Impact of Differences in Land use on Clouds Formation in Matsuyama Plain

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ORIGINAL ARTICLE

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Abstract

The spatial and temporal variation of cloud is important to understand the concept of local climate such as prediction of torrential rainfall. There is an obvious contrast in land use between the urban and rural area along the Shigenobu River in the Matsuyama plain. Thus, the purpose of this study is to investigate the effects of differences in land use on the cloud formation. For this purpose, we analyzed the observations data of solar radiation. Here, clear sky rate was considered as an index to identify the reduction in the solar radiation due to presence of clouds. We observed that, solar radiation over urban area tends to be smaller than that over the rural area in the afternoon on days with a sunshine percentage from 50% to 80%. The difference in the distribution of the clouds in the Matsuyama plain was further validated by the simulation of the cloud cover using a mesoscale model WRF. The simulated results of the amount of solar radiation and the cloud water mixing ratio both suggested the tendency of cloud formation to be more in the urban area as compared to the rural area. These results contribute to strengthen the practicality in the cloud study and local urban climate. The obtained result would also be beneficial for the study of the rainfall pattern in urban watersheds and to understand the effects of urbanization on the local climate.

Keywords: Clear sky rate, solar radiation, land use, surface heat flux, lifted condensation level, mixing layer

1. Introduction

In recent years, the intensity and frequency of localized torrential rainfall in urban area might be increasing due to factors such as climatic change, unplanned land use patterns. Urban flood has large impacts, particularly in terms of direct and indirect economic losses. The impact of such floods on the lives and livelihoods of people, a function of their vulnerability, needs to be understood. To consider the impact of such localized torrential rainfall, many studies have been conducted. Results from METROMEX suggests that the urbanization effects lead to 5-25% increase in precipitation, particular 50-70km downward of the urban centre during the summer month (Changnon et al. 1991). Sakakibana and Matsui 2005, shows a linear relationship between nocturnal heat island intensity and the logarithm of the city population in Japan. The frequency of heavy rainfall in Japan is higher during the summer season (Matsumoto and Takahashi 1999), making it prone to rainfall induced disasters such as shallow landslides due to its topographical and geological conditions (Saito et al. 2010). Fujibe 1988, suggested that increase in temperature caused by urbanization results in localized severe rainfall due to convergence of water vapor. Shimoju et al. 2010, have explained the change in the path of sea breeze due to urbanization, which leads to the localized heavy rainfall.

In addition, there are many studies done on convective clouds, which are the basis of the precipitation. According to Bornstein and Lin 2000, the urban heat island induced a convergence zone, which resulted in the convective rainfall in the urbanized area of Atlanta. Fujibe 2003, found a positive precipitation anomaly related to the urban effect over central and inland areas of Tokyo. Inoue and Kimura 2004, explained the frequency of low-level clouds to be higher over the urban areas than over the rural area.

Shepherd et al. 2010 in their case study for Houston suggested that the urban land cover growth could lead to temporal and spatial precipitation variability in coastal urban microclimate.

Due to the difference in land use the occurrence of heat island effect in the Matsuyama plain has been confirmed (Fujimori et al. 2010). The impact of urban dry island phenomenon on cloud base level in Matsuyama has been studied by Moriwaki et al. 2013. In their study, the Cloud Base Level (hereafter, CBL) was found to be higher in the urban area as compared to the rural area when the wind blew along the border between the urban and rural area (Figure 1). Similar results were also reported by Davies et al. 2004. Williams et al. 2015 also highlighted the decline in the fog formation and increase in the stratus cloud height due to increase in night time temperature as a result of urbanization in the coastal Southern California.

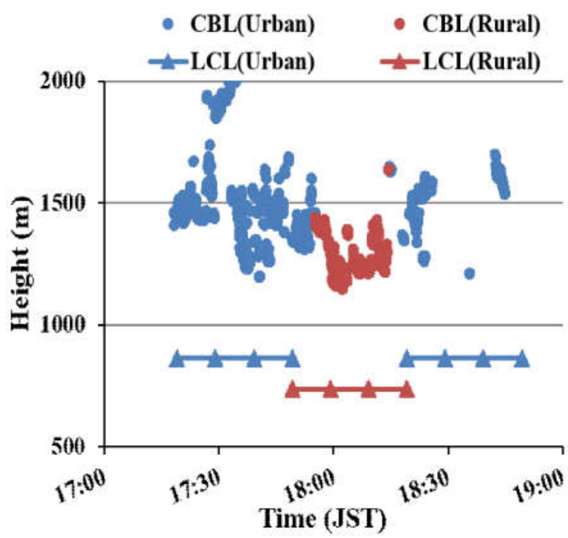

Figure 1: Observation of cloud base level, (CBL) July 6, 2011 (Moriwaki et al. 2013)

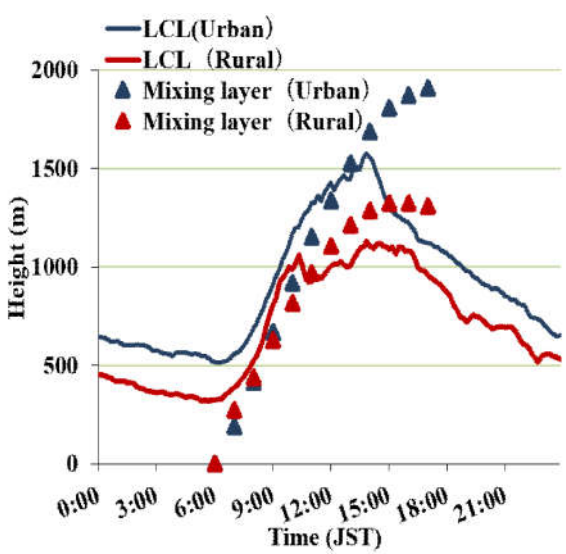

Figure 2: Comparison of lifted condensation level (LCL) and elevation of mixing layer, September 2010 (Morimoto et al. 2013)

According to Moriwaki et al. 2013, due to dry island phenomenon in Matsuyama plain, the relative humidity in the urban area decreases and thus the Lifted Condensation Level (LCL) is larger in urban area as compared to the rural area. To clarify the effect of difference in land use on the cloud formation Morimoto et al. 2013, compared the elevation of the mixing layer developed using the observed dataset of sensible heat flux with the LCL, in which he confirmed the cloud formation to be greater in the urban area of the Matsuyama plain exceeding the LCL due to the significant supply of sensible heat as compared to the rural area.

In past several studies, radiative fluxes and cloud cover from satellite data have been widely used and proved to useful for the cloud simulation by weather forecast model (Gautier et al. 1980; Yang et al. 1999; These study were mostly based on coarse time and spatial resolution.

In this research, field observation data of solar radiation was used to study the effect of differences in land use on the cloud formation. The difference in the distribution of the clouds in the Matsuyama plain was further validated by the numerical simulation and numerical experiment of the cloud cover using a mesoscale model WRF.

2. FIELD OBSERVATION

2.1 Site Description

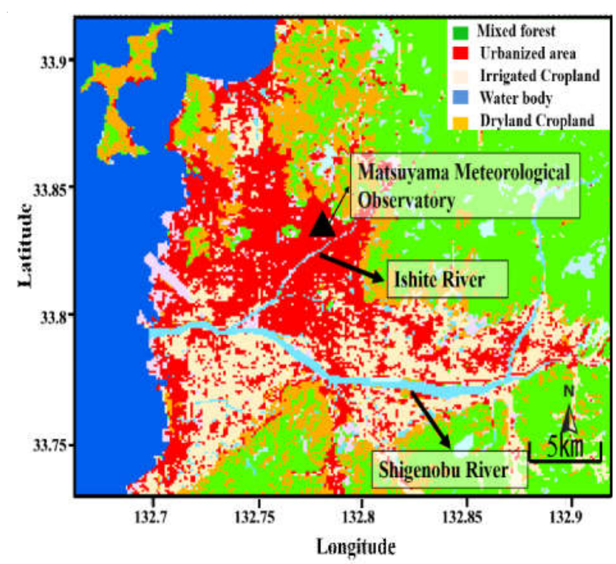

Figure 3: Observation point and land use category of the Matsuyama plain

X Mark: Radiation observation point

(black: urban, white: rural)

Matsuyama plain is located in the north-western part of Shikoku, Japan. It is mainly composed of alluvial fan formed by flooding of Shigenobu River and its territories.

The plain covers about 20 km east-west and about 17 km north-south, with a total area of about 100 km^2. The northern part of the plain is urbanized whereas the paddy fields, farms are located in the surrounding countryside. Figure 2 shows the land use map of the Matsuyama plain created on the basis of land use classification of digital national land information (Geospatial Information Authority of Japan) is shown in Figure 1. As discussed, the difference in the land use is between the central city and the suburb along the Shigenobu River is clearly visible.

a)

b)

Photo 1: Radiation measurement a) urban area and b) rural area

2.2 Observation Method

2.2.1 Radiation Measurement

To study the variation of the solar radiation, the observation data from July 2011 – September 2011 was taken into account. For the instrumentation, the lected as an observation point in the urban area (Black X mark in Figure 3, 132.812962°E, 33.778939°N). The surrounding area mainly consists of commercial buildings, residential apartments and paved roads (Photo 1a). In rural area the instrument was installed in the backyard of the water pumping facility, Masaki-cho (White X mark in Figure 2, 132.771509°E, 33.79559°N). The surrounding area comprised of paddy field (Photo 1b). Upward and downward shortwave and longwave radiation intensities were measured using CNR-4 (Kipp and Zonen) for the urban site and MR-40 (EKO) for the rural site, respectively. In addition, a sonic anemometer (SAT550, Kaijo-sonic) and an open-path gas analyzer (LI-7500, LI-COR) were installed for the flux measurement.

2.2.2 Clear sky rate:

The amount of solar radiation varies with both time and latitude; thus we consider the clear sky rate in order to identify the percentage of solar radiation blocked due to the presence of cloud. Matsuyama has contrasting land use where urban area and rural area is differentiated along the Shigenobu River. The amount of solar radiation tends to vary from urban to rural area as per Moriwaki et al. 2013. Here in each month the highest amount of solar radiation at an interval of 10 minutes was taken into account to create a time series data of a virtually sunny day. Then time series data of the virtually sunny day were compared with the time series data of the target day and the clear sky rate was determined.

The clear sky rate is defined as the ratio of solar radiation of target date to the radiation of a virtually sunny day as shown in Equation 1.

$$\textit{Clear}\ \text{sky rate} = \frac{\begin{array}{c}\text{Radiation of a}\\ \text{target day}\end{array}}{\begin{array}{c}\textit{Radiation}\ \text{of a}\\ \text{virtually sunny day}\end{array}}$$

Figure 4 shows the relationship between the radiation of the target day, the radiation of a virtually sunny day and the clear sky rate of September 15, 2011. The clear sky rate varies between one and zero. A clear sky rate of one indicates a sunny weather condition, whereas values closer to zero indicates the blocking of solar radiation due to the presence of clouds. Thus, we can say that smaller the clear sky rate, larger is the effect due to blocking of solar radiation by the clouds.

On the basis of the data obtained from the Japan Meteorological Agency (JMA) and Matsuyama Meteorological observatory the weather condition, wind direction and sunshine duration was known which was used for the selection of the analysis days.

2.3 Model Configuration:

The Weather Research and Forecasting (WRF) Model is a sophisticated numerical weather prediction system that solves the compressible non-hydrostatic Euler equations cast in flux form on a mass-based terrain-following

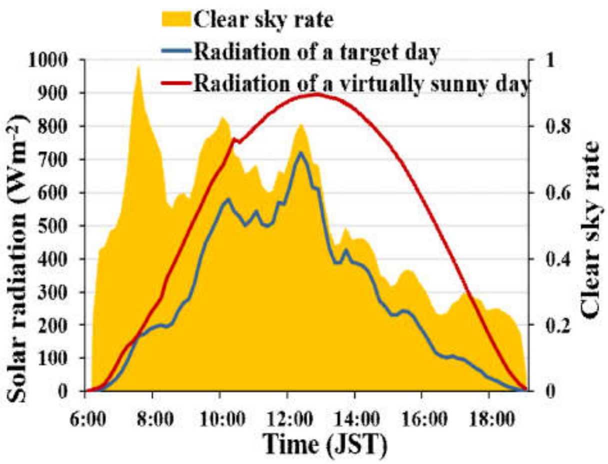

Figure 4: Relationship between the virtually sunny day, solar radiation of a target and the clear sky rate (September 15, 2011)

Table 1: Model setup and resolution setting of the study area

	Horizontal grid number (grid points)	Horizontal domain size (km)	Horizontal grid spacing (km)	Vertical grid number (grid points)
Domain1	75×70	2250×2100	30	28
Domain2	85×81	637.1×607.5	7.5	28
Domain3	69×81	129.7×152.3	1.875	28
Domain4	73×73	34.2×34.2	0.469	28

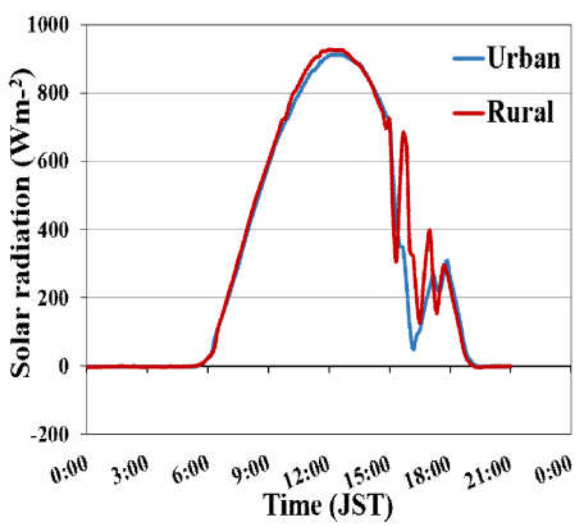

Figure 5: Diurnal variation of solar radiation (August 13, 2011)

vertical coordinate system. The model serves a wide range of meteorological applications across scales from tens of meters to thousands of kilometers. The effort to develop WRF began in the latter part of the 1990's and was a collaborative partnership principally among the National Centre for Atmospheric Research (NCAR), the National Oceanic and Atmospheric Administration (represented by the National Centers for Environmental Prediction (NCEP) and the Forecast Systems Laboratory (FSL)), the Air Force Weather Agency (AFWA), the Naval Research Laboratory, the University of Oklahoma, and the Federal Aviation Administration (FAA) (WRF website). NCEP (National Centers for Environmental Prediction) FNL (Final) Operational Global Analysis data on 1.0 × 1.0 degree grids for every six hours were used for the study. The model uses a terrain-following sigma coordinate in the vertical, with 28 levels. The analysis data include parameters such as surface pressure, sea level pressure, geopotential height, temperature, sea surface temperature, soil values, ice cover, relative humidity, u- and v- winds, vertical motion, vorticity and ozone. A global land use/land cover (LULC) database classified according to the United States Geological Survey (USGS) LULC system is provided with WRF. For radiative transfer associated with clouds, the current schemes in WRF normally use preset tables to represent shortwave and longwave processes associated with clouds. For shortwave radiation, the current choices in WRF include the Dudhia scheme with a simple downward integration of solar flux, accounting for clearair scattering, water vapor absorption, and cloud albedo and absorption. The WRF model was set up by using four nested domains of 30, 7.5, 1.87 and 0.469 km horizontal grid spacing and 28 vertical level for domain 1, 2, 3 and 4, respectively (Refer Table 1). The simulation was run from August 3, 2011 to August 4, 2011 with the 24 hours spin up time.

3. Result and Discussion

3.1 Distribution of Solar Radiation

The formation of cloud is considered by comparing the amount of solar radiation in urban and rural area during a sunny day. Figure 5 shows an example of the diurnal variation of solar radiation in urban and rural area. Here, we consider the reduction of solar radiation due to blockage of radiation by cloud.

In this study, prospective summer afternoon day with sunshine percentage ranging from 50% to 80% in July, August and September in 2011 were taken into consideration. Such days were determined by using the sunshine hours and weather condition data available from the Matsuyama Meteorological Agency. In total 29 days were selected.

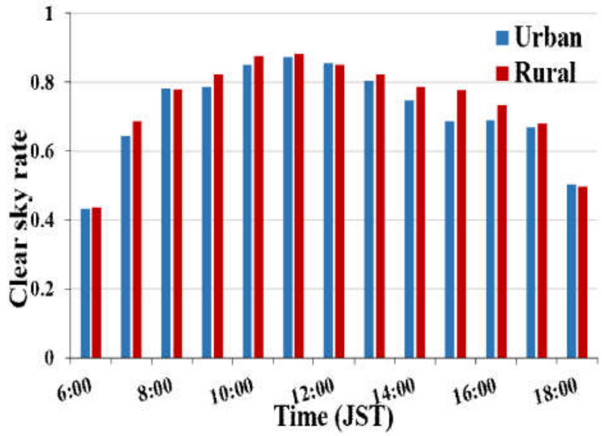

Figure 6: Hourly average of clear sky rate from 6:00 to 18:00

First, we studied the effect of clear sky rate from 6:00 to 18:00 JST, the time period where the blockage of solar radiation due to cloud was greater. Figure 6 shows one-hour average of the clear sky rate from 6:00 to 18:00 JST representing an average value of 29 days in the urban and rural area, respectively.

Here, the clear sky rate was found to be smaller in the morning and then tends to increase with time eventually reaching a peak around mid-day and start decreasing from the afternoon in both urban area and rural area. It suggests that the formation of cloud is likely to occur during the early morning and from afternoon. This is in agreement with the results of Asai et al. 1998 in which he has used the geostationary meteorological satellite observations to study the diurnal variation of the clouds.

The main objective of the research is to study the effect of difference in land use in urban and rural area on the cloud formation, and thus comparing the results, the clear sky rate in urban area was found to be smaller than that in the rural area especially in the afternoon which is believed to be due to blockage of the radiation by the presence of clouds. Figure 7 shows the comparison of the clear sky rate temporally averaged from 13:00 to 17:00 JST of the urban and rural area, respectively. In urban area the clear sky rate is observed to be smaller as compared to the rural area for most of the analysis days. This indicates that the cloudy condition appears more in the urban area as compared to the rural area.

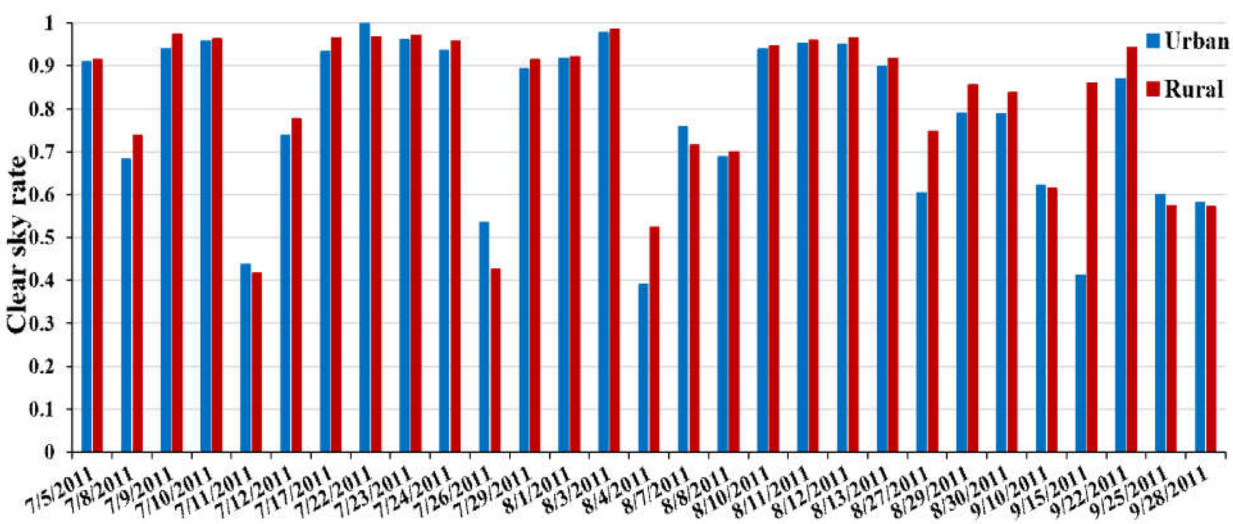

Figure 7: Clear sky rate temporarily averaged from 13:00 to 15:00

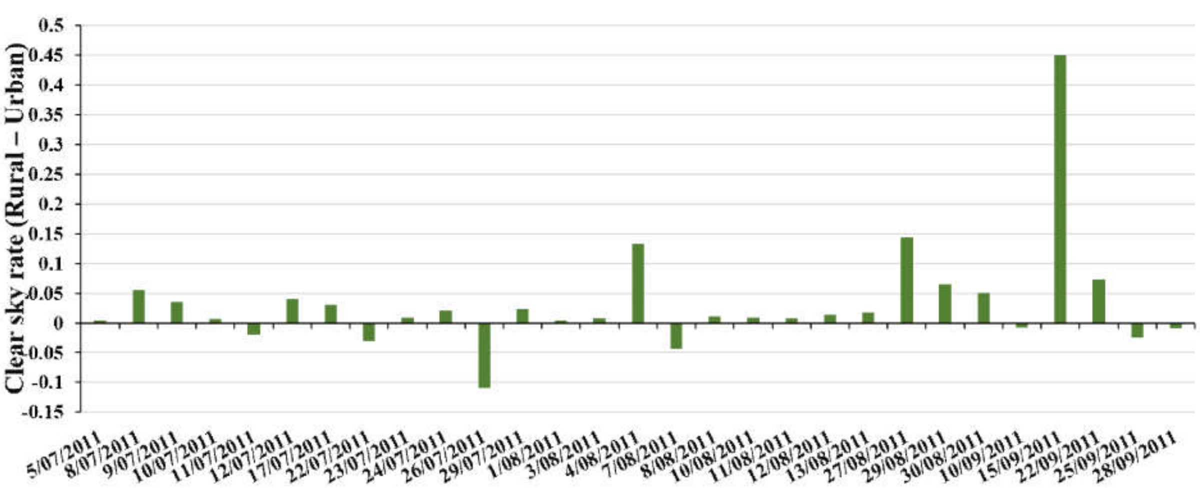

Figure 8: Clear sky rate temporarily averaged from 13:00 to 15:00 (rural clear sky rate – urban clear sky rate)

Figure 8 shows the difference in clear sky rate between the urban area and the rural area from the values represented in Figure 7. The difference is obtained by subtracting the clear sky rate of the urban area by the clear sky rate of the rural area. The larger number of analysis days with positive difference value indicates the formation of clouds in urban area to be more than in the rural area. Here, the difference in clear sky rate ranging from 0 – 0.15 is dominant while such day with difference up to 0.45 was also observed. Thus, differences in the clear sky rate between the rural and urban area were observed, which in turns suggests that the development of clouds are more in urban areas than the rural area.

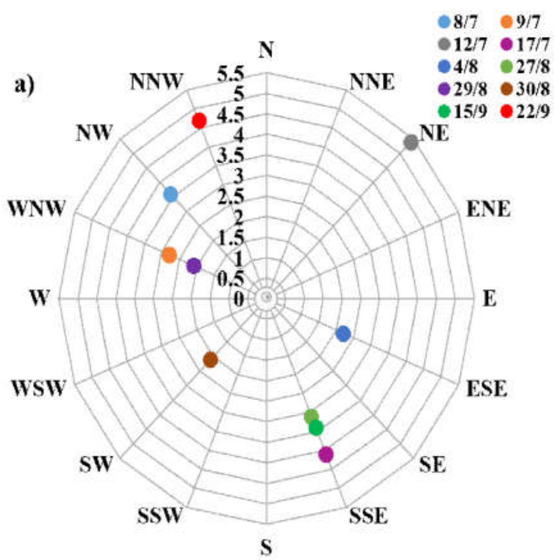

Figure 9: One-hour average of wind velocity and wind direction of analysis days with positive difference value of clear sky rate

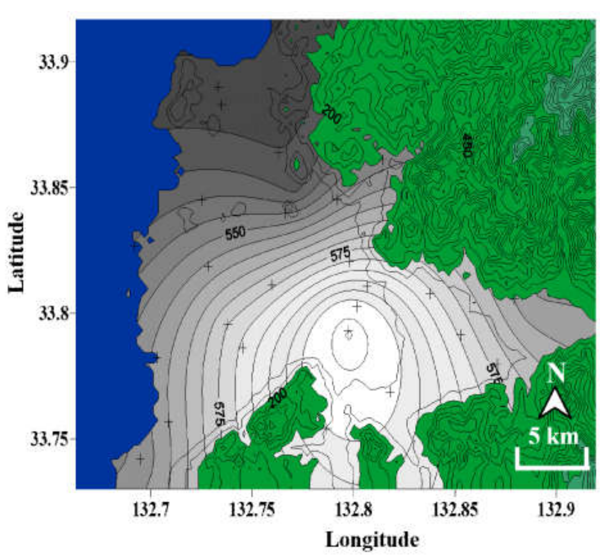

Figure 10: Spatial distribution of the amount of solar radiation (Wm^{-2}) (September 26, 2014) at 15:00

Similar results were obtained by Rastogi et al. 2016, in his study based in the coastal California, where the cloud coverage was found to be high during the afternoon due to the influence of the sea breeze and rainfall to occur during morning. The dominancy of cloud distribution during the morning and the evening in summer season in the island of Hawaii was studied by Barnes et al. 2016.

In order to study the effect of difference in land use on the cloud formation, the influence of the geophysical characteristics of the study area must be considered.

As the area is near the coast, the influence of the sea breeze might affect the result. Matsuyama plain is dominated by the sea breeze usually from 9:00 to 17:00 JST in the warm season, due to this the humid air is transported from the coastal region to the inland area increasing the absolute humidity as studied by Moriwaki et al. 2013. The humid air is transferred to the inland area, especially through the southern part of the Matsuyama plain, i.e. irrigated cropland and along the Shigenobu River (refer Figure 3) as explained by Fujimoto et al. 2012. Figure 9 shows the one-hour average of the wind velocity and direction at 15:00 JST of the analysis days with positive difference value of the clear sky rate (as indicated in Figure 8). Generally, the plain is influenced by the sea breeze on the analysis days, however, on the day with larger difference value, i.e. difference value of clear sky rate greater than 0.1 (4 August, 27 August and 15 September), no significant prevalence of sea breeze was observed. Thus, on a day with weak sea breeze, the presence of cloud leading to the decrease in the clear sky rate might be due to the impact of the difference in land use rather than the influence of wind.

For further verification we considered a dataset of the amount of solar radiation of 26 September 2014 (i.e. day with weak sea breeze) as a reference dataset to understand the spatial distribution of the solar radiation in the Matsuyama plain at 15:00 JST as indicated in Figure 10 (refer Sijapati et al. 2016 for the detail of instrumentation). This also indicates the presence of cloudy condition in the urban area to be greater as compared to the rural area (refer Figure 3) without any influence of the sea breeze. Hence, the difference in the land use tends to effect the cloud formation in the Matsuyama plain.

3.2 Model Validation

For the comparison of the cloud formation in the urban and the rural area, numerical simulation using WRF model was conducted. The simulation was conducted for August 4, 2011, the day with positive difference in the clear sky rate as indicted in Figure 8. The fluctuation of the downward shortwave radiation varies depending on the cloud coverage over the time period. Thus, the simulation was carried out for the amount of soalr radiation of observed and simulated result in both urban and rural area, respectively. Here the amount of radiation starts decreasing from

the afternoon in both urban and rural area, which in turns suggests the decrease in the solar radiation in the urban area to be more as compared to the rural area. The decrease in the solar radiation should be due to the presence of the cloud. Despite the overestimation of the amount of radiation by the simulation of diurnal trend of the solar radiation is similar to the observation result. The overestimation of the shortwave radiation partly explains the underestimation of the clouds and absence of aerosols. The difficulty in the simulation of the cloud and its underestimation of the cloud coverage for short time duration has been reported by Guichard et al., 2002.

Cloud fraction varies greatly with the cloud water mixing ratio (Xu and Randall, 1996) and stratiform cloud increases amount linearly with the cloud mixing ratio as shown in figure 12 also indicates that the cluster of cloud with high cloud water tends to appear in the northern part, namely, urban area of the Matsuyama plain.

For further investigation of the impact of land use on the cloud formation we conducted a numerical experiment of August 4, 2011 using the land use category of approximately 40 years ago. In the experiment we used the land use data of 1976 provided by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), Japan. In the experiment we found that the amount of radiation on both urban and rural area is same as shown in Figure 13 which clearly suggests absence of cloud at the time period. This is further evident with cloud mixing ratio result from the numerical experiment as indicated in the Figure 14 which also shows no significant presence of cloud in the observation area.

Thus comparing the results of the numerical simulation and the numerical experiment we can conclude that the development of the cloud in the Matsuyama plain is effected by the difference in the land use pattern.

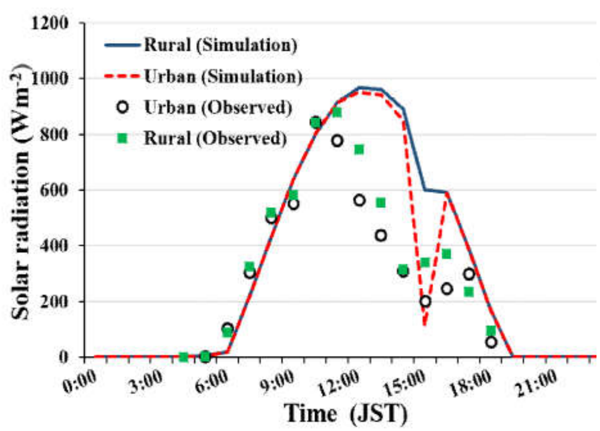

Figure 11: Comparison of diurnal variation of the solar radiation from the numerical simulation and observation (August 4, 2011)

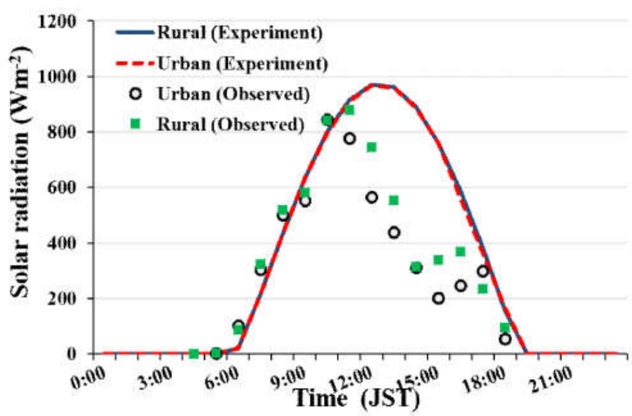

Figure 13: Comparison of diurnal variation of the solar radiation from the numerical experiment and observation (August 4, 2011)

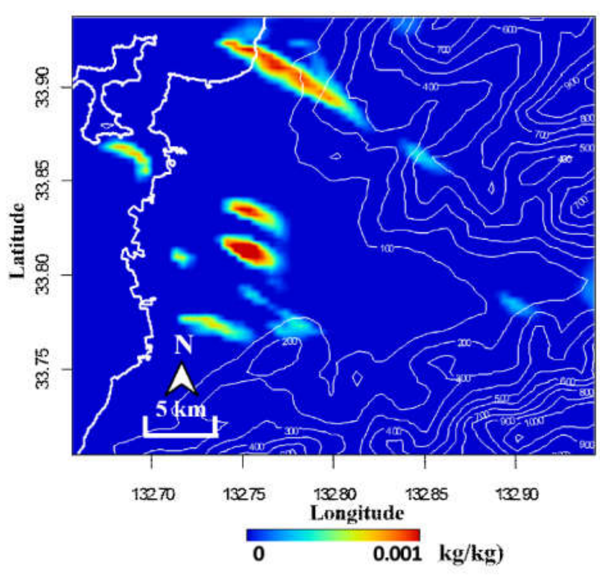

Figure 12: Distribution of average cloud water mixing ratio (kg/kg) in the vertical column on August 4, 2011 at 15:00 from the numerical simulation

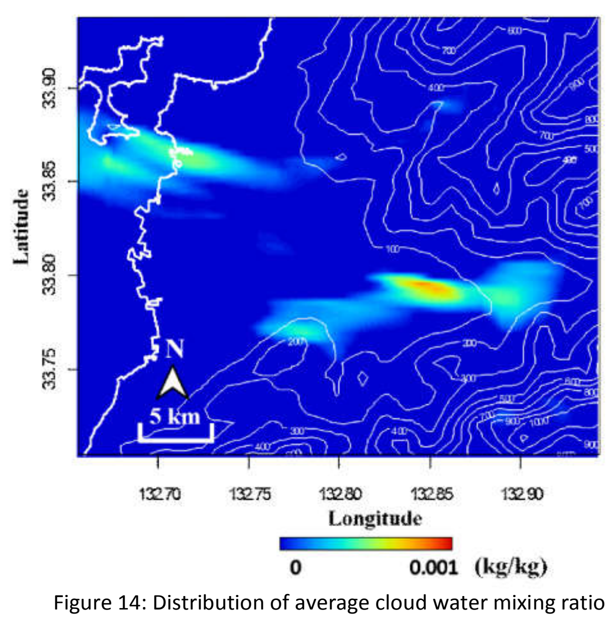

Figure 14: Distribution of average cloud water mixing ratio (kg/kg) in the vertical column on cloud water mixing ratio (kg/kg) of August 4, 2011 at 15:00 from the numerical experiment

4. Conclusions

This study shows that the contrast of the land use in Matsuyama plain effects the formation of the clouds in the rural area and the urban area. Here, the reduction in the amount of solar radiation due to the presence of cloud was taken into consideration. The formation of cloud is likely to occur during the morning and from late afternoon. Considering the clear sky area as an index to identify the reduction in solar radiation, the difference in the cloud formation between the urban and rural area was studied. The clear sky rate in the urban area was found to be smaller as compared to the rural area, which indicates that the tendency for the cloud formation is more in urban area than in rural area. This was further validated by the numerical simulation and numerical experiment of the cloud cover using a mesoscale model WRF. The simulation of the shortwave radiation and the cloud water mixing ratio also suggested the presence of cloud in the urban area of the plain as compared to the rural area. The simulation of the cloud cover is fairly in agreement to the observed results even though the shortwave radiation is overestimated by the simulation model. Thus the contrast of land use in the Matsuyama plain has effect on the development of the cloud aloft. On a day with weak sea breeze the impact of local land use tends to be reflected in the formation of clouds, resulting in tendency of cloud formation to be higher in the urban area as compared to the rural area.

Future work of this study will be to focus on the spatial and temporal variation of the clouds and its classification to understand the rainfall patterns in the Matsuyama plain. This study can be beneficial to understand the effect of urbanization on the local climate such as torrential rainfall.

Acknowledgement

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