Heavy snowfall is often associated with mesoscale bands in extratropical cyclones over the northeast United States. Many previous studies have shown that snowbands associated with extratropical cyclones coincided with frontogenesis in the presence of local conditional symmetric instability (CSI), which forced the localized updraft. Observational studies on snowbands have been conducted using ground or aircraft-based sensors or in-situ observations. However, opportunities to observe snowbands associated with oceanic cyclones have been limited, though many extratropical cyclones exist along the storm track over the oceans. Dual-frequency precipitation radar (DPR) attached to GPM core observatory, which was launched in 2014, can observe 3-dimensional structure of precipitation in mid- and high latitude, and is useful to reveal the structure of the snowbands.

DPR consists of Ku-band (13.6 GHz; 22 mm) radar and Ka-band (35.55 GHz; 8.4 mm) radar, so that newly provides measured Dual Frequency Ratio ($DFR_m$) by taking the difference between measured radar reflectivity of Ku-band and that of Ka-band. If precipitating particles are solid and the attenuation effect is small, $DFR_m$ increases with the median volume diameter of the solid precipitating particles. Using this value, the flags of Heavy Ice Precipitation (HIP) are introduced in DPR classification algorithm. HIP flags indicate the existence of large ice particles such as hail, graupel, and large snowflakes which produce high values of $DFR_m$.

In this study, we found HIP flags distributed over a band (hereafter, the HIP band) in the precipitation area associated with an oceanic extratropical cyclone (Fig. a, b). The HIP band is longer than the DPR swath width of 125 km (shown by red pixels in Fig. b) and is probably longer than that of the KuPR of 245 km. Analysis of ERA5 near the time the HIP band was observed showed that the band occurred along the north of the warm front and the updraft maximum at 600 hPa surface (around a 4 km height), which is about the height of the echo tops of the HIP band. Frontogenesis and CSI are seen slightly above the echo tops of the HIP band, so that slantwise convection induced from releasing CSI could strengthen the updraft near the echo top height. Convective HIP and non-convective HIP are shown by red and green pixels, respectively, in Fig. b, but non-convective HIP rarely occurred. All HIP flags constituting the HIP band are classified into convective. This is consistent with the fact that the updraft is located near the echo tops of the HIP band.

Then we consider the vertical profiles of the HIP band, which is the key to understand the process for growing ice particles. We examined contoured frequency by altitude diagrams (CFADs) and $Z_m$(Ku) -$DFR_m$ diagram for the HIP band. The $Z_m$(Ku)-$DFR_m$ diagram is a 2-dimensional histogram of measured radar reflectivity of Ku-band ($Z_m$(Ku)) and $DFR_m$ with theoretical curves of the relation between $Z$(Ku) and DFR calculated by Mie theory for different average bulk densities. This diagram was used to distinguish precipitation phases such as liquid, melting, and solid in Liao and Meneghini (2011), but we use it to examine the difference of average bulk densities of solid precipitation for the HIP band. In fact, we reveal the difference of the distribution between the echoes of hailstorm in Naples and those of the HIP band.

Considering the vertical structure of the HIP band by the CFAD of $DFR_m$, $DFR_m$ near the echo top from 3.5
km to 4 km height have the positive values and don't change with height. Based on the $Z_m$(Ku)-DFR$_m$ diagram, the distribution near the echo tops (from heights of 4.0 to 3.2 km) is spread over the theoretical curves from rain to an ice density of 0.2 g cm$^{-3}$. Ice particles in the zone near the echo top are considered to be generated, grown, and mixed under the larger updraft. The updraft is likely to be strengthened by releasing CSI. Therefore, this zone is expected to be a seeder zone with generating cells. In the zone below, the CFADs show that the DFR$_m$ increase with decreasing height. This indicates that median size of solid particles is increasing from 3.5 km to 2.5 km. In the zone below 2.5 km, the effect of difference between attenuation of Ku-band and that of Ka-band seems to be large so that we cannot discuss the size of precipitation there. The $Z_m$(Ku)-DFR$_m$ diagram shows that ice particles in the zone from 3.5 km to 2.5 km become less dense from 0.5 g cm$^{-3}$ to 0.1 g cm$^{-3}$ with decreasing height. This zone is associated with weak updraft. Therefore, the density transition (size transition) is probably because precipitating ice particles aggregate others and cloud ice as they fall. This zone is regarded as a feeder zone, where the aggregation of solid particles mainly occurs.

It remains difficult to study the generation process of precipitation particles in the heavy snowband associated with oceanic extratropical cyclones. This study shows that the three-dimensional dual-frequency observation by DPR allow us to examine the microphysical process of the heavy snowband.

Figure. (a) Infrared image of the extratropical cyclone (grey scale). Yellow inside white lines indicates observed area by DPR, and green contours indicate temperature at 850 hPa surface based on ERA5. (b) Enlarged view of the rectangle in (a); convective Heavy Ice Precipitation (HIP), non-convective HIP, convective precipitation (no HIP), and non-convective precipitation (no HIP) are shown by red, green, orange, and cyan, respectively. Gray lines show the edges of the inner swath. Markers indicate the cold (x) and warm (o) fronts at 600 hPa Contours indicate pressure velocity $\omega (≡dp/dt)$ at 0.5 Pa s$^{-1}$ intervals on 600 hPa plane (dashes indicate negative values).

Keywords: GPM/DPR, solid precipitation, ice particle density, extratropical cyclone