Formation and maintenance mechanisms of a thick snow band along the Okhotsk Sea coast of Hokkaido Island, Japan

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Abstract:

A thick snow band often forms along the Okhotsk Sea coast of Hokkaido Island, northern part of Japan. Numerical simulations were made to investigate the formation and maintenance mechanisms of a long-lasted snow band appeared on 26th of December 2008 using Weather Research and Forecasting Model (WRF). The snow band was simulated along the coast of Hokkaido Island, moved offshore toward the Sea of Okhotsk, where it intensified, and was sustained for one and a half days. The results show that Sakhalin Island plays an important role in the maintenance of a convergence line and thus the snow band. Cold air advection from Sakhalin Island produces a strip of warm air between the advected cold air and Hokkaido Island and thus controls the location of the snow band, while topographic blocking by Sakhalin creates the lower level convergence at the Soya Strait and hence enhances the snow band. Temperature and surface-roughness contrast between Hokkaido Island and the Sea of Okhotsk appear to be also important for the initial formation of the snow band.

KEYWORDS snow band; cloud band; numerical study; Weather Research and Forecasting Model (WRF); Hokkaido; Sea of Okhotsk

INTRODUCTION

In winter, the cold Siberian air mass often breaks out from the east coast of the Eurasian Continent toward Japan, and many cloud bands develop over sea areas around Japan (Figure 1). In particular, frequent formations of a thick cloud band are known to occur at specific locations.

Land breeze, coastal shape, and sea surface temperature (SST) patterns are known to have profound effect on the development of such cloud bands. Differential heating between land and sea in the wind path (Atlas et al., 1983; Kawase et al., 2005) or upstream topographic structures can trigger the formation of thick cloud bands (Kawase et al., 2005; Ohtake et al., 2009). Difference in surface roughness between land and sea can also produce a convergence line along a coastline at the lower levels, resulting in a thick cloud band (Roeloffzen et al., 1986).

Fujiiyoshi et al. (2010) reported that thick cloud bands appear frequently along the northeastern coast of Hokkaido Island during cold air outbreaks from the Eurasian Continent. An example is shown in Figure 2a. These cloud bands are usually associated with large snow fall and influence the local climate. Fujiiyoshi et al. (2010) named these bands ‘Thick Cloud Bands along the Okhotsk Sea Coast of Hokkaido’ and showed three-dimensional structures of these bands, using two X-band Doppler radars. They categorized the cloud bands into a strong wind type and a weak wind type, based on the ambient wind speed estimated from the gradient of sea level pressure around the Hokkaido coast. Analysis of satellite images from November 2006 to March 2008 revealed that the strong wind type appears more often (roughly twice) and tends to last longer than the weak wind type (Kamisho, 2010).

Fujiiyoshi et al. (2010) also found that cloud bands of the weak wind type tend to appear in the night time and disappear in the morning. They attributed the formation of weak-wind type bands to the development of land breeze from Hokkaido Island to the Sea of Okhotsk. On the other hand, cloud bands of the strong wind type appear regardless of the local time. Strong-wind type bands form or last even after temperature difference between land and sea reduces (Fujiiyoshi et al., 2010). Accordingly, the mechanism behind the formation and maintenance of strong-wind type cloud bands is also important.
bands is still not clear.

This study focuses on the mechanisms of the formation and maintenance of a long-lasting strong-wind type cloud band. For this purpose, we simulated the cloud band observed on 26 and 27 December 2008 shown in Figure 2a and conducted several sensitivity experiments.

The cloud band investigated here was identified as the strong wind type by Kamisho (2010). It occurred when a synoptic scale low-pressure system was located over the southern part of the Sea of Okhotsk (Figure 2b) and induced strong surface winds (~15 m/s). Doppler radar observations showed that the cloud band first appeared along the north-eastern coastline of Hokkaido and then moved offshore to the Sea of Okhotsk and that it had a width of 10–20 km and a height of 3–4 km (Kamisho, 2010).

MODEL AND DATA SETUP

The numerical simulations were performed using the version 3.3.1 of the Weather Research and Forecasting model (WRF) (Skamarock et al., 2008). The WRF model is a community model widely used for both research and operational forecasting. The dynamic core of the WRF model is fully compressible, non-hydrostatic Euler equations with a terrain-following vertical coordinate. Model consisted of three one-way nested domains (Figure 1), providing the finest domain with the area of the cloud band of our interest. The horizontal grid resolutions are varied with a ratio of three from 13.5, 4.5 to 1.5 km for domain 1 to 3, respectively. The vertical grid consists of 35 η coordinate levels in each domain with 7 levels located below 0.9 η (about 890 hPa over the sea) with the model top at 50 hPa. The model was run from 00 UTC 25 December 2008 to 00 UTC 28 December 2008. The initial and boundary conditions, including the initial snow cover, were derived from National Center for Environmental Prediction (NCEP) Final Analysis data, which has a horizontal resolution of 1.0° × 1.0° and a time interval of 6 hours. SST was based on real-time, global SST analysis (RTG-SST) with a resolution of 0.5° × 0.5° developed at the NCEP. The major physical schemes used in the simulations include the bulk microphysics scheme by Thompson et al. (2008), the Mellor-Yamada-Janjić planetary boundary layer scheme (Janjić, 2002), the Noah land surface model (LSM) for the land surface processes, the Rapid Radiative Transfer Model (RRTM) scheme for long-wave radiation, and Goddard shortwave scheme for short-wave radiation. The Kain-Fritsch cumulus parameterization was used for the 13.5 km domain.

RESULTS

Formation and maintenance of snow band

The simulation reproduced a cold air outbreak from the Eurasian Continent caused by a synoptic scale low pressure system, which moved eastward in the southern part of the Sea of Okhotsk. Figure 3 shows vertically integrated snow mixing ratio and air temperature at 940 hPa. Simulated mixing ratios of cloud ice and graupel produced by the Thompson et al. (2008) scheme are much smaller than the snow mixing ratio and are not shown for brevity. It should be mentioned here that test simulations indicated that simulated amount of each hydrometeor showed considerable variability depending on the choice of microphysics schemes. However, the choice of the ice-phase microphysics scheme does not affect the main conclusion of this study. As the direction of ambient low-level winds turned from north to northwest, a snow cloud band formed along the Okhotsk Sea coast of Hokkaido (Figure 3a) and moved offshore (Figures 3b–d). The simulated snow band (Figure 3b) is similar to the satellite image (Figure 1a) and the one observed by Doppler radars (Kamisho, 2010) at the corresponding time in terms of the shape (length and width) and the location.

As the air temperature decreased over the land and the temperature difference between land and sea increased across the northeastern coast of Hokkaido, a convergence line and a snow band formed along the coast (Figure 3a).
In fact, the difference in surface air temperature exceeded 6 K across the northern coastline of Hokkaido at the time of 1130 UTC 26 December 2008 (not shown). The data from the Automated Meteorological Data Acquisition System (AMeDAS) of Japan Meteorological Agency (JMA) have also shown a similar drop in the temperature over the land along the coast (Kamisho, 2010). Roeloffzen et al. (1986) numerically showed that difference in surface roughness between land and sea can produce a frictionally-induced convergence along a coastline when the geostrophic wind blows along the coast with a land on the right-hand side in the Northern Hemisphere. In the present case, the near-surface geostrophic wind is north-northwesterly as suggested by Figure 2b, thus the wind blows along the coast with the land on the right-hand side. It is difficult to assess the relative importance of the land-ocean temperature contrast that lead to the formation of a land breeze and surface roughness difference in forming the snow band, because a change in the roughness parameter in the model entails a change in the surface heat flux and therefore the near-surface air temperature contrast between the land and ocean. We suppose, however, that the effect of surface roughness difference will be also important in the initial formation of the convergence line, because the direction of the geostrophic wind, along with the large wind speed, is favorable for the formation of frictionally-induced convergence line. The effects of topography over Hokkaido were minor, as discussed later in the next subsection.

After the formation, the snow band moved over to the warm Sea of Okhotsk and became stronger both in terms of width and integrated snow mixing ratio (Figure 3b). The snow band continued to grow owing to the convergent wind field even though the surface air temperature over the land increased (Figures 3c, d).

Meanwhile cold winds from Sakhalin Island created a colder region in the downstream (Figure 3). This cold air advection, together with the cold air over near Hokkaido Island, formed a strip of relatively warm air over the Sea of Okhotsk. The snow band and convergence zone were located on this strip.

Figure 4a shows a vertical cross section of the snow band along the line drawn in Figure 3c at the time of the figure when the snow band was most developed. The snow band was associated with the lower level convergence and upper level divergence, and the top of snow band reached as high as 650 hPa. The convergent wind field was constituted by a relatively strong wind from the cold coast on the left in the figure and a relatively weak wind from the cold region downstream of Sakhalin Island on the right. These relatively cold air masses extended to ~850 hPa on both sides of the convergence (Figure 4b), and the near-surface air temperature increased toward the convergence line where the snow band was situated. The heights of cloud top (3–4 km) and the low-level winds from Hokkaido (1–2 km) are comparable to those measured by Doppler radars (Kamisho, 2010).

The above results suggest that land breeze from Hokkaido Island and the cold air advection from Sakhalin Island contribute to the development and maintenance of the convergence line and snow band.
Sensitivity experiments

(i) Experimental settings

In order to examine the importance of Hokkaido Island and Sakhalin Island for the formation and maintenance of the snow band, five sensitivity experiments were conducted to be compared with the control experiment (CTRL) described in the previous subsection. The effects of Sakhalin and Hokkaido Islands were investigated by removing lands, i.e., land grids in the model domains were replaced by sea grids using spatially interpolated SST (provided by RTG-SST). Sakhalin Island, Hokkaido Island, and both Islands were replaced by sea grid in experiments named NSAK, NHOK, and NSAKNHOKSAK, respectively. To distinguish the dynamical effects of topography from the effects of land-sea contrast, two more experiments were conducted: NTOPSAK with flattened Sakhalin Island and NTOPHOK with flattened Hokkaido Island.

Figure 5a shows a Hovmöller diagram representing the snow band development in CTRL case along the same cross section as shown in Figure 4. It illustrates that the snow band formed along the coastline, moved offshore to the Sea of Okhotsk as the time progressed, and lasted for nearly a day and a half. The snow band intensified as it moved offshore. The intensity of the snow band became maximum at about 00 UTC 27. The snow band stayed around there for ~2 hours. It then started moving offshore again and weakened.

(ii) Effects of Sakhalin

In order to understand effects of Sakhalin Island, the results of NSAK case are firstly described and then the effect of topography is discussed using NTOPSAK case.

In NSAK case (Figure 5b) a snow band was generated along the coast line of Hokkaido Island as in CTRL case, but disappeared in ~9 hours around 1800 UTC 26. This demonstrates the necessity of Sakhalin Island in the maintenance of the snow band. Instead of the disappeared band, another snow band appeared far offshore of the coast at about 2000 UTC 26 (Figure 5b, ~250 km). Figure 6 shows vertically integrated snow mixing ratio with air temperature at 940 hPa and wind vectors at 960 hPa at 2330 UTC 26 December 2008 (the same time as Figure 3c) for NSAK, NTOPSAK NHOK and NTOPHOK cases. Without Sakhalin Island (NSAK case; Figure 6a), the strip of warm air and the convergence shifted northeast compared to CTRL, where large mixing ratio of snow was simulated. This indicates that the effects of Sakhalin Island are substantial in determining the location of the snow band.

A vertical cross section (Figure 7) facilitates the comparison with CTRL case (Figure 4). In NSAK case, land breeze below 850 hPa penetrated farther offshore from Hokkaido (Figure 7b) compared to Figure 4b, which is also seen in the horizontal map (Figure 6a). As the upper level wind was almost the same as in CTRL case, this change of lower-level wind was caused by the absence of cold advection from Sakhalin, which blocked the northeastward propagation of the snow band over the Sea of Okhotsk and enhanced the snow band in CTRL case (Figure 4, 230–300 km).

The topography of Sakhalin Island also affected the strength of snow band. In NTOPSAK case (Figure 5c), the...
snow band was located at the same position as that of CTRL case. In fact, the horizontal distributions of snow band and temperature (Figure 6b) were similar to those in CTRL case. However, the snow band was weaker compared to that in CTRL and was initiated downstream of the Soya Strait. The comparison of the wind field indicates that the topography over Sakhalin Island turned the wind to enhance the convergence at the Soya Strait and thus the snow band along the Hokkaido coast. Therefore we can say that the thermal contrast due to Sakhalin Island maintains the snow band, while topography of Sakhalin Island enhances its strength.

(iii) Effects of Hokkaido

In this subsection, the effects of Hokkaido Island is discussed by comparing CTRL, NHOK, NTOPHOK and NHOKSAK cases. In NTOPHOK case (Figures 5d and 6d), features of the generated snow band (location of generation and its motion) were almost similar to CTRL case, although the snow band was slightly stronger. Thus, topography of Hokkaido Island enhances its strength.

In NHOK case (Figure 5e), the appearance of the snow band was delayed, confirming the importance of land breeze from Hokkaido Island, which was thought to be the dominant cause of the cloud bands of the weak wind type, or land-sea difference in surface roughness was important in the initial formation of the cloud band, whereas topography over Hokkaido had a minor influence. The cold advection from Sakhalin Island would be significant as long as the northwesterly wind is sufficiently strong, whereas it would be insignificant with weak winds since the cold air from Sakhalin would be warmed by air-sea heat exchange before reaching the offshore of Hokkaido. Because the cold advection created horizontal temperature gradient offshore of the Hokkaido coast and blocked the propagation of the snow band further offshore. On the other hand, the land breeze from Hokkaido Island, which was thought to be the dominant cause of the cloud bands of the weak wind type, or land-sea difference in surface roughness was important in the initial formation of the cloud band, whereas topography over Hokkaido had a minor influence.

In summary, the results of sensitivity experiments indicate that 1) the land-sea contrast along the Hokkaido coast largely contributed to the initial formation, 2) the cold advection from Sakhalin Island was important in the maintenance of the snow band, although cold land surface over Hokkaido Island was also important for the enhancement of the snow band, and 3) topography over Sakhalin strengthened the snow band by blocking the low level winds to form the convergence at the Soya Strait.

CONCLUSIONS

Numerical simulations of a thick snow band that appeared along the Okhotsk Sea coast of Hokkaido Island, northern part of Japan, were made to investigate its formation and maintenance mechanisms. The snow band formed on 26 December 2008 along the coast of Hokkaido Island, moved offshore toward the Sea of Okhotsk where it intensified, and was sustained for one and a half days. Sensitivity experiments showed the importance of cold air advection from Sakhalin Island in the maintenance of the snow band and the importance of topography over Sakhalin, which intensified the convergence at the Soya Strait and thus the snow band. The cold advection created horizontal temperature gradient offshore of the Hokkaido coast and blocked the propagation of the snow band further offshore. On the other hand, the land breeze from Hokkaido Island, which was thought to be the dominant cause of the cloud bands of the weak wind type, or land-sea difference in surface roughness was important in the initial formation of the cloud band, whereas topography over Hokkaido had a minor influence. The cold advection from Sakhalin Island would be significant as long as the northwesterly wind is sufficiently strong, whereas it would be insignificant with weak winds since the cold air from Sakhalin would be warmed by air-sea heat exchange before reaching the offshore of Hokkaido. Because the strong northwesterly is often sustained more than a day during cold air outbreaks from Siberia, this is a possible reason for the difference in durations between the weak and strong wind types. In addition to the above effects of islands, Fujiyoshi et al. (2010) suggested the importance of sea ice extent, which would work against cloud band formation. The effect of sea ice extent, as well as the roles of Hokkaido and Sakhalin Islands, should be investigated by simulating various cases to further improve our understanding of the thick snow bands.

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