Development Mechanisms for the Heavy Rainfalls of 6–7 August 2002 over the Middle of the Korean Peninsula

Chul-Su SHIN and Tae-Young LEE

Laboratory for Atmospheric Modeling Research, Department of Atmospheric Sciences, Yonsei University, Seoul, Korea

(Manuscript received 17 August 2004, in final form 23 May 2005)

Abstract

An investigation has been made to understand the development mechanisms for the heavy rainfalls of 6–7 August 2002 over the middle of the Korean peninsula, using both observations and a numerical model. This paper describes 1) the observed heavy precipitation systems, 2) the environment and its relation to the heavy rainfalls, 3) simulated heavy rainfalls and the role of latent heat release, and 4) the mechanisms for the heavy rainfall development.

Heavy rainfalls occurred over the mid-peninsula with a maximum precipitation amount exceeding 300 mm during the 18-h period of 12 UTC 6–06 UTC 7 August. Observations showed that convection bands continuously developed over the Yellow Sea and coastal area near the mid-peninsula. They moved eastward, and embedded convective cells developed into deep convections, producing heavy rainfalls over the coastal and inland areas. A large meso-β-scale rainfall area with several heavy-rain cells formed inland, ahead of the low-level jet (LLJ) maximum area where strong convergence occurred. A close relationship was found among the LLJ, upper-level jet streak (ULJS), and heavy rainfalls. In this event, large-scale conditions not only provided a favorable environment for the development of the heavy rainfalls, but also actively interacted with mesoscale systems.

Simulation using MM5 has well reproduced the convection bands over the coastal area, and the large meso-β-scale rainfall area with heavy-rain cells over the inland area. Simulated results suggest two types of band formation: one initiated by an elongated convergence of large-scale flows, and another initiated by convective cells existing in a strong southwesterly air stream. Simulations also indicate that both the LLJ and ULJS are intensified and maintained by convective heating. A favorable, large-scale environment, and its interaction with convective systems, may be the primary reason for the persistence of the heavy rainfalls.

1. Introduction

A significant portion (normally 53%, or about 700 mm) of the annual precipitation on the Korean peninsula is due to heavy rainfalls during summer (KMA, 2001). Heavy rainfalls during summer occur in association with the summer monsoon of East Asia. The major rainfall period is called the Changma in Korea (the Baiu in Japan and the Meiuy in China). Changma normally starts in late June and ends in late July. Another characteristic feature of the summer-time climate over the peninsula is that heavy rainfalls also occur often in August. However, the heavy rainfalls in August are less intensively studied than those in the Changma period.

Heavy rainfall can be produced by disturbances of several types in Korea. For example, some heavy rainfalls are generated by meso-
scale depressions that originate in China, and propagate eastward along the Changma front (Park et al. 1986; Lee et al. 1998), also by band type convections which develop locally over the Korean peninsula (Sun and Lee 2002), and further by squall lines, isolated storms and typhoons, etc. Lee et al. (1998, 2005) suggest that a strong convergence ahead of a low-level jet (LLJ) plays an important role in the production of the heavy rain associated with an eastward propagating disturbance. Convection bands may develop over the area of large-scale converging flow between the western Pacific subtropical high (WPSH) to the south, and an extratropical cyclone to the north (Sun and Lee 2002). Mechanisms of heavy rainfalls are partially understood in general.

The synoptic environment for the heavy rainfall period may be characterized by the following features: 1) presence of the WPSH to the southeast of the Korean peninsula, 2) an LLJ to the south of the heavy rainfall (Kim et al. 1983; Hwang and Lee 1993), 3) an upper-level jet to the north of the heavy rain area (Kim et al. 1983).

Close relationships between heavy rain and the LLJ have also been found in various studies of the Baiu and Mei-Yu rainfalls (Akiyama 1973; Matsumoto 1973; Chen 1982; Chen and Yu 1988; Nagata and Ogura 1991; Ninomiya and Akiyama 1992). Heavy rain often occurs in the left-front quadrant of the LLJ axis, or in advance of a wind maximum (Chen 1982). Matsumoto (1973) found that the peak of heavy rainfall was in phase with the maximum acceleration of the LLJ. Various suggestions have been made concerning the physical processes through which an LLJ contributes to the occurrence of heavy rainfall. Matsumoto (1973) and Chen (1982) suggested that an upward branch of the secondary circulation associated with an LLJ was responsible for the heavy rainfall. Chen (1977) pointed out that an LLJ was the main mechanism for creating potential instability on the warm side of a Mei-yu front, and for generating the convective heavy rainfall by the associated convergence downstream. Chen (1982) argued that the triggering mechanism of the heavy rain was not the jet itself, but the distribution of the maximum wind speed along the jet.

Coupling of upper- and low-level jets is also suggested as a favorable structure for some heavy rain systems. According to Chen’s (1982) observation, rainfall over China occurs to the south of the entrance region of an upper-level jet (ULJ), and to the north of exit region of an LLJ. And he also suggested that if these two areas moved close to each other, a deep layer of ascending motion and heavy rain should be observed in the area between the two jets. A similar coupling is also found for the present heavy rain system. This is different from the type found by Shapiro (1982) and Uccellini and Johnson (1979) for some heavy rainfalls in the central United States, in which secondary circulation associated with the exit region of a ULJ is coupled with that of an LLJ. It is interesting how the coupling found by Chen (1982) occurs, and how it affects the development of heavy rain.

This study attempts to explain the development mechanisms for the heavy rainfalls of 6–7 August 2002 over the middle of the Korean peninsula (Fig. 1a). The present precipitation systems are described in section 2. The observed environment and its relation to the heavy rainfalls are analyzed in section 3. Numerical experiments are performed to find out the developing processes for precipitation systems and the role of convective heating in section 4. Development mechanisms for heavy rainfall are presented by integrating the results from observational and numerical investigations in section 5. And finally, concluding remarks are given in section 6.

2. Precipitation systems

Heavy rainfalls occurred over the Korean peninsula during the 12-day rainy period of 3–14 August 2002. During this period, the accumulated rainfall amount exceeded more than 600 mm at two stations and 500 mm at 14 other stations. A major portion of the rainfall amount occurred in the 18-h period of 12 UTC 6–06 UTC 7 August 2002, during which much of the mid-peninsula showed a rainfall amount of more than 200 mm, with a maximum exceeding 300 mm (Fig. 1a). Explaining this 18-h heavy-rain event is the target of this study.

A satellite-derived rainfall amount is also shown for 6 August in Fig. 1b using the daily rainfall amount from the Global Precipitation Climatology Project (GPCP) data. Although
this estimate is significantly smaller than the surface observation, it can be used to show the extent and location of a major precipitation area in a situation of a large region devoid of observation. Rainfall along the coastal region of southeastern China was caused by a tropical depression, which had been formerly a typhoon before landing. A typhoon landing in this area sometimes influences the rainfalls over the Korean peninsula. However, it appears that the rainfall over the Korean peninsula in the present case is not directly connected to that over southeastern China.

Enhanced infrared images are shown in Fig. 2. They show small convective cells developing over the Yellow Sea near the west coast of the Korean peninsula at 16 UTC 6 August (not shown). They develop into deep convections, and form bands of convective cells (Figs. 2a, b). The cloud-top temperature is lower than $-50^\circ$C in this convective cloud area. At 21 UTC, convective systems have become organized into a band of strong convection over the sea, and a cluster of convective cells over the inland area (Fig. 2c). Another convective system is found over the west coast to the south of the convection band. It becomes linked to the major system to the north.

Radar images show more clearly the extent and movement of the precipitation systems (Fig. 3). Precipitation bands exist at 1230 UTC 6 August 2002 over the sea and extend to an inland area of the mid to northern peninsula (Figs. 3a, b). They weaken with time, and the band shapes disappear at 1430 UTC (Fig. 3c).

The precipitation systems of our interest can be found at 1630 UTC (marked N and S2, indicating northern and southern bands, respectively). The N band has developed from a part of the previous convection band at 1430 UTC (indicated by an arrow). It extends more than 200 km toward both the coast and the sea. The southern band (S2) is found to the south of the N band. It has evolved from multiple bands developed over the sea (upstream of S1) at 1430 UTC. Prior to this S2 band, another southern band (S1) appeared at the coastal area at 1330 UTC, initiated by convective cells over the area at around 1200 UTC (Fig. 3a).

After 1630 UTC, several new bands develop between the two major bands and also to the southwest of the bands. They mostly combine with the northern band. Eventually, a well-defined band of heavy precipitation forms at 2030 UTC. The band persists until 2200 UTC and then turns and moves southeastward. It becomes part of a wide band of rain area at 0200 UTC 7 August. The entire band begins to move slowly southeastward at around 0400 UTC (not shown). Thus, heavy rainfall over the mid-peninsula ceases, mainly due to the southeastward movement of the whole precipitation band, not due to dissipation. After 0900 UTC 7
August, the precipitation band becomes quasi-stationary again over the southeastern part of the peninsula. This movement is associated with the southward development of a trough over the Yellow Sea at around 6 UTC on 7 August (not shown).

A relatively large rain area is found inland to the east of the major bands for much of the case period, mainly due to the continuous eastward propagation of precipitation systems from these bands, and the northeastward propagation of systems from the southwest. Precipitation systems over some inland areas (e.g., the area marked by a dashed circle in Fig. 3i) do not seem to be detected well by radar images. A 15-minute rainfall amount from a network of automatic weather stations (AWSs) (Fig. 4) may be useful for depicting the propagation and the development of cells in this inland area. The AWS network is a high-density surface observation system, with an average distance between neighboring stations of less than 20 km (locations of AWSs are shown by dots in the last panel of Fig. 4). A large meso-β-scale rain area, with several heavy-rain cells can be found over the inland area. The cells in this area seem to be mostly originated from the bands. The figure also shows cells associated with the two major bands near the west coast. At 1845 UTC 6 August, cells along the northern band are found around Seoul (marked by a “+” in the figure for 1930 UTC). And a cell associated with the southern band is found to the south of Seoul. They move in an eastward or northeastward direction. Some of them seem to last 2 hours or longer. Merging of the two bands is found over an inland area at 1900 UTC.

According to the radar images and AWS
rainfall data, convection bands continuously develop over the sea and coastal area. They move inland and embedded convective cells develop into deeper convections, producing heavy rainfall. It appears that these convection bands are roughly parallel to the LLJ direction (to be shown later in Fig. 6b), while heavy rainfalls in the large meso-β-scale rain area over the inland
area are located ahead of an LLJ maximum. Cells over the sea move northeastward along the bands, and then over the inland area, move eastward, being located ahead of an LLJ maximum.

3. Environment of heavy rainfalls

The following analysis has been made using the global analysis data from the Global Data Assimilation System (GDAS) of the US National Center for Environmental and Prediction (NCEP). These data are provided on 1° × 1° grids at 26 vertical levels from 1000 hPa to 10 hPa every 6 hours. The GDAS is run with horizontal resolution of roughly equivalent to a global 55 km mesh. The detailed information, and references of the GDAS, can be found in the GDAS documentation site (http://www.emc.ncep.noaa.gov/gmb/gdas/documentation).

3.1 Large- and meso-scale environment

Figure 5 shows the geopotential height and temperature fields at 300 and 500 hPa, and surface weather charts at a 12-h interval. Both height and thermal troughs at upper levels extend southwestward from northeastern China. Relatively strong gradients of height and temperature are found at 300 hPa, especially over downstream of the troughs. The western Pacific subtropical high (WPSH) is quite steady during this episode. Overall, the large-scale patterns change quite slowly.

At the surface, an extensive trough is found between a continental high and the WPSH (Fig.
This trough is extended from the tropical depression in southern China to the extratropical cyclone over northern Japan. The present heavy rain occurs in this low-level trough over the middle of the peninsula.

Wind vectors and isotachs at 200- and 850-hPa levels are shown for 12 UTC 6 August in Fig. 6. A well-defined upper-level jet streak (ULJS) is found to the downstream of the upper-level trough (Fig. 6a). It extends northeastward from the northern part of the Korean peninsula. It can be found that heavy rainfall area is located under the right side of the jet-streak entrance region. At 850 hPa, an extended belt of strong southwesterly is found along the northwestern flank of anticyclonic circulation associated with the WPSH (Fig. 6b). Cyclonic circulation associated with the 850-hPa trough is found to the north of the peninsula. The extended strong southwesterly develops due to a strong pressure gradient, caused by the development of a trough along the northwestern flank of the WPSH.

The large-scale condition (extended trough between the WPSH and the continental high) produces a narrow pathway of moist-air transport from southern China to the Korean peninsula. This is well illustrated by Fig. 7. An area of equivalent potential temperature over 340 K is extended along the low-level trough, and becomes squeezed toward northern Japan where the continental high expands southward. In this environment, a strong southwesterly can continuously transport a large amount of warm and moist air to the peninsula.

In this case, a quasi-stationary upper-level trough is located to the northwest of the peninsula. To examine the influence of large-scale
quasi-geostrophic (QG) forcings (Laplacian of horizontal temperature advection, and vertically differential horizontal vorticity advection), Q-vector analysis has been carried out for the entire troposphere. For 12 UTC 6 August, when heavy rainfall begins over the mid-peninsula, a weak to moderate convergence of Q-vector is found over the western part of the mid-peninsula throughout the troposphere, while a moderate divergence is found over the eastern part of the mid-peninsula (not shown). At 18 UTC, when convective systems are very active, a weak convergence of Q-vector is found over the Yellow Sea and the west coast, while a significant divergence of Q-vector is found over the mid- and northern peninsula (Figs. 8a, b). The strongest convergence of Q-vector is found downstream of 500-hPa trough, to the north of the peninsula. These features can be understood by examining the related fields. It can be found that the vorticity advection at 500 hPa is not significant over the mid-peninsula (Fig. 8c). At 850 hPa, a weak advection of warm air can be found over the mid-peninsula (Fig. 8d). However, cold air advection exists at lower levels (e.g., 925 hPa) over the northern peninsula (see Fig. 9a).

The present analysis indicates that QG forcings may provide a favorable environment for the convective systems over the west coast by inducing large-scale rising motion. However, their influence appears to be weak in general, due to their own weakness. Over the inland area, the QG forcings are not favorable for the convective development, especially over the eastern part of the mid-peninsula.

Fig. 6. Wind vectors (arrow) and isotachs (m s\(^{-1}\), solid) at (a) 200 hPa and (b) 850 hPa for 12 UTC 6 August 2002. Contour intervals are 5 m s\(^{-1}\) from 40 m s\(^{-1}\) and 2.5 m s\(^{-1}\) from 15 m s\(^{-1}\) for 200 hPa and 850 hPa, respectively.

Fig. 7. Equivalent potential temperature (K) at 700 hPa for 1200 UTC 6 August 2002. Shading denotes the area with the temperature > 340 K.
Some mesoscale features can be found in the environment shown in Fig. 9 for 18 UTC 6 August. Airflow at 925 hPa over the Yellow Sea near the mid-peninsula shows a converging flow pattern: a weak westerly associated with the low over Manchuria, and a strong southwesterly to the south (Fig. 9a). This low-level flow pattern is similar to that for a convection band studied by Sun and Lee (2002). They suggested that the convection band formed through the interaction between large-scale converging flow and convection. This mechanism can be important for a convection band found in this study. In the mean time, a significant convergence and resultant upward motion is found at low levels ahead of the LLJ maximum (Figs. 9a, c). Upward motion is found through the peninsula, with the strongest ascending motion at the mid-western coast. This rising motion appears to be due to mesoscale convergence ahead of the LLJ and other mesoscale forcings (e.g., convective heating), rather than QG forcings. On the other hand, a significant descending motion is found over the east coast of the mid-peninsula, where the Q-vector divergence is found.

A relatively strong gradient of equivalent potential temperature \( (\theta_e) \) exists over the mid-peninsula (Fig. 9a). And a thermal trough and easterlies are found to the northeast of the in-
land heavy rain area. These are associated with a weak pressure ridge at a low level along the east coast of the northern peninsula (Fig. 5c). This condition may be an important factor inhibiting the northeastward propagation of convective systems. Figure 9b shows a cross-section of $\theta_{e}$ along the line B-B' in Fig. 9a. Low-level air is nearly neutral over the heavy rain area (marked by ●). Some convergence, and rising motion, is found over the area. The air to the south of the major band is potentially unstable with the lifted index (LI) of $-2$ for 18 UTC, according to a sounding at Osan (marked by “○” in Fig. 1a).

3.2 Relationship between heavy rain and jets

In the present episode, heavy rain occurs on the right side of the entrance region of the ULJS with an LLJ maximum to the south. The ULJS (solid), and LLJ (dashed), divergence (shaded) and ageostrophic winds at 200 hPa are shown in Fig. 10. The LLJ extends further northeastward, and strengthens during 06–18 UTC 6 August. At 18 UTC 6, an LLJ maximum is found to the south of the peninsula with a significant gradient of wind speed over the mid-peninsula. The ULJS shows a southwestward development at 18 UTC. Due to these local developments of winds at low and upper levels, the two jets become closer to each other in location during 18 UTC 6–00 UTC 7 August. Relatively strong rainfall has occurred over the mid-peninsula during this period of closely located jets. This may imply a close relationship between the two jets and the development of heavy rain.

A relatively strong upper-level divergence occurs just ahead of the LLJ maximum at 06 UTC 6 August, when the ULJS is some distance away from the LLJ (Fig. 10a). Heavy rainfall occurs in the southern part of the peninsula at around 06 UTC. Scattered convections are found near the entrance region of the ULJS (not shown). At 12 UTC, a weak divergence $(3 \times 10^{-5} \text{ s}^{-1})$ is found between the entrance region of the ULJS and the LLJ (Fig. 10b). Heavy rainfall develops over the mid-peninsula after 12 UTC. Upper-level divergence becomes strong at 18 UTC (Fig. 10c). A satellite image for 18 UTC indicates that the strong divergence is occurring over deep convective systems in the mid-peninsula. This enhanced upper-level di-
vergence seems mainly due to convective activities.

Since the upper-level trough is nearly stationary, air may travel along the jet stream, passing through the trough and the ULJS. Air moving through the right side of the entrance region may experience a vorticity decrease and divergence. According to a calculation using a frictionless form of vorticity equation, the divergence is estimated to be about $2.3 \times 10^{-5}$ s$^{-1}$, if other terms (e.g., twisting term) are neglected [i.e., $D(\zeta + f)/Dt = -\delta(\zeta + f)$, where $\delta$, $\zeta$ and $f$ represent horizontal divergence, relative and earth vorticity, respectively]. This value is comparable to the analyzed upper-level divergence for 12 UTC on the right side of the entrance region, and more than a quarter of the divergence for 18 UTC 6 and 00 UTC 7 August. Note that the upper-level divergence just ahead of the LLJ found for 06 UTC 6 August, in a situation of relatively large distance between the two jets, is as large as that for 18 UTC.

A relatively strong cross-jet ageostrophic motion is found at the entrance region of ULJS (Fig. 10). This ageostrophic motion can contribute to the maintenance of jet streak through Coriolis acceleration (Uccellini and Johnson 1979). Strong westward ageostrophic motion
exists over the upstream area of the jet streak.

The close relationship between convection and jets also can be found in the secondary circulation. Figure 11 shows wind vectors parallel to the plane A-A’ (location of the plane is shown in Fig. 10b). Two major ascending motions are found at 12 UTC 6 August: one below the jet core and the other to the south of the jet streak. At 18 UTC 6 August, a single, strong, ascending motion through the entire troposphere is found over the southern side of the jet streak. A strong low-level convergence is found over the heavy rain area, to the north of LLJ. Both upper-level divergence, and low-level convergence, have been enhanced significantly, as compared to those for 12 UTC.

The coupling of secondary circulations associated with the ULJS and LLJ found in this study is in accord with the type found by Chen (1982) for heavy rain in China. And the upper- and low-level jets are nearly parallel to each other. Uccellini and Johnson (1979) argued that the transverse circulation in the exit region of an upper-level jet superposed above an LLJ could increase the amount of potential instability through differential ageostrophic advection of temperature and moisture. To understand whether the present system is accompanied with such a change in potential instability, the change of potential instability prior to the heavy rainfall has been examined, using the sounding at Osan (marked by “O” in Fig. 1a, located about 40 km to the south of Seoul). Air over Osan for 00–12 UTC 6 August (i.e., prior to the present heavy rainfall) is stable (Table 1). At 18 UTC, when heavy rainfalls are occurring over the mid-peninsula, the air is rela-

Table 1. Convective available potential energy (CAPE) (m$^2$ s$^{-2}$) and lifted index (LI) for 00 UTC 6–06 UTC 7 August 2002 at Osan and Gwangju. Location of Osan is marked by “O” in Fig. 1a. Gwangju is located in the southwestern part of the Korean peninsula (35.1’N, 126.8’E).

<table>
<thead>
<tr>
<th>hour (UTC)</th>
<th>6 August</th>
<th>7 August</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>00</td>
<td>06</td>
</tr>
<tr>
<td>Osan CAPE</td>
<td>776</td>
<td>11</td>
</tr>
<tr>
<td>Osan LI</td>
<td>−3</td>
<td>4</td>
</tr>
<tr>
<td>Gwangju CAPE</td>
<td>1179</td>
<td>1077</td>
</tr>
<tr>
<td>Gwangju LI</td>
<td>−4</td>
<td>−4</td>
</tr>
</tbody>
</table>
tively unstable. However, the convectively available potential energy (CAPE) is still not large. Examination indicates that no significant advective temperature change is found at 500 hPa prior to, and during the heavy rainfall period. The increased instability at 18 UTC is mainly due to the low-level transport of warm and moist air from the southwest. The sounding at Gwangju (35.1°N, 126.8°E), which can represent the inflow condition, shows that potential instability is generally significant throughout the case period (Table 1). A comparison with the Osan sounding indicates that the significant potential instability over Gwangju is mainly due to conditions at low levels (not shown). This analysis indicates that the potential instability required for the convective systems over the mid-peninsula is mostly supplied by the low-level advection.

The present analysis has revealed much about the environment for heavy rainfalls: 1) heavy rain systems develop in the low-level trough, between the WPSH to the southeast and a continental high to the northwest, 2) a quasi-stationary upper-level trough is found throughout the case period, 3) large-scale forcings may provide a favorable environment for the development of convective systems over the west coast area by inducing a large-scale rising motion. However, their influence appears to be weak due to their own weakness, 4) large-scale converging flow is found over the area of the convection bands, 5) a coupling of secondary circulations associated with the upper- and low level jets is found, etc.

4. Numerically-simulated heavy rainfall systems

Analyses shown in the previous sections have revealed much about the precipitation systems and their environment. However, more explanations are necessary for several aspects of the present case: formation of convection bands, development of jets and their roles for heavy rain, the processes of heavy rain development, and persistence of heavy rainfalls, etc. These will be studied further in this section, using a numerical model.

4.1 Numerical model

The PSU-NCAR non-hydrostatic mesoscale model (MM5 version 3) (Grell et al. 1994) is used for the present study. Model physics used here include the mixed-phase microphysics scheme of Reisner et al. (1998), the PBL scheme of Hong and Pan (1996), etc. Cumulus parameterization (CP) is deactivated in both coarse and nested domains, since the simulation (precipitation) without it agrees better with the observation in this case than do several other simulations with it. Park and Lee (2002) also found that heavy precipitation systems did not develop properly with CP in their simulation of a convection band.

The model domain consists of a 30-km grid domain (DO1, 191 × 171 horizontal grid points) and a 10-km grid domain (DO2, 181 × 190 grid points) with 33 vertical sigma levels to the model top, 100 hPa (Fig. 12). A one-way nested grid system is used. The results presented here are from the 10-km grid simulations. The model run is initiated using the GDAS data of NCEP. Numerical integration for the large domain (DO1) is carried out for 36 hours from 00 UTC 6 August 2002. A four-dimensional assimilation of observation is used for the initial 12 hours. The integration for the 10-km grid domain is carried out for 24 hours from 06 UTC 6 August.

4.2 Simulated fields and comparison with observation

Simulated rainfall amount is shown in Fig. 13 for the 18-h period of 12 UTC 6–6 UTC 7 August. The location and the amount of rainfall agree well with the observation shown in
Fig. 1a. And the simulation has also captured well the concentration of rainfall over the peninsula (Fig. 1b).

The simulated 1-h rainfall amount is compared with the observation (from the AWS network) in Fig. 14. The simulation shows continued heavy rainfall over the mid-peninsula as the observation. Although discrepancies are found in the location and amount of rainfall, the simulation has captured some important features of the evolution of heavy rainfall. For example, the formation of convection bands near the west coast, the locations of the two major bands (i.e., the northern and southern bands), eastward movement of convective cells, and merging of the two bands in an inland area, especially for 19 UTC 6 August, are well reproduced. Relatively large discrepancies are found for the early period: cells move slower than the observed ones during 14–16 UTC 6 August, resulting in an over-prediction of the maximum rainfall amount. And the simulated rainfall amounts by the southern band are larger than those by the northern band, unlike the observation (see 19 and 20 UTC in Fig. 14).

Simulated height and wind fields for 850-hPa are shown in Fig. 15. An extended, wide trough is found between the two highs, the WPSH and the continental high. A belt of strong southwesterly is found along the northwestern edge of the WPSH. Significant variation of wind is found over the heavy rain area (the mid-peninsula), ahead of the LLJ. At 18 UTC 6 August, a converging airflow is found between the westerly to the north and the southwesterly to the south over the Yellow Sea off the mid-peninsula. A strong convergence is found in the inland heavy rain area between the northerly and southwesterly winds at 00 UTC 7 August.

Evolution of a simulated precipitation system is shown in Fig. 16. At 13 UTC 6, a southwesterly dominates the Yellow Sea area, except for the northern part where air is from the northwest, and turns cyclonically as it passes over the west coast. A narrow band of weak echo (indicated by an arrow in Fig. 16b) forms at 15 UTC over the sea, where the two large-scale airflows converge. During the next two hours, it develops into a long band (band N) with embedded convective cells. To the south of this band, two strong convection cells are found over the coastal area at 15 UTC, along the northern edge of the LLJ (Fig. 16b). As these cells move inland, new convection cells form successively in the upstream direction. Cell B develops upstream of these cells at 16 UTC (Fig. 16c). Cells tend to grow stronger as they move inland. The two bands meet each other at the inland area, and some cells from the two bands merge, producing a large, heavy rain area at 19 UTC (Fig. 16e). This heavy rain area is located ahead of an LLJ maximum, where strong convergence occurs. These behaviors of cells are consistent with observation.

The convection bands over the sea become integrated into a single band at around 2030–2100 UTC 6 August, as a northerly associated with a cyclonic circulation pushes the northern band toward the south. The time and location of this single-band formation agree with those of the observed. However, the process is somewhat different. In the observation, several narrow bands continuously form between the northern and southern bands, and combine with the northern band to form a single band at a similar time and location.

When compared with the radar images and rainfall data, the simulated fields are consistent with the observation in the following aspects. Heavy rainfall has continued over the mid-peninsula for 12 UTC 6–04 UTC 7 August.
The model has reproduced well the various mesoscale precipitation systems, such as the convection bands over the coastal area, and the large meso-β-scale rain area with heavy rain cells over the inland area. Simulated convective cells, moving inland, develop and maintain their strengths for a few hours. Another important agreement is that simulated convection bands are roughly parallel to the LLJ direction, while heavy rainfalls in the inland area are occurring ahead of an LLJ maximum.

On the other hand, model results show some disagreements in the detailed formation processes of the major band. For example, the southern band prevails to become a single, well-developed band of convection in the simulation. However, in the observation, the single band of intense precipitation develops through continuous integration with newly forming neighbor bands. And the observed southern
band weakens as the single dominant band develops to the north. Another disagreement is that the observation shows many bands, while the simulation produces only 2 or 3 bands.

Although the present simulation shows significant discrepancies from the observation as described above, it can be useful for understanding 1) how the convection bands form, 2) how the convective systems intensify and maintain their strengths for 2–4 hours, producing heavy rain as they move inland, 3) what causes the heavy precipitation systems to maintain over the mid-peninsula for an extended time, and 4) how convective systems and large-scale environment interact, etc. These are investigated further next.

4.3 Formation of convection bands

The southern band in Fig. 16 forms within the air stream of the southwesterly LLJ, while the northern band forms in the area of large-scale convergence. As already mentioned for the northern band type, the interaction between the large-scale converging flows and convective systems is suggested to be a formation mechanism by Sun and Lee (2002). Here, the formation of the southern band is described.

Figure 17 shows wind vector difference from the wind at 12 UTC (i.e., $V_t - V_{12 UTC}$) and convergence at 850 hPa during the formation period. Convergence associated with the northern band occurs in an elongated pattern. It seems to occur mainly due to the change of wind direction (toward westerly or northwesterly) over the northern part of the Yellow Sea. This is similar to that found by Sun and Lee (2002). On the contrary, convergence over the southern band area develops in a cell pattern. It can be found that a new cell develops in the upstream (southwestern) area of a convective cell. This seems due to the creation of convergence in the upstream area by the convective circulation associated with the existing cells. And the results shown in Fig. 18 indicate some differences between the two convection bands in the development of convection (to be described next). The simulated results suggest two types of band formation: one initiated by an elongated convergence of large-scale flows, and the other one initiated by existing convective cells in a southwesterly air stream.
4.4 Development and maintenance of precipitation systems

In this case, convective cells develop in three areas: along a band occurring on the northern flank of the LLJ (convection cells form just to the left of an LLJ maximum and move along the wind direction), along a band occurring over the area of large-scale convergence, and in a large meso-β-scale rain area ahead of an LLJ maximum. The simulation has also shown that precipitation systems of the first two types move inland and then become located ahead of the LLJ in the inland area. This is consistent with the observation. The structure and evolution of the convective cells embedded in the bands are examined here.

Figure 18 shows the circulation associated with, and evolution of cells A and B (in the northern and southern bands, respectively in Fig. 16) in cross-sections (locations are marked as a1, a2 and a3 for 15, 16 and 17 UTC 6 August, respectively, in Fig. 16). The three cross-sections show the same cells with 1-h intervals. Initial convergence for cell A is found at 15 UTC in a layer between 1 km and 2 km. It grows further vertically for the next two hours. Convergence associated with cell B is found in the layer below 2 km at first. It appears to grow
from lower levels near the surface. Cell B rapidly develops into a deep convection within two hours. A strong updraft is found up to the tropopause level at 17 UTC (Fig. 18c). At 16 and 17 UTC (Figs. 18b, c), the strong southerly inflow feeds high-$\theta_e$ air mostly to the convection in the southern band, and the northern band does not receive much high-$\theta_e$ air from the south. The air to the south of the convection area is potentially unstable, with the level of free convection (LFC) below 900 hPa. Thus, lifting by convergence can trigger and maintain convection easily in a situation of continuous supply of high-$\theta_e$ air.

According to AWS rainfall data (Fig. 4), cells from different bands move eastward along each band and form a group of heavy rain cells over the inland area. Numerical simulation has reproduced these behaviors of precipitation systems in a consistent manner. The heavy rainfall systems are located ahead of the southwesterly LLJ maximum (e.g., Fig. 16e). The structure of the large meso-$\beta$-scale system in this area is examined here. Figure 19 shows a horizontal distribution of $\theta_e$ and a cross-section across the system shown in Fig. 19a. A belt of strong $\theta_e$ gradients is found across the northern domain, and the eastern part of the mid-peninsula. Most of these gradients seems due to the presence of two different air masses, that is, relatively cool and drier air to the north and warmer and moist air to the south. However, evaporative cooling may be also important for the significant gradient of $\theta_e$, to the immediate south of the large meso-$\beta$-scale rain area inland. The cross-section in Fig. 19b shows the presence of a cold pool and downdraft below the tilted, strong convergence zone. Strong convergence is found in the layer below 4 km. And a gust front between the southwesterly to the south, and outflow associated with the downdraft, is found at a low level. The convergence at the gust front and the convergence ahead of the LLJ are connected in a tilted manner, lifting a large amount of low-level air. On the contrary, air is lifted in an up-right manner for...
convections over the bands over the sea and coastal area (Fig. 18c).

The above analysis indicates that convective systems embedded in the precipitation band, and in the large meso-β-scale rain area ahead of the LLJ maximum, are different from each other in structure. The convective systems embedded in bands are vertically up-right and do not show a gust front structure, and get inflow as they move eastward. On the other hand, the convective system ahead of the LLJ maximum shows a tilted structure with a gust front. Southwesterly air is continuously moving over the gust front, and is lifted by strong convergence.

Figure 19a shows an area of a northeasterly, and significantly lower \( y \) to the northeast of the inland heavy rain area. This is consistent with the observation shown in Fig. 9a. This low-level structure appears to inhibit the northeastward propagation of the convective systems, confining the heavy precipitation systems to the inland area of the mid-peninsula. Consequently, it may be partially responsible for the development of the large meso-β-scale rain system, with heavy rain cells over the inland area (Figs. 16e, f).

4.5 Interaction between convective systems and jets

a. Coupling of low- and upper-level jets

Isotachs at 200 hPa (solid line) and 850 hPa (dashed line), and vertical velocity at 400 hPa (shading) are shown in Fig. 20. At 15 UTC 6 August, the core of ULJS is located to the northeast of the peninsula, and its entrance region is some distance away from the heavy rain area. Deep convections are found over the mid-peninsula, near the LLJ maximum, and also over the entrance region of the ULJS. The ULJS shows a southwestward development as deep convections continue to develop over the mid-peninsula. The two jets are close at 18 UTC, and deep convections are more active (Figs. 20b, c). At 00 UTC 7 August, the entrance of ULJS is over the west coast, and its core is over the northern peninsula. Location and intensity of the ULJS agree well with the observation.

The simulation has also reproduced the coupling of low- and upper-level jets in the same manner as the observation (Fig. 21). At 15 UTC
6 August, convective systems over the mid-peninsula (between 800–1000 km in x axis) are not coupled to the circulation associated with the ULJS (Fig. 21a). However, they become coupled at 18 UTC, mainly due to a southward development of the ULJS. The low-level jet feeds warm and moist air to the convective systems, and then the convection strongly lifts the air, producing outflow in the upper troposphere. Note that the northward winds at upper levels include both the mean flow and convective outflow.

b. Role of latent heat release

The feedback between the jets and the convective system, is examined using a no-latent-heating experiment (NOLH), in which the latent heat release is turned off at 15 UTC 6 August when convection bands begin to form near the west coast of the mid-peninsula. Geopotential height and temperature fields from the control (CTRL) and NOLH experiments are compared in Fig. 22 for 00 UTC 7 August, 9 hours after turning off the latent heating. Effects of latent heat release are also significant at 850 hPa (Figs. 22c, d). Both experiments show the height trough between the WPSH and the continental high. However, the trough is not deepened much and, consequently, the southwesterly along the flank of the WPSH is weaker when latent heat is neglected.

The effects of latent heat release are shown in terms of the difference between the CTRL and NOLH experiments in Fig. 23. Significant convective heating is found at the 300-hPa level in a region extended from the Yellow Sea to the northeast of the peninsula, with a maximum warming of 6 degrees over the northern peninsula (Fig. 23a). This heating results in a height increase at 300 hPa and, consequently, the increase of a height gradient in the downstream of the trough. At 850 hPa, the temperature difference is relatively small (Fig. 23c). The negative difference over the Yellow Sea near Shandong peninsula seems due to both cold advection and evaporative cooling, while the positive difference over the southern peninsula, and the surrounding seas, seems mainly due to warm advection by the southwesterly flow. Convective heating brings the deepening
around the peninsula at 850 hPa and, consequently, the strengthening of winds to the south and southeast of the peninsula. Ninomiya (1980) and Ninomiya and Tatsumi (1980) also attributed the formation of the LLJ to the increase of the pressure gradient caused by convective warming.

It can be found that the magnitudes of height difference at 300 and 850 hPa are similar to each other. Effects of convective heating on jets are well illustrated in Fig. 24. Both the LLJ and ULJS are weakened significantly at 9 hours after turning off the heating.

Figures 22 and 23 indicate that the increase of upper-level temperature downstream of the upper-level trough causes the trough to be relatively sharp and located differently, as in Figs. 22a, b. Examination has revealed that the upper-level trough has moved more eastward in the NOLH experiment than that for CTRL experiment. This is also confirmed by comparing the movements of vorticity pattern in CTRL...
and NOLH experiments during 15 UTC 6–06 UTC 7 August (not shown). Thus, the convective heating appears to have an effect of retarding the eastward movement of the upper-level trough.

These results indicate that convective heating plays a crucial role for the coupled system. It enhances both the ULJS and LLJ by increasing the height gradients. Then the enhanced ULJS may provide a more favorable environment for deep convection through enhanced upper-level divergence. And the enhanced LLJ can supply more moisture to the convection area, and also provide enhanced lifting through the convergence ahead of it. Therefore, the jets and convective systems in this case interact with each other, making positive feedback.

5. Development mechanisms for the heavy rainfalls of 6–7 August 2002

The results shown in the previous sections are integrated here to describe the process of heavy rain development. Heavy rainfalls are concentrated over the middle of the Korean peninsula for about 18 hours of 12 UTC 6–06 UTC 7 August 2002. Observation indicates that convection bands develop continuously over the west coast of the mid-peninsula during much of the present case period. They move inland and some cells develop rapidly, producing heavy rainfall over the coastal and inland areas. These heavy precipitation cells are a few tens of km wide. Some of them last for several hours. A large meso-β-scale rain area, with several heavy rain cells is found inland, ahead of an LLJ maximum. Cells from the coast continuously move to this rain area. During the later stage of the present case, precipitation systems are produced in a wide band of rain area, which is extended northeastward from the southwestern coast of the peninsula. Precipitation systems continue to occur over the mid-peninsula, until around 06 UTC 7 August. Heavy rainfall ceases over the mid-peninsula, mainly due to the southeastward movement of the whole cloud band.

The present heavy rainfalls develop in a favorable large-scale environment. An extensive low-level trough is found along the eastern coast of Asia between a continental high and the WPSH. Also, an extended belt of a strong southwesterly develops at low levels along the northern flank of the WPSH, due to a strong pressure gradient caused by the development of a low-level trough. Heavy rainfalls occur in this trough over the mid-peninsula. A quasi-stationary, upper-level trough is found to the northwest of the peninsula, and an upper-level jet streak extends northeastward from the

\( \text{Fig. 21. Isotachs (m s}^{-1}, \text{solid and dashed) and circulation vector (arrow) in a cross section along the line (a) in Fig. 20a and (b) in Fig. 20b.} \)
northern Korean peninsula. These large-scale conditions play important roles for heavy rainfall development: the strong, low-level southwesterly transports a large amount of moisture toward the peninsula, large-scale converging flow at low levels may be essential for the development of convection bands, and the quasi-stationary upper-level trough allows a continued presence of the ULJS, with its entrance region over the mid-peninsula. Both upper- and low-level jets appear to strongly influence the present heavy rainfall. Relatively strong rainfall has occurred during the period of closely located jets, with the LLJ to the south, and the entrance of the ULJS to the north.

Numerical simulation has also shown the formation of convection bands over the sea and coastal area. Two types of band formation are identified from the simulated results. The northern band develops in an elongated area of large-scale convergence. It develops through interaction between a large-scale converging flow, and the convective systems. On the other hand, the southern band develops in a southwesterly air stream, as convection cells produce flow convergence to their upstream side. Con-

Fig. 22. Simulated geopotential height (solid) and temperature (dashed) from (a and c) control (CTRL) and (b and d) no-latent heat (NOLH) experiments for 00 UTC 7 August 2002. Upper and lower panels are for 300 and 850 hPa, respectively.
vective cells embedded in these bands move inland and develop further, producing heavy rain. Another important heavy precipitation system reproduced by the model is the large meso-β-scale rain area, with several convective cells over the inland area, ahead of an LLJ maximum. Some cells combine to form a large precipitation system. This precipitation system shows a self-maintaining structure, with the incoming low-level air flowing over a gust front, and being strongly lifted by the convergence ahead of the LLJ maximum. A cooler downdraft is found behind the gust front, with a cold pool near the surface and outflow toward the gust front. Low-level convergence at the gust front, and the convergence of the LLJ air are connected in a tilted manner, lifting a large amount of low-level air. On the contrary, for the
convective cells embedded in the precipitation bands, air is lifted from a low level in an upright manner.

The present analysis indicates that the LLJ is the essential element for the development of heavy rainfall. The LLJ can provide both moisture supply and the mechanism of strong lifting of air. The model results indicate that deep convections over the mid-peninsula bring the southwestward development of the ULJS. Then, the ULJS allows the convective systems over the mid-peninsula a more favorable environment by providing upper-level divergence. Potential instability over the mid-peninsula is not significant prior to, and during the heavy rainfall period. And no significant advective cooling is found at the upper levels (e.g., 500 hPa) over the area. The heavy precipitation systems develop mainly through the release of transported potential instability.

Convective heating plays the key role for the present coupled system, according to the model results. It increases the mid- to upper-level baroclinicity, enhancing the upper-level height gradient and, consequently, the jet streak over the downstream of the upper-level trough. The intensification of the ULJS is accomplished through Coriolis acceleration on cross-jet ageo-strophic winds. These allow a continued presence of the ULJS, and upper-level divergence over the mid-peninsula. The LLJ is also intensified by convective heating. These enhanced jets return positive feedback to the convective systems. Thus the convective systems interact with the jets, exchanging positive feedback.

As previously described, heavy rainfall continued for about 18 hours over the mid-peninsula. The occurrence of this intense, and persistent heavy rain event may be attributed primarily to the favorable, large-scale pressure system, and its interaction with the precipitation systems. The large-scale system provides the important elements for heavy rainfall development as earlier described. And the convective systems affect the large-scale fields, enhancing the low-level southwesterlies, upper-level divergence, etc. Besides the large-scale system, a typhoon landed earlier on southern China may also be an important factor for enhancing moisture transport and trough development at low-levels. Confinement of precipitation systems to the narrow area of the mid-peninsula by the low-level southwesterlies, upper-level divergence, etc. Besides the large-scale system, a typhoon landed earlier on southern China may also be an important factor for enhancing moisture transport and trough development at low-levels. Confinement of precipitation systems to the narrow area of the mid-peninsula by the low-level southwesterlies, upper-level divergence, etc. Besides the large-scale system, a typhoon landed earlier on southern China may also be an important factor for enhancing moisture transport and trough development at low-levels. Confinement of precipitation systems to the narrow area of the mid-peninsula by the low-level southwesterlies, upper-level divergence, etc. Besides the large-scale system, a typhoon landed earlier on southern China may also be an important factor for enhancing moisture transport and trough development at low-levels. Confinement of precipitation systems to the narrow area of the mid-peninsula by the low-level southwesterlies, upper-level divergence, etc. Besides the large-scale system, a typhoon landed earlier on southern China may also be an important factor for enhancing moisture transport and trough development at low-levels. Confinement of precipitation systems to the narrow area of the mid-peninsula by the low-level southwesterlies, upper-level divergence, etc. Besides the large-scale system, a typhoon landed earlier on southern China may also be an important factor for enhancing moisture transport and trough development at low-levels. Confinement of precipitation systems to the narrow area of the mid-peninsula by the low-level southwesterlies, upper-level divergence, etc.
eral heavy-rain cells is also found inland, ahead of a low-level jet (LLJ) maximum, where strong convergence occurs. A close relationship is found between the LLJ, upper-level jet streak (ULJS) and heavy rainfalls over the inland area. In this event, large-scale conditions not only provide a favorable environment for heavy rainfalls, but also actively interact with meso-scale systems.

Simulation using MM5 has fairly reproduced the convection bands over the coastal area, and the large meso-$β$-scale rain area with heavy-rain cells over the inland area. Simulated results suggest two types of band formation: one initiated by an elongated convergence of large-scale flows, and the other one initiated by existing convective cells in a southwesterly air stream. Simulations also indicate that both the LLJ and ULJS are intensified and maintained by convective heating. A favorable, large-scale environment, and its interaction with convective systems, may be the primary reason for the persistence of heavy rainfall.

Several inconsistencies need to be explained to understand the heavy rainfalls more clearly. For example, the northern band prevails as the southern band weakens in the observation, while the opposite is true for the simulated results. And the observation shows many bands, while the simulation produces only 2 or 3 bands. Some aspects of the heavy rainfall development remained to be studied. Terrain effects on the precipitation systems need to be understood, since a significant portion of the heavy rainfalls occur in the mountainous areas. Another important issue may be understanding of the detailed dynamical and physical processes of continued development of heavy precipitation systems within the southwesterly air stream.

The present case is one of the August heavy rainfalls, a post-Changma heavy rainfall. This and other case studies indicate that the Korean peninsula can be a favored location for heavy rain in August conditions [e.g., a large-scale southwesterly belt along the western Pacific subtropical high to the south, and a cyclone (or trough) over, or to the north of the peninsula]. August can be a unique rainy period in the Korean peninsula. Further case studies of August heavy rainfalls are desired for defining rainy weather in August.

Acknowledgments

This research has been supported by the Korea Ministry of Science and Technology through the National Research Laboratory Program and the Korea Meteorological Administration through the R&D program. The authors are grateful to the anonymous reviewers for their valuable comments, which have contributed to the significant improvement of this paper.

References


Shapiro, M.A., 1982: Mesoscale weather system of the central United State. CIRES, Univ. of Colo./NOAA, Boulder, Colo.
