Impacts of the High-Resolution Sea Surface Temperature Distribution on Modeled Snowfall Formation over the Yellow Sea during a Cold-Air Outbreak

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ABSTRACT
High-resolution sea surface temperature (SST) products and idealized SST distributions were used to simulate snowfall over the Yellow Sea during 30–31 December 2007 using the Weather Research and Forecasting Model (WRF). Large differences were found between the SST distributions in the New Generation Sea Surface Temperature (NGSST) and Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) datasets near the Yellow Sea coast. Idealized SST datasets were defined to examine the influence of this difference in detail. The SST differences influenced the cloud streets and resultant snowfall formation. In simulations with the idealized SST distributions, convection developed and intensified later when the SST gradient was increased. In addition, the intensity of cloud streets was enhanced along the center of the flow. The simulations using the NGSST dataset showed widely distributed cloud streets and snowfall and heavier snowfall over the western Korean Peninsula, while those using the OSTIA dataset showed a concentrated distribution of cloud streets and snowfall along the center of airflow and more intense snowfall over North Jeolla Province, Korea, than in other regions. Comparing real SST products with observations qualitatively and quantitatively, OSTIA is found to have simulated the distribution and intensity of snowfall better than NGSST.

1. Introduction

Snowfall can have large effects on today’s society and economy, for example, impacting traffic flow and thus increasing distribution costs. Accurate snowfall predictions play an important role in developing effective strategies for reducing the damage caused by heavy snowfall.

Snowfall in Korea is classified into five types according to the development mechanism involved (Cheong et al. 2006): that associated with airmass transformations, terrain effects during the expanding Siberian high, precipitation systems associated with extratropical cyclones, indirect effects of extratropical cyclones passing over the sea to the south of the Korean Peninsula, and combinations of the effects of the above types (Cheong et al. 2006). Snowfall caused by airmass transformations, which occur during the expanding Siberian high, is responsible for a large portion of the total snow received along Korea’s western coastal region (Lee and Chun 2003).

Many studies have examined snowfall using numerical models. For example, Hong and Lee (1987) simulated a winter cyclone over the Korean Peninsula using the fifth-generation Pennsylvania State University–National Center for Atmospheric Research (PSU–NCAR) Mesoscale Model (MM5). As they noted, numerical simulations can compensate for the temporal and spatial limitations of observational data. Lee and Lee (1994) showed that a low-level current providing heat and moisture under the extension of the Siberian high caused heavy snowfall by an orographic effect over the Taebaek
Mountains. Kang (2000) and Jung et al. (2005) demonstrated the importance of sensible heat flux in heavy snowfall development using the Colorado State University (CSU) Regional Atmospheric Modeling System (RAMS) and the MM5.

During snowfall caused by airmass transformations, cloud streets are often observed around large lakes and the open ocean (Tripoli 2005). These cloud streets develop when cold air masses pass over the relatively warm sea surface, or at the rear of mountains and islands near the coast (Kang and Kimura 1997). Kristovich and Steve (1995) showed that multiple wind-parallel cloud bands were the most common phenomena of planetary boundary layer convection over warm lakes and their formation is strongly associated with the heat transitions between cold-air outbreaks and warm lakes. Using numerical model and observation data analysis, Cooper et al. (2000) simulated that the lower-level wind field, including wind shear, is one of the important factors in the formation of three-dimensional convective roles over Lake Michigan. Young et al. (2002) observed the aspect ratio of convective roll clouds over large lakes during cold-air outbreaks ranged from 1.8 to 12.1 and its range is almost the same for roll clouds over the ocean during cold-air outbreaks.

The cloud streets over the East Sea–Sea of Japan near the Korean Peninsula are also observed frequently due to the active interaction between cold-air outbreaks from eastern Russia and the underlying warm sea. Using numerical assessments, Kang and Kimura (1997) and Kang and Ahn (2008) showed that thick and long cloud streets over the East Sea/Sea of Japan occur due to the strong sensible heat fluxes from the sea surface and their formation type is often determined by the sea surface temperature (SST) distribution.

Along the western Korean Peninsula, snow appears after cloud streets. Nonetheless, research on snowfall in connection with cloud streets is lacking, especially using numerical models. Many studies of snowfall and cloud streets have highlighted the importance of SST (Kang 2000; Kang and Kimura 1997; Kang and Ahn 2008), and many numerical simulations have shown that high-resolution SST data closely represent the spatial distribution of SST and atmospheric structures (Lacasse et al. 2007; Burls and Reason 2008; Yamamoto and Hirose 2008). Kang and Ahn (2008) simulated cloud streets using weekly optimum interpolation sea surface temperature (OISST) data, and Lee and Ryu (2010) simulated a heavy snowfall using the high-resolution New Generation Sea Surface Temperature (NGSST) dataset. However,
while various numerical simulations have applied high-resolution SST data, Xie et al. (2008) showed that there are large differences among the datasets. NGSST, which is widely used over East Asia, showed a large bias and root-mean-square errors (RMSEs) in coastal regions. On the other hand, the Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) dataset, which is newly developed and has been used in few numerical studies over East Asia, gave more realistic values compared to NGSST, especially in coastal regions (Xie et al. 2008).

Although the spatial resolution of these two widely used SST databases is the same at 0.05°, their values reveal some discrepancies, especially near coastal regions. So, it is necessary to clarify the impacts of the SST distributions of these two different datasets on the formation of convective clouds and resultant snowfall formations. We assessed the heavy snowfall events over the Yellow Sea during cold-air outbreaks using the Weather Research and Forecast modeling system (WRF) with two different SST distributions and we also proposed the numerical experiments with idealized SSTs to clarify more clearly the variation in the heat transition between the air and underlying sea with two different SST distributions.

The remainder of this paper is structured as follows. Section 2 describes the SST products. Section 3 outlines the WRF configuration and experimental design. Results are presented in section 4, followed by the summary and conclusions in section 5.

2. Sea surface temperature products

As noted above, this study examined how different spatial SST distributions affect the simulation of cloud streets and the resultant snowfall formation. For this purpose, two high-resolution SST products were used: the NGSST and OSTIA datasets.

NGSST is a high-resolution (0.05° gridded) SST product that has been generated daily since September 2003 by Tohoku University as part of the Global Ocean Data Table 1. Biases in NGSST and OSTIA SSTs (K) relative to buoy observations at Deokjeok, Chilbal, and Geomun Islands on 30 and 31 Dec 2007. Buoy stations are shown in Fig. 2.

<table>
<thead>
<tr>
<th>Date</th>
<th>Station</th>
<th>NGSST – BUOY</th>
<th>OSTIA – BUOY</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 Dec 2007</td>
<td>Deokjeok</td>
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<td>-0.23</td>
</tr>
<tr>
<td></td>
<td>Chilbal</td>
<td>2.75</td>
<td>0.20</td>
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<td>Geomun</td>
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<tr>
<td></td>
<td>Avg</td>
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<td>-0.30</td>
</tr>
<tr>
<td>31 Dec 2007</td>
<td>Deokjeok</td>
<td>2.94</td>
<td>-0.39</td>
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<td>Chilbal</td>
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<td>Geomun</td>
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<td>0.33</td>
</tr>
<tr>
<td></td>
<td>Avg</td>
<td>3.04</td>
<td>-0.06</td>
</tr>
</tbody>
</table>

Fig. 2. Model domains used for all simulations. Domain 1 (outer domain) has 27-km resolution, while domains 2 (d02) and 3 (d03) have 9- and 3-km resolutions, respectively. White squares indicate the buoy stations. The circle in the interior of the peninsula is Gwangju, the circle on the southern coast is Yeosu, the leftmost triangle is Mount Naejang, and the rightmost triangle is Mount Jiri. The leftmost crosses are the points along the intensified axis (I_axe), and the rightmost crosses are the points along the weakened axis (W_axe).
Assimilation Experiment (GODAE) High-Resolution Sea Surface Temperature Pilot Project (GHRSSST-PP; Sakaida et al. 2005). The analyzed product covers the whole of East Asia ($13^\circ$–$63^\circ$N, $116^\circ$–$166^\circ$E). Data from infrared sensors such as the Advanced Very High Resolution Radiometer (AVHRR) of the National Oceanic and Atmospheric Administration (NOAA) and the Moderate Resolution Imaging Spectroradiometer (MODIS) on board Terra, along with microwave sensors such as the Advanced Microwave Scanning Radiometer–Earth Observing System (AMSR-E) of the Aqua satellite, are merged for quality control of the satellite SSTs and optimum interpolation of the 5-day merged SST products (Sakaida et al. 2005). Matchups of 396 254 points in the analyzed area for July 2002 to October 2004 showed that the bias was $-0.15$ K against buoy observations and the RMSE was $0.85$ K (Sakaida et al. 2005).

OSTIA is a global high-resolution (0.05° gridded) SST and sea ice analysis product that is provided daily by the National Center for Ocean Forecast (NCOF) of the Met Office and the GHRSSST-PP (Stark et al. 2007). It uses in situ observations of the temperature and salinity, microwave sensors such as the Special Sensor Microwave Imager (SSM/I) of the Defense Meteorological Satellites Program (DMSP), and the Tropical Rainfall Measuring Mission Microwave Imager (TMI), and infrared sensors such as the Advanced Along-Track Scanning Radiometer (AATSR) of the Environmental Satellite (Envisat), the AVHRR of NOAA, the Spinning Enhanced Visible and Infrared Imager (SEVIRI) of the Meteosat Second-Generation 1 (MSG1). Measurements by all of these sensors are corrected using optimal interpolation analysis (Stark et al. 2007). When compared against independent observations from the Marine-Atmosphere Emitted Radiance Interferometer (M-AERI) radiometer as part of the Etude de la Circulation Océanique et du Climat dans le Golfe de Guinée (EGEE)/African Monsoon Multidisciplinary Analyses (AMMA) experiment in the tropical Atlantic, OSTIA data were found to have a cool bias of 0.17 K and an RMSE of 0.39 K. Recent verification has shown even less bias than this (Stark et al. 2007).

According to Xie et al. (2008), the OSTIA and NGSST products show large differences in the Yellow Sea, which is relatively shallow ($\sim$44 m) near the western Korean Peninsula. The RMSE of NGSST becomes larger as the water depth decreases, but that of OSTIA hardly changes. Figure 1 shows SST distributions and differences between the two products during the experimental period (30 and 31 December 2007). NGSST shows an aliased SST pattern, while the OSTIA SST distribution is smooth. Differences between the two SST products are small at the center of the Yellow Sea but increase toward the coast. In particular, there was a difference of 5 K or more near the coast on 30 December. To examine the accuracy of these SST products, NGSST and OSTIA data were compared with in situ SST data obtained by buoys in the Yellow Sea over the experimental period (Table 1). The average bias between the NGSST and buoy data was 2.63 K on 30 December, and that between the OSTIA and buoy data was $-0.30$ K. On 31 December, the NGSST bias was 3.04 K and the OSTIA bias was $-0.06$ K. The NGSST values were higher than the buoy observations, while the OSTIA values were similar or somewhat lower. Hence, the OSTIA SST distribution was more reasonable than the NGSST distribution.
This temperature distribution difference could impact the modeling of cloud street formation and resultant snowfall formation over the Yellow Sea. However, it is difficult to interpret the influence of a complicated structure of temperature differences. Therefore, idealized SST distribution sets were analyzed to reveal the effects of differences in the SST distribution. Detailed descriptions of the idealized SST datasets are presented in section 3.

3. Model configuration and experimental design

The WRF is a next-generation mesoscale numerical weather prediction system designed to serve both operational forecasting and atmospheric research needs. It is supported as a common tool for the university-research and operational communities to promote closer ties between them and to address the needs of both. The WRF system consists of two dynamic solvers: the Advanced Research WRF (ARW) solver, which was developed primarily at NCAR, and the Nonhydrostatic Mesoscale Model (NMM) solver, which was developed at the National Centers for Environmental Prediction (NCEP). To examine the influence of the high-resolution SST distribution on modeled snowfall formation, the ARW (version 3.1.1) developed for research was used in this study. A detailed description of this model has been given by Skamarock et al. (2008).

Figure 2 shows the model domain used in this study. Simulation domains were set up with the Yellow Sea as the center. Three domains at 27-, 9-, and 3-km resolutions, with 110 \( \times \) 110, 178 \( \times \) 151, and 334 \( \times \) 268 grid points, respectively, and 40 vertical levels were used.
According to Lee (2002), a simulation with 3-km horizontal resolution showed some physical characteristic related to cloud street formation. However, the range of the horizontal wavelength of the cloud streets was 2–20 km at a review for roll vortices in the planetary boundary layer (Etling and Brown 1993), and Brümmer (1999) showed the wavelength below 2 km from many observations. Therefore, 3-km resolution would have limitations when representing the cloud streets in detail, but we used 3-km resolution because of the expensive cost of calculation. The physics options used in this study included the Rapid Radiative Transfer Model (RRTM) longwave radiation, the Dudhia shortwave radiation, the Noah land surface model (LSM), the Yonsei University (YSU) planetary boundary layer (PBL) scheme, and the WRF single-moment six-class (WSM-6) and Kain–Fritsch cumulus parameterizations. The Noah LSM (Chen and Dudhia 2001) provided heat and moisture fluxes for the YSU PBL scheme (Hong et al. 2006). The YSU PBL scheme uses nonlocal K mixing and treats entrainment at the top of the PBL explicitly. The WSM-6 scheme consists of six hydrometeors: vapor, cloud water, cloud ice, rain, snow, and graupel. This scheme is considered the most suitable for cloud-resolving grids (Hong and Lim 2006).

The simulation period was from 1500 LST on 29 December 2007 to 0300 LST on 1 January 2008, during a cold-air outbreak over the Yellow Sea. During this period, the southwest coast of Korea received much snow, with heavy snowfall warnings issued for parts of the region (KMA 2007). As shown in Fig. 3, the 24-h accumulation of fresh snow cover observed by the Korea Meteorological Administration’s (KMA) Automated Synoptic Observing System (ASOS) was 33.48 cm in Gwangju on 30 December and 29.24 cm in Yeosu, South Korea, on 31 December. From satellite infrared images, we observed that cloud streets and roll-type convection were well developed over the sea (Fig. 4).

Two major numerical experiments were performed. The first major experiment used idealized SST distributions for the lower boundary condition over the sea. The second used the real SST products (NGSST and OSTIA). The idealized SST datasets were configured from the spatial distribution difference between the NGSST and OSTIA datasets (Fig. 5), to examine the influence of the SST distribution difference in detail. Three idealized SST datasets were classified by temperature increase: constant, 3.5 K, and 7 K from the coast to the center of the Yellow Sea. Experiments using idealized SST were set to constant (CON), small gradient (SGRD), and large gradient (LGRD), respectively. The 0.5° Final (FNL) Operational Model Global Tropospheric Analyses produced every 6 h by NCEP were used as the initial and boundary conditions for the WRF.

4. Results

When a cold and dry air mass caused by the extension of a strong Siberian high passes over the relatively warm sea, it absorbs heat and moisture from the sea and its properties change (Brümmer 1999; Kang and Ahn 2008; Ninomiya et al. 2006). These changes contribute substantially to the vertical fluxes of heat, moisture, and momentum in the atmospheric boundary layer, and make convection (Brümmer 1999). Convection develops into cloud streets...
and snowfall over the sea (Ninomiya et al. 2006; Takemi et al. 2009). Results from each individual simulation are presented on the basis of the above processes.

a. Idealized SST distributions

The advantage of using the idealized SST distribution was that we could understand the influences on snowfall formation processes more easily than we could using real SST products. Figure 6 illustrates the accumulated snowfall for 6 h. The CON case at 1500 LST on 30 December showed strong snowfall along the flow passing over the Shantung Peninsula and South Hwanghae Province, but weak snowfall over the center of the Yellow Sea. Snowfall over land was dominant in Gyeonggi, South Chungcheong, and North Jeolla Provinces. Snowfall for SGRD and LGRD was concentrated along the center of the Yellow Sea. Over land, both cases showed concentrated snowfall in Jeolla Province, which was intensified in LGRD. Similar patterns appeared at 0300 LST on 31 December. At 0300 LST, the patterns were weakened over the sea and intensified over land in all cases. Differences in the snowfall distributions between the CON and gradient cases (SGRD and LGRD) were clear compared with the situation at 1500 LST. In particular, the snowfall for

![Figure 6](http://journals.ametsoc.org/waf/article-pdf/26/4/487/4647661/waf-d-10-05019_1.pdf)
LGRD appeared to be narrowly distributed and more intense. Comparing the CON snowfall with those of the gradient cases, we observed differences in the center of Jeolla Province (not shown here). North (South) Jeolla had less (more) snowfall as the SST gradient increased. There was an even greater difference in the LGRD case.

Figure 7 shows the vertical wind component fields at the seventh Eta Model level (about 960 m above sea level). This level intersects the convective structures over the Yellow Sea and hence can be used to represent convective intensity. In CON, roll convection of the flow passing by North Jeolla seldom appeared, except in the vicinity of the flow. As the SST gradient increased,
the roll convection passing by North Jeolla intensified, and that in the vicinity of the flow weakened. This was due to the convergence caused by the SST gradient. A large SST gradient causes strong convergence across the flow, which intensifies vertical motion. Regions with wind speeds greater than 0.2 m s$^{-1}$ appeared on the backside of the front portion of the flow with the increase in SST gradient. This meant that higher SST gradients created more rapid convection. These vertical wind fields coincided with the 6-h accumulated snowfall in Fig. 6.

We examined the impacts of SST on the vertical convective structure using cross sections. Figure 8 shows vertical cross sections of the vertical wind component at 2400 LST. The CON case showed horizontally homogeneous ascent–descent of the air current compared to the SGRD and LGRD cases. As the SST gradient increased, convection intensified in the center and weakened on either side. In SGRD (LGRD), the maximum vertical wind speed was more than 0.5 (0.7) m s$^{-1}$. Deeper convection appeared as the SST gradient increased. When the SST gradient was large,
strong convergence occurred toward the center and intensified convection. However, the vertical wind component showed limitations for representing the general structure of roll or cell convections. The nonexistence of convection stronger than 0.2 m s$^{-1}$ in Fig. 7 and the weak convection in Fig. 8 do not seem to simulate the cloud streets having the low horizontal wavelength because of the model horizontal resolution. To examine general features of the convection, we plotted cross sections of the vertical wind component averaged over a fixed area shown in Fig. 2.

Axes of the cross sections were defined as flows passing by two regions that showed intensified–weakened snowfall with increases in the SST gradient. The first axis (intensified axis, I_axis) passed Jeolla, which had intensified snowfall, while the second axis (weakened axis, W_axis) passed Chungcheong, which had weakened snowfall. Each axis was obtained using a streamline and a back trajectory. The streamline was calculated by averaging the simulation over the simulated period, and the back trajectory was calculated from the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model of

Fig. 10. Cross sections of the area-averaged cloud water–ice (shaded, g kg$^{-1}$) and snow–graupel (contours, g kg$^{-1}$) mixing ratios of (a) CON, (b) SGRID, and (c) LGRID at 1200 LST 30 Dec 2007 for (left) I_axis and (right) W_axis.
NOAA. The I_axis had 10 horizontal points and the W_axis had 8 horizontal points (Fig. 2). The vertical wind value at each point on the axis was obtained by averaging 17 × 17 model grid points near the point.

Figure 9 shows cross sections of the area-averaged vertical wind component at 1200 LST. Updrafts occurred near points 5 and 9 along the I_axis. The CON case showed weaker updraft than downdraft. As the SST gradient increased, updrafts intensified considerably. The maximum vertical wind speed was more than 14 cm s⁻¹ for SGRD and more than 18 cm s⁻¹ for LGRD at the ninth point. Updrafts deepened to 3600 m in SGRD and 4000 m in LGRD, and their widths also increased. Conversely, downdrafts weakened near points 6 and 7. At point 10, downdrafts intensified as the SST gradient increased. This happened because the lower SST near the coast made the atmosphere stable in the SGRD and LGRD cases. Along the W_axis, updrafts occurred near points 4 and 7. The maximum vertical wind speed was more than 10 cm s⁻¹ for CON, 4 cm s⁻¹ for SGRD, and less than that for LGRD. The depth and width decreased as the SST gradient increased. As shown in Fig. 9, the convection increased with the SST gradient.

Figure 10 shows cross sections of the area-averaged mixing ratios of hydrometeors: water, ice, snow, and graupel at 1200 LST. In the simulation, clouds consisted of water and ice, and snowfall consisted of snow and graupel. Along the I_axis, the region above the cloud mixing ratio of 0.035 g kg⁻¹ appeared late in the front of the axis as the SST gradient increased. In CON, the mixing ratio of the cloud was 0.065 g kg⁻¹ at point 3, but decreased at the downwind end of the axis. SGRD and LGRD also showed maximum mixing ratios at point 3. These ratios decreased near the end of the downwind region, but were more than the mixing ratio of CON. Cloud depths in SGRD and LGRD were greater at the end of the downwind side. The snowfall pattern was similar to that of the cloud, but it was stronger to one side and at lower levels. CON showed 0.11 g kg⁻¹ at point 5 and 0.05 g kg⁻¹ at point 10, while SGRD showed 0.13 g kg⁻¹ at points 5 and 10, and LGRD also showed 0.13 g kg⁻¹ at points 5 and 9. As the SST gradient...
increased, the cloud and snowfall intensified at the end of the downwind and low levels. Along the W_axe, the cloud mixing ratio of CON was 0.065 g kg$^{-1}$ at points 3 and 4. The maximum cloud mixing ratios of SGRD and LGRD were the same as those of CON, but the cloud was thinner at the downwind end. At point 4, the maximum mixing ratio of CON snowfall was 0.13 g kg$^{-1}$, while those of SGRD and LGRD were 0.11 and 0.09 g kg$^{-1}$, respectively. The snowfall mixing ratio decreased rapidly as the SST gradient increased at the downwind end. As the SST gradient increased, the cloud and snowfall became weakened at the back and low levels.

Consequently, the minus SST gradient near the coast along the W_axe tended to induce the decrease in the vertical motion of the convection cell and also resulted in the decrease in snowfall amount. On the other hand, although the SST gradients along the I_axe in three cases are almost the same, the differences in the intensity of the vertical velocity and snowfall for the three cases are also detected. This indicates that not only are the convective cells located above the area with an SST gradient but also that nearly collocated convection cells are also influenced by the same SST gradient, and their response to meteorological factors are in inverse proportion to those of cells located above the area with the SST gradient.

b. Real SST products

In addition, we also briefly analyzed the influence of real SST products on modeled snowfall. Figure 11 shows convective available potential energy (CAPE) fields at 1200 LST on 30 December 2007 and at 2400 LST on 31 December 2007. The results at 1200 LST using NGSST and OSTIA had very similar patterns to those of the idealized SST. The NGSST case showed a wider distribution and greater intensity of snowfall than the OSTIA case. With OSTIA, the region with CAPE $> 60$ J kg$^{-1}$ developed behind that of NGSST. There were no large differences between the NGSST and OSTIA results at 2400 LST on 31 December, particularly along the front of the western part of the Korean Peninsula. This similarity is attributable to the SST differences between NGSST
and OSTIA being smaller at 1200 LST on 31 December than at the same time on 30 December (Fig. 1). This difference did not have an immediate impact on the CAPE distribution. The influence was only noticeable after 12 h. The CAPE distributions were structurally different on 30 and 31 December. There was a linear distribution (roll-type convection) on 30 December, and a curved distribution (cell-type convection) on 31 December.

Figure 12 displays the surface sensible and latent heat fluxes along the line shown in Fig. 6c at 1200 LST 30 December 2007. The difference in the sensible heat flux between the two cases is not great at the area far from the coast (the left side of 124.5°). However, their difference becomes larger near the coast (right side of 124.5°) and reaches 98 W m⁻¹ at 125.26°. This large difference in the sensible heat flux is caused by the difference in the SST distribution, which for the two cases becomes significant, as was mentioned when discussing Fig. 1. The smaller difference between the cold-air outbreak temperature and the SST for OSTIA should lead to a smaller upward sensible heat flux. And the variation pattern of the latent heat flux also shows the same result as that of the sensible heat flux except for the large fluctuation. The fluctuation in the latent heat flux is strongly associated with the horizontal distribution of roll-type convective cells. Namely, the latent heat flux variation coincided well with the CAPE distribution in Fig. 11.

Figure 13 shows 6-h accumulated snowfall fields at 1500 LST on 30 December 2007 and at 0300 LST on 31 December. In the NGSST case, snowfall was simulated in the area of South Chungcheong and North Jeolla at 1500 LST on 30 December. Strong snowfall (above 13 cm) occurred in South Chungcheong. The OSTIA case showed similar snowfall patterns, but with weakened snowfall in general. Snowfall was concentrated in the south, with a maximum of 8 cm. In the north, snowfall was weakened. South Hwanghae had the weakest snowfall. At 0300 LST on 31 December, there was no difference in the distributions. However, the maximum snowfall was 19 cm in the NGSST simulation and 26 cm in the OSTIA simulation. NGSST showed stronger snowfall on 30 December, while OSTIA showed stronger snowfall on the afternoon of 31 December. This was due to the difference in the SST distribution at 1200 LST between 30 and 31 December.
Similar to the numerical experiments for an ideal SST distribution previously mentioned, the OSTIA data on 30 December 2007 yielded a stronger negative SST gradient than did the NGSST data, which in turn caused stronger convergence to the center of the flow axis. The stronger convergence created stronger convection, more hydrometeors, and more intense snowfall along the center of the flow axis. This is why the distribution and intensity of the snowfall varied regionally.

c. Validation

For qualitative validation of the numerical assessment with real SSTs, we compared the distribution of the 24-h accumulated amount of snowfall for the NGSST and OSTIA cases (Fig. 14). On 30 December 2007, a considerable amount of fresh snow cover was recorded in Jeolla Province, and a maximum fresh snow cover of 33.48 cm was recorded in Gwangju. The NGSST simulation indicated substantial snowfall amounts in South Chungcheong and North Jeolla, with a maximum snowfall amount of 38 cm around Mount Jiri. The OSTIA simulation indicated significant snowfall in North Jeolla and diminished snowfall in South Chungcheong and South Jeolla. The maximum snowfall amount was shown at Mount Naejang. The strong SST in the NGSST simulation produced stronger convection near the coast. This intensified convection influenced the strong snowfall over the inland region. On 31 December, the general distribution of fresh snow cover was similar to that on 30 December, but it was weaker overall. In particular, the fresh snow cover in South Chungcheong weakened considerably. The maximum fresh snow cover was 29.23 cm in Yeosu, while 26.7 cm was
also recorded in Gwangju. The NGSST simulation estimated a maximum snowfall amount of 25 cm around Mount Naejang and a snowfall amount above 15 cm in South Chungcheong. The OSTIA simulation gave a maximum snowfall of 30 cm around Mount Naejang and weaker snowfall than the NGSST model in South Chungcheong. Qualitatively, the overall distribution and intensity of snowfall was better in the OSTIA case than in the NGSST case.

For the quantitative validation, we used the amount of rainfall being equivalent to snowfall. Observations of snowfall amount were too scarce to compare with the simulation results, and it is difficult to directly compare physically observed results with modeled results. Therefore, we used rainfall amounts, which are easy to compare physically. Figure 15 shows time variations of 3-h accumulated amounts of rainfall in the observations and simulations. The target areas were divided into two regions, which showed major differences in the amount of accumulated snowfall between NGSST and OSTIA (Fig. 3b). Except for the morning of 30 December, the NGSST and OSTIA models had similar tendencies. However, there was a difference in the amount of rainfall. The NGSST result showed an average difference of 0.54 mm, while the OSITA result showed a difference of 0.35 mm near South Chungcheong. The NGSST simulation overestimated the rainfall amount compared to the observations most of the time. In Jeolla Province, which had significant snowfall, NGSST produced an average difference of 0.7 mm compared to the observations, while for OSTIA the difference was 0.52 mm. Neither time variations in the OSTIA and the NGSST datasets over the Jeolla region showed a more similar variation tendency of rainfall amount than Chungcheong, but the

![Figure 15](http://journals.ametsoc.org/waf/article-pdf/26/4/487/4647661/waf-d-10-05019_1.pdf)
those of NGSST. OSTIA results gave a more accurate tendency than did those of NGSST.

5. Summary and conclusions

The main objective of this study was to examine the influences of SST distributions on the cloud streets and resultant snowfall formation over the Yellow Sea during 30–31 December 2007. Numerical experiments were conducted using idealized SST distributions and the real SST products NGSST and OSTIA. Comparisons with buoy data from the Yellow Sea showed that OSTIA data produced better accuracy than did the NGSST data. Idealized SST distributions, defined from the difference between NGSST and OSTIA, were used to examine the influence of the SST distribution difference in detail. The idealized SST distributions were as follows: CON with constant SST, SGRD with a small SST gradient, and LGRD with a large SST gradient. The resulting horizontal and vertical structure patterns during snowfall formation were then analyzed.

In the idealized SST experiments, there was a narrowed distribution and weakened intensity of CAPE with increasing SST gradients. This CAPE distribution delayed and weakened the convection, cloud streets, and snowfall. As the SST gradient increased, convergence developed along the center of the flow. The intensified convergence of SGRD and LGRD resulted in stronger convection, cloud streets, and snowfall than in CON along the center of the flow. These differences intensified the simulated snowfall in the southwestern part of the Korean Peninsula with increasing SST gradient. The experiments using the NGSST and OSTIA data gave less clear but similar patterns to those using the idealized SST distributions. The NGSST simulation showed stronger snowfall until the afternoon of 31 December, while the OSTIA simulation indicated stronger snowfall from the afternoon of 31 December. However, the OSTIA case gave stronger (weaker) snowfall in the south (north) compared to the NGSST case. A comparison of the simulated and fresh snowfall amounts showed that the OSTIA data produced a better distribution than did the NGSST data. Comparing with the time variations of the rainfall amount, OSTIA also showed better variations than NGSST. The NGSST data showed somewhat higher precipitation because of the high SST in the Yellow Sea.

Our simulations of snowfall during an extension of the Siberian high revealed different distributions and intensities of snowfall with an increasing SST gradient. When we used OSTIA data, which are accurate in the Yellow Sea, we simulated the snowfall distribution and intensity more closely than when using the NGSST data. Therefore, using spatially more accurate SSTs in shallow seas such as the Yellow Sea can be very important for the simulation of snowfall.

The horizontal resolution of the simulated domain of this study was 3 km. The cloud streets that impacted the distribution and intensity of snowfall have wavelengths between 1 and 6 km. Therefore, further numerical studies at higher resolution are needed to simulate cloud streets and snowfall more accurately.

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