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To cite this article: Taekyun Kim *et al* 2020 *Environ. Res. Lett.* **15** 074024

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Environmental Research Letters



LETTER

OPEN ACCESS

RECEIVED
13 January 2020

REVISED
21 April 2020

ACCEPTED FOR PUBLICATION
28 April 2020

PUBLISHED
26 June 2020

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Dynamical response of atmospheric circulation to below-normal East Sea sea surface temperatures associated with heavy snowfall in eastern Korea

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Keywords: heavy snowfall, East Sea, heavy snowfall-related sea surface temperature, atmospheric circulation

Abstract

Prior studies have shown that above-normal sea surface temperatures (SSTs) enhance snowfall over Korea. Here, we show that heavy snow is also associated with below-normal East Sea SSTs, and we investigate the dynamical response of the atmosphere to this surface condition using observations and numerical modeling. The results indicate that anomalous southeasterly/easterly winds are induced by heavy snowfall-related cold SST anomalies, and consequently, the moisture flux is converged. The existence of the southeasterly winds and the accompanied moisture flux convergence appear to be instrumental in producing the heavy snowfall events. The anomalous southeasterly/easterly winds associated with heavy snowfall-related cold SST anomalies reduce the climatological northwesterly/westerly winds, leading to relatively warm and wet conditions over the east coast of Korea that are favorable for forming and intensifying snowfall events in the region.

1. Introduction

A heavy snowfall accumulation can cause buildings to collapse, as well as blocking roads, paralyzing traffic, and stopping the flow of supplies, resulting in isolation of the city affected by the snowfall, giving rise to the loss of human life and economic assets. Therefore, the ability to accurately predict the time and amount of heavy snowfall with an adequate lead time is needed to prepare for the snowfall and minimize the damage that it can cause. It is well known that heavy snowfalls are highly sensitive to heat and moisture fluxes over the ocean when an air mass moves from ocean into land. Air–sea exchange processes are therefore important for the development mechanism of heavy snowfall. In particular, sea surface temperature (SST) is a key parameter that controls many air–sea exchange processes, and modulates the intensity of the moisture and turbulent heat (sum of the sensible and latent heat) fluxes and the consequent convection, thereby acting as the source of energy for the formation of heavy snowfall (Kim and Jin 2016).

The coastal region of eastern Korea frequently suffers heavy snowfall events, mostly due to the

combined effect of its topography and close proximity to the ocean, i.e. the East Sea (Jung *et al* 2012). For example, unprecedented heavy snowfall occurred on 11–14 February 2011 along the eastern coastal region of Korea; the 24 hour accumulation of fresh snow reached 80 cm in Gangneung (37.804° N, 128.855° E), resulting in tremendous damage, necessitating the deployment of 12 000 soldiers in the region to assist stranded motorists and rescue trapped residents, with the cost of the damage expected to reach approximately 65 million US dollars (Jung *et al* 2012, <http://www.safekorea.go.kr>). Many studies have been performed on heavy snowfall events over the Korean Peninsula (e.g. Cheong *et al* 2006, Kang and Ahn 2008, Kim and Jin 2016). According to these studies, the snowfalls are mainly associated with the air mass transformation by the fluxes across the air–sea interface. Therefore, the influence of the oceanic conditions on heavy snowfall events over the Korean Peninsula has been investigated using numerical models. Ahn and Cho (1998) emphasized the importance of appropriate SST conditions in the numerical simulation of heavy snowfall events by showing that the results depend significantly on

the accuracy and types of the SST data. Lee and Lee (2006) showed that the snowfall in the coastal region occurs due to the oceanic effects caused by the air–sea temperature difference. Cha *et al* (2011) showed that the SST gradient in the coastal region affects the cloud streets and snowfall formation. Lee and Yoo (2014) carried out several numerical studies to understand the relationship between SST distribution and heavy snowfall. They reported that the accuracy of the snowfall amount predictions is strongly associated with the SST distribution not only over the near coast but also over the ocean far from the coast of the Korean Peninsula.

Previous studies have focused on the sensitivity of snowfall simulations to increasing or decreasing SST, and have suggested that positive (negative) SST forcing shows an enhanced (suppressed) precipitation amount due to the change of the moisture and turbulent heat fluxes. In other words, most of the previous studies demonstrated that the local SST affects the snowfall intensity only when the synoptic conditions are favorable for the formation of the heavy snowfall (i.e. the passive effect of the SST under the favorable atmospheric condition for heavy snowfall that is the southeastward extension of Siberian High over the northeastern Korea Peninsula, resulting in enhanced easterly wind anomalies). In this study, however, we pursue a different approach in examining the relationship between the heavy snowfall events in the eastern coastal region of Korea and the oceanographic conditions of the adjacent sea (the East Sea SST conditions). Unlike previous studies, by focusing on the response of the atmosphere to the heavy snowfall-related SST (i.e. the active role of SST in the occurrence of heavy snowfall), we identify an interrelationship between the snowfall-related SST and atmospheric circulation; in other words, we investigate the dynamical process by which East Sea SST providing the favorable conditions for heavy snowfall is communicated with the atmospheric circulations.

2. Methodology

To identify an association between the East Sea SST and heavy snowfall events in eastern Korea, we first qualitatively examine the snowfall tendency and investigate favorable oceanic and atmospheric conditions for heavy snowfall by analyzing long-term observed air–sea state variables. Then, we perform numerical experiments on the sensitivity of atmospheric circulation to the heavy snowfall-related SST in order to investigate the dynamical relationship between the East Sea SST and the atmospheric circulation during the winter season, defined as December through February (DJF).

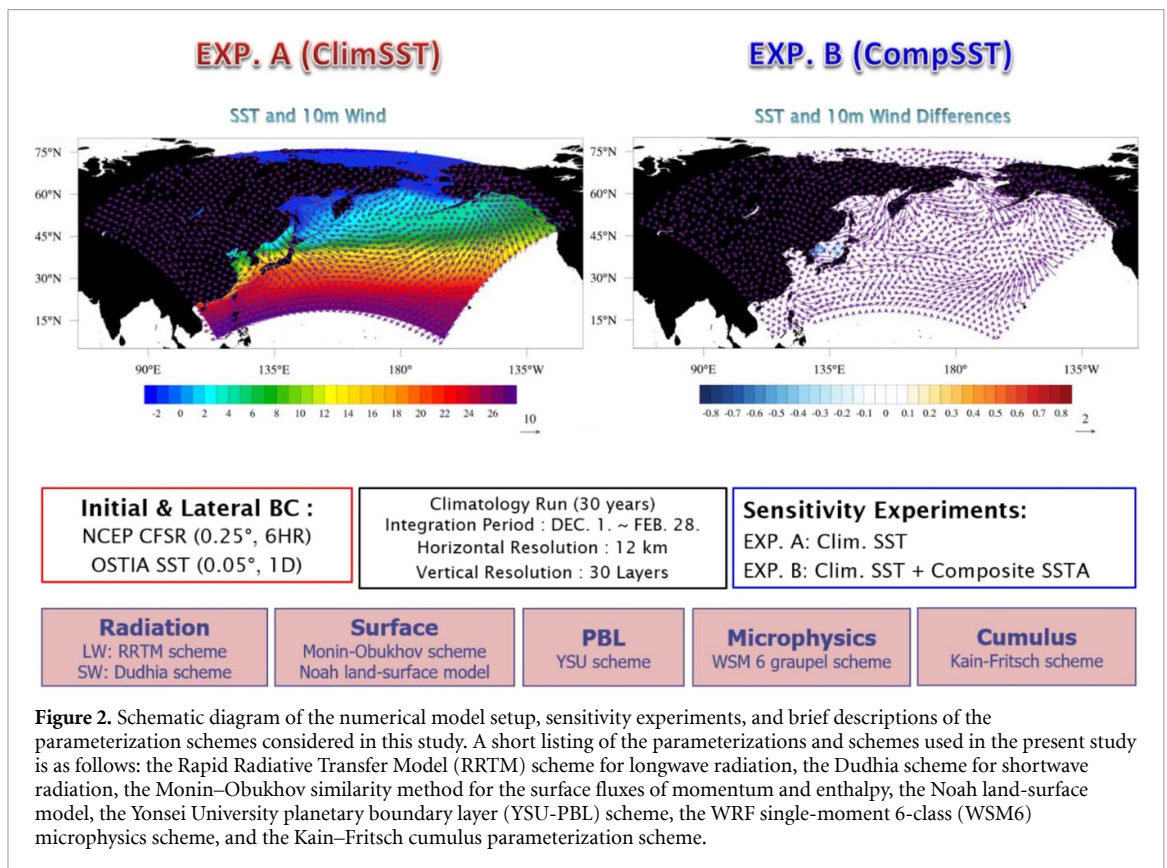
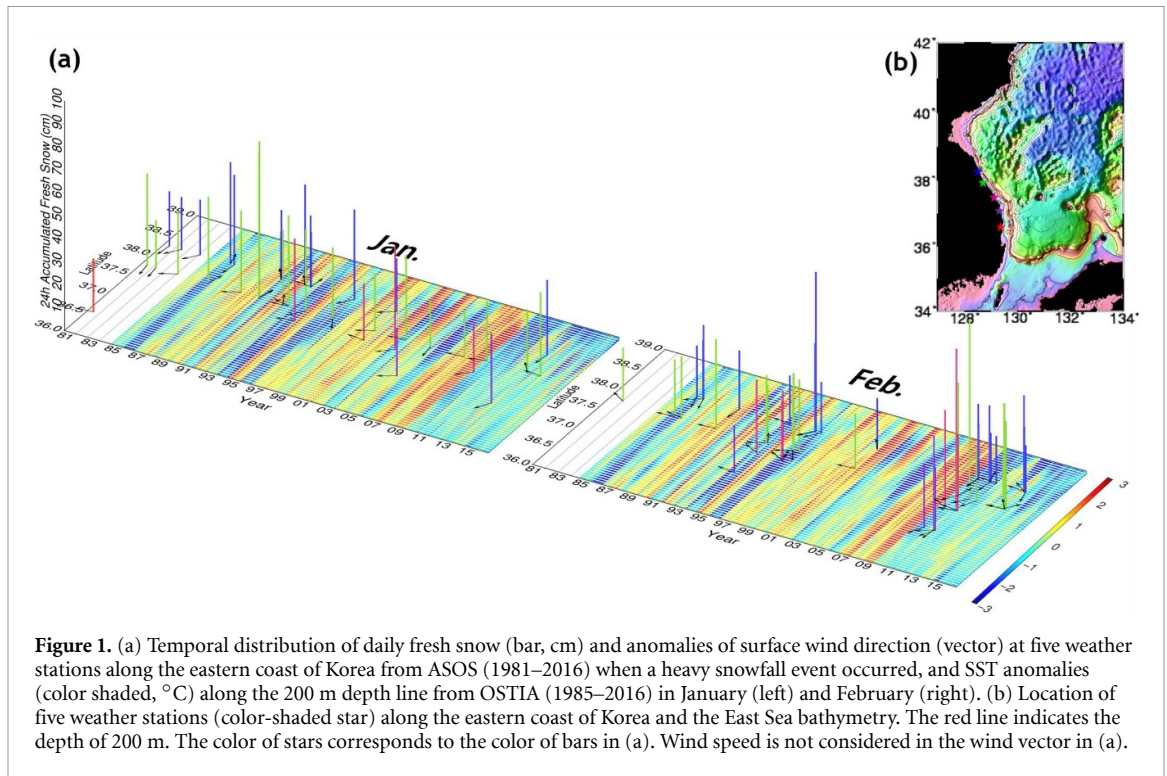
2.1. Description of datasets

In this study, the snowfall tendency in eastern Korea is qualitatively examined by using the daily wind and 24 hour accumulated fresh snowfall observation at five weather stations along the eastern coast of Korea (figure 1(b)) in each January–February time period from 1981 to 2016. These data were obtained from the Automated Synoptic Observing System (ASOS) of the Korea Meteorological Administration (KMA). The SST of high spatial resolution ($0.05^\circ \times 0.05^\circ$, daily) along the coast was taken from the Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) dataset from 1985 to 2016. Then, composite maps of the SST, surface wind, and sea level pressure (SLP) are constructed and favorable oceanic and atmospheric conditions for heavy snowfall are examined using the daily SLP from the European Center for Medium-Range Weather Forecasts (ECMWF) interim reanalysis (ERA-Interim) data of 0.25° horizontal grid spacing from 1981 to 2016 (Dee *et al* 2011), and surface wind data derived from the Cross-Calibrated Multi-Platform (CCMP) project with six-hourly gridded analysis data at a horizontal resolution of 25 km from 1989–2016 (Atlas *et al* 2011).

2.2. Numerical experiments

To investigate the impact of heavy snowfall-related composite SST anomalies in the East Sea on atmospheric circulation, we use the Weather Research and Forecasting (WRF) model, which is a fully compressible and non-hydrostatic model using Arakawa-C grid staggering for the horizontal coordinate and terrain-following hydrostatic pressure for the vertical coordinate (Skamarock *et al* 2008). The model domain, at a 12 km horizontal resolution, covers the North Pacific region, including the East Asian Marginal Seas (figure 2). The initial and boundary conditions are prepared using six-hourly climatology data (1985–2015) based on the National Centers for Environmental Prediction (NCEP)–Climate Forecast System Reanalysis (CFSR) with a resolution of 0.25° (Saha *et al* 2010).

Based on the significant SST anomalies from the composite map, two sensitivity experiments are performed to identify the dynamical relationship between the heavy snowfall-related SST anomalies and atmospheric circulation. In the first simulation (*ClimSST*), the WRF is forced with the climatological daily SST, which is the long-term average daily SST for the period 1985–2015 from the OSTIA with a 0.05° resolution. The second simulation (*CompSST*) is identical to *ClimSST* except for the SST boundary condition, in which time-invariant SST anomaly pattern in the East Sea based on the composite analysis is merged into the climatological SST. In both simulations, SST boundary conditions prescribed outside the East Sea domain are identical to each other, and therefore there is no extra source of



anomalous diabatic forcing outside the East Sea. The climatological condition on 1 December is used as the initial condition and each run is integrated for three months until 28 February. A schematic diagram

of the numerical model setup and sensitivity experiments and brief descriptions of the parameterization schemes considered in this study are shown in figure 2.

3. Results

3.1. East Sea SST as a necessary condition for heavy snowfall in eastern Korea

Figure 1 shows the daily fresh snow and anomalies of surface wind direction at five weather stations along the eastern coast of Korea from ASOS (1981–2016) when the heavy snowfall event occurred, and SST anomalies along the 200 m depth line from OSTIA (1985–2016) in January and February. Here, we define a heavy snowfall event as a day with more than 20 cm of snow in 24 h, which is the threshold snowfall rate that triggers the issuance of a heavy-snowfall warning. Using the above definition of heavy snowfall events for observations, we detect 72 heavy snowfall events (56 d including heavy snowfall events in other regions on the same day) for eastern Korea during 1981–2016. An examination of this figure shows that a large amount of snow tends to fall on the east coast region when the easterly winds are prevailing and the SSTs are below normal. It is interesting that heavy snowfall events are more likely to occur during cold SSTs. Figure 3 shows the scatter diagram of the heavy snowfall events and the satellite-based SST anomalies. While heavy (>20 cm) and extremely heavy (>60 cm) snow can occur during above-normal SST, the majority of heavy snow cases (80%) are associated with below-normal SSTs. Prior work shows that above-normal SSTs provide moisture flux anomalies conducive to higher snowfall, so we interpret the relationship in figure 3 to indicate that the synoptic drivers of heavy snow tend to produce a below-normal SST. Here we investigate the response of the atmosphere to a below-normal SST associated with heavy snow. Accordingly, we explore the potential associations between heavy snowfall in eastern Korea and environmental variables, using composite analysis that is recognized as a simple and effective tool for the identification of the conditions observed during specific states of the climate (Boschat *et al* 2016). In this study, a composite analysis is performed to show the local atmospheric responses and regional SST conditions observed during heavy snowfall events in the coastal region of Korea. To explore the climate signature associated with the observed heavy snowfalls in eastern Korea, the composite maps for SLP, surface wind, and SST are obtained based on the daily maps of the variables for 56 heavy snowfall days, in which the daily SST (0.05°) from the OSTIA, daily SLP (0.25°) from ERA-Interim, and surface wind (0.25°) from the CCMP are used. We calculate the composites of daily anomalies, as a deviation from the daily climatology for that specific calendar day. Additionally, for the significant SST anomalies that are the primary topic of this study, a two-tailed student t-test using the Monte Carlo procedure was utilized to test the significance of the anomalies at the 95% confidence level.

The average anomalous SST, SLP, and wind conditions for the heavy snowfall events are shown in figure 4. These composite maps suggest that heavy snowfalls in eastern Korea are associated with cold SST anomalies with a peak over the East Korea Bay (EKB) and the anomalous northern-high and southern-low SLP pattern accompanying prevailing easterly wind anomalies. It is particularly noteworthy that heavy snowfall is strongly related to cold SST rather than to warm SST anomalies. As mentioned above, many studies have shown that heavy snowfalls occurring in the coastal regions of Korea are more generally associated with warm SST anomalies. However, the results of our analysis contradict the conclusions of the previous studies, revealing a strong linkage between cold SST anomalies and heavy snowfalls. This is because previous studies have mainly focused on the passive effect of the SST, as previously mentioned. They demonstrated the impact of local warm SST on the intensity of snowfall only under the favorable synoptic conditions for the formation of the heavy snowfall. In the following section, the evidence that the cold composite SST anomaly is related to occurrence of heavy snowfall event is provided.

Even though the composites with observed data confirm the association between the regional SST and heavy snowfall events, as highlighted in our empirical relationships mentioned above, caution is required in the interpretation of the physical meaning of the composite analysis because the cold composite SST anomaly itself might not be sufficient for the occurrence of the heavy snowfall events. The cold SST obtained by composite analysis does not always ensure heavy snowfall occurrence, but the condition may cause an increase in the possibility of the heavy snowfall occurrence (figures 1 and 3). In this study, it is demonstrated that the heavy snowfall-related cold SST anomaly, as an active condition for the heavy snowfall, induces favorable synoptic conditions for the formation of heavy snowfall events, using numerical experiments. The numerical approach could help to assess the poorly understood causality between the regional cold SST and the heavy snowfall events in the eastern coastal region of Korea.

3.2. Atmospheric responses to the heavy snowfall-related SST in the East Sea

The atmospheric responses to the heavy snowfall-related composite SST anomalies in the East Sea are examined based on the time mean (DJF) of differences between two simulations (i.e. *CompSST* – *ClimSST*). The changes in SST can affect the overlying atmosphere by changing the air–sea turbulent fluxes. Figure 5 shows the local responses of SLP and surface wind, turbulent heat flux, 2 m air temperature, moisture flux, and planetary boundary layer height to composite SST anomalies in the East Sea. Local

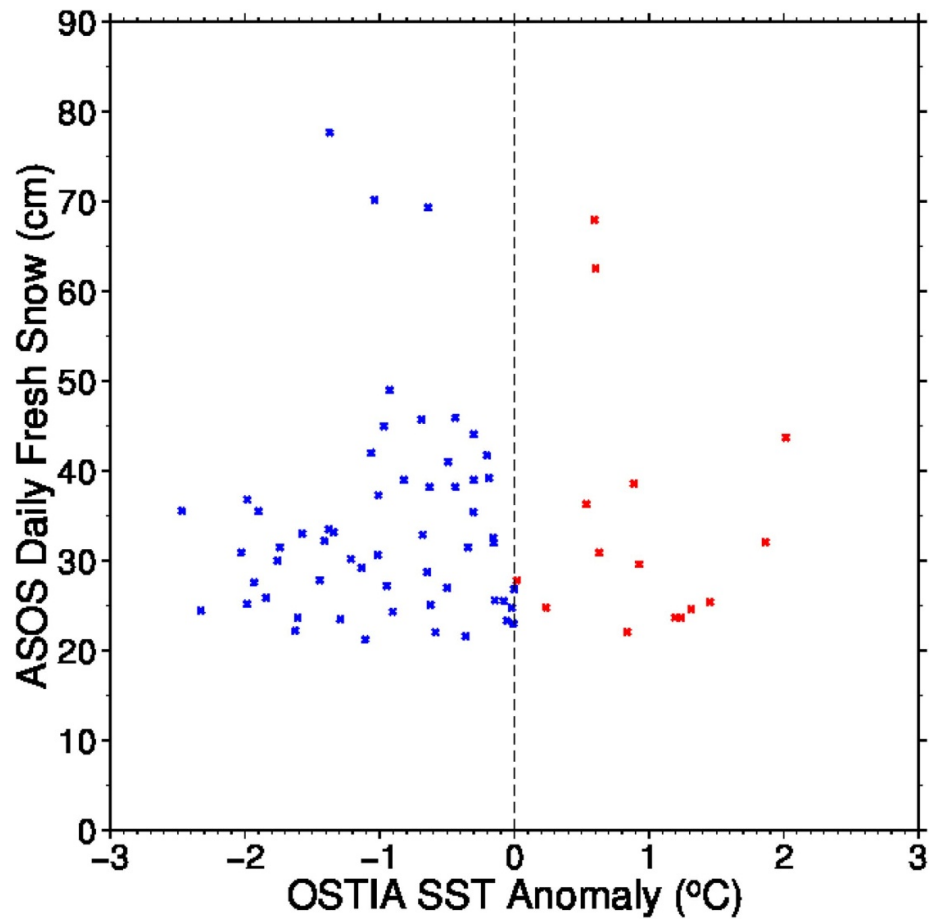


Figure 3. Scatter diagram of the 72 heavy snowfall events from ASOS and the SST anomalies obtained from a satellite. The heavy snowfalls during the cold SST anomalies are denoted by blue dots (57 events, 80%), and the red dots indicate the heavy snowfalls during warm SSTs (15 events, 20%).

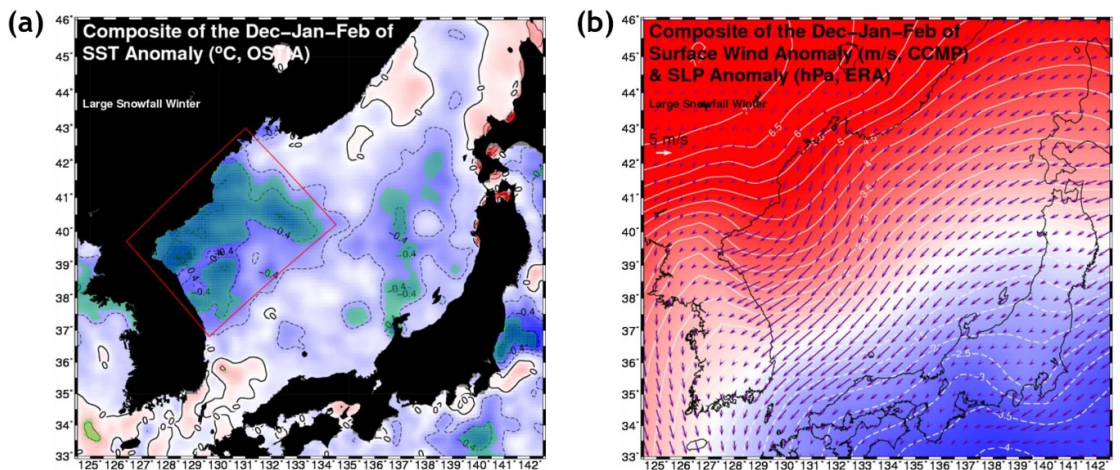


Figure 4. Horizontal distributions of the average anomalous (a) SST from OSTIA, and (b) SLP (color shaded with contours) from ERA-Interim and surface wind (vector) from CCMP for the heavy snowfall events. For the composite SST anomaly, two-tailed student t-test using the Monte-Carlo procedure is utilized to test the significance of anomalies at the 95% confidence level, as displayed by the green dots in (a).

near-surface atmospheric responses to the cold SST anomalies in the East Sea exhibit a typical feature of a linear and symmetric response for the structure and signal of the anomalous diabatic forcing. As expected, negative turbulent heat flux anomalies are present

over the region with cold SST anomalies, indicating the below-normal heat transfer from the ocean to the atmosphere. We can also clearly observe that moisture fluxes also become weak together with the turbulent heat flux over this region, and consequently

the atmospheric boundary layer stabilizes, resulting in the lower planetary boundary layer (PBL) height. In addition, surface air temperature decreases and a localized high SLP anomaly is induced over the region with cold SST anomalies, thereby dominating the easterly/southeasterly wind anomaly over eastern Korea; this corresponds to the anomalous SLP pattern.

It should be noted that the local near-surface atmospheric responses to the heavy snowfall-related composite SST anomalies do not coincide precisely with the distribution of the anomalous diabatic forcing. Upon closer examination, figure 5 reveals that the atmospheric responses to the SST anomalies are rather elongated southeastward from the EKB where the maximum cold SST anomaly occurs (figure 5(a)). The East Sea is subject to strong influence under the East Asian monsoon system. Hence, it is likely that the atmospheric responses to the SST anomalies are extended to the downstream region by the prevailing northwesterly winter monsoon winds. As a result, negative turbulent heat and moisture fluxes as well as surface air temperature are impinged on the downstream region in the shape of a tongue, leading to the extended anomalous high SLP over the corresponding region. Consequently, warm and wet advection from the south can be caused by the anomalous easterly/southeasterly winds along the southwestern flank of the extended high SLP anomaly (figures 5(b) and (d)).

According to the previous studies, with the exception of the easterly/southeasterly wind anomalies, these atmospheric responses to the composite SST anomalies for the heavy snowfall such as negative turbulent heat and moisture fluxes and stable atmospheric boundary layer are rather unfavorable for the occurrence of heavy snowfall events. However, the result of our sensitivity experiments shows that the simulated precipitation in eastern Korea increases with the significant SST anomalies from the composite maps. Figure 6 shows the difference in winter (DJF) mean rainfall and accumulated snowfall between the two sensitivity experiments. We observe substantial increases in the simulated precipitation over eastern Korea in *CompSST* and more rainfall over eastern Korea and the western part of the East Sea, which produces greater snowfall along the eastern coastal region of Korea.

It is useful to compare the distributions of moisture flux convergence (MFC) in the lower troposphere obtained in the two sensitivity experiments, since MFC affects precipitation both directly and indirectly by changing moisture inflow and precipitation efficiency. MFC is a term used in calculations to predict precipitation (Banacos and Schultz 2005) and is more important for the probability of heavier precipitation (Wei *et al* 2016). In particular, in the case of limited surface evaporation over the oceanic region in wintertime, the MFC plays

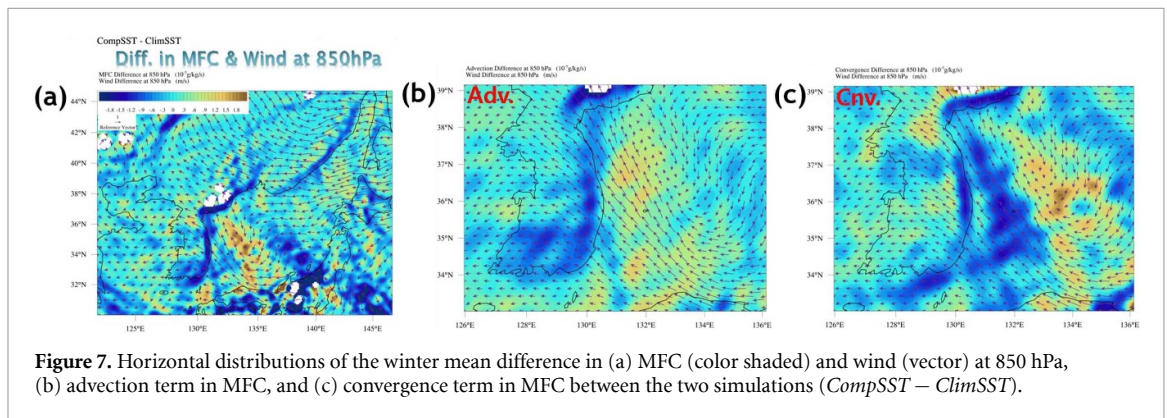
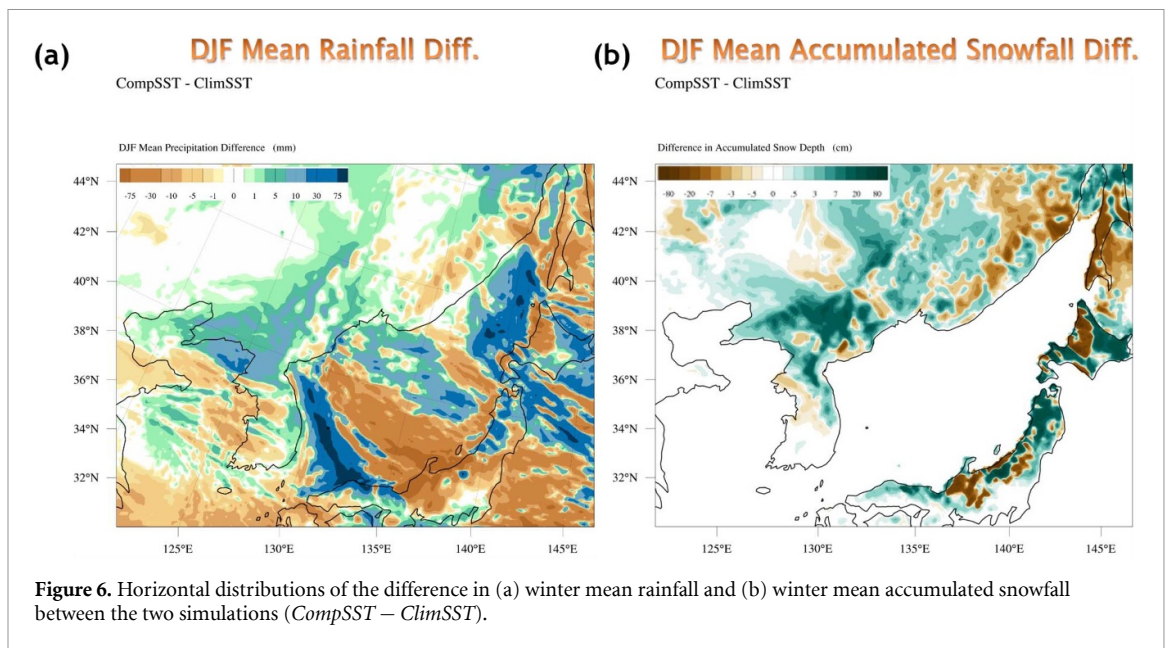
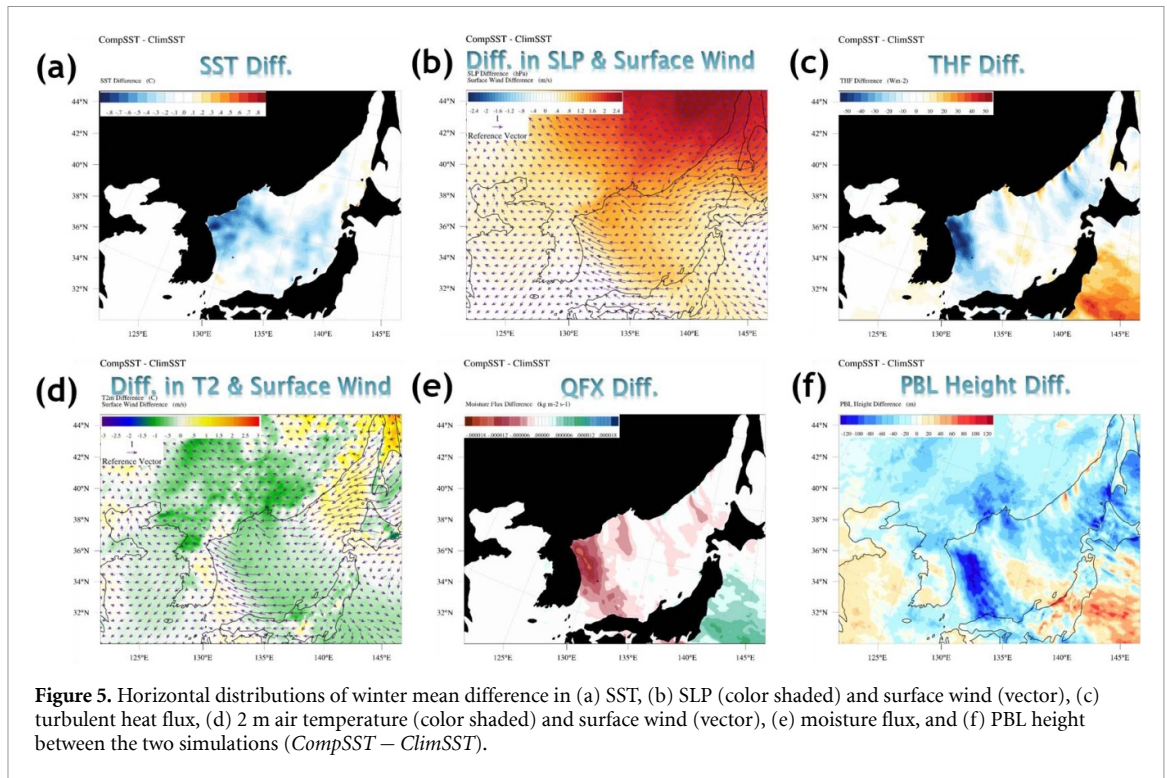
a more dominant role in water vapor supply. The difference in horizontal MFC and wind at 850 hPa between the two sensitivity experiments is shown in figure 7(a), and it is observed that the increased precipitation is most likely associated with the MFC. A negative MFC (i.e. convergence of moisture flux) difference is found over the east coastal region of Korea and west part of the East Sea. This is consistent with the enhanced convergence in the moisture flux leading to an increased amount of rain and snowfall within the region (figure 6). In addition, the simulated atmospheric circulation features imply that anomalous heavy snowfall over eastern Korea is related to low-level southeasterly wind anomalies. As discussed above, anomalous easterly/southeasterly flow over eastern Korea is an important condition for the heavy snowfall events. As expected, the strong southeasterly wind occurs in the west part of the East Sea and east coastal region of Korea in the simulation with significant composite SST anomalies for the heavy snowfall events. This strong southeasterly moisture flux converges on the east coastal region of Korea to form a band of maximum MFC.

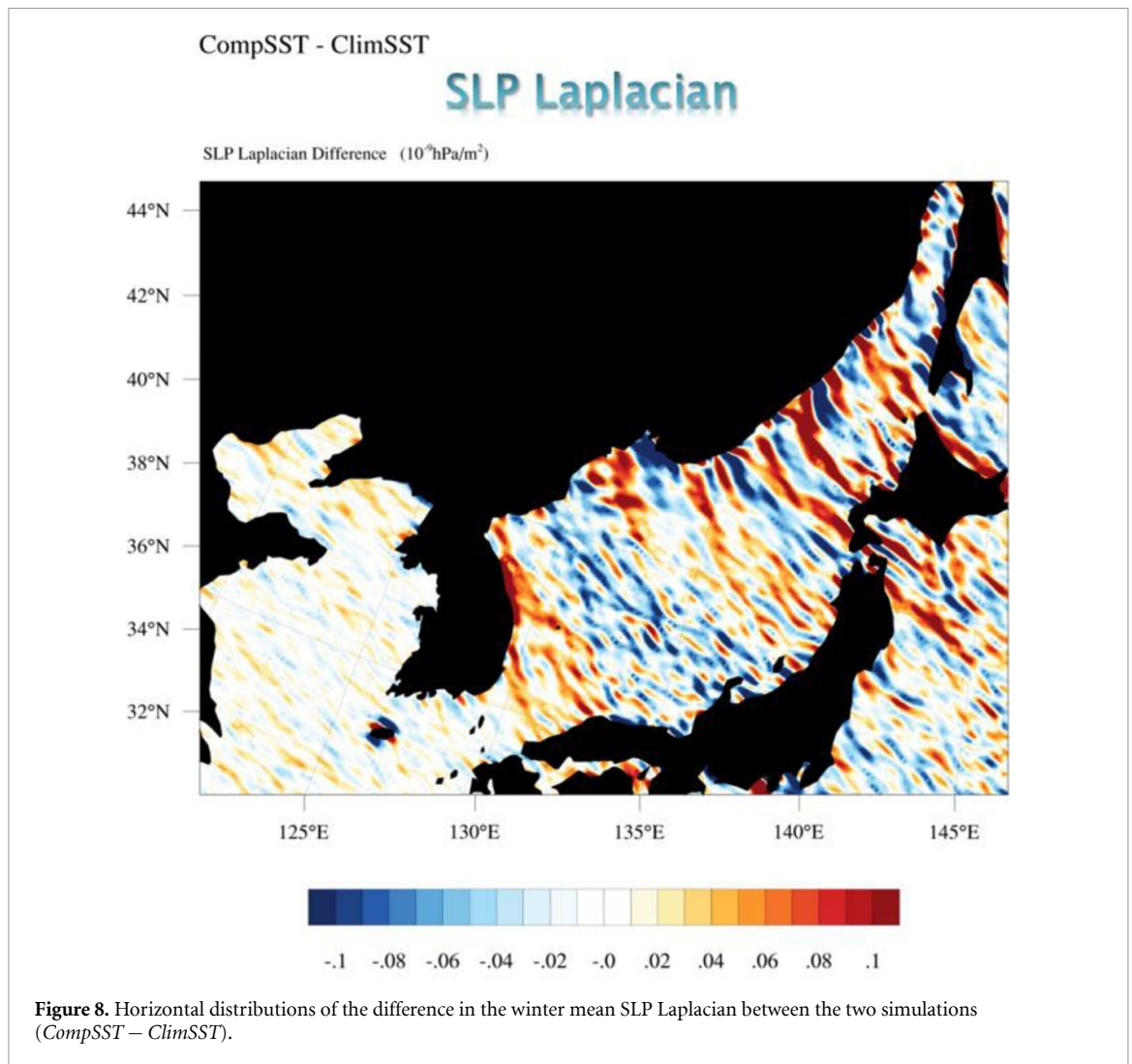
The MFC can be decomposed into the horizontal advection of moisture (advection term displayed in figure 7(b)) and the product of moisture and horizontal air mass convergence (convergence term displayed in figure 7(c) by the following vector identity

$$\text{Horizontal MFC} = -\nabla \cdot (qV_h) = -V_h \cdot \nabla q - q\nabla \cdot V_h$$

where $\nabla = \hat{i}\frac{\partial}{\partial x} + \hat{j}\frac{\partial}{\partial y}$, $V_h = u\hat{i} + v\hat{j}$, and q is the specific humidity. Further decomposition demonstrates that the enhanced MFC induced by the composite SST anomalies for heavy snowfall primarily arises from the enhanced wind convergence over eastern Korea (figure 7(c)). Meanwhile, moisture advection becomes dominant along the east coastal region of Korea and has rather positive values (i.e. divergence) over the region with the cold composite SST anomalies (figure 7(b)). This result implies that the atmospheric moisture for the occurrence of heavy snowfall in eastern Korea is affected more strongly by the large-scale atmospheric circulation. Namely, the enhanced MFC is linked to the atmospheric circulation that controls the moisture transport in the region, exerting an important effect on the local precipitation. Therefore, MFC is a key factor for the generation of heavy snowfall, and the existence of the horizontal air mass convergence and the accompanied MFC appears to be instrumental in producing the heavy snowfall event.

This relationship can be explained using the pressure adjustment mechanism proposed by Lindzen and Nigam (1987), who showed that SLP and underlying SST are related and surface wind convergence is linked to the SLP Laplacian ($\nabla^2 SLP$) by a linear relationship. Therefore, a linear relationship between SST and SLP indicates that the ocean has an impact on the atmosphere. The anomalous SST thermally induces





a density anomaly of the near-surface atmosphere over the region, resulting in anomalous wind convergence or divergence. According to Lindzen and Nigam (1987) and Minobe *et al* (2008), wind convergence is proportional to the Laplacian of pressure. Figure 8 displays the horizontal distribution of the difference between the SLP Laplacian results obtained in our two numerical experiments. In the present numerical experiments, the anomalous SLP is forced by the heavy snowfall-related SST anomaly. The spatial distribution of the SLP Laplacian difference shows that positive values are dominant over the western part of the East Sea and along the eastern coast of the Korea, corresponding to that of the convergence term in MFC (figure 7(c)). This result demonstrates that the pressure adjustment plays a primary role in and is responsible for the momentum convergence.

Our results also show that the presence of an anomalous easterly wind is a favorable condition for the formation of heavy snowfall events, in agreement with the previous studies. However, this study highlights that due to the heavy snowfall-related SST anomaly which is the anomalous cold SST, the anomalous easterly winds are induced and consequently

moisture flux is converged. This is in contrast to most previous studies that emphasized a warm SST as a favorable condition for forming and intensifying snowfall events. Furthermore, the anomalous easterly/southeasterly winds associated with the heavy snowfall-related SST anomalies reduce the climatological northwesterly/westerly winds, leading to relatively warm and wet conditions over the east coast of Korea, which are favorable conditions for forming and intensifying snowfall events in the region.

4. Summary and discussion

Air–sea interaction plays a vital role in the occurrence of heavy snowfalls caused by a cold air outbreak over the relatively warm ocean. Thus, as mentioned previously, air–sea exchange processes are important for the development mechanism of heavy snowfall. In this study, we investigated the atmospheric responses to heavy snowfall-related SSTs in the East Sea. This study followed a different approach to examine the effects of SST anomalies on heavy snowfall events. Unlike many previous studies that have investigated the impact of local SST on snowfall intensity

under favorable synoptic conditions for the formation of heavy snowfall, we focused on the atmosphere responses to heavy snowfall-related SSTs.

Qualitative examination of the heavy snowfall tendency and composite analysis demonstrate that the heavy snowfalls in eastern Korea are closely associated with cold SST anomalies with a peak over the EKB, unlike previous studies that suggested warm SST anomalies provide favorable conditions for forming and intensifying snowfall events. To investigate the dynamical relationship between the heavy snowfall-related composite SST anomalies in the East Sea and atmospheric circulation, we perform numerical experiments on the sensitivity of atmospheric circulation to the heavy snowfall-related SST. Surface atmospheric conditions show a linear response to anomalous cold SSTs in the East Sea; negative turbulent heat and moisture flux anomalies are observed over the region with heavy snowfall-related cold SST anomalies, and consequently the atmospheric boundary layer stabilizes. Furthermore, surface air temperature decreases and a localized high SLP anomaly is induced over the region with cold SST anomalies, resulting in the anomalous easterly/southeasterly winds over eastern Korea.

The results of the numerical experiments imply that due to the prevailing northwesterly winter monsoon winds, these linear atmospheric responses are elongated southeastward from the EKB where the maximum cold SST anomaly occurs. As a result, negative turbulent heat and moisture fluxes as well as surface air temperature are impinged on the downstream region, resulting in the extended anomalous high SLP over the corresponding region. This gives rise to anomalous easterly/southeasterly wind along the southwestern flank of the extended high SLP anomaly. According to previous studies, with the exception of the easterly/southeasterly wind anomalies, these linear atmospheric responses to the composite SST anomalies are rather unfavorable for the occurrence of heavy snowfall events. However, the results of our sensitivity experiments show that the simulated precipitation in eastern Korean increases with the significant SST anomalies from the composite maps.

MFC is the key factor for generating heavy snowfall. The sensitivity experiment forced with the significant composite SST anomalies for heavy snowfall events demonstrates that the heavy snowfall is associated with a pronounced lower-level MFC. The existence of the easterly/southeasterly winds and the accompanied MFC that are induced by the heavy snowfall-related cold SST anomalies appear to play the key role in producing the heavy snowfall events. The cold composite SST anomaly thermally induces an anomalous high SLP over the region and this high SLP system is extended southeastward due to northwesterly winter monsoon, leading to the anomalous wind divergence/convergence. This pressure adjustment plays a primary role and is responsible for the

momentum convergence. Furthermore, the anomalous easterly/southeasterly winds associated with heavy snowfall-related SST anomalies reduce the climatological westerly/northwesterly winds, leading to relatively warm and wet conditions over the east coast of Korea. These conditions are favorable for forming and intensifying snowfall events in the region.

This study illustrates the potential impact of the cold oceanic conditions on the heavy snowfall events. Our results provide important insights for understanding the dynamical process by which the East Sea SST providing the favorable conditions for heavy snowfall is communicated with the atmospheric circulations. The findings of this study contribute to the prediction of the probability of heavy snowfall occurrence and to understanding the role of air–sea interaction in severe weather events.

Meanwhile, the SST in the western part of the East Sea is strongly influenced by the East Korea Warm Current (EKWC) that flows northward along the east coast of Korea as one of the branches of the Tsushima Warm Current, playing a significant role in the northward transport of warm and saline waters. The EKWC flowing northward encounters the North Korean Cold Current flowing southward along the North Korean coast, and then both currents separate from the coast (Kim and Yoon 2010). Consequently, warm and cold conditions in the western part of the East Sea are determined by the location where the EKWC separates from the coast. Therefore, heavy snowfall-related SST may be strongly correlated with the variability of the EKWC. Although not investigated in this study, the potential contribution of the EKWC on heavy snowfall events is an interesting subject for future work.

Acknowledgments

This work was funded by the Korea Meteorological Administration (KMA) Research and Development Program ‘Development of Marine Meteorology Monitoring and Next-generation Ocean Forecasting System’ under Grant No. (1365002979). J-H Moon was supported by a National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (NRF-2019R1A2C1003206). E K Jin was sponsored by a research grant from the Korean Ministry of Oceans and Fisheries (KIMST20190361).

The observed daily winds and 24 hour accumulated fresh snowfall related to and used in this study are available for free download from <https://data.kma.go.kr/cmmn/main.do>. ERA-Interim data are downloaded from <http://apps.ecmwf.int/datasets>. CCMP Version-2.0 vector wind analyses were produced by Remote Sensing Systems. The data are available at www.remss.com. The data for OSTIA are available from the Copernicus Marine

Environment Monitoring Service (CMEMS, <http://marine.copernicus.eu>). The NCEP—CFSR data are also available for free download from <http://rda.ucar.edu/datasets/ds093.1/>.

Data availability statement

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

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