Abstract

Synoptic conditions causing an extreme snowfall event in the Kanto-Koshin district occurred on 14-15 February 2014 are investigated through a reanalysis data set. Associated with a developing cyclone passing the south coast of Japan, persistent snowfall exceeding more than 24 hours over the Kofu-Basin resulted in 112 cm snowfall at Kofu. Slow progress of the south-coast cyclone also contributed to the long snowfall duration. An anticyclone developed over the northern Japan (–1032 hPa) also contributed to this extreme snowfall. This anticyclone brought warm and moist air inflow by southeasterlies forming moisture flux convergence over the Kanto-Koshin district on the morning of 14th when snowfall started in the Koshin district in spite that the south-coast cyclone was located to the south of Kyushu. Further, ageostrophic cold northerlies with high pressure extension from the anticyclone by “cold-air damming (CAD)” would suppress warming with the approaching south-coast cyclone and keep snowfall until the morning of 15th. In other four heavy snowfall events at Kofu, snowfall durations were almost 12 hours. Although anticyclone to the north and CAD were identified in each case, the moisture transport from the southeast was not evident and moisture flux convergence was not formed earlier.


1. Introduction

A heavy snowfall event in the Kanto-Koshin district occurred on 14–15 February 2014 associated with an extratropical cyclone passing the south coast of Japan (hereafter, the south-coast cyclone). Persistent snowfall exceeding more than 24 hours over the Kofu-Basin resulted in 112 centimeters (cm) snowfall at Kofu (35.67°N, 138.55°E) (Fig. 1). Many observatories measured extreme values of the latest snow depths in Yamanashi, Nagano, Gunma, and Saitama prefectures, more than double in some places; Kofu 114 cm (the latest record 49 cm), Kawaguchi-Ko (35.50°N, 138.55°E) 143 cm (89 cm), Karuizawa (36.34°N, 138.55°E) 99 cm (72 cm), Iida (35.52°N, 137.76°E) 81 cm (56 cm), Miebashii (36.41°N, 139.06°E) 73 cm (37 cm), Iruma (35.99°N, 139.07°E) 58 cm (56 cm). This extreme snowfall brought a major disaster. Fire and Disaster Management Agency reported that fatalities and injured numbered 26 and 781, respectively. Further, railroads and highways became blocked for several days, especially in Yamanashi Prefecture. In mountain areas, many avalanches caused the cutoff road networks and isolation of many villages. Many collapses of the roof of facilities and agricultural greenhouses extended to Saitama and Gunma prefectures.

Cyclones passing the south coast of Japan occasionally cause heavy snowfall events over the Kanto-Koshin district. Former studies indicate the importance of path of cyclones and distinction between rain and snow based on vertical profiles of air temperature and humidity (e.g., Yamamoto 1984; Yasuda and Tomine 1998; Takeo 2002; Hara et al. 2013). In the present study, we mainly focus on understanding synoptic conditions and associated large-scale atmospheric variability causing this persistent snowfall in the Kanto-Koshin district. In this manuscript, we use the Japan Standard Time (JST) which precedes nine hours with the Coordinated Universal Time (UTC).

2. Characteristics of snowfall distribution

Figure 1b shows the total snowfall amount for 72 hours for 14–16 February 2014 using the Automated Meteorological Data Acquisition System (AMeDAS) of the Japan Meteorological Agency (JMA). The snowfall is seen widely in Tohoku, Hokuriku, Tokai, and Kinki districts, and more than 50 cm over plains in some places. In Yamanashi Prefecture, snowfall continued for about 28 hours from the morning of 14th to the morning of 15th (Fig. 1c). The snowfall started on the morning of 14th in the Koshin district, but was the weak snowfall of around 1–2 cm h⁻¹ (Fig. 1c). The south-coast cyclone appeared as closed isobars on the night of 13th and was still located to the south of Kyushu on the morning of 14th (Fig. 2a). In the afternoon, it became slightly strong about 5 cm h⁻¹ around the Kofu-Basin, and snowfall gradually started in each place of the Kanto Plain. On the night of 14th, the south-coast cyclone approached the south of the Tokai district, and two pressure troughs became clear from the center of the cyclone, one in the north direction and the other in the northeast direction (Fig. 2b). Associated with the approaching cyclone to the south coast of Kanto on the morning of 15th, the latter trough moved to the north and it gradually changed from snow to rain in the southeastern side of the trough (e.g., Chiba and Ibaraki prefectures). On the other hand, cold northerlies near the surface associated with relatively high pressure regions between the two troughs were prevailing from Tochigi to Kanagawa prefectures (Fig. 2c). Surface air temperatures would be kept to around 0 °C and snowfall continued over there during the night of 14th by the prevailing northerlies. These characteristics are discussed in the next section.

3. Synoptic conditions related to persistent snowfall

Here we investigate why the snowfall duration continued more than 24 hours, especially in Yamanashi Prefecture, based on the Japanese 55-year Reanalysis (JRA-55) data developed at JMA (Kobayashi et al. 2015). Figure 3 shows horizontal moisture flux (arrows) and its convergence (shaded) at the 850-hPa level. On the morning of the 14th (Fig. 3a), a moisture convergence zone has been formed between the south-coast cyclone and the Tokai-Koshin district corresponding to a pressure trough extension in the northeast direction of the cyclone (Fig. 2a), which could cause starting of precipitation over there from the morning of

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14th despite the cyclone being located farther southwest. Since the Koshin district was covered with cold air, snowfall would be expected there. Moisture fluxes from the southeast were brought about by anticyclonic circulations over the ocean southeastward of Japan (Fig. 3a), which was associated with a zonally oriented anticyclone whose central pressure exceeded 1030 hPa over the northern Japan and its extension southeastward (Fig. 2a). The moisture convergence zone gradually intensified during the daytime associated with the approach of the cyclone and robust southeasterlies (Fig. 3b).

On the night of 14th, the moisture convergence further increased in intensity over the Kanto-Koshin district and continued during the night associated with the approaching cyclone, (Figs. 3c and d). A backward trajectory analysis based on the JRA-55, which were interpolated into hourly data before calculating trajectories, showed that air parcels over the Kanto-Koshin district...
at the layer between 750 and 850 hPa above the layer with cold air mass were mainly transported from the southeast. Figure 4a shows that the air parcels over there at the 800-hPa level of 03JST on 15th came from the southeast over the ocean (green lines) where high sea-surface temperature (SST) was observed associated with the meandering of the Kuroshio. Interestingly, they passed near the ocean surface because locations of most air parcels are indicated by red circles whose pressure level is higher than 950 hPa. This fact indicates that warm and moist air masses over the south of the Kuroshio path were transported toward the Kanto-Koshin district (Fig. 4b), and piled up over there where cold air mass covered near the surface.

Through a budget analysis of potential temperature on isobars, decrease in air temperature by diabatic cooling around 950 hPa over the Kanto-Koshin district is confirmed before the start of the snowfall on the morning of 14th (not shown), which may be caused by evaporation of snowfall. Then, the cold air around 0°C over there was kept by ageostrophic northeasteries (Fig. 2c) across “U-shaped” isobars associated with high pressure extension from the developed and zonally-elongated anticyclone over the northern Japan (Figs. 2b, 5a, and 5c), which may be associated with cold-air-damming (CAD; e.g., Bell and Bosart 1988; Bailey et al. 2003).

Associated with isobars oriented in an east-west direction, geostrophic easterlies are prevailing in the southern flank of the high pressure zone. When air parcels approach a meridional mountain range from the east, and ascend upslope of the mountain, their westward moment is reduced under stratified, hydrostatic condition (Markowski and Richardson 2010). Since the northward Coriolis force weakens, the air parcel motion turns toward the south across isobars. Thus formed ageostrophic northerly flow also deflects parcels to the right of the motion (toward

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Fig. 3. Moisture flux vector (g/kg m/s, arrows), and convergence of moisture flux (10⁻⁵ g/kg 1/s, shaded) at 850 hPa level at (a) 09 JST, (b) 15 JST, (c) 21 JST on 14 February, and (d) 03 JST on 15 February based on JRA-55 Reanalysis. Red circles are centers of the south-coast cyclone, respectively.

Fig. 4. (a) Backward trajectories of air parcels for 54 hours from 03 JST on 15 February based on JRA-55 Reanalysis. Color lines indicate the height of the starting points: yellow and green lines for 925 hPa and 800 hPa, respectively. Grayscale shaded indicates sea surface temperature at that time based on Real-Time, Global Sea Surface Temperature – High Resolution Analysis (RTG_SST_HR, Gemmill et al. 2007) and its interval is 5 K. Circles show the position of air parcels every 6 hours and their colors correspond to the pressure level of air parcels there. (b) As in (a), but for specific humidity (g kg⁻¹) at the 850 hPa, and its interval is 1 g kg⁻¹.
the mountain range), resulting in mass accumulation and pressure increases, which forms a pressure ridge associated with high pressure extension from the north. Ageostrophic lower-level cold advection further results in increased static stability and enhances hydrostatic pressure rises (Xu et al. 1996). This pronounced ridge and accompanying cool, stable air mass are often referred to as CAD (e.g., Bailey et al. 2003).

The backward trajectory analysis showed that air parcels over the Kanto-Koshin district at the layers between 950 and 900 hPa were mainly transported from the northeast. Figure 4 shows that the air parcels at the 925 hPa level came from the northeast around the Tohoku district (yellow lines), and could be traced to the northwestward over the Sea of Japan originated from the Northeast district of China 54 hours before. Easterlies over the southern part of the Tohoku district would cause the formation of CAD (Figs. 2b and 5c).

In the upper troposphere, a core of the jet stream is located to slightly east of the northern Japan (Fig. 5e). The lower branch of thermally direct meridional ageostrophic circulation in the confluence region of the upper jet entrance over the northern Japan may enhance the near surface ageostrophic northerlies in the CAD region (e.g. Uccellini and Kocin 1987).

The high pressure zone exceeding 1030 hPa over the northern Japan (Fig. 5a) was associated with cold air mass from the Eurasian Continent (Fig. 5c), which would be brought by a cyclone passed over the south of Japan on 11th, progressed northward and developed in the Sea of Okhotsk (Fig. 5a). A blocking anticyclone developed over the northwestern Pacific which had an equivalent barotropic structure (Figs. 5a, c, and e) would effectively turn cyclones northward (Yamazaki et al. 2015).

4. Comparison with other heavy snowfall cases at Kofu

There were four other heavy snowfall events observed more than 40 cm amount at Kofu after 1952/53 winter: 18−19 February 1986 (49 cm), 15 January 1998 (44 cm), 27 January 2001 (45 cm), and 8 February 2014 (45 cm). Their snowfall durations were almost 12 hours. Around 10-30 cm snowfall had been observed at many weather stations over the Kanto Plain, respectively. Figures 5b, d, and f show composite synoptic maps of the four cases based on the peak time of the snowfall. Since 6-hourly data are used for the composite maps, we define as the peak time when the 6-hourly snowfall accumulation was the largest in each case. The SLP composite map (Fig. 5b) is characterized as a south-coast cyclone located off the Tokai district and an cold anticyclone elongated over the northern Japan with weak high pressure extension towards southwestward over the Kanto Plain associated with cold air mass (Fig. 5d). These characteristics basically reflect those of CAD, which are also identified in each of the four cases.

The south-coast cyclone is rather stronger (~8 hPa) than that of 21JST on 14 February 2014. Although the northern high is associated with cold air masses from the Eurasian Continent, however, its average central pressure (1022 hPa) and intrusion of cold air mass towards the Kanto Plain from the north are about 10 hPa smaller and 3 K warmer than those of 21JST on 14 February 2014, respectively (Fig. 5). Since a core of the jet stream in the upper troposphere is not clearly identified over the east of Japan (Fig. 5f), near-surface ageostrophic northerlies in the damming region would be not so intensified.

In the four-case composite map at the peak time of the snowfall, moisture flux convergence is also evident over the Kanto-
Koshin district (Fig. 6b), which is mainly associated with prevailing southwesterlies transporting moisture with the approaching cyclone. However, the moisture transport from the southeast is not evident. Twelve-hour before the peak time of the snowfall, when the south-coast cyclone is located to the south of Kyushu, moisture flux convergence is weak over the Kanto-Koshin district, (Fig. 6a). Relationship between the convergence and SST distribution is not well identified.

Since the south-coast cyclone was located there 18-hour before the peak time of the snowfall of 14 February 2014 (Fig. 3a), slow progress of the south coast cyclone also would contribute to the snowfall exceeding more than 24 hours at this time. Total amount of condensation by vertical integration of the convergence of moisture flux over the Kanto-Koshin district is 60–110 kg m$^{-2}$ on 14–15 February 2014 (Fig. 7a), which is converted into precipitation in 60–110 millimeter (mm). It explains 70–80% of the total precipitation amount (80–140 mm) observed at many AMeDAS stations in the Kanto-Koshin district. In contrast, that for the four-case composite is 30–45 kg m$^{-2}$ (Fig. 7b).

5. Summary and discussion

A significant heavy snowfall event causing a major disaster in the Kanto-Koshin district occurred on 14–15 February 2014 by a developing cyclone passing near the south coast of Japan. Snowfall duration exceeding more than 24 hours over the Kofu-Basin resulted in 112 cm snowfall at Kofu (Fig. 1). We mainly focused on synoptic conditions and associated large-scale atmospheric conditions causing this persistent snowfall using a reanalysis data set.

Snowfall started on the morning of 14th in the Koshin district with a trough spread in the northeast direction of the south-coast cyclone located to the south of Kyushu (Fig. 2a). Formation of a moisture flux convergence zone extended toward northeastward by southwesterlies with the cyclone and southeasterlies with the anticyclone developing over the northern Japan could cause the earlier start of snowfall over the Koshin district against the location of the cyclone (Figs. 3a and b).

On the night of 14th, snowfall regions gradually spread to the Kanto Plain with moisture flux convergence by prevailing southeasterlies and southerlies from the approaching south-coast cyclone (Figs. 3c and d). Although it gradually changed to rain in the southeastern part of the Kanto Plain, heavy snowfall continued over the northern and western part of the Kanto Plain. Prevailing ageostrophic northerlies by CAD would contribute to keeping snowfall there (Figs. 2 and 5). A backward trajectory analysis also supports this process (Fig. 4).

The strength of the anticyclone developed over the northern Japan and its extension southeastward would be one of important key factors of extreme snowfall event maintained more than 24 hours over the Kanto-Koshin district: (1) warm and moist air inflow by southeasterlies with anticyclonic circulations effectively forms moisture flux convergence before approaching the south-coast cyclone and (2) ageostrophic northerlies with CAD would be intensified by a developing anticyclone located to the north generally associated with cold air mass from the Eurasian Continent (Fig. 5). A core of the jet stream located to the east of the northern Japan in the upper troposphere (Fig. 5e) may also enhance near-surface ageostrophic northerlies in the CAD region.

In four other heavy snowfall events with around 40–50 cm snowfall at Kofu, their snowfall durations were almost 12 hours,
and anticyclones over the northern Japan and air intrusion with high pressure extension with CAD were weaker than those in the case of 14−15 February 2014. Further, the moisture transport from the southeast was not evident.

By a classification of Appalachian CAD over North America (Bailey et al. 2003), the case of 14−15 February 2014 is similar to a high impact type of CAD that is characterized as zonally oriented anticyclone greater than 1030 hPa located to the north and a core of jet stream in the upper troposphere. There are not so many studies considering CAD for characteristics of snowfall associated with the south-coast cyclone in Japan (e.g., Fujibe 1990; Araki and Murakami 2015). Further investigation would be required for the formation mechanism of the anticyclone over the northern Japan associated with CAD and the way of estimation of the intensity of CAD in synoptic scales.

In the synoptic conditions in early February 2014, south-coast cyclones generated every few days, progressed northward through the east coast of northern Japan and developed in the Sea of Okhotsk, which would bring cold air mass over the northern Japan. A strong blocking anticyclone maintained over the northwestern Pacific for about two weeks would contribute such synoptic conditions (e.g., Yamazaki et al. 2015). Approaches from both global and local viewpoints are necessary for understanding of record heavy snowfall events (e.g., Tachibana et al. 2007), also considering the Kuroshio path which would decide cyclone paths or intensification (Nakamura et al. 2012; Hirata et al. 2015).

A large amount of the population concentrates in the Pacific side of Japan, especially in the Kanto district including the metropolitan area. Therefore, occurrence of similar extreme snowfall in this region would have a significant influence for the entire country. In the present study, we have not discussed intensity of snowfall related to total snow amount. So, further investigation would be required to understand reasons why such extreme snowfall amount occurred by theoretical approaches and/or numerical experiments. Preliminary numerical experiments have been already performed, and heavy snowfall with CAD over the Kanto-Koshin district are essentially reproduced, which will appear as a following issue in the near future.

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