Energy and Water Budget of Paddy Field in the Lake Biwa Basin, Japan

Kenji TANAKA, Hiroki HAYASHI, Eiichi NAKAKITA, and Shuichi IKEBUCHI

Water Resources Research Center, DPRI, Kyoto Univ.
Email: tanaka@wrcs.dpri.kyoto-u.ac.jp

1 Introduction

In this study, we analyze the energy and water budget of paddy field in the temperate humid climatic condition. The field observation has been carried out under the Japanese hydro-meteorological project called "Lake Biwa Project". It is very difficult for the existing land-surface scheme to treat the energy and water budget of paddy field properly, since water is introduced or draigned by human controlled irrigation. A new land-surface scheme (P-SiB2) , which is based on SiB2 and specially designed for the paddy field, has been developed and validated using these data.

2 The Lake Biwa Project

The Lake Biwa Project was founded in 1989. A core activity of this project has been collaborative field observation synchronized with the spaceborne and airborne remote sensing. This project has been developed and proceeded by a Japanese group for investigating the hydrological cycle near land surface. The aim of this project is to understand the hydrological cycle in and/or over the Lake Biwa Basin together with establishing ways of scaling up and down the hydrological model within the scale of 100 km $\times$ 100km. Targets of this project are

(1) validation of satellite remote sensing

(2) development of algorithms/models describing hydrological processes

(3) understanding land-atmosphere interactions

(4) evaluation of space/time scale effects in the hydrological cycle

(5) establishment of a land-atmosphere coupled model for the Lake Biwa Basin

The development of this project can be categorized into two stages.

The first stage (from 1989 to 1994)
focused on the targets (1) and (2) with rather point in situ observation. The target field was mainly harvested paddy filed and the largest target spatial and temporal scales were 1 km and 1 day.

The second stage (from 1995 to 2000)
has been focusing on rather targets (3) and (4) by coupled numerical model developed by members. Currently, seasonal variation of energy and water cycle is gradually being added as one of the targets by combining the numerical model with operational information from satellite observation and established regular in situ observation systems. Accordingly, the largest target spatial and temporal scales are shifted to 20 km and 1 week on the viewpoint of up scaling.

The third stage will follow the second stage to establish the target (5).

3 Observation System

Now four observation systems has been installed and operated regularly at different landuse condition (paddy field, forest, lake, urban area) in the Lake Biwa Project. Observation system for paddy field is located at N35.49, E136.23. One tract of paddy field is about 30m width and 100m length, and this field belongs to local farmer. This field has been treated and called as 'intensive field' since 1991. Regular operation of this system started in July 1998.

The system consists of two sub-system. Vertical profile of atmospheric variable near surface is recorded by Grant (SQ1021). On the other hand, radiation and soil related variables are recorded by Campbell (CR10X)

Power source for the system is from solar panel (11.1W, 14.5W) with battery (18.0Ah, 13.5Ah). Observation items and sensors are listed in **Table 1**. In addition to usual heat budget observation system, water temperature and water depth are measured. Light quantum sensors were added to catch the activity of photosynthesis from June 1999.

Figure 1: Observation system

Table 1: Observation items and sensors

item	sensor	height
air temp.	Vaisala VH-G-Z	507,264,111cm
humidity	Vaisala VH-G-Z	507,264,111cm
wind speed	Vector A100L2	523,266,116cm
wind direction	Vector W200	523cm
pressure	Vaisala PTB100	210cm
light quantum	Licor LI-190SA	200cm(up&down)
logger	Grant SQ1021	
soil temp.	Campbell 107	-1,-10,-20cm
water temp.	Campbell 107	1cm
net radiation	REBS Q7	195cm
soil heat	REBS HFT-3	-1cm
long-wave rad.	Eppley PIR	195cm(up&down)
short-wave rad.	Kipp&Zonen CM-14	195cm(up&down)
soil moisture	Campbell CS615	-5,-5,-20,-20cm
water depth	Ikeda KWH-4PHT	
precipitation	Ikeda RT-5	
logger	Campbell CR10X	

If we seek for ideal condition for observation, the site may be located in remote place where electricity and telephone line are not available. Recently service area for mobile phone has extended day by day. So if the site is sightly, mobile phone can be used as communication tool between the office and the field. In case of Lake Biwa Project, mobile phones are connected with special modem at four observation systems. Due to the mobile phone, we can collect data easily and can find the troubles early.

4 Observed Data

Observed data are processed with Bowen ratio method to calculate energy fluxes. As for the heat storage term, it is a total of energy stored in both water and soil, when water layer exists on soil surface.

4.1 Diurnal Variation

Figure 2 shows an example of observed data (energy budget, radiation budget, temperature, soil moisture, water depth, and albedo, respectively) on June 6th in 2000. As water depth data shows, water layer existed on that day, and significant part of net radiation energy was stored as ground heat flux. Clear diurnal variation in albedo data was brought by two reason. One is dependancy of solar angle (low soil reflectance), and another one is photosynthesis activity.

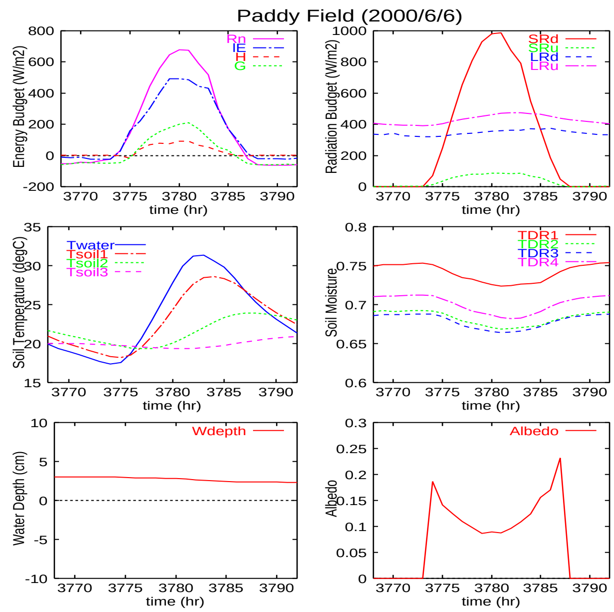

Figure 2: Diurnal variation of observed elements at paddy field (2000/6/6)

4.2 Seasonal Variation

Monthly average energy budget is listed in **Table 2**. Although we have much snow at this field in winter season (from middle of December to the end of Februaly), the observation system is not designed for snow (depth and heat storage). So the accuracy of energy balance in winter season is not so good. Furthermore, when the snow pack exists, we should take the additional energy for snow melt into account.

According to **Table 2**, net radiation energy has its maximum in August and minimum in December. As for heat storage, maximum value is in June. While net radiation increases from June to August, heat storage decreases. This tendency can be explained by the growing of rice crop and existence of water. Basically, soil moisture value keeps relatively high value and Bowen ratio is low (latent heat is dominent) throughout the year. This is due to winter precipitation and field capacity of soil (clay).

Table 2: monthly energy budget(Wm^{-2})

period	Rnet	G	H	lE
99/8/9∼31	119.0	0.8	15.4	102.7
99/9/1∼30	97.3	1.5	15.6	80.2
99/10/1∼31	70.7	-8.1	14.2	64.6
99/11/1∼30	35.9	-9.6	7.1	38.4
99/12/1∼31	22.2	-12.2	2.3	32.1
00/1/1∼31	28.9	-8.3	3.1	34.1
00/2/1∼29	24.9	-10.0	0.4	34.5
00/3/1∼25	67.4	-2.3	5.90	63.8
00/5/16∼31	140.4	-2.7	16.9	126.2
00/6/1∼30	109.2	9.1	11.5	88.6
00/7/1∼/31	150.6	7.2	12.7	130.8
00/8/1∼/17	172.1	5.9	21.0	145.2
average	78.6	-3.0	9.6	72.1

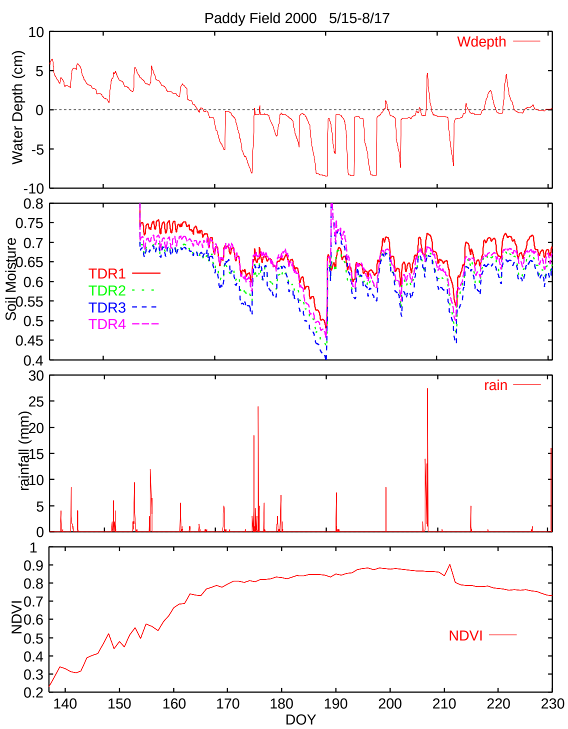

Figure 3: Time series of water depth, soil moisture, precipitation, and NDVI (2000/5/15-8/17)

Time series of water depth, soil moisture, rainfall, and NDVI from 5/15 to 8/17 in 2000 are shown in **Figure 3**. Where NDVI is a good index for vegetation growth and calculated from short-wave radiation and light quantum data. **Figure 3** will be used to decide the parameters in the water control basic rule in the next section.

5 Paddy Field Model (P-SiB2)

In the original version of SiB2, there is no framework to treat the rice paddy field (paddy field is treated same as cropland). According to the numerical simulation with original SiB2, it is difficult to calculate the diurnal variation of temperature and latent heat flux properly when a water layer exists on soil surface.

So in the modified paddy field model, a water layer which has a temperature (T_w) and depth (D_w) is added. Of cource, T_w and D_w are state variable, and the model can judge the situation of water through energy and water budget equations. P-SiB2 can treat both water-covered and water-free case.

5.1 Energy Budget

Prognostic equation for temperature

$$C_c \frac{\partial T_c}{\partial t} = Rn_c - H_c - lE_c \quad (1)$$

$$C_w D_w \frac{\partial T_w}{\partial t} = Rn_w - H_w - lE_w - \lambda_w \frac{T_w - T_g}{D_w/2} \quad (2)$$

$$C_g \frac{\partial T_g}{\partial t} = \lambda_w \frac{T_w - T_g}{D_w/2} - \frac{2\pi C_d}{\tau_d}(T_g - T_d) \quad (3)$$

$$C_d \frac{\partial T_d}{\partial t} = \frac{2\pi C_d}{\tau_d}(T_g - T_d) \quad (4)$$

Radiation budget

$$Rn_c = S\downarrow_c + L\downarrow_c - 2\sigma T_c^4 V\delta t + \sigma T_w^4 V\delta t \quad (5)$$

$$Rn_w = S\downarrow_w + L\downarrow_w + \sigma T_c^4 V\delta t - \sigma T_w^4 \quad (6)$$

$$Rn_g = 0 \quad (7)$$

5.2 Water Budget

Total water storage (M) is introduced to judge the existence of water layer.

If M is larger than saturation total soil moisture storage (S), water layer exists, and the depth of water (D_w) is equal to $M - S$.

M is calculated by water budget equation, which has terms for artificial water control (W_{in}, W_{out}).

total water storage (M)

$$M = \theta_s W_1 D_1 + \theta_s W_2 D_2 + \theta_s W_3 D_3 + (D_d + D_c \quad (8)$$
$$- \frac{E_{wi}}{\rho_w} - \frac{E_{ct}}{\rho_w} - R_o - Q_3 + W_{in} - W_{out})\Delta t$$

saturation total soil moisture storage (S)

$$S = \theta_s D_1 + \theta_s D_2 + \theta_s D_3 \quad (9)$$

depth of water layer (D_w)

$$D_w = M - S \qquad \text{(only for } D_w > 0) \quad (10)$$

Now P-SiB2 can be simulated in three mode.

1: with observed water depth

2: with observed water control

3: with assumed water level control rule

In the simulation mode 1, D_w is externally supplied. In the mode 2, artifitial water supply and drainage terms (W_{in}, W_{out}) are used to calculate D_w. If the evapotranspiration term is calculated in good accuracy, D_w should be very close to observed one from water budget equation. In the mode 3, D_w is fully predicted in the model.

5.3 Artificial Water Control

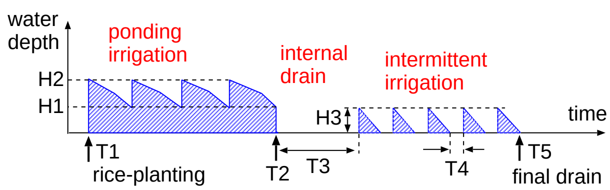

Figure 4: Water depth control rule

Water in paddy field is controlled/operated differently according to the growing stage of rice. Water depth control rule is basically expressed by three stages as follows (see **Figure 5**).

1. **ponding irrigation stage**
   Water is irrigated to keep the minimum water level (H_1)
2. **internal drain stage**
   Water is drained after the date (T_2) and kept below zero for some period (T_3).
3. **intermittent irrigation stage**
   Water level is controlled repeatedly with drying period (T_4).

Parameters used in this basic water control rule are listed in **Table 3**. Although actual variation of water depth is very complicated due to rainfall, we could guess when artitifial water control were done through the detailed analysis of observed data. According to **Figure 3**, parameters for water control were set as in **Table 3**. What has to be noticed is that the value of parameters are not constant. They are changable depending on weather condition. In fact, the value for 1999 and 2000 are different.

Table 3: parameters for artificial water control

definition	symbol	value
water irrigation rate	W_{in}	4.5mm/hr
water drainage rate	W_{out}	1.4mm/hr
rice-planting date	T_1	
internal drain start date	T_2	6/7
period of internal drain	T_3	27day
drain period for intermittent irrigation	T_4	3day
final drain date	T_5	
low level for ponding irrigation	H_1	20mm
high level for ponding irrigation	H_2	30mm
high level for intermittent irrigation	H_3	40mm

6 Numerical Simulation

Some numerical simulations are executed by using meteorological data observed at this field as forcing data. Simulation period is from 5/15 to 8/17 in 2000 and time step is one hour. Some time varing vegetation parameters are set every 10days. Models used in this simulation are as follows.

1. SiB2 (original version)
2. P-SiB2 (with water depth)
3. P-SiB2 (with operation rule)

Owing to much rainfall during this period, soil moisture keeps relatively high value (0.3) even in SiB2 simulation. So simulated energy balance by these models are good accordance with observation. If we discuss the result from the view point of water budget, SiB2 could not simulate the physical process realistically. In the P-SiB2 simulation, soil moisture value are almost same as observation even in August. In another word, the soil moisture value of 0.3 is not too low for energy budget but too low for water budget.

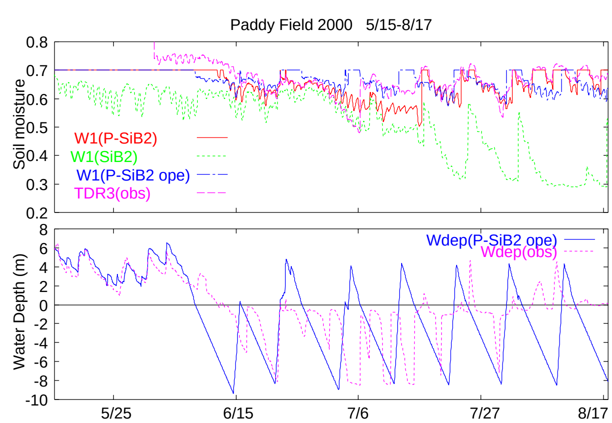

Figure 5: Soil moisture and water depth simulated by SiB2, P-SiB2(mode1), P-SiB2(mode3)