Characteristics of the Potential Temperature Distribution Along Mountain Slopes Experiencing Cross-Mountain Air Currents in the Winter Season

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Abstract

In winter, northwesterly winds in the vicinity of Japan are predominant in the winter pressure distribution pattern that characterizes the climate of the environs of Japan, and on the Kanto Plain cross-mountain air currents frequently occur in winter because the winds pass over the Joshin'etsu mountainous region. A detailed analysis of the cross-mountain air currents is important to understanding the climate in the northwestern inland region of the Kanto Plain on the leeward side. In addition, little research has been conducted on the role of the gap flow in regard to the winter cross-mountain air currents. To address this shortage, advanced meteorological observation was carried out along the channel traversing the Joshin'etsu mountainous region, and that data was used to research the characteristics of the surface atmosphere along the mountain slopes when winter cross-mountain air currents blow. As a result, in the case in which cross-mountain air currents were not blowing, the potential temperature along the mountain slope tended to rise with altitude, in both the Sea of Japan side and Pacific Ocean side. However, in the case in which cross-mountain air currents were blowing, the potential temperature distribution was nearly uniform on the slope of the leeward, Pacific Ocean side, regardless of elevation. The case in which cross-mountain air currents were blowing had characteristics similar to foehn. This also suggests an impact by gap winds that pass through the Uonogawa-Tonegawa channel.

Introduction

The northwestern inland region of the Kanto Plain, which lies between Kumagaya and Maebashi, comprises a semi-basin-like land formation bordered by mountains on three sides: the Taishaku Mountains and the Ashio Mountains to the north, the Echigo Mountains to the northwest, and the Kanto Mountains to the west, southwest, and south. Its climate is massively influenced by these mountain regions. For example, this region experiences intense heat frequently as the weather becomes hotter during the warmer months of the year (May to September), and is one of the areas of Japan where high or extremely high temperatures occur quite frequently; it is considered that it is caused by the inland location, which lessens the impact of sea breezes, and the topographical factors, which include the influence of valley wind circulation and cross-mountain air currents induced by the surrounding mountains. When a record high temperature occurred in Kumagaya on 16 August 2007 (a daily maximum air temperature of 40.9°C), the development of northwesterly foehn winds across the Echigo Mountains was cited as one factor behind this (Shinohara et al., 2009; Watarai et al., 2009; Takane and Kusaka, 2001).

Because a typical sea-level pressure pattern frequently observed in winter around Japan comprises high pressure to the west and low pressure to the east, northwesterly monsoon winds tend to develop on the Kanto Plain on many days during winter. In these cases, it is considered that the air temperature and surface wind in the northwestern inland region of the Kanto Plain are affected by the cross-mountain air currents, which traverse the Echigo Mountains located on the windward side of the plain. When particularly powerful northwesterly winds blow in certain regions, these are referred to as *karakkaze* or *akagi-oroshi* (descending air currents from mountains). Miya and Kusaka (2009) undertook a climatological analysis of *karakkaze* based on the Automated Meteorological Data Acquisition System (AMeDAS) data for 15 winters in order to observe the characteristics of these air currents. The data when the *karakkaze* is blowing showed a clear diurnal variation of wind velocity (strong during the daytime and weak during the nighttime), a drop in relative humidity, an increase in solar radiation, and relatively weakening of the atmospheric stability level. It was suggested that the *karakkaze* follows the characteristics of foehn winds, and surface winds grow stronger in the daytime by heat convective mixing.

As has been explained in detail by Saito (1994), the two-dimensional behavior of the atmosphere when air currents traverse mountains will vary depending on the wind velocity to the windward side, the height of the mountain and the static stability. However, actual mountain regions are not perfectly two-dimensional, and cross-mountain air currents exhibit three-dimensional behavior due to topographical influences. When fully stable stratification develops in the atmosphere, air currents that circumvent the mountains in a horizontal direction frequently develop, and air currents that follow the paths of the saddle-shaped recesses and channels in mountain ranges grow stronger. Saito (1992) carried out numerical experiments on the cross-mountain air currents that traverse mountain ranges possessing saddle-shaped recesses, which revealed a tendency for particularly powerful descending air currents to develop to the leeward side of such saddle-shaped recesses. The kinds of effects brought about by air currents that emerge from channels in this manner have also been noted in foehn winds in the Alps. In a review by Drobinski et al. (2007), who compiled the results of a series of intensive observations and model research studies looking at foehn winds in the Alps, shows instances of gap winds forming in the channels of certain alpine valleys (shallow foehn) as the initial stage of a foehn wind, before transitioning into cross-mountain air currents (deep foehn) that cross the ridgelines at the center of the mountains, and instances in which temperatures rise markedly due to compensatory air flows from the upper atmosphere, which develop due to the dispersal of shallow foehn wind at the exit point of valley. In the case of the northwestern inland region of the Kanto Plain, channels where the development of gap winds has been suggested are found in the mountain regions, such as the Uonogawa-Tonegawa channel which cuts across the Echigo Mountains, and the Chikumagawa-Usuigawa channel in the Kanto Mountains. However, little research focusing on the role of these channels in relation to cross-mountain air currents has been undertaken.

In order to investigate in detail the structure and formation mechanisms of cross-mountain air currents and gap winds, which affect the northwestern inland region of the Kanto Plain regardless of the season, it is important to advance research through a combination of finely-detailed spatio-temporal observations and numerical simulations of the nearby Joshin’etsu mountainous region. However, it has to be admitted that obtaining sufficiently detailed observation data for the Joshin’etsu mountainous region from the existing meteorological observation network is no easy task, and a limited range of meteorological elements are available to be used. Therefore, our research group has expanded the spatio-temporally dense network of surface meteorological observation along the channels that traverse the Joshin'etsu mountainous region in particular, and carried out a series of observations based on this network, under the Rissho University Joshin'etsu Mountainous Region Meteorological Observation Project. The objective of this paper is to clarify the characteristics of the surface atmosphere along the slopes of such channels during the winter season, both when cross-mountain air currents are blowing and when no such currents are blowing, based on our data.

1. Overview of the Observations and Data Used

1.1 Advanced meteorological observations from the Joshin'etsu mountainous region

As set out previously, our research group conducted advanced meteorological observations from the Joshin'etsu mountainous region. As these observations were intended to target the cross-mountain air currents that cut in a traverse line across the Joshin'etsu mountainous regions as well as gap winds, we developed the surface observation network by setting out two observation lines which followed major channels that were relatively large in scale and which more or less intersect at the main ridgelines of the mountain range. One observation line followed a course of traverse along a channel passing from Uonogawa on the Sea of Japan side through Tonegawa on the Pacific Ocean side, and straddling Mikunitoge (hereinafter referred to as the "Uonogawa-Tonegawa line"), while the other observation line followed a course of traverse along a channel that passes from Chikumagawa on the Sea of Japan side through Usuigawa on the Pacific Ocean side, and straddling Usuitoge (the "Chikumagawa-Usuigawa line"). A total of 24 observation sites were set up, comprising 16 points along the Uonogawa-Tonegawa line, seven points along the Chikumagawa-Usuigawa line and one point close to the summit of Mt. Akagi, which is located in the far northwest of the Kanto Plain. Three elements were noted in the observation: temperature, relative humidity and atmospheric pressure. We envisaged that conserved values such as potential temperature and equivalent potential temperature could be derived from the simultaneous observation of these meteorological elements, enabling conjectures to be formed about the behavior of the atmosphere close to the surface level. Shigeta et al. (2013) may be referred to for a more detailed overview of the observation.

1.2 Data used

Out of the 24 meteorological observation sites in the Joshin'etsu mountainous region, data were used from a total of 16 observation sites along the Uonogawa-Tonegawa Line (shown in open circles in Fig. 1). The data cover a four-month period over winter from December 2013 to March 2014, and include three meteorological elements (temperature, relative humidity and atmospheric pressure) sampled at 10-minute intervals.

This study conducted an analysis of two cases (26 and 28 February 2014) in which the daytime temperatures were elevated markedly above temperatures for normal years during times when the northwestern Kanto Plain experienced sunny weather. As there was no wind data among our observation items, we used data for surface wind direction and wind velocity that had been observed at the Maebashi Local Meteorological Observatory and at the AMeDAS observation sites (Numata, Minakami, Yuzawa, Koide and Nagaoka), near the Uonogawa-Tonegawa Line. We also referred to data on temperature, relative humidity and sunshine duration taken from the Maebashi Local Meteorological Observatory. The relative positions of our observation sites compared to the various Japan Meteorological Agency weather stations and AMeDAS sites are shown in Fig. 1. Finally, we also confirmed the stratification on the Sea of Japan side (Wajima) and the Pacific Ocean side (Tateno) on the two dates in question by using radiosonde observation values provided via the University of Wyoming website.

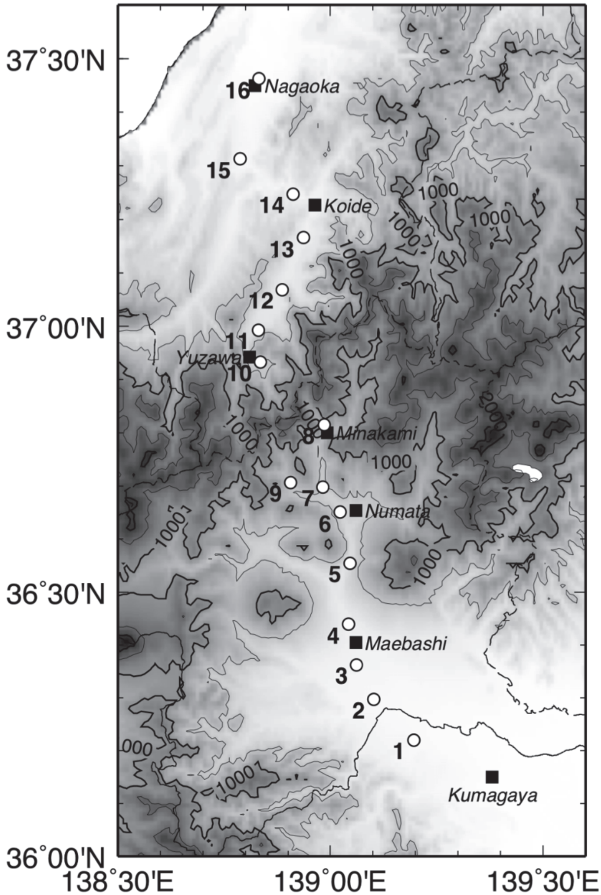


Fig. 1 The locations of the 16 observation sites (represented here by open circles) out of the advanced meteorological observation network in the Joshin'etsu mountainous region whose data was used in this study. The figures here show the number of each observation site. The isolines show the elevation (the isolines being taken at 500m intervals), and the dashed lines show the prefectural boundaries. The black squares represent the weather offices of the Japan Meteorological Agency and AMeDAS sites which are close to observation sites.

2. Results

2.1 Surface potential temperature distribution during the winter of 2013–2014

Fig. 2 shows the mean surface potential temperature distribution over a four-month period from December 2013 to March 2014, created based on the advanced meteorological observation data for the Joshin'etsu mountainous region. Comparing the data for the slope on the Pacific Ocean side (shown below the central bold line in Fig. 2) and that for the slope on the Sea of Japan side (shown above the same line), some major differences are apparent in the characteristics of the potential temperature distribution along these slopes. On the slope on the Pacific Ocean side, the potential temperature is approximately the same at elevations of 100m to 500m, the central area of the slope, particularly during the daytime. It is evident that on the Pacific Ocean side at elevations of less than 600m the tendency is that the lower the elevation of the slope, the higher the potential temperature tends to become, with potential temperatures in the plains area where the elevation is below 100m being somewhat higher than in the central areas of the slopes, while the potential temperatures in areas of the slopes above 500m in elevation are somewhat lower than in the central areas. Conversely, on the Sea of Japan side, in areas of the slope with altitudes of 100m or above the tendency is that the higher the elevation, the higher the potential temperatures tend to be.

Fig. 2 shows the mean values throughout the whole period, including sunny days and stormy days. With "sunny days" being defined as those with eight or more hours of sunlight and "cross-mountain air current days" defined as those days in which the prevailing wind pattern was west-northwest to north-northwest and in which the daily mean wind velocity was 3m/s or more, 51 days out of a total of 121 days across the period corresponded to such a definition (42% of the total), based on observation values from the Maebashi Local Meteorological Observatory. When we created a composite figure for the potential temperatures only for the cross-mountain air current days, the characteristics were almost the same as in Fig. 2 (figure omitted).

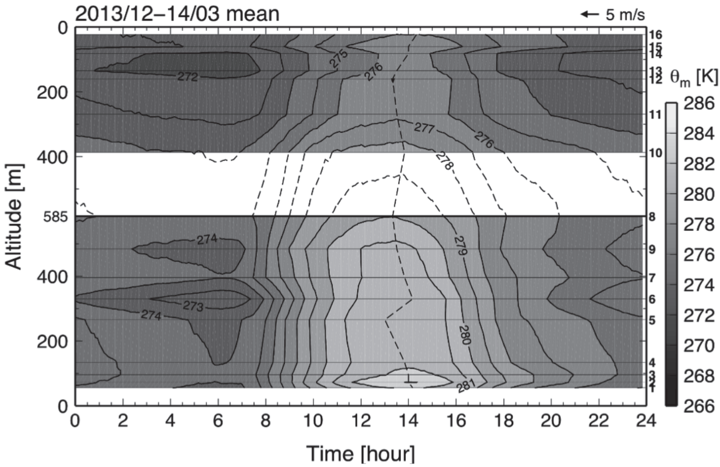


Fig. 2 Mean potential temperature distribution for four-month period from December 2013–March 2014 based on the advanced surface observation data along the Uonogawa-Tonegawa channel. The vertical axis shows the elevation in line with the course of traverse, with the area above the central bold line being the Sea of Japan side, and the area below this line being the Pacific Ocean side. The dashed line connects together the maximum values for potential temperature throughout the day.

2.2. Case of February 26, 2014

On February 26, 2014, there was fairly light wind, the prevailing wind direction was northwest, and the daily mean wind velocity was 2.2m/s at the Maebashi Local Meteorological Observatory. Fig. 3 (a) shows a surface weather chart for 09:00 on February 26. A migratory anticyclone covered much of the Japanese archipelago centering on the point to the immediate north of the Noto Peninsula, and conditions across this region (excluding Kyushu and the Nansei Islands) developed under the influence of the high atmospheric pressure. The environs of the Kanto region experienced high atmospheric pressure throughout the day, resulting in sunny weather. The graph indicated in gray in Fig. 4 shows the air temperature and relative humidity at Maebashi. The air temperature at Maebashi fell to almost 0°C at around 6:00 in the morning, but then rose at sunrise to reach a daily maximum temperature of 13.1°C (deviation from normal year: +2.8°C), which was recorded

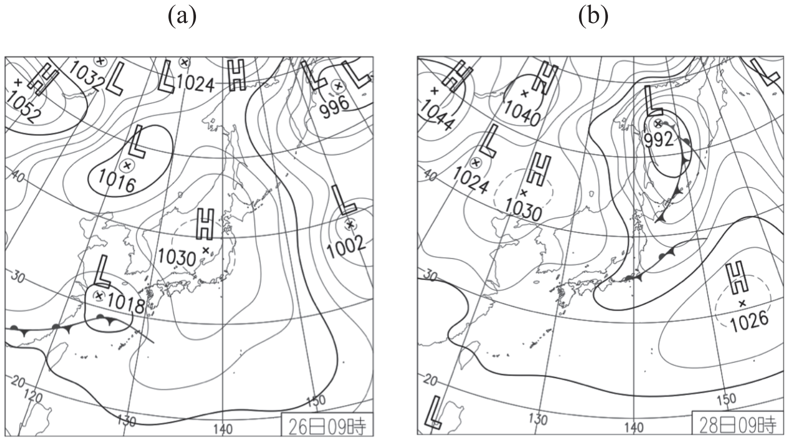


Fig. 3 Surface weather charts for (a) February 26, 2014 and (b) February 28, 2014 (taken from the Japan Meteorological Agency). Both taken at 09:00 (AM).

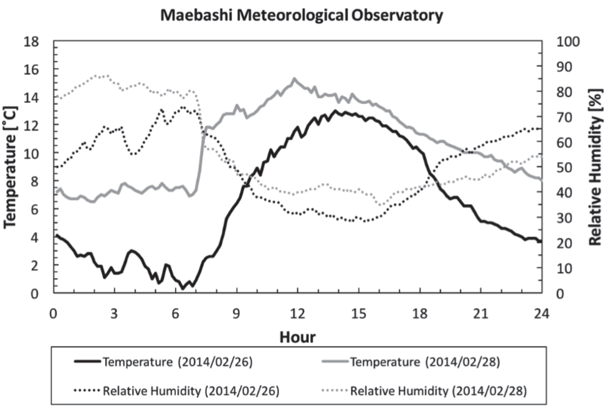


Fig. 4 Temporal change in the surface air temperature (represented by solid lines) and relative humidity (dotted lines) taken from the Maebashi Local Meteorological Observatory for February 26, 2014 (gray lines) and February 28, 2014 (black lines).

at 14:37. Following this, the air temperature fell gradually from evening through the night, following a pattern of diurnal variation that is typical for a sunny day. The relative humidity level was inversely correlated with the air temperature, with a daily minimum humidity level of 27% reached at 14:43.

Fig. 5 shows a vertical profile based on the radiosonde data gathered for 09:00 on 26 February at Wajima on the Sea of Japan side and Tateno on the Pacific Ocean side. An inversion layer at 800–900 hPa was observed, with the air in the layers above this being extremely dry. This could be a subsidence inversion layer with a migratory anticyclone. There is a tendency for the equivalent potential temperature and saturation equivalent potential temperature to increase at the higher levels of the atmosphere, indicating an extremely stable state in the atmosphere. It is evident that the vertical profiles for Wajima and Tateno are extremely similar, and that there are few differences in the stratification of the lower atmosphere for the Sea of Japan side and that for the Pacific Ocean side, while the horizontal potential temperature gradient is extremely small.

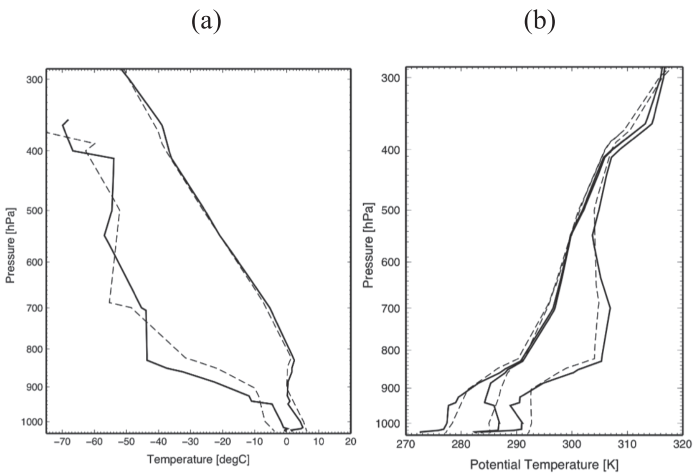


Fig. 5 Vertical profiles at Wajima (solid line) and Tateno (dashed line) at 09:00 on February 26, 2014. (a) shows the air temperature and frost point (from the center-right side of the chart), and (b) shows the potential temperature, equivalent potential temperature and saturated equivalent potential temperature from left side of the chart.

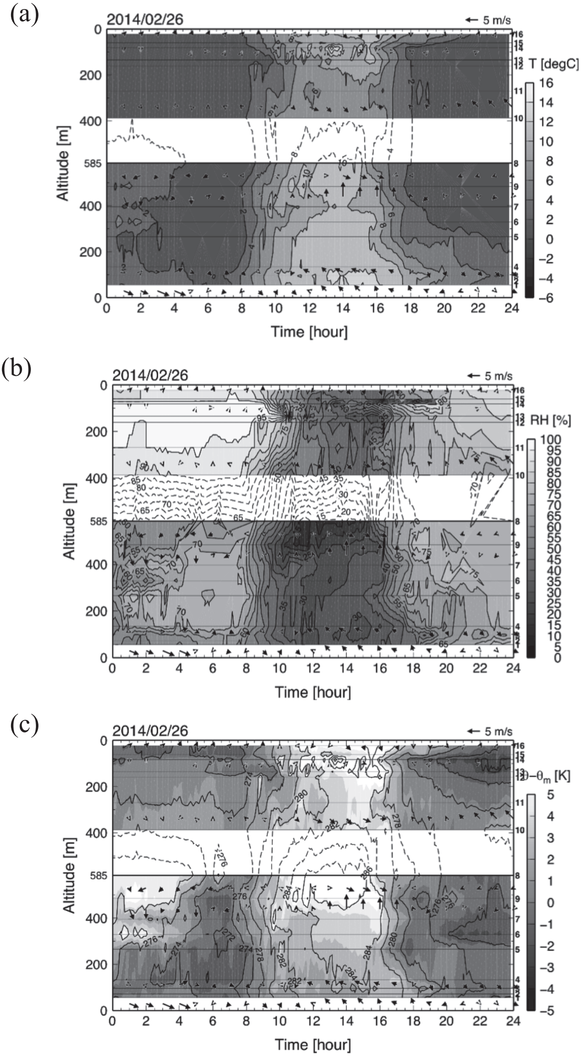


Fig. 6 Isopleths based on observation data for the Joshin'etsu mountainous region on February 26, 2014, with (a) showing the surface air temperature, (b) the relative humidity and (c) the potential temperature. The vertical axis is the same as in Fig.2. The arrows show the hour-by-hour values for surface wind taken from the observatories and AMeDAS sites which are closest to the course of traverse.

The isopleths for the temperature, relative humidity and potential temperature taken from the observation data from the Joshin'etsu mountainous region are shown in Fig. 6. Looking at the surface air temperature (Fig. 6a), the figure shows a tendency for temperatures to be somewhat higher for the plains area where the elevation is below 100m, compared to the slopes above this elevation during both daytime and nighttime. However, for the slopes at elevations of approximately 100–400m, a more or less uniform temperature distribution is found, and the disparity between the Sea of Japan side and Pacific Ocean side is small at the same level of elevation. Overall, lower values are observed for the relative humidity for the slopes on the Pacific Ocean side than for the Sea of Japan side (Fig. 6b), but at elevations of approximately 400m and above during the daytime, slopes on both sides are characterized by extreme dryness. Looking at the potential temperature distribution (Fig. 6c) derived from the air temperature and atmospheric pressure values taken from the observation data, a tendency for the potential temperature to rise as the elevation grows higher can be observed on both slopes (a point which differs from the mean distribution graph for the four-month period; Fig. 2), with a distribution pattern that is close to symmetry with respect to the ridgeline. The surface air on the slopes during the daytime is almost isentropic, but the potential temperature is somewhat higher at elevations of approximately 400m and above. Based on the fact that this region corresponds to the air zone of extreme dryness, it is suggested that this is due to the effect of the downward wind which accompanies the migratory anticyclone. In the isopleths, the surface wind at the meteorological observation sites and the AMeDAS observation sites is recorded together with the elevation at the observation sites; looking at the surface wind during the daytime, some elements are observed to converge in the mountain range on the slopes for the surface wind, based on which it is suggested that valley wind circulation has developed. However, due to the suppression created by the downward wind with high pressure, it is surmised that in the formation of the valley wind circulation is weak, and that the circulation is low in height if these are formed.

2.3 Case of February 28, 2014

On February 28, 2014, two days after the first case, it was a sunny day with 9.2 hours of sunlight at the Maebashi Local Meteorological Observatory, and the prevailing wind direction, daily mean wind velocity, and daily maximum wind velocity showed at north-northwest, 4.4m/s, and 8.6m/s (measured at 14:02; wind direction at north-northwest), respectively. Fig. 3 (b) shows the surface weather chart for 09:00 on February 28: two low-pressure points to the north and south (with the south point dissipating by 09:00) passed by the environs of Japan before shifting to an atmospheric pressure distribution pattern that is typical for winter. There was slight precipitation until 4:00 at Maebashi due to the influence of the stationary front that developed to the south of Kanto region at 09:00. Although the precipitation then dissipated, considerable cloud cover persisted throughout the entire day (daily mean cloud cover: 9.5). However, as stated previously, the sunshine duration for the day was long at 9.5 hours, and most of the cloud cover was light in degree throughout the day. A northwest to north-northwest wind blew throughout almost all the day from around 8:00 onwards; i.e., a cross-mountain air current was predominant in the northwestern Kanto Plain. The black lines in Fig. 4 show the air temperature and relative humidity at Maebashi on 28 February. The diurnal air temperature range at Maebashi on 28 February was smaller than on 26 February; this is due to the fact that, on 28 February the daily maximum air temperature at 15.5°C was higher than on 26 February, the air temperature did not fall in the morning on this day due to heat remaining from the previous day, and the effects of greater cloud cover throughout the day. Another notable feature was the somewhat rapid rise in air temperature at a rate of 4.7°C/hour between 7:00 and 8:00, at the same time as a fall in relative humidity at a rate of 22%/hour. Based on the fact that the northwesterly cross-mountain air current became prominent more-or-less between the boundaries of this timeframe, it is surmised that there is a relationship between these developments.

According to the vertical profile (Fig. 7) for 09:00 on 28 February, the lower troposphere can be divided into a lower humid layer and an upper dry layer at 750hPa. This characteristic is observed both at Wajima on the Sea of Japan side and at Tateno on the Pacific Ocean side. At Tateno, the areas close to the surface under 1,000hPa were mostly saturated, and it can be assumed that clouds were found there. In addition, when the potential temperature profiles at Wajima and Tateno are compared, there is a disparity of approximately 1,000m in height, for example, 290K being located at approximately 800hPa in Wajima but at approximately 900hPa in Tateno. This suggests that there is a large horizontal gradient for potential temperature for the Sea of Japan side and the Pacific Ocean side, with this characteristic being observed

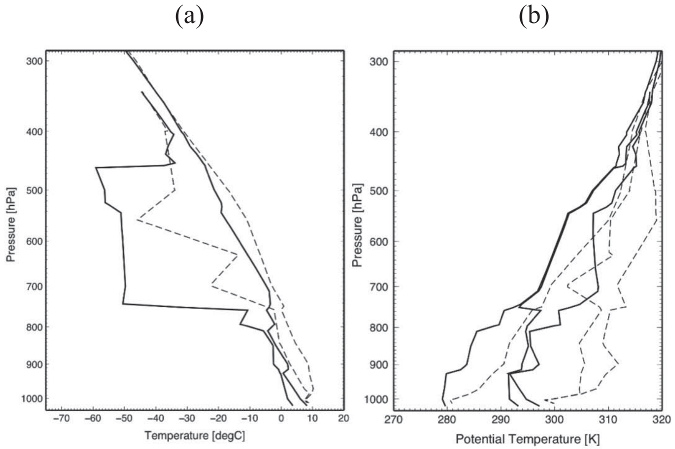


Fig. 7 Vertical profiles at Wajima (solid line) and Tateno (dashed line) at 09:00 on 28 February 2014. (a) shows the air temperature and frost-point (from the right side of the chart), while (b) shows the potential temperature, equivalent potential temperature and saturated equivalent potential temperature from left side of the chart.

around the 1,000 to 400hPa layer.

Fig. 8 shows the isopleths for the temperature, relative humidity and potential temperature along the mountain slopes on February 28. There is a major contrast between the Sea of Japan side and the Pacific Ocean side for both temperature (Fig. 8a) and relative humidity (Fig. 8b), with low temperature and high humidity on the Sea of Japan side compared to high temperature and low humidity on the Pacific Ocean side. The values for the Pacific Ocean side show a distribution pattern in which the lower the altitude, the higher the temperature and lower the humidity, particularly during the period throughout the day from 08:00 onwards. In the distribution patterns for potential temperature (Fig. 8c), the potential temperatures for each slope are similar during the daytime regardless of the height on the slope, but there is a major disparity in potential temperature between the Pacific Ocean side and the Sea of Japan side, with that for the Pacific Ocean side being higher by approximately 10K. When the potential temperature for the slopes is compared with that for the plains area, on the Sea of Japan side of the plain, the plains area is somewhat lower than that of the slope, whereas on the Pacific

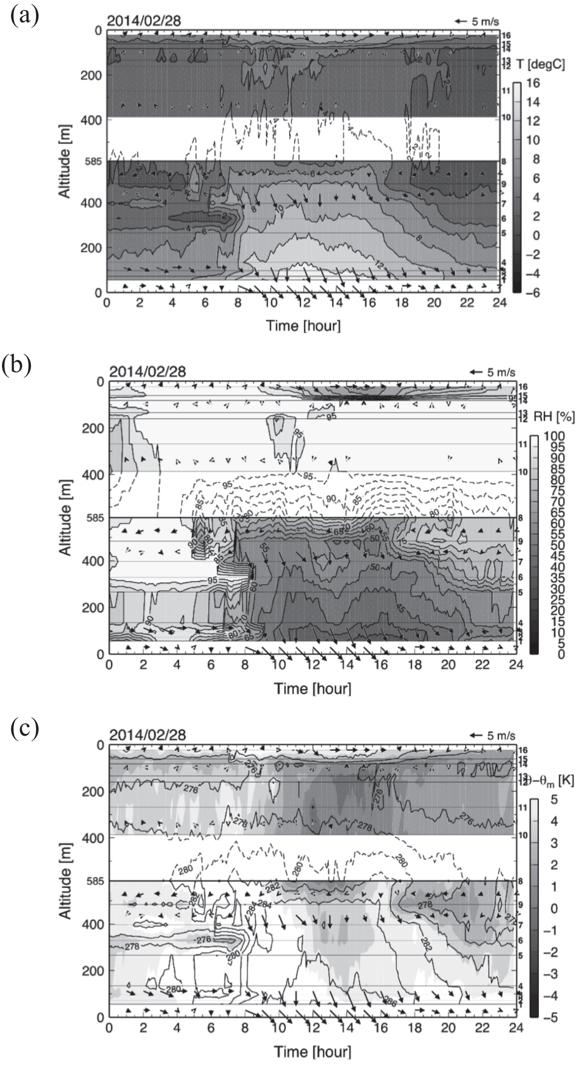
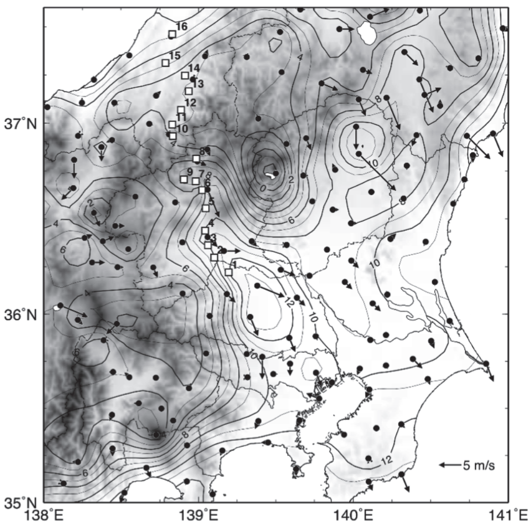


Fig. 8 Isopleths based on observation data for the Joshin'etsu mountainous region on February 28, 2014, with (a) showing the surface air temperature, (b) the relative humidity and (c) the potential temperature. The vertical axis is the same as in Fig. 2. The arrows show the hour-by-hour values for surface wind taken from the observatories and AMeDAS sites which are closest to the course of traverse.

Ocean side of the plain, the potential temperature for the plains area is somewhat higher than that of the slope, resembling the characteristics of the mean winter values which were observed in Fig. 2. However, the contrast between the Sea of Japan side and the Pacific Ocean side is emphasized more clearly when the potential temperature distribution for February 28 is compared with the mean winter potential temperature. Looking at surface winds, for the Pacific Ocean side, a somewhat strong wind moving towards the plains was observed in the timeframes and heights where the potential temperature was approximately uniform to the slope, and the development of a katabatic wind and an adiabatic heating effect accompanying this is surmised. Conversely, the winds on the slope on the Sea of Japan side remained quiet throughout the day. Based on this, it is speculated that the cross-mountain air current of February 28 gave rise to a blocking effect in the lower layers on the Sea of Japan side throughout the day from 08:00 onwards and to a dynamic foehn wind effect accompanying this, which blew downwards along the slope on the Pacific Ocean side.

Fig. 9 (a) shows the observation values from the Maebashi Local Meteorological Observatory for the distribution pattern for surface air temperature and surface wind at 08:00 on February 28 immediately after an abrupt rise in the air temperature and a fall in relative humidity were observed, and Fig. 9 (b) shows how surface air temperature rose during the one-hour period from 07:00 to 08:00 on 28 February. These graphs are based on the surface observation values taken from the weather stations of the Japan Meteorological Agency and AMeDAS data, but the data for surface air temperature and disparities in surface air temperature was created by using air temperature data taken from the surface observation sites (represented by square symbols on the figure) in the Joshin'etsu Mountainous Region Meteorological Observation Project. Looking at the surface temperature at 08:00 on February 28 (Fig. 9a), the high-temperature zone is seen to spread from the Tonegawa channel into the northwestern Kanto Plain region in a northwest-to-southeast direction. This high-temperature zone develops in response to the zone developed when the northwesterly surface wind blows relatively strongly. In addition, this zone also accords closely to the zone in which the rise in air temperature over the previous one-hour period as shown in Fig. 9 (b) occurs at a rate of over 2°C/hour, suggesting that a foehn phenomenon has developed in accordance with a cross-mountain katabatic wind. In central Saitama Prefecture, the rise in air temperature was particularly

(a)



(b)

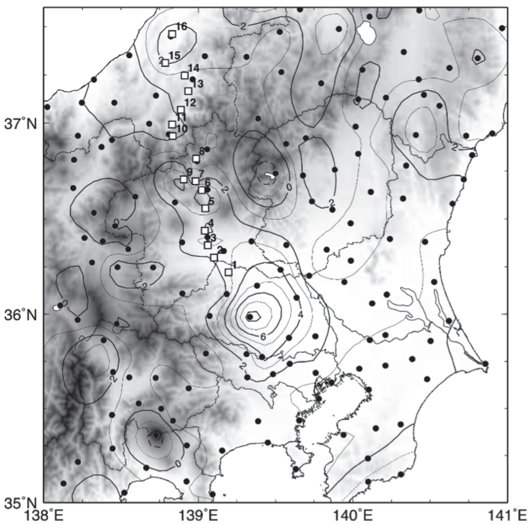


Fig. 9 (a) shows the surface air temperature (isolines; °C) and the surface wind (arrows) at 08:00 on February 28, 2014, and (b) shows the distribution of the extent of the rise in surface air temperature from 07:00 to 08:00 on February 28, 2014 (°C/hour).

marked with temperatures exceeding 12°C at 08:00 on February 28, a rise in air temperature of 4°C/hour. Looking at the surface wind in Fig. 9 (a), the surface wind emerging from the valley at Tonegawa can be observed to be greatly dispersed in a horizontal direction near central Saitama Prefecture. It is possible that the rise in temperature has become particularly marked in this region due to the addition of what has been referred to as the shallow foehn, but further investigations are required to examine this.

3. Summary

The objective of this study was to clarify the characteristics of the surface atmosphere along the mountain slopes in two cases showing markedly high temperatures in the daytime in the northwestern inland region of the Kanto Plain over the winter of 2013–2014, using original surface observation data. We investigated two cases: that of February 26, 2014 in which a cross-mountain air current did not become predominant under the influence of a migratory anticyclone, and that of February 28, 2014 in which a cross-mountain air current did become predominant under a sea-level pressure pattern typical for winter. It is speculated that on February 26 a downward wind by the anticyclone and a low-level valley wind circulation appeared, and that on February 28 a dynamic foehn wind was observed due to the blocking effect on the windward side of the mountains.

Investigations based on a combination of numerical models are an effective way to examine questions such as the kind of behavior seen in the atmosphere on and around the mountain slope, and whether this exhibits the kind of characteristics possessed by the shallow foehn wind observed in the Alps in which the wind selects a channel as the course of traverse. As this study analyzed only one example of each type (one in which a cross-mountain air current was predominant and one in which no such current was predominant), it is necessary to conduct further case study analyses and statistical analyses to ascertain whether the characteristics that became evident in this study are generally applicable or not. We hope to consider this issue in the future.

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Notes

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