Urban dry island phenomenon and its impact on cloud base level and solar radiation

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Matsuyama plain, Japan has an obvious contrast of land use in urban and rural area. The purposes of this study is to investigate the features of Urban Dry Island (UDI), Clouds base level, and solar radiation. On the basis of field measurements in the Matsuyama Plain, the following main outcomes are obtained. The urban absolute humidity was lower than rural absolute humidity. Following the manner of urban heat island phenomenon, we call this phenomenon “urban dry island” (UDI). The UDI phenomenon was significantly found at the daytime during the fine day due to the difference in water vapor fluxes at urban and rural sites. Cloud base level over urban area was higher than that over rural area when wind blew along the border of the abrupt change of land use. This was demonstrated by lifted condensation level, which was estimated from the surface air temperature and water vapor content. Solar radiation over urban area tends to be smaller than that over the rural area during afternoon of days with a percentage of sunshine ranging from 50% to 80%. This was demonstrated by the development of mixing layer estimated from surface heat flux.

Keywords: Urban Dry Island, cloud base level, solar radiation, urban heat island phenomenon, surface heat flux, lifted condensation level

1. Introduction

In recent years much attention has been paid on urban local climate such as heat island phenomenon and severe rainfall. The urban heat island is a phenomenon where urban temperature is higher than rural temperature due to anthropogenic activities. Fujibe[1)] suggested that increase in temperature caused by urbanization results in localized severe rainfall due to convergence of water vapor. In addition, Shimoju et.al.,[2)] have shown the change in the path of invasion of sea breeze due to urbanization, which leads to the localized heavy rainfall. On the basis of field measurements in Matsuyama plain, we also found that urban absolute humidity was lower than rural absolute humidity. Following the manner of urban heat island phenomenon, we call the phenomenon “Urban Dry Island” phenomenon, UDI. Here, first we examined the features and physical causes of UDI phenomenon on the basis of the long term field observation of the spatial distribution of surface humidity and surface energy balance. Then, we investigated the impact of UDI on the formation of clouds using datasets of cloud base level and solar radiation which was obtained by using ceilometer in summer.

2. Field observation:

2.1 Site description

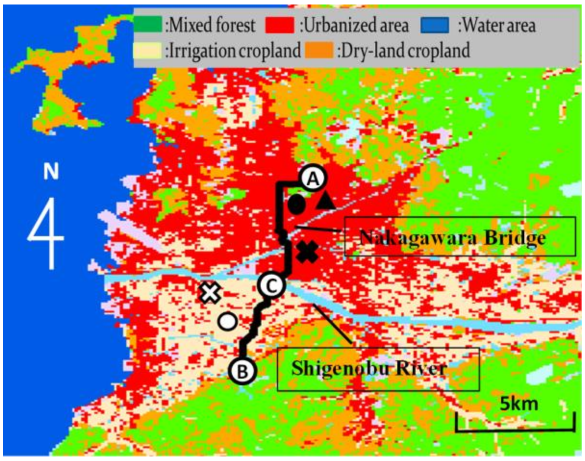

Figure 1: Observation point and land use of Matsuyama plain
Point A : Ehime University Point B : In front of Ueno post office
Point C : Nakagawara Bridge

The Matsuyama plain is located in the north-western part of Shikoku, Japan. Matsuyama plain is mainly composed of alluvial fan formed by flooding of Shigenobu river and its territories, in the plain about 20 km east-west and about 17 km north-south, with total area of about 100 km^2. The urbanization with current population of approximately 520,000 is concentrated in the northern part of the plain whereas the rice paddy fields, farms are located on the surrounding countryside. Figure 1 shows the land use map of Matsuyama plain created on basis of land use classification of digital national land information (GIS) in 2006. As described above difference in the land use is clear and the distinction between the central city and the suburb is clear especially along the Shigenobu River.

2.2 Experimental setup:

2.2.1 Spatial distribution of water vapor:

In order to understand the spatial and temporal distribution of temperature and humidity of Matsuyama plain, we installed 21 thermo-hygrometers (U23-001, Onset). The sensors are installed into a Stevenson screen at elementary schools and in a natural ventilation shelter. The measurement was made from June 24, 2010 to September 2012. The sensors were calibrated in laboratory every year so that the relative standard error for temperature and relative humidity is less than 0.1^{o}C and 0.6%, respectively. The urban site is represented by Bancho elementary school at Nibancho, Matsuyama City (Black circle in Figure 1) whereas Kitaiyo elementary school of Iyo-gun Masaki-chō (White circle in Figure 1) represents the suburban area.

2.2.2 Surface energy fluxes:

For the surface evaporation, the difference in the heat balance and heat radiation were conducted in both urban and rural area from September 2010 to September 2012. As the urban and rural site, branch office of the Ministry of Land, Infrastructure, Transport and Tourism at Higashiishi (Black X mark in Figure 1) and the backyard of the water pumping facility at Masaki cho (White X mark in Figure1) were selected respectively. The instruments were installed at an altitude of 26.5m a.g.l in urban areas and 2.5m a.g.l in the rural areas. The 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. In addition, a sonic anemometer (SAT550, Kaijo-sonic) and an open-path gas analyzer (LI-7500, Li-COR) were installed for the flux measurement, latent heat flux using eddy correlation method. For the evaluation of diurnal courses in sunny days, we used data only from fair-weather days, i.e. days with a percentage of sunshine exceeding 50% determined by using data the Japan Meteorological Agency.

2.2.3 Cloud base altitude:

A Ceilometer (CL31, Vaisala) was used for the determination of Cloud Base Level (hereafter CBL). Ceilometer is a LIDAR (Light Detection and Ranging) device that detects the back scatter of light from the atmosphere aloft. A laser pulse with duration on the order of nanoseconds is sent through the atmosphere. As the beam travels through the atmosphere, tiny fractions of the light are scattered back after they hit the clouds. The presence or absence of the clouds at an altitude is then determined from the intensity of the backscattered light the time taken by the light to scatter back to the injection laser is taken into account.

Cloud Base Level was compared with the Lifted Condensation Level (LCL). When a surface air parcel is lifted aloft adiabatically, the water content in the air parcel is condensed at LCL and cloud is formed. LCL (m) is calculated using Henning equation as shown in equation 1.

$$LCL = 125(T_0 - \tau_0) \qquad (1)$$

Here, T_0 is the surface air temperature and τ_0 is the surface dew-point temperature.

3. Urban Dry Island intensity

In urban areas absolute humidity was lower than rural absolute humidity. In order to analyze the diurnal and seasonal change of this phenomenon we defined UDI intensity as the following equation,

$$\Delta H = -(H_{urban} - H_{rural}) \qquad (2)$$

Here, H_{urban} and H_{rural} is absolute humidity in urban and rural site, respectively. In this study we classified urban and rural site using the 100 m - mesh based land utilization segmented dataset of National Land Numerical Information, provided by National and Regional Policy Bureau.

4. Results and Discussion

4.1 Diurnal course of UDI intensity:

Diurnal course of Urban Dry Island (UDI) intensity is depicted in Figure 2. In the figure the solid line indicates UDI intensity on 26th August. The seven days were selected from the days when the feature of sea breeze was almost similar to the target day in August and September 2010. Two lines show a similar temporal change and thus indicates that the target day is one of the typical days. It is noted that UDI intensity is generally positive except for a few of time zone. This means that the UDI phenomena is generally occurred in Matsuyama plain. One of the main features of the diurnal pattern is the UDI intensity peaks around 9:30 and 18:30. UDI starts to increase at 6:00, peaks at 9:30, and then rapidly decreases. After the morning peak UDI gradually decreases in the daytime, peaks again around 18:30, and decreased in the nighttime. Figure 3 shows the diurnal change in the wind vector at the Matsuyama meteorological observatory on 26th

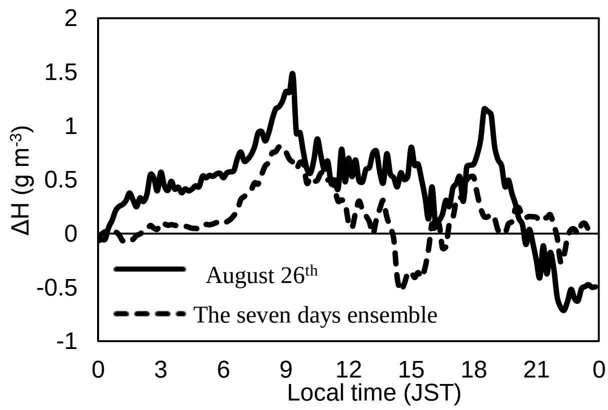

Figure 2: The diurnal course of urban dry island (UDI) intensity

August. The land breeze was altered by the sea breeze (westerly wind) in the morning. Similarly, the sea breeze was altered by the land breeze in the late afternoon. Figure 4 shows the temporal changes in wind between 9:00am and 10:00 am respectively

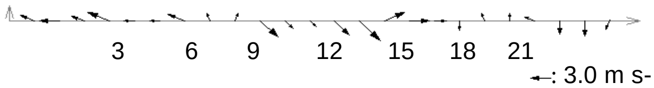

Figure 3: The diurnal change of wind vector

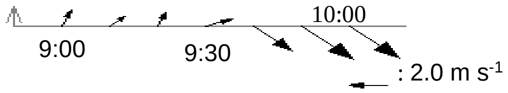

Figure 4: The temporal change of wind vector

4.2 Observation of Cloud Base Level (CBL)

CBL was measured by moving a Ceilometer installed at the back of a truck, and in total 16 observations were made from June to November 2011. We generally focused on the case where clouds were present at an altitude of 1000-2000 m in presence of the atmospheric boundary layer, and with continuous spatial distribution of cloud from rural to urban area. In total, 3 cases were considered, Case-A: the CBL is higher in urban area than the rural area (3 times), Case-B: CBL in both urban and rural area is same (3 times), Case-C: If not included in above two cases. In addition, Table 1 shows the meteorological parameters and observation date and time of each case. On the basis of the data obtained from Matsuyama meteorological observatory, the mean wind direction in each observation points was known. First, we consider the case where CBL is higher in urban area than the rural area. Considering the heat island phenomenon in Matsuyama plain, the urban latent heat flux was much higher than the rural latent heat flux. As the temperature is decreased, the relative humidity is increased in the rural area, thus LCL in urban area is higher than that of the rural area as shown in Figure 5. However, on the day, the CBL was observed higher than the LCL because the convection was weak due to cloudy weather so the air mass could not be lifted adiabatically. By comparing the meteorological parameters of case A and case B we further study the case where the CBL is almost constant in urban and rural area. The calculated result of LCL for case B as per observation time and date are shown in Figure 6. Here, the difference between the LCL of urban and rural was found to be small. The difference in the cloud base altitude may be due to the influence of the direction of the wind as, in case-A the wind direction was east-west whereas in case-B it was north-south. Summarizing the above points we consider that the CBL is influence by the differences in land use pattern in urban and rural area.

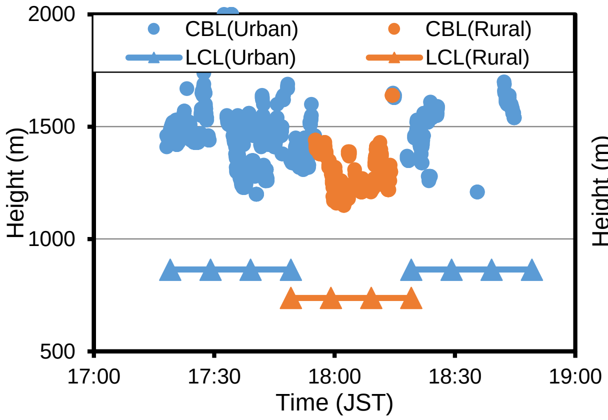

Figure 5: Observation of Cloud Base Level (case-A: 2011-7-6 17:00 pm)

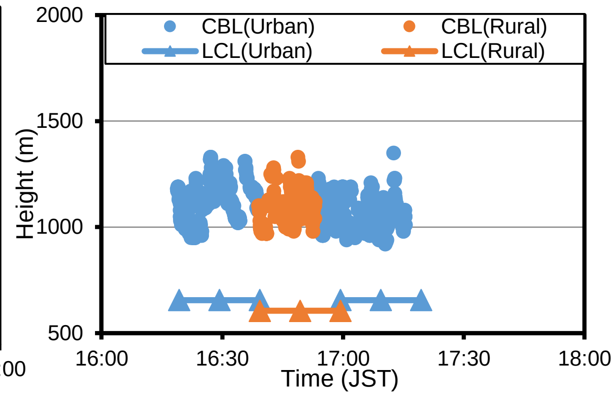

Figure 6: Observation of Cloud Base Level (case-B: 2011-9-21, 16:00pm)

Table 1: Meteorological parameter of 6 cases

Case	Time and date (JST)	Air temperature(℃)			Relative humidity (%)			Dew-point temperature (℃)			LCL (m)			Wind direction
		Urban	Rural	Difference	Urban	Rural	Difference	Urban	Rural	Difference	Urban	Rural	Difference	
A	2011.6.13. 9:40~10:50	—	—	—	—	—	—	—	—	—	—	—	—	West
	2011.7.26. 17:20~18:50	30.2	29.4	0.8	66.6	70.6	-4	23.3	23.5	-0.2	864	738	126	West
	2011.7.27. 6:00~7:00	26.8	26	0.8	70.5	76.4	-5.9	21	21.5	-0.5	729	561	168	East
B	2011.9.21. 16:20~17:20	22.9	22.5	0.4	72.4	74.2	-1.8	17.7	17.7	0	655	605	50	North
	2011.9.21. 18:20~19:20	22	21.6	0.4	72.5	75.5	-3	16.8	17.1	-0.3	646	564	82	North
	2011.10.13. 11:20~12:20	21	20.6	0.4	85.5	87.3	-1.8	18.5	18.4	0.1	317	275	42	South

4.2 Solar radiation amount and heat balance data:

The formation of clouds is considered by comparing the amount of solar radiation in urban and rural area during a sunny day. Figure 7 shows the diurnal variation of solar radiation in urban and rural area. Here, we consider the reduction of solar radiation due to the fact that solar radiation has been blocked by clouds present in the sky at that time. In this study, prospective summer afternoon day with sunshine percentage ranging from 50% to 80% on July, August and September in 2011 was selected. In total 29 days were selected. First, we studied the effect of solar radiation reduction rate per hours from 6:00 after sunrise to 18:00 before sunset, the time period where the solar radiation was blocked by cloud was greater. The main objective of the research is to study the effect of difference in land use in urban and rural area has on the cloud formation, so comparing the results we found that the cloud formation in urban areas is higher during the daytime to evening in the urban area. The solar radiation reduction rate calculated from the integrated value of 4 hours, from 13:00 to 17:00 were compared between the urban and rural area where the value in urban area was found to be larger than that of the rural area. It is observed that the absolute value of the difference is relatively small on the day when solar radiation reduction rate of urban and rural area is small. Here, the elevation of the mixing layer developed using integrated value of sensible heat flux obtained from the observation was compared with the LCL. Figure 8 shows the diurnal variation of sensible heat flux obtained from the observation. Here, since the data from July, August, and September 2011, has been missing due to a failure of the observation equipment, average

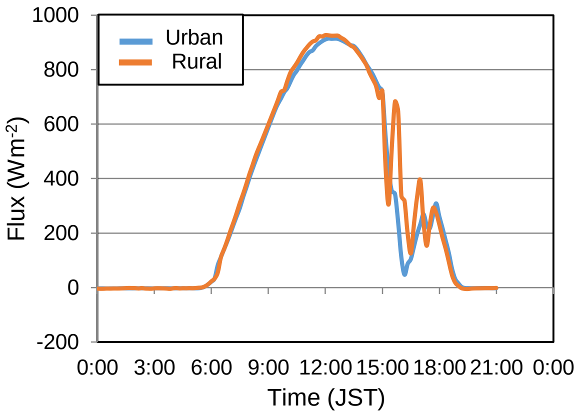

Figure 7: Diurnal variation of solar radiation

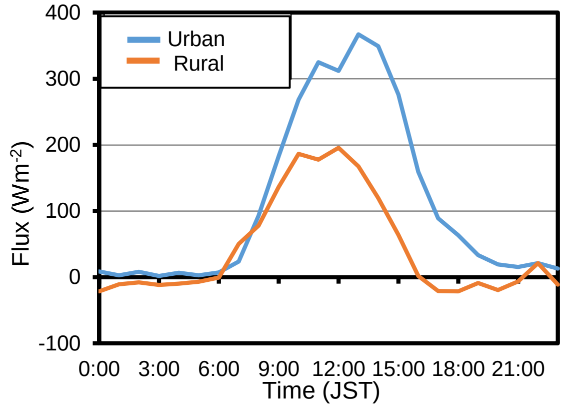

Figure 8: Diurnal variation of sensible heat flux

of days with a percentage of sunshine ranging from 50％ to 80％ from September 2010 was taken as the representative data. In total 9 data observation mixing layer until 18:00 until sunset (Figure 9). Taking 0 as the initial value at 6:00 after sunrise, we estimated the development of the mixing layer until sunset. Using equation 3, elevation of mixed layer was estimated.

$$h = \left(\frac{2Q}{\Gamma C_p \rho} \right)^{1/2} \qquad (3)$$

Here, h: Mixing layer (m), Q: Integration sensible heat flux (Jm^{-2}), Γ: Gradient of potential temperature (Km^{-1}), $C_p\rho$: Volume heat capacity of air ($JK^{-1}m^{-3}$). In urban site, development of cloud was noticed even after the mixing layer reached the LCL at about 1300m around 12:00, whereas in rural site, no noticeable development was noticed after the mixed layer reaches LCL at about 900m altitude around 11:00 as shown in Figure 9. From this, that there is a tendency that clouds are likely to develop in the evening, which future relate that cloud is likely to develop in urban areas than rural area.

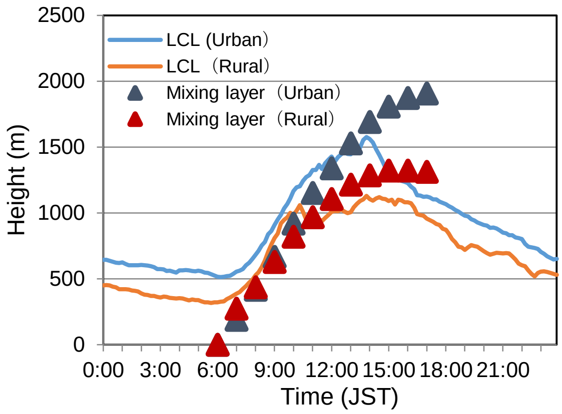

Figure 9: Comparison of LCL and mixed layer height

5. Conclusion

In this study, using the weather data the contrast of land use observed in the Matsuyama plain, we studied the features of Urban Dry Island and its impact on the formation of clouds using datasets of cloud base level and solar radiation. The UDI affected the cloud base level over urban and rural areas. Differences in land use of the land surface area urban and suburbs areas give rise to differences in cloud base altitude, which is further affected by the wind direction. If the wind blows along the boundary of rural areas and urban areas, cloud base altitude will be higher in urban areas than rural areas. On the other hand if the wind blows toward the boundary of suburban areas and urban areas, the difference cannot be seen in the cloud base altitude of rural areas and urban areas due to the mutual influence of the atmosphere between. This was demonstrated by lifted condensation level, which was estimated from air temperature and water vapor content.

Differences in land use of the land surface area of urban and suburbs areas can affect the development of the cloud. There is a tendency for clouds to be developed in the urban area due to development of the mixing layer by the supply of sensible heat is large as compared to the rural area.

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