NOTES AND CORRESPONDENCE

Estimation of Land Surface Hydrology in JMA Global Model by Using the Runoff Ratio in Major River Basins

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(Manuscript received 19 January 1998, in revised form 6 August 1998)

Abstract

Using an atmospheric general circulation model (JMA89), basinwide water balances of 27 major rivers were estimated and compared with actual observations. Two different deep cumulus convection schemes were used in the 10-year integrations from 1979 to 1988 that were forced by the observed global sea surface temperature boundary conditions.

Results show that the Prognostic Arakawa-Shubert (PAS) scheme can simulate more realistic global distributions of annual mean precipitation than the Kuo scheme. In both cases, simulated annual mean precipitation, and simulated runoff coincides with the observations fairly well. The differences in precipitation or runoff between model simulations and observations are caused by the land surface hydrology and other parts of the model, and these two factors cannot be distinguished from each other. To check the reliability of the parameterizations in land surface hydrology in a simple biosphere (SiB) model, simulated runoff ratio (runoff/precipitation) is compared with the observations for each river basin. There are considerable difference between simulations and observations for runoff ratios. Differences in runoff ratios (observations minus simulations) for each river basin are significantly negative because when compared to the observations simulated runoff has been considerably overestimated. Simulated runoff has been greatly overestimated in most river basins where the observed runoff is less than 200 mm/year and the runoff ratio is less than 0.2. It is demonstrated that the parameterizations of land surface hydrology in the SiB model tend to overestimate the runoff or to underestimate the evapotranspiration in dry regions.

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1. Introduction

The atmospheric general circulation model (AGCM) is a powerful tool in the search for a better understanding of the mechanisms associated with global water circulation. To gain a more accurate representation of land-surface processes in AGCM, various kinds of hydrological parameterizations including biospheric models, have been developed, such as the biosphere atmosphere transfer scheme (BATS) of Dickinson *et al.* (1986) and the simple biosphere (SiB) of Sellers *et al.* (1986). However, very few observed data are available to validate the parameterizations of land-surface hydrology. Runoff is one of the important components of the hydrological cycle through large-scale river basins, and the long-term observation data is readily available. The comparison of model-simulated runoff with observations is a very useful method for checking the reliability of the parameterizations of land-surface hydrology.

The annual mean runoff for the world's major rivers is derived from AGCM, and further compared with observations (Russell and Miller, 1990). Their results show that runoff depends to a great extent on model precipitation and the parameter of ground-water storage and evapotranspiration, influenced by soil type and vegetation. Sausen *et al.* (1994) also simulated runoff using an AGCM in conjunction with a river transport scheme, and model simulated runoff equate well qualitatively with the observations. Oki *et al.* (1995) attempted to estimate runoff using an atmospheric water balance method, and showed that generally there was a good correspondence between their estimation and the observations, especially in the mid- and high-latitude regions of the Northern Hemisphere.

The purpose of this paper is to validate the reliability of land surface hydrology simulated by an AGCM using the method of basinwide water balance. The deep cumulus convection scheme directly changes the global distributions of precipitation, furthermore it also has a considerable influence on the simulation of land surface hydrology. Therefore, we compare the differences in precipitation patterns between observations and the results of the two convection schemes. The annual mean precipitation and runoff for each major river basin are computed based on 10-year integrations employing prescribed observed sea surface temperatures (SSTs), and are compared with these observations. The simulated runoff ratio is also compared with observations for each vegetation type to estimate the land surface hydrology in the SiB model.

2. Model description and observational data

The model used for this study is a T42 GCM version of the Japan Meteorological Agency (JMA)

global model for operational weather forecasting (JMA, 1993; Sugi *et al.*, 1990). The horizontal resolution of the model is equivalent to approximately 2.8° latitude $\times$ 2.8° longitude. The model has 21 unevenly spaced levels, the top of which is at 10 hPa. A simple biosphere (SiB) model is used for the parameterizations of land-surface hydrologic processes (Sato *et al.*, 1989). Two different deep convection schemes, modified Kuo (Kuo, 1974) and the prognostic Arakawa-Schubert (PAS) (Arakawa and Schubert, 1974), were used for the present study. Using the observed SST data for the Atmospheric Model Inter-comparison Project (AMIP), the model output of the 10-year integration from 1979 to 1988 were used to compute the basinwide water balances of major rivers.

Runoff data observed at gauging stations is provided by the Global Runoff Data Centre. The 27 major rivers selected all have areas greater than 100,000 km². Long-term mean values were obtained by averaging the data for the period available at each station. The river basins were defined with the use of published world maps on the basis of a horizontal resolution of approximately 2.8 degrees both in longitude and latitude. Precipitation amounts observed at gauging stations were based on the Monthly Station Precipitation Data derived from NOAA Baseline Climatological Data Sets (Baker *et al.*, 1994), and all gauging station data for a specific river basin was averaged on a monthly basis.

3. Comparison of the results of the two different convection schemes

3.1 Global distributions of precipitation

The differences in annual mean precipitation between the Kuo and PAS schemes, and the observations are shown in Figs. 1a and 1b, respectively. Dark/light areas of shading denote that the simulated variables of the Kuo or PAS scheme are less/more than those observed. Precipitation patterns simulated by the Kuo scheme show large differences with the observations. The annual mean precipitation simulated by the Kuo scheme is lower than the observations over the inland regions of the Amazon and the western regions of Central Africa. Conversely, the simulated values by the Kuo scheme are larger in the vicinity of the Amazon estuary, the eastern regions of Central Africa and the Tibetan Plateau. Sugi *et al.* (1995) reported that the 34-year integrations using by the JMA global model with the Kuo scheme showed several differences from the observations in these three areas. It suggests that these differences in precipitation patterns are derived from the characteristics of the Kuo scheme. In the case of the PAS scheme, the simulated annual mean precipitation is smaller than the observations in South America's southern regions, the Africa western regions, over the coastal regions of

Fig. 1. The difference of more than 500 mm/year in annual mean precipitation between the Kuo (a) or PAS (b) scheme and observations, respectively. Dark/light areas of shading denote that the simulated variables of the Kuo or PAS scheme are less/more than those of observation.

Table 1. Comparisons between simulated and observed precipitation and runoff (modified Ichianagi *et al.*, 1997). Underlining defined in Subsection 4.1.

River Name (Region)	Precipitation (mm/yr)			Runoff (mm/yr)		
	NOAA	Kuo	PAS	GRDC	Kuo	PAS
Amazonas (S. America)	2197	1355	2110	1053	491	990
Zaire (Africa)	1527	1052	1331	349	412	459
Ob (Russia)	440	433	303	134	205	151
Yenisei (Russia)	482	493	471	229	252	236
Lena (Russia)	347	413	370	216	218	207
Parana (S. America)	1172	1191	913	268	<u>582</u>	<u>429</u>
Amur (Russia)	467	652	561	150	248	237
Changjiang (Asia)	851	1988	1518	465	1370	905
Mackenzie (N. America)	346	478	469	168	187	184
Volga (Russia)	534	628	457	188	276	222
Missouri (N. America)	580	462	496	54	<u>140</u>	<u>147</u>
Niger (Africa)	450	217	<u>39</u>	34	50	26
Murray (Australia)	534	426	112	8	31	21
Zambeze (Africa)	800	945	991	112	<u>404</u>	<u>396</u>
Indus (Asia)	583	<u>207</u>	<u>304</u>	86	93	184
Danube (Europe)	749	573	795	253	153	264
Huanghe (Asia)	408	<u>970</u>	530	56	<u>511</u>	<u>211</u>
Colombia (N. America)	432	584	627	4	<u>365</u>	<u>313</u>
Colorado (N. America)	329	296	245	280	<u>159</u>	<u>102</u>
Dniepr (Russia)	576	564	552	101	<u>214</u>	<u>202</u>
Brahmaputra (Asia)	1507	1810	1270	1541	1183	643
Northern Dvina (Russia)	550	629	534	302	320	271
Xijiang (Asia)	1427	2010	1664	681	1038	657
Blue Nile (Africa)	929	<u>2137</u>	1050	150	<u>1542</u>	<u>735</u>
Araguaia (S. America)	1677	1327	1439	604	444	569
Fraser (N. America)	455	<u>838</u>	<u>917</u>	396	504	551
Euphrates (Asia)	684	345	513	269	163	172

Australia and the ocean regions of Asia: By contrast, the simulations with this scheme are larger than in the Tibetan Plateau.

Comparing the Kuo and PAS schemes, the simulations of global distribution of precipitation calculated by the PAS scheme are more accurate than those calculated by the Kuo scheme, especially over the inland Amazon regions and the eastern regions of Central Africa. However, the Kuo and PAS schemes tend to simulate lower levels of precipitation in the western regions of Africa, and higher levels over the Tibetan Plateau.

3.2 Basinwide precipitation and runoff

Next, we examined which cumulus convection scheme can realistically reproduce water balance for specific river basins. The 27 rivers selected in this study are listed in Table 1. The basinwide precipitation and runoff are the summation of precipitation and runoff at each grid box within each river basin, respectively. Comparisons between the model simulations (Kuo and PAS) and the observations are also shown. Figures 2a and 2b are the scatter diagrams of the model-simulated precipitation and runoff with observations, respectively. The correlation coefficients

of precipitation between the Kuo and PAS schemes and the observations are 0.67 and 0.88, respectively. Figure 2a indicates that there is a good correspondence between the amount of precipitation simulated by both schemes and that of the observations, the PAS scheme is closer to the observations.

The correlation coefficients of runoff between the Kuo and PAS schemes and the observations are 0.51 and 0.68, respectively. Figure 2b indicates that the Kuo scheme tends to both over estimate and underestimate in the river basins where the observed runoff is less than 500 mm/year or more than 1,000 mm/year, respectively. The PAS scheme evidently overestimates in most river basins except the Brahmaputra river basin. Comparing the Kuo and PAS schemes, it is apparent that the PAS scheme can simulate annual mean precipitation and runoff more accurately than the Kuo scheme.

4. Differences in the runoff ratio between simulations and observations

4.1 Basinwide runoff ratio

As a result of the comparisons between the Kuo and PAS schemes, it is clear that the PAS scheme

can simulate global distributions in annual mean precipitation and basinwide water balance more accurately than the Kuo scheme. The differences in precipitation or runoff between model simulations and observations are caused not only by the land surface hydrology, but also by the other parts of AGCM. For example, if the simulated precipitation is similar to observation and simulated runoff is not, the correlation coefficient of precipitation between model simulation and observations will be better. But, the parameterizations of land surface hydrology is still inaccurate. It is better to use the runoff ratio for each river basin, to check the reliability of the parameterizations in land surface hydrology. The precipitation is divided into evapotranspiration, runoff and soil storage, and it is possible to omit soil storage by considering the long-term averaged water balance. The simulated runoff ratio is then compared with the observations for each river basin.

The runoff ratio for each river basin is estimated based on the annual mean precipitation and runoff in Table 2. In the Brahmaputra river basin, the runoff ratio is greater than unity because the observational period of runoff in this river was too short, and this figure cannot represent the annual mean value. Therefore, we will not consider the Brahmaputra river basin in further study. Figure 3 is the scatter diagram of the runoff ratio between model simulations and observations. The correlation coefficients of runoff ratio between the Kuo and PAS schemes and the observations are 0.39 and 0.21, respectively. There is no relationship between the simulations and the observations, and differences between the Kuo and PAS schemes in terms of the runoff ratios are not evident. In both cases, the runoff ratio is more or less than the observations, especially for the river basins where the observed runoff ratio is less than 0.20 (group A) and more than 0.80 (group B), respectively. It is very interesting that basinwide precipitation and runoff show good correlations between the simulations and the observations, but basinwide runoff ratio does not. This result shows that the differences between simulations and observations for the river basins where precipitation and runoff are small, are increased by the standardization of precipitation. It suggests that the parameterizations of land surface hydrology in the SiB model can not reproduce a realistic water balance in these river basins.

We consider which scheme differs from the observation in terms of precipitation and runoff. Simulated annual mean precipitation, runoff and the runoff ratio in group A and B are underlined in Table 1 and 2. For several of the river basins (Niger, Indus, Huanghe, Blue Nile and Fraser) there are large differences in the figures for precipitation. Those for runoff disparities are observed for most of the river basins in group A (Parana, Missouri, Zam-

Fig. 2. The scatter diagrams of simulated annual mean precipitation (a) and runoff (b) with observations, for each river basin.

beze, Indus, Huanghe, Colombia, Colorado, Dniepr and Blue Nile) in Table 1. This result clearly shows that the differences in the runoff ratios are mainly caused by overestimations in the runoff simulations.

4.2 Runoff ratio for each types of vegetation

The runoff in the SiB model is simulated from the result of precipitation minus evapotranspiration, and its hydrological process has two components. One is surface runoff, which occurs when the effective precipitation rate is more than the infiltration rate into the surface soil, and the other is the gravitational river of water in soil layers. These parameters, which simulate the amount of evapotranspiration and runoff, are determined by the types of indigenous vegetation. Therefore, we considered

Table 2. Comparison between simulated and observed runoff ratios. For groups A and B and indigenous vegetation type refer to Fig. 3 and Table 3, respectively. Underlining defined in Subsection 4.1.

River Name (Region)	Runoff Ratio			Group A, B	Vegetation Type
	Obs.	Kuo	PAS		
Amazonas (S. America)	0.48	0.36	0.47		1
Zaire (Africa)	0.23	0.39	0.34		6
Ob (Russia)	0.31	0.47	0.50		4
Yenisei (Russia)	0.47	0.51	0.50		4
Lena (Russia)	0.62	0.53	0.56		5
Parana (S. America)	0.23	<u>0.49</u>	<u>0.47</u>	A	6
Amur (Russia)	0.32	0.38	0.42		5
Changjiang (Asia)	0.55	0.69	0.60		3 and 11
Mackenzie (N. America)	0.48	0.39	0.39		4
Volga (Russia)	0.35	0.44	0.49		3
Missouri (N. America)	0.09	<u>0.30</u>	<u>0.30</u>	A	7
Niger (Africa)	0.08	0.23	<u>0.67</u>	A	8
Murray (Australia)	0.02	0.07	0.19		6
Zambeze (Africa)	0.14	<u>0.43</u>	<u>0.40</u>	A	2
Indus (Asia)	0.15	<u>0.45</u>	<u>0.61</u>	A	9
Danube (Europe)	0.34	0.27	0.33		3
Huanghe (Asia)	0.14	<u>0.53</u>	<u>0.40</u>	A	11
Colombia (N. America)	0.01	<u>0.63</u>	<u>0.50</u>	A	4
Colorado (N. America)	0.85	<u>0.54</u>	<u>0.42</u>	B	4 and 8
Dniepr (Russia)	0.18	<u>0.38</u>	<u>0.37</u>	A	2
Brahmaputra (Asia)	1.02	<u>0.65</u>	<u>0.51</u>		11
Northern Dvina (Russia)	0.55	0.51	0.51		4
Xijiang (Asia)	0.48	0.52	0.39		1
Blue Nile (Africa)	0.16	<u>0.72</u>	<u>0.70</u>	A	6
Araguaia (S. America)	0.36	0.33	0.41		1
Fraser (N. America)	0.87	<u>0.60</u>	<u>0.60</u>	B	4
Euphrates (Asia)	0.39	0.47	0.34		7

Fig. 3. The scatter diagram of simulated runoff ratios with observations for each river basin. Groups A and B show the river basins where the difference is greater than 0.2.

the difference in runoff ratios between model simulations and observations for each type of vegetation. There are 13 types of indigenous vegetation in the SiB model, which are listed in Table 3. When a vegetation type predominates in a river basin, we define it as the representative vegetation type for that river basin. However, we could not obtain appropriate vegetation types in the Changjiang and Colorado river basins because those river basins have more than two types of indigenous vegetation. The runoff ratio for each river basin is shown in Table 2, but there are no river basins with vegetation types 10, 12 or 13. Figure 4 shows the differences in the runoff ratios (observations minus simulations) for each vegetation type. A notable feature is that the differences in runoff ratios tend to be negative for most of the vegetation types, and there are some river basins in group A which contain many vegetation types (2, 4, 6, 7, 8, 9 and 11). In addition, there is a wide range of runoff ratios for vegetation types 4, 6 and 8. These results show that the differences in runoff ratios between model simulations and observations can not be explained only by the differences in vegetation types.

Table 3. The list of 13 vegetation types in the SiB model (quoted from Sato *et al.*, 1989).

Number and explain of vegetation types in SiB Model (quoted from Sato <i>et al.</i> , 1989)	
1:	broadleaf evergreen
2:	broadleaf deciduous
3:	mixed broadleaf deciduous and needleleaf evergreen
4:	needleleaf evergreen
5:	needleleaf deciduous
6:	grass and broadleaf shrubs
7:	grass
8:	broadleaf deciduous shrubs
9:	broadleaf deciduous shrubs, growing singly or in patches (semi-desert)
10:	tundra
11:	desert
12:	cultivated land represented by wheat
13:	glacier or permanent land ice cover

Fig. 4. The difference between the observed (GRDC/NOAA) and simulated runoff ratios for each vegetation type.

Fig. 5. Observed annual mean runoff (GRDC) and runoff ratios for each river basin distinguished by the vegetation types and groups.

Figure 5 shows the observed runoff (GRDC) and runoff ratio for each river basin excluding the Changjiang and Colorado river basins. Observed runoff is more than 600 mm/year in all river basins where broadleaf evergreen is predominant (vegetation type 1). There is a wide range in the runoff ratios in the river basins where needleleaf evergreen and grass and broadleaf shrubs are predominant (vegetation type 4 and 6). The annual mean runoff is less than 200 mm/year and the runoff ratio is less than 0.2 in all the broadleaf deciduous, broadleaf deciduous shrubs, broadleaf deciduous shrubs growing singly or in patches (semi-desert) and deserts (vegetation type 2, 8, 9 and 11) river basins and in a few river basins where needleleaf evergreen, grass and broadleaf shrubs and grass predominate (vegetation type 4, 6 and 7). Most of them belong to groups A or B. Clearly there are large differences in the runoff ratios between the model simulations and observations for most of the river basins, where the annual mean runoff is less than 200 mm/year and the runoff ratio is less than 0.2.

5. Conclusions

Basinwide water balances for 27 major river basins simulated by the JMA89 global model with the Kuo and PAS deep cumulus convection schemes, were compared with observed data. The PAS scheme was found to simulate the global distribution in annual mean precipitation, and basinwide precipitation and runoff, more accurately than the Kuo scheme. However, in both schemes simulated runoff ratios were much larger than the observed data. The differences between the runoff ratios of the observations and those of the simulations are significantly negative because simulated runoff was overestimated to a considerable extent. Specifically, simulated runoff was remarkably overestimated in those river basins where observed runoff is less than 200 mm/year, and the runoff ratio is less than 0.2. It shows that the parameterizations of land surface hydrology in the SiB model tend to overestimate the runoff, or underestimate the evapotranspiration in dry regions.

Acknowledgments

The authors would like to thank NOAA and the Global Runoff Data Centre, for providing precipitation and runoff data sets, respectively. The GRDC data sets used here are from the Mushiaki Laboratory in the Institute of Industrial Science, University of Tokyo. Special thanks go to Dr. I. Yagai and Dr. R. Kawamura at the National Research In-

stitute for Earth Science and Disaster Prevention, Dr. K. Takata at the National Institute for Environmental Studies and Mr. S. Iizuka at the Institute for Global Change Research for their helpful advice on this manuscript.

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大河川流域の流出率による気象庁全球モデルの陸面水文過程の評価

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気象庁全球モデル (JMA-GSM89) の陸面水文過程を評価するために、流域面積の大きな 27 の河川について降水量と流出量を計算し、観測値と比較した。陸面水文過程には SiB モデルを、積雲対流スキームは Kuo 方式と PAS 方式の 2 つを用いた。1979–1988 年の海面温度を境界条件として 10 年間積分し、その年平均値について解析した。

モデルの降水量の全球分布は、PAS 方式が Kuo 方式よりも観測値に近い。流域ごとに見ると、両方式ともモデルの降水量と観測値はかなり高い相関があるが (相関係数、Kuo 方式：0.67、PAS 方式：0.88)、流出量はこれより相関が低い (相関係数、Kuo 方式：0.51、PAS 方式：0.68)。モデルの降水量や流出量は、モデルの陸面過程以外の部分の影響も大きく受ける。そこで、陸面水文過程の評価を行うために流出率 (流出量/降水量) を計算し観測値と比較した。モデルの流出率は観測値よりも大きい河川流域が多く、Kuo 方式、PAS 方式ともに観測値との相関は小さい。とくに観測値の流出量 200 mm/year より少なく、流出率が 0.2 の河川流域では、モデルは流出量を過大評価している。このことは、SiB モデルが乾燥地域で流出量を過大評価する、あるいは蒸発散量を過小評価する傾向にあることを示している。

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