An Observational Study of Heavy Rainfall with Mesoscale Convective Systems over the Korean Peninsula

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1. Introduction

During the period from night of 26 to morning of 27 July 1996, heavy rainfall resulted form MCSs occurred over the middle Korean Peninsula. The heavy rainfall caused devastating flash floods and landslides which to result in 86 fatalities and about 480 million US dollars worth of property damage. This case is a good example of unusually strong convective events responsible for heavy rainfall after the Changma period (Lee et. al., 1998). For analysis of this case study, the WSR-88D radar data was one of the important observation data set available in Korea. In this study we focus on mesoscale convective systems (MCS) which were most responsible for flash floods over the central Korean Peninsula for 6 hours. We investigate what are indicators and predictors were in the evolution, movement and propagation of convective storms resulting in heavy rainfall, and the reliability of radar-retrieved rainfall data to improve very short-range forecasts.

2. The environments of the heavy rainfall case

2.1. Synoptic- and storm-scale environments

Figure 1 shows the surface chart and 850 hPa height, mixing ratio and wind with the locations of upper-level jet (UJL) and low-level jet (LLJ) based on NCAR reanalysis data at 1800 UTC 26 July 1996. Approximately at this time, the MCSs producing the flash flooding began to be organized over the central Korean Peninsula. A quasi-stationary frontal system over northern Korea extended from a weak low center locating in the northern East Sea. Typhoon Gloria also approached the southeast coastal area of China followed by Typhoon Herb in the same track as Gloria. More moisture was supplied to the Korean Peninsula by Typhoon Gloria which also contributed to intensified low-level jet. A weak upper-level jet approached the Korean Peninsula from northern China to increase instability in the region. Figure 2 shows mesoscale surface analysis at 1800 UTC 26 July. The antecedent MCS generated around 0900 UTC and dissipated 1600 UTC, and a new MCS initiated just after 1800 UTC. A meso-high pressure dominated over the eastern part of the central Korean Peninsula while a meso-low pressure located over the northern Korean Peninsula and a mesoscale trough also located approximately along a convective rain band passing through central Korea. A cold core collocated with the centers of meso-high and warm sector over the Yellow Sea and west coast. The
central Korean Peninsula was almost saturated resulting from the antecedent MCS from 0900 to 1600 UTC 26 July. The lifting condensation level (LCL) of 360 m and the level of free convection (LFC) of 760 m were relatively low. The CAPE value was 1779 J/kg. The vertical wind shear difference between mean wind of 0-500 m and mean wind of 0-6km was strong (7.8 m/s) and the Bulk Richardson Number (BRN) was 30 at 1800UTC 26 July 1996.. The atmosphere was potentially unstable \( \frac{\partial \theta_e}{\partial z} < 0 \) below 600 hPa. At 1800 UTC high relative humidity was caused by the antecedent MCS, and the sudden increase of relative humidity below 750 hPa was resulted from the transport of warm and humid air by increased LLJ due to increased circulation of the landfall tropical cyclone over southern China.

2.2. Topography in the middle Koran Peninsula

Figure 3 illustrates the topography of the middle Korean Peninsula with coverage range of WSR-88D (RKSG) with 50 km intervals. The Taeback Mountain (TBM) range with the height over 1.5 km running from north to south is the backbone of the Korean Peninsula. The east and southeast side of Chorwon and Yonchon are surrounded by the mountains while the west and northwest side are exposed. The steep topography played a role in preventing the convective storm systems from moving further eastward, making them quasi-stationary, and then resulting in heavy rainfall. Figure 4 shows the time series of the hourly rainfall amounts at stations, Chorwon, Deasung and Inje during the target period from 1800 UTC 26 to 0300 UTC 27 July of this case study. The maximum rainfall rate was 33 mm/hr (2300 UTC 26) at Chorwon and 65 mm/hr (2100 UTC 26) at Daesung (a ROKAF station) near Chorwon. The 63% at Chorwon and 74% at Daesung of 24-hour accumulated rainfall (259 and 243.5 mm) occurred during the target period causing wide spread flash floods and land slides at
the Imjin River basin and mountain areas.

3. Mesoscale features from Radar

Fig. 3 Topography of the central Korean Peninsula and radar coverage of WSR-88D with 50km intervals (upper) and vertical distribution of topography along the line A-B

Fig. 4 The time series of the hourly rainfall amounts at Chorwon, Deasung, and Inje from 1800UTC 26 to 0300UTC 27 July 1996

3.1. Heavy rainfall evolution and vertically integrated liquid

The storm cell identification and tracking (SCIT) algorithm for WSR-88D radar (Johnson, et al, 1998) indicated that during the target period of this study, most convective storms in MCSs were abruptly initiated on the west coastal and inland, rapidly developed, and then merged into a large convective storm near the flooding area. This process progressed in a very short time so that it was difficult to detect heavy rainfall at the operation services. Even though composite radar reflectivity field data can provide the structure of convective storms embedded in cloud bands, sometimes precipitation intensity and area are exaggerated, because they display or map the maximum radar reflectivity factor at any elevation angle as a function of location at the surface. The vertically integrated liquid (VIL) which is the sum of all radar reflectivity (converted to liquid water content) in a vertical column above a level can be a sensitive indicator to the potential of heavy rainfall. VIL has been used as an indicator for hail, and high VIL-values and the occurrences of severe thunderstorms were well correlated (Rhoda and Pawlak, 1999). Figure 5 shows the composite reflectivity greater than 40 dBZ with VIL contours greater than 10kg/m² at 2200 UTC, and the temporal patterns of VIL, reflectivity, echo base, and echo top of convective cells locating over Chorwon during the period of maximum precipitation intensity (2200-2300 UTC). In radar reflectivity, convective storms covered relatively wide areas compared to high VIL values in which convection areas were well outlined like individual cells. The composite reflectivity had a monotonic pattern from 2100 to 2300 UTC, but the precipitation patterns recorded at Chorwon was concentrated during a shorter time period from 2130 to 2230 UTC with the fluctuation of precipitation intensity with time. From 2130 to 2230 UTC the reflectivity values at Chorwon did not change significantly with increasing time, while VIL values fluctuated with approximately 30-minute intervals along with the depth of convective storms. The time variation of VIL was in agreement with observed
rainfall in this study.

**Fig. 5** Composite Reflectivity (≥35dBZ) and contour of Vertically Integrated Liquid (VIL) (≥ 10kg/m2) at 2200UTC (upper) and Trend of VIL, Reflectivity, Echo base, and Echo top from 2130UTC to 2232UTC with 5 minute interval

### 3.2. Storm evolution and movement

The movement and intensity of convective storm are main factors for the amount and location of flash flood in a heavy rainfall event (Doswell et al., 1996). The storm evolution in the MCSs was investigated by composite reflectivity and radial radial velocity field from 1900UTC to 2300UTC with 1 hour intervals (upper panel in Figure 6) and the time-height cross-section of reflectivity and radial velocity was constructed along the line A-B the most significant convective activities detected by WSR-88D at 2200UTC for investigating vertical structure (lower panel in Figure 6). From 1900UTC to 2000UTC 26 July, the well-developed convective lines paralleled with a mesoscale convergence line extended over the Taebaek Mountain Ranges, but the convective lines were broken and strong convective storms were generated after the easterly outflows resulted from the preexisting convective storms began at 2100UTC. The outflow boundaries changed into a very complex shape with time and generated very small-scale meso-cyclones ahead of the convective storms. The vertical cross-section shows new storms in the MCSs were initiated upstream of the leading convective storms, and the storm movement was very limited. The strong middle-level westerly flow (red) and low-level and upper-level easterly flow (green) dominated in the MCS. The vertical wind shear with a middle-level jet seemed to play an important role in the development of quasi-stationary multi-cell storms (Weisman, 1992).

**Figure 6.** Composite reflectivity and radial velocity from 1900UTC to 2300UTC and vertical cross-section of reflectivity and radial velocity along line A-B. Black and blue dotted line denoted each convergence line and outflow boundary, and open arrow showed the direction of flow in
the multi-cell storms

To investigate movement and propagation of the convective storms, we tracked the edges of convective storms (not shown). A convective line extended from the west coast to the TBM range during the initiation phase. However, the eastern edges of the convective line were shrunk to the west as the MCS developed and new storms were continuously generated in the upstream region of the MCS, so called quasi-stationary or backward propagation. Under the absence of strong synoptic-scale forcing which might be expected to control the movement of convective storms, the eastward movement of storms was restricted by the easterly outflows resulted from decaying storms over Taeback Mountain Ranges. The high elevated terrain along the mountain ranges near the heavy rainfall area and the easterly outflows resulted from the existing mature convective storms controlled the storm evolution and movement in this case.

3.3. Rainfall derived from WSR-88D reflectivity

Figure 7 shows the hourly rain amount derived from WSR-88D reflectivity data using the reflectivity-radar rain rate (Z-R) relationship as $250R^{1.2}$ in the WSR-88D rainfall algorithm (Fulton et al., 1998) and surface observed rainfall at Chorwon from 2000 UTC 26 to 0300 UTC 27 July 1996. The WSR-88D rainfall algorithm uses 9 bins (3×3) centered on a target point and estimates maximum, minimum and area-averaged (about 40km$^2$) rain data. The maximum values exceeded a double the minimum values at 2100UTC. The maximum and area-averaged radar rain much exceeded surface observation through the overall period except for 2300 UTC 26 and 0300 UTC 27 July 1996. The differences between and observation and radar rain might be resulted from size of the convective storms, because surface observation only represents a point value while radar rain is calculated using area-mean reflectivity values (3×3).

Figure 7. 1 hour accumulated rainfall from WSR-88D and surface observation from 2000UTC 26 to 0300UTC 27 July 1996

Figure 8 shows the spatial distribution of hourly accumulated rainfall amount of surface observation (left) and estimated radar rain (right) from 2000UTC 26 to 0200UTC 27 July 1996. The areas of radar rain amount greater than 20mm/hr more widely spread than surface observation, and the area of greater than 50mm/hr located along the convective storm line from 2000 to 2200 UTC 26 July 1996. The radar rain had twice more than surface observation during this period. A core of radar rain from 2300 UTC 26 to 0200 UTC 27 corresponded to flash flooding regions near Yonchon and the Imjin river. The local government office reported that the 24-hour rainfall amount exceeded 500mm at Yonchon and Imjin river basin in the early morning 27 July 1996. The radar rain amounts about 400mm for 6 hours roughly corresponded to the unofficial report of observed rainfall amount over Yonchon and the Imjin river basin. With the Z-R relationship calibrated based on climatology, the rain amount derived from radar reflectivity might be an alternative parameter to be
applied to data-sparse areas for the use of flash flood warning.

![Rainfall Maps](image)

**Fig 8.** 1 hour accumulated rainfall amounts of surface observation (left) and retrieved from WSR-88D radar (right) from 2000UTC 26 to 0200UTC 27 July 1996. Areas radar estimated rainfall amount greater than 50mm/hr are shaded.

4. Summary and Discussion

In this case, the heavy rainfall was resulted from well-organized multi-cell type convective storms in MCSs. The storms abruptly initiated on the west coast and land, and then merged into a large convective storm near the Imjin River basin and Chorwon region within less than 2 hours. The multi-cell type convective storms were developed mainly by the low-level vertical wind shear induced by the outflow boundaries of decaying convective storms over the Taeback mountain ranges. The land-sea contrast along the west coast and the eastward steeply increasing mountainous topography of central Korea were favorable conditions to initiate and evolve convective storms. Relatively low LCL and FCL, moderate CAPE, low BRN number and lower troposphere vertical wind shear about 5-6 hours before the target rainfall were key parameters to indicate intense convective development. The low-level vertical wind shear controlled the propagation of convective storms. The intensity in radar reflectivity was not significantly changed with time, while VIL values fluctuated with approximately 30-minute intervals in accordance with intensity of the convective storms during the period of the heavy rainfall. The change in VIL patterns were in agreement with observed rainfall. VIL pattern was a potential indicator of intensity and movement of the storms in this case. The radar-retrieved rain pattern slightly shifted westward compared to observed rainfall, but corresponded well to the flash flooding regions near Yonchon and the Imjin river basin, although its rain amount much exceeded observed rain amount before the target period of the heavy rainfall.

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References


