Journal of Hydroscience and Hydraulic Engineering
Vol. 30, No.1 May, 2012, 1-14

REQUISITE CONDITIONS FOR POST-MONSOON RAINFALL IN CAMBODIA BY LOOKING THROUGH 2009 RAINFALL DATA

By

Kumiko Tsujimoto

Earth Observation Data Integration and Fusion Research Initiative, The University of Tokyo, Bunkyo-ku, Tokyo, Japan

and

Toshio Koike

Department of Civil Engineering, The University of Tokyo, Bunkyo-ku, Tokyo, Japan

SYNOPSIS

An analysis of data recorded by an automatic weather station and 30 rain gauges showed that about 30%~40% of post-monsoon rainfall in western Cambodia occurred without water-vapor convergence throughout Cambodia, especially rainfall from midnight to early morning. Numerical simulations have suggested that land–lake–atmosphere interaction in the vicinity of Tonle Sap Lake induced such rainfall. By clarifying the mechanism of post-monsoon rainfall in western Cambodia, three requisite conditions for these rainfall events were deduced: (1) an abundance of precipitable water (more than ~40mm), (2) development of a land breeze from the southwest of the lake, and (3) a large-scale northeasterly wind of moderate strength.

INTRODUCTION

The prime industry of Cambodia is agriculture and most of the agricultural land in Cambodia is rain-fed. Since there is no widespread large-scale systematic irrigation system it is difficult to manage rain-fed paddy fields in tropical monsoon climatic areas with distinct dry and rainy seasons. The authors conducted interviews with farmers in western Cambodia, and learned that each farmer guessed the available water resources at the beginning of the dry season and in this manner decided planting times, plant areas, and crop types strategically. These farmers refer to three information sources: (i) information from local government and/or the water-use commune, (ii) their own experience, and (iii) "traditional predictions" (a kind of fortune-telling). Farmers rely on (ii) and (iii) in addition to (i) because sophisticated weather forecasting is not carried out in Cambodia. Thus, at this moment, the accuracy of information provided by local government in charge of water resources and meteorology is limited. As a result, it is difficult for the local government to provide information at such a level that it is directly relevant to the decision making of farmers.

In fact, it is well known by local people that it rains not only during the rainy season but also in the pre- and post- monsoon seasons. These rainfalls are called as "phleang koker" in the local parlance and this word is used as a symbol of happiness. However, the number of the published papers on the post-monsoon rainfall in the Indochina Peninsula are very limited [e.g., Matsumoto (1)], while the studies on the pre-monsoon rainfalls in the Indochina Peninsula [e.g., Kanae (2), Zhang (3)] and the studies on the post-monsoon rainfalls in India [e.g., Ramesh and Goswami (4), Sinha et al (5)] have received considerably more attention by researchers.

One of the noteworthy characteristics of Cambodia is that it has the largest freshwater lake in Southeast Asia, Tonle Sap Lake, in the center of the country. Previous studies by the authors (6), (7), (8) that examined the mean atmospheric conditions of the post-monsoon season in this region using a mesoscale numerical simulation model suggested that the interaction of this lake and the surrounding land results in local atmospheric water circulation on a spatial scale of 400×400km that covers almost all Cambodia. Furthermore, these studies show that there is sometimes rainfall even after the withdrawal of the Asian Summer Monsoon. Especially on the western side of the lake, there is rainfall even in the dry season and a numerical simulation suggests that this rainfall results from local atmospheric water circulation from midnight to early morning because of the existence of the lake. In addition, this region is one of the most important grain-production regions in Cambodia and thus water resource management in this region is essential for the nation's food production and economy.

Despite the existence of such a large lake, the study of atmospheric water circulation over this region has been limited owing to the limited availability of in situ data [Masumoto et al., (9)]. In Cambodia, many hydrometeorological observation instruments and experts were lost during the civil war in the 1970s and so routine observations are difficult to make even now. Thus, there are no available routine radiosonde observation data for Cambodia, and reanalysis global data obtained using a general circulation model (GCM) do not include in situ observation atmospheric vertical profile data for Cambodia. Since GCM reanalysis data are generally required for the initial and boundary conditions of a regional atmospheric model, there are model errors related to the initial conditions for the Cambodian region. Thus, physical downscaling from a reanalysis dataset would be appropriate only for the mean field and it would be difficult to reproduce an individual event.

Considering the above-mentioned characteristics of rainfall and agriculture in Cambodia, seasonal prediction of rainfall for the dry season would be useful. As aforementioned, although it has been suggested that there is local rainfall in western Cambodia in the post-monsoon season, there are many difficulties in making actual daily predictions without the prospect of restarting routine radiosonde observations. In this paper, therefore, we do not carry out numerical simulations using a regional atmospheric model, but focus on the large-scale atmospheric condition derived from GCM reanalysis data and search for an empirical correspondence relationship between the large-scale atmospheric condition and local rainfall.

The problem here is that the availability of rainfall data in Cambodia is very limited, and on that basis, the authors (10) have suggested that rainfall estimation using the TRMM/3B42 product is considerably inaccurate. We thus reconstructed a ground-based rain-gauge network for the whole of Cambodia. We newly installed rain gauges at 13 stations and restarted the maintenance and data collection at 17 stations that had not been maintained for more than 1 year after the termination of an ODA project. In these field activities, the first author went into the field with Cambodian governmental staff and carried out instrumental maintenance, checked data quality and collected data. We trained local staff at the same time to maintain instruments and to ensure data quality. In this manner, we have operated a total of 30 stations and continued ground-based rainfall observations with rain gauges.

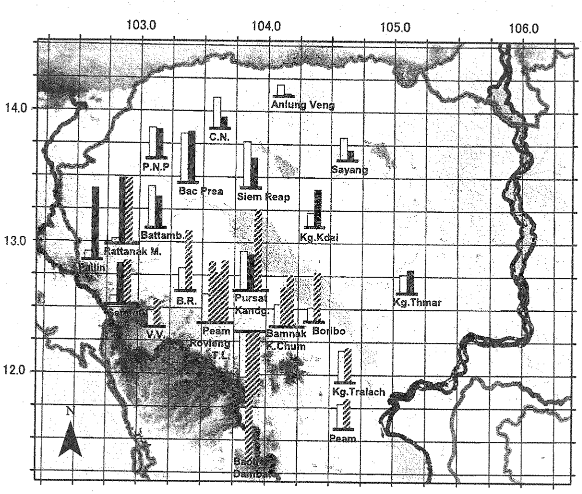
In addition to these rain gauges, we installed an automatic weather station (AWS) on the southwestern lakeshore (the location is shown in Fig. 2) and observed meteorological elements, sampling every 1 second and recording the average over 10-minute intervals. In a previous study, the authors (11) indicated that this location is important in clarifying the mechanism of the target local rainfall in this area.

The purpose of this study is to examine the requisite conditions for post-monsoon rainfall, focusing on phenomena suggested in our previous studies (6), (7), (8) and using both in situ and reanalysis data, in order to ameliorate rainfall prediction in further studies. While the previous studies numerically examined the averaged conditions, this study examines the individual event by using the observation data in 2009.

DATA COLLECTION

Rainfall data

As mentioned in our previous studies (10), we used data recorded at 30 rain-gauge stations. The locations of the rain gauges are shown with black horizontal bars in Fig. 1. For each location in Fig. 1, the rainfall amounts measured by rain gauges and given in the TRMM/3B42 product are shown. The rainfall amounts do not match well and there are wide discrepancies between rain-gauge data and TRMM/3B42 data at some locations. As aforementioned in the previous section, we maintained thoroughly the rain gauges and checked the quality of rain-gauge data; therefore, only rain-gauge data are considered in the remainder of the paper.



raingauge	new(UT)	Existed (JICA)
type	ONSET RG3M	Ota Keiki
resolution	0.2mm	0.5mm
installed on	Sep.-Oct. 2009	2003-2006
height	0.50m	1.50m

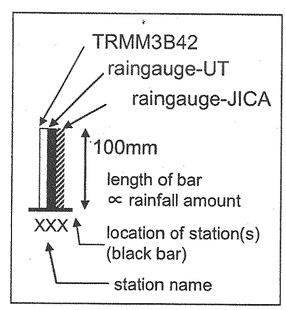


Fig. 1 Rainfall amounts recorded by rain gauges and given in the TRMM/3B42 product (accumulated values for the period from 24 October to 31 November 2009). The horizontal bar shows the location of a station. The light grey bars show the rainfall amounts given in the TRMM/3B42 product. Data are presented separately for new (rain gauge-UT; black solid bars) and existing (rain gauge-JICA; black hatched bars) rain-gauge instruments. At the stations "Rattanak M." and "Samlot", we installed both types of instrument and thus there are two black bars, which match very well. Other cells with several black bars contain several rain-gauge stations in a 0.25×0.25° TRMM/3B42 grid. Detailed information concerning this figure was published by Tsujimoto et al. (10).

AWS data

The location of the AWS is shown in Fig. 2. As shown in this figure, the direction from the lake to the AWS almost corresponds to a wind direction of 45°.

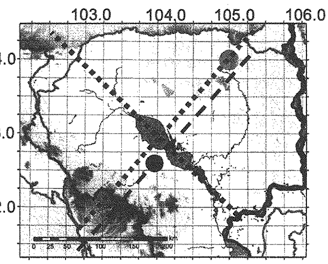


Fig. 2 Location of the AWS (•). The black broken line is the direction perpendicular to the long axis of the lake (shown by a black dotted line). The direction from the lake to the AWS is nearly a wind direction of 45°. The site marked ● is at 14°N, 105°E and is refered to frequently in the latter half of the paper. The grey dotted line is a line perpendicular to the long axis of the lake.

Large-scale atmospheric condition

In this study, we used NCEP/FNL reanalysis data with horizontal spatial resolution of 1.0 degree and temporal resolution of 6 hours.

DISCUSSION ON THE OBTAINED DATA

Definition of the "post-monsoon season"

In the many earlier studies on the definition of the monsoon season [e.g., Fasullo and Webster (12); Kiguchi and Matsumoto (13); Wang and Lin (14); Zhang et al. (15)], researchers have used various indices such as rainfall, outgoing longwave radiation, and large-scale atmospheric circulation. The offset (i.e., end) of the monsoon, which progresses much more gradually than the onset, has not been studied as much as the onset and there is thus no consensus for the definition of the offset.

This paper investigates whether rainfall in the target area results from convergence of abundant ocean-origin water vapor through large-scale atmospheric circulation or from local circulation driven by land–atmosphere interaction in the target region. For this purpose, we define the monsoon period by taking a large-scale atmospheric circulation as the index. More specifically, we follow the method adopted by Kiguchi and Matsumoto (13), who discussed the onset of the Asian Summer Monsoon in terms of zonal wind at 700 and 850hPa. We define the final day of the Asian Summer Monsoon to be the day previous to the day on which the zonal wind at both 700 and 850hPa becomes continuously negative (i.e., easterly) over Cambodia (11°~15°N, 102°~106°E). The final day of the Asian Summer Monsoon is thus defined as October 23rd, 2009. Therefore, this paper investigates rainfall after October 24th, 2009 and defines the "post-monsoon" season as being from this day until December 31st, 2009 (for the sake of convenience).

For reference, the zonal wind (daily averaged values at 700 and 850hPa) and water vapor convergence amount (daily average calculated with Eq. 1 below) are shown in the first and second rows of Fig.3 from September 1st to December 31st, 2009. These values are shown as the area-averaged values over the Indochina Peninsula, since we focus on the area-averaged conditions for these parameters. The third and fourth rows show water vapor mixing ratio (at 01:00LT and 07:00LT) and precipitable water (at 01:00LT and 07:00LT) for the same period. Since we focus on the condition at the windward side of the lake (location: ● in Fig. 2), we display values at the location of (14°N, 105°E) for these two parameters. The light-grey vertical broken line and the dashed line mark the days of October 24th and

November 19th, 2009, respectively. Although day-to-day variation is large, in general, after October 24th, 2009, which we define as the first day of the "post-monsoon" season, an easterly wind prevails, water vapor is divergent, and the amount of precipitable water decreases.

Then, from daily rainfall data during the post-monsoon season which is shown in Figure 4, the following two distinctive characteristics are fond for the discussion.

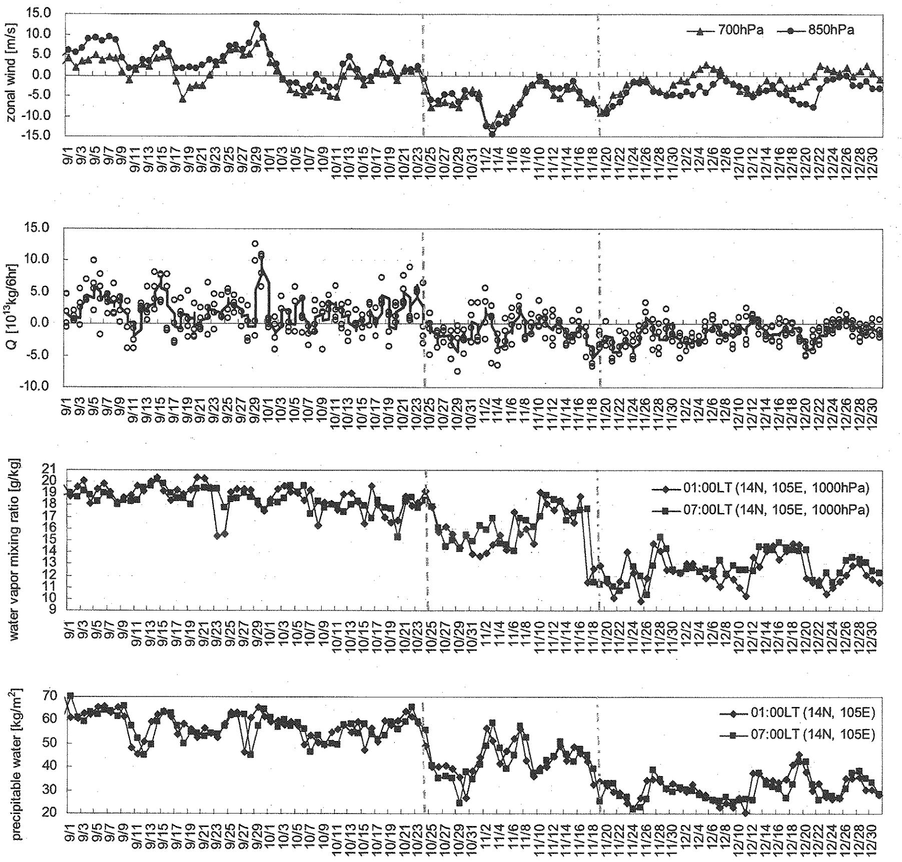


Fig. 3 Seasonal changes for each element. The first row shows the zonal wind over Cambodia (daily averages at 700 and 850hPa). The second row illustrates water vapor convergence Q toward the Cambodian region, positive for convergence and negative for divergence; the symbol ○ is the six-hourly value and the solid line is the daily average. The third row is the water-vapor mixing ratio at 1000hPa (01:00LT, 07:00LT) and 14°N, 105°E on the windward (northeast) side of the lake. The fourth row is the same as the third row but for the precipitable water amount.

Discussion point 1

Figure 4 shows the daily rainfall amount (accumulated rainfall amount for the 30 rain gauges) for the post-monsoon season. While there is frequent precipitation immediately after the withdrawal of the Asian Summer Monsoon, there is not so much precipitation after November 19th, 2009. In addition, as clearly shown in Fig. 1, most of the rainfall occurs on the western side of the lake.

If the precipitation results from local circulation driven by the thermal contrast between the lake and land at night as suggested by the authors (7), there should also be precipitation after November 19th, 2009. Thus the reason why there is a lack of precipitation after November 19th, 2009 needs to be explained.

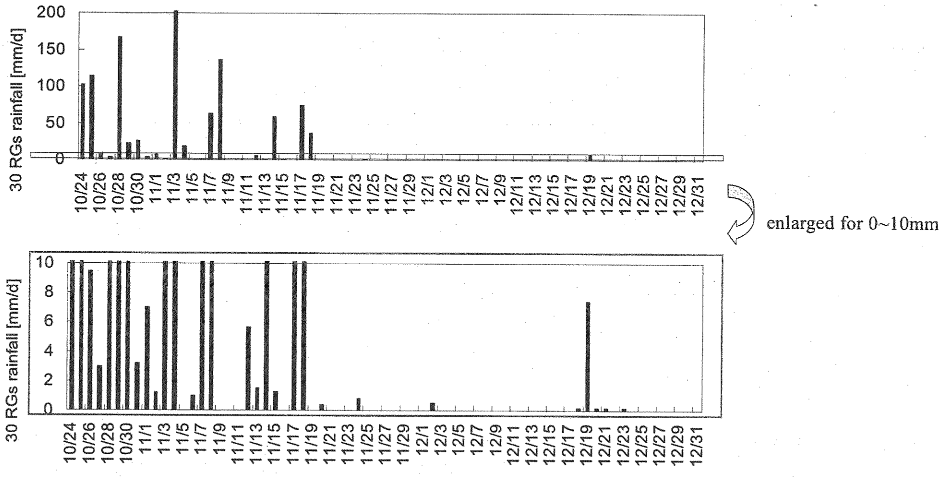


Fig. 4 Daily rainfall amount in the target period (accumulated rainfall amount for 30 rain gauges). On November 3rd, 2009, the amount of precipitation was off the graph and had a value of 630 mm. To examine the small amount rainfall events in detail, the graph is enlarged underneath for rainfall amounts of 0~10mm.

Discussion point 2

As shown in Fig. 4, even before November 19th, 2009, precipitation is not observed on all days. While point 1 relates to the difference in precipitation before and after November 19th, 2009, here we discuss the fluctuation prior to November 19th, 2009 and investigate why there was not precipitation on all days.

EXAMINATION OF DISCUSSION POINT 1: THE SEPARATION OF POST-MONSOON SEASON INTO RAINY PERIOD AND DRY PERIOD

The authors (7) have numerically demonstrated that post-monsoon rainfall in western Cambodia is concentrated on days when the nocturnal northeasterly is strong. Therefore, we focus on a point on the northeast (windward) side of the lake (14°N, 105°E; the location is shown in Fig. 2). The seasonal changes in the water vapor mixing ratio at 1000hPa and precipitable water at this point are shown in Fig. 3.

In Fig. 3, the amount of water vapor in the low atmosphere suddenly decreases around November 19th, 2009 and the amounts of water vapor and precipitable water are low afterward. Figure 5 of the vertical profile of the water vapor mixing ratio also shows that the amount of water vapor is less in the later period (from 19th to 24th November 2009) than in the earlier period (from 13th to 18th November 2009) in the lower atmosphere below 650hPa. Moreover, the calculated precipitable water amounts were 43.57mm (01:00LT) and 45.07mm (07:00LT) in the first period and 27.93mm (07:00LT) and 28.52mm (01:00LT) in the latter period, showing a clear decrease.

From the above analysis, we concluded that the decrease in the amount of precipitable water, especially the decrease in the amount of water vapor in the lower atmosphere, is a reason for the unfavorable conditions for rainfall.

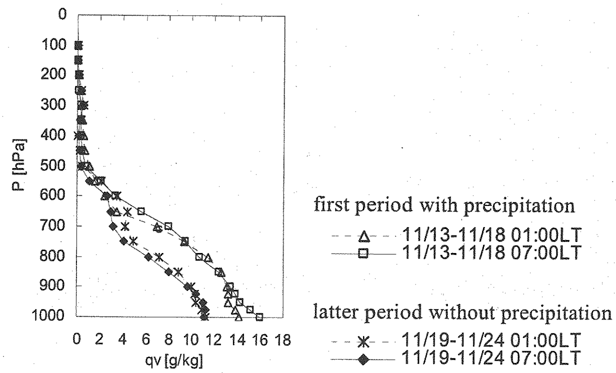


Fig. 5 Vertical profiles of the water vapor mixing ratio at 14°N, 105°E. The averaged values for the two periods with and without precipitation are shown.

Next, we examined the process of the decrease in water vapor in this period. For this purpose, we calculated the vertical integrated water-vapor convergence amount Q [kg] over the Cambodian region (11°~15°N, 102°~106°E).

$$Q = \frac{1}{g}\left\{\left(\int_{300}^{P_{sfc}} uqdp\right)\Big|_{102E} - \left(\int_{300}^{P_{sfc}} uqdp\right)\Big|_{106E} + \left(\int_{300}^{P_{sfc}} vqdp\right)\Big|_{11N} - \left(\int_{300}^{P_{sfc}} vqdp\right)\Big|_{15N}\right\}, \quad (1)$$

where g is acceleration due to gravity [m s^{-2}], P_{sfc} is surface pressure [hPa], u is zonal wind [m s^{-1}], v is meridional wind [m s^{-1}], q is specific humidity [kg kg^{-1}], and p is pressure [hPa]. In the six-hourly NCEP-FNL reanalysis product, there are 276 time steps in the target period (from October 24th to December 31st, 2009). Water vapor was convergent at 71 of these time steps (25.7% of the total time steps) and divergent at the other time steps. Thus, the environment is mostly divergent. Q [kg/6hr] ranges from -7.5×10^{13} to 6.5×10^{13} and we removed the time steps for which there was very weak convergence or divergence according to $-1\times10^{13} < Q < 1\times10^{13}$. Therefore, in the first period with precipitation (from October 24th to November 18th, 2009), convergence and divergence account for 27.3% and 72.7% of the time steps respectively, and the latter period without precipitation (from November 19th to December 31st, 2009) has 9.4% convergence and 90.6% divergence. Thus, with the seasonal march, water vapor becomes more frequently divergent and the amount of water-vapor in the target area thus largely decreases and there is hardly any rain in the latter period.

Checking the amount of precipitable water and wind field at 1000hPa for each period in Fig. 6, we found the amount of precipitable water in China largely decreases in the latter period while there was no clear difference in the strength of the northeasterly. Thus, the change in the outflow volume of water vapor mentioned in the previous paragraph is due to not the seasonal change in the strength of the northeasterly (Winter Monsoon) but the change in the amount of precipitable water in China on the windward side of Cambodia.

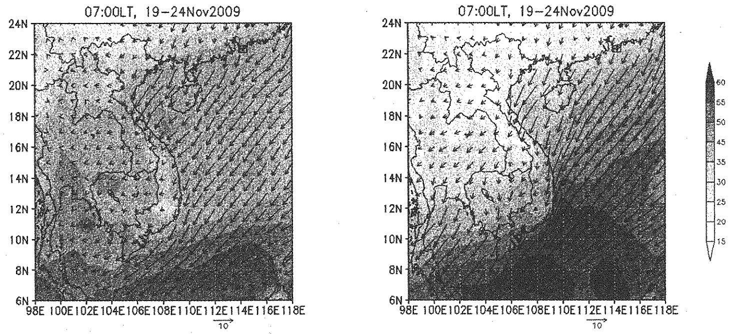


Fig. 6 Large-scale distributions of precipitable water (color shading) and wind fields at 1000hPa for the first period with precipitation (left) and the latter period without precipitation (right).

EXAMINATION OF DISCUSSION POINT 2: INTERMITTENCY OF RAINFALL EVEN DURING THE RAINY PERIOD

Is the amount of precipitable water the key as similary as point 1?

In the previous section, we found a large difference in the precipitable water amount between the first and latter periods and pointed out that this difference would be the controlling factor of whether there is precipitation. In fact, however, it only rained on some days during the first period. Therefore, we wonder whether the amount of precipitable water also controls precipitation in the first period.

To answer this question, three-hour averages of the amount of precipitable water for rainy hours and non-rainy hours were checked from 01:00LT to 07:00LT in the first period. The results are shown in Fig. 7. Taking into account the standard error, Fig. 7 shows no clear correspondence between the occurrence of precipitation and the amount of precipitation. Therefore, this suggests that not only the amount of precipitable water but also other factors control the occurrence of precipitation.

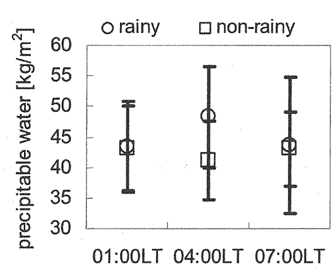


Fig. 7 Amount of precipitable water in rainy hours and non-rainy hours in the first period when precipitation is likely to occur (24 October~18 November 2009).

Large-scale precipitation and locally induced precipitation

As aforementioned in the previous section, the amount of precipitable water is mainly determined by the inflow/outflow of the water vapor from/to the outer region, and there are relatively large water-vapor inflows into the region on some days during this target period. We classified the amount of precipitation into two categories: that under the whole-Cambodia-scale convergent condition and that under the whole-Cambodia-scale divergent condition. As a result, the rainfall amount under the convergent conditions was 1528.6mm, accounting for 67.8% of the total rainfall amount (2253.2mm) recorded by the 30 rain gauges in the target period (these rainfall amounts were derived by simply summing up for the each of 30 rain gauge for the period of from October 24^{th} to November 18^{th}, 2009). At this stage, we examined the large-scale atmospheric column so that assume that rainfall nearly balances evaporation and thus internal variability within the column dominates. Then, the results above reveals that about 60%~70% of rainfall in Cambodia in the post-monsoon season of 2009 was under the large-scale atmospheric condition of water-vapor inflowing from outside Cambodia, and as much as 30%~40% of rainfall was due to the redistribution of water vapor within the Cambodian region through local circulation. The previous study by Tsujimoto (7) also showed that there is precipitation not only under the large-scale convergent condition but also under the weak divergent condition.

The same analysis was carried out for data averaged over three hours to examine the diurnal characteristics. Figure 8 shows that while rainfall from afternoon to evening dominated under the whole-Cambodia-scale convergent condition, from midnight to early morning (01:00LT, 04:00LT, 07:00LT), the rainfall under the whole-Cambodia-scale non-convergent condition dominated. This suggests that local rainfall resulting from the redistribution of water vapor in the region through local atmospheric water circulation was prevalent from midnight to early morning.

The authors (7) have numerically demonstrated that in this region the land breeze from the southwest of the lake flows onto the lake at night and converges with a large-scale nocturnal northeasterly over the lake, resulting in precipitation from midnight to early morning in the west of the lake on the leeward side when the large-scale nocturnal northeasterly is moderately strong. The results presented in Fig. 8 correspond well with that numerical result, and using rain gauge data, we have thus confirmed that local rainfall dominates from midnight to early morning in this region and season.

As seen above, even under the condition that water vapor does not converge on a whole-Cambodia scale, there is local convergence in the study area owing to local circulation (southwesterly land breeze) and a large-scale nocturnal northeasterly, which brings precipitation to the region. Therefore, as shown in Fig. 7, under the conditions of abundant water vapor (which holds for the target period in this section), the existence or non-existence of precipitation and the amount of precipitable water do not have a clear relationship.

Although there is more large-scale precipitation (i.e., precipitation under the whole-Cambodia-scale convergence condition), it should be noted that locally induced precipitation (i.e., precipitation under the whole-Cambodia-scale divergence condition) accounts for 30%~40% of the total rainfall amount. The mechanism of this rainfall is as follows. (i) There is a condition of abundant water vapor as seen in the previous section. (ii) The land breeze driven by the lake and katabatic wind from the southwestern mountains (both being southwesterly winds) form local circulation. (iii) The land breeze from the southwest increases the atmospheric instability when it meets the hotter and more humid airmass over the lake. (iv) The southwesterly land breeze then locally converges with the large-scale nocturnal northeasterly. In this manner, the rainfall is highly affected by local effects that can be initiated even under whole-Cambodia-scale non-convergent conditions. In practice, the timing of this kind of precipitation occurs is important to water resource management in the dry season in this area and thus we will examine its requisite conditions in the next section.

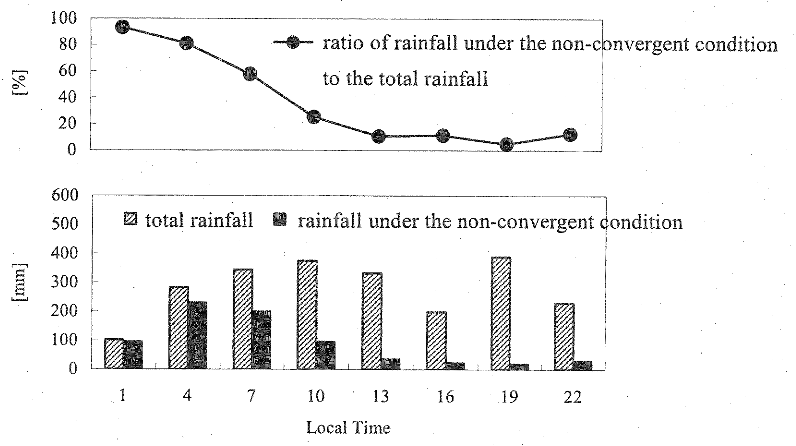


Fig. 8 Three-hour precipitation (total precipitation and precipitation under the non-convergent condition) [bottom] and the ratio of precipitation under the non-convergent condition to the total precipitation [top]. The amount of precipitation is the total accumulated amount for the given hour ± 90min recorded by the 30 rain gauges. For the purpose of calculation of three-hour convergence, we interpolated the six-hour NCEP-FNL reanalysis data.

Unfavorable conditions for initiating locally induced precipitation

As mentioned previously, if it rains because of local circulation driven by the nocturnal thermal contrast between the lake and land as suggested numerically [Tsujimoto (7)], it would be no surprise if there were a similar phenomenon every day and if it rained every day. However, in reality, it rains only on certain days. This section focuses on days without precipitation and investigates the reasons for the lack of precipitation.

First, we calculated the land-breeze (southwesterly) component that flows onto the lake perpendicular to the long axis of the lake from wind data (observation height of 10m) recorded at the AWS station to the southwest of the lake (location shown in Fig. 2). We then calculated the hourly averaged wind speed for each day. Figure 9 shows the results from night to early morning. In Fig. 9, the days when water vapor flows from outside Cambodia are shaded in gray and these days are not considered in this section. In addition, the days shaded in light blue are the days with precipitation, and the days without shading are the target of this section; that is, the days without locally driven rainfall.

Figure 9 shows that when the land breeze around 22:00~03:00LT is weak ($<0.15ms^{-1}$) (i.e., October 26th and November 16th, 2009) and when the land breeze does not develop at all (i.e., the northeasterly is dominant on the southwestern side of the lake; November 5th, 2009), it does not rain. On the other hand, there are days when the land breeze at such times is strong but still it does not rain. We indicate these days with a question mark in Fig. 9. To explain this phenomenon, we examined the strength of the northeasterly at 1000hPa on the northeastern side of the lake (Fig. 10). The days in shaded pale yellow are the days when the weak or absent land breeze is the reason for no rainfall. Thus, the days not shaded are the days on which the reason for the absence of rainfall is unknown at this time. In Fig. 10, except for October 31st, 2009, the days without shading have very weak northeasterly winds ($<0.6ms^{-1}$). Earlier numerical studies carried out by the authors (7) found two factors which played a role in precipitation: (i) the generation of weak convection over the lake via increased instability resulting from intrusion of the land breeze into the hotter and dryer airmass over the lake and (ii) transportation of water vapor from the lake to the convergence zone via the mechanical energy of the strong large-scale nocturnal northeasterly accompanying disturbances. Therefore, when the nocturnal northeasterly is very weak and there is only weak convection over the lake, precipitation cannot be initiated. From the results of this study, the phenomena previously shown numerically were confirmed by both in situ data and reanalysis data.

On November 5th, 2009, on the other hand, the nocturnal northeasterly was very strong and there is no southwest land breeze after 23:00LT according to the AWS data in Fig. 9. When the nocturnal northeasterly is too strong, it prevents the development of the land breeze on the southwestern lakeshore and convection over the lake does not form. Therefore, rainfall is not initiated under that condition.

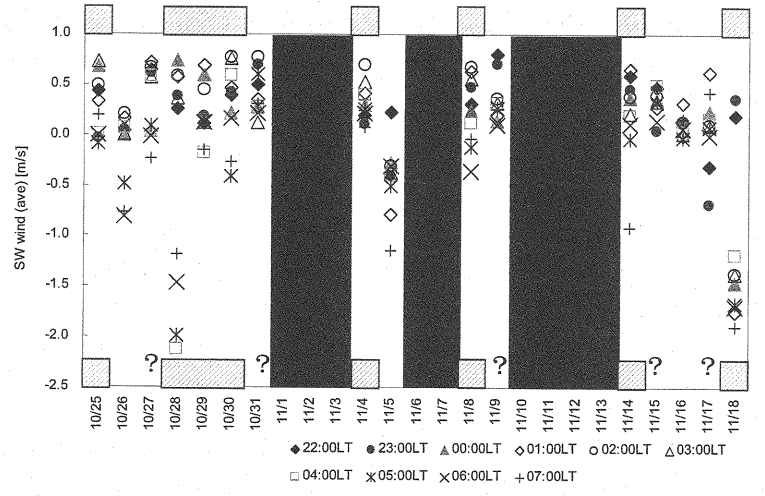


Fig. 9 The southwesterly (i.e., land breeze) component calculated from the observed wind speed at 10m height at the AWS southwest of the lake. Hatched shading indicates days with rainfall from midnight to early morning; Dark gray shading indicates days when the water vapor converges from outside Cambodia, which are not considered in this study; question marks indicate days without rainfall even though the land breeze was strong.

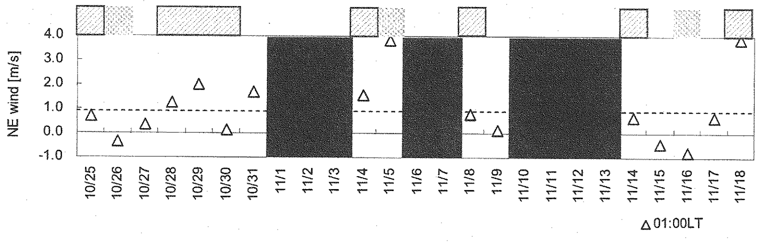


Fig. 10 Northeasterly component obtained from NCEP-FNL reanalysis data in the northeastern part of the lake (14°N, 105°E, 1000hPa) at 01:00LT. The hatched and dark gray shadings have the same meaning as in Fig. 9. The cross-shading indicates days without rainfall due to a very weak or the absence of a southwesterly land breeze (i.e., remaining days other than those having question marks in Fig. 9).

CONCLUSIONS

The characteristics of post-monsoon rainfall and its occurrence factors were clarified for the year 2009 in this study.

In the year 2009, around one month after the "monsoon season", which was defined by large-scale atmospheric circulation (from the middle of October to the middle of November), precipitation occurred mostly on the western side of Tonle Sap Lake. "Large-scale precipitation" induced by the inflow and convergence of water vapor from outside Cambodia accounted for 60%~70% of this rainfall while "local precipitation" that fell even under the whole-Cambodia-scale non-convergent condition and was due to the redistribution of water vapor within Cambodia accounted for 30%~40%. The ratio of local precipitation to total rainfall was high from midnight to early morning and this is in line with the results of earlier numerical studies carried out by the authors (7) that suggested that a southwesterly land breeze and large-scale nocturnal northeasterly converge over the lake and initiate local precipitation from midnight to early morning.

From late November, on the other hand, there was almost no precipitation. In this period, the water-vapor field was continuously divergent with the seasonal march, which decreased the precipitable water in Cambodia and made for an unfavorable precipitation conditions. Nocturnal precipitable water for the period with local precipitation was 45mm, whereas that without local precipitation was 28mm. Therefore, for the initiation of local precipitation, not only local wind convergence but also an abundance of water vapor to some extent is a prerequisite, even though this area is located in the tropical Asian Monsoon region and generally has a large amount of water vapor.

Even before mid-November with sufficient precipitable water, there were days without local precipitation. The wind field reveals that when the land breeze from the southwest lake shore was very weak ($<0.15ms^{-1}$), there was no precipitation. Furthermore, even when the southwestern land breeze was relatively strong, if the northeasterly from the northeast side of the lake was weak ($<0.6ms^{-1}$), there was no precipitation. In contrast, when the nocturnal northeasterly was very strong ($>4.0ms^{-1}$), it prevented the development of the southwestern land breeze, and thus, there was no precipitation. Such a relationship between the strength of the large-scale nocturnal northeasterly and the local southwesterly and the existence or non-existence of precipitation matched the results of earlier numerical studies carried out by the authors (7), and the relationship was thus confirmed quantitatively in part with in situ data for the first time in this paper. However, since there is a non-linear internal variability in a convective activity, we cannot make any definite conclusions. This result shows that the requisite conditions pointed out in this study exists as a major factor of the elementary processes in this region. As mentioned in the first section, Cambodia does not have routine radiosonde data and the initial atmospheric condition in modeling is therefore not clear. In such a situation, the reproduction and/or prediction of the atmospheric field by means of numerical model simulations is generally difficult. However, by grasping and utilizing the role of Tonle Sap Lake, which greatly controls the atmospheric water circulation in this area, as we did in this study, it is possible to simulate reasonably well the atmospheric field in this area.

Finally, as shown in Fig. 1, for the target period and region, the amount of rainfall given by TRMM/3B42 was much smaller than the rain-gauge rainfall on the southwestern side of the lake, and the rainfall data considered for the discussion in this paper corresponded to zero values in the TRMM/3B42 product. In addition, the land breeze (southwesterly) that is discussed in this paper was driven by local circulation and thus is not expressed in the NCEP-FNL data. We thus maintain that the findings of this paper can be derived by field activity, including the installment of observation instruments and strict data quality management, and they highlight the importance of in situ data in similar studies.

ACKNOWLEDGEMENTS

This study was partly conducted as part of the Global Earth Observation System of Systems (GEOSS) Asian Water Cycle Initiative (AWCI) and the Space Application for Environment (SAFE) project funded by the Japan Aerospace Exploration Agency (JAXA). We thank the Ministry of Water Resources and Meteorology (MOWRAM) of Cambodia for their kind support of field activities.

REFERENCES

1. Matsumoto, J: Seasonal transition of summer rainy season over Indochina and adjacent monsoon region, Adv. Atmos. Sci., 14, 231-245.
2. Kanae, S., Oki, T. and Musiake, K.: Principal condition for the earliest Asian summer monsoon onset, Geophys. Res. Lett., 29, 1746, 2002.
3. Zhang, Z., Chan, J. C. L. and Ding, Y.: Characteristics, evolution and mechanisms of the summer monsoon onset over Southeast Asia. International J. Climatology, Vol.24, pp.1461-1482, 2004.
4. Ramesh, K. V. and Goswami, P.: Reduction in temporal and spatial extent of the Indian summer monsoon, Geophys. Res. Lett., 34, L23704, 2007.
5. Sinha, A., Cannariato, K. G., Stott, L. D., Cheng, H., Edwards, R. L., Yadava, M. G., Ramesh, R., and Singh, I. B., A 900-year (600 to 1500 A.D.) record of the Indian summer monsoon precipitation from the core monsoon zone of India, Geophys. Res. Lett., 34, L16707, 2007.
6. Tsujimoto, K. and Koike, T.: Mechanism of locally-induced convection development and its effects on vapor transportation over Tonle Sap Lake are, Annual Journal of Hydraulic Engineering, Vol.52, pp.247-252, 2008.
7. Tsujimoto, K.: Land-lake-atmosphere interaction in the lower Mekong basin and its effects on local water use, Ph.D. thesis at the department of civil engineering, the University of Tokyo, 2009.
8. Tsujimoto, K. and Koike, T.: Effects of the locally-induced precipitation on the stream flow during the dry-season at the vicinities of Tonle Sap Lake, Annual Journal of Hydraulic Engineering, Vol.53, pp.337-342, 2009.
9. Masumoto, T., Tsujimoto K. and Somura, H.: Hydro-meteorological observation and analysis of observed data at Tonle Sap Lake and its environs, urban and paddy areas, report of national institute for rural environment, Vol. 206, pp.219-236, 2007.
10. Tsujimoto K., Koike, T., Aida, K., So Im, M., Preap, S. and Long, S.: Characteristics of the post-monsoon rainfall in 2009 as detected by the reconstruction of the ground-based rainfall observation network in Cambodia, Proceedings of 2010 Annual Conference, Japan Society of Hydrology and Water Resources, pp.32-33, 2010.
11. Tsujimoto, K. and Koike, T., Land–lake breezes at low latitudes: The case of Tonle Sap Lake in Cambodia, submitted to JGR-atmosphere, 2012.
12. Fasullo, J. and Webster, P. J.: A hydrological definition of Indian monsoon onset and withdrawal, J. Climate, Vol.16, pp.3200-3211, 2003.
13. Kiguchi, M. and Matsumoto, J.: The rainfall phenomena during the pre-monsoon period over the Indochina Peninsula in the GAME-IOP Year, 1998, J. Meteor. Soc. Japan, Vol. 83, pp. 89-106, 2005.
14. Wang, B. and Lin, H.: Rainy season of the Asian–Pacific summer monsoon., J. Climate, Vol.15, pp.386–398, 2002.
15. Zhang, Y., Li, T., Wang, B. and Wu, G.: Onset of the summer monsoon over the Indochina Peninsula: climatology and interannual variations, J. Climate, 15, 3206–3221, 2002.

APPENDIX – NOTATION

The following symbols are used in this paper.

g = acceleration due to gravity

p = pressure

P_{sfc} = surface pressure

q = specific humidity

Q = water vapor convergence

u = zonal wind

v = meridional wind

(Received Jun, 13, 2011 ; revised Nov, 30, 2011)