Factors and Mechanisms Affecting the Air Temperature Distribution on a Clear Winter Night in a Snow-Covered Mesoscale Plain

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Abstract

There is an increasing need for accurate winter agrometeorological forecasts, which is facilitated by a better understanding of the evolution process of nighttime air-temperature distribution. However, studies on how air-temperature distributions evolve in mesoscale plains have been limited. To clarify how the low temperatures in winter nights form, we analyzed the effects of topography and boundary-layer wind on the temperature distribution of the Tokachi region for a winter night using numerical simulations by the Japan Meteorological Agency Nonhydrostatic Model (JMA-NHM) with horizontal grid spacing of 2 and 5 km. We also analyzed vertical profiles of boundary-layer atmospheric conditions.

The results show that although boundary-layer wind is expected to affect the temperature distribution over the entire Tokachi region, the effects were generally confined to the northwestern part. Widespread effects over the Tokachi region were found only under strong wind conditions. We found that the mountain pass in the northwestern part of the Tokachi region is an important wind path, and the downslope winds as well as the sensible

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heat transfer by turbulent mixing in the boundary layer also was important in the evolution of the air-temperature distribution. On the night we considered, a moderate boundary-layer wind was maintained throughout the night, but the surface wind speed decreased from the northern and southern parts of the Tokachi region; this can be attributed to the development of an inversion layer. A drainage flow was observed to originate from the southern part of the Tokachi Plain, reaching the central part of the Tokachi region in the night. We find that radiative cooling and sensible heat transfer by turbulent mixing in the surface layer do not adequately explain the temporal change in observed surface air temperatures. The development of an inversion layer and katabatic drainage flow drastically change the temperature distribution, despite moderately strong wind conditions in the boundary layer.

**Keywords**  inversion layer; katabatic drainage flow; radiative cooling; topography; turbulent mixing

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1. **Introduction**

Low temperatures negatively impact structures and agricultural products, including orchards. On the other hand, agricultural techniques have been developed in cold and snowy regions to use low temperatures in applications such as soil frost-control weeding (Hirot et al. 2011, 2013; Shimoda et al. 2015; Yanai et al. 2017; Yazaki et al. 2013b; Shimoda and Hirota 2018) or buildings and storage-area cooling (Kimura et al. 2010). These applications increase the need for accurate winter agrometeorological forecasts, especially for air temperature. Temperature forecasts are also important because the Japan Meteorological Agency issues low-temperature advisories to prevent structure damage (e.g., water-pipe freezing) when extremely low temperatures are predicted. Despite their necessity, temperature forecasts, especially morning (daily minimum) air-temperature predictions, are difficult, because complex processes caused by terrain and local wind lead to large regional temperature variations (Yazaki et al. 2017).

Clarifying the processes by which temperature distributions form will facilitate the development of more precise temperature forecasts and temperature information. In snow-covered regions in the winter, the nocturnal air-temperature distribution is more strongly influenced by topographic and boundary-layer conditions than by microsite conditions (e.g., surface moisture, canopy, and exposure), because the ground surface is covered with a thick snowpack that thermally insulates the ground surface from warmer soils (Kondo 1982). In snow-covered regions, the daily minimum air temperature within a mesoscale plain several tens of kilometers in scale is strongly correlated with the daily mean air temperature (Yazaki et al. 2017); local variations in daily minimum air temperature determine the regional temperature-related climate. Understanding the mechanisms of nocturnal cooling and the factors affecting it is important for accurately forecasting winter minimum temperatures.

Many studies of winter air temperature have been performed in basins or valleys (Hogan and Ferrick 1997; Kondo et al. 1989; Magono et al. 1982; Sasaki et al. 2012; Whiteman et al. 2001). These studies showed how strong inversion layers and cold air pooling formed in the lower basin layers on clear, calm nights. Few studies have assessed formation mechanisms for winter air-temperature distributions in a plain several tens of kilometers in scale.

A recent study conducted in a plain surrounded by mountains on three sides (Yazaki et al. 2017) revealed that the boundary-layer wind over the upwind mountain pass is important for the development of the nocturnal temperature distribution. That study showed how radiative cooling and sensible heat transfer from turbulent mixing in the boundary layer affect the temperature distribution. However, the effects of the topography and boundary-layer wind were not fully revealed. The study also did not fully discuss how the details of heat and air parcel movements relate to the temperature distribution in the low-temperature zones.

In this study, we aim to clarify the effects of topography and boundary-layer wind conditions on the temperature distribution and to analyze the development of high- and low-temperature zones in a mesoscale plain. To do this, we analyzed an episode during a night with a typical temperature distribution. We first conducted a sensitivity experiment, wherein the
altitude of the mountain pass and the boundary-layer wind speed and direction were changed. Then, to clarify how the temperature distribution developed, we assessed the spatial distributions of atmospheric conditions, including vertical wind speed, potential temperature, and vapor-mixing ratio.

2. Materials and methods

2.1 Study region

The study region, Tokachi, is located in the eastern part of Hokkaido Island in northern Japan (Figs. 1a, b). The region is surrounded by mountains on three sides (the Hidaka Mountains in the west, the Ishikari Mountains in the north, and the Shiranuka Hills in the east) and faces the Pacific Ocean in the south. In the southern part of the Tokachi Plain, there are gentle undulations with hills and valleys. The Karikachi Pass, a saddleback between the Hidaka Mountains and the Ishikari Mountains, is located in the northwest part of Tokachi and has an elevation of 644 m. The Tokachi River flows from the Ishikari Mountains and runs through the center of the Tokachi Plain before flowing into the Pacific Ocean. The region’s largest city, Obihiro, is located in the center of the Tokachi Plain. More detailed climatological characteristics of the region are described in Yazaki et al. (2013a).

2.2 Observational data

We used air-temperature data collected at a height of 1.5 m from 19 automated meteorological stations (Fig. 1a) monitored by the Japan Meteorological Agency (2016). To assess the dynamics of cold air in the Tokachi Plain, we showed the changes in air temperature, vapor-mixing ratio, and wind speed and direction during clear nights with wind-speed decreases. We also used wind speed and direction data collected at a height of approximately 10 m at 19 automated meteorological stations, including Sarabetsu, Obihiro-Izumi, and Obihiro. To evaluate the surface vapor-mixing ratio, we used relative humidity data from a height of 1.5 m in Obihiro. To evaluate the mixing ratio near Sarabetsu, we used air-temperature and relative humidity data collected at 1.9 m in a crop field (shown as “Sarabetsu2” in Fig. 1a) approximately 6 km east-southeast of Sarabetsu (Sb2 in Yazaki et al. 2017).

2.3 Model descriptions

Simulation experiments were performed using the Japan Meteorological Agency Nonhydrostatic Model (JMA-NHM) (Saito et al. 2006, 2007) to quantitatively evaluate the effects of topography and wind conditions on the temperature distribution. The JMA-NHM was developed by the Numerical Prediction Division of the Japan Meteorological Agency in partnership with...
with the Meteorological Research Institute of Japan. It is a high-resolution, nonhydrostatic model for the analysis of various mesoscale phenomena, including heavy rainfall (Saito et al. 2006).

The model top extends to a height of 22 km, with the lowest level of the model at a height of 20 m above the surface. Surface topography data were adopted from 30″ resolution data (GTOPO30) from the U.S. Geological Survey (USGS). The domain of the simulation, along with the surface topography, is presented in Figs. 1b and 1c. In the previous study using JMA-NHM for the same Tokachi region, observed air temperatures were well reproduced by the simulated air temperatures, with an accuracy within 5°C in most cases (Yazaki et al. 2017). The wind speed and direction were also generally well reproduced by the same simulation (Yazaki et al. 2017).

The NHM simulations were conducted as shown in Fig. 2 for the night of January 15–16, 2012; this represents a case with moderate boundary-layer wind conditions, as shown in previous research that analyzed observational data (Yazaki et al. 2017). That night was clear with a moderate northwesterly wind (10–15 m s$^{-1}$ at 925 hPa) that continued to blow in the central part of the Tokachi Plain (Fig. 3). The temperature distribution was typical for the region (Miwa 1963), with large intersite variations (Yazaki et al. 2017). We first ran a coarser NHM5 simulation (NHM with a horizontal grid spacing of 5 km) to provide boundary conditions for a finer-resolution NHM2 simulation (horizontal grid spacing of 2 km).

The initial time for the NHM5 calculations was 15:00 local time on January 15, and the calculations were continued until 06:00 on January 16. Japan Meteorological Agency mesoscale analysis data were used as the initial and boundary values for the calculations. The NHM5 results were nested down to the finer resolution grid of the NHM2 simulation.

Fig. 2. Schematic representation of the NHM2 simulation.

Fig. 3. Topography map and distribution of calculated boundary-layer wind speeds at an altitude of 788 m (925 hPa) from the evening of January 15, 2012 through dawn on January 16, 2012.
The NHM2 calculations were then started at 18:00 on January 15 and continued until 06:00 January 16. For both simulations, we applied parameterized moist convection processes. Other properties of the simulation (listed in Table 1) were set as described in previous studies (Saito et al. 2006, 2007; Yazaki et al. 2017).

2.4 Sensitivity analysis: the effect of topography and wind on the temperature distribution

To quantitatively evaluate how the topography of the wind path (the Karikachi Pass) and the boundary-layer wind conditions affect the temperature distribution, we performed sensitivity experiments. First, to clarify how the Karikachi Pass affects the temperature distribution, we compared the output of simulations in which the elevation of the pass was raised by 300 m to the output of the control run. Next, to quantify the effect of the boundary-layer wind speed and direction on the temperature distribution, we compared the control run to simulations with boundary-layer wind speeds 200% and 50% of the control wind speed and to simulations with different wind directions (270° and 330°). The frequency of occurrence of each wind direction was 36% (36 cases) at 259–281° (centered at 270°), 45% (45 cases) at 281–311° (centered at 293°), and 18% (18 cases) at 311–349° (centered at 330°) for 99 clear nights during three winters from 2010 to 2012. In these sensitivity tests, we changed the wind speed or wind direction in the initial and hourly boundary conditions below the 788 m (925 hPa) layer.

2.5 Characteristics of an air parcel in the boundary layer

When water condensation or evaporation occurs, the vapor-mixing ratio of an air parcel changes without any movement of that parcel. On the night we analyzed, the relative humidity of central Tokachi (Obihiro) stayed unsaturated and conditions remained clear, indicating that no vapor condensation occurred. Moreover, the air temperature was below 0°C, so evaporation would be very limited. Thus, air parcels are unlikely to experience stationary changes in the vapor-mixing ratio, making the mixing ratio an appropriate tracer of an air parcel’s origin.

The Tokachi region is in the orographic shadow of the Hidaka and Ishikari Mountains (Hirota et al. 2006), and the air parcel from the western part of Hokkaido Island over the mountains contains higher concentrations of water vapor than that originating over the Tokachi Plain. Therefore, we regarded regions with high vapor mixing ratios to consist of air parcels that originated from over the mountains. We used the mixing ratio to distinguish whether an air parcel was influenced by the downslope flow from the Karikachi Pass or whether it originated from the northern or southern parts of the Tokachi Plain without being influenced by the wind from the Karikachi Pass.

To examine the characteristics of an air parcel in the boundary layer of the Tokachi region, we calculated the horizontal and vertical distributions of wind speed and potential temperature using the JMA-NHM. To determine how the downslope wind affects the temperature distribution, the mixing ratio of an air parcel was used as a tracer. The formation mechanisms of the temperature distributions in the mesoscale plain were then assessed using the horizontal and vertical distributions of mixing ratio.

3. Results

3.1 Effects of topography and boundary-layer wind on the temperature distribution

The simulations with different elevations for the Karikachi Pass revealed that the pass elevation locally affects the temperature and wind distributions (Fig.
4). When the pass (region A in Fig. 4) was raised by 300 m (Fig. 4a), the calculated temperature at the Karikachi Pass was lower (−15.2°C) than that of the control run (−13.6°C) by 1.6°C. The temperature downwind of the pass around Shintoku (region B in Fig. 4) in the northwestern part of the Tokachi Plain was lower (approximately −17°C; Fig. 4c) than the temperature in the control run (approximately −11°C; Fig. 4d). The northwesterly wind from the Karikachi Pass was weaker when the elevation of the pass was increased. However, the temperature and wind distributions elsewhere in the Tokachi region were similar to those of the control run.

Simulations with different wind speeds in the boundary layer revealed that the boundary-layer wind speed considerably affects the air temperature of the Tokachi region (Fig. 5). In the simulation where the boundary-layer wind speed was twice that of the control run (Fig. 5a), the high-temperature zone (defined as temperatures higher than −15°C) covered a larger portion of the Tokachi region than in the control run (Figs. 5a, b). The high-temperature zone spread eastward from Shintoku as a result of the reinforced wind blowing down (from 3.0 m s$^{-1}$ in the control run to 3.5
m s\(^{-1}\) in the doubled wind speed) from the Karikachi Pass (Figs. 1a, 5a). For comparison, in the simulation with a boundary-layer wind speed half that of the control run, the low-temperature zone covered a larger proportion of the Tokachi region (Figs. 5b, c); the wind from the Karikachi Pass weakened to 2.5 m s\(^{-1}\) (Figs. 5b, c).

Analysis of the simulations with different boundary-layer wind directions revealed that the wind direction also affects the temperature distribution (Fig. 6). In the simulations with a wind direction of 270° (wind coming from the west), the temperature around Shintoku (region B in Fig. 6a) was high (−10°C to −15°C), and the temperature in the northern to northeastern part of Tokachi was very low (colder than −20°C); this was also the case in the control run, which had a wind direction of about 300°. However, compared to the control run, the high-temperature zone reached farther eastward in the simulation with a wind direction of 270°.

This extension of the high-temperature zone corresponds to a wind blowing down from the Karikachi Pass. In the simulation with a wind direction of 330° (wind coming from the north-northwest), the wind blowing down was weaker, and the high-temperature zone was smaller. In this simulation, the low-temperature zone (colder than −20°C) formed to the west and south of Obihiro (region C in Fig. 6c), while the high-temperature zone formed in the northern and northeastern parts of the Tokachi region (Fig. 6c).

3.2 Distributions of surface air temperatures, wind conditions, potential temperatures, and vapor-mixing ratios

The temperature drop pattern differed between sites within the Tokachi region (Fig. 7). At 15:00 local time on January 15, the air temperatures at most of the observatories were between −4°C and −8°C (Fig. 7). A northwesterly wind, parallel to the boundary-layer wind (at 18:00, 11.3 m s\(^{-1}\) and 302° WNW to NW at 925 hPa over Obihiro, as obtained from the Japan Meteorological Agency mesoscale analysis), predominated over the Tokachi region (Fig. 7). At 18:00, the northwesterly wind began to calm in the northeastern and southern parts of the Tokachi Plain. At 21:00, the air temperature in northeastern and southern Tokachi dropped below −15°C, with the wind shifting into a slight mountain breeze. In contrast, the air temperature in the central part of the Tokachi region stayed above −10°C, and the wind conditions were similar to those at 15:00 (Figs. 7, 8a). The low-temperature zones spread from the north and south toward the central part of the Tokachi Plain, covering the central plain by 06:00 on January 16; at this time, the air temperature dropped below −15°C everywhere except for the two northwestern stations (which recorded temperatures...
around −9°C) where a westerly wind blowing down from the pass was still occurring.

Abrupt temporal changes in air temperature, vapor-mixing ratio, and wind speed at three sites, from the margin to the center of the Tokachi Plain (along B–B′ in Fig. 1) transect, can be observed along with the change in the wind direction (Fig. 8). At 15:00 on January 15, the temperature, wind speed, and wind direction are similar for all three sites (Fig. 8). After 17:00, the air temperature and mixing ratio gradually dropped at Sarabetsu (the southernmost site; Figs. 8a, b); this was accompanied by a decrease in wind speed (Fig. 8c) and a change in wind direction from the northwest to the south or west (Fig. 8d).

A similar gradual drop in temperature and wind speed was observed at Obihiro-Izumi around 21:00. Finally, abrupt changes in air temperature, mixing ratio, wind direction, and wind speed were observed at Obihiro around 04:30 on January 16. The observed changes started in the south and progressed toward the central Tokachi Plain overnight (Fig. 8).

The timing of the northwesterly wind attenuation differed among the nights considered. On December 27–28, 2011 (Figs. 9a–d), a moderate northwesterly wind blew before 18:00, but the wind attenuated after 18:00 at Sarabetsu and Obihiro-Izumi. The southwesterly wind (mountain breeze), however, continued to blow. The air temperatures and mixing ratios at these stations continued to decrease until 00:00 and remained low up until 04:00. At Obihiro, contrarily, the air temperature and mixing ratio decreased after the drastic changes in wind speed and direction (around 01:00). This indicates that the conditions at this station were similar to those of the January 15–16 event. On February 19–20, 2012, northwesterly winds had already attenuated at 15:00 (Figs. 9e–h), and the mixing ratio was stable throughout the night (18:00–06:00). The westerly breeze from the mountains (mountain breeze), which is considered to be a katabatic wind, was also observed.

The vertical cross sections of the vertical wind, potential temperature, and vapor-mixing-ratio profiles along line A–A′ in Fig. 1 expressed downwind characteristics from the Karikachi Pass (Figs. 10, 11a–c). The iso-potential temperature line fell above Shintoku, and the strong downslope wind (negative vertical wind speed) from the west-northwest was apparent from the Karikachi Pass, through Shintoku, and down to central Tokachi at 06:00 (Fig. 10). The wind near Shintoku was directly influenced by the downslope draft, with high potential temperatures and turbulent mixing blowing down from the Karikachi Pass.

The low potential temperature zone formed near the terrain surface in central Tokachi (Fig. 10), where
the surface was covered with an air parcel with a low mixing ratio at 06:00 (Figs. 11c, 12c); this shows the development of a strong air-temperature inversion layer in the central part of Tokachi. Although the boundary-layer wind was moderately strong (approximately 10–15 m s\(^{-1}\) at 925 hPa), the surface wind speed at the center of the Tokachi Plain was weak (Figs. 3, 13).

The low-temperature zone expanded drastically during the night, affecting the distribution of mixing ratios. At 18:00, the vertical mixing-ratio profile from the surface to an altitude of 1 km was calculated to be fairly uniform from the Karikachi Pass to the Pacific Ocean (Fig. 11a) and throughout the Tokachi Plain (Fig. 11d); this shows the air parcel over the Tokachi region, including the Karikachi Pass, was influenced by the remains of convective mixing by solar radiation and the downslope wind in the boundary layer from the mountains. The mixing ratio was uniform from near the Karikachi Pass to the Pacific Ocean (Fig. 7).
Fig. 8. Temporal changes in (a) air temperature (1.5-m height), (b) vapor-mixing ratio (1.5-m height), (c) wind speed (10-m height) and (d) wind direction (10-m height) at stations along the line B–B′ in Fig. 1a from 15:00 to 06:00 on January 15–16, 2012.

Fig. 9. Temporal changes in (a, e) air temperature (1.5-m height), (b, f) vapor mixing ratio (1.5-m height), (c, g) wind speed (10-m height) and (d, h) wind direction (10-m height) at stations along the line B–B′ in Fig. 1a from 15:00 to 06:00 on (a–d) December 27–28, 2011 and (e–h) February 19–20, 2012.
Fig. 10. Vertical cross section of the vertical wind-speed profile (color), the horizontal wind direction and speed (wind symbol), and potential temperature (isopleth) along the line A−A’ in Fig. 1a in the early morning (06:00) on January 16. Negative vertical wind speeds indicate downdraft.

Fig. 11. Vertical cross sections of the vertical vapor-mixing-ratio profile along the (a−c) A−A’ and (d−f) B−B’ lines in Fig. 1a at (a and d) 18:00, (b and e) 21:00, and (c and f) 06:00 on January 15–16, 2012.
11a), indicating that the effects of turbulent mixing by the strong wind in the planetary boundary layer over the wide range of the Tokachi region.

At 21:00, the high-mixing-ratio zone began to shrink as the low-mixing-ratio region near the surface expanded from the north and south (Figs. 11e, 12b); the mixing ratio near the terrain surface decreased. As a result, a vertical-mixing-ratio gradient formed (Fig. 11e), indicating a reduction in turbulent mixing. Thereafter, the high-mixing-ratio zone mostly disappeared (Fig. 12c), and, at 06:00 on January 16, a strong vertical gradient in the mixing ratio had formed in the surface-boundary layer with a thickness of ~100 m (Figs. 11c, f).

4. Discussion
4.1 Effects of wind conditions and topography on the temperature distribution

The sensitivity analysis for the mountain-pass elevation showed that the effect of topography on the temperature distribution was confined to the northwestern part of the Tokachi region (Fig. 4). In the winter, the northwesterly monsoons from Siberia predominate on Hokkaido Island and blow onto the Tokachi Plain over the Hidaka Mountains (Hayashi et al. 2005; Rikiishi and Yomogida 2006). However, the surface wind speed decreased in the center of the Tokachi region, and the air temperature dropped (Figs. 7, 8), even though the boundary-layer wind was still moderately strong (Figs. 3, 13). Although the Kari-kachi Pass is an important wind path (Fig. 3), other wind processes and the transfer of sensible heat by turbulent mixing are also important considerations in the temperature distribution development.
On the night we analyzed, a moderate northwesterly wind (10–15 m s\(^{-1}\)) blew over the central Tokachi Plain throughout the night (Fig. 3). Although the boundary-layer wind is expected to affect the temperature distribution throughout the Tokachi region, we instead see that its effects are mostly confined to the northwestern parts, at the foot of the mountains, except in cases of strong wind conditions (Figs. 5a, b, 6). At 21:00, when the surface wind was strong, the high-temperature zone in the control run extended from the Karikachi Pass to the east-southeastern portion of the central Tokachi Plain (Fig. 14a).

In contrast, the simulation with a north-northwesterly wind direction (330°) showed a high-temperature zone extending from the Karikachi Pass toward the east-southeastern part of the Tokachi Plain at 21:00 (Fig. 14b). However, the high-temperature zone disappeared in the morning (Fig. 6c), despite moderate wind conditions in the boundary layer. These results show that the boundary-layer wind direction can influence the temperature distribution, but other processes are also involved in the distribution development.

Compared to the northwestern and central parts of the Tokachi region, the northern and northeastern parts reacted differently to changes in the boundary-layer wind direction, as seen in the simulated air temperatures in Fig. 6. The Tokachi Plain is surrounded by mountains on three sides (Fig. 1a). The differences in the wind direction effects between the northerly and westerly winds are probably due to the elevations of the western and northern mountains. The Hidaka Mountains (western mountains) are taller than 1,000 m, except for the Karikachi Pass, which is 644 m asl. On the other hand, the elevation to the east of the Ishikari Mountains is lower than 500 m. When northerly winds predominate, the air current enters from the east of the Ishikari Mountains, enhancing turbulent mixing to form a high-temperature zone (Fig. 6c). In contrast, when westerly winds predominate, the air current preferentially enters from the Karikachi Pass, weakening the wind speed and forming a low-temperature zone in northern to northeastern Tokachi (Fig. 6a).

This study analyzed the relationship between land relief and boundary-layer wind conditions using sensitivity analyses for wind speed under a typical wind direction in winter. However, this study did not clarify the effect of wind speed on nights with different wind directions. The analyses for nights with different wind directions would improve our understanding of the more general effects of wind conditions on nocturnal air-temperature distributions.

4.2 Processes driving the temperature-distribution development

Potential temperature isolines can be considered as mean streamlines under adiabatic conditions (Lilly...
and Zipser 1972). The downslope wind follows isopotential temperature lines, which fall downwind of the mountains (Lilly and Zipser 1972; Saito 1994) over the region near Shintoku (Fig. 10). An air parcel over the Karikachi Pass will become warmer due to dry adiabatic heating as it flows down toward Shintoku (Fig. 10); therefore, the airflow has the characteristics of a foehn. It is reported that there are two types of foehn winds: a thermodynamic (wet) foehn wind caused by diabatic heating by water vapor condensation and a dynamic (dry) foehn wind caused by adiabatic heating (Asai 1996; Takane and Kusaka 2011).

The wind is probably a dynamic (dry) type because of the lack of condensation of water vapor. Thus, the air temperature at Shintoku remains high, because it is influenced by the high potential temperature downslope flow (Fig. 10). The sensible heat transfer from the upper atmosphere compensates for the energy loss due to radiative cooling near the ground surface during the night in northwestern parts of the Tokachi region, from the Karikachi Pass to the area around Shintoku (Fig. 15: Yazaki et al. 2017).

The temperature distribution is also influenced by the intensity of turbulent mixing in the boundary layer. Northern and southern parts of the Tokachi region, including Sarabetsu and Obihiro-Izumi, were already covered with cold air after sunset (18:00 in Fig. 8). Strong winds are unlikely to reach these areas, because they are isolated from the central Tokachi wind path from the Karikachi Pass (Figs. 3, 5b); therefore, radiative cooling prevails.

Laughlin and Kalma (1987) predicted minimum temperatures in mesoscale regions in Australia using a multiple-regression model. They showed that sites with concave terrain were consistently colder than predicted by the model, and they attributed this to an increased degree of sheltering from turbulent mixing. Within basins, the lowest temperatures are often observed at the center, where cold air accumulates and is sheltered from turbulent mixing (Aoki et al. 1992; Lu and Zhong 2014; Magono et al. 1982). The Tokachi region is unlike these basins, because the cooling begins in the northern and southern parts of the plain, where the minimum temperature is often recorded.

Fig. 15. Topography map and simulated surface sensible heat flux from 21:00 to 06:00 on January 15–16, 2012.
Although the boundary-layer wind continued to blow moderately (10–15 m s⁻¹ at 925 hPa; Fig. 3), the surface wind speed from the northern or southern to central parts of the Tokachi region was weak (Figs. 7, 8). This difference in the wind speeds can be formed by the development of an inversion layer, thereby limiting the amount of turbulent mixing in the boundary layer. In the early evening (18:00 on January 15), inversion layers did develop in the northern and southern parts of the plain (Figs. 11d–f), and such strongly stable conditions would restrict turbulent mixing (e.g., Oke 2002) even with a moderate boundary-layer wind conditions. If turbulent mixing in the boundary layer is stopped, the sensible heat flux (i.e., the sensible heat transfer from the upper atmosphere to the ground that compensates for the radiative energy loss) is reduced to zero, allowing radiative cooling to predominate. The slightly negative sensible heat flux in the southern part of the Tokachi Plain (Fig. 15) is attributable to some heat supplies from upper-layer flows (Soler et al. 2002) or from katabatic drainage flow (mountain breeze) from the western mountains.

In the central part of the Tokachi Plain, a strong wind zone with a high vapor-mixing ratio was maintained at an altitude of 200–500 m (Figs. 11, 13). At Sarabetsu and Obihiro-Izumi in the southern part of the Tokachi Plain (Fig. 1a), a weak southeasterly to westerly wind continued to blow during the night (Figs. 8c, d). The topographic gradient between southern Sarabetsu and central Obihiro (which have elevations of 190 m and 38 m, respectively, and are 30 km apart) is approximately 1/200, and Thompson (1986) shows that this is sufficient to generate a katabatic drainage flow. Thus, the cold, low-vapor-mixing ratio air that accumulated in the north and south (Figs. 11d–f) could move downslope to the lower part of the Tokachi Plain in a downslope katabatic drainage flow classified as a mountain breeze (Figs. 7, 8). Therefore, the abrupt drop in air temperature at Obihiro around 04:00 is likely caused by the cold-air advection from southern Tokachi.

Fujibe (2018) commented that meteorological stations with large winter nighttime temperature variations tend to be located on a col or a slope, where the surface-inversion layer is likely to be easily disturbed by any kind of atmospheric motion. Moreover, variable wind direction is a characteristic of downslope drainage flow (Mahrt et al. 2010). This is consistent with the observed wind direction variability at the Sarabetsu and Obihiro-Izumi sites (Figs. 8c, d).

This study revealed the processes of inversion-layer development and the expansion of a low-temperature zone by the katabatic drainage from the southern and northern parts of the Tokachi Plain using observations and analyses of the vapor-mixing-ratio profile. An earlier study conducted in the same plain showed that the nocturnal air-temperature distribution was determined by radiative cooling and sensible heat transfer from turbulent mixing (Yazaki et al. 2017). This is generally true, but the detailed development of the temperature distribution is not quite this simple. In addition to turbulent mixing in the boundary layer from the Kari-kachi Pass, the development of an inversion layer (Fig. 11) and the katabatic drainage flow (Figs. 8, 9) from the northern and southern Tokachi Plain are also important for temperature distribution dynamics. Many basins begin to cool in the central part in the shade of the boundary-layer wind (Laughlin and Kalma 1987; Aoki et al. 1992; Lu and Zhong 2014; Magono et al. 1982). Contrarily, the center of the Tokachi Plain is a wind path (Figs. 3, 13), and radiative cooling and inversion-layer development begins from the southern and northern edges of the plain to the central part of the plain.

The findings of this study are applicable to the identification of extremely cold sites; these are regions where hazardous conditions are possible, but they also have the highest availability of low-temperature resources. Extremely low temperatures are often observed in Rikubetsu, in the northeastern part of the Tokachi region; these temperature are attributable to basin topography (Sorai et al. 2016). In contrast, such extremely low temperatures were not observed by the stationary automated meteorological stations installed by the Japan Meteorological Agency in the southern part of the Tokachi Plain, because this region is not a basin (Fig. 1) but is instead characterized by a terrain with gentle slopes and undulations. However, Yazaki et al. (2017) observed extremely low temperatures in an arable field located in a shallow valley (Sarabetsu2 in this study). The daily minimum hourly air temperature (−27.2°C) was nearly as low as the Rikubetsu measurement (−28.2°C) on the same day as this study. Thus, this extreme temperature drop was influenced by finer-scale topography as well as larger-scale topography; both the local and regional boundary-layer winds affected the temperature distribution (Yazaki et al. 2017).

5. Conclusions

Earlier studies provide only a limited amount of information about the effects of topography and wind conditions on winter nocturnal air-temperature
distributions. To explore how nighttime-temperature distributions develop in a mesoscale plain in a snow-covered region, we used a numerical model to analyze the relationships among topography, boundary-layer conditions, and air-temperature distributions on the Tokachi Plain during a night with large interregional temperature variations. Our sensitivity analyses for topography and the speed and direction of the boundary-layer wind using this model revealed that the wind over the Karikachi Pass significantly affects temperatures in the northwestern part of the Tokachi region. However, the fact that the effect is limited to the region near the Karikachi Pass implies that mechanisms besides the downslope wind drive the temperature distribution in the Tokachi region.

Analyses of vertical wind speed and potential temperature in the boundary layer revealed that the air parcel from the Karikachi Pass downslope wind has a high potential temperature. Although a moderate boundary-layer wind continued to blow during the night, the surface wind speed decreased in the northern and southern portions of the Tokachi region. This can be attributed to the restriction of turbulent mixing by the development of an inversion layer. In addition to turbulent mixing in the boundary layer from the Karikachi Pass downslope wind, the development of the inversion layer and katabatic drainage flow also affects the dynamics of the temperature distribution.

Our results indicate that, in a plain surrounded by mountains on three sides, the development of an inversion layer and katabatic drainage flow contribute drastically to the temperature distribution, along with radiative cooling and turbulent mixing of the boundary layer by wind from the mountain pass. The inversion layer can form in the central part of the plain’s wind path, even when moderately strong winds continue to blow. These findings may facilitate more precise temperature prediction and provide more accurate temperature information.

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