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Article

Diurnal variation in precipitation and cloud formation during winter in Rikubetsu, inland Hokkaido, northern Japan

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Abstract

Rikubetsu (43.5°N, 143.8°E) lies to the east of the central mountain range in Hokkaido, and is separated from the Sea of Japan side where there is a lot of snowfall due to the flow of moist air across this sea. Snowfall in Rikubetsu is primarily associated with synoptic-scale disturbances that move around Hokkaido during the winter season. This study investigated the diurnal variations in precipitation and cloud formation in Rikubetsu in the winters of 2013–2014 and 2014–2015. The results showed that the diurnal precipitation cycle had early morning and afternoon modes throughout the winter of 2013–2014, and a single, early morning mode in the winter of 2014–2015. However, examining only days with low precipitation intensities that were not markedly affected by synoptic-scale disturbances revealed that the early morning and afternoon modes appeared in both winters. The afternoon mode is associated with mountain-valley breezes, with cloud formation beginning in the morning and precipitation occurring in the afternoon. The mechanism for the early morning mode is left for future studies, but it does not involve the development of clear-sky precipitation due to radiative cooling.

Keywords: snowfall, precipitation, cloud, diurnal variation, Rikubetsu

1. Introduction

The accurate measurement of snowfall is affected by factors such as the capture rate of snow particles by instruments, which decreases as the wind speed increases, and the evaporation of captured snowfall before it can be measured. In an attempt to quantitatively clarify and correct for these factors, the World Meteorological Organization (WMO) conducted three international projects titled, “Solid Precipitation Intercomparison Experiment (SPICE)”. We participated in the most recent SPICE project using data collected at our observation site in Rikubetsu (Hirasawa *et al.*, 2018) during the winters of 2013–2016 (*e.g.*, Nitu *et al.*, 2018, Qiu, 2012).

Rikubetsu (43.5°N, 143.8°E, 217 m above sea level) is located on the eastern side of the central mountain range in Hokkaido (Fig. 1a). The mountains separate the site from the Sea of Japan side of the island, which typically experiences heavy snowfall during the Asian winter monsoon. The winter monsoon is characterized by cold air being blown from the Eurasian continent toward the Pacific Ocean. The air becomes moist as it crosses the Sea of Japan and causes snowfall on the windward side of mountain ranges as it passes over the Japanese archipelago (*e.g.*, Manabe, 1957). During the heavy snowfall on the Sea of Japan side of Japan during the winter monsoon, most of the areas on the Pacific Ocean side of Japan, including Rikubetsu, generally experience clear skies. Snowfalls in Rikubetsu are mainly due to frontal activity associated with synoptic-scale disturbances passing through the region, which is a common feature of the snowfall/precipitation on the Pacific Ocean side of Japan in winter. As a result, the cumulative precipitation in areas on the Pacific Ocean side of Japan is lower than that on the Sea of Japan side. For example, the amount of cumulative precipitation in Rikubetsu was approximately 150 mm for the period from December 2013 to March 2014 (2013–2014 winter) and 300 mm from December 2014 to March 2015 (2014–2015 winter), while the regions on the Sea of Japan had approximately 1,000 mm of precipitation during the same time period.

Rikubetsu, which is a slightly elevated area that extends from Kitami city in the north to Obihiro city in the south, is one of the coldest areas in Japan (Sorai *et al.*, 2016), with daily winter minimum air temperatures often reaching approximately -30°C. The area is also characterized by clear-sky precipitation (so-called diamond dust) during the coldest hours of the evening (*i.e.*, from midnight to early morning), which occurs due to radiative cooling. This phenomenon may result in diurnal variation in precipitation, but the underlying mechanisms have not yet been investigated in detail.

Most studies on the diurnal variation in precipitation have been conducted in the warm season or at lower latitudes, such as the in the subtropics (*e.g.*, Watters *et al.*, 2021), and the process of such events is typically discussed in association within the context of land-sea breezes or mountain-valley breezes. Watters *et al.* (2021) emphasized the importance of improving the representation of precipitation amount and frequency in climate models, including in the diurnal cycle.

Oki and Musiake (1994) and Fujibe *et al.* (2006) investigated the diurnal precipitation cycle in Japan. Both groups reported three types of diurnal variation: a single maximum in either the early morning or in the afternoon, and maxima at both times. However, as the analyses of both studies had relatively few observation points in Hokkaido —two in the former study and one in the latter study— their findings are considered to be insufficient for generalizing the features of snowfall in inland Hokkaido. Nonetheless, their results are helpful for this study. Noh *et al.* (2004) reported a diurnal cycle in snowfall around Wakasa Bay, on the Sea of Japan side of Honshu, the main island of Japan. Maximum snowfall was observed over the land during the daytime and over the ocean at night in association with localized land-sea breezes.

In order to better understand the climate of cold regions, it is important to estimate the quantitative contribution and mechanisms of diurnal variation in precipitation and moisture circulation. However, our knowledge of the current situation in Hokkaido in winter is lacking. This study therefore investigated the diurnal variation in precipitation and cloud formation in Rikubetsu in the winters of 2013–2014 and 2014–2015 which were treated as being representative of inland conditions on the Pacific Ocean side of Hokkaido.

2. Observations

We have been conducting snowfall and meteorological measurements at the observation site in Rikubetsu since 2012 (Fig. 1b). The data used in this study were collected using a ceilometer (CT25K, Vaisala, Finland; Fig. 1c), a snowfall weighing gauge (T-200B, Geonor, Norway; Fig. 1d) (referred to as Geonor), a disdrometer (Laser Precipitation Monitor (LPM), Theis, germany; Fig. 1e), and a meteorological sensor (WXT530, Vaisala). The Geonor measurements provided the reference data for the SPICE project.

The ceilometer recorded the cloud-base height and vertical profile of backscatter intensity every 15 s. The LPM recorded the precipitation intensity derived from laser attenuation measured every 1 min. The Geonor recorded the precipitation intensity based on changes in the weight of captured and cumulative precipitation in the gauge every 1 min. Understanding the differences in measured snowfall intensities between various instruments was one of the aims of the SPICE; however, such comparisons were beyond the scope of this study, which used the Geonor to check the measurements by the LPM. The main instrument used to measure precipitation in this study was the LPM because most snowfall in Rikubetsu was light, and the LPM detected light snowfall better than the Geonor.

The WXT530 meteorological sensor was used to measure pressure, temperature, relative humidity, wind speed, and wind direction every 15 s. The wind sensor was of the ultrasonic type. Since the temperature and humidity sensors employ natural ventilation, the temperature may have been overestimated when insolation was high and wind speeds were low. However, these factors were not considered to be problematic in this analysis because we did not perform quantitative evaluations, such as heat balance calculations.

The observation periods were December 1, 2013–March 31, 2014 and December 1, 2014–March 31, 2015, with a start date of December 15, 2013 for the meteorological observations.

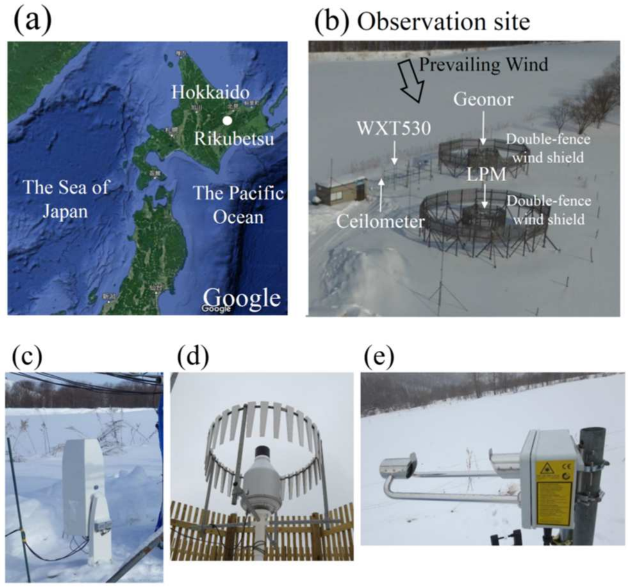

Fig. 1 (a) Map of Hokkaido showing Rikubetsu and topography of region. (b) Landscape surrounding observation site. (c) Ceilometer. (d) Geonor within double-fence windshield. (e) Disdrometer.

3. Precipitation and cloud formation

3.1 Precipitation amount

Figure 2 shows the time series of precipitation intensity and cumulaive precipitation for the two winters. The cumulative precipitation increased step-wise at higher precipitation intensities, mainly due to synoptic-scale disturbances around Hokkaido. The cumulative precipitation measured by the LPM and the Geonor differed slightly. Nonetheless, the timing and magnitude of the step-wise increases were consistent with each other, except for an event on December 17, 2014.

The total snowfall measured by the LPM in the 2014–2015 winter was 384.4 mm, nearly twice the value of 221.5 mm for 2013–2014. The 2014–2015 winter had more frequent and larger precipitation events than those in 2013–2014.

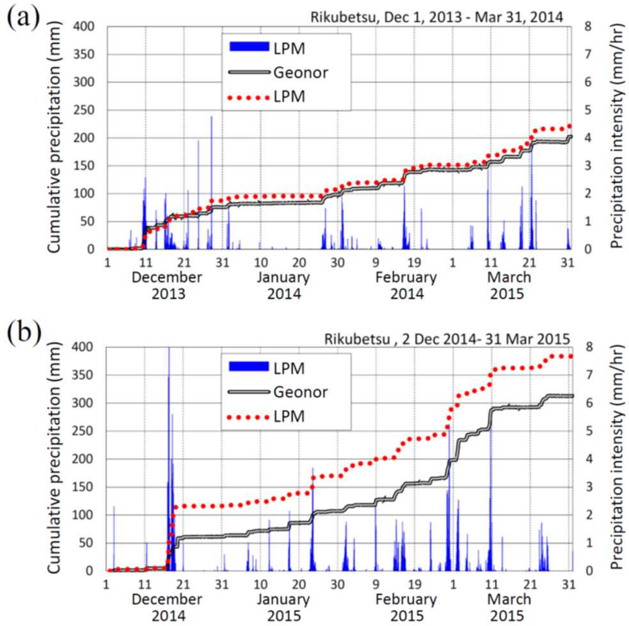

Fig. 2 Time series of cumulative snowfall (mm water equivalent (w.e.)) measured by LPM, Geonor, and precipitation intensity (mm/hr w.e.) measured by LPM (a) for 2013–2014 winter and (b) for 2014–2015 winter.

3.2 Diurnal variation in precipitation

Figure 3a shows the diurnal changes in hourly cumulative precipitation for each of the two winters: while the winter of 2013–2014 had a bimodal variability with local maxima in the early morning and afternoon, the winter of 2014–2015 had a broad peak from 22:00 to 8:00 with a local maximum from 7:00 to 8:00.

The analyses by Oki and Musiake (1994) and Fujibe *et al.* (2006) show that the early morning and afternoon modes tend to appear in the diurnal cycle of precipitation in Japan. In this analysis of the two winters, the early-morning mode was observed frequently in both winters, while the afternoon mode appeared only in the 2013–2014 winter.

Although the passage of synoptic-scale disturbances, which is the main cause of precipitation in Rikubetsu, should be independent of the diurnal precipitation cycle, the findings suggest that the atmospheric circulation associated with synoptic-scale disturbances may be influenced by the diurnal cycle.

Next, we examined the diurnal cycle of precipitation events that were not related to synoptic-scale disturbances, including relatively intense precipitation of 0.5 mm/hr or more. Therefore, days with weak precipitation intensity (minor precipitation days) were selected based on the following two criteria: 1) precipitation did not exceed 0.5 mm/hr on that day; 2) precipitation on that day was not an extension of a precipitation event of 0.5 mm/hr or more that started on the preceding day, or that extended to the following day. Minor precipitation days numbered 36 days in the winter of 2013–2014 and 30 days in the winter of 2014–2015. The total precipitation attributed to these minor precipitation was 10.7 mm (4.8% of the winter total) and 5.3 mm (1.4%), respectively.

Figure 3b shows the diurnal cycle in hourly cumulative precipitation for these minor precipitation days. Both winters had a bimodal variation pattern, with early morning and afternoon modes. The results suggested that afternoon precipitation is stronger than early morning precipitation when synoptic-scale disturbance effects are relatively weak and diurnal forcing is more strongly in effect.

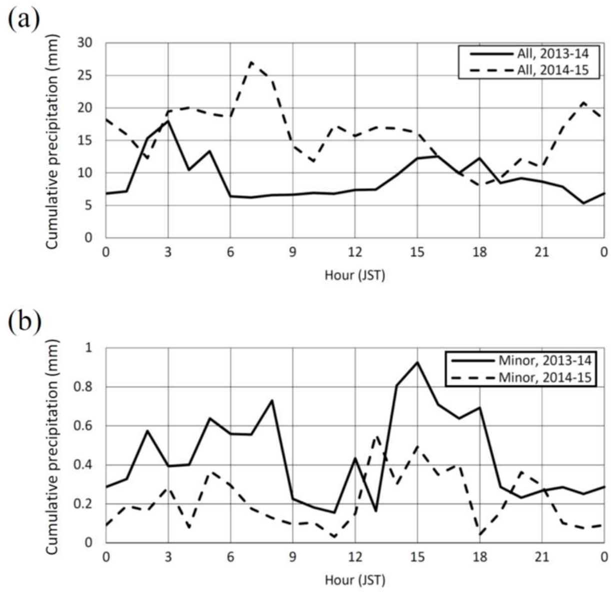

Fig. 3 Diurnal cycle of hourly cumulative precipitation (mm) during winter, (a) for all days in 2013–2014 and 2014–2015 winters, and (b) for days with minor precipitation in 2013–2014 and 2014–2015 winters.

3.3 Diurnal variation in cloud formation

Figure 4 shows the diurnal cycle of clouds in the lower troposphere (<3000 m elevation) as detected by the ceilometer. The vertical axis is the number of days when clouds were detected at that time during the study period; *i.e.*, data for all 121 days from December to March are shown in Fig. 4a, and data for all 36 (30) days with minor precipitation during the 2013–2014 (2014–2015) winter are shown in Fig. 4b.

For all days in the 2013–2014 winter (Fig. 4a), the number of days with clouds increased from 9:00 to 10:00

(JST) and decreased from 17:00 to 18:00. There were 60 to 70 days when cloud formation occurred during the daytime, and 40 to 50 days when cloud formation occurred at night. The number of days with clouds during the daytime was about 1.5 times that at night. On the other hand, in the 2014–2015 winter, a small-amplitude diurnal cycle appeared with more frequent (approximately 60 or 50 days) cloud formation from midnight to early morning from late morning to evening.

The main features in Fig. 4b are the same as those in Fig. 4a. In the 2013–2014 winter, the afternoon mode was more pronounced for the minor precipitation days (25 days, 69%) than for all days (72 days, 60%). In the winter of 2014–2015, although an afternoon mode did not appear for minor precipitation days, there was a relative increase in the ratio of minor precipitation days (21 days, 70%) in the afternoon compared to all days (58 days, 48%), which may be related to the afternoon mode of precipitation.

The difference between the two winters in the diurnal cycle of cloud frequency may be due to differences in the frequency of synoptic-scale disturbance effects, but further study is needed.

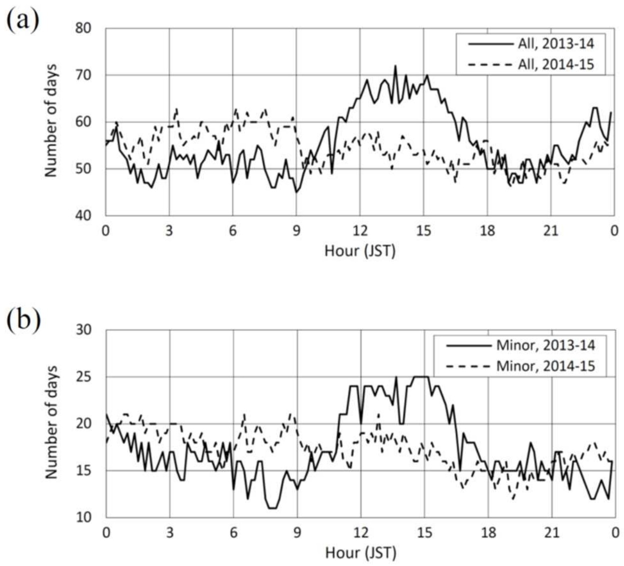

Fig. 4 Diurnal cycle of clouds in lower troposphere (*i.e.*, <3000 m elevation) as detected every 10 min by ceilometer, (a) for all days in 2013–2014 and 2014–2015 winters, and (b) for minor precipitation days in 2013–2014 (36 days) and 2014–2015 (30 days) winters.

4. Discussion

4.1 Afternoon mode

Figure 5 shows a time-altitude section of the backscatter coefficients observed using the ceilometer (Fig. 5a) and the time series of cumulative precipitation observed by the LPM (Fig. 5b) on February 7, 2014, which was one of the minor precipitation days. The ceilometer was used to continually observe clouds with relatively intense backscatter coefficients from 10:00 to 21:00 at altitudes below 3000 m. Touchdowns of the ceilometer signals with the ground indicate precipitation. The LPM detected precipitation from 15:00 to 18:00, but no precipitation was detected at 12:00 and 13:00, when the backscatter coefficients were relatively weak. On the other hand, no precipitation was detected by the LPM when relatively strong backscatter was detected around 20:00; however, it is possible that this was associated with fog. In this case, cloud formation began around 10:00, with relatively strong precipitation observed after 15:00. These features are representative of the daytime mode of cloud formation seen during the 2013–2014 winter season (Fig. 4a) and the afternoon mode of precipitation (Fig. 3b).

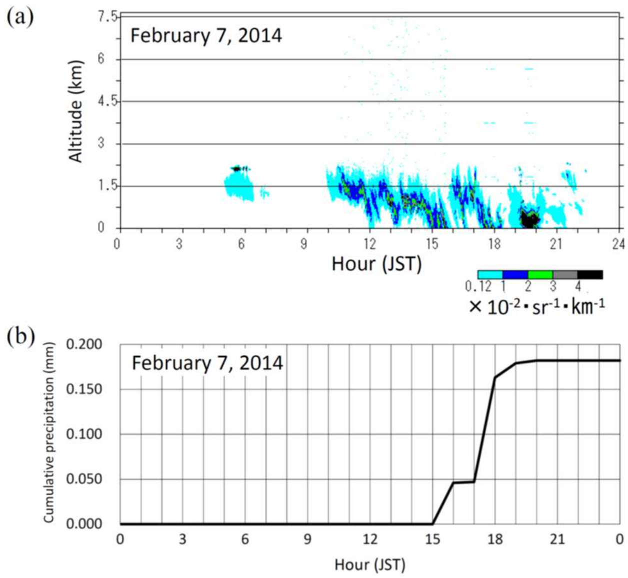

Fig. 5 Daily time series of clouds and precipitation on February 7, 2014. (a) Time-altitude section of backscatter coefficients determined by ceilometer. The color bar shows the magnitude of the backscatter coefficients. (b) Time series of hourly cumulative precipitation observed by LPM.

Figure 6 shows hourly changes in air temperature, relative humidity to ice (Fig. 6a), wind speed (WS), and wind direction (WD) (Fig. 6b) on February 7, 2014.

At approximately 7:00, when the temperature began to rise, the wind speed decreased, and the wind direction became less constant from the west at night. At approximately 10:00, when clouds began to form, the wind speed increased and the wind direction became constant to the south-southwest. The daily variation of this wind system represents the mountain-valley breeze cycle. Further, the formation of clouds during the daytime and precipitation in the afternoon can be attributed to the diurnal cycle in this wind system. On the other hand, the wind direction is from the Pacific Ocean, but the wind speed is weak, which means that the air over the sea will not reach Rikubetsu during the diurnal cycle alone.

By the time the relatively strong precipitation occurred, the wind speed had weakened again, and the wind direction was not constant. It is considered likely that the wind was no longer forced upslope at this time of day. The increase in the relative humidity from 15:00 to 18:00 can be attributed to evaporation (sublimation) of precipitation particles.

In the event that the precipitation particles evaporate (sublimate) completely as they fall from the cloud base, no precipitation would be observed on the ground while clouds were forming. Such a case was observed on January 17, 2013, as shown in Fig. 7, which shows a time-altitude section of the backscatter coefficients determined by the ceilometer. The ceilometer continually observed clouds with relatively intense backscatter coefficients at an altitude of approximately 1500 m from 11:00 to 16:00, with no touchdowns of the signals on the ground. In this case, no snowfall was detected by the LPM or the Geonor.

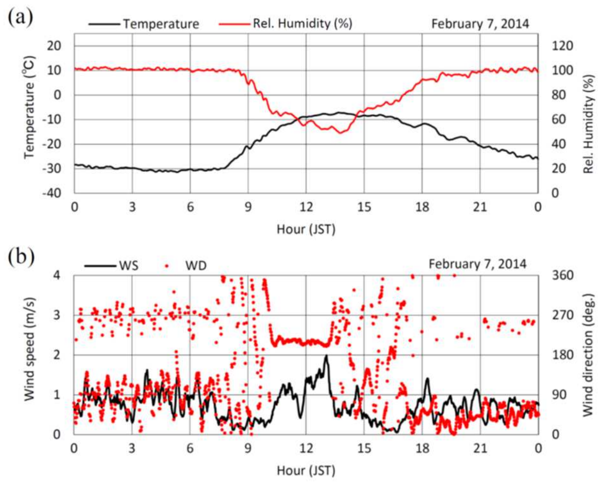

Fig. 6 Daily time series of (a) air temperature, relative humidity to ice, and (b) wind speed and direction on February 7, 2014. The data interval is 1 min, but the wind direction is a 10-min moving average.

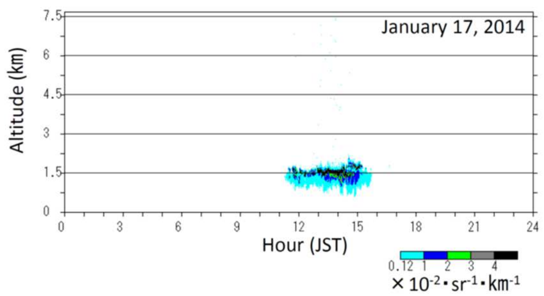

Fig. 7 Same as Fig. 5a, but for January 17, 2014.

4.2 Early morning mode

Figure 8 shows the time series of the cumulative precipitation amount (mm) measured by the LPM during 5:00–8:00 on the minor precipitation days. Twelve of the 36 minor precipitation days had early morning (5:00-8:00) precipitation. The precipitation amount during this period was less than 1 mm on almost all days.

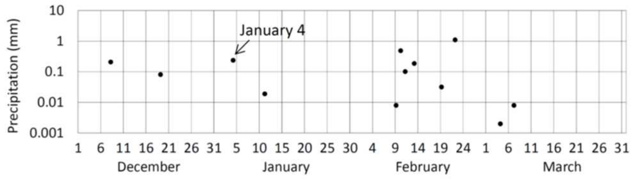

Fig. 8 Time series of cumulative precipitation (mm) measured by LPM during 5:00-8:00 on minor precipitation days. Subsequent figures show the data observed on January 4, 2014.

Figure 9 shows a time-altitude section of the backscatter coefficients determined by the ceilometer (Fig. 9a) and the time series of cumulative precipitation observed by the LPM (Fig. 9b) on January 4, 2014, which is one of the minor precipitation days. The ceilometer observed touchdowns with relatively intense backscatter coefficients below 3000 m from 5:00–12:00, and relatively weak ones from 15:00–20:00. Precipitation was detected by the LPM during the former time period.

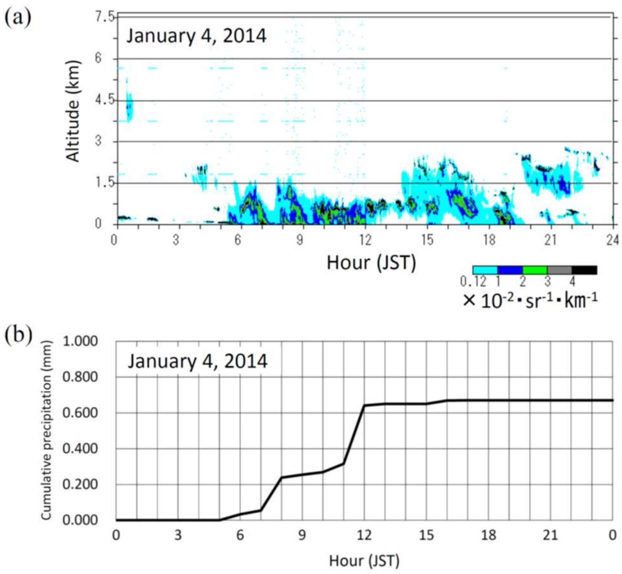

Fig. 9 Same as Fig. 5, but for January 4, 2013.

Figure 10 shows the daily time series of air temperature and relative humidity to ice on January 4, 2014. Temperatures reached their lowest point at around 5:00 when precipitation began. Since this was before sunrise, the increase in temperature after 5:00 is considered to be due to the suppression of radiative cooling by the increase in downward longwave radiation caused by cloud formation. The relative humidity was typically maintained at 100% when there was no precipitation during the night (see Fig. 6a), but on this morning, the relative humidity fell below 100% with the onset of precipitation. In all other cases of early morning precipitation, the relative humidity was also below 100% during the precipitation period, implying that the early morning precipitation observed in this study is not clear-sky precipitation.

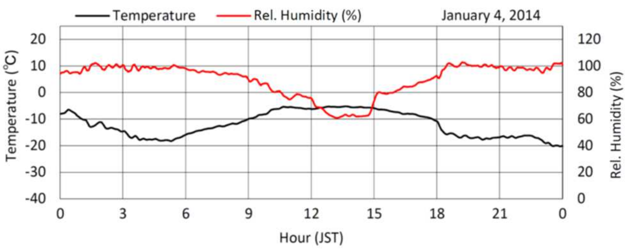

Fig. 10 Same as Fig. 6a, but for January 4, 2013.

5. Conclusion

Rikubetsu is located on the eastern side of the central mountain range in Hokkaido, which separates the site from the Sea of Japan side of the island. Snowfall in Rikubetsu is mainly brought about by synoptic-scale disturbances around Hokkaido that occur several times during the winter season from December to March. This study investigated the diurnal variation in precipitation and cloud formation in Rikubetsu in the winters of 2013–2014 and 2014–2015. The total precipitation in the 2014–2015 winter was nearly twice that in the 2013–2014 winter, implying that the influence of synoptic-scale disturbances was greater in the 2014–2015 winter.

The results showed that the diurnal cycle of precipitation had early morning and afternoon modes throughout the 2013–2014 winter, but only a single mode in the early morning in the 2014–2015 winter. Examining only the days of weak precipitation intensity (minor precipitation days), which are not considered to be strongly influenced by synoptic-scale disturbances, the early morning and afternoon modes appeared in both winters. The afternoon mode is associated with mountain-valley breezes, with cloud formation beginning in the morning and precipitation occurring in the afternoon. On the other hand, the mechanism underlying the early morning mode is left for future studies, but it is not attributed to the formation of clear-sky precipitation due to radiative cooling.

References

Fujibe, F., Yamazaki, N., and Kobayashi, K. (2006): Long-Term Changes in the Diurnal Precipitation Cycles in Japan for 106 Years (1898-2003). *J. Meteorol. Soc. Japan*, **84**(2), 311–317. https://doi.org/10.2151/jmsj.84.311

Hirasawa, N., H. Konishi, K. Nishimura, C. Genthon and project group of Japan Meteorological Agency (2018): SPICE site report: Rikubetsu, Japan. WMO Solid Precipitation Intercomparison Experiment (SPICE), *Instruments and Observing Methods*, **131**, Annex 8.3, December 2018.

Nitu, R., and 42 co-authors (2018): WMO Solid Precipitation Intercomparison Experiment (SPICE). *Instruments and Observing Methods*, **131**. https://library.wmo.int/opac/

Noh, Y.-J., Liu, G., Balas, N., Aonashi, K., and Koike, T. (2004): Diurnal variations of snow precipitation in Wakasa Bay during winter. *J. Meteor. Soc. Jpn.* Ser. II, **82**, 1117–1128. https://doi.org/10.2151/jmsj.2004.1117

Oki and Musiake (1994): Seasonal Change of the Diurnal Cycle of Precipitation over Japan and Malaysia. *Journal of Applied Meteorology and Climatology*, **33**(12), 1445–1463.

Qiu, J. (2012), Snow survey hopes for avalanche of data, *Nature*, **491**, 312-313. https://doi.org/10.1038/491312a

Sorai, T., H. Hamada, T. Kameda, and S. Takahashi (2016): Rikubetsu, the coldest town in Japan: according to the meteorological data by Japan Meteorological Agency from 2007 to 2016 in winter seasons. *Tenki*, **63**, 879-887. (in Japanese)

Watters, D., Battaglia, A., and Allan, R. P. (2021): The diurnal cycle of precipitation according to multiple decades of global satellite observations, three CMIP6 models, and the ECMWF reanalysis. *J. Climate*, **34**, 5063–5080. https://doi.org/10.1175/JCLI-D-20-0966.1

Yamashita, K., S. Nakai, and H. Motoyoshi (2018): Measurements at Joetsu (Japan) for the WMO/CIMO SPICE Project. WMO Solid Precipitation Intercomparison Experiment (SPICE), *Instruments and Observing Methods*, **131**, Annex 8.4, December 2018.

Summary in Japanese

和文要約

北海道内陸部陸別町における冬季の降水量と雲形成の日変化

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陸別（北緯 43.5 度，東経 143.8 度，標高 217m）は，北海道の中央山脈の東側に位置し，日本海を渡る湿潤な気流により降雪量の多い日本海側とは隔てられている．陸別の降雪は主に北海道付近を通過する総観規模擾乱によってもたらされ，冬季に数回発生する．本研究では 2013-14 年と 2014-15 年の 2 冬における陸別の降水量と雲形成の日変化を調査した．その結果，降水量の日変化には，2013-14 年冬には早朝と午後に極大があり，2014-15 年冬には早朝に極大があることが分かった．また，総観規模擾乱の影響を強く受けていないと考えられる降水強度の弱い日だけを調べると，両冬とも早朝と午後に極大が現れた．午後の極大は山谷風と関連しており，午前中に雲形成が始まり，主に午後に降水が発生する．早朝の極大は放射冷却に伴う晴天降水ではないことが示され、その仕組みの解明は今後の研究に残した．

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