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Analysis of cloud properties in the Matsuyama plain downward solar radiation dataset from a Geostationary Satellite

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The purpose of this study is to analyze the downward solar radiation dataset from a geostationary satellite in the Matsuyama plain and to investigate the impact of land use and the geographical landscape variation on clouds. Matsuyama has different geographical features including a plain, which shows contrasting land uses for urban and rural areas. The satellite dataset was validated by data observed in the field. In this study decrease ratio of solar radiation (DRSR) was used as an index of cloud thickness because solar radiation generally decreases when sky is covered by clouds. The following are the main outcomes. DRSR is likely to be higher in mountainous areas rather than plain areas. DRSR of noncoastal areas have a significantly higher value than coastal areas in the afternoon. In summer, urban DRSR are larger than rural area in the afternoon, but the magnitude is almost same in the winter.

1. Introduction

Recently, much attention has been given to the urban climate such as urban heat island, urban dry island and local severe rainfall. The Urban heat island is well known as the phenomenon where urban temperatures are higher than in rural areas. Investigation of such urban climate phenomena has been reported in many cities[1), 2)]. The impact of cities is not only for air temperature but also for humidity. Moriwaki et al. (2013) [2)] reported that urban absolute humidity is lower than the rural absolute humidity. Fujibe (2004)[3)] suggested that local severe rainfall is caused by urbanization. However, less attention has been given to the cloud formation in local scale, probably because the spatial distribution of cloud has been hard to monitor. Lately, a new technique for the estimation of cloud data and solar radiation was established with the help of a geostationary satellite[6)]. While this dataset has the potential for a larger scale analysis of solar radiation, this dataset was used for a local solar radiation analysis in this study.

We have selected the Matsuyama plain as our analysis site mainly for two reasons: a) for its different kinds of geographical features and land types like mountain, plain, sea, rural, urban etc. b) many sensors in different places have been installed with the solar radiation dataset, which though is not sufficient, still can be used for the validation of the satellite dataset.

The objective of this study is to analyze cloud properties according to geographical features like mountain, plain, coastal and non-coastal areas using the downward solar radiation dataset from a geostationary satellite. It also includes the comparison of diurnal variation of cloud thickness by calculating the decrease ratio of solar radiation in different geographical variations.

2. Materials and Methods

2.1 Site description and data set

Matsuyama is located in the northwestern part of Shikoku Island, Japan. It is a plain, which is almost triangular in geometry. The Matsuyama plain is mainly an alluvial fan which was formed by the material deposited through the flooding of the Shigenobugawa River and its territorials. The plain area runs about 20 km from east to west and is about 17 km from north to south with a total area of about 100 km^2. The population of the plain is approximately 5,200,000, most of which is concentrated in the northern part. The plain has become more urbanized since the 1980s. The Shigenobugawa River generally divides the plain into urban and non-urban area. The northern part of the river is densely populated, whereas the southern part consists almost entirely of rice paddy fields. The plain is surrounded by mountains to the east and south. To the north and west is the inland sea coastal area as shown in Fig.1.

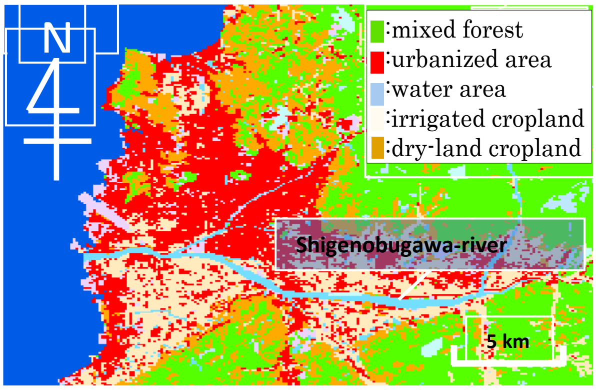

Fig.1 Land use category of National Land Numerical Information and location of observations

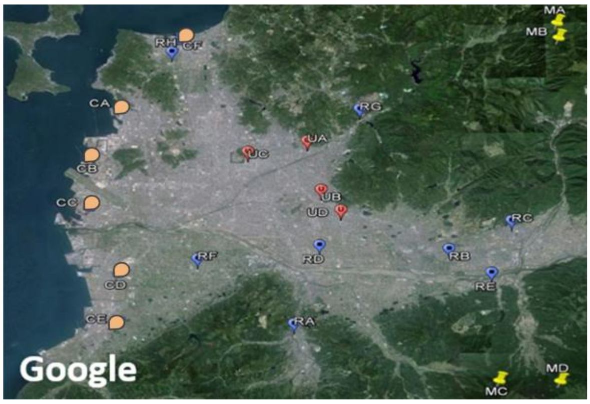

Fig.2 Locations of different geographical and land use points

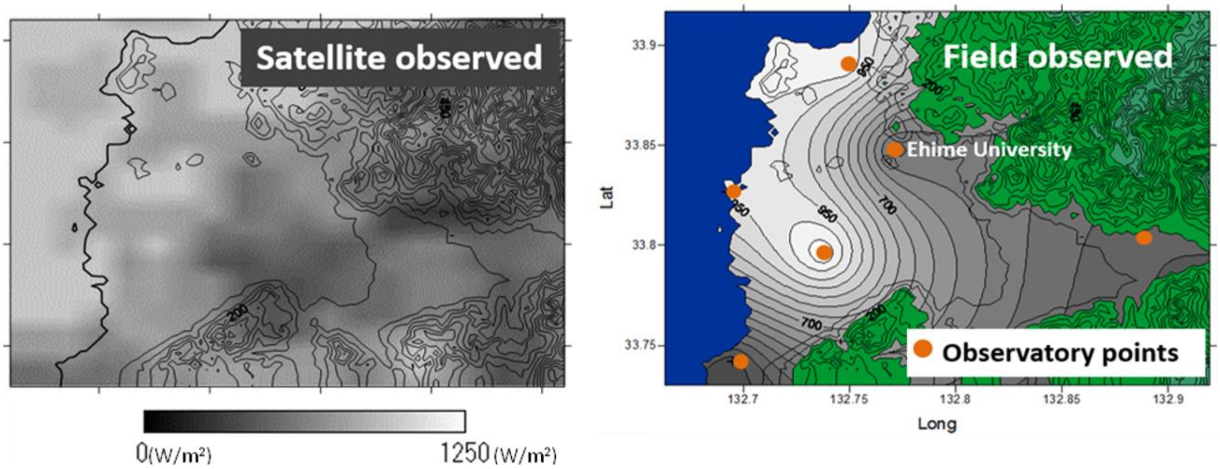

Fig.3 Verification of spatial satellite dataset with a solar radiation dataset (Wm^{-2}) (2014/08/19 -12:01pm) from field observations

The key dataset used in this study is downward short wave (SW) radiation from geostationary satellite developed by Takenaka et al.[4]. The dataset (semi-real time with high-spatial resolution) is estimated from Multi-functional Transport Satellite-1 Replacement (MTSAT-1R) using radiative transfer calculations and neural network technique. Six sensors (CMP3, PREDE Pyranometer) were installed in different parts of the Matsuyama plain including Ehime University as shown in **Fig.3**. The temporal and spatial satellite datasets were validated by comparing it with field-observed data. A good correlation between satellite and observed dataset were found in both spatial and temporal datasets. **Fig.3** and **Fig.4** show the spatial and temporal verification of the satellite dataset respectively.

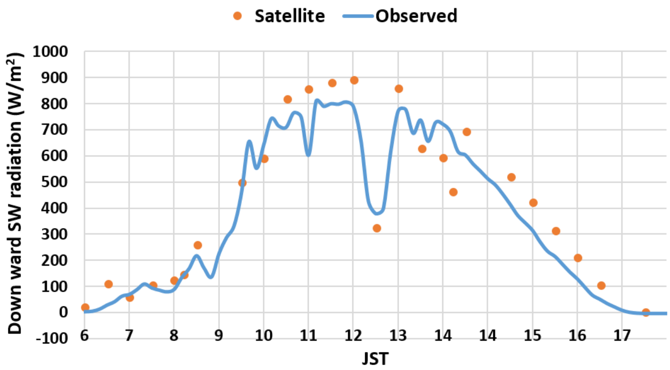

Fig.4 Verification of temporal satellite dataset with field-observed data (at Ehime University)

2.2 Decrease Ratio of Solar Radiation (DRSR)

Solar radiation generally decreases when sky is covered by clouds. Thus in this study reduction of solar radiation was used as an index of cloud presence. Decrease of solar radiation due to the blockage of cloud was calculated using the following concept. An ideal time series dataset was created by selecting the maximum values of each time series for every month. The ideal time series data resembles solar radiation on a virtually perfectly sunny day (without any clouds). The time series dataset of target day is then subtracted from the ideal time series dataset and normalized by ideal SW to get decrease ratio of solar radiation (DRSR).

$$\mathrm{DRSR} = \frac{\text{ideal SW} - \text{target day SW}}{\text{ideal SW}}$$

The higher the DRSR, the higher the cloud coverage and the cloud thickness, while the lower the DRSR, the lower the cloud coverage and the cloud thickness.

2.3 The relation between thickness and DRSR

To know the relationship between cloud thickness and DRSR, a ceilometer (CL31, Vaisala) and (CMP3) pyranometer were set up at Ehime University, on the top of the Faculty of Engineering building. Backscatter intensity by ceilometer was vertically integrated (represent thickness of cloud) and then compared to DRSR by pyranometer (**Fig.5)**. The graph shows a reasonable linear relation between cloud thickness and DRSR using a pyranometer. Hence, DRSR has equitable relation with thickness of the cloud.

2.4 The relation between thickness and DRSR

To compare the monthly temporal DRSR of different areas, various points were selected according to their geographical locations and land use as shown in **Fig.2**. where 'C' represents the coastal locations, 'M' represents mountainous (Peak of four mountains in the study area) locations, 'R' represents rural locations, 'U' represents urban locations; Urban and rural points are chosen same as the Moriwaki et al.[2)] (Table 1) study. 'R' and 'U' also represent non-coastal locations. The temporal results are then verified with the temporal and spatial variation DRSR contour graph. To compare DRSRs, we analyze partially sunny days (days with percentage of sunshine, time per day is between 50 and 80) in sunny months (September and January). The sunshine percentage was calculated using the sunshine time data from the Japan Meteorological Agency in Matsuyama. 11 days out of September and 15 days out of January were partially sunny. The days were selected using the sunshine time data from the Japan Meteorological Agency in Matsuyama. The effects of solar radiation were seen between 6:00AM until 6:00PM in September. Difference of DRSR were also calculated to see the variation pattern of cloud in two different places.

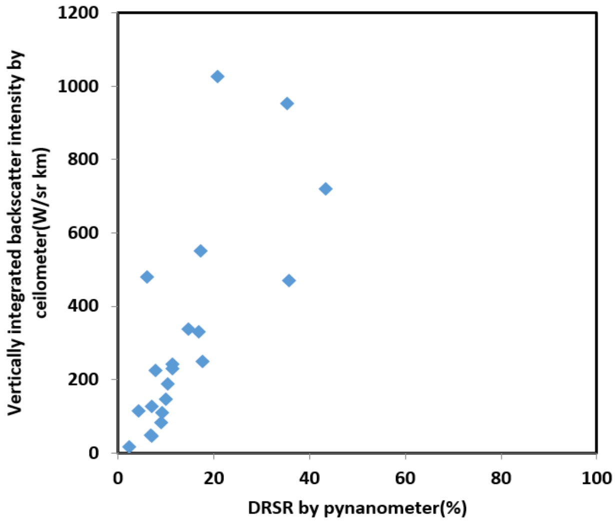

Fig.5 Comparison of vertically integrated backscatter intensity by ceilometer and DRSRs by pyranometer

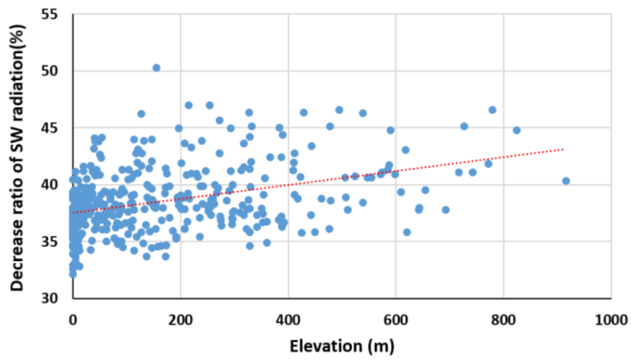

Fig.6 Variation of DRSR with altitude, September 2013 (1:32pm)

3. Results and Discussion

3.1 Variation of cloud thickness with respect to altitude

DRSR at 1:32 pm for September was plotted against elevation. The graphical trend shows that the DRSR has a fair relation to elevation. This means cloud thickness reasonably increases with an increase in altitude.

3.2 Comparison between mountains and the plane

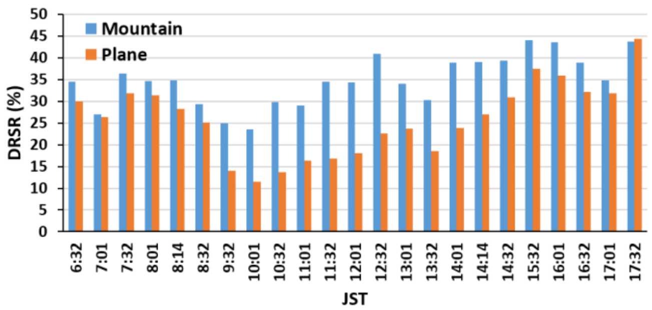

Fig.7 Solar radiation rate from 6:32 am to 17:32 pm on September 2013 (Mountain-Plain)

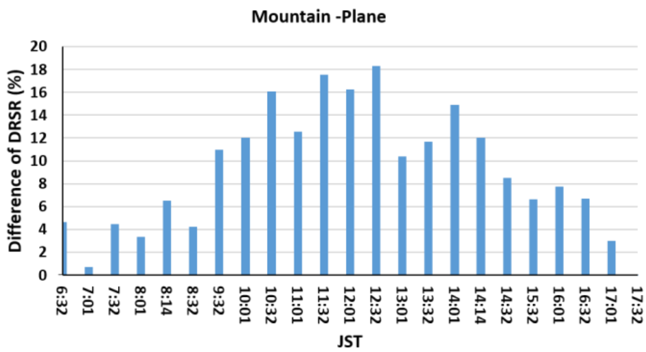

Fig.8 Difference of downward SW radiation reduction rate between 6:32 am to 17:32 pm on September 2013

Four points from the mountainous areas and nine points from the plain areas were selected, which are at an altitude greater than 130 meters and less than 530 meters above sea level respectively for calculating DRSR. **Fig.7** shows the rate and trend of decrease ratio of downward SW radiation between mountainous areas and the plain area on September 2013. It can be seen that DRSR tends to be larger in the morning and in the late afternoon (especially in the plain). This is similar with precipitation results in studies by Fujimoto et al.[5)], and Fujibe et al.[6)].

Fig.8 shows the difference of DRSR between the mountainous area and the plain area. The positive values show that DRSR is higher in mountainous areas than in plain areas whereas the negative values show that the value is greater in the plain area. The difference gradually picks up midday and declines in the afternoon. It suggests that the difference in cloud thickness between the mountainous area and the plain are increases midday and gradually decreases until evening. This may be because sea breeze from the west forces the air mass over the Matsuyama plain to move eastward. The mountains in the east block the air mass. The blocked air mass gains altitude due to the sloping nature of mountains. The rising air mass quickly cools down adiabatically, forming clouds. The peak midday value may be due to the high wind velocity towards the mountains. In Matsuyama, the sea breeze is active approximately at 9:00am until 6:00 pm in the summer as shown in **Fig.9**.

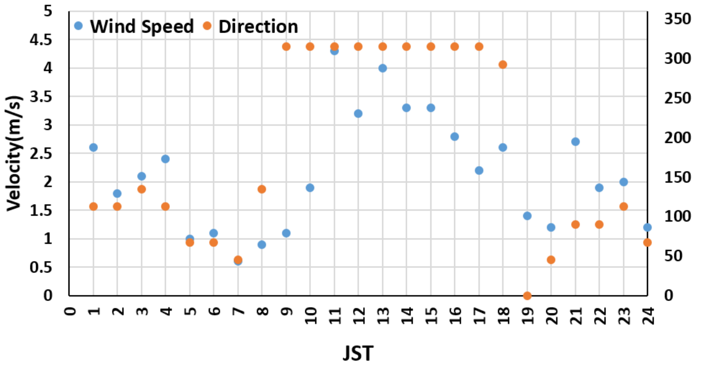

Fig.9 Diurnal changes of wind velocity and direction at Matsuyama meteorological observatory

3.3 Comparison between Coastal areas and the non-coastal areas

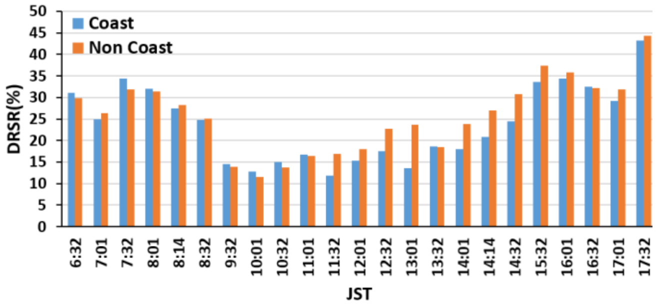

Fig.10 Same as **Fig.7** but for coastal and non-coastal areas

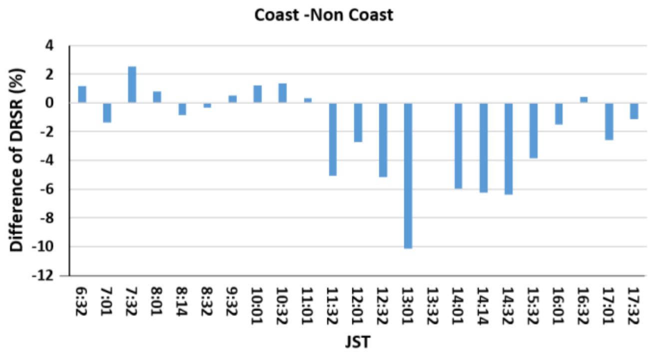

Fig.11 Same as **Fig.8** but for coastal and non-coastal area

Six coastline points within 1.2 km from the sea line and another nine points at least 10 km far from the sea line were selected as non-coastal areas as shown in **Fig.2**. **Fig.10** shows the trend of DRSR between the coastal areas and the non-coastal areas on September 2013. It can be seen that DRSR is larger in the early morning, late afternoon and the evening in both coastal and non-coastal cases compared to late morning to early afternoon. It clearly suggests that the formation of clouds is likely to occur high in the early morning, late afternoon and in the evening.

The difference of DRSR between the coastal and non-coastal areas is shown in **Fig.11**. The positive value shows that the DRSR is higher in coastal areas than in non-coastal areas, whereas the negative value shows that the value is greater in non-coastal areas. The graph shows that the absolute difference is considerably smaller in the mornings and in the evenings compared to the afternoons. Non-coastal areas have significantly higher values in the afternoon. This may be because air parcels lifts due to the convergence of the air from the north and the east in non-coastal area. Kanda and Inoue[7)] have suggested that air parcels lift due to

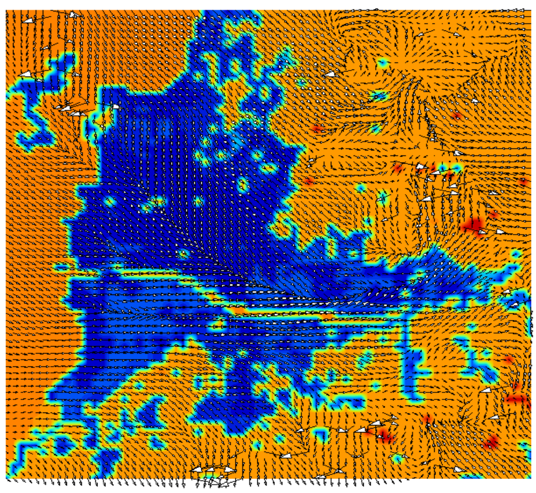

Fig.12 Convergence of wind in the Matsuyama plain (Miyagawa et al. 2014)

convergence, which can cause the formation of clouds. Miyagawa et al.[8] (**Fig.12)** have shown the presence of convergence in noncoastal areas.

3.4 Comparison of SW radiation according to land use

To compare the solar radiation reduction rate and trends between the urban areas and rural areas, four points from the area, and eight points from the plain area were selected; the points are selected in such a way that each group of points represents the core urban and rural area respectively as shown in **Fig.2.**

3.4.1 Summer analysis

Fig.13 shows the urban and rural areas' DRSR for September. It clearly suggests that the formation of clouds is likely to occur high in the early morning, late afternoon and in the evening.

Fig.14 shows the comparison of DRSR between the urban and rural areas. The graph is compared by subtracting the decrease ratio of SW radiation of urban values from rural values. The positive value shows that the DRSR is higher in urban areas than rural areas, whereas the negative value shows that the value is greater in rural areas.

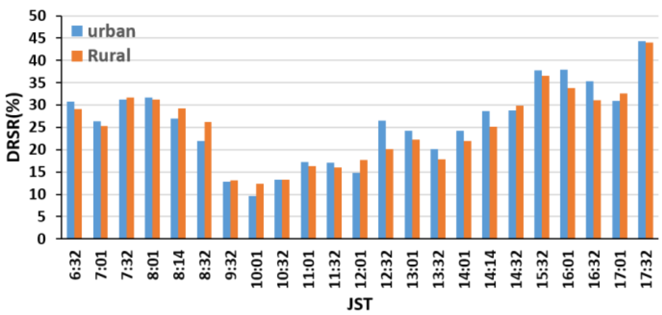

Fig.13 Same as **Fig.7** but for urban and rural areas (September)

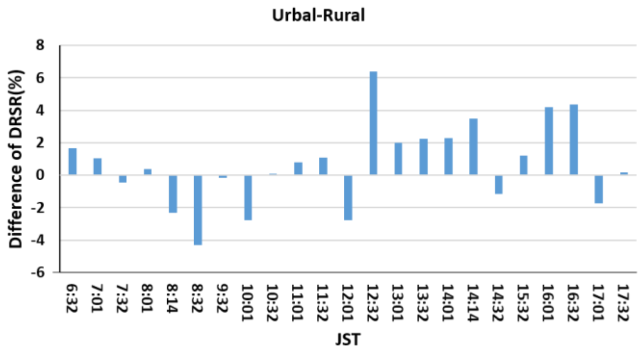

Fig.14 Same as **Fig.8** but urban and rural area (September)

The graph shows that the absolute difference is considerably greater in the afternoon. The result suggests that urban clouds are thicker than rural clouds in the afternoons. Furthermore, it also suggests that the clouds form more thickly over urban areas in the afternoon. Morimoto et al.[9] have described similar results through the relation of the mixing layer and lifted cloud level (LCL). The research says that the formation of clouds over urban areas was noticed even after the mixing layer reached the LCL around 12:00pm until evening, whereas in rural sites, no noticeable development was noticed. This may be because of lower wind speeds and higher temperatures in urban areas during daytime. Studies in many cities have shown that average wind speeds are generally lower in built-up areas than in rural areas [10, 11, 12]. Average temperatures in urban areas in Matsusyama city are higher than its surrounding rural environment due to the heat island effect[13]. Increased temperatures may provide a source of unstable air. The warmer air parcel at the surface will rise under the influence of convection. As the parcel rises, it will adiabatically expand and cool due to the decrease in temperature (the altitude effect) resulting in the formation of clouds.

The afternoon air pollution may also result thicker cloud in the urban areas. Schaefer (1968)[14] has suggested that the increased pollution from stationary sources and vehicles in urban areas, in particular particles of lead which have combined with iodine or bromine, increases the amount of clouds and precipitation above and downwind of urban areas.

3.4.2 Winter analysis

Fig.15 shows the urban and rural areas' DRSR for January. It suggests that the trend of cloud formation is likely to occur almost similarly throughout the morning up to the late afternoon in both rural and urban area compared to the summer analysis. It may be because of the surface air temperature and humidity intensity difference between urban and rural areas according to the seasonal variation. Moriwaki et al.[2, 15] have suggested that "when the wind direction is west to East, the surface air temperature and humidity at urban and rural will tend to be different and the

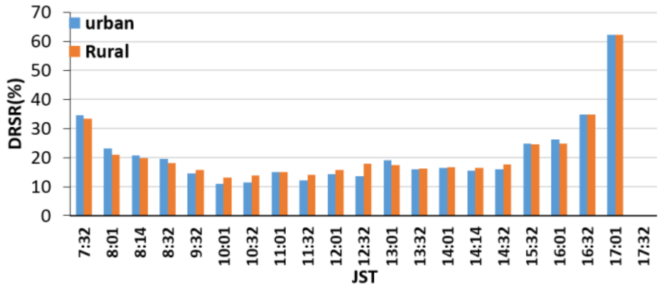

Fig.15 Same as **Fig.7** but for urban and rural areas (January)

difference will be maintained aloft through vertical convection in each area. In contrast, when the wind direction is northerly or southerly, the air is transported across the border of land use and thus the difference between two areas become low". In the Matsuyama plain, the westerly and easterly wind is prominent in summer, whereas the northerly and southerly wind is dominant in winter due to monsoon carrying wind. Because of very small differences in surface air temperature and humidity, intensity between urban and rural areas in winter, the formation of clouds may have been almost similar throughout the day.

4. Summery

Downward SW radiation satellite dataset was used for the analysis of clouds over different geographical features and land use patterns. The study concludes that the thickness of cloud increases with increases in altitude. The comparison between mountainous and plain areas suggest that the thickness of clouds is likely to be higher in mountainous areas than plain areas. The comparison between coastal areas and noncoastal areas suggest that non-coastal areas have a significantly higher thickness than coastal areas in the afternoons. Another comparison between rural and urban area suggests that in summer, urban clouds are thicker than rural clouds in the afternoons but in winter, the thickness is almost the same.

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