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GLOBAL ENERGY AND WATER BALANCE SIMULATION USING BUCKET MODEL FOR GSWP2

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1. INTRODUCTION

The second Global Soil Wetness Project (GSWP-2), which is charged with producing global estimates of soil moisture, surface fluxes etc. by integrating uncoupled land surface models (LSMs) using surface forcings and standardized soil and vegetation distributions, has started (Dirmeyer et al. 2002). One of the goals of the project is to compare the participating LSMs which should aid future model development. At that time, it may be helpful to the participants to provide a standard output, or a simulation result of the simplest LSM whose calculation process is entirely published. We decided to build an uncoupled bucket model (Manabe, 1969). Bucket model is a non-biosphere model, however, it is still widely used in GCM studies and moreover, early studies indicated that its simulation result compared well with basic water/energy budget components nevertheless its simplicity (Robock et al 1995). One of the merits to use simple model is that it requires less integration time compared with complex models. Also it require less workload if we modify the parameter or parameterization in the source code. Simple model is adaptable to various requests or simulation condition.

In this paper, first, we describe the model and integration process in detail. The structure of bucket model has been described in a number of earlier scientific papers, however the model output is sensitive to the parameterizations of potential evaporation or other energy/water budget components or, etc. Finally, we discuss the preliminary analysis of the result of the GSWP-2 baseline simulation.

2. MODEL DESCRIPTION

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Basically the model is identical to the model described in Robock et al 1995, which is also identical to the bucket model used by Geophysical Fluid Dynamics Laboratory (GFDL) and National Center for Atmospheric Research (NCAR) GCM in those days. The major difference between our model and that of Robock et al. 1995 is, to deal with diurnal cycle, force restore method (Bhumralkar 1975) is applied for surface temperature calculation. The schematic procedure of integration is shown in Figure. 1.

2.1 Albedo

Albedo is calculated for snow-free condition and for with snow condition respectively. Since bucket model has single vegetation class, we assumed all land area is grass land. For snow-free condition, surface albedo is fixed as

$$a = a_{base} = 0.18$$

where a is surface albedo, a_{base} is ground albedo which corresponds to the natural grass cover. For with-snow condition, or snow water equivalent (SWE) is larger than 0, surface albedo is calculated as a function of surface temperature.

$$a = a_{snow}$$

$$a_{snow} = 0.60 \quad (if\ T_S \le T_{crit} = -10^o C)$$

$$a_{snow} = 0.45 \quad (if\ T_S = T_{fra} = 0^o C)$$

$$a_{snow} = \frac{0.45(T_S - T_{crit}) + 0.60(T_{fra} - T_S)}{T_{fra} - T_{crit}} \quad (if\ T_{crit} < T_S < T_{fra})$$

where a_{snow} is snow albedo, T_s is surface temperature, T_{fra} and T_{crit} are threshold surface temperatures. For grass cover with thin snow cover (<2.0-cm water equivalent depth or SWE < 20.0 kg/m^2)

$$a = a_{base} + (0.05 \times SWE)^{1/2}(a_{snow} - a_{base})$$

Albedo parameterization is identical to Robock et al 1995.

2.2 Evaporation

The soil is allowed to evaporate at its potential rate until it reaches a critical value of soil moisture, W_C, assumed to be 75 % of its field capacity. For soil moisture values lower than W_C, evaporation is given as a fraction of its potential rate.

$$E = bE_p(T_S)$$

$$b = \begin{cases} 1 & for \quad W \geq W_C \\ \dfrac{W}{Wc} & for \quad W < W_C \end{cases}$$

where E is evaporation, E_p is potential evapotranspiration, W is soil moisture. E_p is calculated as

$$E_P(T_S) = C_D r |V| (q(T_S) - q_a)$$

where C_D is the bulk transfer coefficient = 0.003, r is the density of air, V is the wind speed, $q(T_S)$ is the specific humidity of saturated humidity, q_a is the specific humidity of air.

2.3 Sensible heat

Sensible heat (H) is given as

$$H = C_p^* r C_D |V| (T_s - T_a)$$

where C_p^* is specific heat of moist air=0.003.

2.4 Energy balance equation

In this paper, force restore method is applied to calculate surface temperature (T_S).

$$C_g \frac{\partial T_g}{\partial t} = S_D(1-a) + L_D - sT_S^4 - LE - H - C_g(T_S - T_g)w$$

$$\frac{\partial T_g}{\partial t} = -\frac{w}{\sqrt{365}}(T_g - T_S)$$

where C_g is heat capacity of soil =3.0x10^3 JK^{-1}m^{-2}, S_D is downward shortwave radiation, L_D is downward longwave radiation, s is the Stefan-Boltzman constant = 5.67x10^{-8}W(m^{2}K^4)$^{-1}$, i is latent heat of vaporization =2.50x10^6 Jkg^{-1}, w is the frequency of a day=1.16x10^{-5} sec^{-1}. T_S is calculated using iterative techniques. Finally, ground heat G is calculated as follows.

$$G = S_D(1-a) + L_D - sT_S^4 - iE - H$$

2.5 Snowmelt

Snowmelt is calculated when the land surface is covered with snow (SWE > 0) and surface temperature is above freezing point (T_{surf} > 273.15K). At that time, surface temperature is set to the freezing point (T_{surf} = 273.15K) and surface albedo, surface fluxes and energy balance is re-calculated, and energy of fusion (Q_F) is obtained.

$$S_D(1-a) + L_D - sT_S^4 - LE - H = Q_F$$

2.6 Rainfall refreezing

Rainfall refreezing is calculated when the surface temperature is below the freezing point (T_{surf} < 273.16K) and rain (not snow) falls. At that time, first, all the rainfall is assumed to be turn into snowpack and heat transferred to snowpack by rainfall (Q_a) is calculated.

$$Q_a = i_f P$$

where i_f is the energy of fusion=0.334x10^6 Jkg^{-1} and P is rainfall rate.

2.7 Snow balance

Snow mass balance is given as

$$\frac{dSWE}{dt} = S - E - M$$

where S is snowfall rate, E is sublimation of ice from soil, M is snow melt. Snow melt is drained into soil. Notice that only snow water equivalent (SWE) is taken into account and snow depth or snow density is neglected.

2.8 Water balance and runoff

The model assumes a 15-cm field capacity of available soil moisture in the uppermost 1m of the soil. Changes in available soil moisture over a given time step (3 hour) are computed using the water balance equation.

$$\frac{dW}{dt} = P - E_{soil} + M - R$$

$$E_{soil} = \begin{Bmatrix} E & for\ SWE = 0 \\ 0 & for\ SWE > 0 \end{Bmatrix}$$

$$R = \begin{Bmatrix} \dfrac{W - W_f}{dt} & for & W \geq W_f \\ 0 & for & W < W_f \end{Bmatrix}$$

where E_{soil} is evapotranspiration from soil, R is runoff.

W_f is field capacity. Evaporation from soil is allowed only in snow-free condition, and runoff is allowed if the soil moisture exceeds the field capacity.

3. Integration

The integration is followed the instruction of "B0 baseline integration" described in Dirmeyer et al. 2002. The forcing data is provided at 3-hour interval ranging from Jul/1st/1982 to Dec/31st /1995, covering whole global land area at 1^{o} resolution. The following data is forced to the model. 1) short wave radiation, 2) long wave radiation, 3) air temperature, 4) specific humidity, 5) air pressure, (6) wind speed, 7) rainfall rate, 8) snowfall. Notice that convective rainfall rate is not used in our integration. The time step is set to 3 hours and published forcing data was not further temporally interpolated. The spin-up is performed using data from Jul/1st/1982 to Dec/31st 1985. We judged that our model is sufficiently equilibrated in this two-and-half-year integration. After this spin-up, the model is integrated for 10-year period from Jul/1st/1986 to Dec/31st/1995.

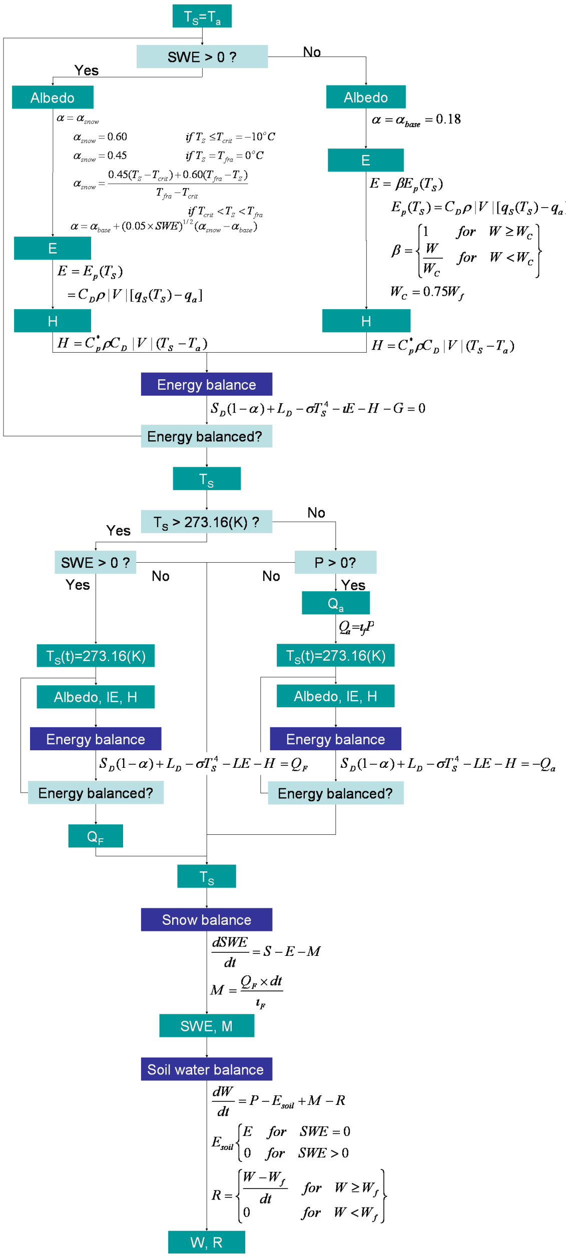

Figure 1. Schematic procedure of integration. See text for abbreviation

4. Results and discussion

The model intercomparison will be conducted by GSWP-2 Inter Comparison Center (ICC). In this paper, the simulation result was compared with the result of Project for Intercomparison of Land-surface Parameterization Schemes (PILPS) 2(a) (Chen et al., 1997) to validate our simulation. Note that forcing data used in PILPS 2 experiments (used point observed meteorological data) and that of our integration (used synthetic global data, gridded in 1^o longitude/latitude resolution, based on reanalysis, field observation, etc.) is not identical.

In PILPS 2(a) experiment, one year observed meteorological data for 1987 at Cabauw, the Netherlands (51^{o}58'N, 4^{o}56'E) is forced to the LSMs. We prepared the simulation result of 1^o longitude/latitude computational grid box at N51^{o}30', E4^{o}30' from Jan/1st/1987 -Dec/31st/1987 and compared each other.

Figure 2 shows the results of monthly surface temperature. Our simulation result is systematically higher than that of PILPS model mean, and the both are higher than the observed value. The mean annual surface temperature of our simulation is 281.8K and observed radiative temperature is 280.6K. Chen et al. 1997 mentioned that most PILPS models predicted radiative temperature between 281K and 282K and our model lies within the range.

Figure 3 shows monthly latent heat flux. The figure shows consistent overestimation from April to October. It can be attributed to relatively high estimation of soil moisture or the tendency of overestimation of surface temperature.

Figure 4 shows the monthly sensible heat flux. By contrast to the case of latent heat flux, calculated sensible heat flux is underestimated by 10-20 W/m^2. The bucket model participated to the PILPS 2(a) also overestimated latent heat and underestimated sensible heat. Chen et al. 1997 mentioned that this is because bucket model did not include stability adjustments in its bulk transfer relations. We are investigating whether we should modify this parameterization. Figure 5 shows the surface energy budget.

Figure 6 shows daily soil moisture. Since the critical value of soil moisture, W_C , was assumed to be 75 % of its field capacity (i.e. 112.75 kg/m^2), soil moisture evaporated in its potential rate in the most of calculation period. Unfortunately, soil moisture was not observed at Cabauw for 1987, so we suspend further validation.

Figure 7 shows calculated monthly water components and Table 1 shows the annual water budget. First, our forcing precipitation is almost double of that of observed. This high precipitation caused the high estimation of evaporation and runoff. The critical problem of annual calculation is that the water components do not balance. We validated our model altogether 3 stations, however, no such imbalance was observed. We will modify the problem until the annual meeting.

Figure 8 shows calculated snow water equivalent (SWE). Snow component was not mentioned in Chen et al. 1997. We checked the SWE calculation at PILPS 2(d) experiment site (Valdai, Russia, 57^{o}58'N, 33^{o}14'E) (Slater et al., 2001), and confirmed that the typical SWE pattern of the site is satisfactorily reproduced (not shown).

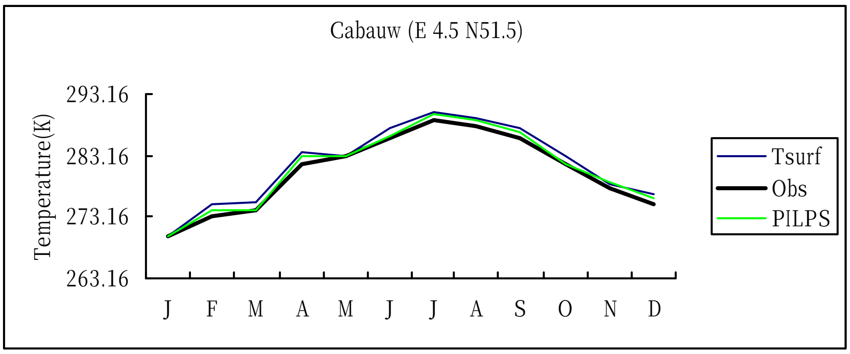

Figure 2. Calculated bare soil temperature of grid cell (N51^{o}30', E4^{o}30') and the corresponding results of PILPS 2(a)

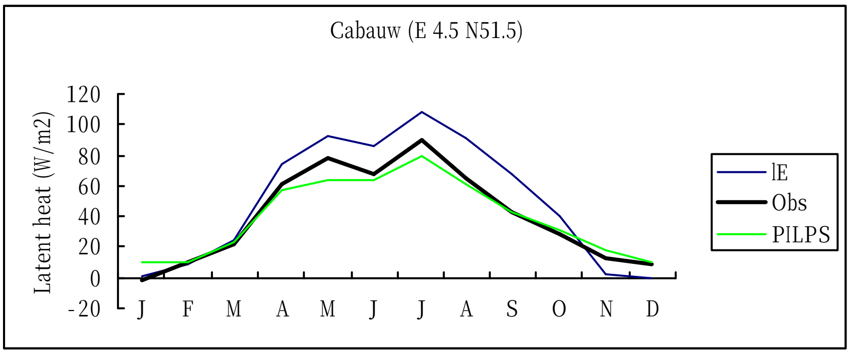

Figure 3. Calculated latent heat flux of grid cell (N51°30', E4°30') and the corresponding results of PILPS 2(a)

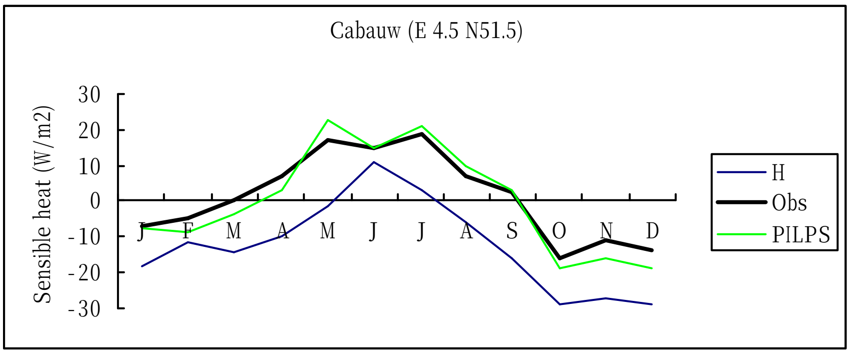

Figure 4. Calculated sensible heat flux of grid cell (N51°30', E4°30') and the corresponding results of PILPS 2(a)

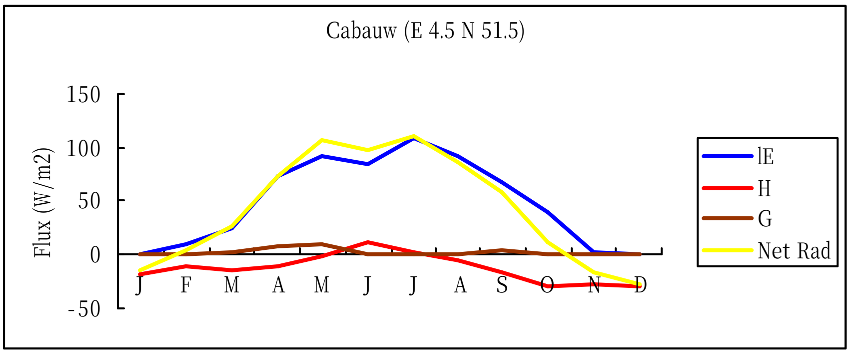

Figure 5. Calculated surface fluxes of grid cell (N51°30', E4°30')

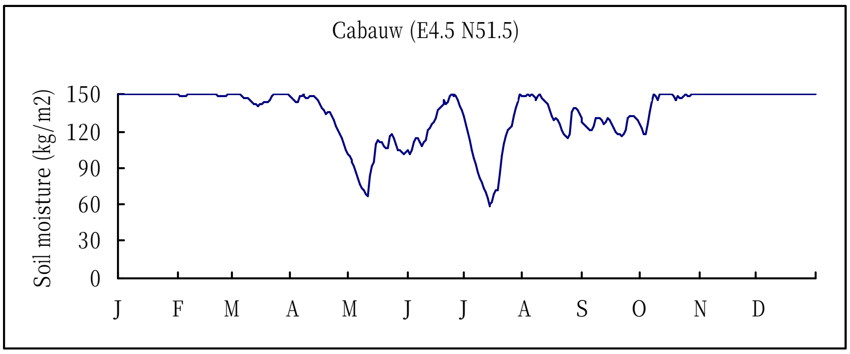

Figure 6. Calculated soil moisture of grid cell (N51°30', E4°30')

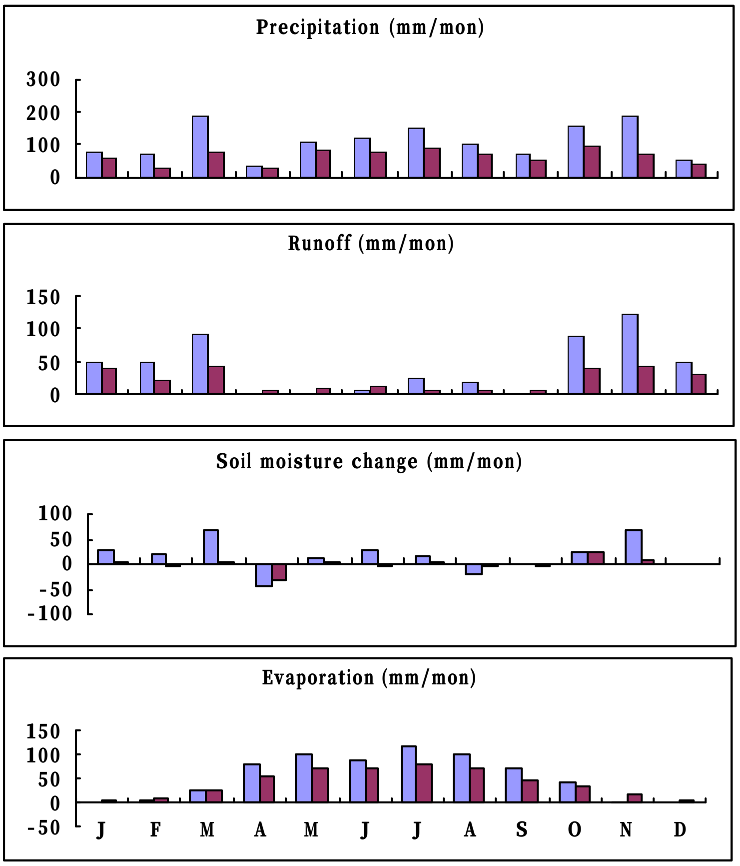

Figure 7. Calculated water budget components.

Blue for our calculation, red for model mean (except precipitation) of PILPS 2(a)

Table 1. Calculated water budget of grid cell (N51°30', E4°30') and the corresponding results of PILPS 2(a)

	Calculation	Ratio	Bucket*	Ratio	Observation**	Ratio
Total precipitation (mm/year)	1323	1	776	1	776	1
Total evaporation (mm/year)	631	0.48	705	0.91	526	0.68
Runoff (mm/year)	505	0.38	71	0.09	250	0.32
Balance (mm/year)	187	0.14	0	0	0	0

* Bucket model participated in PILPS 2(a) ** Estimation using latent heat flux observation

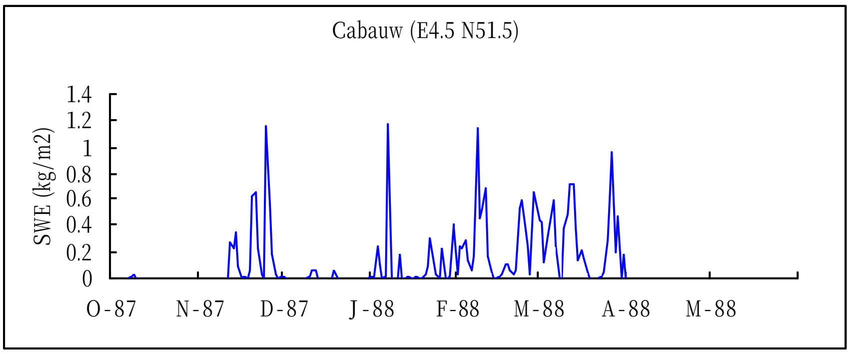

Figure 8. Calculated snow water equivalent (SWE) of the grid cell (N51°30', E4°30')

Summary

A bucket model for uncoupled integration was developed for GSWP-2 and its parameterization and integration procedure were described in detail. Our simulation result was validated with observed and model mean data of PILPS 2(a). Although the forcing data for each project was not identical, our energy balance components agreed well with both observed and model mean ones. Water balance components, however, showed large discrepancy between two projects. It is due to the large difference in precipitation forcing data. Besides this, a critical problem is found that annual water components do not balance. We must promptly fix the problem.

Our model has much simpler source code and requires less integration time compared with complex biosphere models. Our model can be utilized for various sensitivity studies for LSMs intercomparison

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