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Modeling Surface Hydrology for Global Water Cycle Simulations

Taikan OKI

Associate Prof., Institute of Industrial Science, University of Tokyo,
Tokyo106-8558, Japan

Abstract—The role of the river in global water cycles and the modeling of horizontal water transport by rivers in the global scale are discussed. Due to the consolidation of various hydrological information about the planet, it is possible now to monitor and simulate the quantity of water carried by rivers. Land surface models, that were developed originally for giving the boundary condition of the atmospheric and/or climatic models, can be used fairly well for river runoff simulations on at least a monthly scale. This promising approach will be a powerful tool to investigate future water resources management.

INTRODUCTION

Validation studies of energy and water balances estimated by various land surface models (LSMs) were performed under the global soil wetness project (GSWP). As a part of these activities, river runoff data were used as an independent observational value to examine the accuracy of estimated water balance. In this report, research activities and findings before the GSWP, the major outcomes from the validation study under GSWP, and future perspectives are briefly introduced.

RIVER—THE MISSING HYDROLOGIC LINK

Rivers carry water mass, sediment, chemicals, and various nutritional matters from continents to seas. Without rivers, global hydrologic cycles on the earth will never close.

The fresh water supply to the ocean has an important effect on the thermohaline circulation because it changes the salinity and thus the density. It also controls the formation of sea ice and its temporal and spatial variations. Annual fresh water transport by rivers and the atmosphere to each ocean is summarized in Table 1 based on the atmospheric water balance (Oki, 1999). Some part of the water vapor flux convergence remains in the inland basins. There are a few negative values in Table 1, suggesting that net fresh water transport occurs from the ocean to the continents. This is physically impossible and is caused by errors in the source data. Although a detailed discussion of the values in Table 1 may not be meaningful, it is nevertheless interesting that such an analysis does make at least qualitative sense using the atmospheric water balance method with geographical

Table 1. Annual fresh water transport from continents to each ocean (10^{15} kg year^{-1}). "Inner" indicates the runoff to the inner basin within Asia and Africa. $-\nabla_H \cdot \vec{Q}$ indicates the direct fresh water supply from the atmosphere to the ocean. N.P., S.P., N.At., and S.At. represent North Pacific, South Pacific, North Atlantic, and South Atlantic Ocean.

	N.P.	S.P.	N.At.	S.At.	Indian	Arctic	Inner	Total
from Rivers								
Asia	4.7	0.4	0.2		3.3	2.7	0.1	11.4
Europe			1.7		0.0	0.7		2.4
Africa			–0.2	0.9	–0.2		–0.4	0.1
N. America	2.9		4.8			1.1		8.8
S. America	0.5	0.4	5.7	8.3				14.9
Australia		0.1			0.1			0.2
Antarctica		1.0		0.1	0.8			1.9
Total	8.1	1.9	12.2	9.3	4.0	4.5	–0.3	39.7
from Atmosphere								
$-\nabla_H \cdot \vec{Q}$	9.9	–11.1	–12.7	–14.0	–14.0	2.2		–39.7
Grand total	18.0	–9.2	–0.5	–4.7	–10.0	6.7	–0.3	0.0

information on basin boundaries and the location of river mouths. In this analysis, it should be noted that the total amount of fresh water transport into the oceans from the surrounding continents has the same order of magnitude as the fresh water supply that comes directly from the atmosphere, expressed by $-\nabla_H \cdot \vec{Q}$.

The annual fresh water transport in the meridional direction has been also estimated based on atmospheric water balance with results shown in Fig. 1. The estimates in Fig. 1 are the net transport, *i.e.*, in the case of oceans, it is the residual of northward and southward fresh water flux by all ocean currents globally, and it cannot be compared directly with individual ocean currents such as the Kuroshio and the Gulf Stream. Transport by the atmosphere and by the ocean have almost the same absolute values at each latitude but with different signs. The transport by rivers is about 10% of these other fluxes globally (this may be an underestimate because $-\nabla_H \cdot \vec{Q}$ tends to be smaller than river discharge observed at a land surface). The negative (southward) peak by rivers at 30°S is mainly due to the Parana River in South America, and the peaks at the equator and 10°N are due to rivers in south America, such as the Magdalena and Orinoco. Large Russian rivers, such as the Ob, Yenisey, and Lena, carry the freshwater towards the north between 50–70°N.

These results indicate that the hydrological processes over land play non-negligible roles in the climate system, not only by the exchange of energy and water at the land surface, but also through the transport of fresh water by rivers which affects the water balance of the oceans and forms a part of the hydrological circulation on the Earth among the atmosphere, continents, and oceans.

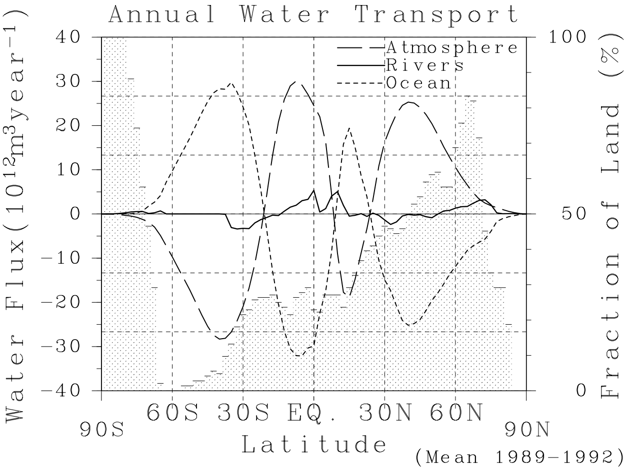

Fig. 1. The annual fresh water transport in the meridional direction by atmosphere, ocean, and rivers (land) (Oki *et al.*, 1995). Water vapor flux transport of 20 × 10^{12} m^3year^{-1} corresponds to approximately 1.6 × 10^{15} W of latent heat transport.

Table 2. Coupling levels of river routing schemes with GCMs.

Discharge	to where?	when?
Level –1	nowhere (disappear)	immediately
Level 0	everywhere	immediately
Level 0.5	nearest ocean grid	immediately
Level 1	designated river mouth	immediately
Level 2	designated river mouth	after river routing
Level 3	+ interactions at downstream grid boxes	

LEVELS OF RIVER REPRESENTATION IN GCMS

As shown in the previous section, rivers are the important players in the global hydrologic cycles that form the climate system; however, rivers have been excluded from the conventional modeling of the climate system.

We can classify the levels of representation of rivers within GCM simulations (Table 2 (Oki *et al.*, 1999)). Level –1 through 0.5 are used for short term weather forecasting. In the case of ocean-atmosphere couplings, coupling level 1 may be adopted in order to close the mass balance of water in the model. Recently a few GCMs use level 2 coupling (Miller *et al.*, 1994; Sausen *et al.*, 1994; Kanae *et al.*, 1995).

Level 3 coupling represents the effect of both artificial and natural water redistribution down stream from a river channel to the surrounding land surface.

Runoff water from an upstream grid box can evaporate at a downstream grid box by such an approach; only this process can produce negative runoff, which is actually derived from observed discharge data for drainage areas located in dry regions. Even though the effect may be regional, the process should change the water and energy balance of the neighboring land surface and have some effect on the climate system. Efforts to clarify these processes using fully coupled (level 3) atmosphere-land-river-ocean models are expected in the future, and improvements of LSMs and river routing schemes are required in order to achieve the objective.

DIGITAL RIVER

At least three components are required in order to accomplish a digital river in GCMs. These are;

(i) a river routing scheme,

(ii) information on the direction of the lateral water movement (a global river channel network), and

(iii) river discharge data.

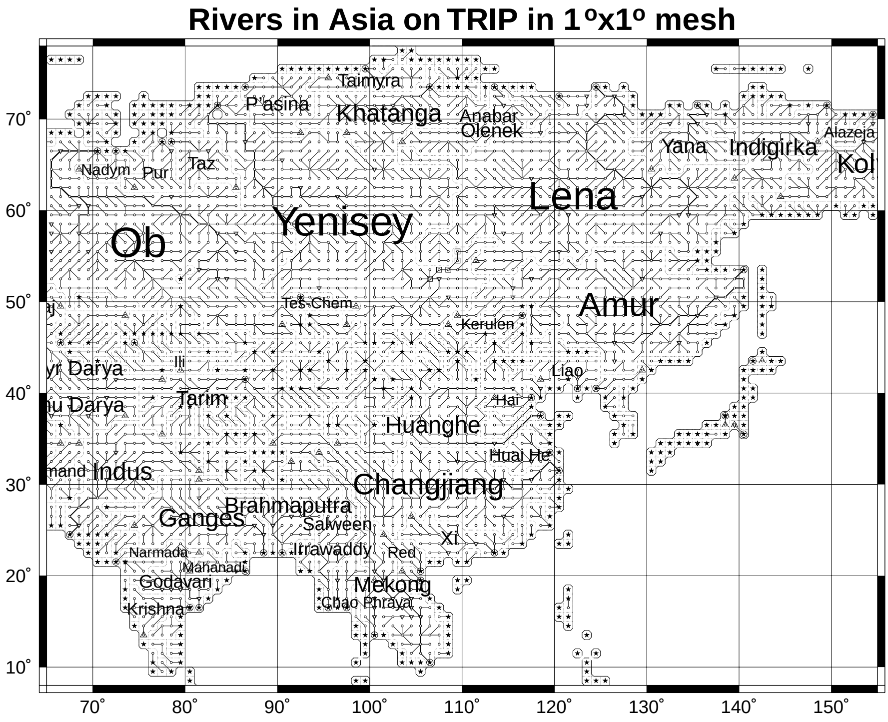

Fig. 2. A part of the 1° grid Total Runoff Integrating Pathways (TRIP), in the Asian region.

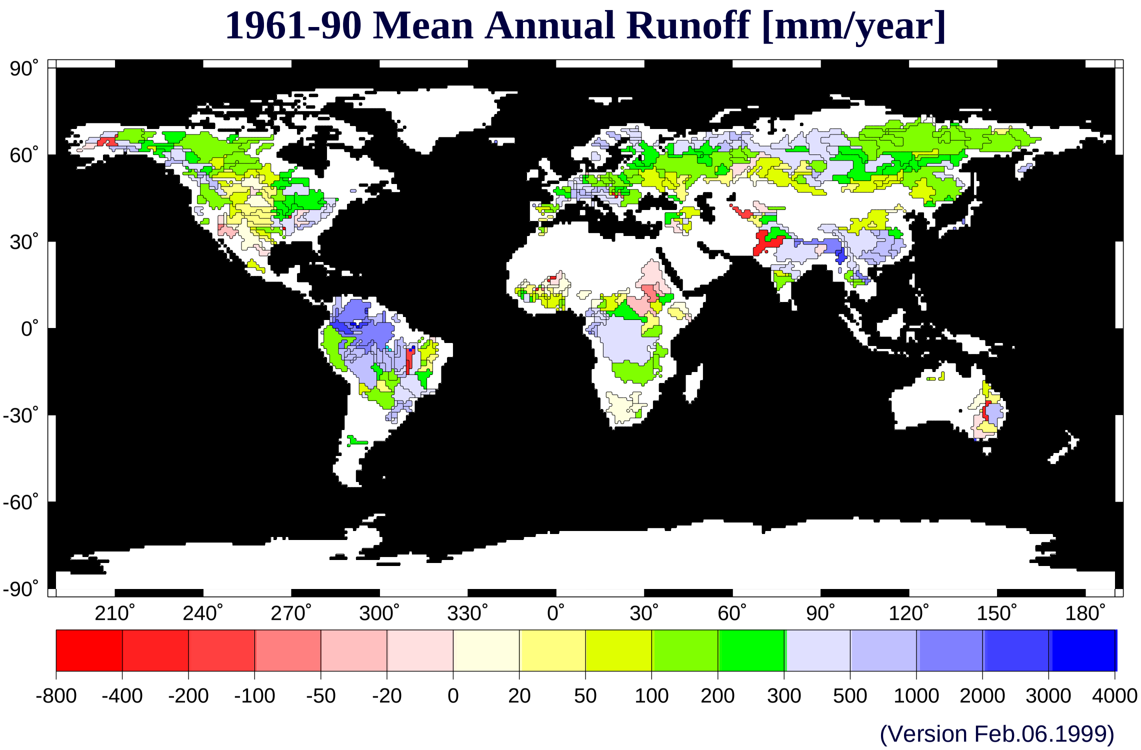

Fig. 3. Mean annual runoff (mm/y) based on gauge data. (Mean 1961–90.)

River routing schemes are commonly based on the one-dimensional Navier-Stokes equation. Because of the limitations both in obtaining all the necessary coefficients and the computational burden, simplified equations, consist only of mass conservation and the balance of friction with gravitational forcing, are widely used.

For river routing purposes, global river channel network was used in Miller *et al.* (1994), Sausen *et al.* (1994), Kanae *et al.* (1995), and Vörösmarty *et al.* (1997). However, the accuracies of these global templates and global river channel networks were not necessarily known. Accordingly, (Oki and Sud, 1998) carefully prepared a global river channel network in 1° × 1° grid boxes, named Total Runoff Integrating Pathways (TRIP). TRIP is opened for public uses and used in various research studies. A part of TRIP in the Asian region is shown in Fig. 2 (accessible from http://hydro.iis.u-tokyo.ac.jp/TRIPDATA).

Another necessity for the digital river is the observed discharge data for the validation of the simulated results. River runoff may not have significant direct influence on climate; however, it is the only observational data which represents the water balance in a large area. Therefore river runoff data are used for the validation of GCM simulations and the assessments of the interannual variations of hydrologic cycles on a global scale.

Figure 3 shows the mean annual runoff for 1961–90. The figure is derived purely from observational data at river discharge gauging stations with the templates based on 1 degree mesh TRIP. The East-West transition of the runoff in North America can be seen; high runoff values are found in South America and Southeast Asia. The negative runoff in some rivers, such as the Indus, Colorado, and other desert rivers, attract attention. It is physically reasonable because, unlike the ordinary runoff which is converted from the river discharge using the whole drainage area upstream of the station, gridded runoff is estimated using the net discharge which is the divergence of the discharge water to the grid box. Therefore, for instance, gridded runoff can be negative when the outflow from the grid is smaller than the total inflow to the grid area. Such a situation can occur either naturally or artificially due to the seepage of river water to the surrounding area of the river channel or the diversion of river water for irrigation, etc.

In many cases anthropogenic effects are not favored by researchers, and “natural” flow is estimated and simulated by numerical models. However, considering the importance of river discharge in the climate system, the simulation of “real” flow should have more importance. That also leads to the need of future development of level 3 coupling of an atmosphere-land-river-ocean model where the evapotranspiration of water originated from the river water is allowed and annual evapotranspiration can be larger than precipitation regionally due to the process. It will change the atmospheric circulation as well; some socially relevant problems, such as the termination of the river flow at the lower reach of the Yellow River in China, will not be simulated without the level 3 coupling.

Figure 4 illustrates how current land surface models can simulate river discharge using the digital river of TRIP and the linear river routing scheme with observed forcing data (Oki *et al.*, 1999). The result shows that river runoff can be

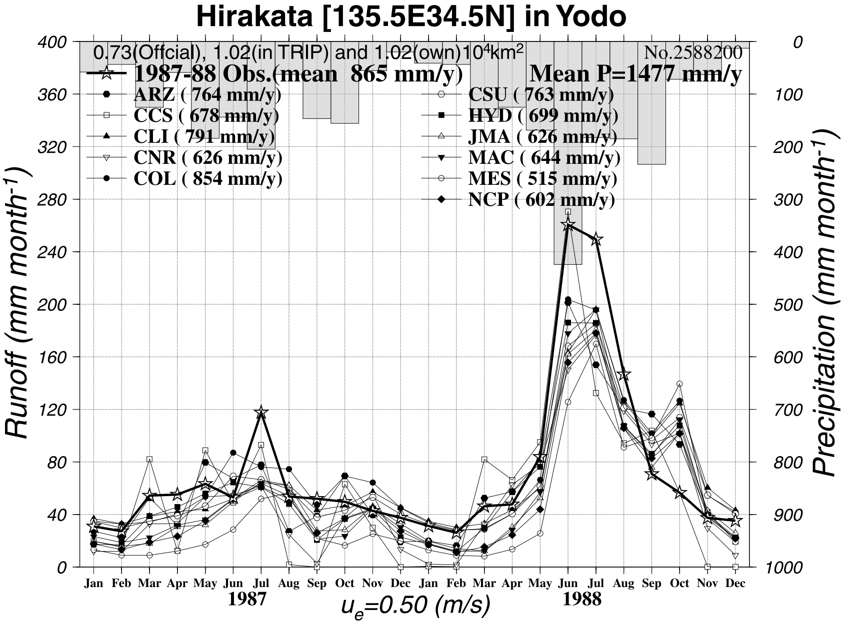

Fig. 4. Monthly runoff after river routing for the whole drainage area at Hirakata in the Yodo River Basin, Japan.

simulated fairly well with good forcing data of precipitation, radiation, etc. It is really an encouraging result and we can expect more sophisticated and consistent modeling of whole hydrologic cycles on the earth in the near future.

GSWP VALIDATION BY ANNUAL RUNOFF

Annual runoff estimated by 11 LSMs were averaged in each incremental sub-basin for 250 gauging stations, and were compared with the corresponding observations.

The mean bias of annual runoff obtained by 11 LSMs for each incremental drainage area is compared with the density of rain gauges in Fig. 5. The scatter of the bias is large for the areas with a small density of rain gauges, and the bias decreases for the areas with a larger density of rain gauges. A few plots with certain negative bias for the area with density more than 500 [/10^6 km^2] are the plots of a tiny incremental drainage area. In this case, the observed runoff may have a significant error because of the operations subtracting drainage areas and discharges in order to obtain incremental values.

The RMSE (root mean square error) for each LSM was calculated with the weight of the size of an incremental drainage area only including the drainage areas with the density of rain gauges equal to or more than certain threshold

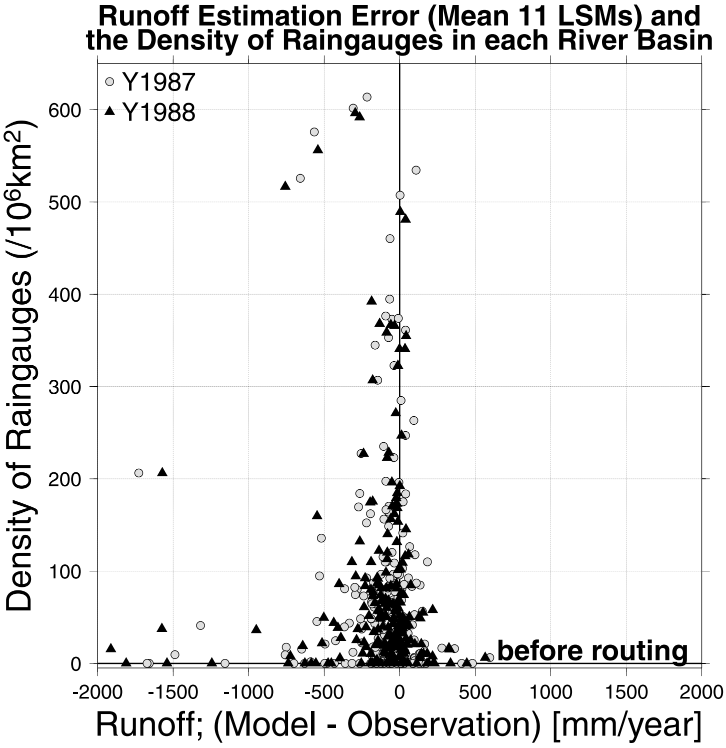

Fig. 5. Comparisons between the density of rain gauges [/10^6 km^2] used in preparing the forcing precipitation and the mean bias error [mm/y] of 11 LSMs.

values, and normalized by the weighted mean of runoff observations (Fig. 6). Generally, RMSE decreases for any LSM with the higher threshold of the minimum density of rain gauges. The dotted line in Fig. 6 denotes the number of incremental drainage areas having equal to or more than the threshold density.

From Fig. 6, the minimum density of rain gauges required to prevent the effect of poor forcing precipitation seems to be approximately 30 to 50 [/10^6 km^2]. Runoff estimates in the drainage areas with the density of rain gauges equal to or more than that do not depend on the density of rain gauges. On the contrary, if the forcing precipitation for LSMs is based on the data from rain gauges with densities of less than 30 [/10^6 km^2], the outputs from the LSMs may not be realistic and they may contain considerable errors.

The relative RMSE of annual runoff was approximately 40% for most LSMs for areas with good forcing *P*. Annual mean precipitation is approximately 800 [mm/y] for the river basins used in this study, and the mean runoff is 250 [mm/y]. Therefore the relative RMSE for estimating annual evapotranspiration by LSMs is $(100/550) \times 100 \approx 18\%$.

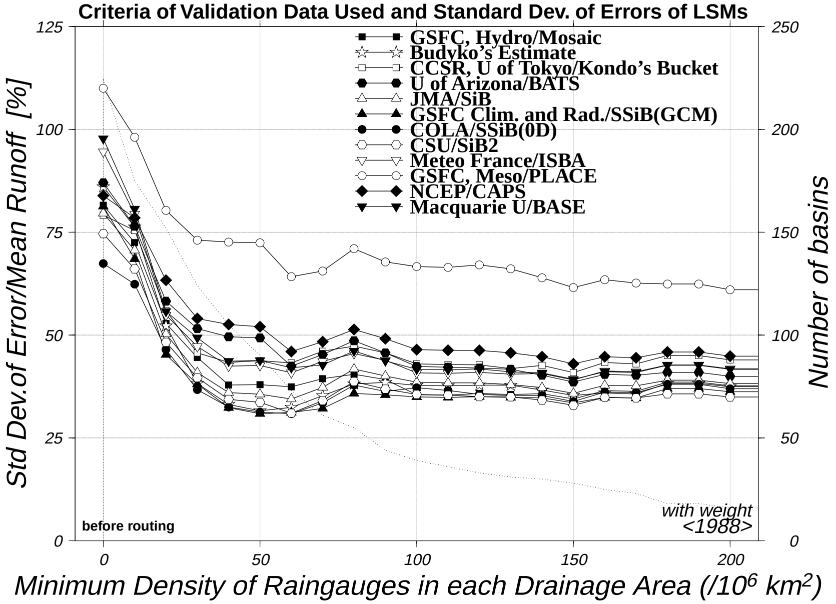

Fig. 6. Threshold of the minimum rain gauge density [/10^6 km^2] and the relative standard deviation error [%] of LSMs.

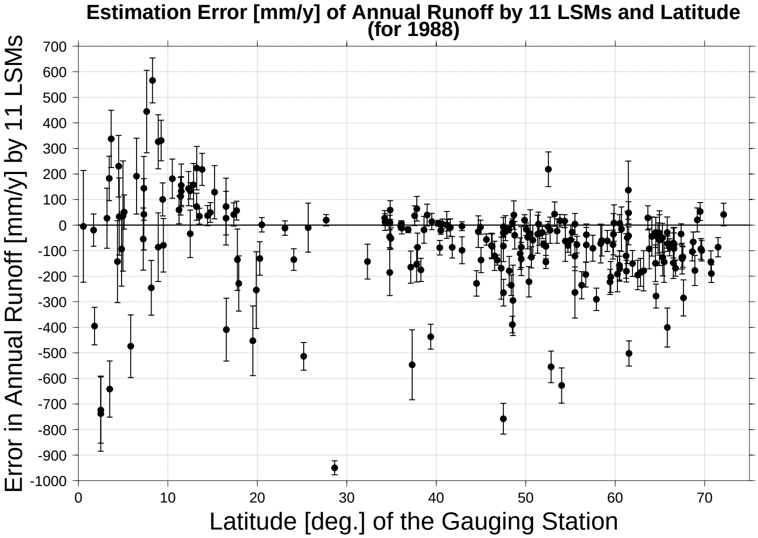

Fig. 7. Errors in annual runoff [mm/y] estimated by 11 LSMs for 1988 and latitude [deg.] of the gauging station. Vertical bars indicate the range of 1 standard deviations among 11 LSMs.

Figure 7 shows the relationship between the errors in annual runoff estimates and the latitudes of the gauging stations. The vertical bar indicates one standard deviation of errors by 11 LSMs. It is clear that the LSMs tend to underestimate the annual runoff.

Two causes of the underestimates by LSMs may be considered. One is related to the disaggregation of the monthly precipitation into 6 hourly. If the rainfall intensity is weaker and more continuous than reality, the evapotranspiration from intercepted water should be larger than reality and result in too low soil moisture and runoff. Direct runoff calculated by LSMs should be lower for weaker rain rate, as well. The same situation should happen if the partitioning of convective precipitation is smaller than that LSMs are expecting.

Another cause of the underestimates could be the observational problem of rain gauges. Strong wind will reduce the capture ratio of a rain gauge, and consequently the rain gauge will observe lower precipitation than reality. This effect is especially significant for snow; hence the underestimates are significant for higher latitudes as shown in Fig. 7.

GSWP IN THE FUTURE

Reflecting the success of the GSWP-pilot phase, the GSWP follow-on has been planned. The major changes considered are:

- 12 years of forcing data (1986–97) from ISLSCP (International Satellite Land Surface Climatology Project) Initiative II data set (CD-ROM) and
- 0.5 degree mesh over global land.

The longer period will allow us to investigate the interannual variation of energy and water budgets at the land surface, and their relationships with climatic variations. It will also reduce the spin up problem of land surface models, which is caused by the uncertainties in determining the initial values for the numerical simulations, particularly in soil wetness. The second point regarding the horizontal resolution may be controversial because atmospheric forcing data at present and in the near future may not have enough horizontal resolution to give reliable information in a 0.5 degree mesh globally. However, expectations, mainly from hydrological and ecological groups, are quite high for higher global resolution and all the data will be unified into a 0.5 degree mesh and used in the next phase of GSWP.

At this moment, the ISLSCP Initiative-II data set is scheduled to be released in late 2001. However, it will use the ECMWF Reanalysis 40 (ERA40) which may not be ready and will cause the release of Initiative-II in the year 2002. Therefore it is now proposed to organize an international coordinated project such as "GSWP-1.5." In the GSWP-1.5, a few topics are proposed;

- more numerical experiments of derived soil moisture coupled with GCMs
- regional and high resolution GSWP, probably in CSE (Continental Scale Experiment) areas under GEWEX (Global Energy and Water Cycle Experiment)

- the higher resolution GSWP results may be coupled with meso-scale models
- re-run of GSWP-1 with forcing data of high (and/or better) quality
- prepare international information infrastructure for land surface models.

This proposed framework of GSWP-1.5 will help validate/compare the interactions between the land-surface and the simulated climate or the seasonal forecasts. Further it will be a good preparation for the GSWP-2 frame work which will contribute to the validation of the inter-annual variability simulated by land-surface schemes. Regional estimates of soil moisture will still be effective for the calibration, validation, and improvements of LSMs if the target area is a data-rich region, such as CSE areas. Figure 8 illustrates the simulation of the energy flux observed at Sukhothai Paddy Field in the Chao Phraya River Basin, Thailand (99.7°E, 17.1°N, 50 m) during the GAME-Tropics Intensive Observation Period (IOP), 1998. Since no special treatment for a paddy field is considered in the original SiB2 (Sellers *et al.*, 1996), ponding water in reality just runs off in the model. It forces the surface too dry for a few days without rain and causes an unrealistic diurnal cycle. Therefore a higher capacity of water inundation and independent water temperature are introduced in the original SiB2 code, which was named SiB2-Pad; the results are shown in Fig. 9 (Arai *et al.*, 2000; Kim *et al.*, 2001). The simulation was surprisingly improved by the inclusion of a water

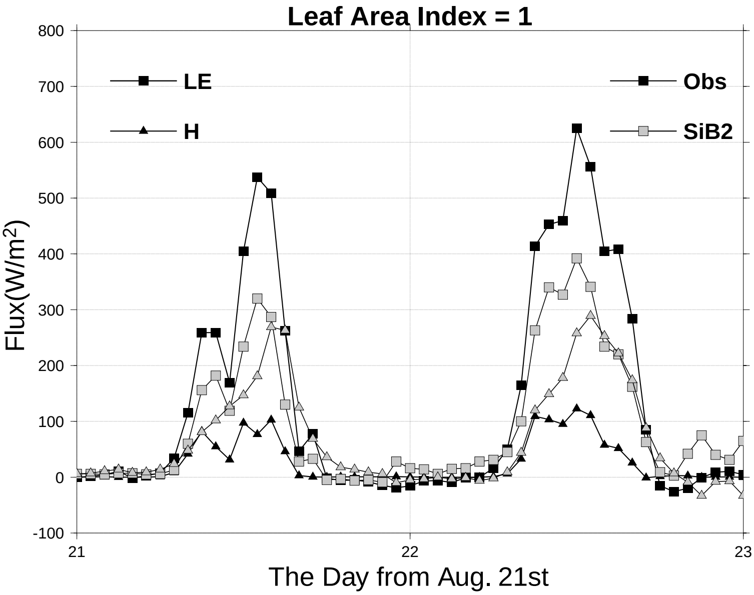

Fig. 8. Simulated diurnal cycle of the energy balance by the original SiB2 compared with observation at Sukhothai Paddy Field in the Chao Phraya River Basin, Thailand (99.7°E, 17.1°N, 50 m) during GAME-T IOP, 1998.

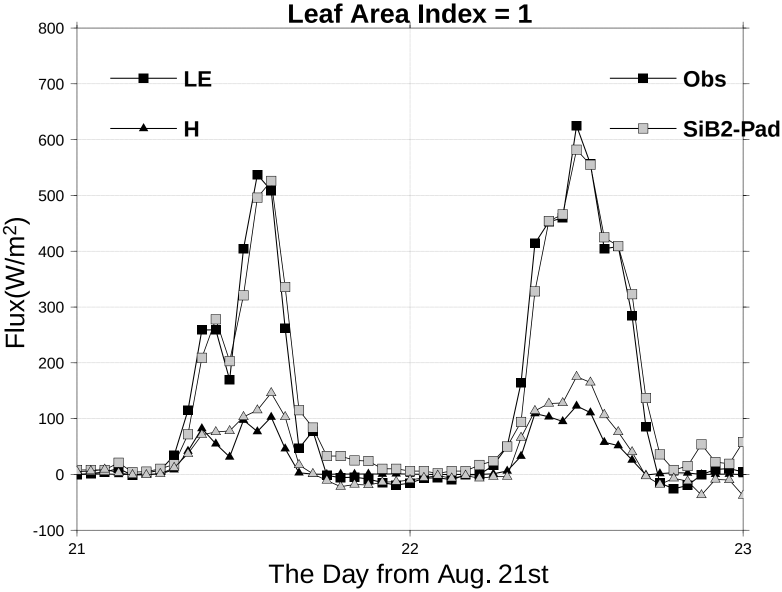

Fig. 9. Same as Fig. 8 but by a modified SiB2, SiB2-pad, with a water body.

body. This means regional runs in CSE areas will give us more opportunity to test LSMs under various conditions around the globe.

Before concluding, the importance of the "International Information Infrastructure" for land surface models should be addressed. The importance of the graphical and interactive user interface to LSMs, a Web-based database, and data visualization are recognized through the pilot-phase of GSWP. Computational resources may also be required and critical for some cases. In preparation for the future phase of GSWP, a data visualization system, using Virtual Reality Mark up Language for ISLSCP-Initiative I data, has been developed at IIS, Univ. of Tokyo, and an interactive and graphical interface with SiB2-pad is also under development. Both systems can be accessed at http://www.tkl.iis.u-tokyo.ac.jp:8080/DV/. Such activities should be underway at a few organizations separately now, but the standardization of data exchange, model portability, and benchmark tools will help for more efficient development of the systems. Those will accelerate the final achievement of the projects aiming the better land surface models for GCMs.

These research activities are now organized under the "Global Land Atmosphere System Study (GLASS)." Various intercomparison studies with point, regional, and global spatial scales, coupling issues with atmospheric models, and the international information infrastructure are included in GLASS. GLASS is now proposed for international academic communities and is evolved in 2000. Detailed information can be obtained from http://hydro.iis.u-tokyo.ac.jp/GLASS/.

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T. Oki (e-mail: taikan@iis.u-tokyo.ac.jp)