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Synoptic features of orographically enhanced heavy rainfall on the east coast of Korea associated with Typhoon Rusa (2002)

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[1] A record-breaking heavy rainfall event, with a 24-hr accumulated rainfall of 870.5 mm, occurred in a coastal area at the foot of a mountain range in the central-eastern part of the Korean Peninsula during the passage of Typhoon Rusa (2002). Synoptic features of this case were investigated via high-resolution numerical analysis and forecast fields obtained from the PSU/NCAR MM5. The main causes of this localized heavy rainfall include: 1) strong low-level convergence of moist air from the sea into the coastal/mountainous area; 2) consequent orographic lifting; 3) low levels of lifting condensation and free convection; and 4) release of potential instability by orographic lifting to trigger deep convection. **Citation:** Park, S. K., and E. Lee (2007), Synoptic features of orographically enhanced heavy rainfall on the east coast of Korea associated with Typhoon Rusa (2002), *Geophys. Res. Lett.*, *34*, L02803, doi:10.1029/2006GL028592.

1. Introduction

[2] Because about 70% of the Korean Peninsula is covered by mountains, most meteorological systems that pass over it are affected by its complex topography. A tropical cyclone is a major meteorological system where circulation may interact with terrain to produce orographically induced convective systems, often causing localized heavy rainfall.

[3] As a tropical cyclone moves onshore, the rainfall around high mountains can be strongly controlled by orographic forcing, rather than being associated with the original rainbands accompanying the tropical cyclone itself [e.g., *Lin et al.*, 2002]. Heavy orographic rainfall may also occur much earlier, before the landfall of a tropical cyclone, as a result of the influence of terrain in a conditionally unstable air stream associated with the cyclone's outer circulation [e.g., *Lin and Chiao*, 2001]. Furthermore, rainfall enhancement in regions of complex terrain can also be partly explained by the seeder-feeder mechanism in which precipitation produced by a high-level cloud (seeder) falls into an orographically induced low-level cloud (feeder) thus enhancing the orographic precipitation [e.g., *Barros and Kuligowski*, 1998]. General reviews on orographic precipitation are referred to by *Barros and Lettenmaier* [1994] and *Roe* [2005]. Typhoons and their interactions with terrain of Taiwan is well reviewed by *Wu and Kuo* [1999].

[4] Some specific synoptic features may also be necessary to develop heavy orographic rainfall, in addition to topography. *Lin and Chiao* [2001] suggested several common ingredients for heavy rainfall, and insisted that heavy orographic rainfall requires significant contributions from any combination of the common ingredients. They also noted the importance of a potentially unstable airflow to help trigger deep convection, as suggested by *Doswell et al.* [1996], in heavy orographic rainfall.

[5] In late August 2002, an intense tropical cyclone, Typhoon Rusa, passed over the Korean Peninsula. It made landfall on the south coast of the peninsula and crossed over the central-east coast. The coastal areas of the central-eastern part of the peninsula were devastated by this storm, especially the heavy rainfall. The rainfall was particularly intense in the area on the eastern side of the Taebaek Mountain Range (TMR), oriented in a northwest-southeast direction (see Figure 1). A record-breaking daily rainfall of 870.5 mm occurred at Gangneung, a coastal city on the eastern foot of the TMR. The western side of the TMR had a relatively small amount of rainfall. This contrast suggests that the localized heavy rainfall on the eastern side of the TMR was strongly linked to the orographic effect associated with the outer circulation of the typhoon, as well as the rainfall accompanying the typhoon itself.

[6] In this study the orographic effect, and some specific synoptic features linked to this heavy rainfall, were investigated through various analysis/forecast fields using the PSU/NCAR MM5 model. Results from a high-resolution numerical simulation appear in our companion paper (E. Lee and S. K. Park, Numerical simulation of orographically-enhanced heavy rainfall in the east coast of Korea associated with Typhoon Rusa (2002), manuscript in preparation, 2007, hereinafter referred to as Lee and Park, manuscript in preparation, 2007). Section 2 describes data and methodology while section 3 provides discussions on dynamical and thermodynamical features related to the heavy rainfall. Conclusions are provided in section 4.

2. Case, Data and Methodology

[7] Typhoon Rusa (2002) made landfall on the south coast of the Korean Peninsula around 0600 UTC (1500 LST) on 31 August, with a maximum wind speed of 38 m s^{-1} and a minimum pressure of 960 hPa. The sea surface temperature at the southern end of the peninsula stayed over 26°C, higher than normal by 2–3°C, thus maintaining the storm's strength before it made landfall. On the same day, a 24-hr accumulated rainfall of 870.5 mm was observed at Gangneung, 712.5 mm at Daegwallyeong, and 295.5 mm at Sokcho. Daegwallyeong is a mountain pass of the TMR,

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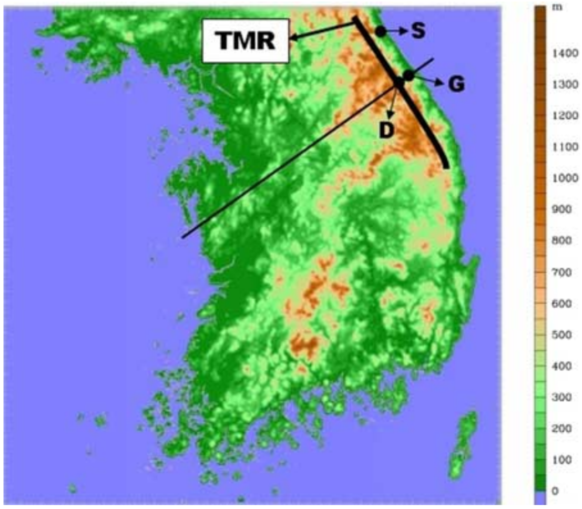

Figure 1. Topography of the Korean Peninsula indicating the Taebaek Mountain Range (TMR) and three locations – Gangneung (G), Daegwallyeong (D) and Sokcho (S). The straight solid line represents the axis for vertical cross sectional analyses.

located to the west of Gangneung, whereas Sokcho is located about 70 km northwest of Gangneung (see Figure 1 for location of each site). The TMR is steeper on its eastern side, resulting in narrow coastal plains along the range, with a gentler slope on the western side. Rusa (2002) remained on the Korean Peninsula for 21 hrs before it passed on to the East Sea (hereafter ES) (Sea of Japan) around 0300 UTC (1200 LST) on 1 September.

[8] In order to make a high-resolution analysis, a data analysis package of the MM5 modeling system was employed. Standard rawindsonde and surface data were used along with the NCEP global analysis data (2.5° × 2.5°) as a background field. Analyses were performed in horizontal resolutions of 27 km and 9 km. Topography, mountain ranges and locations of the above-mentioned sites, along with the axis of cross-sectional analysis, are shown in Figure 1.

[9] Since the NCEP data are provided every 6 hr, model-integrated fields are also used for 1-hr interval analyses. A real high-resolution (both in space and time) analysis is possible only if the relatively coarse observations are complemented by model output fields. This approach can be adopted only when the model outputs and observations are in good agreement [see *Buzzi et al.*, 1998]. Because our model results compare quite well with the observations (Lee and Park, manuscript in preparation, 2007), this approach was employed for high-resolution analysis of dynamical and thermodynamical features of environmental air associated with Typhoon Rusa.

[10] For the numerical simulation, the MM5 (version 3) was initialized at 0000 UTC on 30 August 2002 using the NCEP global analysis data and conventional synoptic observations. The model was integrated up to 48 hrs. Physical processes include the mixed-phase explicit scheme, the Kain-Fritsch cumulus scheme, and the MRF PBL scheme, all described in detail by *Grell et al.* [1993]. Both the 6-hr interval analysis fields and the 1-hr interval model output fields were used for the detailed analyses and discussions set out below.

3. Results

[11] Analyses on various scales are provided in this section to understand mechanisms that induced localized heavy rainfall associated with Typhoon Rusa. An observed hourly rainfall amount demonstrated two peaks at all three sites (i.e., Gangneung, Daegwallyeong and Sokcho) over 24 hrs from 0000 LST to 2400 LST 31 August. The first peak occurred at 0900 LST (0000 UTC; 6 hrs before the landfall) and the second at 2300 LST (1400 UTC; 8 hrs after the landfall). The maximum hourly rainfall in this 24-hr period corresponded to the second peak at each site, with 100.5 mm at Gangneung, 60.5 mm at Daegwallyeong, and 59 mm at Sokcho, respectively. The occurrence of two peaks in rainfall implies that the mechanism for inducing rainfall of one peak might be different to that of the other.

[12] Figure 2 shows the 850 hPa map analysis at 0000 UTC (0900 LST) on 31 August. The movement of Rusa was retarded by a strong ridge in the north caused by an extension of the North Pacific High. A thermal trough intruded deeply over the northern part of the Korean Peninsula and the ES while a warm core existed in the southern ES. Southeasterly to easterly warm and moist flows predominated over the east coast of the central part of the peninsula, caused mainly by the outer circulation of Rusa. In addition, northeasterly cold and moist flows, blowing from the edge of the North Pacific High, converged in the same area. This resulted in a strong moisture convergence in the coastal area and the growth of unstable air over the central ES near the coast.

[13] The area of interest (i.e., the central-east coast of the Korean Peninsula) was located right underneath the entrance of the upper-level jet streak (not shown). Thus, upper-level divergence and low-level convergence developed over that area, through a thermally direct circulation [see *Bluestein*, 1993]. That is, prior to the landfall

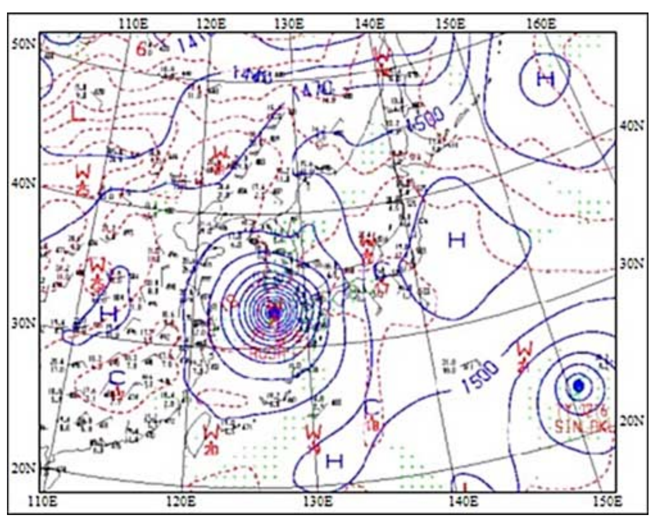

Figure 2. The 850 hPa map analysis at 0000 UTC 31 August 2002 for geopotential height (solid), temperature (dashed), and moisture (dots).

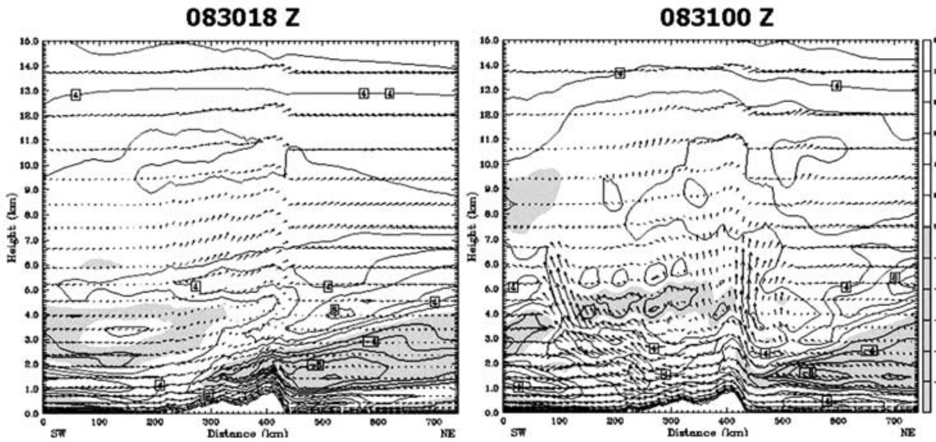

Figure 3. The vertical cross section of the potential instability in a 9 km domain (contour with negative areas shaded; in °K km^{-1}) and wind vectors at 1800 UTC on 30 August and 0000 UTC on 31 August 2002.

of Rusa, a low-level convergence was formed over the central-eastern coastal areas, as a result of synoptic-scale forcing. This low-level convergence was enhanced by northeasterly winds blowing around the edge of the North Pacific High, and further strengthened later by the outer circulation of Rusa as it approached the peninsula.

[14] The vertical sounding analysis for Sokcho at 1200 UTC on 30 August revealed that moist low-level jet and potentially unstable air were being enhanced by the easterly flows before the landfall of Rusa (not shown). The lifting condensation level (LCL) was as low as 0.2 km, hence a small amount of lifting would be sufficient to

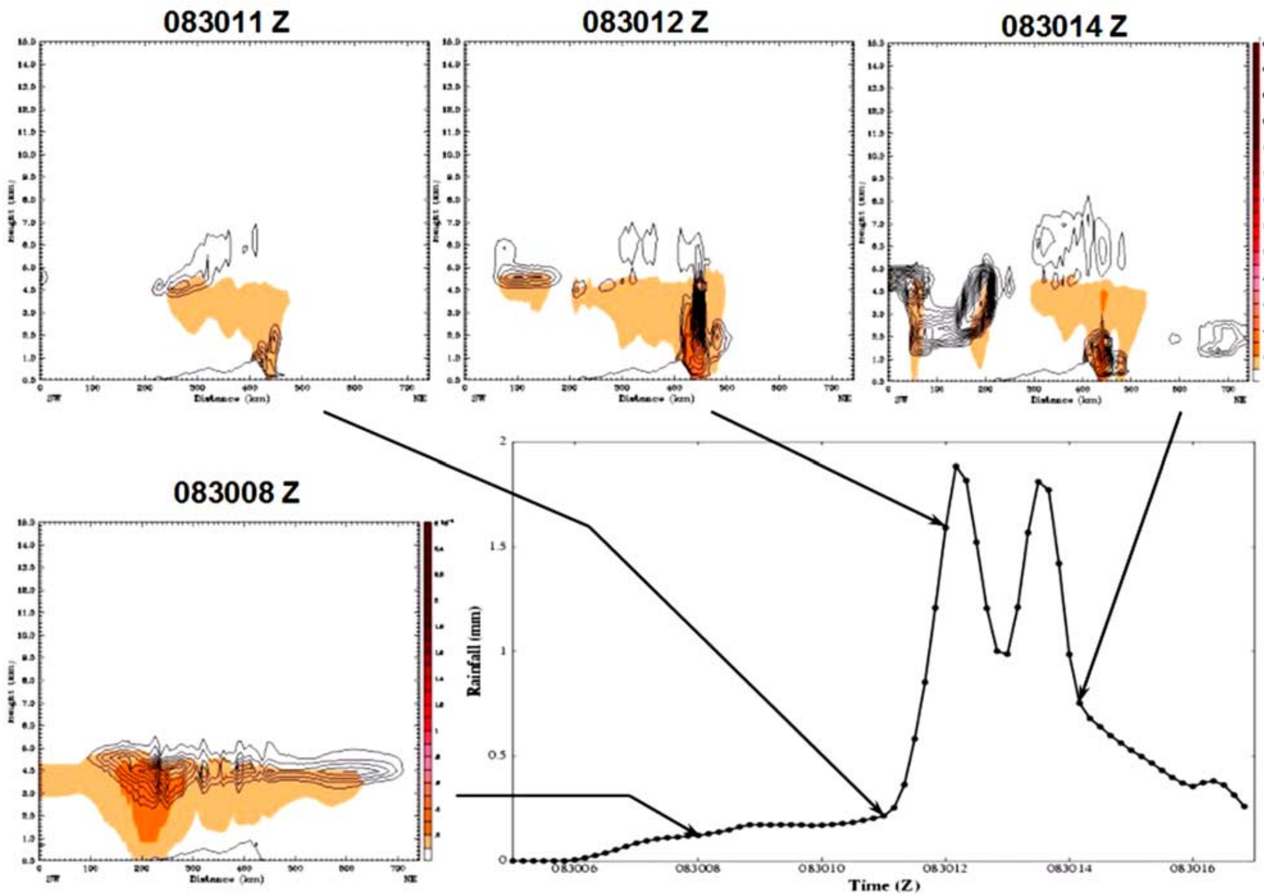

Figure 4. The vertical cross section of the mixing ratios of cloud water (contour) and rainwater (shaded) at 0800, 1100, 1200, and 1400 UTC on 30 August 2002 along with time series of 10 min rainfall (in mm) from 0005 to 1700 UTC on 30 August 2002.

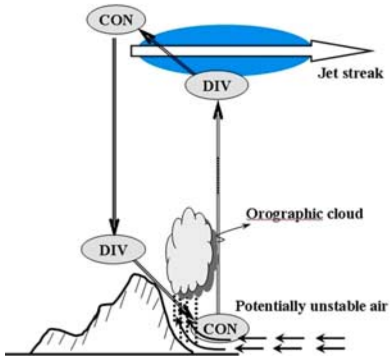

Figure 5. Schematic diagram describing major ingredients for the heavy rainfall event, including the divergence (DIV) and convergence (CON) fields.

form clouds. The level of free convection (LFC) was around 4 km – deep convective clouds can be created through an appropriate mechanism for lifting the low-level moist air up to the LFC [see *Banta*, 1990]. Development of such clouds was possible through strong convergence on the coastal area and consequent orographic lifting.

[15] Figure 3 depicts the vertical cross section of potential instability ($\partial\theta_e/\partial z$) and wind vectors at 1200 UTC on 30 August, in the direction of northeasterly inflow (see the line in Figure 1). A potentially unstable area had been formed in the lower atmosphere over the Korean Peninsula and the ES before the landfall of Rusa. The instability was enhanced as the typhoon approached, especially over the ES. The potential (convective) instability was released through strong orographic lifting, thus triggering deep convection [e.g., *Doswell et al.*, 1996].

[16] In Figure 4, in order to check the possibility of an abrupt increase in rainfall associated with the development of orographic clouds, the vertical cross sections of the mixing ratios of cloud water and rainwater passing Gangneung are compared with the time series of the 10-min rainfall at Gangneung. At 0800 UTC on 30 August, light precipitation falling from the mid-level cloud was observed although the orographic cloud had not yet developed. At 1100 UTC an orographic cloud developed over the mountain. In fact this cloud started to form around 0900 UTC, but did not produce much precipitation for 2 hrs. During the next one hour, the orographic cloud grew in depth with a precipitous increase in rainfall. After the peaks of rainfall, the orographic cloud became relatively shallow with a decrease in precipitation. These events demonstrate that the steep rainfall increase in this case was strongly linked to the development of deep orographic convection. Although the mid-level precipitation falling into the shallow orographic cloud might have contributed to a subsequent increase in rainfall through the seeder-feeder mechanism [e.g., *Barros and Kuligowski*, 1998], it may have been less effective for such a relatively high and steep mountain.

[17] Overall, dynamical and thermodynamical ingredients, such as strong low-level convergence and potential instability, relatively low LCL and LFC, mid-level synoptic clouds, and intense orographic lifting, resulted in heavy rainfall in the coastal area, in association with topography and the approach of typhoon.

4. Concluding Remarks

[18] In this study, detailed synoptic features were investigated for an orographically enhanced heavy rainfall at the central-east coast of the Korean Peninsula, associated with Typhoon Rusa (2002). As the typhoon approached to the peninsula, a record-breaking localized heavy rainfall occurred on an central-east coastal area, which is quite narrow and lies along the Taebaek Mountain Range (TMR) oriented in a northwest-southeast direction.

[19] High-resolution numerical analysis and forecast fields were used to understand dynamical and thermodynamical structures by employing a nested grid system (27 and 9 km) of the PSU/NCAR MM5. A schematic diagram is shown in Figure 5 to represent synoptic features associated with this heavy rainfall event.

[20] Prior to the landfall of Rusa (2002), there existed a strong low-level convergent flow into the coastal/mountainous area from the East Sea (ES) (Sea of Japan) due to thermally direct circulation of the upper-level jet streak and northeasterly flow at the edge of the North Pacific High. The low-level convergence was further enhanced by the outer circulation of Rusa as it approached to the peninsula.

[21] The potential instability developed over the Korean Peninsula and the ES as cold moist air from the northeasterly and warm moist air from the typhoon met, even before the typhoon made landfall. This area of instability was conveyed by advection to the coastal/mountainous area to be released by orographic lifting, thus triggering deep convection at the upstream side of the TMR.

[22] Although the contribution by the seeder-feeder mechanism may have been less dominant for this heavy rainfall event, it will be interesting to assess its effect through more detailed analyses and well-designed numerical experiments in future study.

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