of local SST to intensifying the amount of snowfall in Yeongdong region.

The respect of this paper is organized as follows. The relationship between EAWM and the interannual variability of snowfall in Yeongdong region are described in chapter 2. The local effect of SST over the East Sea on the intensity of snowfall is presented in chapter 3. Finally, the summary and concluding remarks and references of this research are given in chapter 4 and chapter 5, respectively.

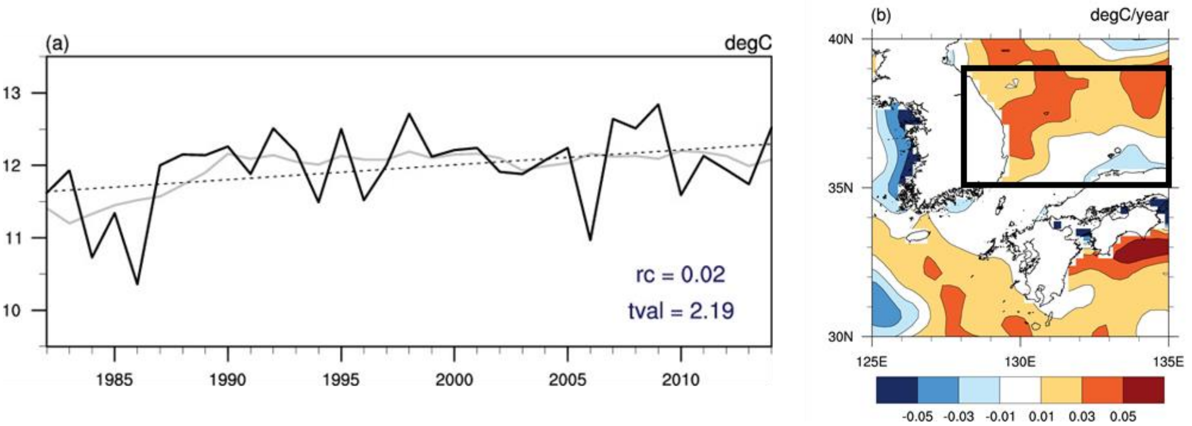

Figure 1.1. (a) Time series of area-averaged SST (solid back line, degC) and (b) linear regression coefficient of SST (degC year-1) from January and February in 33 years (1982~2014) over the East Sea. [Box in (b) indicates the area used in averaging SST at (a) and solid gray line and dotted black line represents the time series of 7 years moving average value and the linear trend line, respectively.].

Chapter Ⅱ

Relationship between East Asian Winter Monsoon and Snowfall

2.1 Datasets

Two gridded datasets are used in this research. Sea level pressure (SLP) and wind data are obtained from the National Centers for Environmental Prediction (NCEP) – Department of Energy (DOE) Reanalysis monthly data (Kanamitsu et al., 2002), which has a horizontal resolution of 2.5-degree latitude x 2.5-degree longitude. SST data is acquired from the Optimum Interpolation Sea Surface Temperature (OISST) monthly data (Reynolds et al., 2007; Smith, 2016) produced by the National Oceanic and Atmospheric Administration (NOAA) and its horizontal resolution is 0.25-degree latitude x 0.25-degree longitude. Besides, the observed amount of snowfall in Yeongdong region is obtained from 4 stations through the National Climate Data Service System (NCDSS) of the Korea Meteorological Administration (KMA). Four stations are Sokcho (SC), Daegwallyeong (DG), Gangneung (GN), and Uljin (UJ) which have the daily data of snowfall since 1982. All data sets cover 33 years (1982~2014), but only January and February data were selected as a winter season of this study because most snowfall is concentrated on those two winter months.

2.2 Impact of EAWM on the Interannual Variability of Snowfall

To explain the relationship between EAWM and snowfall in Yeongdong region, we calculated the correlation coefficient between EAWMI and the amount of snowfall. As a result, the interannual variation of winter precipitation over study area has a negative correlation with EAWMI, and the value was -0.45. This correlation coefficient shows the dominant effect of the synoptic factor on the variability of snowfall amount. The negative correlation pattern is also shown in time series (Fig. 2.1). The peaks of two-time series intuitively appear as the opposite. For example, EAWMI has the largest peaks in 1984 and 2012, but the negative anomalies are presented in time series of snowfall. On the contrary to this, the heaviest snow episodes have been recorded in 1989 and 1990, but EAWMI for those two winter seasons shows the lowest values among 33 years. To better understand how the EAWM affects snowfall, we defined three strong winter monsoon years and six weak winter monsoon years (Table 2.1) based on the one sigma value of EAWMI (dashed line in Fig. 2.1a). The three strong winter monsoon years are 1984, 1985, and 2012, while the six weak winter monsoon years are 1989, 1990, 2002, 2006, 2007, and 2014. Interestingly, all of three strong EAWM years have the expressively less amount of snowfall compared with the 33 years’ climatology. Not only that, among the six weak EAWM years, 1989, 1990 and 2014 have recorded the heaviest snowfall in recent 33 years. The strong negative correlation which means the winter monsoon circulation greatly influences the amount of snowfall is also well presented through those two-time series.

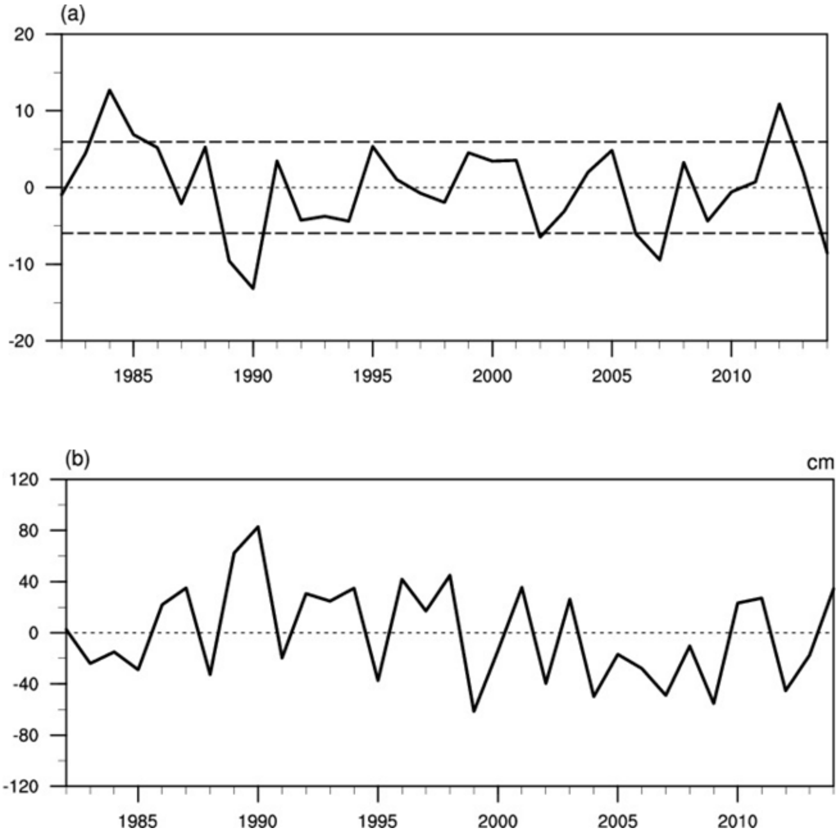

Figure 1.1. Time series of (a) EAWMI and (b) anomaly of snowfall amount (cm) from January and February in 33 years (1982~2014) in Yeongdong region. [Dashed lines indicate ∓1 sigma values of EAWMI.]

Table 2.1. Strong EAWM and Weak EAWM years among 33 years (1982~2014)

	Years
Strong EAWM	1984, 1985, 2012
Weak EAWM	1989, 1990, 2002, 2006, 2007, 2014

2.3 Strong and Weak Monsoon Composites

The composite maps of anomalies of the meteorological variables (SLP, wind vector at 850hPa, and SST) for strong monsoon winters and weak monsoon winters are shown in Fig. 2.2 to 2.4. All anomaly patterns in strong monsoon winters are obviously opposite with those in weak monsoon winters. This is because winter monsoon in East Asia is strongly associated with the zonal pressure gradient, which depends on the development of Siberian High and Aleutian Low. In this study, we concentrated on analyzing the atmospheric and oceanic conditions for the weak monsoon years rather than for the strong monsoon years because high negative correlation (-0.45) showed that most of the heaviest snowfall occurred during the weak EAWM seasons. The weak monsoon winters are characterized by the weakening of the typical pressure pattern (the deepened Aleutian low, the developed Siberian High and the strengthened northeasterly winds at the 850hPa) in the winter season of East Asia. The developed Siberian High means that the core of Siberian High is strengthened at the central area of a Siberian region. In the case of snowfall in Yeongdong area, the eastward surge of Siberian High to the northeastern part of the Korean Peninsula (same meaning with the eastward expansion of Siberian High) is a much more important than the developed core of Siberian High. The reason is the eastward surge of Siberian High could induce the easterly wind into Yeongdong region, but the only enhanced Siberian High without any surge could not make the inflow of the easterly wind that is the most necessary condition to occur snowfall in our study area. In figure 2.2, there is the positive anomalies of SLP over the northeastern part of the Korean Peninsula where Siberian High frequently surges at the time of snowfall in Yeongdong region. Furthermore, the enhanced easterly wind flow near the eastern coastal region explains the most essential condition for snowfall is situated during the weak EAWM years (Fig. 2.3).

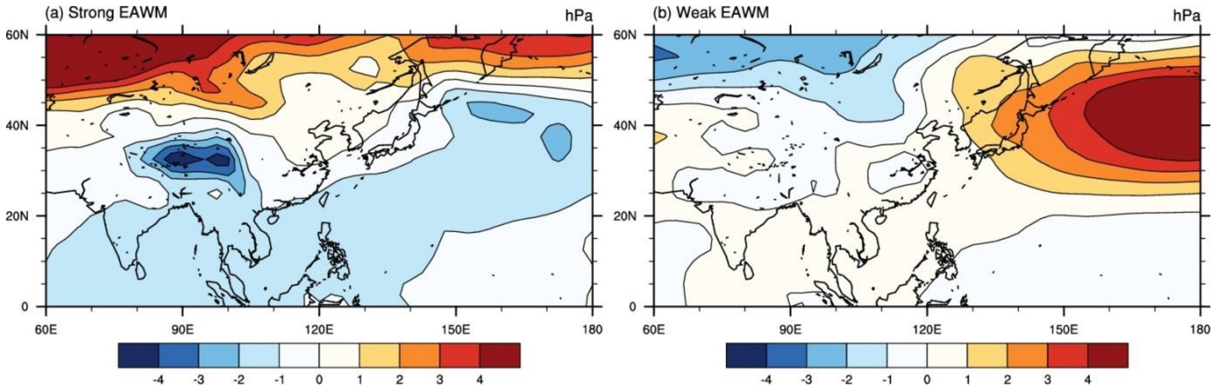

Figure 2.2. Composite maps of sea level pressure anomaly (hPa) for (a) strong monsoon winters and (b) weak monsoon winters.

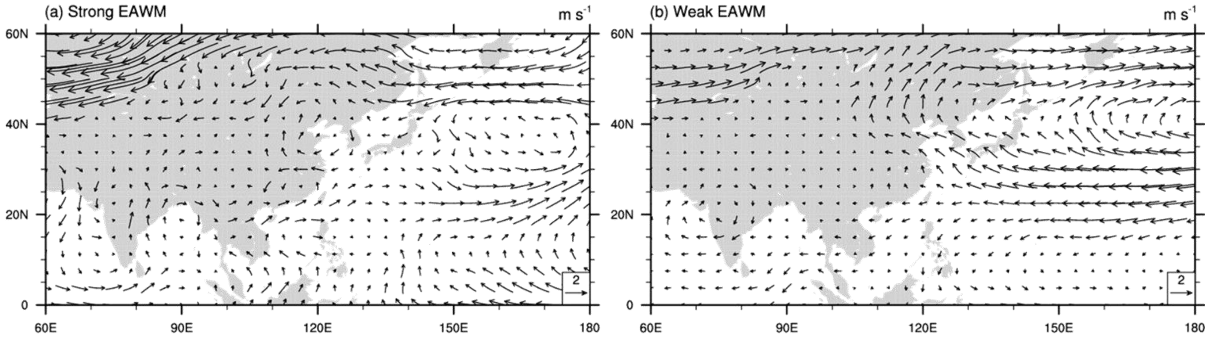

Figure 2.3. Same as Fig. 2.2 but for wind vector anomaly (m s^{-1}) at 850hPa.

Not only there is the mechanically favorable environment for snowfall, but also there is the thermally favorable condition during the weak monsoon years. Figure 2.4 shows the anomaly of warm SST near the Korean Peninsula for each monsoon winters, and it represents the anomalous warm SST in the weak monsoon winters, particularly at the East Sea region. The warm SST could provide sufficient heat and moisture from the ocean to the easterly wind that induced into Yeongdong area. Therefore, both atmospheric and oceanic conditions are the better environment for heavy snowfall in Yeongdong region when the winter monsoon circulation is weakened.

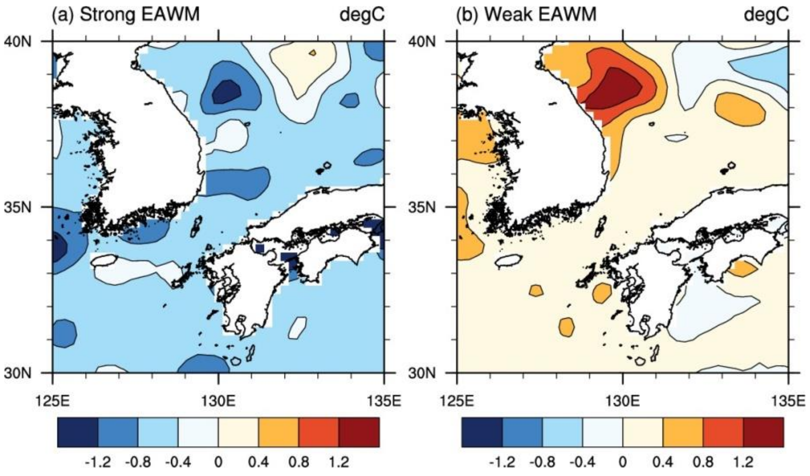

Figure 2.4. Same as Fig. 2.2 but for sea surface temperature anomaly (degC).

Chapter Ⅲ

Local Impact of Sea Surface Temperature on the Intensity of Snowfall

3.1 Observational Analysis

In the previous chapter, it is revealed that the amount of snowfall in Yeongdong region is significantly related to EAWM and there is a negative correlation (-0.45) between EAWMI and the interannual variability of snowfall. In addition, both atmospheric (the surge of Siberian High over the northeastern region of the Korean Peninsula and the enhanced inflow of easterly wind into Yeongdong area) and oceanic (the anomalous warm SST near the Korean Peninsula, especially warm at the East Sea region) condition illustrate that the weak EAWM year has much more favorable environment for heavy snowfall in Yeongdong region.

Table 3.1. Total snowfall amount (cm) and atmospheric and oceanic conditions for each weak monsoon winters

	Total snowfall amount	**Atmospheric condition**	**Oceanic condition**
1989	126.7 cm	Favorable	Favorable
1990	147.2 cm	Favorable	Favorable
2002	24.8 cm	Not favorable	Favorable
2006	36.6 cm	Favorable	Not favorable
2007	15.5 cm	Not favorable	Favorable
2014	109.5 cm	Favorable	Favorable

However, there is a difference in the total accumulated amount of snowfall among the weak monsoon years (Table 3.1). There were three large snowfall years (1989, 1990, and 2014) and more than 100 cm of snowfall were observed for those three years. On the other hand, there were other three years which called as small snowfall years (2002, 2006, and 2007). During the small snowfall years, the total amount of snowfall was under 50 cm. Especially, in 2007, there was no heavy snow date (the day when the daily accumulated amount of snowfall is over 5 cm), and the maximum amount of daily snowfall was the lowest among the six weak monsoon years. To identify the difference of snowfall amount within the weak EAWM years, atmospheric and oceanic conditions for each weak monsoon year were analyzed by using observation and reanalysis data (datasets were described in Chapter 2.1). Table 3.1 shows the analysis of mechanical and thermal conditions for each year. “Favorable” of the atmospheric condition means the anomalous surge of Siberian High to the northeastern region and that of the oceanic condition means the anomalous warm SST over the East Sea during each monsoon winter. Then, it is investigated that both atmospheric and oceanic conditions are completely better environment for heavy snowfall at the large snowfall years.

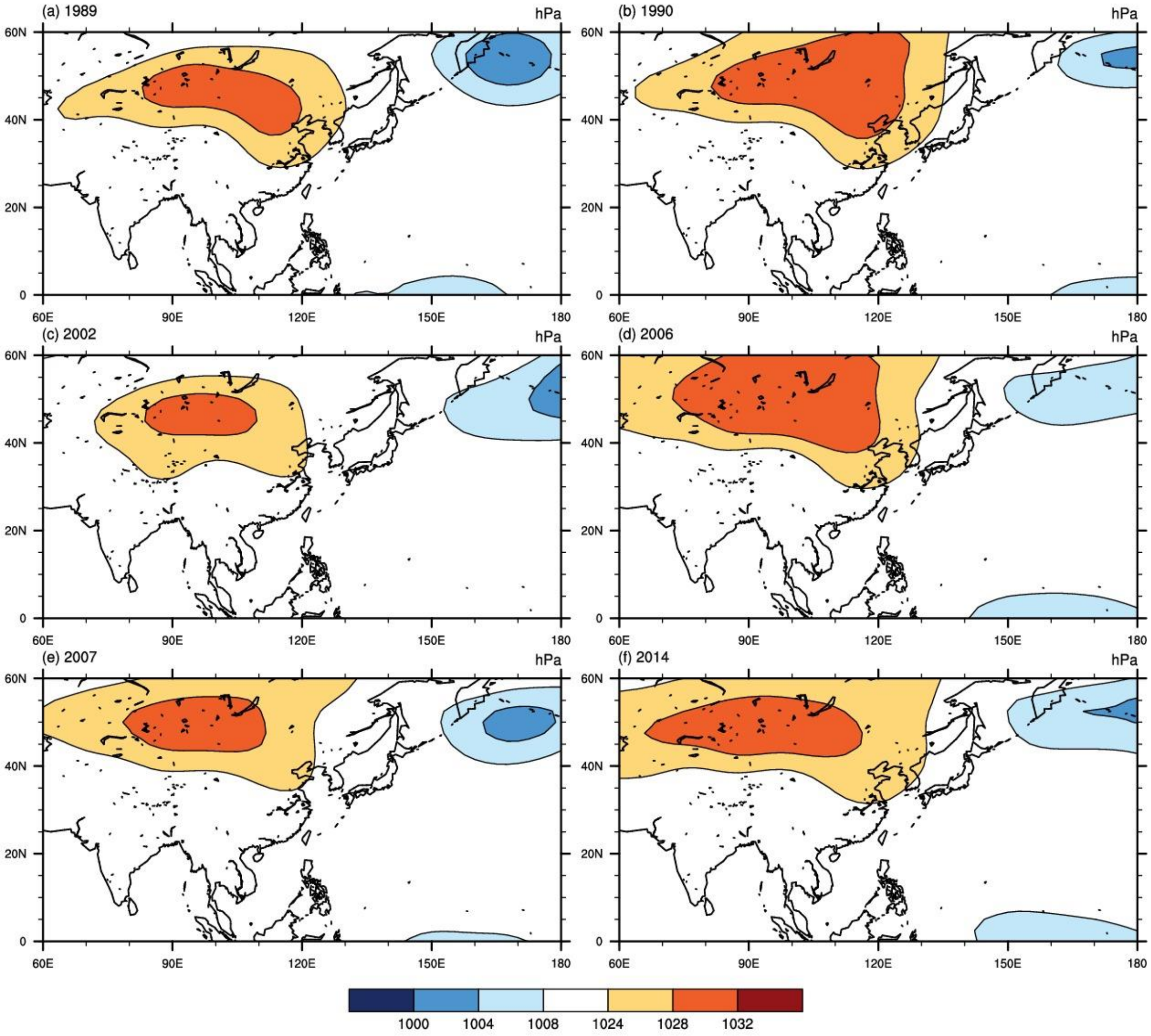

Figure 3.1. Two months (January and February) averaged sea level pressure (hPa) for each weak EAWM year.

Figure 3.1, 3.2 and 3.3 display the seasonal mean field of sea level pressure and the anomaly of zonal wind speed at 850hPa and sea surface temperature for each weak monsoon year, respectively. As previously noted, the eastward expansion of Siberian High to the northeastern part of the Korean Peninsula is the most dominant pressure pattern for the occurrence of snowfall in Yeongdong region. The core of Siberian High is in the central area of the Siberian region (located at 40°-60°N, 80°-120°E) for every weak monsoon years (Fig. 3.1). However, the magnitudes of the surge are different within the weak EAWM years, and that may vary the induced easterly wind into Yeongdong region and the intensity of snowfall.

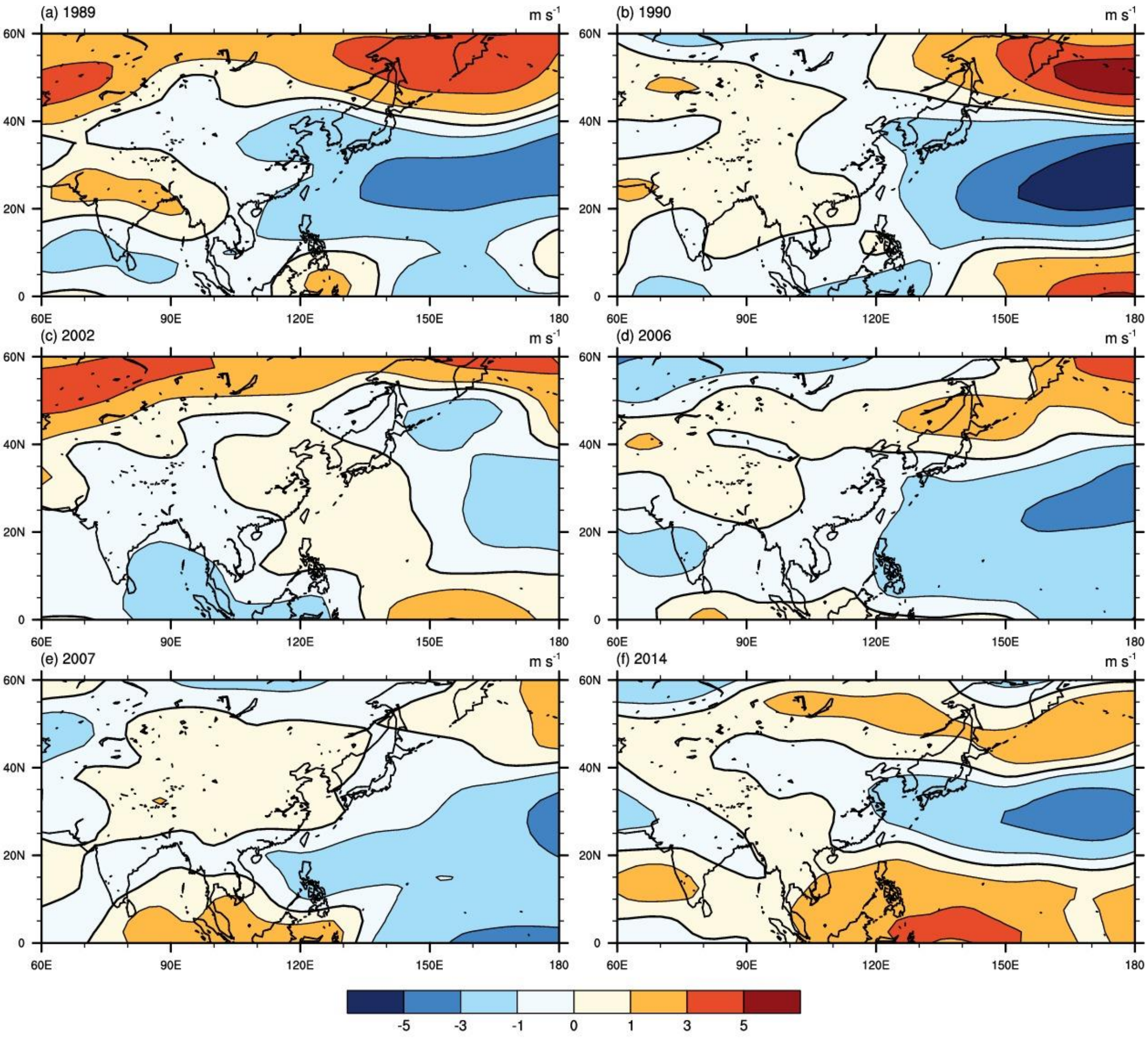

Figure 3.2. Same as Fig. 3.1 but for the anomaly of the zonal wind speed (m s^{-1}) at 850hPa.

During the large snowfall years (1989, 1990, and 2014), Siberian High evidently expands to the northeastern region of Korea. The eastward surge of Siberian High generates the easterly winds over the East Sea, and that cold and dry air gets heat and moisture from the relatively warmer ocean. Then, the easterly winds transport the developed convective clouds over the ocean into Yeongdong region. It is well represented in the anomaly of the zonal wind speed at 850hPa (Fig. 3.2). The enhanced easterly wind is existed for the large snowfall years.

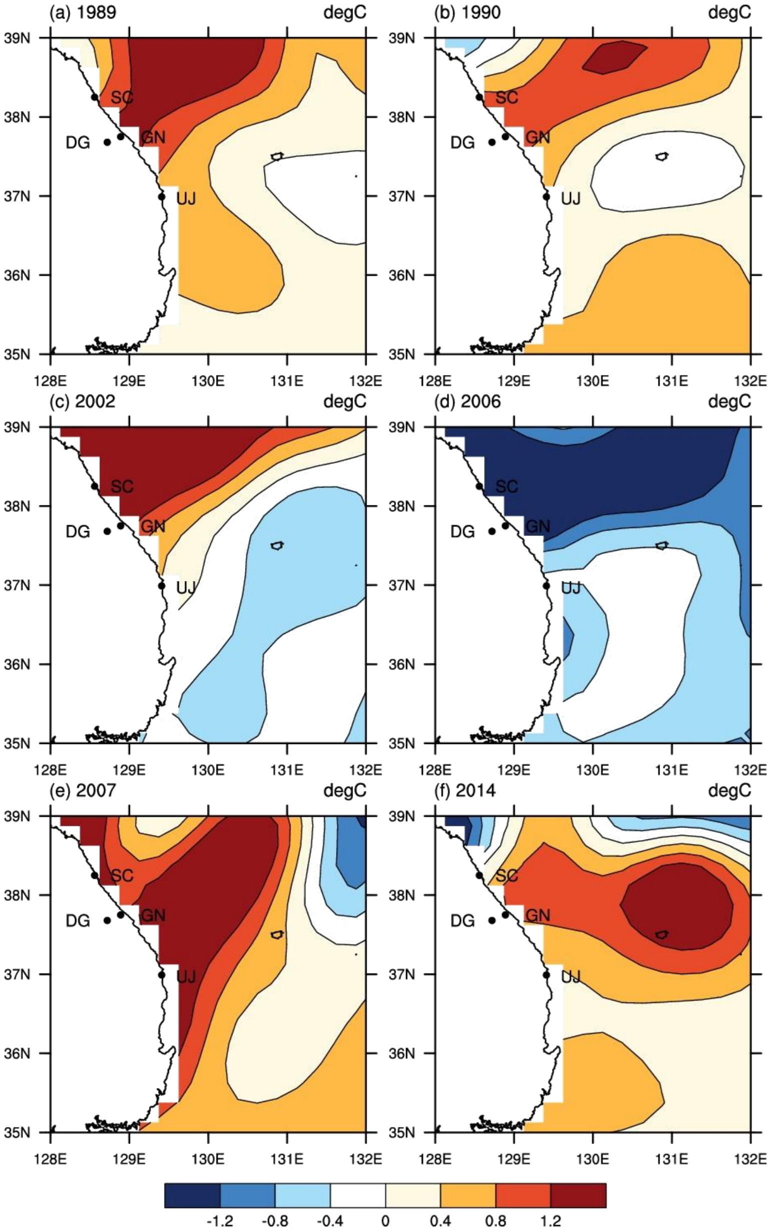

Figure 3.3. Same as Fig. 3.1 but for the anomaly of sea surface temperature (degC).

On the other hand, during the small snowfall years (2002, 2006, and 2007), the surge of Siberian High and the induced easterly wind into the Korean Peninsula are not enhanced, except in 2006. The inflow of the easterly wind is the most necessary condition for the occurrence of snowfall in Yeongdong region. Therefore, the atmospheric condition (that is the most important condition for snowfall) was not satisfied in 2002 and 2007. However, although the mechanical condition is favorably formed in 2006 (Fig. 3.1d and Fig. 3.2d), the total accumulated amount of snowfall (36.6cm) was less than climatology. Table 3.2 indicates the anomalous inflow of the easterly wind over Yeongdong region and the larger value means that there is sufficient easterly wind blew into the study area. Then, in 2007, the value is the biggest within the weak monsoon years, and it explains there is nearly no inflow of the easterly wind into Yeongdong region and this is related to the smallest amount of snowfall.

Table 3.2. Inflow of the easterly wind (m s^{-1}) at 850hPa into Yeongdong region

1989	**1990**	**2002**	**2006**	**2007**	**2014**
2.01	1.28	-0.11	0.19	-0.58	1.25

The oceanic condition over the East Sea, meanwhile, indicates the different pattern of anomalies at the atmosphere (Fig. 3.3). There is an only negative anomaly in 2006 and others have the warmer SST than 33 years' climatology. It means that the thermal condition is favorable for all weak monsoon years except for 2006. Although the favorable oceanic condition is formed during the five weak monsoon years (1989, 1990, 2002, 2007, and 2014), there are only three years of the large snowfall (1989, 1990, and 2014) when the atmospheric condition supports the local impact of local SST on heavy snowfall. Therefore, the influence of SST on the intensity of snowfall is not the most dominant because there is very little snowfall although quite high SST anomalies exist in 2002 and 2007. However, the significant effect of SST is represented when the atmospheric condition is favorably situated for heavy snowfall such as 1989, 1990, 2006, and 2014. To understand the complicated relationship between the synoptic and local impact on snowfall in Yeongdong region, we implemented the SST sensitivity experiments for the East Sea by using RCM.

3.2 Model Description and Experimental Design

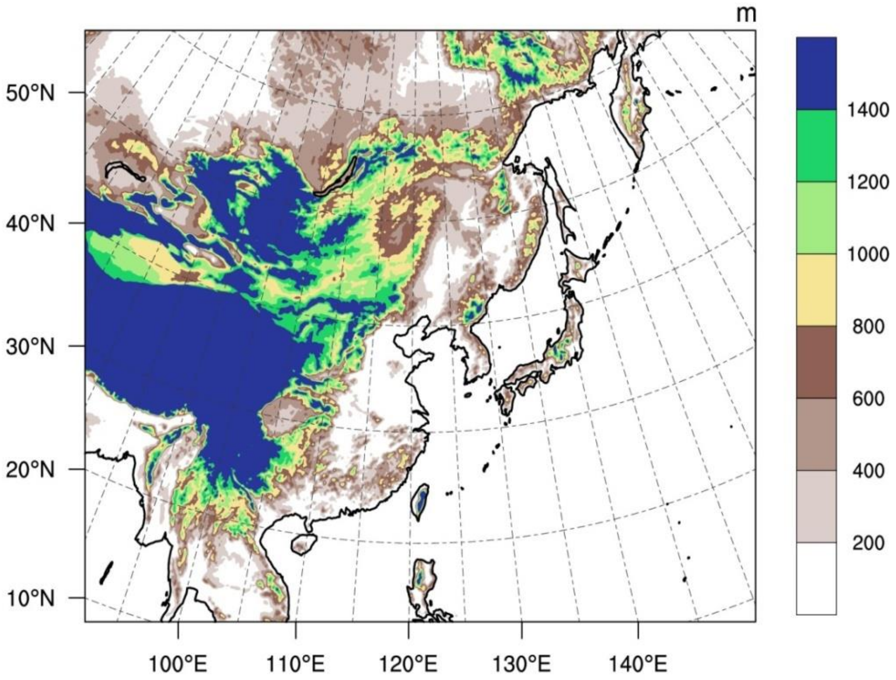

Figure 3.4. RCM domain with topography (m).

The RCM used in this study is WRF (version 3.7.1) model described by Skamarock et al. (2008). WRF is a next-generation mesoscale numerical weather prediction system designed for both atmospheric research and operational forecasting needs. For SST sensitivity experiments, we used physical parameterizations including the Dudhia shortwave radiation scheme (Dudhia, 1989), the RRTM longwave radiation scheme (Chou et al., 1994), the Unified Noah land surface model (Tewari et al., 2004), the MM5 similarity surface layer scheme (Beljaars, 1995), and the Kain-Fritsch cumulus parameterization scheme (Kain and John, 2004). Also, the Lin et al. scheme (Lin et al., 1983) and Asymmetric Convection Model 2 scheme (Pleim et al., 2007) was selected for microphysics scheme and planetary boundary layer parameterization, respectively. Cohen et al. (2015) investigated the effects of physical parameterizations on the simulation of the snow event to advance the accuracy of simulated snowfall. Fernandez-Gonzalez et al. (2015) analyzed the influences of different parameterization schemes, and the results indicated that the planetary boundary layer and microphysics schemes have a strong influence on the surface precipitation pattern. Microphysics processes are controlling the formation of cloud droplets and ice crystals, their growth and fallout as precipitation and planetary boundary layer processes deal the vertical transport of heat, moisture and momentum and low-level cloud development. WRF model offers multiple options for most physics parameterizations, enabling users to optimize the model for a range of spatial and temporal resolutions and climatologically different regions. Therefore, we determined the optimal combination of microphysics and planetary boundary layer schemes that are used in this research through various sensitivity experiments of physical parameterizations before we start this research.

Table 3.3. Summary of each experiment

	CTL	**CSST**
SST	default	33 years climatological SST (only East Sea)

Figure 3.4 shows the RCM domain with topography for the control simulation (CTL). We used a single domain focused on the East Asia. The horizontal resolution of the domain is 12km with 601 x 509 grid points. The vertically stretched grid consists of 33 levels. Initial and boundary conditions came from the ERA-Interim data produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), and these data are on 0.75-degree by 0.75-degree. Our regional climate model was run for two months (January and February) for each 33 year (1982~2014) when snowfall in Yeongdong region is concentrated. SST, which acts as low boundary forcing in the RCM, is obtained from OISST daily data whose horizontal resolution is 0.25-degree by 0.25-degree.

In addition to the CTL experiment, sensitivity experiments for SST was performed, and a major difference between two experiments is summarized in Table 3.2. For the climatological SST (CSST) experiment, all model configurations are used same as for the CTL experiment, but it is different to use the real SST of the year in the CTL experiment and averaged SST for 33 years in the CSST experiment over the East Sea. Only SST over the East Sea region, which is in the region 35°-39°N, 128°-135°E, is changed for the CSST experiment to examine the influence of local SST at that region effectively and it is boxed in Fig. 1.1b. Therefore, the difference between CTL and CSST experiments can describe the impact of SST over the East Sea on the intensity of snowfall in Yeongdong area.

3.3 Model Evaluation

To evaluate the performance of the RCM, the result of CTL was compared with the observation data. As mentioned previously, the observed data is acquired from 4 stations (SC, GN, DG, and UJ) located in Yeongdong region and each location is presented in Fig.3.3. To identify more certain effects of SST in winter time, the amount of snowfall was used rather than precipitation. The 3hourly amount of snowfall from the RCM was interpolated to the location of each station, and the snow ratio equation (Byun et al., 2008) was applied to change the liquid phase of precipitation to the solid phase of snowfall. Each snowfall amount of the year represents the total accumulated value which occurred during January and February and the average of 4 stations.

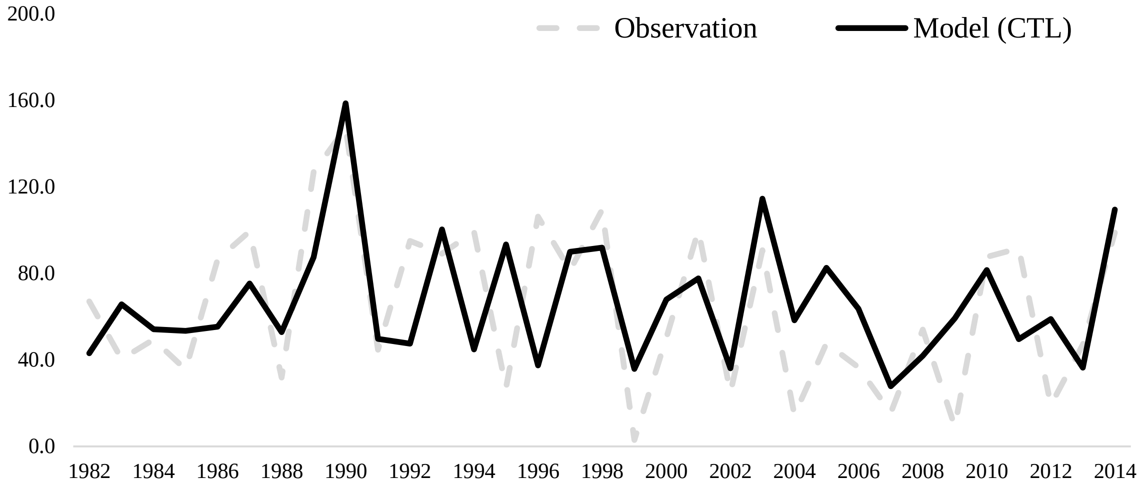

Figure 3.5. Time series of total snowfall amount (cm) during January and February from observation (dashed gray line) and RCM (solid black line).

Figure 3.5 shows the interannual variability of snowfall from observation data and the RCM for 33 years. Although snowfall from the model is the output of regional climate simulation (run time is two months), it realistically reproduced the interannual variability of snowfall in Yeongdong region. The temporal correlation coefficient between the RCM and observation is 0.56, and the value is a significantly high at comparing the amount of precipitation. Not only that, the RCM showed the dominant impact of EAWM on the interannual variability of snowfall. The correlation coefficient between EAWMI and the amount of snow obtained from the RCM is -0.36.

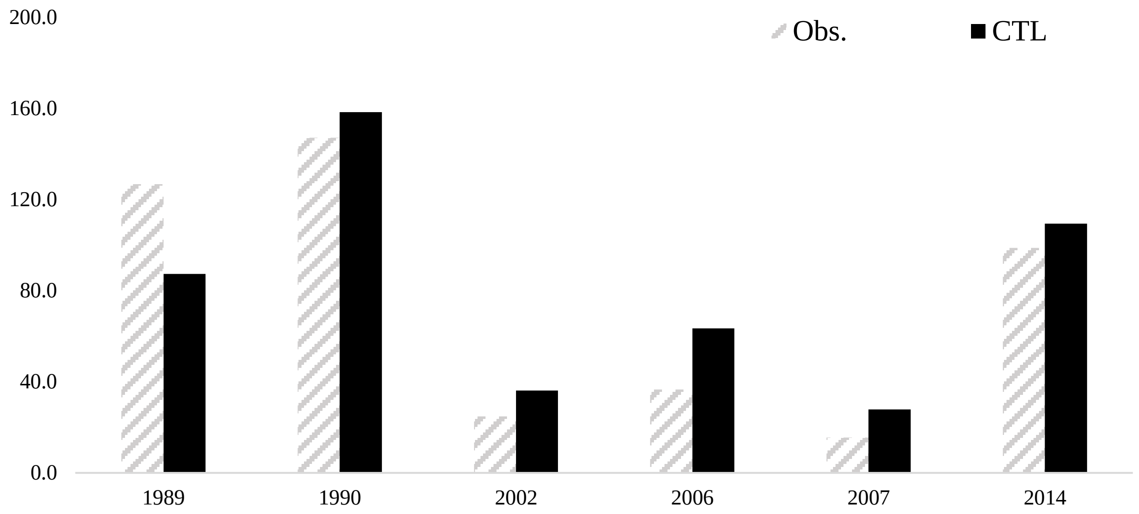

Figure 3.6. Total snowfall amount (cm) of each weak monsoon year from observation (dashed gray bar) and RCM (black bar) during January and February.

In this study, we focused on snowfall during the weak monsoon winters and then we did the additional evaluation for the weak EAWM years (Fig. 3.6). Figure 3.6 presents the total snowfall amount for six weak monsoon winters from observation and the RCM. The RCM produced the overestimated snowfall in most of the weak monsoon years, except in 1989. However, the RCM reasonably simulated the temporal distribution of snowfall, and it distinguished very well the years when the heavier snowfall was occurred (such as 1989, 1990, and 2014) and when the snowfall was less (2002, 2006, and 2007). Therefore, the interannual variability and the amount of snowfall from the RCM are reliable to analyze the impact of SST on snowfall in Yeongdong region.

3.4 Results of SST Experiment

Table 3.4 indicates the area-averaged amount of snowfall from 4 stations in Yeongdong region during each weak monsoon winter. As previously shown, there is only cold SST anomaly in 2006 and other weak monsoon years have warm SST anomaly over the East Sea (Fig. 3.3). It means that the CTL simulation has the higher SST at the ocean except for 2006. Also, the CTL experiment of 2006 has only colder SST at the East Sea region. Then, the difference of snowfall between CTL and CSST experiments showed that the amount of snowfall is greatly related with SST forcing in the positive and negative ways. Positive forcing (SST of the year was colder than the climatology at the East Sea) enhanced the intensity of snowfall in Yeongdong region while negative forcing (SST of the year was higher than the climatology at the East Sea) suppressed snowfall. In other words, the higher SST at the ocean showed the decreased intensity of snowfall in the CSST simulation. On the other hand, in 2006 when the colder SST at the ocean, showed the increased intensity of snowfall in the climatological experiment. However, there is nearly no change in the accumulated snowfall in 2007 although SST is significantly higher than normal.

This change pattern of snowfall also appears in the horizontal difference field of snowfall (Fig. 3.7). Similarly, there is much larger snowfall in the CTL simulation when there is warm SST anomaly, and the smaller snowfall is represented when there is cold SST anomaly such as 2006. The increase of SST tends to enhance the winter precipitation as considerable moisture and heat flux are supplied. Therefore, results shown in Table 3.4 and Fig. 3.7 were somewhat expected. However, in the case of 2007, the total accumulated snowfall of the CSST experiment not exhibited the regional effect of SST on the intensity of snowfall.

Table 3.4. Total snowfall amount (cm) of each experiment and relative change rate (%) of the CSST from the CTL simulation

	CTL (cm)	**CSST (cm)**	**Relative Change (%)**
1989	87.4	49.9	- 42.9
1990	158.5	51.4	- 67.6
2002	32.2	22.4	- 30.4
2006	63.5	108.9	+ 71.5
2007	27.8	28.2	-
2014	109.5	91.2	- 16.7

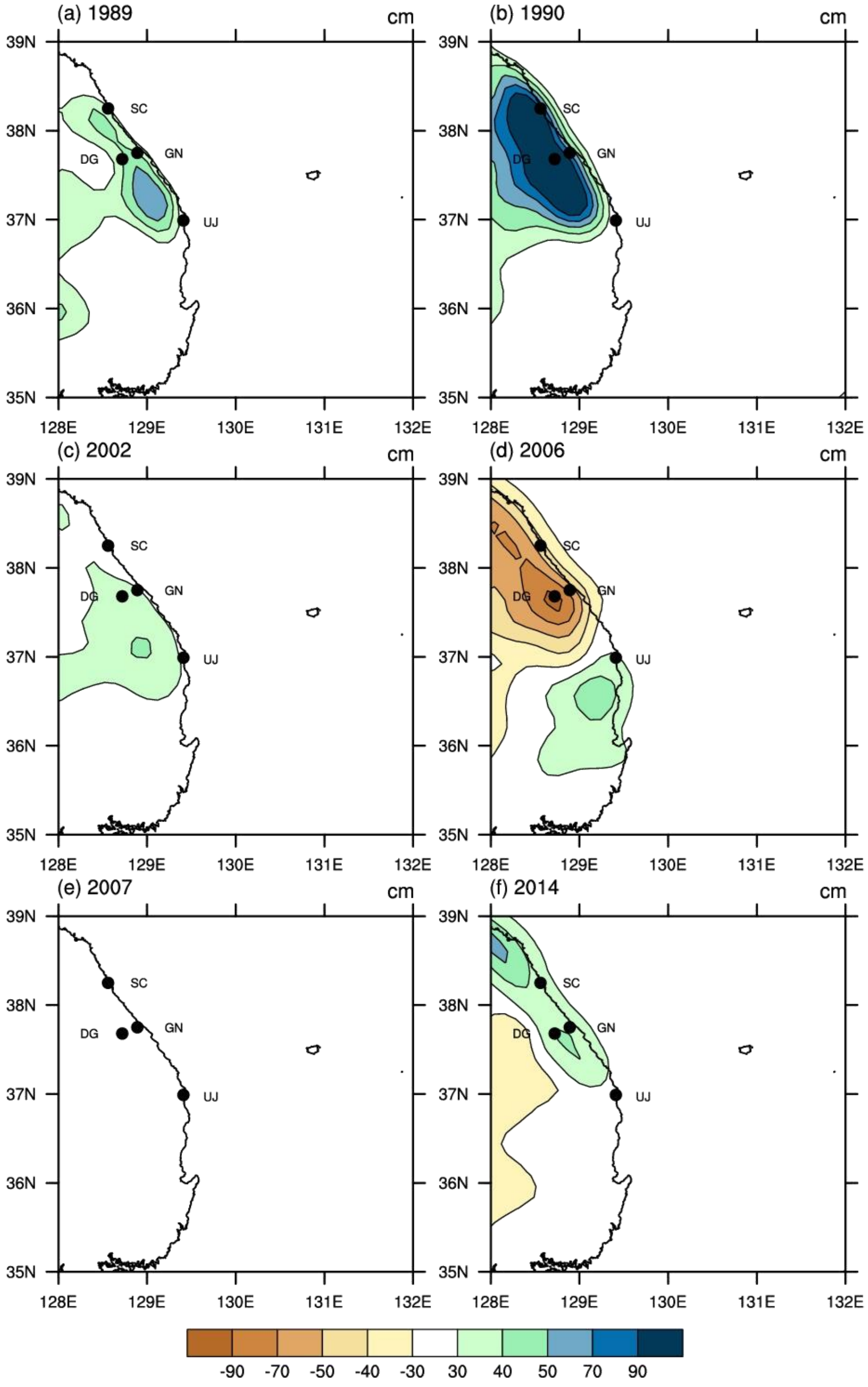

Figure 3.7. Difference of total accumulated snowfall (cm) from the CTL simulation.

To identify the thermodynamic effect of SST on the intensity of snowfall, the difference of latent heat flux between CTL and CSST experiments is analyzed in Figure 3.8. Compared to SST distribution (Fig. 2.4), the difference of latent heat is consistent with the anomaly pattern of SST. The year with the warm SST anomaly showed the positive difference in latent heat flux (1989, 1990, 2002, 2007, and 2014) and oppositely that with the cold SST anomaly displayed the negative difference (2006). This is because the higher SST increases the latent heat flux from the ocean to the atmosphere. For example, the result of 2006 demonstrates the abundant moisture over the East Sea in the CSST experiment affect the increased snowfall. Likewise, the opposite situations appear in 1989, 1990, 2002, and 2014 that the deficient moisture in the CSST experiment influence on the decreased amount of snowfall. Therefore, SST condition could thermodynamically modify latent heat flux, and thereby the changed heat flux modulates the main source of energy for the formation of heavy snowfall. However, in 2007, even if the oceanic condition is favorably situated over the ocean, the little impact of latent heat is presented in the difference of snowfall. The sufficient inflow of the easterly wind into Yeongdong region is necessary to be influenced by the modified latent heat flux at the ocean, but as we noted in the observational analysis, there is the insufficient inflow of the easterly winds than other years.

Figure 3.9 indicates the difference of vertical moisture fluxes between the simulations at GN. The enhanced moisture convergence appears with the positive forcing of SST anomaly, and it implies that the inflow of the easterly wind into Yeongdong region gets more heat and moisture from the warmer East Sea. The easterly wind is not prevailing during the winter season in Yeongdong area. However, when Siberian High is expanded to the eastward, the northeasterly or easterly wind is induced into Yeongdong region. Therefore, there is the significant influence of the increased latent heat in 1989, 1990, 2002, and 2014. Also, there is the negative difference of moisture convergence in 2006 when Siberian High surges over the northeastern region and the sufficient inflow of the easterly wind exist, but SST condition is not favorable in the CTL experiment. Meanwhile, there is any moisture convergence and divergence in 2007 when there is no change of snowfall amount in Yeongdong area.

These results are also shown in the following figure. Figure 3.10 demonstrates the difference of moisture convergence at 850hPa for each weak monsoon year. As same as Fig. 3.9, the difference of moisture convergence was presented in opposite ways according to the anomaly of SST. The year when there is warm SST anomaly (1989, 1990, 2002, and 2014) showed the positive difference of moisture convergence and the year when there was cold SST anomaly (2006) presented the negative difference in Yeongdong region. Also in case of 2007, there is any change of moisture convergence and divergence.

To summarize the results of observational analysis and SST sensitivity experiment, heavy snow event could occur when both atmospheric and oceanic conditions are completely formed for snowfall. By comparing 2006 and other large snowfall years (1989, 1990, 2014), the significant impact of local SST under the favorable formed atmospheric condition. Also, by comparing 2007 and others, the local effect of SST is not that much without the eastward surge of Siberian High and the enhanced easterly wind blew into Yeongdong region. These results imply the impact of local SST relies on the atmospheric condition.

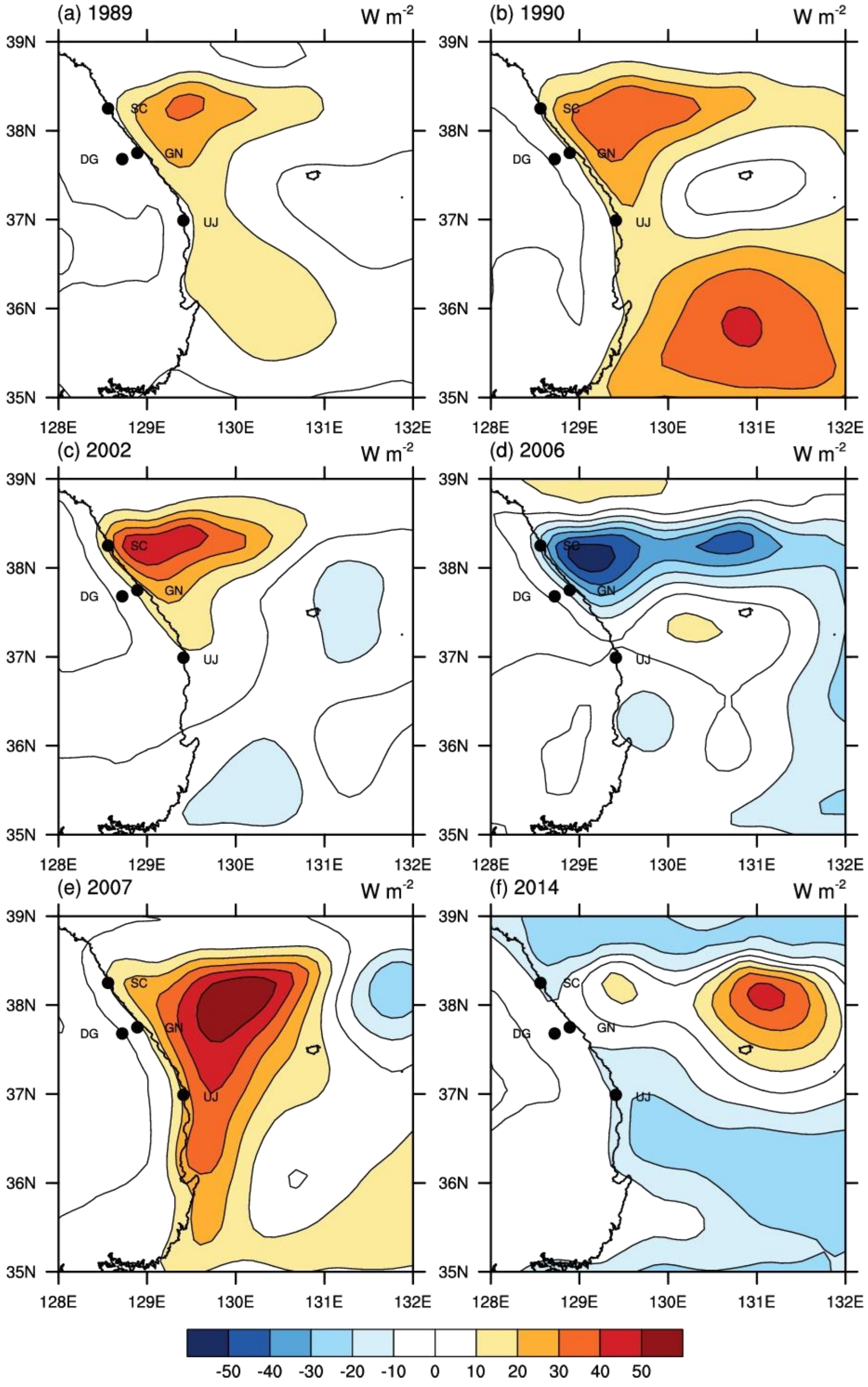

Figure 3.8. Same as Fig. 3.7 but for the averaged latent heat flux (W m^{-2}).

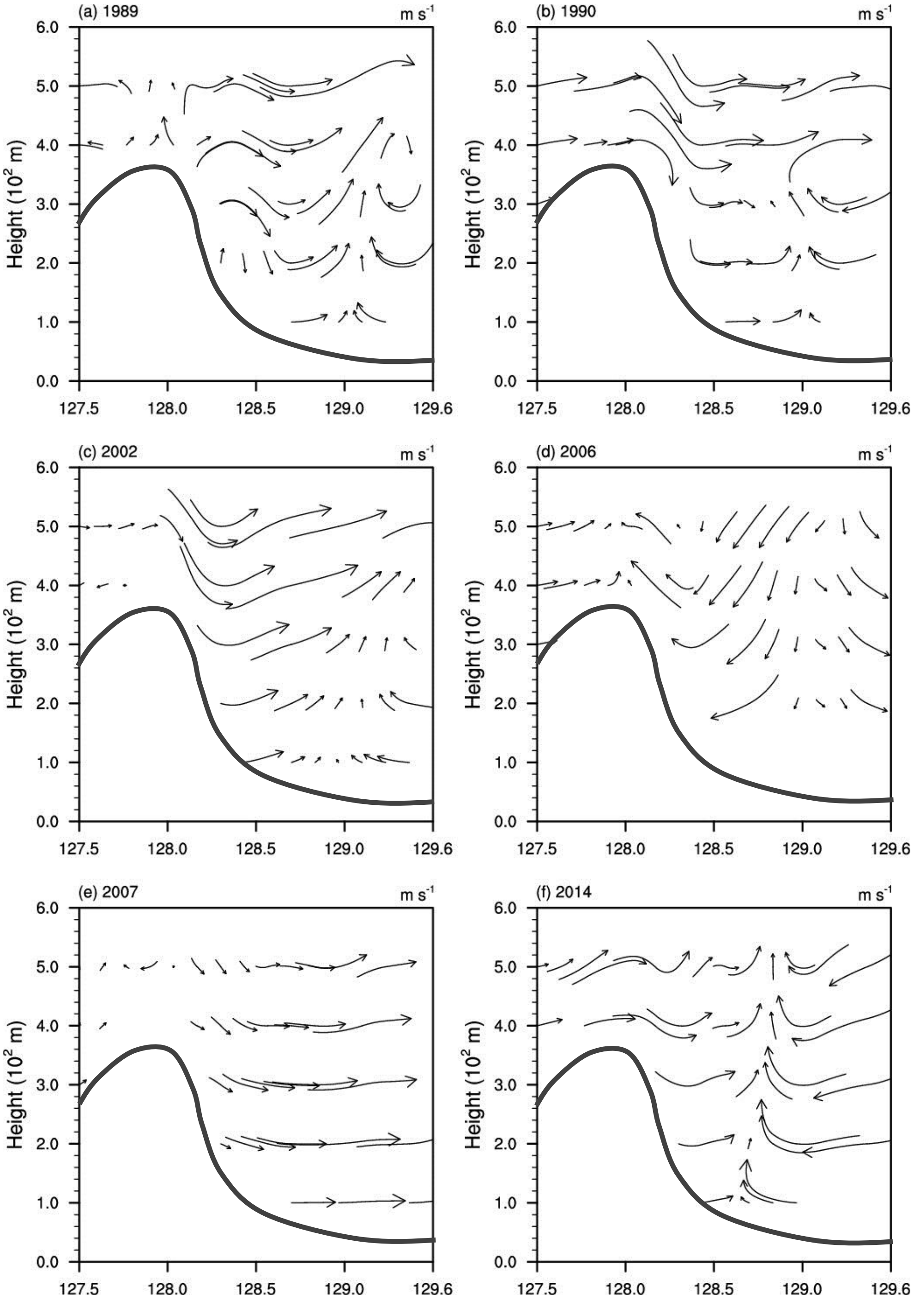

Figure 3.9. Same as Fig. 3.7 but for the vertical moisture flux (m s^{-1}).

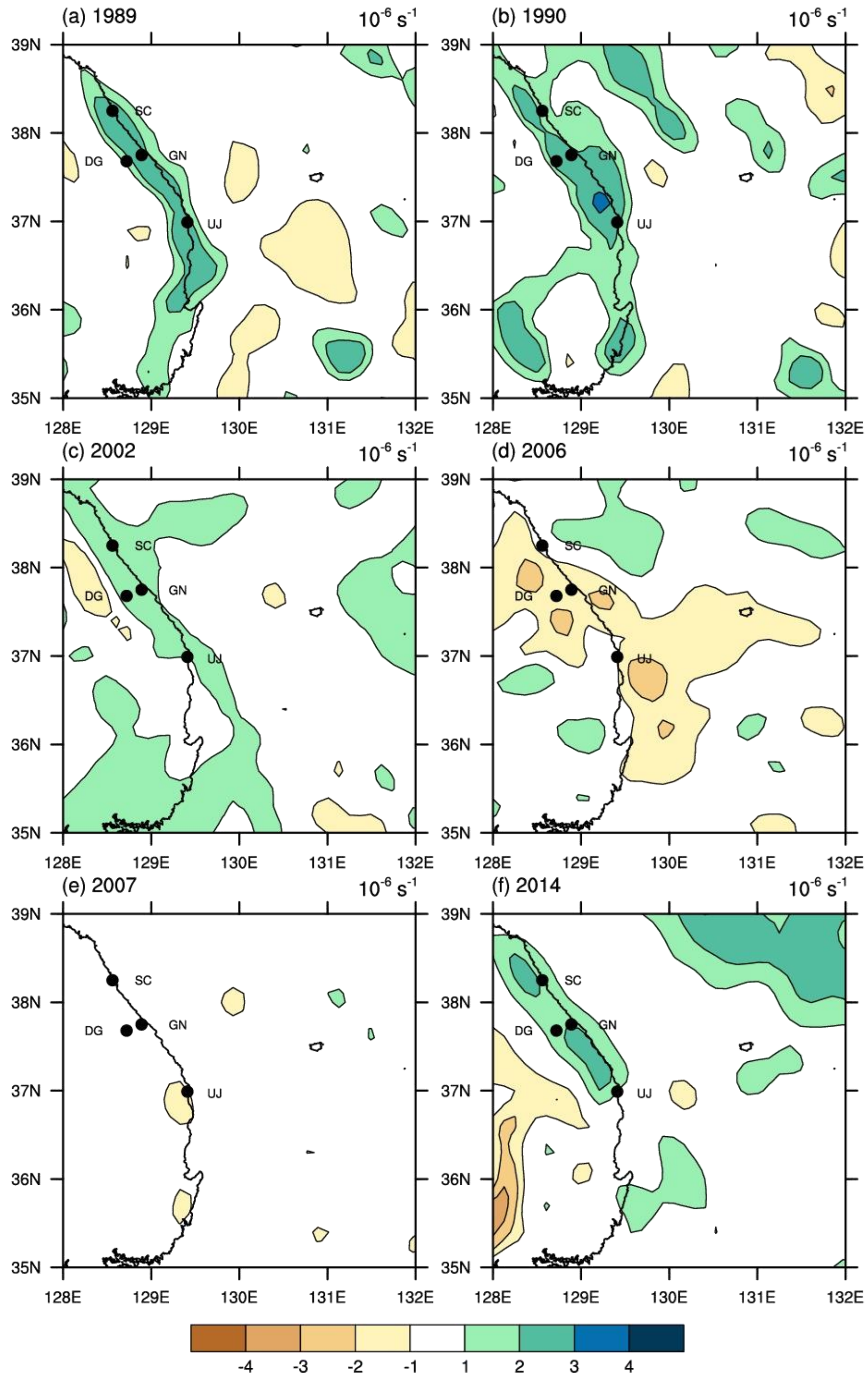

Figure 3.10. Same as Fig. 3.7 but for the averaged moisture convergence (s^{-1}).

Chapter Ⅳ

Summary and Concluding Remarks

In this study, we investigated the impact of local SST on the intensity of snowfall in Yeongdong region that is strongly dominated by a synoptic scale factor (EAWM). The negative correlation coefficient (-0.45) exists between the winter monsoon circulation and the interannual variability of snowfall. Analyses of the composite maps for each strong and weak EAWM year demonstrate the reason of the heavier snowfall when the winter monsoon is weakened. The favorable synoptic conditions (ⅰ. eastward surge of Siberian High over the northeastern part of the Korean Peninsula, ⅱ. enhanced easterly wind blew into Yeongdong area, and ⅲ. anomalous warm SST over the East Sea) make a large amount of snowfall during the weak monsoon year.

However, the observational analysis shows the amount of snowfall is not exactly large during the weak EAWM. The observed snowfall presents a difference in total accumulated amount of snowfall depending on atmospheric and oceanic conditions. The heavy snow event could occur when both mechanical and thermal conditions are completely favorable for snowfall. Then, sensitivity experiments by using RCM were implemented to examine the local effect of SST on the intensity of snowfall. WRF model was used as the RCM, and SST over the East Sea was replaced with the climatological SST (CSST). Analyses of SST experiment suggest how local SST influences on the amount of winter precipitation.

1) There is no significant impact of SST on snowfall amount without the favorable atmospheric condition.
2) However, if the atmospheric environment is favorably situated (the surge of Siberian High and the inflow of the easterly wind), the local effect of SST becomes significant on the intensity of snowfall.

The higher SST acts as a source of energy for the formation of heavy snowfall, and it regulates heat and moisture at the ocean. Thus, if there is the sufficient inflow of the easterly wind into Yeongdong region, the convective clouds for heavy snowfall could be influenced by the modified latent heat flux and abundant moisture from the ocean. Consequently, local SST could thermodynamically influence on the intensity of snowfall in Yeongdong region. Then, the conclusion of this research is as follows.

1) Local effect of SST has the significant impact on the intensity of snowfall in Yeongdong region when the atmospheric condition is favorably formed.
2) Both atmospheric and oceanic conditions are important to occur the irregular and uneven heavy snowfall in Yeongdong region. In other words, the heavy snow event occurs both atmospheric and oceanic conditions are completely favorable for snowfall.
3) There is much more possibility of severe snowfall during the weak monsoon winter when both atmospheric and oceanic conditions are favorably situated.
4) The increasing trend of SST at the East Sea could make the relationship among synoptic factor, regional factor, and snowfall more complicated.
5) This study could contribute to predicting the intensity of heavy snow event on Yeongdong region in medium- and long- range forecast.

ChapterⅤ

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감사의 글

설렘과 두려움을 안고 시작했던 석사 과정을 비로소 마치며, 부족한 저에게 많은 도움을 주셨던 분들께 이 짧은 지면으로 나마 감사의 마음을 전합니다.

학문에 있어서나 삶에 있어서 저에게 가장 많은 가르침을 주신 차동현 교수님, 교수님을 향한 감사의 마음이 저의 부족한 필력으로는 다 표현이 될 수 없겠지만 진심으로 감사 드립니다. 자상하면서도 냉철한 조언과 따뜻한 격려를 아낌없이 해 주신 교수님 덕분에 제가 무사히 학위 논문을 완성할 수 있었습니다. 맡은 일에 언제나 긍정적이고 열정이 넘치셨던 모습을 마음속에 늘 간직하며 조금이나마 닮을 수 있도록 노력하겠습니다. 교수님의 연구실에 첫 졸업생이 될 수 있어서 너무 영광이고, 부끄럽지 않은 제자가 되도록 하겠습니다!

아울러, 바쁘신 가운데에도 제 학위논문의 심사위원을 맡아 주시고 많은 조언을 주신 이명인 교수님과 강사라 교수님께도 깊은 감사를 드립니다. 학부 시절부터 5년이라는 짧지 않은 시간 동안 교수님들께 가르침을 받은 것은 제 학문적 지식에 밑거름이 되었을 뿐만 아니라 앞으로 나아가야 할 미래에 큰 자극이 될 것 같습니다.

힘들고 방황할 때면 큰 힘이 되어주던 우리 HWPL 연구실 박사님, 친구들, 오빠들, 동생들에게도 진심으로 감사함을 전합니다. 한참 후배인 저희 학생들에게 언제나 밝은 에너지를 전해주시고 선배처럼 많은 조언과 재미난 이야기들을 해주시는 박창용 박사님 (저에겐 영원히 "박박사님"), 항상 가까이에 계신 것처럼 멀리서도 저희를 챙겨 주시는 춘지 선생님, 잠깐이지만 저의 대학원 생활에 많은 도움을 주신 미남시리 진천실 박사님과 소리 없이 강한 레간자 최용한 박사님께 제 인생에 너무 좋은 영향을 주신 것에 큰 감사를 드립니다. 그리고 벌써 6년째 가장 가까이에서 동고동락하고 있는 나의 소중한 동기들, 제주도 예민 보스 문지홍이랑 이제는 눈감고도 그릴 수 있는 24시간 메이트 김가영에게도 감사함을 전합니다. 동기가 되었다면 더 좋았을 진짜 친 오빠 같은 굿럭 기리기리 길오빠와 힘든 졸업학기에 가장 큰 힘이 되어준 듬직한 저저와 명우오빠에게도 진심으로 감사하다는 말 전하고 싶습니다. 실험실 첫 여자 후배인데 많이 못 챙겨 준 것 같아 미안한 우리 하숙이 소현이, 마찬가지로 챙겨 준 것 없는데 누나라고 배려 많이 해 준 큐리큐리 민규, 나랑 평행이론인 것 같은 유일한 부사수 2015년 또염이 동혁이, 알

게 모르게 졸업 준비에 많은 도움 줬던 떨어지세여~ 현재, 매일매일 시트콤 같은 에피소드로 즐겹게 해주는 약간 진영이, 절묘한 타이밍에 자꾸 트러블 발생하는 귀여운 막둥이 경민이에게도 이렇게 좋은 사람들 덕분에 제가 졸업할 수 있었음에 진심을 담아 고마움을 전합니다.

회사 생활과는 다른 대학원 생활 패턴 때문에 섭섭함을 많이 느꼈겠지만 진심으로 응원해주고 마음으로 힘이 되어준 지혜, 민수, 윤희, 혜원이 그리고 같은 학교 안에서 서로 위로가 되어주었던 하연이, 호정이, 이지, 유나 그리고 특히 어쩌다 고등학교부터 대학원까지 계속해서 같은 길을 걷고 있는, 같은 층에만 있어도 힘이 되는 민정이에게도 고마움을 전하고 싶습니다.

마지막으로, 대학원 진학이라는 쉽지 않은 결정을 응원해주시고 언제나 저의 생각을 존중해주시고 믿어 주신 부모님, 그리고 하나밖에 없는 내 동생 현진이에게 가장 감사하고 사랑한다고 전하고 싶고 저의 짧으면서도 길었던 유니스트 생활의 결실인 이 논문을 받칩니다.

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