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Effect of Farmers' Water Management on Water Temperature Changes in Paddy Area with Independent Irrigation and Drainage Canal Settings

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Abstract

In this study, we continuously observed water temperatures in the main irrigation canal and the main branch and farm drains of a paddy area with independent irrigation and drainage canals. We focused on the flow-down pathway that changes with various water management practices. As a result, we found that the maximum temperature in the farm drain was higher in July than in August, a trend similar to reported temperature changes of water stored in paddy plots. It appears that water temperature in the farm drain strongly reflects paddy outflow. At drainage canals, water temperature was reduced in July and rose in August. Our findings clarified that water temperature changed in the drainage canal not only because of heat exchange due to weather conditions but also because of inflow from the irrigation canal and outflow from the paddy plots. This study provides evidence for the strong impact of water management on paddy area water temperatures with independent irrigation and drainage canal settings, as farmers control the amount of inflow from irrigation canals and outflow from drainage water, depending on the stage of growth and weather conditions.

Discipline: Irrigation, drainage and reclamation
Additional key words: air temperature, distribution management water, solar radiation

Introduction

Water temperature in paddy areas is an important factor that affects agricultural production and the habitats of aquatic organisms. Suitable water temperatures for the green algae found in paddy plots are different for each individual species (Yamagishi & Hashizume 1974). Furthermore, several irrigation water management practices can decrease the risk of high-temperature injury to rice plants (Tomosho & Yamashita 2009). Much attention has been paid to the water temperature of paddy areas, and water management focused on controlling temperature to minimize the environmental impact on crops and aquatic organisms that inhabit those areas.

Many studies have measured water temperatures in irrigation canals and paddy plots. For example, Sakata et al. (2012) showed that irrigation water is hotter than the ponding water in a paddy field after the heading season. A water temperature prediction model in paddy plots was constructed based on leaf area index, solar radiation, and wind speed (Kuwagata et al. 2008).

Drainage water temperature, however, has not been investigated, likely because the purpose of previous studies was to clarify the influence of water temperature on agricultural production. In Southeast and East Asia, as in Japan, return flow from an upper paddy area is reused as irrigation water in lower areas. The water temperature of drainage in the upper area affects both river water and paddies in the lower area. Therefore, the water temperature of drainage is also important for considering

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water temperature change in river basins.

There have been a few studies on water temperature in canals that reuse drainage water in the same paddy area as irrigation water. Examining a dual-purpose canal, Kimura et al. (2013) noted that water temperature can increase due to meteorological factors and a reverse flow of paddy plots, and that temperature was significantly elevated downstream. Moreover, in a numerical simulation analysis, Sugiyama et al. (2013) reported that the temperature of drainage water under cyclic irrigation decreases due to the inflow of irrigation water. These results show that the reverse flow of paddy plots and inflow of irrigation water affect the water temperature in drainage canals.

In a previous study, Shimmura and Taniguchi (2013) reported that the temperature of drainage water was lower than that of irrigation water in August (the hottest month in Japan) in a paddy area where irrigation and drainage canals could be set independently. In such an independent canal network, percolation water, lot-management water that flows from the surface of paddy plots (Fig. 1), and distribution management water that flows directly from the irrigation canal without passing through paddy plots (Fig. 2) comprise most of the drainage water. The outflow route and flow rate within a paddy area fluctuate due to farmers' water management practices. Watanabe and Maruyama (1984) reported that about 30% of intake water flows out to drainage canals as lot-management water, and that both agricultural and water management practices affect the quantities. Taniguchi and Satoh (2006) reported that in an independent canal network, the amount of distribution management water varies depending on how the farmers operate the paddy inlets and divide the work for irrigation canals, and that the ratio of distribution management water to the total water supply ranged between 20-35%. These inflow water sources have a large effect on water temperature in drainage canals as water from various sources flows into the canals. Thus, it is necessary to consider farmers' water management practices, as well as to clarify water temperature change at drainage canals in a paddy area with an independent network.

In this study, water temperatures in the main irrigation canal and the main, branch and farm drains were continuously observed in a paddy area with independent irrigation and drainage canals. Our focus was on the flow-down pathway that changes with various water management practices.

Materials and methods

A paddy area located in the Fukuoka-zeki Land Improvement District (LID) of the Kanto Plain, Japan, was selected as the study area (Fig. 3). The benefit area of the Fukuoka-zeki LID comprises 2818 ha. The irrigation period is from April 25 to August 23, with 24-h continuous irrigation on all days except those with heavy rain. The area takes irrigation water from the Kokai River via the Tamei irrigation system, creating a reservoir in the river by means of a weir. Irrigation water is distributed by gravity through concrete-lined irrigation canals. Drainage water returns to the Kokai River through drains with concrete retaining walls.

During the irrigation period in 2013, water level and temperature sensors (Levelogger; Solinst Canada Ltd., Georgetown, Ontario) with measurement accuracy of ±3

Fig. 1. Photo of lot-management water flowing into a farm drain

Fig. 2. Photo of distribution management water flowing into a branch drain

mm and ±0.05°C, respectively, were installed at several points described below (Figs. 3 and 4). The time interval for data collection was set to 10 min.

First, to measure the water temperature change during the flow process in the main irrigation canal, we set upstream (IRu), midstream (IRm), and downstream (IRd) observation points located at 0.4, 4.7, and 10.4 km downstream from the upper end of the main irrigation canal, respectively. The canal widths at the observation points were 5.24 m (upstream), 4.13 m (midstream), and 2.71 m (downstream).

Second, a detailed observation area with a 30-ha benefit area was set near IRm to measure the change in water temperature after passing through the paddy plots. The observed temperature at IRm was used as the area's irrigation water temperature for a comparison with the drainage water temperature. The detailed observation area included several paddy plots, and the farmer on each plot conducts water management individually. As outflow from the paddy plots and the paddy water temperature differ greatly depending on the management of each paddy, it is difficult to measure both at each paddy plot separately. Therefore, the drainage water temperature was measured at the terminus of the farm drain (DRf) that gathered all outflow consisting of percolation water and surface outflow from the paddy plots. By comparing the temperatures of the irrigation water and drainage water, we assessed the change in water temperature after passing through the paddy plots. The canal width at the DRf was 0.63 m.

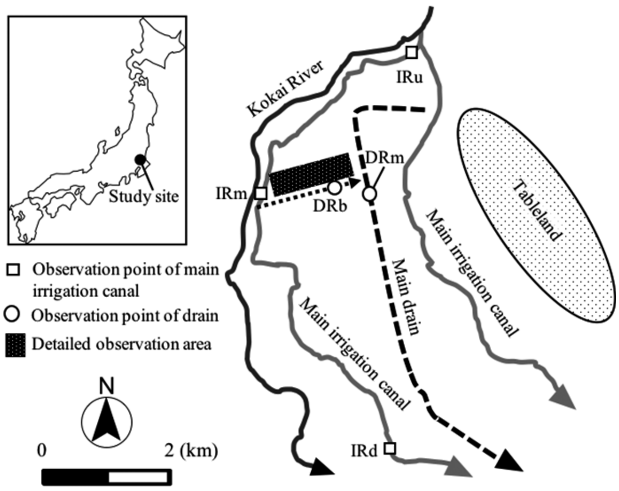

Fig. 3. Schematic outline of the study site

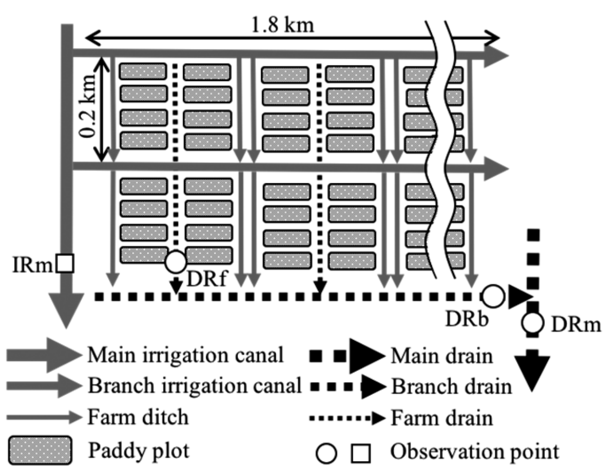

Fig. 4. Outline of the detailed observation area

Third, we set up an observation point in the branch drainage canal (DRb), which was located 1.4 km downstream from the DRf, to clarify water temperature changes due to water management and weather conditions in the process of flowing through the drain. The canal width at the DRb was 3.2 m. Fourth, we set up an observation point (DRm) in the main drainage canal, which was located 1.8 km downstream from the DRf observation point, to confirm the seasonal relationship between the water temperatures of intake and outflow of the whole paddy area. Water in the main drainage canal included the inflow of groundwater from the tableland located east of the study area (Fig. 3). The canal width at DRm was 3.7 m.

Flow rate was also measured at each observation point by two kinds of flow meters (StreamPro ADCP, Teledyne RD Instruments, San Diego, CA, USA; FLO-MATE Model 2000; Marsh-McBirney, Inc., Frederick, MD, USA). Water level was continuously recorded by installed sensors, and converted into flow rate by an H-Q curve derived from the observed flow rate and water level. A pyranometer (MS-602; EKO Instruments Co. Ltd., Tokyo, Japan) was also installed at the site to assess the effects of solar radiation on water temperature. Air temperature data gathered at the Tateno Agrological Observatory located 12-km northeast of the study area were used in our analyses.

Results and discussion

1. Water temperature changes of inflow and outflow in paddy area

Figure 5 shows the variation of water temperature at IRu and DRm on sunny days in August. The mean maximum water temperatures in August at IRu and DRm were 28.8°C and 29.6°C, and the mean minimum water temperatures were 27.9°C and 24.7°C, respectively. Water temperature at IRu was hotter than at DRm most of the time, with mean water temperatures at IRu and DRm of 28.3°C and 26.6°C, respectively. As is the case with a previous study (Shimmura & Taniguchi 2013), water temperature at DRm was lower than at IRu in August. Thus, a common magnitude correlation of water temperature was confirmed between inflow and outflow in a paddy area with independent irrigation and drainage canals.

The mean daily ranges of water temperature at IRu and DRm were about 1.0°C and 4.8°C, respectively. The temperature range at IRu was very small. Figure 6 shows the daily maximum and minimum water temperatures at IRu. The temperature range at this point was about 1.4°C throughout the irrigation period. In contrast, the range of water temperature in the upper area of the Kokai River was about 4°C (Shimmura & Taniguchi 2013). In the Tamei irrigation system, river water is stored in the river channel for a while, thus stabilizing the variation of water temperature.

2. Changes in irrigation water temperature

As water flowed through the main irrigation canal on the sunny days of August 14-17, the mean water temperatures at IRu, IRm, and IRd were 28.3°C, 29.3°C, and 29.1°C, respectively (Fig. 7). The water temperature was ordinarily higher at IRm than at IRu. In contrast, the water temperatures at IRm and IRd were similar during the daytime, but the temperature was about 0.5°C lower at IRd than at IRm at night. The water temperature was sufficiently warmed during the flow process from IRu to IRd.

Shimmura and Taniguchi (2013) noted that water temperature rises during the flow process in the main irrigation canal due to the influence of air temperature and solar radiation during the day, and does not change after sunset. We noted a similar trend in the relationship between IRu and IRm, whereas the daily maximum temperature at IRd compared to IRm was slightly higher or equal, and the daily minimum temperature was clearly lower. In other words, the water temperature increased more during the day and cooled more during night at IRd than at IRm.

The mean daily ranges of water temperature increased in a downstream direction (i.e., 2.0°C, 2.9°C, 3.5°C). The average water depths at IRu, IRm, and IRd were 1.34, 1.06, and 0.76 m, respectively. In the irrigation canal, farmers withdraw water depending on weather conditions and cultivation period. Water depth and flow velocity are changed by increases or decreases in water intake. As the irrigation water is distributed from upstream to downstream, the water level downstream is lower than that upstream. Thus, the water temperature at IRd was likely strongly influenced by heat exchange based on weather conditions.

3. Water temperature changes passing through paddy plots

To clarify the influence of passing through the paddy fields on water temperature, the temperatures of irrigation water (IRm) and drainage water at the DRf were compared over two periods: July 8-11 and August 14-17.

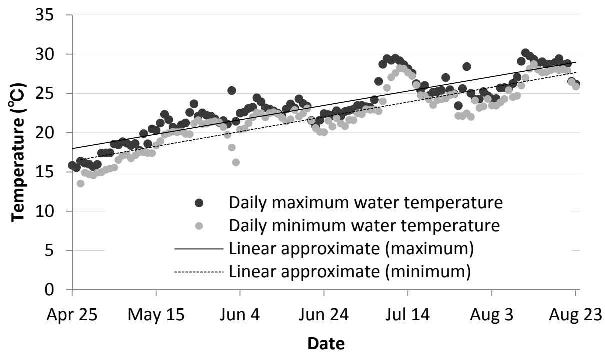

Fig. 6. Daily maximum and minimum water temperatures at upstream point of the main irrigation canal (IRu)

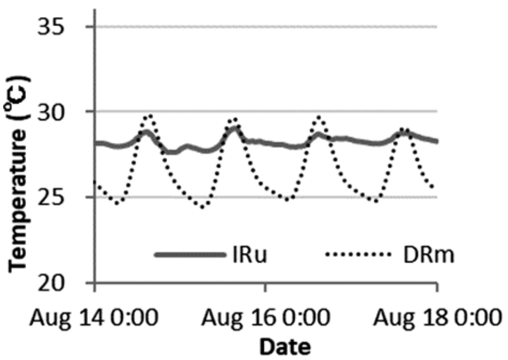

Fig. 5. Irrigation (IRu) and drainage water (at DRm) temperatures on sunny days in August

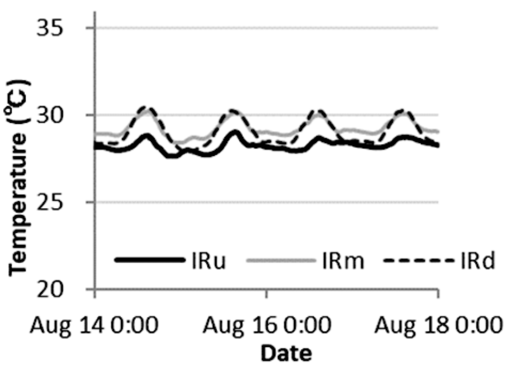

Fig. 7. Variations in water temperature at the main irrigation canal on sunny days in August

In July, the diurnal range of irrigation water temperature was 26-31°C and that of drainage water at the DRf was 25-34°C (Fig. 8). In August, however, the temperature of irrigation water was around 29°C, and the temperature at the DRf varied from 25-29°C (Fig. 9). That is, the diurnal temperature range at the DRf was 5°C lower in August than in July. In July, the daily maximum and minimum temperatures of water at the DRf were higher and lower, respectively, than those of irrigation water.

The temperature of water before flowing into the farm ditch from the main irrigation canal was examined to reveal the section in which water temperature decreased. A branch canal branches off at 220-m east of the main irrigation canal, and leads to farm ditches near the DRf. The water depth at the upper end of the branch irrigation canal varied from 0.3-0.5 m, and it took roughly 7 min. of flow time to reach the farm ditches near the DRf. The water temperature change from the main irrigation canal to the farm ditch was calculated using the prediction model of water temperature in a river by Kondo (1995) and the above hydraulic conditions. Water temperature in the irrigation canal decreased about 0.1°C when conditions were most favorable for a temperature change.

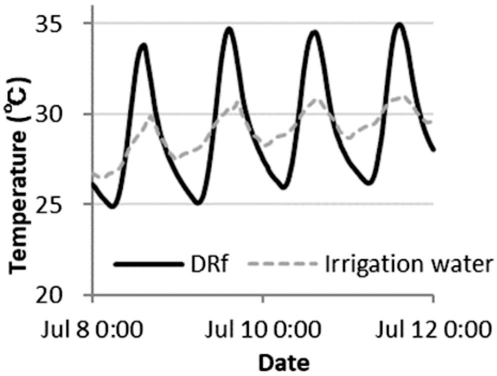

Fig. 8. Irrigation and drainage water temperatures (at DRf) on sunny days in July

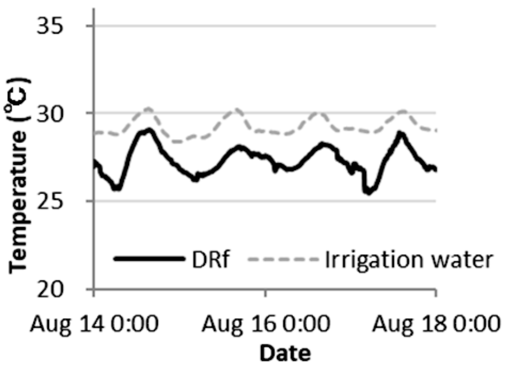

Fig. 9. Irrigation and drainage water temperatures (at DRf) on sunny days in August

In short, the water temperature only decreased in paddy plots and at the DRf, and not in the irrigation canals.

Webb and Zhang (1997) have clarified that net radiation accounts for a large percentage of energy gain and heat loss in the heat balance of water temperature. Therefore, we considered the effect of solar radiation on water temperature by comparing sunny and cloudy periods in July and August. Figure 10 illustrates the relationship between water temperature at the DRf and solar radiation and air temperature on sunny days (July 8-11, > 20 MJ/m^2 radiation and no rain). The daily averages of total radiation, maximum water temperature at the DRf, and maximum air temperature in the sunny period were 25.3 MJ/m^2, 34.5°C, and 34.6°C, respectively. Those during the cloudy period (June 29-July 2, < 20 MJ/m^2 radiation and no rain) were 18.6 MJ/m^2, 27.3°C, and 26.2°C, respectively. The daily average of total radiation was 6.7 MJ/m^2 lower during the cloudy period compared to the sunny period. The maximum temperatures of the DRf and air were 7.2°C and 8.4°C lower, respectively, during the cloudy period.

Figure 11 shows data from the sunny period of August 14-17; the daily averages of solar radiation and maximum air temperature were 22.4 MJ/m^2 and 34.5°C, respectively. During the cloudy period (July 30-August 2), the daily averages of solar radiation and maximum air temperature were 15.4 MJ/m^2 and 29.1°C, respectively. As in July, the daily averages of total radiation and maximum air temperature were lower in the cloudy period than in the sunny period. Although air temperature changed according to the magnitude of solar radiation, the daily averages of maximum water temperature at the DRf during the sunny and cloudy periods were 28.6°C and 28.2°C, respectively, thus showing a marginally small difference. Moreover, the mean maximum water

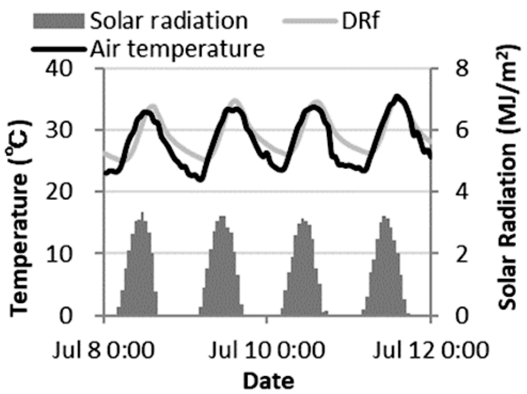

Fig. 10. Air and drainage water temperatures (at DRf) and solar radiation on sunny days in July

temperature at the DRf was 5.9°C lower during the sunny period in August than in July.

It is unlikely that the difference in water temperatures reflected variation in the flow rate from the outflow of paddy plots. There was no marked difference in mean flow rate at the DRf during the sunny periods of July (0.02 m^3/s) and August (0.02 m^3/s). The trend of water temperature at the DRf in August being lower than in July was similar to the reported changes in the temperature of water stored in paddy plots. Ichimura et al. (1965) found that the diurnal range of water temperature at paddy plots decreased with growing rice plants. Thus, it appears that the water temperature at the DRf is more sensitive to the outflow of lot-management water it receives than to heat exchange due to weather conditions during such flows. Note that the temperatures of lot-management water and water at the farm drain are not necessarily equal, because percolation water flows into the farm drain in addition to lot-management water.

4. Comparison of water temperatures in drains

(1) Analysis of continuous observation data in July and August

We next examined the water temperature changes as water flowed down from the DRf to the DRb. Figures 12 and 13 show the changes in the water temperature of drainage canals from July 8-11 and August 14-17, respectively, during which similar weather conditions were experienced before and after the heading stage. Mean daily maximum temperatures before the heading stage at the DRf and DRb were 34.5°C and 33.5°C, and mean daily minimum temperatures were 25.6°C and 25.7°C, respectively. Minimum water temperatures at the DRf and DRb were almost the same. However, maximum water temperature decreased in the downstream direction (Fig. 12). The coefficients of determination between maximum air temperature and maximum water temperatures at the DRf and DRb during the irrigation period were 0.57 and 0.79, respectively (Table 1), indicating that the correlation strengthened toward the lower drainage. The temperature of drainage water at the DRf before the heading stage was high, due to the effect of solar radiation warming the paddy water. Heat exchange with the atmosphere likely occurred as water flowed down the system, as the maximum water temperature at the DRf was slightly higher than the air temperature (Fig. 10). In addition, the irrigation water temperature was about 3°C lower than the DRf water temperature in the daytime during this period (Fig. 8).

According to a rough estimate based on a water temperature prediction model (Kondo 1995), the temperature of distribution management water, which flows from the tail end of the farm ditch, was about 1.0°C higher in the daytime than the irrigation water. In other words, the temperature of distribution management water was still lower than that of the DRf, even considering the temperature change while water flowed through the farm ditch. Therefore, it is possible that distribution management water, which flows directly from the irrigation canal to the DRb without passing through the paddy plots, affects the drainage water temperature. Taniguchi and Satoh (2006) reported that the ratio of distribution management water to the irrigation inlet is between 20-35%. This shows that a sufficient amount of distribution management water flows into the branch drain to change water temperature in the drainage canal. As the flow of distribution management water changes depending on whether or not a farmer draws water into a paddy plot, it is difficult to quantify the influence of distribution management water on the water temperature in drains.

The maximum temperatures at the DRf and DRb after the heading stage were 28.6°C and 31.1°C, respectively (Fig. 13). Mean daily minimum temperatures at the DRf

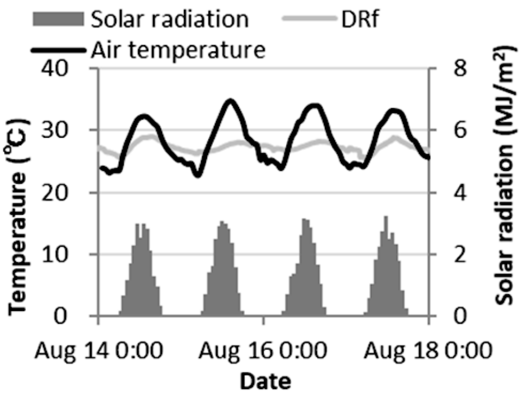

Fig. 11. Air and drainage water temperatures (at DRf) and solar radiation on sunny days in August

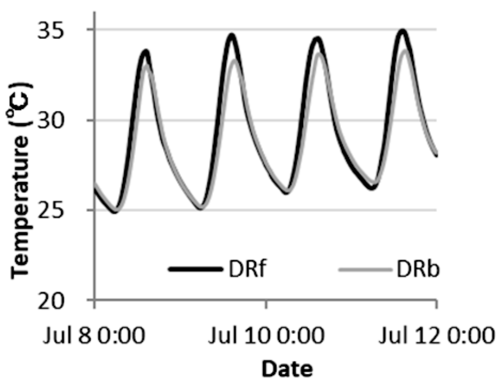

Fig. 12. Water temperatures at each drainage canal on sunny days in July

and DRb were 26.1°C and 25.7°C, respectively. As in July, the difference in maximum water temperature between the DRf and DRb was larger than that of minimum water temperature. However, unlike in July, the maximum water temperature increased as water flowed from the DRf to the DRb. Mean flow rate at the DRb was 0.43 m^3/s in July and 0.45 m^3/s in August. As with the DRf, there was no difference in inflow water. The maximum water temperature at the DRf was lower after the heading stage than before the heading stage. Moreover, the maximum water temperature at the DRf was lower than that of irrigation water and the maximum air temperatures during this period (Figs. 9 and 11). Therefore, heat exchange and distribution management water contribute to increasing the temperature of water as it flows to the DRb.

(2) Water temperature change during irrigation period

The daily maximum temperatures at the DRf and DRb in August were 5.9°C and 2.4°C lower, respectively, than those in July. The regression line slopes between daily maximum air temperature and daily maximum water temperature at the DRf from May-August were 0.756, 0.758, 0.834, and 0.457 (Table 1). Likewise, at the DRb, the regression line slope in August between daily maximum air temperature and daily maximum water temperature was smallest during the irrigation period. However, the result of the regression line slope at the irrigation canal in August does not show this tendency. In August, the rise in water temperature at the DRf was much smaller than that of air temperature due to low temperature outflow from the paddy plots. This effect was sustained in the flow processes of the DRb. The coefficients of determination between daily maximum water temperatures at the DRf and daily maximum air temperatures from May-August were 0.51, 0.50, 0.75, and 0.44. At the DRb, the same trend was observed except in August; the coefficients of determination were low in May and June, and high in July. The maximum water temperature at the DRf and air temperature on sunny days were similar (Fig. 10). However, the maximum water temperature at the DRf was higher than the air temperature on cloudy days in July. In May and June, when the maximum air temperature did not rise to an extreme even on sunny days, the correlation with water temperature was low.

The coefficients of determination between maximum air temperature and maximum water temperature at the DRb in August were larger than those at the DRf. As noted earlier, the difference in maximum temperatures at the DRb between July and August was smaller than that at the DRf. Thus, the suppression of increased water temperature caused by rice plant coverage gradually decreases as water flows down the drainage canals by heat exchange with weather conditions and the inflows of distribution management water.

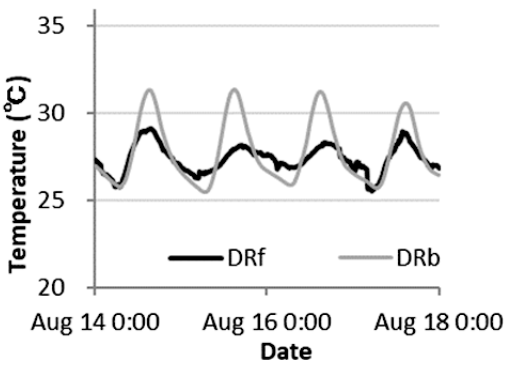

Fig. 13. Water temperatures at each drainage canal on sunny days in August

Conclusions

1) In the main irrigation canal, the water temperature increased to maximum as water flowed down the irrigation system. The temperature range in the downstream portion increased because of the lowered water level due to water intake.
2) The maximum temperature in the farm drain on sunny days was higher in July and lower in August than that of irrigation water. The differences in water temperature at the DRf between July and August were likely caused by the change in solar radiation reaching the water surface in paddy plots, which depends on the plant cover. It appears that the water temperature in the farm drain strongly reflects the outflow of paddy plots.
3) In July, the water temperature decreased as water flowed from the DRf to the DRb. The distribution management water and air temperatures were lower than the water temperature of the DRf. Therefore, the inflow of distribution management water and heat exchange due to weather conditions decreased water temperature in

Table 1. Gradients and coefficients of determination in each month between daily maximum air temperature and daily maximum water temperature at each observation point

	DRf	DRb	Irrigation canal
Irrigation period	0.531 (0.57)	0.699 (0.79)	0.609 (0.73)
May	0.756 (0.51)	0.622 (0.59)	0.377 (0.37)
June	0.758 (0.50)	0.739 (0.65)	0.016 (0.00)
July	0.834 (0.75)	0.799 (0.87)	0.457 (0.48)
August	0.457 (0.44)	0.583 (0.81)	0.559 (0.49)

the drainage canal during flow. Conversely, in August, water temperature in the drainage canal was increased by the inflow of distribution management water and heat exchange due to weather conditions, as water temperature at the DRf was lower than the distribution management water and air temperature.

Our findings clarified that water temperature changes not only because of heat exchange due to weather conditions but also because of intake water in the case of an irrigation canal, and distribution management water from the irrigation canal and outflow from paddy plots in the case of a drainage canal. The depth in the irrigation canal varies depending on how much farmers increase and decrease intake water. The ratio of distribution management water and the outflow from paddy plots also differs according to each farmer's water management and the cultivation period. The temperatures of these water sources thus change with different outflow pathways.

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