Observed Evidence of Enhanced Probability of Mesoscale Convective System Initiations due to Land Surface Heterogeneity in Semiarid East Asia

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Abstract

This study investigated the impact of land surface heterogeneity on Mesoscale Convective System (MCS) initiations in East Asia, using geostationary satellite data during June–August from 1996 through 2018. The detected MCSs over land exhibited clear diurnal variation with the lowest existence frequency at 10:00 and highest initiation frequency during 12:00−17:00 local time. To quantify land surface heterogeneity, the spatial standard deviation of equivalent Black-Body Temperature (TBB) within a cloud-free 0.35° × 0.35° box (σLSTBB; Land Surface TBB) was computed for 10:00 each day. A comparison of the σLSTBB and MCS databases revealed that the probability of MCS initiations increased with increasing σLSTBB in East Mongolia while the probability was not sensitive to σLSTBB in East China. This indicated that MCSs tend to form over heterogeneous land surface conditions in the semiarid region. We found that the impact of land surface heterogeneity on MCS initiations was highest over flat terrain in East Mongolia, where the convection trigger due to topographically-induced circulation was absent. These results suggest that the impact of land surface heterogeneity on MCS initiations during the warm season varies with climate zones and terrain complexities in East Asia, with strongest impact in semiarid and flat regions.


1. Introduction

Mesoscale convective systems (MCSs), clusters of cumulonimbus clouds, often cause severe weather events. Therefore, their characteristics have been investigated throughout the world (e.g., Houze 2004). MCSs often occur during the warm season (e.g., Laing and Fritsch 1997; Mathon and Laurent. 2001; Morel and Senesi 2002a). Over land, they tend to form around mountains (e.g., Machado et al. 1998; Laurent et al. 2002; Morel and Senesi 2002b), which show clear diurnal variation with the highest frequency during the daytime (Morel and Senesi 2002b; Huang et al. 2018). Convective activities have been investigated over the vast continental climate zone in East Asia (Sato et al. 2007; Iwasaki et al. 2008). However, statistical analysis related to MCSs has not yet been conducted.

There are various factors affecting MCS formations. It is known that MCSs are preferentially generated in an unstable atmosphere which induces upward vertical motion (e.g., Maddox 1983; Xia et al. 2018). The impact of the land surface has also been noted in recent years. Land surface conditions modulate surface fluxes and the structure of boundary layers, and therefore affect the growth stage of mesoscale convection (e.g., Betts and Ball 1998; Eltahir 1998; Santanello et al. 2018). Surface fluxes are very sensitive to soil moisture in semiarid regions (e.g., Guo et al. 2006; Kohler et al. 2010; Seneviratne et al. 2010). When soil moisture is heterogeneously distributed, mesoscale convection is more likely to form over the drier parts of the land (Taylor et al. 2012; Lee et al. 2019) as a result of low-level convergence linked to mesoscale circulation. In the semiarid region of the West African Sahel, the probability of MCS initiations increased with greater spatial heterogeneity of soil moisture (Taylor et al. 2011). Therefore, it is highly probable that the land surface heterogeneity influences the likelihood of MCS initiations in the semiarid region of East Asia.

In addition to atmospheric and land surface forcings, the formation of mesoscale convection is also affected by topography (Houze 2012). However, a question arises as to how strongly land surface conditions influence MCS formations over mountainous regions. Based on an idealized numerical experiment, the impact of soil moisture heterogeneity on precipitation becomes weaker with increasing terrain complexity (Imamovic et al. 2017). However, there has been little confirmation of the results through observational data.

This study aimed to understand the impact of land surface heterogeneity on MCS formation in East Asia. The study domain is 20°N−55°N and 95°E−130°E (Fig. 1). We used geostationary satellite data to objectively identify MCSs and to analyze land surface properties. The relationship between MCSs and land surface properties was investigated mainly over two sub-regions, East Mongolia (40°N−50°N, 100°E−120°E) and East China (25°N−37.5°N, 110°E−120°E), to examine how the relationship differs from semiarid to humid regions in East Asia (Fig. 1a). Furthermore, motivated by the complex terrain features in East Asia (Fig. 1b), this study also examined how terrain complexity modulates the impact of land surface heterogeneity on MCS formation.

2. Data and methods

2.1 Data

This study used hourly visible and infrared images observed by geostationary satellites (GMS-5, GOES-9, MTSAT-1R, MTSAT-2, Himawari-8; see Supplement 1 for the analyzed period and specifications for each satellite). The satellite data, visible reflectivity and equivalent Black-Body Temperature (TBB), were provided by Kochi University. The spatial resolution for the satellite products was 0.05° × 0.05°. The analysis period was June–August from 1996 through 2018. TBB data for the detection of MCSs and their initiations (Section 2.2) were available for approximately 94% of the entire study period. Both TBB and visible data for the land surface analysis (Section 2.3) were available for approximately 92% except for 2006 when the visible data were unavailable.

2.2 Detection of MCSs and their initiations

This study detected MCSs and their initiations using the TBB images derived from the satellites. We defined an MCS as a contiguous area of TBB less than −40°C with an extent greater than 5,000 km². These threshold values have often been used in the detection of MCSs (e.g., Morel et al. 2002a; Taylor et al. 2011; Huang et al. 2018). When an MCS was detected, we then determined the location where the MCS was originally generated. The
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16:00 LT. We analyzed the land surface properties for each MCS initiation event as shown in the following sections.

2.3 Analysis of land surface heterogeneity

Here, we examined the relationship between land surface properties at 10:00 LT and MCS initiations during 12:00−17:00 LT, based on the evidence that the frequency of MCSs is lowest at 10:00 LT in East Asia and more than half of the MCS initiations occur during 12:00−17:00 LT (explained in Section 3.1). To investigate the possible precursor effect of land surface anomalies on MCS initiations, land surface properties at 10:00 LT were analyzed. Grid points with visible reflectivity larger than 0.20 or TBB less than 10°C were assumed to be cloudy and were eliminated. We confirmed that the main results in this study are not very sensitive to the choice of threshold values for visible reflectivity and TBB (Supplement 2). For the remaining cloud-free grid points, TBB was assumed to reflect the land surface properties (hereafter, LST\textsubscript{BB}).

We then computed the standard deviation of LST\textsubscript{BB} within 10:00 LT. The method followed the procedures of Taylor et al. (2011) and is described below. Using the hourly snapshots of the satellite image, the MCS was iteratively tracked back in time by identifying the overlapped cloud cover that accompanies TBB below −40°C. The earliest detected cloud(s) were regarded as the initiation stage of the MCS (hereafter, MCS initiation). The initiation time and location, defined as the spatial centroid of the cloud cover, were recorded. This procedure may detect multiple initiation locations and times for an MCS, which enables the collection of enough MCS initiation events for statistical analysis. Applying this methodology, 153,551 initiations were detected over 23 summers. The mean tracking duration from the MCS initiation (i.e., detection of the first cloud with low TBB) to the first MCS detection (i.e., detection of horizontally extended low TBB) was 1.9 hours. Figure 2 shows an example of the detected MCSs and their initiations on 5 June 2002. At 13:00 LT (Local Time), six initiation locations around the border between Mongolia and China developed into multiple MCSs at 14:00−15:00 LT, merged into a large MCS at 16:00 LT. We analyzed the land surface properties for each MCS initiation event as shown in the following sections.

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each 0.35° × 0.35° (approximately 40 km) grid box (hereafter, \( \sigma_{LST} \)) to quantify how heterogeneously \( LST_{\text{min}} \) was distributed. We adopted this spatial scale because the impact of land surface heterogeneity on MCS initiations was high at the scale of around 40 km (Taylor et al. 2011). The required condition for calculating \( \sigma_{LST} \) was that all grid points within 0.35° × 0.35° must be cloud free; otherwise, the \( \sigma_{LST} \) was not calculated. Out of a huge number of \( \sigma_{LST} \) samples, 6,941 samples were obtained for the dates and locations corresponding to the MCS initiation events that occurred during 12:00–17:00 LT. Hereafter, they are referred to as pre-initiation \( \sigma_{LST} \) because they represent \( LST_{\text{min}} \) heterogeneity prior to the MCS initiation.

Figure 3 illustrates an example of \( LST_{\text{min}} \) and \( \sigma_{LST} \) distributions at 10:00 LT on 5 June 2002. Interestingly, many of the MCS initiations occurred over high \( \sigma_{LST} \). Although the formation mechanism of high \( \sigma_{LST} \) is out of the scope of this study, we noticed that the pattern of high \( \sigma_{LST} \) tended to overlap with the pattern of MCS passages during previous 24 hours. This suggests that the formation of heterogeneous \( LST_{\text{min}} \) might be attributed to mesoscale precipitation in the recent past that caused heterogeneous soil moisture patterns. In the following sections, we show the results of a statistical analysis of \( \sigma_{LST} \) linked with MCS initiations.

3. Results

3.1 Characteristics of detected MCSs and their initiations

Figure 4 illustrates the diurnal variation in the frequencies of detected MCSs and their initiations. In both East Mongolia and East China, the peak time was 14:00 LT for the initiations and 17:00 LT for the existing number of MCSs. The result showed the distinct diurnal variation in the MCS activities in East Asia where the statistical characteristics of MCSs were yet to be understood. This was consistent with the characteristics of convective activities around Mongolia revealed by Sato et al. (2007) and Iwasaki et al. (2008). The number of MCSs initiations is higher over mountainous regions and humid regions than arid regions (Supplement 3).

3.2 Land surface properties around the initiation locations

Figure 5a shows the locations of the MCS initiations and their \( \sigma_{LST} \) at 10:00 LT on the corresponding days (i.e., pre-initiation \( \sigma_{LST} \)). It seemed that the pre-initiation \( \sigma_{LST} \) was generally higher over arid and semiarid regions around East Mongolia than over humid regions around East China. However, this result might be attributed to the climatological characteristics of \( \sigma_{LST} \). Thus, we redrew the pre-initiation \( \sigma_{LST} \) as a deviation from the climatological value based on all the available \( \sigma_{LST} \) samples (i.e., all the cloud-free days) at each initiation location (Fig. 5b). Here, the \( \sigma_{LST} \) was classified into terciles, namely low, normal, and high categories where each category had the same sample number (i.e., one-third of the total sample number at the same location). If the pre-initiation \( \sigma_{LST} \) belonged to the upper tercile category, it meant that the initiation occurred on a day when \( \sigma_{LST} \) was higher than normal. In this case, it implied that a more heterogeneous land surface was favorable for MCS initiations. Figure 5b depicts the tercile category of each pre-initiation \( \sigma_{LST} \). Over East Mongolia, the upper tercile category was dominant (high: 779, normal: 451, low: 394), which suggested that MCSs were more likely to be initiated over higher-than-normal \( \sigma_{LST} \). A similar result was found over the arid region around the Gobi Desert although the number of initiations was small. In contrast, over East China, the number of pre-initiation \( \sigma_{LST} \) was more evenly distributed for each tercile category (high: 492, normal: 394; low: 457), which suggested that probability of MCS initiations remained similar regardless of \( \sigma_{LST} \). To quantitatively measure the impact of land surface heterogeneity on MCS initiations, the number of \( \sigma_{LST} \) samples belonging to upper and lower tercile categories was compared. The sample number ratio between upper and lower tercile categories (represented as the red-to-blue ratio in Fig. 5b) in every 2.5° grid box indicated the impact...
of surface heterogeneity on MCS initiations (Fig. 5c). Hereafter, the ratio is referred to as the Surface Heterogeneity Impact (SHI) index. If the probability of MCS initiations increased (decreased) with $\sigma_{LST_{BB}}$, the SHI index was larger (smaller) than 1.0. In Fig. 5c, over arid and semiarid regions around East Mongolia, the SHI index was high, which meant land surface heterogeneity enhanced the probability of MCS initiations. Furthermore, the SHI index tended to be low over mountainous regions. We investigate the topographic effect on the modulation of SHI index in the next section.

3.3 Topographic effect on the role of land surface heterogeneity in MCS initiations

To assess the complexity of the terrain, the standard deviation of elevation within each $1^\circ \times 1^\circ$ grid box ($\sigma_{ALT}$) was calculated considering that the effects of terrain complexities to local circulation would be maximized at around this scale (Kimura and Kuwagata, 1995). We used GTOPO30 data provided by U.S. Geological Survey which comprises of geographical altitude with 30 arc-second resolution. Figure 6 depicts the SHI index with respect to $\sigma_{ALT}$. In East Mongolia, the index increased with decreasing $\sigma_{ALT}$, which suggested that MCS initiations were enhanced due to land surface heterogeneity over gentle terrain. Therefore, the impact of surface heterogeneity on MCS initiations was highly dependent on topography, with a greater impact over gentle terrain than rough terrain in East Mongolia. In contrast, the SHI index in East China was close to 1.0 regardless of the terrain complexity ($\sigma_{ALT}$). These results are consistent with the fact that the initiation of MCSs is strongly regulated by the terrain complexity in both regions (Fig. 6b).

4. Conclusion and discussion

This study investigated the impact of land surface heterogeneity on MCS initiations in East Asia during June–August from 1996 through 2018 using geostationary satellite data. Detected MCSs and their initiations showed a distinct diurnal variation with an afternoon peak, which was consistent with the characteristics of convective activities around Mongolia revealed by Sato et al. (2007) and Iwasaki et al. (2008). The analysis of land surface properties around the initiation locations revealed that the probability of MCS initiations was enhanced by the heterogeneity of land surface equivalent black-body temperature in East Mongolia. This result was consistent with Taylor et al. (2011), who found an enhanced probability of MCS initiations in the Sahel with increasing soil moisture heterogeneity. However, MCS initiations were not sensitive to land surface heterogeneity in East China. Thus, it is speculated that the impact of land surface heterogeneity
surface heterogeneity. This might contribute to the extension of the prediction of MCSs or deep convection particularly in their over semiarid and flat regions. These findings are applicable for tude across regions (Fig. 7). The strongest impact was observed conditions.

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(Eltahir, E. A. B., 1998: A soil moisture-rainfall feedback mecha -

numerical model simulations are needed to better understand the mechanism of the surface heterogeneity influence on MCS initia -

ity on MCS initiations varies with climate zones and is a unique feature in semiarid regions. Land surface fluxes are known to be very sensitive to the land surface conditions over semiarid regions (Guo et al. 2006; Kohler et al. 2010; Seneviratne et al. 2010), and the sensitivity becomes weak when the vegetation grows (Kohler et al. 2010). Thus, it is considered that the different sensitivity of the surface fluxes to vegetation condition alters the impact of land surface heterogeneity on MCS initiations under different climate zones. This might be the cause of contrasting results between East Mongolia and East China. In humid regions, MCS initiations are more likely controlled by atmospheric forcing than land surface conditions.

This study also examined the effect of topography on the role of land surface heterogeneity in MCS initiations. It was revealed that the heterogeneity impact was high over gentle terrain and low over complex terrain in East Mongolia, which was consistent with the results of the idealized model experiments conducted by Imamovic et al. (2017). Over mountainous regions, there are well-known orographic effects favorable for deep convection (Houze 2012), and those effects are considered to be stronger than the land surface thermal heterogeneity effect on MCS initiations.

In conclusion, the impact of land surface heterogeneity on MCS initiations was evident in East Asia with varying magni -


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