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Enhancement of orographic precipitation in Jeju Island during the passage of Typhoon Khanun (2012)

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ABSTRACT

Typhoon Khanun caused over 226 mm of accumulated rainfall for 6 h (0700 to 1300 UTC), localized around the summit of Mt. Halla (height 1950 m), with a slanted rainfall pattern to the northeast. In this study, we investigated the enhancement mechanism for precipitation near the mountains as the typhoon passed over Jeju Island via dual-Doppler radar analysis and simple trajectory of passive tracers using a retrieved wind field. The analysis of vertical profiles of the mountain region show marked features matching the geophysical conditions. In the central mountain region, a strong wind (≥ 7 m s^{-1}) helps to lift low-level air up the mountain. The time taken for lifting is longer than the theoretical time required for raindrop growth via condensation. The falling particles (seeder) from the upper cloud were also one of the reasons for an increase in rainfall via the accretion process from uplifted cloud water (feeder). The lifted air and falling particles both contributed to the heavy rainfall in the central region. In contrast, on the leeward side, the seeder-feeder mechanism was important in the formation of strong radar reflectivity. The snow particles (above 5 km) were accelerated by strong downward winds (≤ -6 m s^{-1}). Meanwhile, the nonlinear jumping flow (hydraulic jump) raised feeders (shifted from the windward side) to the upper level where particles fall. To support these development processes, a numerical simulation using cloud-resolving model theoretically carried out. The accreting of hydrometeors may be one of the key reasons why the lee side has strong radar reflectivity, and a lee side weighted rainfall pattern even though lee side includes no strong upward air motion.

1. Introduction

Many isolated islands comprise a single mountain peak due to volcanic activity. These bell-shaped islands can be considered to have an upslope and a downslope, which lead to orographically induced convection and precipitation. The variation in geographical shape of each island causes different airflow patterns, especially when there is a sufficient forcing to lift air over the upslope. When the background wind is strong, the surface air rises over the mountain or immediately descends downstream after passing the summit. This geophysical airflow commonly generates clouds or enhances precipitation on both the upslope and downslope regions. Most studies have focused on the windward region that can contribute to the production or enhancement of orographic rainfall by rising airflows and through the condensation process (Hamuro et al., 1969; Pandey et al., 1999; Lin et al., 2001). The condensation process depends upon the length of the upslope (Kirshbaum and Durran, 2004; Smith et al., 2009a; Yu and Cheng, 2013) and many observations and simulations have shown that mechanical air lifting by the obstacles can produce heavy rainfall (Hobbs et al., 1973; Geerts et al., 2000; Wu et al., 2002; Jiang, 2003; Colle, 2004; Kirshbaum et al., 2007).

However, if the slope serves an environment which can produce cloud and rainfall despite not long enough (small hills), the rainfall can be described in seeder-feeder process (Bergeron, 1965). Hill et al. (1981) indicated that Bergeron's seeder-feeder mechanism is strongly affected by low-level wind speed, with precipitation enhanced most just above the hilltops. Smith et al. (2009a) explained that almost all rainfall in front of a small barrier (such as Dominica) is caused by accretion growth of raindrops and their fallout. This is because on a short upslope there is insufficient time for a substantial amount of advection to occur, thereby preventing the growth of a convective cell. The observational results reveal the effects of the seeder-feeder mechanism on the

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windward side (Sibley, 2005; Fernández-González et al., 2016), but the process can also enhance precipitation on the leeward side. The orographic lifting mechanism can cause snow particles to shift and fall, influencing the leeward precipitation. Misumi (1996) showed that snow particles and cloud water transported by the downdraft can lead to enhanced rainfall. Tang et al. (2012) also investigated the interaction between leeward mountain airflow associated with local instability and displaced hydrometeors from the windward side.

There were some previous studies about Jeju Island's orographic rainfall were conducted at mesoscale convective systems (MCSs) with low-level convergence and low Froude number (Fr) < 0.5 (Lee et al., 2010; Lee et al., 2012; K. O. Lee et al., 2014). At Jeju Island, most MCS cases included a type of lee side enhancement by deflected around the terrain. Houze (1993) introduced this enhancement type, in which the precipitation is enhanced by low-level convergence on the lee side.

In the high Fr (> 1.0) condition, however, the wind and precipitation patterns can be different from a low Fr condition since the air is likely to flow over the terrain. In windy and humid environments that are typical of typhoon weather, differences can be more prominent because forced lifting and nonlinear behavior (hydraulic jump) of air affect microphysical processes. Typhoon Khanun (2012) is a prime example of the occurrence of different precipitation patterns compared with the MCS that occurs around Jeju Island. The maximum rainfall from Typhoon Khanun occurred in the vicinity of the mountain, with a weighted rainfall present toward the northeast region. Nonlinear behavior of the air was evident, resulting in an increase in precipitation on the lee side. In particular, because Khanun was the closest typhoon to Jeju Island, it is possible to analyze the enhancement mechanism of precipitation from strong winds. These singularities indicate that the study of this case is of sufficient value.

Although many studies have reported the effects of a mountainous enhancement mechanism on precipitation in a typhoon environment, the rainfall enhancement varies greatly with geographical and environmental conditions (Carruthers and Choularton, 1983; Chen et al., 2008). Therefore, in this study, we investigated the vertical profile and retrieved wind fields in the typhoon environment at Jeju Island using two ground-based Doppler radars to understand the specific precipitation enhancement occurring due to a single isolated bell-shaped island (width 78 km, height 35 km). Furthermore, we attempted to overcome the limitations of data acquired from observation by analyzing the results of a cloud-resolving model for the distribution of hydrometeors near terrain that could not be marked by a single-polarization radar.

2. Data and methods

2.1. Radar, surface and sounding data

Two ground-based S-band Doppler radars were used to analyze the enhancement mechanism of Typhoon Khanun on Jeju Island. These two S-band Doppler radars were located at Gosan and Seongsanpo meteorological stations in Jeju Island (Fig. 1), operated by the Korea Meteorological Administration (KMA). These radars were both able to observe the typhoon track. KMA operated at 15 elevations volume scans (0.5°, 0.6°, 0.8°, 1.0°, 1.5°, 2.0°, 2.5°, 3.5°, 4.5°, 6.0°, 7.8°, 10.5°, 13.8°, 18.1°, 24.0°) which proved sufficient to observe the typhoon's structure. To avoid topographical observation errors such as ground clutter and beam blockage, we used managed data which were eliminated instances near mountain regions. Furthermore, non-meteorological targets (birds, sea clutter, and other unreasonable values) were removed using the texture and vertical gradient of reflectivity, as proposed by Zhang et al. (2004). Following these procedures, the preprocessed data were interpolated onto a Cartesian coordinate system (Cressman, 1959). A 1 km horizontal resolution and 0.25 km vertical resolution were used, with effective radii of 1.5 and 1.0 km, respectively. Composed constant altitude plan position indicator (CAPPI) images were used at 2.5 km above sea level (ASL) to reveal the typhoon's structural features represented in the radar reflectivity, as this height is unobstructed by orography.

The surface weather elements (rainfall, wind, pressure, temperature and humidity) were recorded by Automatic Weather Systems (AWS) at 25 sites. A minimum curvature method without tension (T = 0) was used (Smith and Wessel, 1990) to show a spatial distribution of accumulated rainfall, considering a potential field. The surface conditions as geographical features are presented by three AWS stations. These three stations have different geographical positions: A1 is on the windward side, A2 in the mountain peak region and A3 on the leeward side.

Additionally, we used upper air sounding data from the Gosan station (47185) at 1200 UTC on 18 July 2012 to calculate the environmental stability and Fr, i.e. the kinematic energy of rising air. The parameter is defined as follows:

$$\mathrm{Fr} = U_o/Nh \tag{1}$$

where U_o is the average of wind speed below the height of the mountain, N is the Brunt-Väisälä frequency, and h is the height of the mountain (1950 m). U_o is recalculated based radar retrieved wind instead of upper air sounding. The high Fr (> 1.0) air is tend to flow over the mountain, while the low Fr (< 1.0) air is likely to be deflected around mountain.

2.2. Wind synthesis and trajectory

Three-dimensional wind fields are commonly produced from the radial velocity of two or more Doppler radars using a variational method suggested by past studies (Scialom and Lemaître, 1990; Protat and Zawadzki, 1999; Gao et al., 1999, 2004; Mewes and Shapiro, 2002). The variational-based wind analysis addresses problems involved in the specification of the boundary condition between the top and bottom levels. This has advantages over previous approaches to vertical velocity (Liou and Chang, 2009). However, Jeju Island is the bell-shaped mountain region (Mt. Halla). This makes wind retrievals of orographic forcing difficult and noisy. An advanced radar wind synthesis method to produce three-dimensional wind fields over non-flat surfaces was suggested by Liou et al. (2012), and was implemented without conversion to a terrain-following coordinate system by using an immersed boundary method (Tseng and Ferziger, 2003).

Following this, we created three-dimensional wind field data by the Wind Synthesis System using Doppler Measurements (WISSDOM) algorithm designed by Liou et al. (2012). This algorithm uses the resolving anelastic continuity equation and simplified vertical vorticity equation to retrieve reasonable wind patterns in regions with terrain forcing. Therefore it is suitable for determining a baseline wind field. Jeju Island has a mountain region along the baseline between the two radars; therefore, WISSDOM is the only current method that can retrieve observational wind fields for this topography.

Furthermore, the wind fields were utilized for the trajectory of passive tracers (Cheong and Han, 1997). The tracking experiments are implemented to prove the conjectured microphysical processes based on the observation results conclusively. We conceived the experiments for both droplet (gravitationally neutral) and drop (gravitating) of the cloud. Although each hydrometeor has a different fall velocity as their size, the simple relationship between reflectivity and fall velocity have been widely used for ease of calculation. The fall velocity of the drop is estimated as Shapiro et al. (1995).

$$w_t = 3.088Z^{0.0957} \tag{2}$$

All of the trajectories in the experiment follows the atmospheric motion and the equation of the trajectory is then:

$$\frac{dX}{dt} = \overline{V} \tag{3}$$

where X is the position vector of the objects during a time step. In this experiment, the backward scheme is used to trace next position of the