Numerical Simulation of Heavy Snowfall and the Potential Role of Ice Nuclei in Cloud Formation and Precipitation Development

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1. Introduction

A heavy snowfall event occurred in the Kanto region from 14 to 15 February 2014, when a winter extratropical cyclone rapidly developed along the south coast of Japan. The snow depth exceeded the historical record in the region, and the event caused many losses of human life. Accurate forecast of such heavy snowfall events is highly required but remains challenging because the precipitation system deeply involves complicated processes of synoptic- and meso-scale dynamics, boundary layer, cloud microphysics, and diabatic process due to phase changes of cloud and precipitation particles. In terms of cloud microphysics, understanding of the aerosol indirect effect by ice nuclei is required. In order to examine the characteristics of cloud microphysics and potential role of ice nuclei in cloud formation and precipitation development during the event, we performed numerical experiments with a horizontal grid spacing of 1.5 km using the Japan Meteorological Agency (JMA) non-hydrostatic model (NHM; Saito et al. 2006) with bulk cloud microphysics scheme. The initial and boundary conditions were provided from 3-hourly JMA mesoscale analysis and the model domain covered the central part of Japan Island, including the Kanto region. The model was run for 33 hours from 0300 Japan Standard Time (JST; JST = UTC + 9 h) on 14 February 2014.

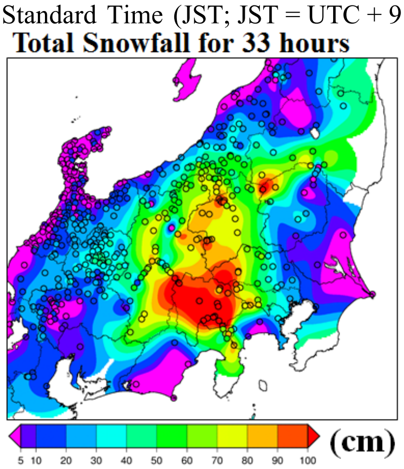

Figure 1. Horizontal distribution of 33-hour accumulated snowfall (cm) from 0300 JST on 14 Febr to 1200 JST on 15 Febr obtained from the sum of the differences of 1-hourly snow depth observations.

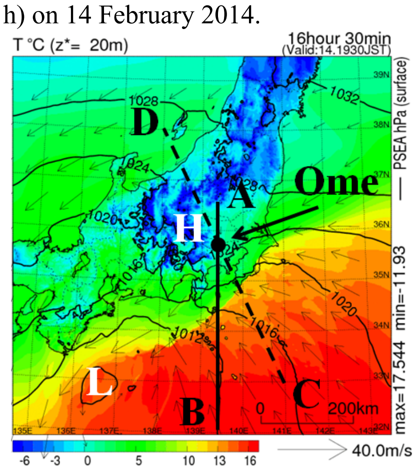

Figure 2. Horizontal distribution of simulated temperature (shade) and sea level pressure (contour) converted from pressure at 20 m above the surface at 1930 JST on 14 Febr. Vectors indicate horizontal wind at the same level.

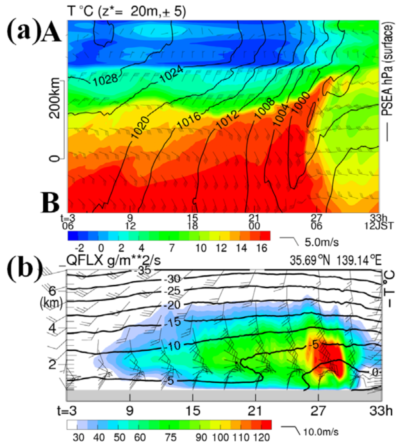

Figure 3. (a) Time-range cross section of simulated temperature at 20 m above the surface (shade) and sea level pressure (contour) along the solid line AB in Fig. 2. (b) Time-height cross section of water vapor flux (shade) and temperature (contour) at the Ome city. Barbs indicate horizontal wind.

2. Microphysical structures in precipitating clouds and the impact of ice nuclei

The snow depth observations provided by many national organizations and local governments revealed the detailed distribution of snow depth, where the 33-hour accumulated snowfall exceeded 1 m in the mountain areas (Fig. 1). The control experiment successfully reproduced the distribution of snowfall (Fig. 4). By comparisons with the surface observation, wind profiler, and liquid water path retrieved from ground-based microwave radiometer data in these regions, simulated dynamic and thermodynamic environment and cloud microphysical properties reasonably agreed with observations (not shown). A coastal front was formed in the south of the Kanto region, and the feature of the cold air damming as U-shaped contour of sea level pressure was found in the Kanto region (Fig. 2). The coastal front got distinct as the north-south gradient of sea level pressure increased (Fig. 3a), and diabatic cooling by sublimation/evaporation/melting of precipitation particles in lower troposphere also contributed to the formation and maintenance of coastal front and cold air damming. A distinct meso-scale vortex, usually called *zipper low*, was formed on the front before the passage of the cyclone (Fig. 2), and would play a role in the maintenance of the coastal front. Warm and moist southeasterly wind flowed on the front, and brought a large amount of water vapor (Fig. 3b), resulting in the heavy snowfall in the Kanto region. The synoptic-scale features of upper-level coupled jet structure, causing acceleration of low-level ageostrophic flows and enhancement of the coastal front, were also found by JMA mesoscale analysis (not shown), which was quite similar to the situation of heavy snowfall events in the east coast of the United States (Uccellini and Kocin 1987).

Clouds composed of solid cloud and precipitation particles were simulated in the 8–12 and 2–4 km layers, and the latter cloud layers were formed both above the surface of the coastal front and on the windward side of the mountains (Fig. 5). Number density of snow was large at a layer between 5 and 10 km altitude and another layer between 2 and 4 km altitude, and mixing ratio of snow was large below about 8 km altitude. In this case, there were two layers of stratiform ice clouds to the north of the coastal front and on the windward side of the mountains, and the other low-level clouds were also formed by orographically-induced updraft in the mountain regions, resulting in the seeder-feeder mechanism which contributed to the increase of snowfall amount (Houze 2012). On the other hand, the 33-hour accumulated precipitation by graupel reached 20 mm in some parts of the Kanto region (Fig. 4), which was formed by riming growth during the passage of the cyclone over the Kanto plain, where sufficient water vapor supply and super-cooled cloud water locally existed near the center of the cyclone in low-level troposphere.

In order to investigate the effect of ice nuclei (number of cloud ice) on cloud formation and precipitation development, sensitivity experiments were performed by changing coefficients in the formulas of deposition/condensation-freezing-mode ice nucleation (Meyers 1992) and immersion-freezing-mode ice nucleation (Bigg 1955) by factors of 0.1 (IN01) and 10 (IN10). As a result, there were differences of accumulated snow precipitation by of –5 mm in water equivalent for IN01 case and +5 mm for IN10 case as compared with INdef case on the windward side of mountain regions. On the leeward side of mountain regions, there were opposite differences of accumulated precipitation by snow of +5 mm for IN01 and –10 mm for IN10. The accumulated rainfall increased more than 15 mm for IN01 and decreased more than 20 mm for IN10 on the coastal region, whereas the similar amount of rainfall decrease/increase was found off shore. Since there were sufficient water vapor supply below about 6 km altitude (Fig. 3b) and rather low number concentrations of snow for INdef, the conversion of cloud ice into snow and consequent snowfall amount decreased in IN01 and increased in IN10, respectively (Fig. 5). For IN10 case, large number of cloud ice were converted into snow on the windward side of the coastal front over the ocean, and amount of rain produced from melted snow particles increased off shore and decreased on shore and vice versa for IN01 case. The similar contrast was produced on the windward and leeward of low-level orographic clouds; the increase and decrease of snowfall amount on the leeward side of mountains in IN01 and IN10, respectively. This contrast of low-level orographic clouds would be caused by the differences of water vapor supply which increased in IN01 and decreased in IN10 on the windward side of mountains, respectively. On the other hand, precipitation amount by graupel decreased by about 5 mm for IN01 case and increased by more than 10 mm for IN10 case in a part of the Kanto region during the passage of the cyclone. Since there were a large amount of low-level water vapor and supercooled cloud water fluxes as compared with number concentration of snow for INdef case, the increase in snow number concentrations due to enhanced ice nucleation may lead to the increase in graupel precipitation.

3. Conclusions and remarks

The synoptic, mesoscale, and cloud microphysical factors causing a heavy snowfall were investigated through a case study. It’s found that the maintenance of the coastal front and the seeder-feeder mechanism were important in the increase of snowfall amount. The result also suggests that concentrations of ice nuclei (cloud ice) considerably affect snowfall amount and its distribution. It’s required to develop a numerical model which properly handles the aerosol effects on the cloud formation and precipitation development.

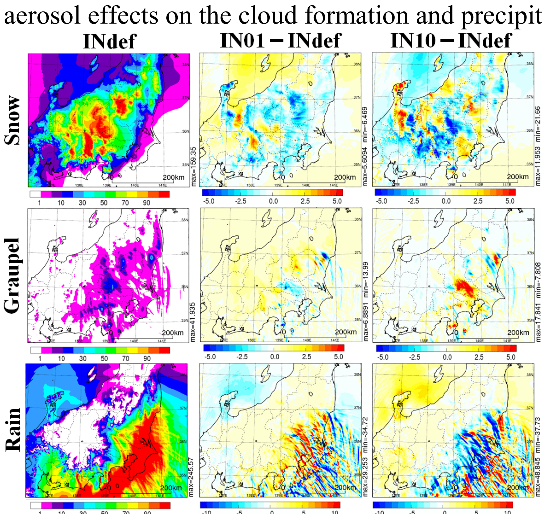

Figure 4. Horizontal distributions of 33-hour accumulated precipitation (mm) from 0300 JST on 14 to 1200 JST on 15 by snow, graupel, and rain simulated by INdef (left panels). Horizontal distributions of the difference between IN01/IN10 and INdef (center/right panels).

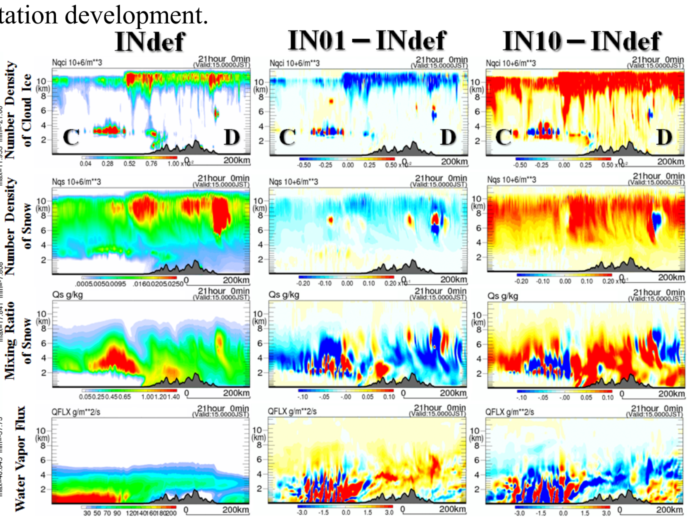

Figure 5. Vertical cross sections of number densities of cloud ice and snow, mixing ratio of snow, and water vapor flux along the broken line CD in Fig. 2 at 0000 JST on 15.

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