Diurnal Variation of Convective Activity and Precipitable Water around Ulaanbaator, Mongolia, and the Impact of Soil Moisture on Convective Activity during Nighttime

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ABSTRACT

The diurnal variations of convective activity and precipitable water were investigated using a C-band airport radar and GPS receivers around Ulaanbaator (UB), Mongolia; this location was considered as an example of an arid region. The convective activity exhibited a pronounced diurnal cycle; it increased rapidly at 1100 local solar time (LST; 0300 UTC), reached the maximum at 1400 LST, and almost disappeared after 1900 LST. On the other hand, no diurnal variation of precipitable water could be observed, which implied that there was no considerable evapotranspiration, and the diurnal variation of the convective activity was irrelevant to the variation of water vapor. The reason why the deep convection could not develop at night is discussed using numerical modeling from the viewpoint of soil moisture. In the moist soil conditions assumed for humid simulations, an increase in the water vapor in the boundary layer due to evapotranspiration led to a potentially unstable condition that was sustained until night. Deep convection was formed at the southern foot of mountains where topographical convergence was expected. On the other hand, in the dry soil conditions assumed for the arid simulations, deep convection did not occur during nighttime even though topographical convergence was expected over the southern foot of the mountains. These features of dry soil conditions were consistent with the results from radar observations around UB. In other words, since the soil around UB is too dry in practice to sustain an unstable condition until night, the deep convection had to decay by night and could not be initiated at night.

1. Introduction

The diurnal cycle of convective activity is pronounced worldwide. Studies on the diurnal variation of convective activity have been carried out mainly over humid regions; however, there are few studies over arid region due to the lack of accessible precipitation data with high temporal resolution.

One of the interesting features over humid regions is the maximum convective activity from late night to early morning, for example, in the United States (e.g., Wallace 1975) and northern Bangladesh (e.g., Islam et al. 2005). The evening maximum is also pronounced around north Kanto District in Japan (Fujibe 1988; Iwasaki and Miki 2002). It is of interest that these deep convection maxima are not synchronized with the diurnal cycle of solar radiative heating. The propagation of precipitation systems from mountains is important for the nocturnal maximum over the United States (Riley et al. 1987) and Indochina (Satomura 2000; Okumura et al. 2003). In addition, the atmosphere is more unstable at night over northern Bangladesh (Kataoka and Sato-
mura 2005) and north Kanto District (Iwasaki and Miki 2002) due to an increase in the water vapor in the boundary layer, which is a favorable condition for the development of deep convection. A possible source of the water vapor is evapotranspiration (Sasaki and Kimura 2001; Iwasaki and Miki 2001, 2002). These studies have clarified that the diurnal variation of water vapor and soil moisture are also important to fully understand the diurnal variation of deep convection.

On the other hand, the diurnal variation over arid regions has received little attention. Research on the diurnal variation over arid regions is important not only for understanding the variation but also for an increased understanding of the diurnal variation over humid regions by comparing the two regions. In this study, we direct our attention to the Mongolian rangeland as a typical arid region. An intensive observation was conducted from June to August 2003 around Ulaanbaatar (UB), Mongolia, in order to elucidate the precipitation climatology for several time scales, including the diurnal variation. With regard to the feature of diurnal variation over Mongolia, there are only a few studies. A large number of mesoscale cloud clusters are observed to appear at 1900 local solar time (LST; LST = UTC + 7) by using 6-hourly geostationary meteorological satellite infrared (IR) microfilm (Takeda and Iwasaki 1987; Iwasaki and Takeda 1993; Kato et al. 1995). However, since these satellite IR microfilms were too coarse with regard to the temporal resolution, they should be reexamined using precipitation data with fine temporal resolution. We will clarify the features of the diurnal variation of convective activity using C-band radar data. Previous studies on the humid regions had indicated that the diurnal variation of water vapor was essential for the diurnal variation of convective activity depending on the circumstances, and they suggested that evapotranspiration could be important to increase the water vapor in the boundary layer. We will elucidate the relationship between the diurnal variation of convective activity and that of the precipitable water content estimated using GPS data. Furthermore, the impact of soil moisture on the diurnal variation of convective activity will be discussed based on the numerical modeling.

2. Data and method

a. Analysis period

Since the precipitation amounts around UB increase rapidly from the beginning of June and decrease rapidly in the middle of August, and approximately 70%–80% of the annual precipitation occurs during this period (e.g., Endo et al. 2006; Iwasaki and Nii 2006), the periods of June–August of 2003 and 2004 were selected for analysis. However, the squall line associated with a cold front in the evening of 20 June 2003 was extremely strong and the feature of diurnal variation was significantly deformed (see Fig. 6a); therefore, the day was excluded from the analysis period.

b. Airport radar data

1) Observation

The diurnal variation of convective activity is analyzed using UB airport radar data. Table 1 shows the characteristics of this radar. The radar covers a wide area that has a radius of 180 km, and this is the analysis region of this study. Although the radar site is located on the top of a small mountain, a lot of mountains are located around the radar site in all the directions except the west (Fig. 1), which creates partial and/or total radar beam blockage in the analysis region (see Fig. 2 in Iwasaki 2006b). Since CAPPI data for an altitude lower than 4 km AGL would contain a considerable number of beam blockage, CAPPI data for 5 km AGL (=6.5 km MSL) are used for the present analysis; however, a small beam blockage still remains in the eastern part of the range (Fig. 1).

A volume scan consists of 15 elevation angles from 0.0° to 40.0° with approximately 10-min intervals. The observation was occasionally stopped during very fine weather conditions and when some problems occurred. However, since missing data do not depend on the local time, as shown in Fig. 2, this dataset is of sufficient quality to elucidate the diurnal variation of convective activity.

2) Definition of convective activity

The hourly CAPPI data for 5 km AGL are calculated from each volume scan data. For convenience, hourly
precipitation values greater than 5 mm (about 35 dBZ) at 5 km AGL are regarded as precipitation originating from cumulonimbus clouds. In this analysis, the hourly precipitation amount greater than 5 mm at 5 km AGL is defined as the convective activity in order to describe the feature of deep convection. For example, the hourly precipitation amount of 10 mm in the 5-km CAPPI data is represented by convective activity 10.

Since precipitation at 5.0 km AGL where temperatures are below 0°C is retrieved using a generic Marshall–Palmer Z–R relationship (Table 1), convective activity does not necessarily correspond to precipitation amount at surface. However, the convective activity averaged over the area without beam blockage is correlated well with radar precipitation amount at 1 km AGL averaged over the same area, and their correlation coefficient is 0.78. This high correlation means that convective activity is a proxy data of precipitation amount observed at surface.

c. GPS precipitable water

Three GPS receivers are installed to investigate the diurnal variation of precipitable water associated with thermally induced local circulation from 14 June to 10 September 2003 (Fig. 1). BYAN and MUMO are located near the Khenty Mountains where the annual precipitation is relatively high (greater than 200 mm). KBUL is in a large grassland with low annual precipitation (less than 150 mm).

The GPS precipitable water (GPS PW) is estimated from the values of the total zenith delay of the GPS signal by using measurements of the surface temperature and pressure (e.g., Bevis et al. 1994). The total zenith delay of the GPS signal is directly calculated from the GPS data at intervals of 30 min using Bernese GPS software, version 4.2 (Hugentobler et al. 2001). The rms error in the GPS PW during the summer season is approximately 2.0 mm when compared with the data from water vapor radiometers or radiosondes (e.g., Iwasaki et al. 2000).

d. Soil moisture and hydrometeorological components

The volumetric water content of the soil (5 and 25 cm in depth) has been observed since March 2003 at KBUL by using a time domain reflectometry (TDR) sensor and hydrometeorological components. The 30-min mean flux data were processed for the cospectral correction of water vapor fluxes using the algorithm proposed by Eugster and Senn (1995). The latent heat

Fig. 1. Location of the Ulaanbaatar airport radar. Elevation contours are drawn every 500 m. The three dark circles indicate GPS sites. The broken line is the boundary of the shadow area in the 5 km CAPPI.

Fig. 2. Frequency of radar observation data from 1 Jun to 31 Aug for 2003 and 2004.
flux (in units of watts per square meter) was converted to increments of precipitable water (millimeters) in order to easily compare it with the GPS PW.

e. Numerical modeling

The impact of soil moisture on the diurnal variation of convective activity over the arid regions was discussed using the results of numerical modeling performed with a modified version of the Regional Atmospheric Modeling System (RAMS), which is the Terrestrial Environmental Research Center RAMS (TERC-RAMS; e.g., Sato and Kimura 2005). The specifications of the TERC-RAMS and the details on the calculation will be described in section 6.

3. Seasonal variation of convective activity

Figures 3 and 4 show the time series of the daily convective activity integrated over the analysis region and the meteorological parameters for 2003 and 2004, respectively. Since the time series of GPS PW for three sites and the precipitable water estimated using sonde data at UB exhibit almost the same tendency, the GPS PW in KBUL is considered to be representative of the analysis region.

Active periods during which the daily convective activity integrated over the analysis region was more than 100 were observed for more than three consecutive days, and denoted by labels P1–P9. The synoptic-scale situations around UB are examined for P1–P9 using...
the Asian Pacific Surface Weather Chart provided by the Japan Meteorological Agency and summarized in Table 2. All the active periods were associated with the passage of a synoptic-scale low and/or trough in 2003; however, the deep convection in 2004 occurred even under a synoptic-scale high or ridge (P6, P8, and P9). The synoptic features for the active periods differed from year to year, which was consistent with previous studies in which mesoscale cloud clusters over eastern Mongolia occurred under a high in 1986 (Iwasaki and Takeda 1993) and under a low in 1979 (Kato et al. 1995).

Despite the different synoptic features, the Showalter stability index (SSI$_{500-800}$) at UB, which is defined by using 800-hPa temperature and humidity (approximately 500 m AGL) instead of 850 hPa, is low during the active periods (Figs. 3d and 4c). The SSI$_{500-800}$ is negatively correlated to the GPS PW, which implies that an increase in water vapor in the lower troposphere causes unstable conditions.

4. Diurnal variation of convective activity
   
a. General features

Figure 5 shows the distribution of convective activity integrated over the analysis period of 1 June to 31 August for 2003 and 2004. Deep convection was active over the northern part with a lower elevation, while it was absent over the southeastern part; this is consistent with the distribution of annual precipitation observed by the Mongolian rain gauge network, as shown by Endo et al. (2006) and Iwasaki (2006a). It is interesting that the convective activity is relatively low over mountains higher than 2.0 km MSL, and convective activity is rather large at the foot of mountains with a height of 1.5 to 2.0 km MSL; this means that deep convection is less prevalent over the peaks of the Khenty Mountains.

Figure 6 shows the diurnal variation of the hourly convective activity integrated over the analysis region for 2003 and 2004. The convective activity increases rapidly from 1100 LST, reaches a maximum at 1400 LST, and almost disappears after 1900 LST. The convective activity around UB exhibits a pronounced diurnal variation, and these features are common for 2003 and 2004. It should be noted that little deep convection exists after 1900 LST, and the reason why deep convection did not occur at night will be discussed using numerical modeling in section 6.

The relationship between the diurnal variation and topographical features will be examined. Figure 7 shows the distribution of convective activity every 2 h from 1000 LST for 2003 and 2004. Since the time interval is too short, the convective activity is calculated with all the radar echoes so as to elucidate its features. Deep

<table>
<thead>
<tr>
<th>No.</th>
<th>Dates</th>
<th>Synoptic situation*</th>
<th>Total convective activities</th>
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<tbody>
<tr>
<td>P1</td>
<td>15–17 Jun 2003</td>
<td>PL</td>
<td>3046</td>
</tr>
<tr>
<td>P2</td>
<td>15–18 Jul 2003</td>
<td>PL</td>
<td>24 478</td>
</tr>
<tr>
<td>P3</td>
<td>21–25 Jul 2003</td>
<td>PL and PT 48320</td>
<td></td>
</tr>
<tr>
<td>P4</td>
<td>12–16 Aug 2003</td>
<td>PLs</td>
<td>2091</td>
</tr>
<tr>
<td>P5</td>
<td>12–14 Jun 2004</td>
<td>PLs</td>
<td>23 822</td>
</tr>
<tr>
<td>P6</td>
<td>6–14 Jul 2004</td>
<td>PL (6–10 Jul) and PH (12–14 Jul)</td>
<td>20 020</td>
</tr>
<tr>
<td>P7</td>
<td>16–19 Jul 2004</td>
<td>Trough located in eastern Mongolia</td>
<td>4825</td>
</tr>
<tr>
<td>P8</td>
<td>23–25 Jul 2004</td>
<td>PH (23–24 Jul) and PT (25 Jul)</td>
<td>10 202</td>
</tr>
</tbody>
</table>

* The abbreviations represent the following quantities: PH: passage of a high, PR: passage of a ridge, PL: passage of a low, and PT: passage of a trough. “Low” and “high” imply that closed circulations were recognized on the surface weather map. “Trough” and “ridge” do not accompany any closed circulations on the surface weather map.
convection begins to appear over the slopes of the Khenty Mountains between 1.5 and 2.0 km MSL at around 1100 LST; these clouds are observed over both the mountainous and plain regions around 1400 LST when the convective activity reaches the maximum. The regions over which deep convection is more active are observed to be located in the plane at 1800 LST. These features of the relationship between the diurnal variation of convective activity and topographical features have been reported by many researchers (e.g., Astling 1984; Fujibe 1988), and it is considered that these features are associated with the local circulation. The relationship between the diurnal variation of convective activity and the local circulation will be described using the surface wind and GPS PW in section 5b.

b. Diurnal variation during each active period

Figure 8 shows the diurnal variation of the normalized convective activity for active periods P1–P9. The activity reaches a maximum from 1200 to 1600 LST, except for P4, P7, and P8, whose convective activity is relatively low (see Table 2). The convective activities for P2, P6, and P9 have two maxima around noon and in the afternoon, which correspond to the convective maximum over the Khenty Mountains and the foot of the mountains, as shown in Fig. 7. Active periods P6, P8, and P9 in 2004 are associated with the passage of a synoptic-scale ridge. However, the convective activity reached a maximum around 1400–1800 LST and almost disappeared after 1900 LST; these characteristics are similar to those of the diurnal variation associated with the passage of a synoptic-scale trough. Convective activities exhibit features similar to the diurnal variation in spite of different synoptic situations.

5. Diurnal variation of GPS precipitable water

a. General features

A pronounced diurnal variation of convective activity is recognized around UB. In this section, the diurnal variation of water vapor, which is the energy source for cumulonimbus clouds, will be examined using GPS data.

Figure 9 shows the diurnal variation of the GPS PW averaged over P1–P4 (top panel) and the GPS observation period from 20 June to 31 August 2003 (bottom panel). The maximum magnitude of the diurnal variation of GPS PW is 2 mm, which is less than the standard deviation. It is clear that a significant diurnal variation is not observed, even during the period when the diurnal variation of convective activity is prominent. A diurnal variation of GPS PW that was in phase with the convective activity was not observed, even for the individual days of P1 and P4 (not shown). Therefore, it is concluded that the diurnal variation of water vapor is irrelevant to the understanding of the prominent diurnal variation of convective activity.

This relationship between the diurnal variation of precipitable water and convective activity is considerably different from the evening convective maximum over north Kanto District (e.g., Iwasaki and Miki 2002;
Iwasaki 2004) and over northern Bangladesh (Kataoka and Satomura 2005).

b. Weak thermally induced local circulation around the Khenty Mountains

As shown in Fig. 7, radar echoes began to appear at the foot of the Khenty Mountains from 1.5 to 2.0 km MSL around 1000–1200 LST, which seemingly suggested moisture transport and/or parcel lifting from the foot of the mountains to the top of the mountains due to a thermally induced local circulation. In fact, by using GPS PW a similar process was observed around noon over the high mountains in north Kanto District (Iwasaki 2004). However, observation data suggest that the thermally induced local circulation was not very strong.

To examine the diurnal variation of the surface wind and GPS PW, the 10 days during which deep convection was active from 1000 to 1200 LST over the Khenty Mountains were extracted for 2003. These days belonged to active periods P1–P3. Figure 10 shows the diurnal variation of surface wind direction around the Khenty Mountains for the 10 days. Little or no diurnal variation was recognized during daytime even during the period when deep convection was active over the Khenty Mountains.

According to previous studies on the diurnal variation of GPS PW associated with the thermally induced local circulation over Kanto District (Kimura and Kuwagata 1995; Iwasaki and Miki 2002; Iwasaki 2004) and the Tibetan Plateau (Takagi et al. 2000; Kuwagata et al. 2001), the GPS PW in the valley is expected to decrease.

Fig. 7. Distribution of convective activity at an altitude of 5 km calculated with all radar echoes (top) 2003 and (bottom) 2004: (a), (d) 1000–1200; (b), (e) 1300–1500; and (c), (f) 1600–1800 LST. Open circles in (a), (d) indicate the location of GPS sites. The dotted lines, solid lines, and thick solid lines denote elevations of 1.0, 1.5, and 2.0 km, respectively. The thick broken line is the boundary of the shadow area in the 5 km CAPPI.
during the daytime due to compensating downdraft of the valley-wind circulation. Figure 11 shows the diurnal variation of the mean anomalous GPS PW for three GPS sites. The anomalies of 30-min GPS PW from 0000 LST were averaged over the 10 days. As shown in Fig. 1, MUMO is located in the valley with a horizontal scale of 100 km, where the GPS PW is expected to decrease during the daytime. However, the GPS PW in MUMO did not decrease during 1000–1200 LST, and it did not exhibit any significant diurnal variation. It is concluded that the thermally induced local circulation was too weak to be detected by using the surface wind and the GPS PW even in the period that deep convection was active over the Khenty Mountains.

6. Impact of soil moisture on convective activity from evening to night

a. Diurnal variation of GPS PW and soil moisture at KBUL

The GPS PW did not exhibit a large diurnal variation, unlike that in some humid regions. The reason can be inferred from consecutive operational data on the soil moisture and latent heat flux at KBUL. Figure 12 shows the time series of the integrated latent heat flux from 0800 to 2000 LST, the increment in the GPS PW for the same period, the daily rainfall amount, and the hourly soil moisture. The maximum integrated latent heat flux is 2.5 mm, even for the day following a rainy

![Diurnal variation of normalized convective activity for P1–P9 for (a) 2003 and (b) 2004.](image)

![Diurnal variation of mean GPS precipitable water for the three GPS sites: (a) BYAN, (b) MUMO, and (c) KBUL.](image)
FIG. 10. Histograms for wind direction from (left) 0200 to 0800 and (right) 1100 to 1700 LST during the 10-day period when deep convection was active daytime over the Khenty Mountains: (top) MUMO, (middle) BYAN, and (c) UB. Black and white bars indicate wind speed more than 5 m s\(^{-1}\) and less than 5 m s\(^{-1}\), respectively. The location of MOMU, BYAN, and UB are denoted in Fig. 1.

FIG. 11. Diurnal variation of anomalous GPS PW from 0000 LST for the three GPS sites: (top) MUMO, (middle) BYAN, and (c) KBUL. Anomalous GPS PW values are calculated for the 10-day period during which cumulonimbus clouds were active in the mountainous region from 1000 to 1200 LST in 2003. The error bars indicate the std dev for each 30-min interval.
day (Fig. 12a); this is a negligible value in comparison with the variation of the GPS PW in Fig. 12c. In addition, the soil moisture is maintained at a low value throughout the warm season (Fig. 12d). It is inferred that the small latent heat flux resulted from the dry soil condition and that latent heat flux was too small to cause a significant diurnal variation in the precipitable water. At the same time, it is well known that the soil moisture is low over Mongolia (e.g., Robock et al. 2000; Kaihotsu et al. 2004); therefore, dry soil conditions and a small latent heat flux are expected in the analysis region of the present study.

If evapotranspiration is significant, then the water vapor in the mixing layer increases during the daytime and the precipitable water tends to exhibit a maximum in the evening (Sasaki and Kimura 2001; Iwasaki and Miki 2001). As the results of numerical modeling in section 6b suggest (see Fig. 16a), there is a tendency for the dynamic range of the diurnal variation of precipitable water to be large, and the precipitable water exhibits a large value from evening to early night under high soil moisture conditions. In other words, the dry soil conditions around UB are a major reason for the insignificant diurnal variation of the GPS PW.

b. Results of TERC-RAMS modeling

As shown in Figs. 6 and 8, intense deep convection almost disappeared after evening; this is quite different from the features of the diurnal variation over some humid regions that were described in section 1. In this section, we will discuss why deep convection cannot develop in the evening around UB by using numerical modeling and from the viewpoint of soil moisture.

1) EXPERIMENTAL DESIGN

Figure 13 shows the model domains for the coarse grid system (domain A; horizontal resolution 100 km), semifine grid system (domain B; horizontal resolution 20 km), and fine grid system (domain C; horizontal resolution 4 km). The center of each domain is the location of the radar site, and domain C includes the radar observation area of Fig. 1. The top of the model
is at 22 km MSL. The model uses 30 vertical layers for all the three domains with the finest resolution of 110 m at the lowest level; the resolution increases up to 900 m in the upper layers. The depth of the soil model using 11 vertical layers is 1.8 m. The precipitation is calculated using both microphysics and cumulus parameterizations (Table 3).

The initial and boundary conditions, including surface temperature, are obtained by using the 6-hourly National Centers for Environmental Prediction–National Center for Atmospheric Research reanalysis data. The type of vegetation and soil are assumed to be short grass and sandy clay loam, respectively.

The run types are summarized in Table 4. The initial soil moisture (ratio of soil water content to saturated water content) varies from 0.1 to 0.7 and is assumed to be uniform for all depths and over all the domains from A to C. According to a field survey near the hydro-meteorological station, the void contents of the soil for 4–9 and 16–21 cm depths were 0.50 and 0.45, respectively. The soil moisture at a depth of 5 cm, which was obtained from the volumetric water content using a void content of 0.50, varied from 0.1 to 0.4 in the warm season. The soil moisture from the surface to a depth of 20 cm, a distance that the soil water can move in a short time scale, is less than 0.3 except for the day following a rainy day. Thus, initial soil moistures of 0.1–0.3 and 0.5–0.7 are assumed for simulations of arid and humid regions, respectively.

Time integration is conducted for each day of the active period P3 (21 to 25 July 2003) by starting at 1200 UTC of the previous day and integrating for 30 h. The results of the first 6 h are discarded, and the results of the subsequent 24 h (0100–0100 LST) for each day are analyzed over the radar observation area of Fig. 1.

2) RESULTS AND DISCUSSION

Figure 14 shows the diurnal variation of the 5-day integrated hourly rainfall over the analysis region for each run type. Most of the rain originates from deep convection. In the cases relating to dry soil SM01 and SM03, the rainfall amount rapidly increases at 1100 LST and reaches the maximum at 1400 LST; and little deep convection exists after 1900 LST. These features are fairly consistent with the results of the radar observation, as shown in Figs. 6 and 8. It is considered that these dry soil cases represent the real features of the diurnal variation around UB. As for the moist soil cases SM05 and SM07, the time at which the rainfall amount reaches the maximum is 1 h later than that in the dry soil cases, and the rainfall amount increases dramatically by 2–3 times in comparison to the dry soil cases. These features are consistent with previous numerical studies (Clark and Arritt 1995; Pan et al. 1995). Furthermore, it should be noted that the deep convection is maintained even from evening to night.

Figure 15 shows the distribution of the 5-day rainfall for SM03 and SM05. In the dry soil case, the rainfall is localized around the peak of the Khenty Mountains, and this feature is clearer in SM01. On the other hand, in the moist soil case, the rainfall amount increases remarkably around the southern foot of the Khenty Mountains, which contributes to the rainfall during the nighttime (Fig. 14).

To elucidate the mechanism for the development of the deep convection from evening to night in the moist

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**Table 3. Specifications of the model.**

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<th>Dynamical process</th>
<th>Compressive nonhydrostatic equations</th>
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<td>Terrain-following coordinate</td>
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<td>Radiation scheme (Nakajima et al. 2000)</td>
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<td></td>
<td>Surface process (Louis 1979)</td>
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<td>Soil model (Tremback and Kessler 1985)</td>
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<tr>
<td></td>
<td>Cloud microphysics (Walko et al. 1995)</td>
</tr>
<tr>
<td></td>
<td>Cumulus convection (Kuo 1974; Tremback and Kessler 1985)</td>
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**Table 4. Run types.**

<table>
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<tr>
<th>Run type</th>
<th>SM01</th>
<th>SM03</th>
<th>SM05</th>
<th>SM07</th>
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<td>Initial soil moisture*</td>
<td>0.1</td>
<td>0.3</td>
<td>0.5</td>
<td>0.7</td>
</tr>
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</table>

* Soil moisture implies the ratio of soil water content to saturated water content.
soil cases, we focus on 22 and 23 July during which cumulonimbus clouds developed at night. Since differences in the nighttime rainfall result from the initial soil moisture, we will first elucidate the influence of soil moisture on the water vapor environment around the Khenty Mountains. Figure 16 shows the time series of the precipitable water, SSI_{500-800}, and mixing ratio of water vapor at 800 hPa averaged over the southern Khenty Mountains, which is denoted by the dotted frame in Fig. 15a, for all the runs. All through the analysis period—except 24 July when atmospheric conditions were disturbed by a mesoscale convergence and cold outflow from a convective line—there is a clear tendency for the mixing ratio at 800 hPa in moist soil conditions to increase after 1000 LST due to evapotranspiration (Fig. 16b), and the precipitable water at night is

**Fig. 15.** Distribution of 5-day rainfall during the active period P3 for (a) SM03 and (b) SM05. The contour interval for the rainfall amount is 50 mm. The dotted lines, solid lines, broken lines, and the thick solid lines denote elevations of 1.0, 1.5, 1.75, and 2.0 km, respectively. The dotted frame is the region in which precipitable water, SSI_{500-800}, and $q$ at 800 hPa are averaged in Fig. 16.

**Fig. 16.** Time series of (a) precipitable water, (b) mixing ratio of water vapor at 800 hPa, and (c) SSI_{500-800}. These parameters are averaged over the dotted frame in Fig. 15.
larger in moist soil conditions (Fig. 16a). Even though temperature in the lower atmosphere decreases from noon to night, a high mixing ratio leads to a potentially unstable condition under moist soil conditions (Fig. 16c), which means that the evapotranspiration sustains a potentially unstable condition until night. As for dry soil conditions, there are no large diurnal variations in mixing ratio of water vapor, and temperature decreases significantly from noon to night in the lower atmosphere, which leads to a stable condition and low convective activity after the evening.

Next, the evolution of deep convection on 22 and 23 July for SM05 during which the atmosphere was still potentially unstable from evening to night is described. Figure 17 shows the distribution of the rainfall integrated from 1700 to 2500 LST and the wind field averaged from 1700 to 2100 LST. Southwesterly to southerly winds are dominant over the south half of domain B during both days, and the low-level winds are associated with a synoptic-scale disturbance and not with the local circulation. Rain areas A–D are initiated and developed at the southern foot of the Khenty Mountains where forced lifting on a local scale is expected due to the topographical convergence of low-level winds. The cumulonimbus clouds associated with rain area E can be traced to an area near rain area D, and these trajectories almost correspond to the wind direction at 500 hPa. These cumulonimbus clouds are redeveloped at 1900 LST as a result of the convergence due to a cold outflow from the previous cumulonimbus clouds that had occurred around the top of the mountains at 1400 LST.

The mesoscale topographical convergence had played an important role in the initiation of deep convection under potentially unstable conditions from evening to night. Since deep convection was hardly initiated in dry soil cases even though a similar topographical convergence had occurred, a potentially unstable atmosphere is also a necessary condition for the initiation of deep convection from evening to night. That is, the mechanism for the initiation of deep convection from evening to night under a moist soil condition is considered to be as follows: 1) the water vapor in the mixing layer increases due to evapotranspiration and it makes the lower atmosphere potentially unstable, 2) the potentially unstable conditions remain until night, and 3) the topographical convergence of low-level winds over the southern foot of the Khenty Mountains leads to the initiation of deep convection. In other words, since the soil around UB is too dry in practice to sustain an unstable condition until night, the deep convection has to decay by night.

This mechanism for nighttime rainfall in moist soil cases is basically the same as that for the evening con-
vective maximum around north Kanto District, as discussed by Iwasaki and Miki (2001, 2002), except that the low-level winds are not caused by the thermally induced local circulation. According to the results of Murakami (1983) and Dai (2001), evening to early night convective maxima is widely observed over the interior of the tropics to the midlatitudes. The mechanism discussed in the present paper would contribute to the nighttime rainfall maxima over humid regions.

7. Conclusions

The diurnal variation of the convective activity and precipitable water were investigated using a C-band airport radar and GPS receivers around UB, Mongolia, which was considered as an example of an arid region. Synoptic features for the active periods of convective activity were classified into two patterns: the active periods associated with the passage of a trough and those under a ridge. In both the patterns, the SSI$_{500-800}$ at UB was rather unstable and features of the diurnal variation of convective activity were the same.

The convective activity exhibited a pronounced diurnal cycle. The convective activity increased rapidly at 1100 LST around the top of the mountains and reached a maximum at 1400 LST. The regions over which deep convection is more active are observed to be located in the plain by 1800 LST, and the little deep convection exists after 2000 LST. On the other hand, the diurnal variation of precipitable water could not be observed, suggesting that there is neither considerable evapotranspiration from the surface nor a significant thermally induced local circulation around the Khentiy Mountains. Therefore, diurnal variation of convective activity is irrelevant to the variation of water vapor around UB.

The deep convection almost disappeared after evening, which is a feature different from some humid regions. The reason deep convection did not develop at night was discussed using numerical modeling from the viewpoint of soil moisture. In the dry soil cases assumed for the arid simulations, the diurnal variation of the deep convection was consistent with the results of radar observations; that is, deep convection did not occur during the nighttime. In the moist soil condition as assumed for the humid simulations, the increase in the water vapor due to evapotranspiration resulted in a potentially unstable condition. The potentially unstable condition was sustained until night and deep convection was initiated at the southern foot of the mountains where topographical convergence was expected. Since the topographical convergence occurred over the southern foot of the mountains even in dry conditions, it is considered that the potentially unstable atmosphere due to evapotranspiration is a necessary condition for the initiation of deep convection from evening to night. In other words, the deep convection around UB had to decay by night and could not be initiated at night since the soil around UB was too dry in practice to sustain an unstable condition until night.

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