Spatial and diurnal variation of precipitation systems over Asia

Masafumi Hirose[1] and Kenji Nakamura[2]
1). JAXA/EORC, Japan,
2). HyARC, Nagoya University, Japan

ABSTRACT

The spatial and diurnal variation of rainfall over Asia was investigated using the spaceborne radar data for four seasons during 1998–2003. The regional variation of the prevailing precipitation systems most closely associated with the maximum hourly rainfall was shown by examining the fine-spatial distribution of rainfall amount and scale-based precipitation systems.

Small precipitation systems ($< 10^2$ km^2) occurred most frequently around early afternoon over most land. The south-facing slopes of the Himalayas, especially south of Mount Evelest and the upper portion of the Brahmaputra valley, is the most obvious region of the daytime genesis of the cumulus-scale systems over the Asian landmass. Over the Tibetan Plateau, the occurrence of the small systems was larger than over inland India and the foothills. Large systems ($> 10^4$ km^2) developed mostly in the evening over near-flat landmasses. Wide-spread systems with intense rain pixels developed over the foothills of the Himalayas in late night-early morning period, that was distinct from the daytime-convection. Over ocean, in addition to the morning signature, spatially inhomogeneous and systematic characteristics were evident over the offshore region, for example, around the Maritime Continent.

Large systems, which are strongly associated with terrain, have a great influence on the total number of rain pixels and the total amount of rainfall. For 86 % of the region where large system is dominant, the time of maximum rainfall is within 3 hours of the time of maximum rainfall for large systems.

Introduction

The first spaceborne Precipitation Radar (PR) on the Tropical Rainfall Measuring Mission (TRMM) satellite has provided a unique opportunity to observe the spatial variability of the seasonal and diurnal cycles of precipitation systems. It has observed precipitation structure evenly over land and ocean for various local times from its non-sun synchronous orbit since the end of 1997. The representation of the universal and local characteristics is a good step to obtain some insight into the mechanisms of the different types of convective activity.

Several investigations of the diurnal cycle with the TRMM PR showed general characteristics in bulk over relatively wide regions considering the temporal and spatial resolution. They mainly focused on continuously variable physical properties and implicitly included regional characteristics of many different kinds. For observational studies by one non-sun synchronous orbital satellite sampling remains the substantive problem. In order to take the sampling variabilites evenly or to detect the first few harmonics accurately, the spatial and temporal resolution of TRMM data analyses have been coarse (*e.g.,* Nesbitt and Zipser 2003). However, high spatial frequency features should be examined to understand relationships between precipitation and the topography (Lang and Barros 2002). In this study, understanding global and regional characteristics of rainfall by fine-scaled analyses is sought using TRMM PR data. It will help to extract precipitation regimes influenced by the topography or geography. The target domain is Asia, which is known for significant seasonal and diurnal variation of rainfall and convective activity. The purpose of this study is to show the spatiotemporal variation of the prevailing precipitation systems by examining the diurnal variation of precipitation properties.

Sampling biases on diurnal variation

Six years (1998–2003) of rainfall rate data were used in this study. In order to cope with sampling biases, we calculated monthly and hourly rainfall amount using the number of samples for each hour in each month, and then averaged the hourly data for multiple months. The procedure was performed for all regional and gridded analyses in this study. The grid scales were 0.2 and 1 degree as shown in the following section. In the case of August, monthly rainfall with disregard to the sampling biases was about 10 % overestimated over Tibet in conjunction with the afternoon rainfall (not shown). The spatial frequency of rain is the number of rain pixels divided by the total number of observed fields of view (FOVs), that is, a normalized rain area in each grid. Peaks of rainfall or spatial frequency of rain used the hourly data averaged with plus and minus one hour data to smooth the temporal variation. Thus, hourly rainfall amount and spatial frequency of rain are obtained. Such modification should be considered when one studies seasonal and diurnal variation of rainfall or the number of systems, especially in cases with a weak diurnal signature, such as over ocean at midlatitudes. It should, however, be kept in mind that these methods possibly exaggerate hourly rainfall amount over lightly sampled regions, especially over the midlatitudes (around 35° latitude, e.g., over Japan) and over the tropics showing checkerboard patterns in the sampling (Negri *et al.* 2002). Although the total number of samples in the midlatitudes is about four times larger (twice a day) than that around the equator, the minimum number of hourly samples is much smaller if three years of data are used. A few clock hours remain poorly covered for the monthly dataset during three years (*e.g.,* Kishtawal and Krishnamurti 2001). Using TRMM data for more than six years has greatly improved the temporal sampling.

Spatial variation of time of maximum rainfall

The diurnal cycle of precipitation does not simply exhibit sinusoidal behavior and may not be well represented in harmonic analysis (*e.g.,* Ohsawa *et al.* 2001). For the purpose of clarifying the prevailing precipitation systems, we focus on the spatial variation of the time of maximum rainfall. Figure 1 shows the time of maximum rainfall during June–August. Over ocean where the diurnal signature is generally weak and over regions with few samples in the checkerboard patterns (Negri *et al.* 2002), hourly-rainfall amount exhibits sharp fluctuations due to the few rain samples. We de-emphasized the pixels having negative anomaly one-hour before or after the time of maximum rainfall (light-colored shadings). We mainly focused on the significant diurnal features with the consecutive positive anomalies for more than three hours (dark-colored shadings). Pixels with few rain samples (the spatial frequency of rain < 1 %) were excluded. A rain frequency of 1 % corresponds to precipitation systems covering a 0.2°×0.2° grid box around the equator more than 40 rain samples (more than two overpasses) for consective three months during 1998–2003.

During June–August, the rainfall distribution spreads farther into the foothills of the Himalayas, and the Tibetan Plateau (Fig. 1). Early–afternoon (14–16 LT) rainfall is conspicuous over most of the Tibetan Plateau and other regions higher than 2000 m. In detail, even over 4000 m, nighttime (18–4 LT) rainfall prevails south of the peaks of the Himalayas (> 5500 m). The terrain-forced diurnal pattern may be explained by the effects of the gravity wave and the regional–scale circulations (*e.g.,* Barros and Lang 2003). Eastern Tibet shows an evening peak. Major mountains and valleys on the plateau are aligned along an east-west direction. The valley region along with the Yarlung-Zangbo river clearly shows maximum rainfall in the late evening. The spatial inhomogeneities of mountains and valleys seem to modulate the afternoon and morning rainfall maximum (*e.g.,* Kurosaki and Kimura 2002). Tibet clearly shows the topographic dependence of the diurnal cycle since the environment would be suitable for generating afternoon dominated systems. The lower southern side of the steep slopes widely show maximum rainfall in the midnight to early morning period. In view of the spatial uniformity of the time of maximum rainfall, most of the regions south of the Himalayas and the Sichuan Basin would have the significant diurnal signal although they are de-emphasized due to the sharp fluctuation shown in the following section. The northeastern part of Thailand, the mideastern part of India, and the eastern part of the south foothill of the Himalayas including the Brahmaputra valley (around 27°N, 93°E) show early-morning rainfall maxima as reported by previous research (Barros and Lang 2003). The foothills on the Aravalli range (∼ 250 m in altitude), show near-dawn rainfall maxima. As well as the south-facing slope of the Himalayas, the Sulaiman Range (northwest of the Thar desert) also has rainfall maximum in the afternoon. Over a large part of China, afternoon rainfall appears (Kato *et al.* 1995) in this season. Maximum rainfall in the southern part of the Bay of Bengal and nearby coast appears in the early-afternoon and in the morning, respectively. This may be associated with southward advection of precipitation systems and land effects studied by Zuidema (2003). Unlike other tropical islands, evening peak appears around ocean west of Luzon island, where the monsoonal flow converges. The Maritime Continent is known as the region with the most significant diurnal signal (*e.g.,* Nesbitt and Zipser 2003). Afternoon rainfall is dominant over the coastal regions and relatively higher mountains such as the Barisan Mountains on the island of Sumatra (the southwestern side), the Maoke and Bismarck Mountains on the island of New Guinea (the center line over northwest–southeast), and the Iran Mountains on the island of Kalimantan (the northwestern part). On the lower part of these mountains, the peak time of rainfall shifts to evening–midnight (18–2 LT). This figure clearly shows that it is important to consider the island properties of not only the area of the island but also the topography and the shape in order to understand the diurnal cycle over the islands. The time of maximum rainfall over the adjacent ocean seems to be shifted from midnight to late morning from the coast to offshore.

Impact of the scale–based systems in rainfall

A "precipitation system" is defined as contiguous rain-certain pixels observed by TRMM PR (Hirose and Nakamura 2004). Here, the scale-based precipitation systems were grouped into the three classifica-

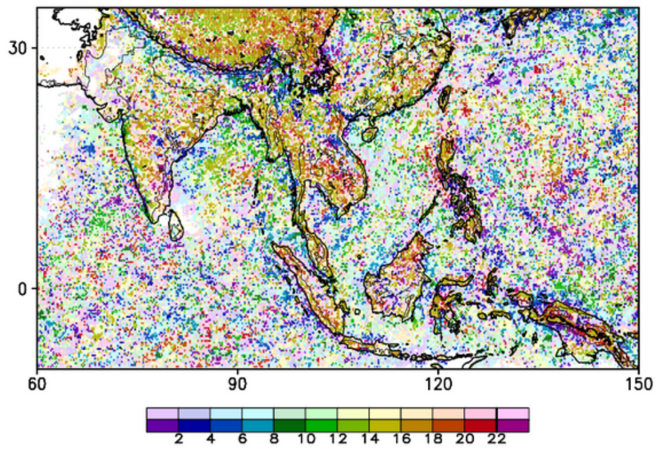

Figure 1: Seasonal differences of time of maximum rainfall at each 0.2°×0.2° grid for June–August. Dark-colored shading indicates that rainfall within 1 hour of the time of maximum rainfall preserves positive anomalies. Topographic contours are drawn with 200, 2000 (thick), and 4000 m, respectively. Pixels with few rain samples that the spatial frequency of rain was less than 1 % are blanked out.

tions; small "cumulus-scale" systems less than 100 km^2, medium systems with rain area between 100–10000 km^2, and large systems greater than 10000 km^2. Over a large part of the landmasses, there is a clear tendency for a change of prevailing systems from small to large through the afternoon and evening (not shown). In order to generalize the local characteristics, the impact of each scale systems was focused upon. Figure 2 shows the time of maximum rainfall for each scale of systems. Where the time of maximum rainfall is not within 3 hours of the time of maximum rain frequency (normalized bulk rain coverage), the grid box is given a white edge. The rainfall is temporally averaged as Fig. 1. For 75 % of the grids over land and 67 % over water the time of maximum rainfall is within 3 hours of the time of maximum rain frequency (the top panel). Over the regions with strong correlation, the prevailing systems which provide large amounts of rainfall could be understood in terms of the largest spatial frequency of rain providing maximum rainfall amount for each system classification by horizontal scale. On the other hand, the places for which the time of maximum rainfall does not correspond to that of maximum rain frequency need to be considered in terms of the strength of rain. In the case of the mature monsoon season over India, the number of heavy rainfall rates decreased while the number of large systems increased, so that the averaged rain intensity changed even for similar scale systems between different precipitation regimes (Hirose and Nakamura 2004). Such contribution of relatively small (large) but intense (weak) precipitation systems and significant rainfall with minor frequency appeared on the white-edged grid boxes in Fig. 2. Over land, a large number of the grids showed an afternoon rain maximum implying that the rain coverage had less impact than heavy afternoon rain.

The second panel shows a clear contrast between afternoon rain over land and morning rain over ocean. Small systems generally dominate in the early afternoon over land even over mountains. In detail, higher regions such as over the Tibetan Plateau and the northern part of the Indochina Peninsula include late morning rainfall. Over ocean, there are regional trends. Near-dawn peaks are shown over the southern part of the East China Sea, early morning peaks over the northern part of the East China Sea and the Indian Sea, midnight to early morning peaks around the open ocean under the Pacific High. The third panel shows the case of medium systems. The peaks over land shift later. Nighttime maxima are seen over the Himalayas and the eastern mountains of the Indochina Peninsula. Japan has an evening rain peak surrounded by early morning rain over the nearby ocean. Large systems (the bottom panel) show the geographical pattern more clearly. The early morning peaks are clear around the lower side of high terrain such as south of the Himalayas, the lower region in the Maritime Continent such as east of the Barisan Mountains, and the mideastern part of the Decan Plateau. The evening peaks over the Tibetan Plateau, inland India, lowland of the Indochina Peninsula are localized. The contrast between the eastern and the western part of the southern facing Himalayas is clearly shown as early morning and near dawn peaks, respectively. Over ocean, morning rainfall dominates. Rainfall over the adjacent ocean west Luzon Island where large systems frequently occur has a late-evening peak. That is different from the morning peak west of the Indochina Peninsula. Over the southern Bay of Bengal, the afternoon signature is shown. By comparison with the time of maximum rainfall in the top panel, few but large systems affect the total rainfall significantly. For example, the pattern of large system occurrences is similar to that of maximum rainfall over the southern part of the Himalayas, the eastern part of the Tibetan Plateau, the Sichuan Basin, the Maritime Continent, the ocean west of the Indochina Peninsula, and inland India. Numerous large systems prevail in the Bay of Bengal in the morning.

We investigated the rain area fraction of large precipitation systems from June to August (not shown). The fraction indicates % of total spatial frequency of rain due to large systems. For 56 % of the region, the time of maximum rainfall coincides with the time of maximum rainfall for large system. The region where the phase lag is within 3 hours accounts for 81 % of the domain. For 60 % of the region, the rain area fraction of large systems is greater than 50 %. And 86 % of the region where large system is dominant has the phase lag within 3 hours. The significant proportion indicates that the variation of large systems is the prime factor in regional characteristics of rainfall. The time of maximum rainfall is a few hours prior to the peak of large systems over the Tibetan Plateau. The impact of large systems is not significant over the region where the rain area fraction of large systems is less than 30 %.

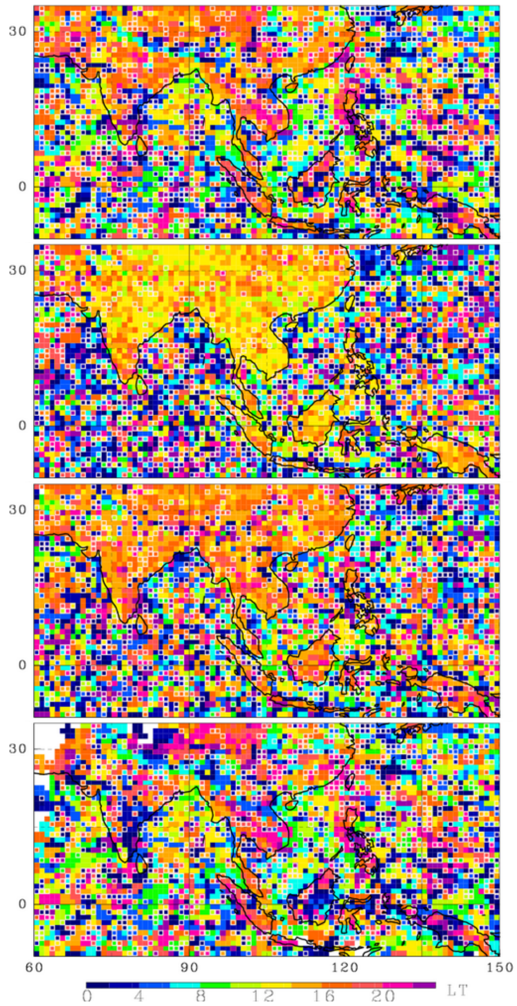

Figure 2: Time of maximum rainfall for scale-based precipitation systems at each 1°×1° grid from June to August. The top, second, third, and bottom panel indicate all, small (< 100 km^2), medium (100–10000 km^2), and large (greater than 10000 km^2) systems, respectively. White-colored squares indicate that the difference from the time of the maximum number of rain pixels is greater than 3 hours.

Concluding remarks

Our simple scale-based analyses could explain a large part of rain distribution by the spatial frequency of rain and the total rainfall amount. Furthermore, seasonal and regional system-type differences should be investigated on the basis of the global and regional understandings (*e.g.,* Nesbitt and Zipser 2003). Further morphological understandings of the mesoscale/synoptic-scale systems for a particular climatic regime would make possible interpretation of the precipitation climatology and the mechanisms therein more specifically. Again, understanding the dynamic state of large systems is of prime importance. Fuller studies on the genesis of the precipitation systems need more comprehensive analyses with atmoshperic properties.

Acknowledgements. This paper is currently under review by JGR. The authors would like to express their gratitude to the members of the TRMM project, especially in JAXA/EORC. The authors would like to express their gratitude to Prof. T. T. Wilheit, T.N. Rao, Mr. B. C. Bhatt and Ms. P. Singh for their constructive comments.

References

Barros, A. P. and T. J. Lang, 2003: Monitoring the Monsoon in the Himalayas: Observations in central Nepal, June 2001. *Mon. Wea. Rev.*, **131**, 1408–1427.

Hirose, M. and K. Nakamura, 2004: Spatiotemporal variation of the vertical gradient of rainfall rate observed by the TRMM Precipitation Radar. *J. Climate*, **17**, 3378–3397.

Kato, K., J. Matsumoto and H. Iwasaki, 1995: Diurnal variation of Cb-Clusters over China and its relation to large-scale conditions in the summer of 1979. *J. Meteor. Soc. Japan*, **73**, 1219–1234.

Kishtawal, C. M. and T. N. Krishnamurti, 2001: Diurnal variation of summer rainfall over Taiwan and its detection using TRMM observations. *J. Appl. Meteor.*, **40**, 331–344.

Kurosaki, Y. and F. Kimura, 2002: Relationship between topograhy and daytime cloud activity around Tibetan Plateau. *J. Meteor. Soc. Japan*, **80**, 1339–1355.

Lang, T. J. and A. P. Barros, 2002: An investigation of the onsets of the 1999 and 2000 monsoons in central Nepal. *Mon. Wea. Rev.*, **130**, 1299–1316.

Negri, A. J., T. L. Bell and L. Xu, 2002: Sampling of the diurnal cycle of precipitation using TRMM. *J. Atmos. Oceanic Technol.*, **19**, 1333–1344.

Nesbitt, S. W. and E. J. Zipser, 2003: The diurnal cycle of rainfall and convective intensity according to three years of TRMM measurements. *J. Climate*, **16**, 1456–1475.

Ohsawa, T., H. Ueda and T. Hayashi, 2001: Diurnal variations of convective activity and rainfall in tropical Asia. *J. Meteor. Soc. Japan*, **79**, 333–352.

Zuidema, P., 2003: Convective clouds over the Bay of Bengal. *Mon. Wea. Rev.*, **131**, 780–798.